Universidade de Aveiro Departamento de
Electrónica, Telecomunicações e Informática,
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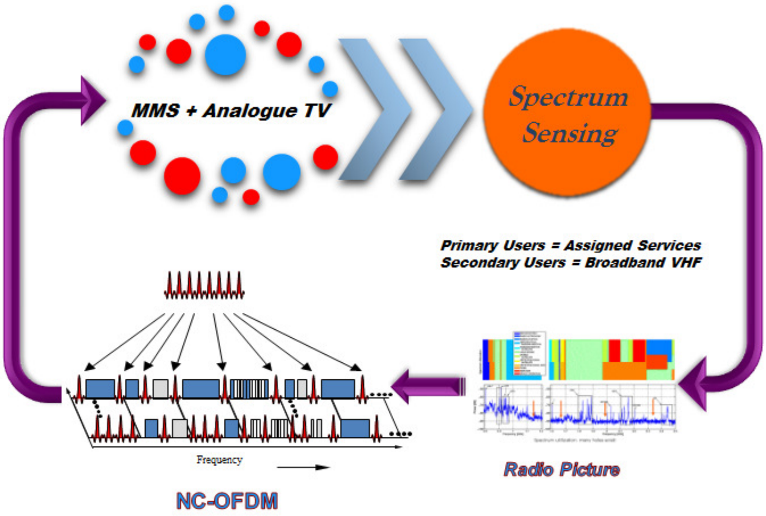
Broadband VHF Maritime Communications Based on Cognitive Radio



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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Electrotecnica, realizada sob a orientação científica do **Professor Doutor Nuno Miguel Gonçalves Borges de Carvalho**, *Professor Catedrático* do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro e co-orientação científica do **Professor Doutor José Manuel Neto Viera**, *Professor Auxiliar* do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro e do **Doutor Paulo Manuel Dinis Mónica de Oliveira**, *Capitão-de-mar-e-guerra, na Reserva*, e ex-Diretor do Centro de Investigação Naval.

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presidente / president

Prof. Doutor Luís Filipe Pinheiro de Castro
Professor Catedrático da Universidade de Aveiro, por delegação do Reitor da Universidade de Aveiro

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Prof. Doutor Nuno Miguel Gonçalves Borges de Carvalho
Professor Catedrático da Universidade de Aveiro (Orientador)

Prof. Doutor José Alberto Peixoto Machado da Silva
Professor Associado da Faculdade de Engenharia da Universidade do Porto

Prof. Doutor Roberto Gómez-García
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Prof. Doutora Ana Maria Perfeito Tomé
Professor Associada da Universidade de Aveiro

Prof. Doutor António José Castelo Branco Rodrigues
Professor Auxiliar do Instituto Superior Técnico da Universidade de Lisboa

Aos meus ratos, Coca, Pipas e Piniu, que, tal como este percurso, transformaram a minha forma de ver o mundo.

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palavras-chave

Very High Frequency, Banda-larga, Radio-cognitivo, Comunicações Marítimas, Sistemas Oportunisticos, Deteção Espectral, Full-Duplex Sensing.

resumo

Tradicionalmente, a economia do mar está associada ao transporte marítimo, que representa cerca de 90% do comércio mundial, e à pesca, mas as novas atividades associadas à inovação tecnológica estão a transformar o contexto económico dos serviços e aplicações marítimas. No futuro, a utilização massiva de tecnologia no suporte às atividades desenvolvidas no mar, nomeadamente em transportes marítimos inteligentes e sistemas autónomos, conduzirá a uma federação de sistemas marítimos integrados.

Contudo, as comunicações marítimas existentes não estão preparadas para dar suporte a esta alteração de paradigma. Atualmente, os sistemas dedicados baseiam-se em comunicações de banda estreita, onde a telefonia e a transmissão de dados de baixo débito são os serviços mais comuns, e aplicações de banda larga específicas, como o acesso a Internet, são disponibilizados através de comunicações por satélite (SATCOM). Infelizmente, as redes UMTS/LTE não providenciam soluções consistentes, devido à fraca cobertura sobre o mar. Por conseguinte, existe uma clara necessidade de capacidade adicional que possa disponibilizar desempenhos adequados a baixo custo e que possa constituir um complemento, ou mesmo uma alternativa, ao satélite.

Nesta tese é proposta uma solução de comunicações de banda larga em VHF, baseada em rádio cognitivo (CR-B-VHF), que permite disponibilizar uma adequada conectividade de suporte aos requisitos atuais de troca de informação e a futuros desenvolvimentos nos serviços e aplicações marítimas, evitando as desvantagens da utilização do satélite. Esta rede foi concebida para operar num contexto de escassez de espectro, assumindo um modelo de acesso hierárquico, e utiliza conceitos de rádio cognitivo para implementar um sistema dinâmico que possa ativar e desativar sub-portadoras, de acordo com as oportunidades para transmitir, garantindo um adequado nível de interferência com os serviços dos incumbentes.

O principal contributo deste trabalho é a proposta de um conceito de CR-B-VHF e a demonstração da sua adequabilidade, exequibilidade e aceitabilidade. A análise de relevância apresentada, proporciona uma perspetiva do estado da arte das atividades marítimas associadas à economia do mar e dos sistemas de informação e comunicação que lhes dão suporte, bem como uma perspetiva dos requisitos futuros e as aplicações para acessos de banda larga a baixo custo. As soluções desenvolvidas para a deteção e exploração de múltiplas e não-contíguas oportunidades de banda estreita na banda marítima de VHF, e as suas previsíveis prestações, abrem boas perspetivas relativamente ao potencial dos sistemas oportunísticos na banda de VHF e a sua futura implementação. Finalmente, é apresentada uma discussão sobre questões regulatórias e de normalização, cujo objetivo é contribuir para a solução do problema da utilização partilhada do espectro, providenciando uma perspetiva de utilizador final, num modelo de acesso hierárquico ao espectro.

keywords

Very High Frequency, Broadband, Cognitive Radio, Maritime Communications, Opportunistic Systems, Spectrum Sensing, Full-Duplex Sensing.

abstract

Traditionally, maritime business is associated to transportation, which represents about 90% of global trade, and fishery, but new activities at sea, opened up by technological innovations, are transforming economical context of maritime services and resources. In the future, the massive use of technology to support endurance and ranging of maritime operations, namely in intelligent transport systems and autonomous vehicles areas, would lead to federations of maritime based embedded computing devices.

Nevertheless, existing systems are not prepared to support such paradigm change. Currently, stovepiped systems rely on narrowband communications systems, where voice and low data rate are the most common used services, and specific broadband applications, such as Internet access, are supported by satellite communications (SATCOM). Unfortunately, UMTS/LTE networks do not provide consistent solutions, due their limited sea coverage, so there is a need for an additional capacity that can provide acceptable performances at low cost, which might act as a complement or even an alternative to satellite.

We propose a Cognitive Radio based Broadband VHF (CR-B-VHF) communications solution to provide appropriate connectivity to support current information exchange requirements and enable future developments on maritime services and applications, thus avoiding SATCOM inconveniences. This CR-B-VHF network would operate in a context of spectrum scarcity, within hierarchical spectrum access model, and use cognitive radio based concepts to implement a dynamic system that can activate and deactivated subcarriers, according to spectrum opportunities, ensuring an adequate interference level at incumbent's live services.

The main contribution of this thesis work is the proposed CR-B-VHF framework and the demonstration of its suitability, feasibility and deployability. The presented relevancy analysis provides an overview of the state of the art on maritime business and its associated support communications and information systems, and prospects future requirements and applications for low-cost broadband access. The developed solutions for detection and exploitation of multiple non-contiguous narrowband spectrum opportunities in maritime VHF band, within a hierarchical spectrum access context, and their envisage performances, provide good indications regarding attainability of opportunistic B-VHF systems and their future deployment. Finally, the discussion on regulatory and standardization issues intend to contribute for a shared problem solving, providing an end user perspective of hierarchical spectrum access.

Despite the fact that technical aspects are nor the main issues on opportunistic systems deployment, novel proposed Spectrum Coherences Detector and its experimental demonstrated performances might be an important enabler and an additional argument to convince maritime communications stakeholders.

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> *“You don't understand the problem until you have developed a solution.”*
>
> *Conklin \& Weil*

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List of Acronyms

Analogue to Digital Converter (ADC)

Automatic Identification System (AIS)

Acceptable Level of Interference (ALI)

Angle of Arrival (AoA)

Auto Regressive (AR)

Advanced Research and Projects Agency (ARPA)

Additive White Gaussian Noise (AWGN)

Communications and Information Systems (CIS)

Cruise Lines International Association (CLIA)

Close-Loop Power Control (CLPC)

Cognitive Radio Network (CRN)

Carrier Sense Multiple Access (CSMA)

Digital to Analogue Converter (DAC)

Dynamic Spectrum Access (DSA)

Digital Selective Calling (DSC)

Digital Signal Processing (DSP)

Delay-Tolerant Networking (DTN)

Electronic Chart Display and Information System (ECDIS)

Electromagnetic Compatibility (EMC)

Federal Communications Commission (FCC)

Full-Duplex Sensing (FDS)

Global Maritime Distress and Safety System (GMDSS)

Gaussian Minimum Shift Keying (GMSK)

Half-Duplex Sensing (HDS)
High Frequency (HF)

Integrated Bridge Systems (IBS)
International Hydrographic Organization (IHO)
International Maritime Organization (IMO)
Integrated Navigation Systems (INS)
Internet Protocol (IP)
Intelligent Transport Systems (ITS)
International Telecommunication Union (ITU)

Line-Of-sight (LOS)
Long Range Identification and Tracking (LRIT)
Long Term Evolution (LTE)

Media access Control (MAC)
Mobile Ad-hoc Network (MANET)
Meteorological and Oceanographic (METOC)
Medium Frequency (MF)
Moment Generating Function (MGF)
Maritime Mobile Service (MMS)
Maritime Safety Information (MSI)
Mega samples per second (Msps)
Multi-Taper Method (MTM)

North Atlantic Treaty Organization (NATO)
Navigational Telex (NAVTEX)
Narrowband Direct Printing (NBDP)
National Regulatory Authority (NRA)

Probability Density Function (PDF)

Power Spectral Density (PSD)

Quality of Service (QoS)

Radio Frequency (RF)

Radio Line-Of-Sight (RLOS)

Receiver Operating Characteristics (ROC)

Radio Regulations (RR)

Search and Rescue (SAR)

Satellite Communications (SATCOM)

Spectral Coherences Detector (SCD)

Software Defined Radio (SDR)

Signal-to-Noise And Distortion ratio (SINAD)

Square Law Combining (SLC)

Service Level Requirement (SLR)

Signal-to-Noise-plus-Interference-Ratio (SNIR)

Signal-to-Noise Ratio (SNR)

Services Oriented Architecture (SOA)

Self-Organized Time Division Multiple Access (SOTDMA)

Unmanned Autonomous Vehicles (UAV)

Universal Mobile Telecommunications System (UMTS)

Universal Software Radio Peripheral (USRP)

Very High Frequency Data Exchange System (VDES)

Very High Frequency (VHF)

Vessel Traffic Service (VTS)

World Radiocommunication Conference (WRC)

Chapter 1

Introdution

Strategic and economical relevance of maritime activity never stopped to grow. From transportation to resources exploitation, from tourism to maritime-based sports activities, oceans provide infinite opportunities. According to International Maritime Organization (IMO), maritime transportation represents about 90% of global trade, being the most efficient and cost-effective method of international transportation of goods. Despite this share, it is expected that sea trade continue to expand. The maritime traffic increasing would result not only from transport, but also due to other uses, such as offshore exploitation of traditional and renewable energy sources, fishing and tourism, including cruise shipping and other maritime-based leisure activities.

Traditionally, maritime information exchange requirements have been centered in Maritime Safety Information (MSI) and Meteorological and Oceanographic (METOC) related information. Ships operation processes demand for vessel safety and environment condition information, which have been resulted in worldwide deployment of several dedicated systems. Available technologies, implemented in a multitude of independent systems, like the Automatic Identification System (AIS), the Vessel Traffic Service (VTS) and the Global Maritime Distress and Safety System (GMDSS), provide support to: Search and Rescue (SAR); response to pollution incidents; ship and port safety and security; and protection of critical marine resources. Such systems are mainly supported by the Maritime Mobile Service (MMS), an internationally allocated radio service providing for safety of life and property at sea and on inland waterways.

Nevertheless, it is expected an important paradigm change in command and control of navigation, drive by on-going deployment of *e-navigation* concept. Safety is no longer an unique requirement for maritime Communications and Information Systems (CIS). The logistics and economical aspects of ships' operation have an increasing role in overall business process, with considerable impact on board systems. At information domain, the paradigm would evolve from terminal centric, where specific information is provided by a stove piped dedicated system, towards network centric, where the information is distributed over a network. Despite information management related challenges, such paradigm change have unquestionable impact on performance requirements at network level, not only in terms of throughput, but also at availability and costs.

Furthermore, world fleet evolves towards emerging concepts and technologies in areas such as Intelligent Transport Systems (ITS) and Unmanned Autonomous Vehicles (UAV), to improve processes automatization and efficiency. Currently, exploitation of marine resources is still a costly and risky activity. The maritime environment is adverse for human activity and highly exigent for systems operation, which restricts solid deployments due to unbalanced cost-benefit trade-offs. In most cases, the role of human operation or supervision, and its associated costs, tend to discourage technology development and utilization that would take advantage of oceans opportunities. However, initiatives such as proposals for continental shelf extensions are posting technological challenges on operations endurance and ranging. It is necessary to find alternatives to support sea operations in a diversity of sectors, which goes from mineral resource exploration to marine renewable energy development. The answer might be on federation of maritime based embedded computing like devices ecosystem, which would share service oriented information without requiring human interaction in a Internet of (Maritime) Things (Io(M)T). A convergence of multiple technologies, from embedded systems to wireless communications, is expected to offer advanced connectivity to devices, systems and services, and covers a variety of protocols, domains and applications [1].

Complementary, demanding for Internet access at sea has been increasing over the past few years. Not only for ships operation purposes, but also for morale, welfare and recreation of crew members. Additionally, the amount of cruise passengers has been growing dramatically with tremendous global economical impact. These facts post complementary challenges in maritime communications domain, mostly associated to the amount and density of users and their demand for broadband Internet access.

Nowadays, terrestrial based maritime communications are restricted to voice and narrowband data services, and mobile solutions, such as Universal Mobile Telecommunications System (UMTS) or Long Term Evolution (LTE) networks, do not provide consistent solutions. Voice services and low rate data (<9.6kbps) are well consolidated in Medium Frequency (MF) and Very High Frequency (VHF) bands: transmission services in VHF are restricted to AIS data, DSC and voice, all of them narrowband technologies; on the MF/HF side, available services are even slower (e.g. 100 bps), with narrowband digital services such as Navigational Telex (NAVTEX) and Narrowband Direct Printing (NBDP), despite better coverage characteristics. There are some on-going initiatives to speed up VHF digital data transfer to 307 kbps, through the combination of four-narrowband radio 25 kHz duplex channels [2]. In any case, such performances are clearly below the requirements to support broadband services. Alternatives, such as UMTS/LTE, can be used as a complement of MMS, but their limited sea coverage is definitely an important operational constraint. The gigahertz based solutions, such as Wi-Fi, Wi-MAX, etc, have analogous drawbacks, namely coverage problems and spectrum allocation difficulties, which result from highly occupied, spectral demanding and commercially attractive bands, that impose restrictions on transmitted power.

In practice, there are no available alternatives to Satellite Communications (SATCOM), for maritime high-speed communications, even within shore radio horizon. Satellite services, either by commercial geostationary, medium earth orbit or low earth orbit, provide end-to-end mobile communications for operational communications and safety services, through unique proprietary solutions in nearly global coverage. However, most of the offered satellite services are narrowband, i.e. up to 64 or 128 kbps, and available broadband services are very expensive (up to $ US 30 per Mbyte). Unfortunately, it is not expected that SATCOM tend to decrease, due to overall cost of launching and operating satellite constellations. Naturally, SATCOM services have an important role in maritime communications and, probably, cannot be replaced by another system with equivalent coverage. Nevertheless, there are operational conditions that might be supported by alternative systems, with better performances and reduced costs.

The need for non-SATCOM maritime broadband services is evident. In addition to performance and costs, transmission diversity and its associated advantages of flexibility, would represent a tremendous improvement in maritime networking capacity and consequently in information availability and sharing at sea. The capacity to provide an affordable network layer opens a whole field of opportunities, namely the deployment of concept of "information as a service" concept, which can expand, for example, ITS principles not only to ships, but also to water vehicles and its operation as a whole. In fact, in a near future, maritime autonomous vehicles and sensor networks will have a massive deployment, which emphasize the need for adequate CIS infrastructures to automatize and optimize business processes.

1.1 Objectives & Scope

Taking into consideration all advantages and disadvantages, summarized in Figure 1.1, a maritime VHF based solution for high-speed data links would be the "natural" solution to provide a network layer with appropriate performance and cost. Despite transoceanic trips, world sailing activity occurs mostly within 40 miles, served by VHF coastal stations, and do not take advantage of this band, due the lack of high-speed data services provision. The foundation for this routes choice is naturally related with safety, which has been resulted in the implementation of infrastructures that allow full coverage of areas that lies within the range of shore-based VHF coastal stations (up to 40 nautical miles) and medium-range MF stations (up to 200 nautical miles) providing radio services, such voice and automated distress alerting. Considering bandwidth natural limitations, MF/HF are not attractive alternatives to pursuit. Alternatively, higher frequencies, associated to UMTS/LTE, WiFi and WiMAX operating bands, have several unfavorable factors that discourage such choice, namely cellular industry lobbying, signal attenuation and fading in a maritime environment, etc. Finally, VHF band is the most popular band among mariners, not only due to its ability to propagate well beyond Line-Of-sight (LOS), but also because it has a well consolidated allocated spectrum for MMS. Either way, solution seems to be on resources side, which requires not only authorizations and licenses, but also innovative ways to convince spectrum stakeholders.

Ultimately, maritime broadband VHF communications require spectrum availability, which is a recurrent issue in every new wireless system. It is particularly difficult to find and allocate spectrum for new services, especially contiguous spectra for broadband. In the past, the fear of harmful interference led to static allocation strategies, which have been largely successful in the protection of assigned users, but poorly efficient in terms of overall spectrum utilization. Typically, frequency bands are assigned to a specific user or service, which are guaranteed to have exclusive access to that portion of spectrum, no matter how often it is used. Hence, any efficiency improvement, within actual frameworks, would involve a re-evaluation of demands and reassignment of spectrum, which is obviously unfeasible due to natural constraints associated to live operations and legal issues. Consequently, the solution would necessary involve an flexible and dynamic spectrum management processes, as those included in Dynamic Spectrum Access (DSA) strategies.

The management models, based on DSA, have enormous potential to mitigate spectrum scarcity, support interference mitigation/avoidance and allow performance-based management

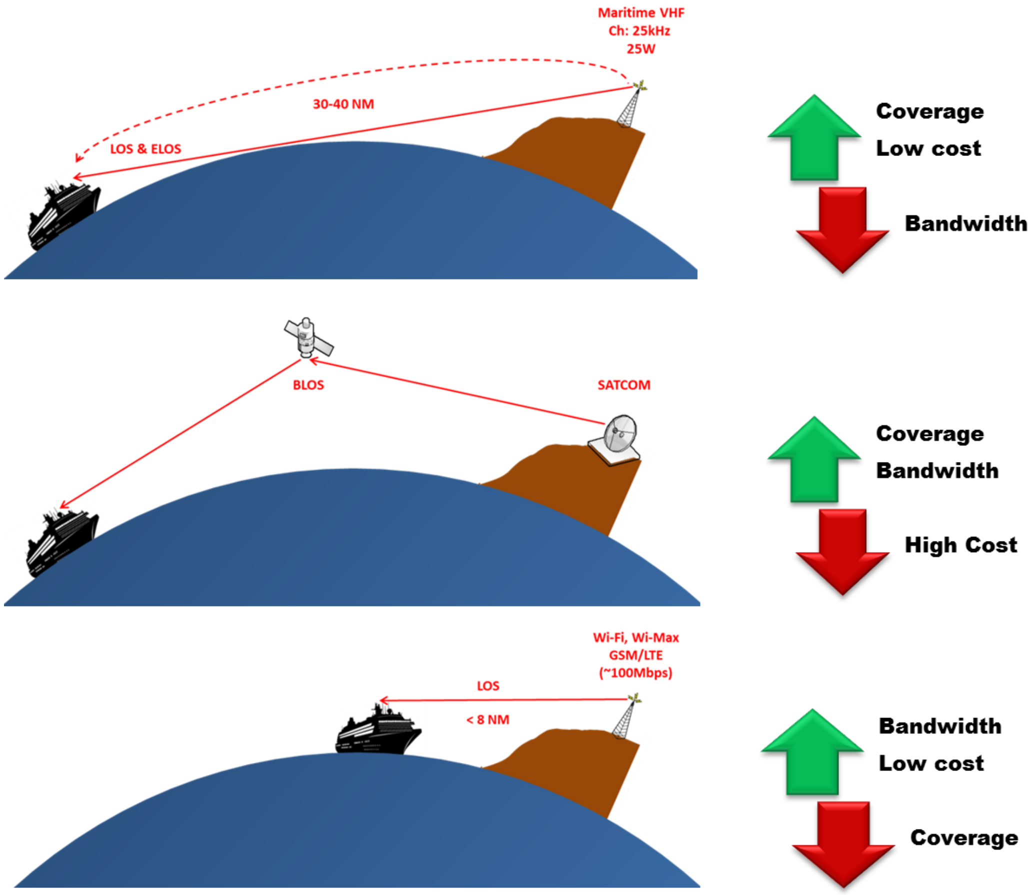


Figure 1.1: Operational context of communication services for mariners.

by the selection of bands that maximize communication link throughput. However, practical application of DSA has not been simple, essentially due to a lack of technological tools that can assure an efficient implementation of those concepts. Fortunately, CR, initially proposed by Joseph Mitola III [3], provides the required functionalities to implement DSA and increase efficiency in spectrum usage. The basic idea behind CR is to take advantage of inactive spectrum segments through the implementation of radio scene awareness and adaptive mechanisms that permit detection and exploitation of spectrum opportunities. Considering that a frequency band assigned to a specific user may not be incessantly used, there are circumstances where an unlicensed user can get access to spectrum, as long as it does not cause any disruption or interference on live services. The efficiency of spectrum usage associated to CR is reached through opportunistic unlicensed access to licensed radio spectrum bands that are not being used in that time frame. Consequently, CR is not only an enabler for the implementation of a DSA strategy, which might increase the spectrum usage efficiency, but also crucial for the deployment of any maritime non-SATCOM broadband system.

Thereby, we propose a Cognitive Radio based Broadband Very High Frequency (CR-B-VHF) solution to implement a maritime non-SATCOM communications system that is able to support appropriate connectivity for current information exchange requirements and enable future developments on maritime services and applications, thus avoiding satellite inconveniences. The idea is to come up with a system that would take advantage of unoccupied spectra in MMS band, in a opportunistic basis, exploring new emerging concepts and technologies in order to provide solutions for high-speed data links between ships and shore that can act as a complement to SATCOM, meeting the demand of equivalent performances and defeating its costs. This new approach includes a combination of recent advances in cognitive radio, multi-carrier modulation techniques and smart antennas that may provide a way to conceive a system that can benefit from spectrum opportunities and efficiently use them to deploy adaptive broadband capabilities to support network based services over radio channels.

Certainly, as in any other broadband radio system, feasibility and practical deployment of a CR-B-VHF system demand the fulfillment of several requirements or, otherwise, it will be reduced to a set of good intentions. Such requirements include: spectrum, technology, licenses, infrastructures and financial support. The financial support depends on investors perspectives on future financial return, which in this case, and assuming the potential amount of customers, is subject to final system performance and associated costs. Considering that littoral countries have implemented infrastructures that allow full coverage of coastal areas, within the scope of safety related projects, as GMDSS and VTS, there might be opportunities for further maritime systems deployments negotiations. This means that feasibility issues can be reduced to regulatory and standardization related aspects, associated to spectrum management paradigm change and spectra designation for opportunistic usage, and technological support for CR-B-VHF deployment.

The spectrum availability for a CR-B-VHF deployment depends on several factors and stakeholders, and cannot be solved instantaneously. In fact, depending on CR-B-VHF application area, different kind of spectra can be provided for opportunistic use, and different time lines might be expected for its deployment. There is a great potential for government applications, particularly for Navy, Coast Guard and Maritime Police, which would find relatively fast solutions for required spectrum management issues. Even though, a global general purpose CR-B-VHF network, with different national designated channels in MMS assigned spectrum, is not simple and quick to achieve. In the mean time, it is important to discuss possible solutions and transition plans to evolve regulatory framework towards a more flexible and dynamic management process that would be able to support opportunistic systems deployment, particularly in maritime VHF band.

For the time being, it is possible to address spectrum management and discuss feasibility aspects associated to regulatory issues. Maritime transportation strategic sectorial spectrum exigencies cannot be solved by current (MMS) allocated spectrum, due to narrowband assignments and current availability problems [C4]. The need for new allocation strategies to enable broadband transmission is critical for maritime operations and business information exchange development, namely within the scope of ITS [4]. It is important to address deployment challenges and management paradigms, and discuss the regulatory and standardization aspects of a practical implementation of DSA strategies and potential issues that would rise from Quality of Service (QoS) enforcement and operational caveats. Such analysis has to be centered on paradigm change, new policy definition, enforcement mechanisms and transition plans.

The technological challenges, associated to CR-B-VHF deployment, can be condensed in detection and exploitation of spectrum opportunities in MMS assigned band. Such essential capabilities require situation awareness of surrounding radio environment and ability to deal with the fact that eligible spectrum for opportunistic usage would not be contiguous. Furthermore, incremental approach to regulatory paradigm change would recommend a hierarchical spectrum access model, at least in early stages of maturity, which ensure incumbents exclusive access to spectrum and the possibility of opportunistic users to take advantage of spectrum, when primary users are not using it. In fact, this spectrum access model might be the only feasible scheme that might be supported by regulatory authorities and maritime stakeholders. Therefore, any designated scheme to detect and explore spectrum opportunities, in MMS assigned band, must take into consideration that incumbent services have the right to use spectrum, so opportunistic systems shall be turned off whenever primary users start to transmit.

Additionally, CR-B-VHF concept development has to include an experimentation component, at early stages. Despite eventual merits of a theoretical characterization of CR-B-VHF concept and comprehensive analysis of mathematical models and simulations, it would be very difficult to convince maritime stakeholders to accept such a disruptive way of doing business without a prototype and a proof of concept. On the other hand, several constraints would prevent a full prototype development during this PhD program. Therefore, envisage impact of CR-B-VHF on maritime business is significant enough to justify a joint venture to investigate and develop solutions that would support future deployments.

The willingness, triggered by this research work, intend to provide a satisfactory answer to fundamental problems associated to spectrum sensing and transceiver design, but other initiatives made a contribution on the same direction. Hence, once the concept development has been consolidated, within the scope of current work (2012), it was possible to plan two independent tasks to achieve experimentation objectives: one to be accomplished within current thesis work and another that has been assigned to a Naval Research Center colleague Germano Capela, to be performed within his masters thesis, acting the author as his co-advisor. At the end, it would be possible to demonstrate (experimentally) the implementation of a dynamic system, which activates and deactivates Non-Contiguous Orthogonal Frequency Division Multiplexing (NC-OFDM) subcarriers, according to spectrum opportunities, ensuring exclusive access to incumbent users and an adequate interference level at their live services.

Capela has been assigned to an implementation of CR-B-VHF concept, focusing on complete cognitive communication system and integrating essential processing components to achieve dynamic spectrum access, network integration and over-the-air network synchronization. Considering planning constraints and good practices in systems integration, a modular configuration has been adopted for developed solution, as presented in Figure 1.2, so spectrum sensing functionalities have been implemented in a module with essential features to allow system validation. The objective was the implementation of a CR-B-VHF prototype that might be able to demonstrate essential features in an open sharing environment.

The scope of current thesis includes the development of a spectrum sensing scheme that considers a hierarchical spectrum access model and maximizes opportunistic spectrum usage efficiency, ensuring acceptable levels of harmful interference with incumbent's services. The design and experimental validation of this sensing module would allow it to be integrated in the developed prototype and close CR-B-VHF demonstration endeavor.

Spectrum sensing requirements depend on the considered dynamic access model. Despite open sharing model, where all users have the right to use spectrum in an availability basis,

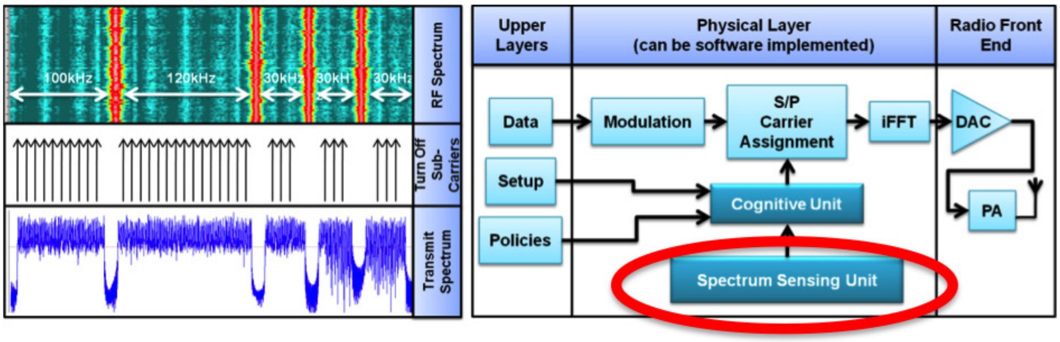


Figure 1.2: System architecture of implemented CR-B-VHF concept [T1].

detection of incumbent's activity might be required to be performed, not only before opportunistic system starts to take advantage of inactive band, but also while it is transmitting in that band, ensuring acceptable level of harmful interference. This "small detail" make the whole difference and is an essential feature for hierarchical dynamic access model, because it would allow spectrum exclusive access of incumbents. Additionally, it will bound spectrum usage efficiency, since time-difference, between secondary system turn off and primary service start to operate, would restraint overall efficiency performance. Herewith, spectrum sensing, in such a context, goes beyond a simple signal detection.

Essentially, there are two approaches to spectrum sensing for hierarchical dynamic access, which involve an interruption of opportunistic system transmission either in a synchronous or asynchronous way. The former corresponds to the obvious methodology of time-sharing between sensing and transmitting, where sensing is performed in a half-duplex way. This is a typical solution for cases of well characterized primary activity profiles, since it is focused on finding optimal parameters for sensing cycle, i.e sensing and transmitting times. Alternatively, one can perform sensing and transmission simultaneously, i.e. in a full-duplex way, avoiding prior required information for optimization processes. This presents obvious gains, in terms of efficiency, but requires a self-cancellation scheme that would allow an appropriate level of interference to enable detection. Naturally, each one of these approaches has its own theoretical advantages and drawbacks, which requires specific analysis to evaluate its feasibility and, if so, decide on the best solution.

The foundations for the idea behind this thesis rely on the author's practical perspective about the lack of alternatives to SATCOM and its impact on maritime related information exchange. Once the problem and the research opportunity have been identified, it was necessary to justify its relevancy and discuss the worthwhileness of such study and its consequences. Afterwards, a solution shall be provided and a feasibility analysis has to be accomplished, knowing that no theoretical or simulation evidences would beat an experimental validation. Complementary, and recognizing that regulatory decisions are far from being based on technical arguments only, it has been considered to be important to address spectrum management and discuss an imperative evolution on regulatory framework.

Therefore, we planned our work to follow this framework, defining the objectives and scope of the current thesis, succinctly, as:

1. Present an analysis on maritime business relevancy and available CIS, anticipating evolution on information exchange demands and upcoming requirements on transmission services;
2. Propose a CR-B-VHF framework to overcome maritime communications dependency on SATCOM, for broadband access, and address its feasibility issues;
3. Characterize fundamental aspects associated with detection of spectrum opportunities in maritime VHF band, namely operational context of marine users, incumbent services and propose a theoretical model for communications channel;
4. Design a half-duplex based sensing scheme, for multiple non-contiguous narrowband channels, which can manage hierarchical dynamic access mode;
5. Design a full-duplex based sensing scheme, for multiple non-contiguous narrowband channels, which can manage hierarchical dynamic access mode;
6. Demonstrate the feasibility of spectrum sensing on multiple non-contiguous narrowband channels for hierarchical dynamic access;
7. Discuss evolution of regulatory framework towards a more flexible and dynamic management process, centering the discussion on regulatory and standardization issues associated to the application of CR concepts to maritime VHF band.

1.2 Contributions & Outline

The main contribution of this thesis is the CR-B-VHF framework and the demonstration of its suitability, feasibility and deployability. The presented relevancy analysis provides an overview of the state of the art on maritime business and its associated support CIS systems, and prospects future requirements and applications for low-cost broadband access, which emphasized the peremptory relevancy of non-SATCOM communications systems. The proposed solutions for detection and exploitation of multiple non-contiguous narrowband spectrum opportunities in maritime VHF band, and their envisage performances, opens perspectives about attainability of opportunistic B-VHF systems and their future deployment.

Additionally, there are specific contributions on mathematical modeling and analysis, development of a novel Spectral Coherences Detector (SCD) to be used on a proposed Full-Duplex Sensing (FDS) framework, experimental demonstration on designed and implemented Cognitive Radio Test bed for Maritime Applications, and discussion on regulatory framework evolution towards a more flexible and dynamic management process.

Hence, the main contributions can be summarized in the following:

- Comprehensive analysis on evolution on maritime information exchange demands, anticipating demands and envisage requirements for transmission services, which bring into prominence the need for non-SATCOM communications;
- Derivation of a closed form expression for quadratic detector over fading channels, by modeling the maritime channel through a Nakagami-m random variable and sea conditions being represented by the m parameter;

- Analysis of spectrum sensing of multiple narrowband signals detection for hierarchical spectrum access, from Half-Duplex Sensing (HDS) and FDS perspectives;
- Development of a novel SCD for FDS and experimental demonstration of its performance;
- Development of a FDS framework for detection of multiple narrowband signals in VHF band;
- Implementation of Cognitive Radio Test bed for Maritime Applications;
- Discussion on evolution of regulatory framework, particularly on regulatory and standardization issues associated to the application of CR concepts to maritime VHF band.

Most of the concepts and results discussed in this thesis were either published or submitted to scientific journals or presented in conferences, as listed in the following, enumerated by relevance and date of appearance.

Journal and Conference Papers

[J1] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”A Spectral Coherences Detector for Full-Duplex Sensing in Maritime VHF Band”, *Manuscript submitted to IEEE Transactions on Signal Processing*

[J2] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”The Role of Cognitive Radio in Future Maritime Systems”, *Manuscript submitted to Elsevier International Journal of e-Navigation and Maritime Economy*

[J3] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”Opportunistic Usage of Maritime VHF Band ? Deployment Challenges for a New Regulatory Framework” Wireless Engineering and Technology, Vol. 5 No. 1, pp. 1-10. doi: 10.4236/wet.2014.51001, 2014

[C1] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”Narrowband Signal Detection for Maritime B-VHF Cognitive Radio Based Systems”, Conftele 2015, Aveiro, Portugal, September, 17th to 18th, 2015.

[C2] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”Maritime Cognitive Radio Networks: Boosting e-Navigation towards Service Oriented Architectures”, Conftele 2015, Aveiro, Portugal, September, 17th to 18th, 2015.

[C3] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”e-Navigation and the Internet of (Maritime) Things”, 7^{th} Congress of the Portuguese Committee of URSI, Lisbon, Portugal, Nov. 22nd, 2013.

[C4] E. Bolas, ”Maritime Communications - Strategic Sectorial Spectrum Needs”, in Conference on ”Spectrum Management: Perspectives, Challenges and Strategies, Lisbon, Portugal, Sep. 20th 2013.

[C5] E. Bolas, N. B. Carvalho, J. N. Vieira, P. M. Oliveira, ”Regulatory and Standardization Issues on Cognitive Radio based Maritime B-VHF Communications”, 6th Congress of the Portuguese Committee of URSI, Lisbon, Portugal, Nov. 16th, 2012.

[C6] E. Bolas, "Software Defined Radio: A Plataforma para o Futuro das Comunicações Navais", Workshop on Software Defined Radio, Instituto de Estudos Superiores Militares, Lisbon, Portugal, Nov.2010.

Additionally, the proposed CR-B-VHF framework has been implemented in a software defined radio, within the scope of [T1], and results have been presented in the following conferences:

[C7] G. Capela, A. Rodrigues, J. Sanguino, E. Bolas, "Opportunistic usage of Maritime VHF band using a Software Defined Radio", URSI Atlantic Radio Science Conference (URSI AT-RASC), Gran Canaria, Spain, 18-22 May 2015.

[C8] G. Capela, A. Rodrigues, J. Sanguino, E. Bolas, "Implementação de um rádio definido por software para comunicações marítimas cognitivas". 8th Congress of the Portuguese Committee of URSI - "Drones and Autonomous Vehicles: Present and Future Challenges", Lisbon, Portugal, Nov. 2014.

Complementary, the author has been advisor or co-advisor in master thesis on CR-B-VHF related subjects. In addition to the previously mentioned work, there were two more research initiatives at Naval Research Center. One that discussed specific spectrum management paradigm change and introduction of cognitive radios in Navy operational context, and another that addressed modeling of spectrum occupancy in maritime VHF band, particularly within Navy assigned spectrum, as the following:

Masters Thesis Advisory

[T1] Germano Gonçalves Capela, "Development of a Software Defined Radio for Cognitive Radio Communication Systems", Instituto Superior Técnico, 2015.

[T2] Tiago Ventura Viegas, "Novos Paradigmas de Gestão de Espectro e Introdução de Radios Cognitivos na Marinha", Escola Naval, 2015.

[T3] Luis César Menezes, "Oportunidades para a utilização dinâmica do espectro na banda de VHF do serviço móvel marítimo", Escola Naval, 2015.

Furthermore, the CR-B-VHF concept has been considered, by Instituto de Telecomunicações, to be included in a COST Action proposal on maritime communications and two project proposals to be submitted to the 7^{th} Framework Programme for Research and Technological Development (FP7), as the following:

CR-B-VHF Based Submitted Projects

[P1] COST Action to create a European Network on Maritime Communications (NeMarCo), the first scientific European platform for aspects of maritime communications, submitted on March 2015.

[P2] Sea Cognitive Broadband Wireless Communications (SeaWiCom), submitted to FP7-ICT-2013-11: Call 11 - ICT 2013.1.1 Future Networks: Instituto de Telecomunicações lead a Consortium, composed by Naval Research Centre, PTInovao, Wavecom (Portugal), Centre Tecnolgic de Telecomunicacions de Catalunya (Spain), Universitat Politcnica de Catalunya (Spain), MIER (Spain), MEUSONIC (France), MIDRA (Italy), to submit a proposal to build a data-link demonstrator for high-speed maritime VHF based data links between shore and vessels, exploiting the usage of cognitive radio/white space solutions and NC-OFDM systems. The project was not funded, even though evaluation report assigned a total score of 12 (within threshold 10 and a maximum grade of 15).

[P3] Sea Wireless Communications (SeaWiCom), submitted to FP7-ICT-2011-8: Call 8 - ICT 2011.1.1 Future Networks - Instituto de Telecomunicações lead a Consortium, composed by Naval Research Centre, PTInovao, Wavecom (Portugal), Centre Tecnolgic de Telecomunicacions de Catalunya (Spain), Universitat Politcnica de Catalunya (Spain), MIER (Spain), MEUSONIC (France), MIDRA (Italy), to submit a proposal to build a data-link demonstrator for high-speed maritime VHF based data links between shore and vessels, exploiting the usage of cognitive radio/white space solutions and NC-OFDM systems. The project was not funded, even though evaluation report assigned a total score of 11 (within threshold 10 and a maximum grade of 15).

Finally, the NATO Task Group IST 104/RTG-050 invited the author to present proposed CR-B-VHF framework on Lisbon's Meeting (23-25FEB2015) and to provide contributions to:

Technical Reports Contributions

[R1] STO Technical report, Task Group IST 104/RTG-050, Cognitive Radio in NATO II.

In Figure 1.3, it is presented a time perspective of research progress, publications and other related activities, previously mentioned.

This thesis is organized in eight chapters that cover: the problem and its context; proposed solution and its feasibility issues; characterization of fundamental aspects related with detection of spectrum opportunities in maritime VHF band, namely operational context of marine users, incumbent services and communications channel modeling; theoretical modeling and simulation analysis and design for Half-Duplex Sensing (HDS); development of a FDS framework, based on a novel SCD, and its experimental demonstration on designed and implemented Cognitive Radio Test bed for Maritime Applications; and discussion on regulatory framework evolution towards a more flexible and dynamic management process.

In Chapter 2 it is presented the fundamentals to understand the problem and its justification and the reason why it is worthful to address it. Economical relevancy of maritime business is discussed and evolution on information exchange demands is foreseen, stressing the lack of alternatives to SATCOM to support future concepts and demands, namely those associated to ITS and federation of maritime based embedded computing like devices. Traditional MSI and METOC systems are presented and emerging concepts such as *e-navigation* are introduced to prospect breakthrough of ITS and Io(M)T. The state of the art on maritime communication systems is addressed, coming to the conclusion that broadband VHF is essential for a future maritime wide area heterogeneous network and the most adequate solution for an alternative to SATCOM.

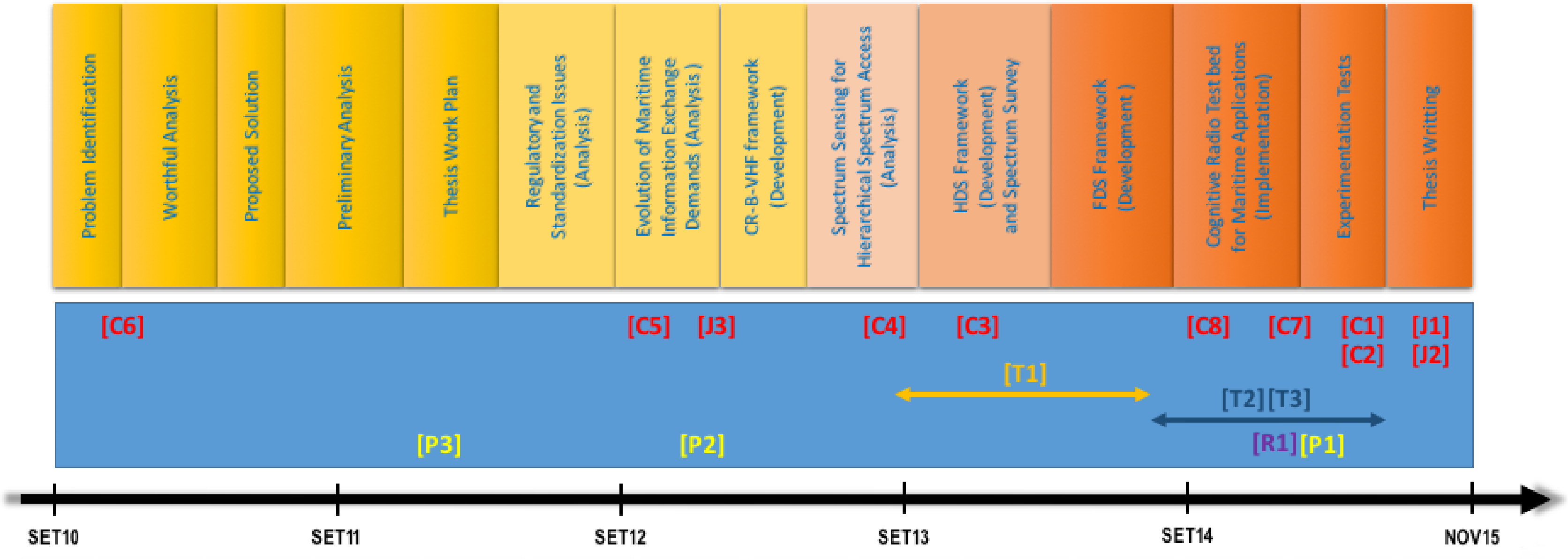


Figure 1.3: Research progress, publications and other related activities.

The proposed CR-B-VHF framework is presented in Chapter 3, where spectrum challenge is discussed and the usage of DSA concepts is proposed to overcome spectrum scarcity deadlocks. Cognitive radio is introduced, as a technological tool to support such spectrum management paradigm changes, and it is presented the proposed CR-B-VHF concept and potential system architecture, founded on a shore based infrastructure. The enabling technologies, which can support CR-B-VHF implementation, are examined and specific technological issues are discussed. Finally, feasibility and deployability issues are investigated, concluding that development of a spectrum sensing scheme, which might be able to support opportunistic operation in a hierarchical dynamic access model, is a major subject to pursuit in this thesis.

Chapter 4 is dedicated to radio scene analysis background and maritime operational context, MMS assigned services and communications channel characteristics. Within radio analysis, spectrum opportunities and spectrum sensing concepts are presented, detectors characteristics analyzed and metrics are discussed. Additionally, maritime environment context and incumbents services are described and a communications channel is characterized and modeled as a Nakagami-m random variable, where sea conditions are expressed through m parameter. Finally, spectrum sensing objective function is formulated in terms of maximum achievable capacity of opportunistic system, and it is identified the fundamental options to pursuit spectrum sensing design.

The HDS is addressed in Chapter 5, where design focus is on optimal sensing cycle that maximizes achievable capacity of opportunistic system, fulfilling primary service harmful interference levels. It is considered a quadratic detector, instead of commonly used energy detector, for narrowband signal detection in the VHF band, and a closed form expression is derived for its Receiver Operating Characteristics (ROC) over Nakagami-m fading channels. Additionally, a diversity gain analysis is presented, for cases of insufficient antenna separation and limited amount of processed branches, and overall detection performance is estimated. The spectrum efficiency optimization problems are analyzed, for single 25 kHz channel and multiple channels aggregation, and dependency of prior information on primary channels activity profiles is discussed. Simulation and parametric nonlinear regression models are used to estimate performance of arbitrary aggregation of multiple channels, when field information is scarce.

Alternatively, it is presented, in Chapter 6, a FDS framework that enables spectrum sensing and opportunistic transmission, simultaneously, in a given frequency band. A novel SCD is proposed for FDS, based on spectral coherences evaluation of received signals at two sensing antennas, which revealed significant advantages regarding HDS, namely flexibility, adaptability and channel profile statistics independency. Naturally, this approach requires the implementation of adequate tools to mitigate self-interference effects and enable detection of primary users activity, so detection capacity is discussed and a adaptation of Thomson's framework for cyclostationarity evaluation is proposed to ensure spectral estimator accuracy and resolution, while self interference control proficiency impact is evaluated through GNU radio simulations. Finally, it is presented the Cognitive Radio Test bed for Maritime Applications that had been implemented for experimental validation of proposed FDS framework and test results are discussed.

Current regulatory framework is not prepared for emerging radio communications technologies, so governing issues are still an active area of discussions. Hence, in Chapter 7, we address evolution of regulatory framework towards a more flexible and dynamic management process, centering the discussion on regulatory and standardization issues associated to the application of CR concepts to maritime VHF band. Practical aspects, related with QoS enforcement to ensure incumbents live operations and legacy systems coexistence, namely figures of merit, are also tackled. Eventually, some of the presented proposals might contribute for paradigm change in specific cases, such as government agencies, Navy, Coast Guard or Maritime Police, which can manage their own assigned spectra, and can take advantage of less complex and bureaucratic decision processes to materialize a flexibilization on spectrum management and an improvement on spectrum utilization efficiency. These can also apply to international organizations, such as North Atlantic Treaty Organization (NATO), where coalition operations require efficient spectrum management. Obviously, this subject is too complex to be wrapped with this exercise, but we expect to contribute for on-going discussions, which, hopefully, will enable VHF based maritime broadband services in a near future.

Finally, in Chapter 8, we draw some conclusions and present suggestions for future work, which include research initiatives that can contribute for the implementation and testing of a pre-industrial prototype.

Chapter 2

Maritime B-VHF Communications Relevancy Analysis

Economical relevance of maritime business is tremendous. Despite impressive achievements of traditional areas, such as transportation and fishing, new blue economy related activities, such as cruise tourism, offshore oil, gas and wind, mining or ocean renewable energies, represent an increasing share of 5.4 millions of jobs and 500 B€/year, just in Europe. These facts have implication on worldwide maritime traffic and offshore infrastructures and consequently on communications and information systems demands.

The obvious consequence of maritime traffic increasing is on navigation safety. The need for more reliable and user friendly decision support tools to reduce errors and improve safety at sea, requires automatization of processes, information seeking, processing and sharing technologies. Traditional stovepiped MSI and METOC systems evolve towards implementation of *e-navigation* concept, enabling further developments on intelligent transport systems area.

Furthermore, the massive use of technology to support maritime operations endurance and ranging, namely through autonomous systems, would lead to federations of maritime based embedded computing devices. Information sharing, without requiring human interaction, requires convergence of multiple technologies, from embedded systems to wireless communications, to offer advanced connectivity for devices, systems and services in a *"Internet of (Maritime) Things"* [C3].

However, existing systems are not prepared to support such paradigm change. Currently, stovepiped systems rely on narrowband communications systems, where voice and low data rate are the most common services, and specific broadband applications, such as Internet access, are supported by satellite communications (SATCOM). There is a clear request for an additional capacity that can provide acceptable performances at low cost, which might act as a complement or even an alternative to SATCOM.

The maritime VHF band is definitely the right choice for these broadband services deployment. In addition to its popularity among mariners, VHF communications have the ability to propagate well beyond LOS and have an allocated spectrum band for MMS. Therefore, any broadband solution, within this band, for high-speed data links that may overcome this limitation would represent a significant improvement and a driver for a paradigm change in different domains. Cost savings, resilience and performance are significant enough to justify the interest for an investigation on shore based broadband VHF.

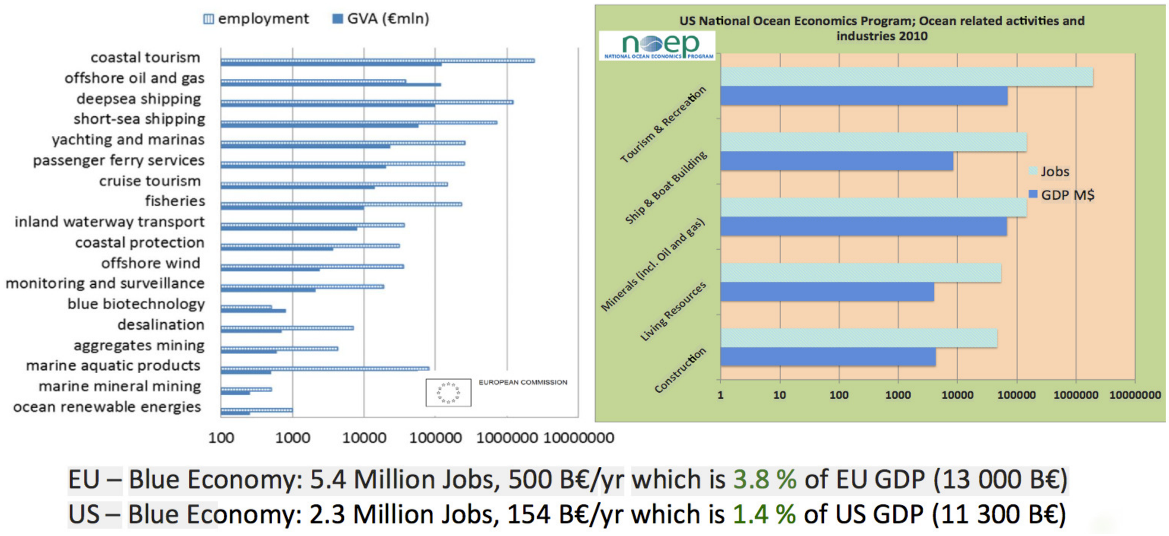
In this chapter, we discuss economical relevancy of maritime business, foreseen evolution on information exchange demands and the lack of alternatives to SATCOM to support future concepts and demands, namely those associated to intelligent transport systems and federation of maritime based embedded computing like devices. Furthermore, we raise up B-VHF relevancy as an alternative solution to SATCOM and its role on a future maritime wide area heterogeneous network.

The remainder of the chapter is organized as follows: in Section 2.1 we present a brief perspective of maritime business and its economical relevance; Section 2.2 is dedicated to discussion on evolution on information exchange demands, where traditional MSI and METOC systems are presented and emerging concepts such as *e-navigation* are introduced to prospect breakthrough of ITS and Io(M)T; the existing systems that are currently support shipping activities and initiatives to deploy new systems are presented in Section 2.3; while the role of B-VHF in maritime context is discussed in Section 2.4; final remarks are enounced in Section 2.5.

2.1 Maritime Business

Traditionally, maritime business is associated to fishery and transportation. In fact, the latest data from European Member States suggests that the European fishing fleet achieved a gross profit of €1.2 billion in 2014, almost 90% of the EU external freight trade is seaborne and more than 400 million passengers embark and disembark in European ports, each year. Nevertheless, these impressive numbers only reflect a part of the so called blue economy importance, as presented in Figure 2.1.

According to IMO, maritime transportation represents about 90% of global trade, being the most efficient and cost-effective method of international transportation of goods. Despite



EU – Blue Economy: 5.4 Million Jobs, 500 B€/yr which is 3.8 % of EU GDP (13 000 B€)
US – Blue Economy: 2.3 Million Jobs, 154 B€/yr which is 1.4 % of US GDP (11 300 B€)

Figure 2.1: Blue economy numbers. *Source*: European Commission and US National Ocean Economics Program.

this share, it is expected that sea trade continue to expand. In fact, Stopford [5] estimates that, if the trade growth trend of the last 150 years continues, by 2060 the 8 billion tonnes of cargo will have grown to 23 billion tonnes, and unless something is done about it, it will expand the shipping carbon footprint by 300%, as presented in Figure 2.2. This maritime traffic increasing would result not only of transport, but also due to other uses, such as offshore exploration of traditional and renewable energy sources, fishing and tourism, including cruise shipping and other maritime-based leisure activities.

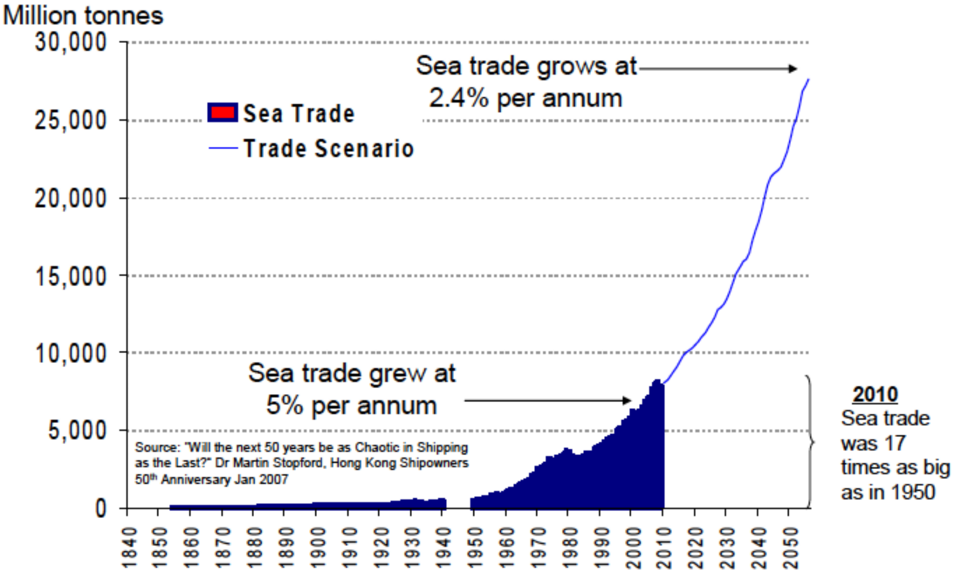


Figure 2.2: Sea Trade 1840-2010 & extrapolation to 2060 [5]

Actually, cruiser industry represents an important stakeholder in maritime business. The number of cruise passengers has grown dramatically over the past few years and the global economical impact is tremendous. According to Cruise Lines International Association (CLIA) one of the world's largest cruise industry trade association, during an economic downturn, the 13.44 million people, who cruised in 2009, represented a 4.8 per cent increase on 2008 and the forecast for 2014 has been of 21.7 million passengers, representing a global economical impact of $US 100 billion [6], as presented in Figure 2.3. These facts post complementary challenges in maritime communications domain, mostly associated to the amount and density of users and their demand for broadband Internet access.

Furthermore, new activities at sea, opened up by technological innovations, are transforming economical context of maritime services and resources. Several areas experienced strong growth and are drag along other related industries. Energy sector is expanding towards sea, not only on shale gas and oil extraction, but also wind farms and ocean renewable energies, pipes and high voltage cables, etc. Deep-sea mining, sand and gravel extraction fields have been increasing their productions and profits. Biotechnology and aquaculture are also important segments, with a lot of room for expansion and innovation. Size and importance of the blue economy are close connected to exigencies on efficient use of resources (energy, food) and less environmental impact.

Figure 2.3: 2014 CLIA annual state of the industry press conference data [7]

Complementary, world fleet evolves towards the application of emerging concepts of ITS that would support processes automatization and increase business efficiency. There is a significant effort and applied research in this area, namely in European Commission programmes such as [8], where main concerns are the merits of introducing new technologies and development and demonstration advanced solutions for river information services, vessel traffic management and integrated ship control centers. Nowadays, European Transport Policy includes ITS and ITS Directive (Directive 2010/40/EU) is the legal instrument for the deployment of ITS in Europe. The European Union, US Department of Transportation and Japanese communication ministries signed high level agreements global activities for harmonization, standardization and cooperative ITS applications, as well as a roadmap for deployment.

2.2 Evolution on Information Exchange Demands

Usually, maritime information exchange requirements are centered in MSI and METOC related information. Ship's operation demands for information related to safe operation of the vessel, safety of its crew and environment conditions, which has been resulted in the worldwide deployment of several dedicated systems. Available technologies provide support to SAR, response to pollution incidents, ship and port security and protection of critical marine resources, through a multitude of independent systems: AIS, Electronic Chart Display and Information System (ECDIS), Integrated Bridge Systems (IBS), Integrated Navigation Systems (INS), Advanced Research and Projects Agency (ARPA), radio and satellite based navigation systems, Long Range Identification and Tracking (LRIT), NAVTEX, VTS and GMDSS. Despite such information sources diversity, current maritime information paradigm is terminal centric, where information has limited scope and is presented on a assigned terminal, in most cases supported by specific communications systems. Most of these stovepiped systems rely on dedicated infrastructure to provide specific information that have a sink at marine end user.

Maritime stakeholders have recognized the need for new approaches to information management and associated processes, so several on-going initiatives are focusing on these issues. According to IMO, 60% of collisions and groundings are caused by direct human error [9]. In order to minimize this problem, authorities are committed to improve navigation safety and reduce errors, by introducing automatic information seeking, processing and sharing technologies, thus resulting in more reliable and user friendly maritime navigation and communications. This led to the introduction of the *e-navigation* concept, which has been summarized in the following statement: *"There is a clear and compelling need to equip shipboard users and those ashore responsible for the safety of shipping with modern, proven tools that are optimized for good decision making in order to make maritime navigation and communications more reliable and user friendly. The overall goal is to improve safety of navigation and to reduce errors"* [10]. This idea has been fostering and promoting the development of promising new generation decision support tools to drive a paradigm change at system, integration and operation level. Several international and intergovernmental organizations, such as IMO, International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and International Hydrographic Organization (IHO) are sponsoring these changes and promoting its practical implementation.

Since then, several initiatives have been resulted in significant achievements in different areas, such as user's requirements, positioning, navigation, communications and ship/shore side architectures. Furthermore, recent advances, including field trials of draft architectures, have demonstrated the feasibility of *e-navigation* services. Definitely, *e-navigation* concept have been consolidated as a promising new generation tool that, in a near future, might deliver added value, not only to safety and accident prevention, but also to general maritime operations environment, with obvious commercial benefits.

There is no consensus regarding what *"e"* stands for: electronic, enhanced or even a brand. In any case, for IALA, *e-navigation* is *"the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment"* [10]. In other words, *e-navigation* intend to integrate all the relevant navigational aids information and provide an appropriate tool for decision making to contribute to improve maritime safety in general, reducing errors and increasing navigation and communications to reliable and user friendly forms. The *e-navigation* strategy implementation plan [10] aims to integrate a several electronic aids to navigation already available or under development. Currently, technologies provide support to search and rescue, responding to pollution incidents, ship and port security and protection of critical marine resources. Actually, IMO understanding of *e-navigation* includes the *"present and future user needs through harmonization of marine navigation systems and supporting shore services"* [11]. This, apparently simple, requirement involves tremendous challenges in information and communications domains. The diversity of information sources, mainly MSI and METOC related information, their specific formats, data models, availability and criticality are as demanding as the need for data fusion and area of operations oriented information.

E-navigation is about cooperative information management between marine users, integrating several dedicated stovepipe CIS, presently spread-out through the maritime ecosystem. The IALA presented in [12] an initial perspective for *e-navigation* architecture, where relevant devices within ship technological environment are: transceiver station; data sources and data sinks connected to the transceiver station; and INS and IBS, as presented in Figure 2.4. The entities to be taken into account in this architecture are users and their requirements, regulations, functions and processes, technical services and systems, interactions, information and data.

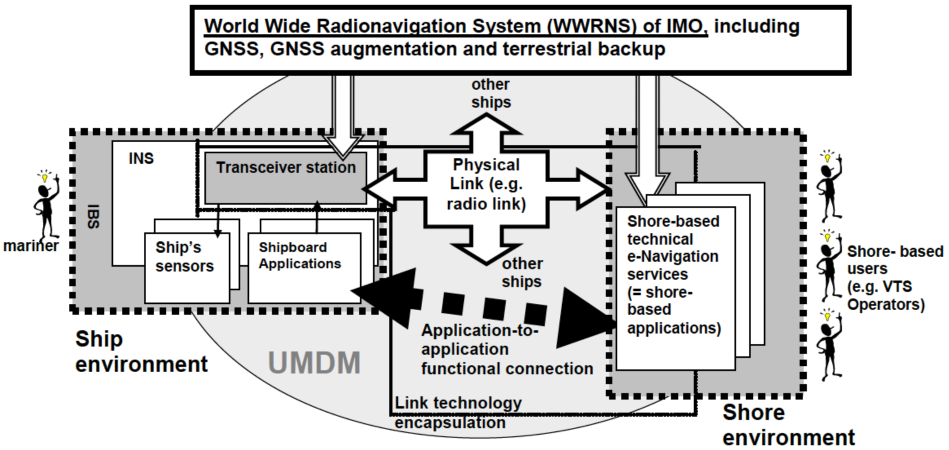


Figure 2.4: The IALA overarching *e-navigation* architecture, which includes a ship-side and a shore-side infostruture connected through functional and physical links, shows IMO's World Wide Radio Navigation System (WWRNS).

The classical approach to *e-navigation* can be interpreted as a typical node centric paradigm, where the focus is on the node's capabilities for information collection, integration, analysis and presentation. The infostructure is composed by interconnected (ashore and afloat) nodes, each one with its own navigation electronic aids and maritime related information systems; maritime business processes are supported by local data fusion of both its own sensors/receivers and information received from any other network nodes. In this context, and independently of its nature (ashore or afloat nodes), *e-navigation* architecture may be generically represented as in Figure 2.5. Naturally, different nodes have different amounts of communication resources and navigation electronic aids; hence the resulting amount of marine knowledge may differ among nodes.

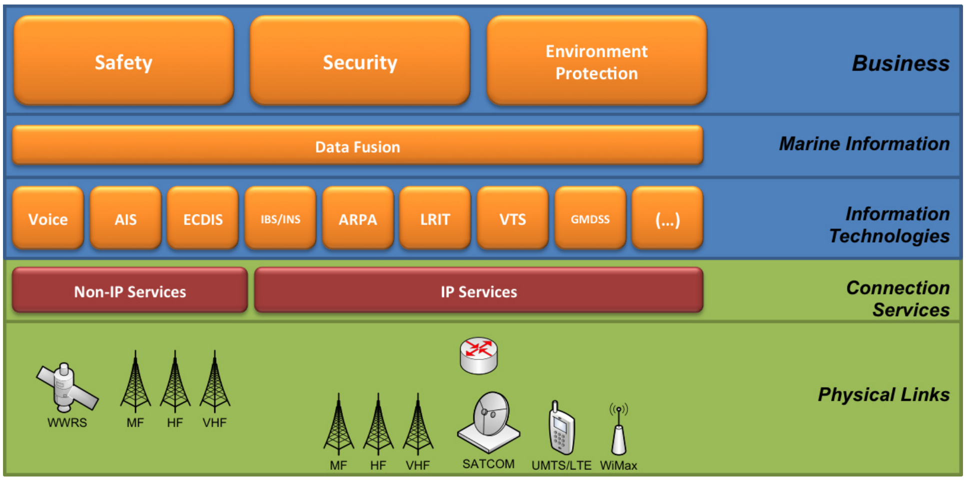


Figure 2.5: Author's interpretation of a classical (ashore or afloat) approach to *e-navigation* node stack architecture.

However, *e-navigation* concept might be interpreted from a different perspective, at information centricity level. Instead of being a node centric, where the focus is on information collection, integration, analysis and presentation, *e-navigation* can be viewed as a network centric paradigm, focusing is information services provision. In fact, the added value of a pool and share option is potentially higher, in short and long terms, them a ”simple” terminal data fusion. This approach is in the basis of Services Oriented Architecture (SOA), which relies on service orientation to create a federation of resources and where users can access independent services that can potentially address novel requirements by recomposing the same services in different configurations [13]. Earlier stages of *e-navigation* maturity level tend to evolve towards a node centric paradigm, where an interface with stovepipe systems would support information fusion, and consolidated presentation to end users, but at later stages, a network centric paradigm can be reached, focusing on the availability of information, to be provided/consumed by node entities.

The capacity to provide a network layer, with appropriate performance, to maritime users opens a whole field of opportunities in services domain. Instead of node centric, *e-navigation* can be viewed within a network centric paradigm, focused on information services provision. In this paradigm, (ashore or afloat) nodes act as maritime information service providers, feeding the e-navigation infostruture through web services. This alternative architecture has three fundamental components, as presented in Figure 2.6: systems sensors, enterprise service bus and internal/external services. The systems sensors are terminals to get access to electronic aids to navigation available through specific technologies and which cannot be provided by any other mean. Service bus provides the way for information translation (interoperability) and sharing. Finally, the internal/external services contribute with separated functions, over the network, in order to allow users to combine and reuse information for required processes and applications, in order to produce the appropriate business support.

Web services are the building blocks to generate maritime knowledge. Hence, in SOA paradigm, the key point is the definition and granularity of provided services. Considering navigation aids as a whole, it is easy to realize a significant overlapping of systems and sup-

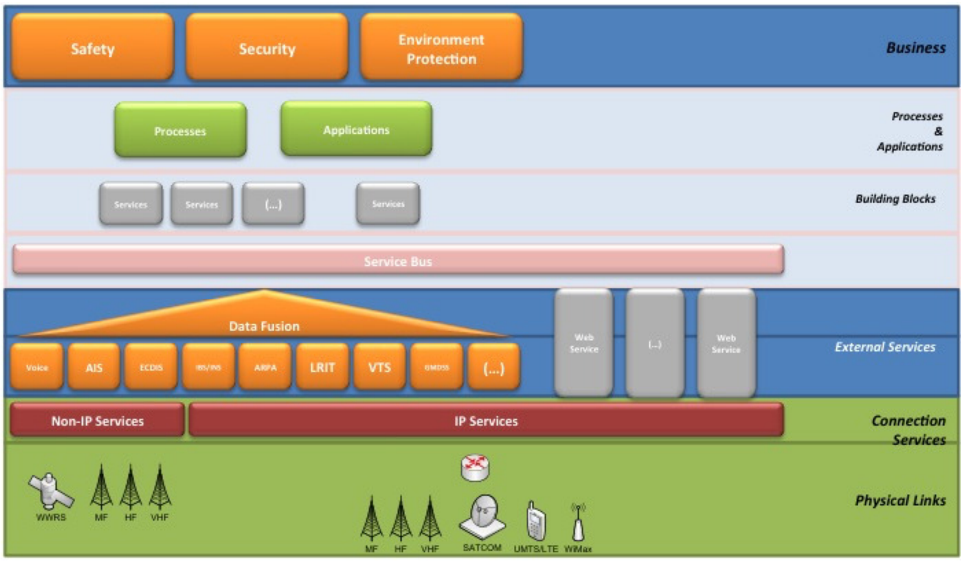


Figure 2.6: SOA for any user within maritime information system ecosystem.

porting shore services. Despite of its interest for diversity purposes, information redundancy is sometimes useless or even counterproductive. Thus, it is critical to evaluate an optimal way to provide MSI and METOC related services in order to maximize the added value of each maritime network node to accurately and efficiently implement the desired business logic. The granularity of services has a significant impact on complexity and performance. Coarse-grained services are obviously more complex than fine-grained services and typically include data that might not be required for a specific task. Due to the fact that web services are remotely accessed, through band limited radio networks, the service requests, the message's size and the amount of transaction data need to be carefully addressed to avoid potential network overloads. In the limit, depending on the design, the amount of exchanged messages may not be appropriate for maritime radio networks.

The implementation of *e-navigation* in a SOA is an important enabler for the application of ITS concepts to maritime environment. In fact, e-navigation might be interpreted as a practical contribution for the development of a maritime ITS concept, where automatization will be extended far beyond navigation and safety, and will include logistics and business processes. Network centric maritime related information can improve navigation safety and reduce errors by introducing automatic information seeking, processing and sharing technologies. Emerging ITS concepts and technologies might be applicable not only to the ships, but also to the water vehicles and its operation as a whole. In a near future, maritime autonomous vehicles and sensor networks would have a massive deployment, which emphasize the need for adequate CIS infrastructures to automatize and optimize business processes, with obvious impact on their commercial efficiency and revenue.

Nowadays, exploitation of marine resources is still a costly and risky activity. The maritime environment is adverse for human activity and demanding for systems operation, which restricts solid deployments due to unbalanced cost-benefit trade-offs. In most cases, the role of human operation or supervision, and its associated costs, tend to discourage the development and utilization of technology to take advantage of oceans opportunities. Although, initiatives such as the Portuguese proposal for the extension of continental shelf, which sets forth the outer limits of Portuguese continental shelf beyond 200 nautical miles are posting technological challenges on operations endurance and ranging. Considering that Portuguese territory shall be about 4 million km^2, equivalent to 91% of the EU's land area, it is necessary to find alternative ways of supporting exploitation operations in a diversity of sectors, which goes from mineral resource exploration to marine renewable energy development.

The answer might be a federation of maritime embedded computing like devices ecosystem, which would share service oriented information without requiring human interaction in a *"Internet of (Maritime) Things"* (Io(M)T) [C3]. The concept of *Internet of Things*, launched in 1997 by ITU, under the title "Challenges to the Network", encompasses a convergence of multiple technologies, from embedded systems to wireless communications, and is expected to offer advanced connectivity of devices, systems and services. New generation of wireless networks, referred to as "Ubiquitous Sensor Networks", which are build on embedded and connected small devices to provide different services to different users in a heterogeneous environment, can be applied to maritime systems to extend connectivity to all required sea domains and applications. In Figure 2.7 it is presented a typical four layer model, where it is exposed the equivalence between "conventional" and maritime environments for device, network, service and contents segments. This presents a extraordinary potential and opens a new field of services and applications that definitely will change the way of doing business and post new challenges for maritime communications systems.

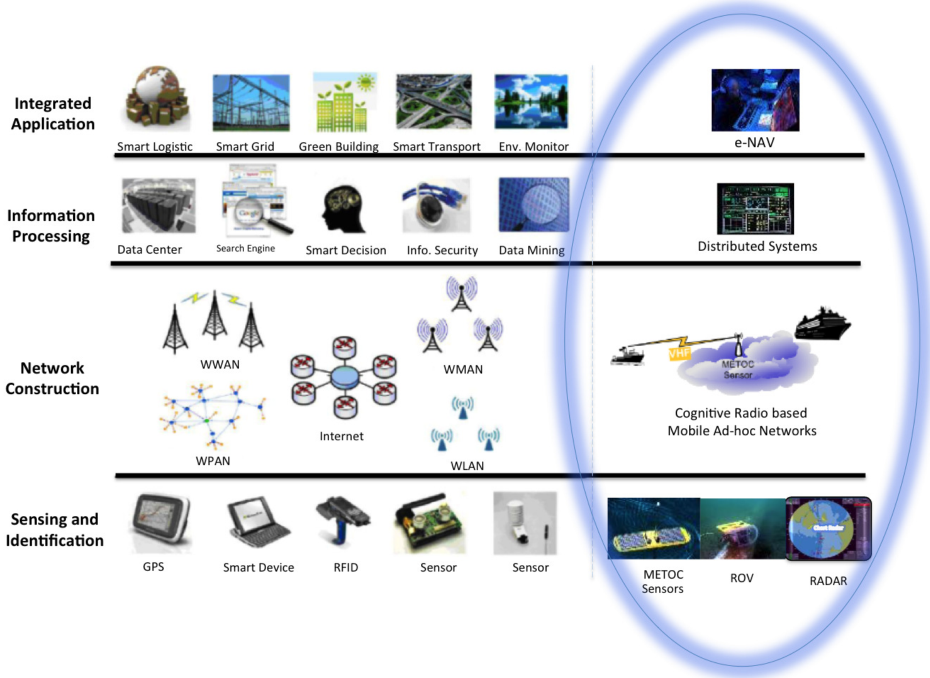


Figure 2.7: Four layers model for IoT and correspondence to maritime applications example.

2.3 Existing Systems

The amount of maritime systems have been growing dramatically since magnetic compass development. As depicted in Figure 2.8, shipboard and shore based systems diversity is significative, but provided information has been centered in MSI and METOC. Recently, *e-navigation* and ITS have introduced new requirements associated to processes' automation and efficiency, and new paradigms to integrate safety and business processes as a all. Even though, the core of existing systems is still stovepiped and narrowband based systems.

Shipping activities are mainly supported by MMS, which includes a variety of services that goes form mobile-satellite to radio determination services. The MMS supports stovepiped MSI and METOC oriented systems, based on voice and low rate data, but there are also general-purpose maritime voice applications. Specific data services, with requires broadband access, are typically supported by SATCOM links over the Internet.

Essentially, mariners rely on three main stove piped systems: AIS, VTS and GMDSS. The former has no fixed infrastructure and the laters require shore based facilities. The AIS is a maritime navigation safety communication system, standardized by ITU and adopted by IMO, which is used for automatic tracking on ships, or by VTS services, to locate and identify of other vessels [14]. It is an autonomous and continuous broadcast system, operating in the VHF MMS band and SATCOM, which can provide information regarding vessel's identity, type, position, course, speed, navigation status and other safety-related information [15]. Appropriately equipped shore stations, other ships and aircraft, which can monitors and tracks ships and exchanges data with shore-based facilities, automatically receive this information sharing. The AIS can handle multiple reports at rapid update rates and uses

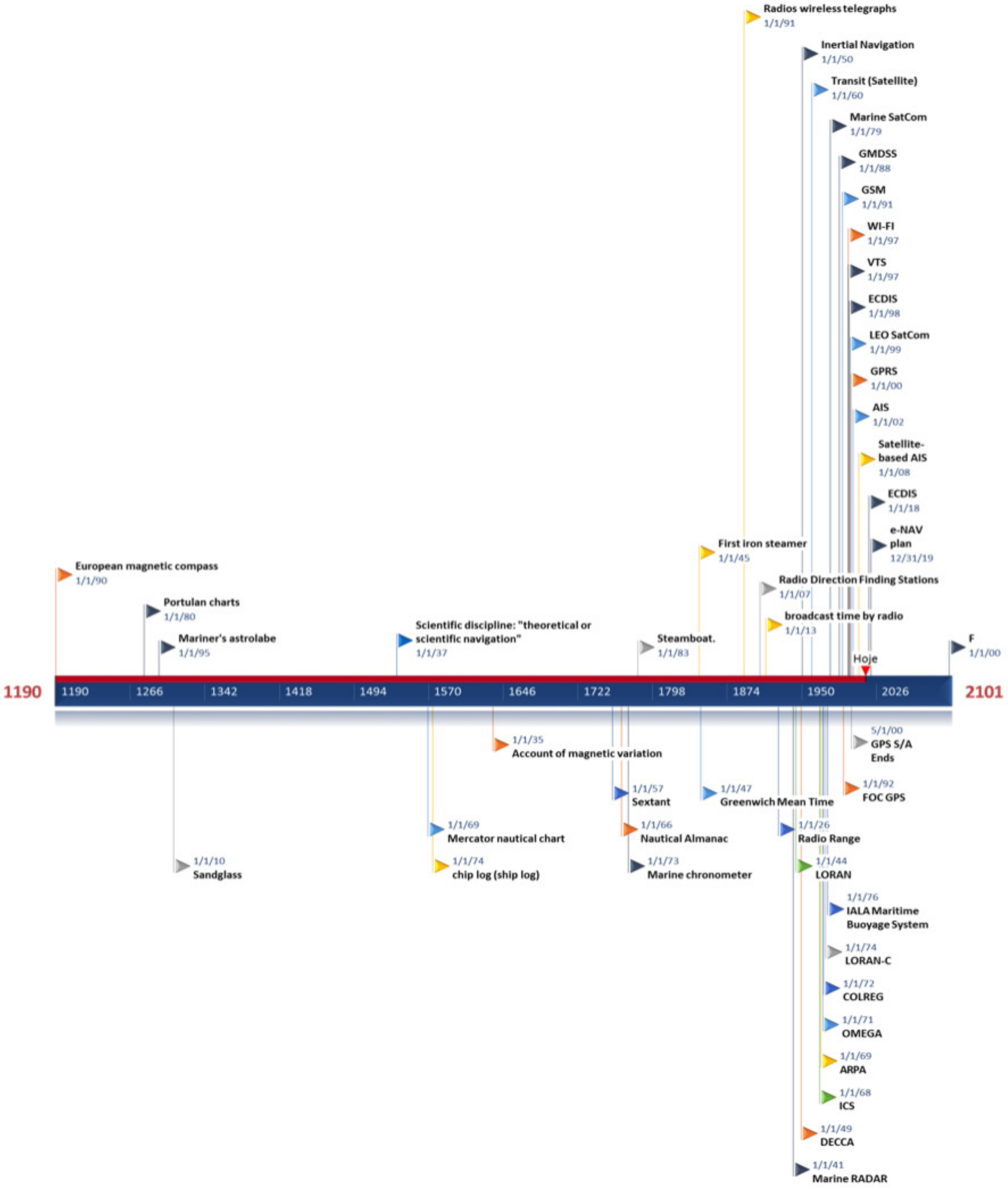
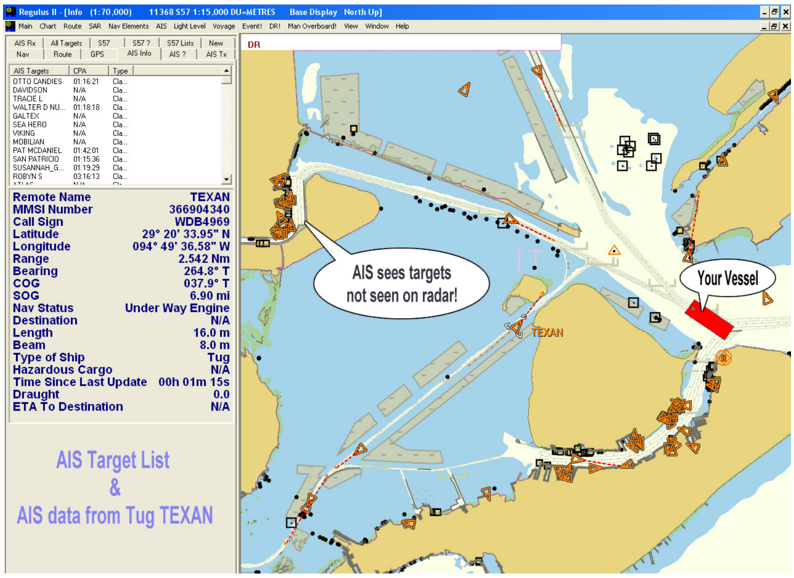


Figure 2.8: The context of marine navigation technology [Author: Victor Plácido]

Self-Organized Time Division Multiple Access (SOTDMA) technology to meet these high broadcast rates, ensuring reliable and robust operation [16]. In Figure 2.9 it is presented a typical AIS information display. Primarily, AIS is intended to allow ships to view marine traffic in their area and it requires a dedicated VHF AIS transceiver. Shore-based facilities may be equipped with receivers only to get access to AIS information.



AIS Targets	CPA	Type
OTTO CANDIES	01:16:21	Cla...
DAVIDSON	N/A	Cla...
TRACIE L	N/A	Cla...
WALTER D NU...	01:18:18	Cla...
GALTEX	N/A	Cla...
SEA HERO	N/A	Cla...
VIKING	N/A	Cla...
MOBILIAN	N/A	Cla...
PAT MCDANIEL	01:42:01	Cla...
SAN PATRICIO	01:15:36	Cla...
SUSANNAH_G...	01:19:29	Cla...
ROBYN S	03:16:13	Cla...

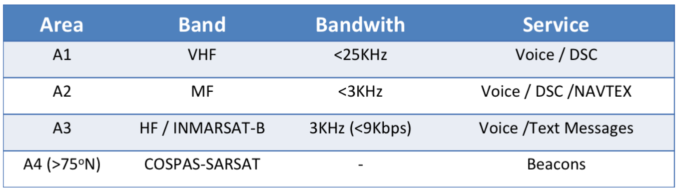
Remote Name	TEXAN
MMSI Number	366904340
Call Sign	WDB4969
Latitude	29° 20' 33.95" N
Longitude	094° 49' 36.58" W
Range	2.542 Nm
Bearing	264.8° T
COG	037.9° T
SOG	6.90 mi
Nav Status	Under Way Engine
Destination	N/A
Length	16.0 m
Beam	8.0 m
Type of Ship	Tug
Hazardous Cargo	N/A
Time Since Last Update	00h 01m 15s
Draught	0.0
ETA To Destination	N/A

Figure 2.9: Example of a AIS display [17].

The VTS, presented in Figure 2.10 is another important maritime system designed to improve safety and efficiency of navigation. It is a marine traffic monitoring system, similar to air traffic control for aircrafts, which is used to prevent occurrences of dangerous maritime traffic situations and provide safe and efficient movement information of vessel traffic within the VTS area. The VTS traffic image is collected and compiled by different sensors, such as radar, direction finding and closed-circuit television, and through AIS and VHF radiotelephony and can be exchanged between shore-based systems and relevant external parties, including *e-navigation* stakeholders [18].

Figure 2.10: Example of Portuguese VTS system (left) [19] and GMDSS concept (right).

Finally, GMDSS is the most important maritime system. It consists of several subsystems to support distress alerting, search and rescue coordination, MSI broadcasting, general communications, and bridge-to-bridge communications. Littoral countries have implemented infrastructures that allow full coverage of areas that lies within the range of shore-based VHF coastal stations (up to 40 nautical miles) and medium-range MF stations (up to 200 nautical miles) providing radio services, such voice and automated distress alerting via Digital Selective Calling (DSC). On ships side, licenses to sail requires radio installations for ship-shore communications at vessel's area of operations, as represented in Figure 2.10: VHF is mandatory for A1 area of GMDSS, to ensure mobile two-way radio communication within an slightly extended geometric LOS range, typically up to 35 nautical miles; MF is mandatory for A2 area of GMDSS and allows beyond LOS communications, typically up to 200 nautical miles; Finally, INMARSAT (SATCOM) is mandatory for A3 area of GMDSS, for long range ($>$ 200 nautical miles) communications [20]. These mandatory requirements are due to SAR importance for maritime safety and the need to interact with GMDSS shore based infrastructure, deployed in every maritime nation according to a IMO master plan [21].



Area	Band	Bandwith	Service
A1	VHF	<25KHz	Voice / DSC
A2	MF	<3KHz	Voice / DSC /NAVTEX
A3	HF / INMARSAT-B	3KHz (<9Kbps)	Voice /Text Messages
A4 (>75ºN)	COSPAS-SARSAT	-	Beacons

Figure 2.11: GMDSS areas

Despite all these VHF radios proliferation, when data services are required, SATCOM is the preferable choice for most of mariners, besides performance, associated costs or shore proximity. A survey [22] revealed that only (very) low rate ($<$ 9 kbps) services are supported by maritime non-SATCOM communications systems. Satellite services provide end-to-end mobile communications not only for operational communications and safety services, but also for personal communications and entertainment. However, most of the offered satellite services are narrowband, i.e. up to 64 or 128 kbps, and the available broadband services are very expensive. For instance, speeds up to 432 kbps would cost up to $US 20.85 per Megabyte (!), in the case of Inmarsat FleetBroadband Global [23].

The terrestrial fixed/mobile based solutions do not provide consistent solutions that might be considered viable alternatives to SATCOM. The UMTS/LTE networks can be used as a complement of MMS, but their limited sea coverage is definitely an important operational constraint. Some vendors announced field trials with ultra wide base stations that reached 50 nautical miles, with extended power, but power constraints (40 W), due to increasing (and associated spectrum inefficiency) of shore cells size and limited terminal available power, prevent cellular networks footprint to exceed 15 nautical miles.

The gigahertz based solutions, such as Wi-Fi or Wi-MAX, have analogous drawbacks, namely coverage problems and spectrum allocation difficulties, which result from highly occupied, spectrally demanding and commercially attractive bands, that impose restrictions on transmitted power. Even though, there are numerous initiatives in this area, mostly addressing upper layers problems, like in TRITON project, in which a wireless mesh network to support multi-hop data delivery in maritime network is investigated [24], or in multi-hop WiMAX and mesh network proposed solution, presented in [25], which intend to provide Internet access in the Mediterranean Sea without satellite. The former project addresses problems related to routing and scheduling design considerations and provides a framework for fair and equal opportunity access to users [26], while the later includes Mobile Ad-hoc Network (MANET) management and traffic issues. One can find many other WiMAX-based mesh technology studies in literature, mostly in networks that include SATCOM links, like in [27], whose fundamental topics are MANET management, Delay-Tolerant Networking (DTN) routing protocols and traffic issues. Unfortunately, most of the projects in this area are strictly academic or proofs of concept, associated with upper layers, with slack connections to real world maritime operations.

2.4 The Role of Maritime B-VHF

The unavoidable dependency on SATCOM has impact on (lack of) redundancy, performance and costs of maritime communications, which is inappropriate and undesirable, especially when it includes safety systems. Hence, any radio based alternative for high-speed data links that may overcome this limitation would represent a significant improvement and a driver for a paradigm change in different domains, such as command and control of navigation, security and safety, or even in afloat information exchange. In fact, cost savings might be crucial to convince future users like cruise liners and recreation sailors, which in littoral countries, like Portugal, may represent a customer potential quite important. This fact, by itself, is significant enough to justify the interest of an investigation on the possibility of implementation of a shore based broadband system that can support high speed services at low cost.

According to [11], *e-navigation* requires stable broadband VHF, High Frequency (HF) and satellite data communications. Currently, there are no such services in VHF or MF/HF and broadband SATCOM is quite expensive, so available options are predictable and can be summarized in Figure 2.12. Besides SATCOM, none of existing technologies are able to effectively provide broadband access to marine users, so alternatives are either increase spectrum assignments/allocations on existing maritime bands, or provide new allocations for maritime usage in different bands. Considering bandwidth natural limitations, MF/HF are not attractive alternatives to pursuit. On the other hand, higher frequencies, like LTE, WiFi, WiMAX operating bands, have several unfavorable factors that discourage such choice, namely cellular industry lobbying, signal attenuation and fading in a maritime environment, etc. The VHF band is the ”natural” choice for maritime broadband communications, due to its ability to propagate well beyond LOS, but unfortunately MMS has no broadband allocations and it would require an International Telecommunication Union (ITU) decision or, alternatively, national regulators assignments. Either way, the solution seems to be on the resources side, which requires not only authorizations and licenses, but also innovative ways to convince spectrum stakeholders.

Complementary, shore relative positioning of maritime operations and marine users concentration is an important aspect to take into consideration. Despite transoceanic trips, world sailing activity occurs within 200 miles from cost line, mostly within 40 miles, as can be observed in Figure 2.13. Besides the regional and local traffic, mostly fishing vessels and recreational boats, international cruisers, cargo ships and tankers plan their journeys as close

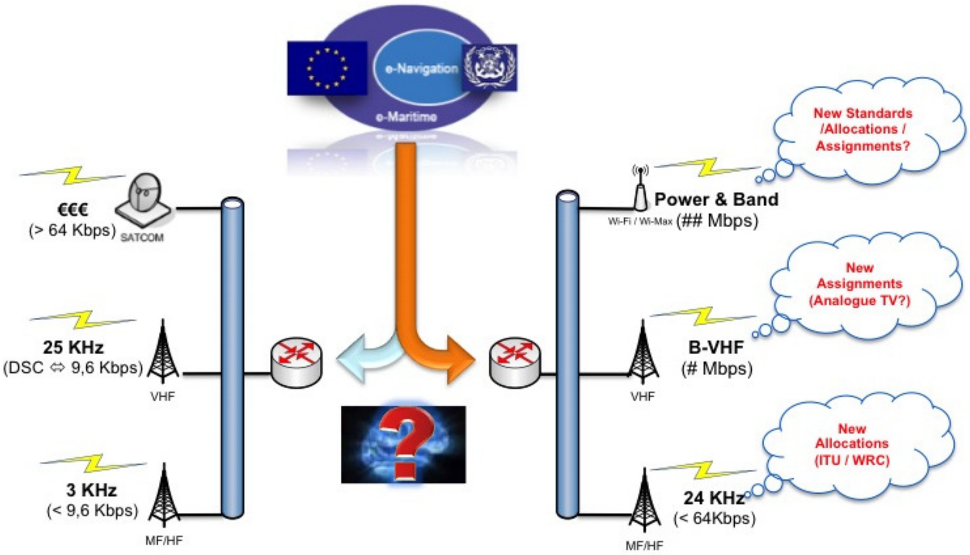


Figure 2.12: Spectrum challenges and possible solutions for broadband systems.

as possible to shore. The foundation for this routes choice is naturally related with safety, but has consequences in congestion and ultimately in maritime accidents. Therefore, traffic separation schemes and other ship routing systems have been established in most of the major congested shipping areas to mitigate the amount of collisions and groundings. The idea is to contribute to safety of life at sea, safety and efficiency of navigation and/or protection of the marine environment by regulation traffic in dense shipping areas where ships can go in different directions. Europe has one of the highest concentrations of shipping and includes several of the busiest shipping lanes in the world. Particularly, in Portuguese waters, the European gateway to Atlantic, the amount of sea traffic within shore's LOS is quite substantial.

The fact of the matter is that ships are travelling, most of the time, within shore LOS, served by VHF coastal stations, and do not take advantage of this band, due the lack of high-speed data services provision. Broadband communications requires spectrum availability, which is a recurrent issue in every new wireless system. Nevertheless, the role of maritime VHF communications in safety and shipping operations has been well recognized and supported by both national and international regulatory bodies. Since the early days, successive World Radiocommunication Conference (WRC) have contributed to spectrum allocation adaptations that could accommodate technological evolutions in MMS that enabled significant improvements in maritime communications capabilities. Just to recall some examples, 1938 Radio Regulations (RR) Conference, in Cairo, acknowledges the fact through the allocation of 157-162 MHz frequency band for mobile regional maritime service [28]. Since 1983, all maritime radio equipment is required to conform to Resolution 308 (WRC-79); in other words, 25 kHz channelling with a maximum deviation of ± 5 kHz. Later, WRC-00 updated Resolution 342, with the introduction of new technologies to improve efficiency in the use of the frequency band of 156-174 MHz by stations in the MMS. Additionally, RR Appendix 18 has been modified to permit the use, on a national basis, of various frequency bands for future introduction of technology. Subsequent WRCs have introduced minor changes to the frequency arrangements in RR, which predominantly permit national flexibility that do not affect or influence the global maritime environment [28].

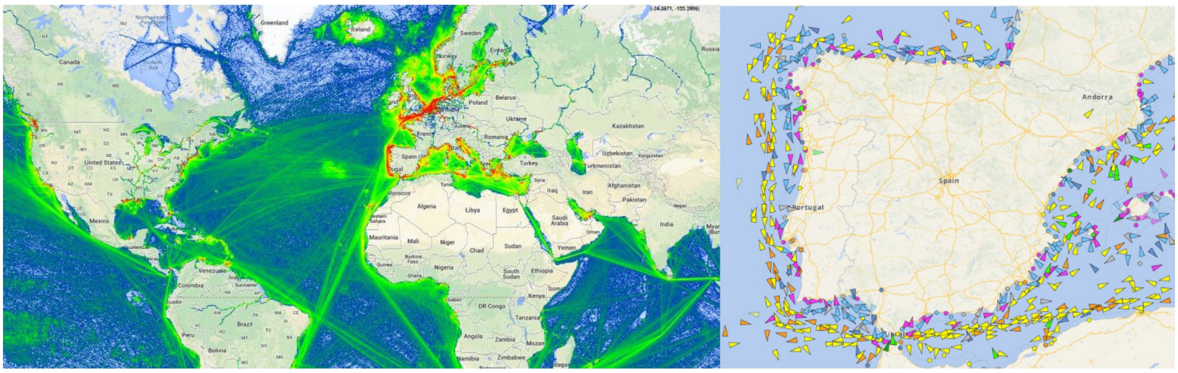


Figure 2.13: Maritime traffic snapshot, obtained in a dedicated vessel traffice tracking system, available online at [29].

Recently, ITU initiatives focused in spectrum usage efficiency and digital data exchange. Interim solutions for efficiency improvement in the use of 156-174 MHz band by stations in the MMS are addressed in [30], while [31] and [32] address the characteristics of VHF radio systems and equipment for exchange of data and electronic mail in MMS and Electromagnetic Compatibility (EMC) assessment of shore-based electronic navigation (*e-navigation*) infrastructure and new draft standards for data exchange in the VHF maritime mobile. In general, ITU recommendations point to the use of Appendix 18 channels to support future digital technologies in MMS. However, mostly of rationalization and optimization initiatives, namely migration to 5 KHz channelling or interleaving with 25 KHz and 12 KHz channels [30] are based on the current allocation paradigm, and consequently have limited room for improvement.

In fact, at the WRC of 2012, maritime broadband communications have been addressed in several points. In agenda item 8.2, IMO recognized that *e-navigation* could not be deployed without additional frequency allocations for advanced communication systems, while Resolution 360 considered regulatory provisions and spectrum allocations for enhanced AIS technology applications that established an agenda item for WRC-15. Following WRC-12, IALA initiated its studies of new AIS technology applications and possible new applications to improve maritime radio communications, which has been resulted in standardization of Very High Frequency Data Exchange System (VDES).

The VDES concept, depicted in Figure 2.14, assumes a maritime digital data communication system using VHF band, including AIS functionality, and SATCOM capability. It would provide an opportunity for a globally interoperable capability of significantly higher speed and larger volume data exchange than AIS, and potentially with worldwide coverage. The objective is to have the possibility of exchanging data at 307.2 kbps using 100 kHz band and, if SATCOM capability is realized, covers beyond the range of shore based VHF radio station, so seamless one band, VHF, worldwide radio communication becomes possible. Furthermore, if new frequencies can be allocated, *Application Specific Messages* that uses existing AIS 1 and 2 channels for its transmission now, will be moved to these channels [33]. Unfortunately, such initiative depends on ITU successful development of its Recommendation for VDES technical characteristics and WRC-15 allocation of new frequencies for VDES.

Another example of the need for alternatives to SATCOM came from IMO several initiatives have been resulted in significant achievements in different areas, such as user's requirements, positioning, navigation, communications and ship/shore side architectures. Recent advances, including field trials in Baltic Sea Region [34], have demonstrated the feasibility of *e-navigation* services, using a Universal Maritime Data Model (UMDM) [34], supported in AIS and Internet (through cellular networks and SATCOM). Despite the limited scope of tested services and functions, prototype included all the ingredients to provide a realistic flavour of future deployments feasibility, based on similar solutions. Nevertheless, lessons learned revealed that Internet links used (>128 kbps) were sufficient to assure prototype services, but there is a need for alternative communications systems to AIS. Actually, these conclusions pointed out the fact that maritime Internet Protocol (IP) based broadband networks are critical enablers for future *e-navigation* architectures. On the other hand, performance and cost of currently available SATCOM services, associated to the lack of alternatives for high-speed communications, even within shore radio horizon, bring back an ancient ambition of supporting broadband services over maritime radio bands.

Moreover, in a different context, the European Commission funded, by Sixth Framework Program, a B-VHF research project to support Air Traffic Management (ATM) system [35]. The concept was to develop a multi-carrier to be deployed within the aeronautical VHF band, to support air-to-ground communications through the implementation of a multi-application broadband cellular full-duplex system based on OFDM. On top of that, the ground stations applied Code Division Multiple Access (CDMA), resulting in Multi-Carrier CDMA, and aircrafts use different groups of OFDM sub-carriers instead of CDMA, realizing Orthogonal Frequency-Division Multiple-Access. This project was completed in September 2006 and the results of B-VHF activities have been published in [27], [24] and [26].

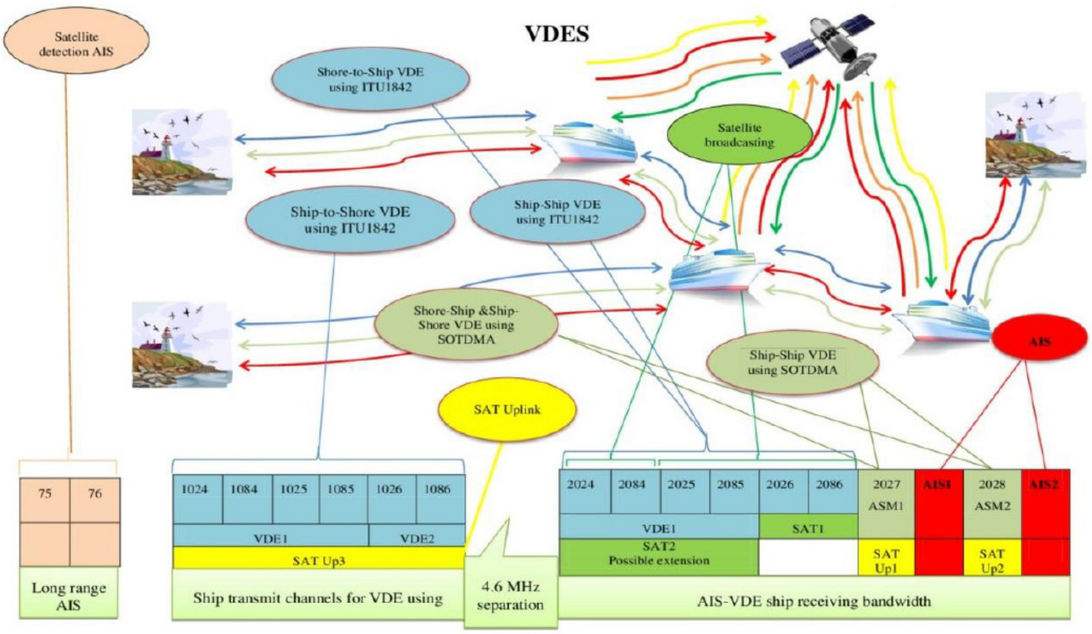


Figure 2.14: VDES Concept (note: channel plan is tentative) [33].

In resume, future challenges in maritime information exchange domain require a wide area heterogeneous network with broadband links. However, mobile (shipboard) nodes have different levels of requirements for data availability, integrity and confidentiality, as well as, distinct implementation constraints. Considering communications systems characteristics, depicted in Figure 1.1, it is foreseeable that VHF systems will always be essential for maritime operations and B-VHF would fulfill most of marine community data communications requirements.

2.5 Concluding Remarks

There is a common understanding regarding the need for alternatives to SATCOM. Flexibility, low cost and coverage requirements are critical for any successful deployment, but bandwidth availability is the major constraint for systems development. Even though, maritime community future information exchange demands pushes stakeholders to provide the means to evolve to more efficient and secure ways of doing business.

A good example to stress the need and significance of this subject and the role of VHF based communications can be found in VDES initiatives and on the amount and nature of worldwide associated stakeholders. Nevertheless, and despite expected improvements provided by its eventual deployment, 307 kbps might not be the expected performance to overcome SATCOM demand, at least in most cases.

The role of a general-purpose B-VHF system and its relevance for maritime business is significant enough to an effort to pursuit alternatives to overcome spectrum unavailability. In the following chapter, we present our proposal to break through such dead lock and discuss the way to go for required solution.

Chapter 3

A Cognitive Radio Based Solution

The role of VHF band in maritime communications has been analyzed and a B-VHF raised as a "natural" solution for alternative non-SATCOM broadband access. Nevertheless, a worthful maritime broadband system requires spectrum, which includes not only availability, but also appropriate bandwidth. Unfortunately, none of these exigencies are easy to accommodate without an unconventional approach. We propose an opportunistic usage of VHF spectra to enable the implementation of B-VHF networks that would provide appropriate connectivity to marine users to support current information exchange requirements and enable future developments on maritime services and applications.

In the current chapter, we address the spectrum challenge, in Section 3.1, as the major issue for any development in wireless communications and discuss the usage of DSA concepts to overcome spectrum scarcity deadlocks, introducing cognitive radio as a technological tool to support such spectrum management paradigm changes. In Section 3.2, it is presented the proposed CR-B-VHF concept and a potential system architecture, founded on a shore based infrastructure. Moreover, it is considered the MMS assigned spectrum as the most presumable band to be eligible for opportunistic usage, but, depending on application, other bands can be considered as well, namely analogue TV released bands or government assigned spectra. Within the same section, it is described the enabling technologies that can support CR-B-VHF implementation and examined its availability and maturity level. Section 3.3 is dedicated to a feasibility issues analysis, where general aspects associated to deployment of new systems are examined and specific technological issues, associated with CR-B-VHF deployment, are discussed. Finally, in Section 3.4, some concluding remarks are presented.

3.1 The Spectrum Challenge

The major challenge in the implementation of maritime B-VHF services is unquestionably the spectrum availability and management. The solution for such constraint might be one of the following: either pursue VDES similar procedure and use WRC to request for new frequency allocations for maritime B-VHF networks, in order to have a global solutions; or promote initiatives in order to have VHF assigned spectrum, by national regulatory authorities, to support specific maritime applications; or foster evolution of regulatory framework towards a more flexible and dynamic management process, in order to overcome spectrum underutilization and scarcity. In some bands the spectrum access is more problematic than its physical scarcity [36], there are heavily used bands, which correspond to the most attractive portions of spectrum to support commercial wireless communications and services, while others are just partially occupied or unoccupied most of the time [37]. An improvement on spectrum usage efficiency is an enabler for shortage problems and a low risk solution for deployment of new communications systems.

In the past, the fear of harmful interference led to static allocation strategies, which have been largely successful in the protection of assigned users, but poorly efficient in terms of overall spectrum utilization. Typically, frequency bands are assigned to a specific user or service, which are guaranteed to have exclusive access to that portion of spectrum, no matter how often it is used. Hence, efficiency improvement, within actual frameworks, would involve a re-evaluation of demands and reassignment of spectrum, which is obviously unfeasible due to natural constraints associated to live operations and legal issues. Spectrum scarcity claims for new approaches to management, more flexible, adaptable and efficient.

The solution that has been pointed, for cases where frequency allocations might be difficult to achieve, is the usage of DSA [37], defined in [38] as *"a new spectrum sharing paradigm that allows secondary users to access the abundant spectrum holes or white spaces in the licensed spectrum bands (...) alleviating the spectrum scarcity problem (...)"*. A dynamic tackle, such as DSA, has a tremendous potential to overcome deadlocks associated to lack of spectrum and improve services diversity and performance. Nevertheless, potential risk of harmful interference is significantly higher, than in static case, which sometimes results in mistrust on dynamic model adequacy to support live operations. This represents an additional challenge for all spectrum management stakeholders, including system designers.

On the other hand, an evolution to DSA strategies must pursuit recognition of interference protection assurance and a commitment to preserve incumbent's on-going operations. The challenges for deployment of a new spectrum management paradigm are not only coupled with the benefits of static allocation, concerning interference, but also related with coexistence of systems with different precedence. The role of regulatory agencies is crucial in this course, through mediation of the processes and definition of standard rules and metrics, which allow key players to cope in this dynamic and "quasi-chaotic" environment.

Any DSA strategy deployment has to increase spectrum usage efficiency, ensure harmful interference level of legacy (incumbent) systems and promote an applicable regulatory paradigm change. The later requirement is critical to such spectrum management initiative, while interference control is essential to its acceptability. However, spectrum efficiency maximization depends on operational context, type primary services and users activity profiles.

There are several models for DSA: Dynamic Exclusive Use Model, Open Sharing Model and Hierarchical Access Model. In the exclusive use model, there are two approaches (spectrum property rights [39] and dynamic spectrum allocation [40] that intend to increase spectrum efficiency through dynamic allocations, either based on spectrum trading or service statistics, but within a classical framework of regulatory authorities. The open sharing model, a.k.a. spectrum commons [41] and [42], is based upon the principle that all the users have the right to use a (spectrum) common resource in an available basis, where share strategies can be centralized or distributed. In hierarchical model, users are classified as primary (incumbents) and secondary (opportunistic) in order to ensure formers exclusive access and laters possibility to take advantage of spectrum, when primaries are not using it. There are two approaches to hierarchical model: either primary and secondary users can operate at the same time, with limited interference levels (*underlay*) i.e. constraint on transmission power, or radio operation is exclusive (*overlay*), i.e. constraint on when and where to transmit. Naturally, spectrum overlay is the most adequate scheme for spectrum dynamic access in maritime VHF band, not only due to its ability to handle different channels priority and relevancy, but also because it is in a better position to receive extended support from marine community, which is primordial to obtain a regulators authorization to operate in that band.

Nevertheless, DSA schemes require technological tools to manage such fast-developing environment and ensure users minimum operational requirements. These essential conditions are more pertinent when it is necessary to differentiate and prioritize users. In fact, reluctance associated to dynamic spectrum management, specifically hierarchical models, results from the lack of reliable technology that can ensure users' quality of service, namely incumbents rights. However, the application of CR to dynamic spectrum access, seems to be the solution for most of challenges associated to users necessity to learn from and adapt to evolving environment and a fundamental line of reasoning for defenders of a change on regulatory framework.

According to Federal Communications Commission (FCC) [43] CR is *"a radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets."* To perform its assignment, a CR must build a real time radio environment multidimensional picture that includes profiles of transmitters and receivers, within interference range, which accommodate the randomness and uncertainties of communication channel. Such constraints required that a CR must incorporate some sort of intelligence to manage all variables and anticipate situation changes.

However, the nature of modern wireless environment demands for more than an intelligent system. It requires the ability of dynamic reconfiguration [44]. The set of cognitive capabilities such as awareness, learning, adaptivity, reliability, and efficiency, rely on modern techniques like digital signal processing, networking, machine learning, computer software, and computer hardware, while the reconfiguration capability is brought by the convergence of digital radio and computer software, which results in a platform called Software Defined Radio (SDR) [45]. Therefore, SDR emerges as the natural stage for practical implementations of CR.

Basically, a CR system operation is based upon two main tasks in a closed loop: spectrum sensing and adaptation. Spectrum sensing is required to search the radio environment, over a wide frequency band, for unoccupied spectrum, while the adaptation process, which includes changes in transmit power, carrier-frequency and modulation strategy, is required to minimize interference, namely with incumbents. For one-way communication path, these two main tasks may be splitted in a set of cognitive tasks iterations. Specifically, the cognitive process, represented in Figure 3.1, starts each iteration with probing of radio environment to collect a radio frequency stimulus and finishes it with a transmitted signal. Each cycle is repeated according to predicted variability of radio environment. The situation analysis would provide information to define spectral availability and channel characteristics, like noise floor statistics and channel capacity, to allow dynamic adaptation and/or reconfiguration of transmitted signal to maximize the throughput of the link.

As represented on Figure 3.1, signal processing cycle of a CR follows human mind behavior: observing and learning from radio environment and adapting and controlling the communication processes to facilitate radio connections between users. In learning process, it is crucial to detect spectrum holes, estimate their power contents, and predict its availability

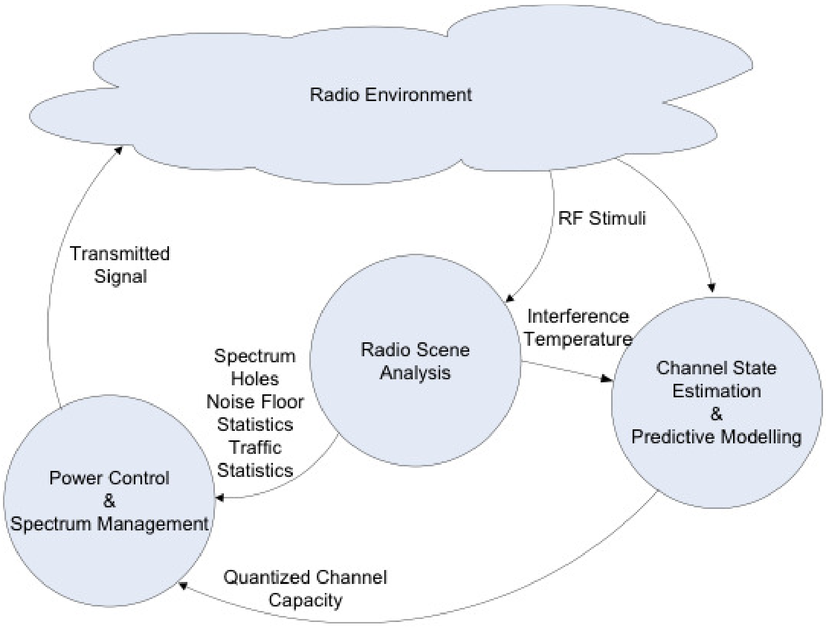


Figure 3.1: Cognitive tasks iterations for link management in a one-way communication path [44].

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to support high reliable communications. Thus, radio scene analysis includes the detection of spectrum holes and the evaluation of noise floor and traffic statistics that will be used as inputs for adjustments in power and spectrum management. Additionally, it is required another input, which provides an estimation of channel capacity and allow coherent detection. These represent interesting challenges, whose impact goes from regulatory paradigm change approval to new systems development.

Eventually, the deployment of CR technology is decisive to increase the efficiency of electromagnetic radio spectrum usage and overcome its scarcity. Naturally, expected efficiency improvement is proportional to the level of cognition functionalities available in a CR. This means that CR ability to exploit inactive frequency bands will depend upon its faculty to find the so-called opportunities to operate and consequently on its spectrum sensing techniques capabilities. Under those circumstances, detect and classify spectrum holes with accurate level of spectral resolution, estimate the direction of arrival of interferers and computational feasibility in real time, will make a difference. On the other hand, spectrum management is close connected to power control, due to its relationship with interference in adjacent bands, and requires implementation of an effective and efficient strategy. The maximization of throughput involves an adaptive strategy of power control and spectrum management. In a Cognitive Radio Network (CRN) environment, power control must be considered as a general issue and the selection of transmission power must take other nodes into consideration. The optimal power will jointly maximize data rates in the network and shall not exceed the harmful interference limits.

3.2 Maritime CR-B-VHF concept

The proposed solution for maritime B-VHF communications, in a context of spectrum scarcity, is a CR based system that uses a multicarrier modulation scheme to take advantage of unoccupied spectra, in a opportunistic basis. A CR is characterized by its ability to understand the environment and dynamically adapt itself (in terms of transmit power, carrier, modulation, etc.) to accommodate the requirements of reliable communication links with efficient utilization of the spectrum. The awareness of surrounding radio situation requires a spectrum sensing capacity, which in this case must deal with the fact that eligible spectrum for opportunistic usage would not be contiguous, and transmitted signals have to be a variant of OFDM, composed by a set of Non-Contiguous OFDM (NC-OFDM) subcarriers, where each carrier is placed on available spectrum holes, according to the spectrum opportunities, and activated and inactivate according to the level of interference in the assigned channels.

Conceptually, CR-B-VHF can be represented as in Figure 3.2. It is considered a hierarchical spectrum access model and assumed a pool of assigned (incumbents) spectrum designated for opportunistic usage, where eligible spectrum is selected from MMS assigned channels, former analogue TV bands or any other service assigned spectrum in military/government agencies (in the cases of official networks applications). Hence, the idea is to implement a dynamic system that can activate and deactivate subcarriers, according to spectrum opportunities, ensuring an adequate interference level at incumbent's live services. Sensing techniques detect inactive spectrum segments and build up a channel availability picture. Furthermore, through the activation and deactivation of a set of NC-OFDM subcarriers, it is possible to take advantage of an interesting amount of spectra to support broadband communications.

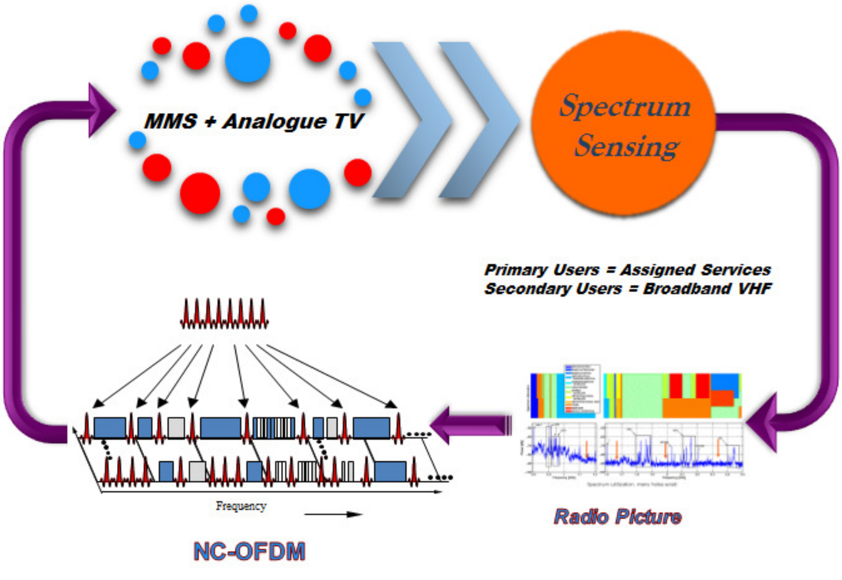


Figure 3.2: Maritime CR-B-VHF concept

Early maturity level stages of CR-B-VHF networks might be limited to an infrastructure mode configuration, while later phases can progress towards ad-hoc modes, through incremental deployment of capabilities. Similarly to wireless local area networks, in infrastructure mode the mobile nodes (ships) communicate with each other through a cognitive node (radio station), while in ad-hoc network mode, each mobile station routes by forwarding data to any other nodes, thus extending CRN footprint coverage. Eventually, this strategy would allow quicker deployments and a better consolidation of information exchange requirements. Nevertheless, mobile nodes play an important role in a CR-B-VHF, not only for spectrum sensing diversity purposes, but also for footprint enhancement and increased routing alternatives.

Moreover, particular characteristics of such networks recommends an architecture design that takes into consideration data exchange and performance requirements, namely the asymmetric nature of information consumption. A shore-based infostructure is expected to provide most of the required services, supplying fused data to consumers. The shore-ship direction is, therefore, more demanding in terms of interface data rate. On the user side, ships do provide added value to the full system, namely providing own ship's area of operations related information, but the amount of generated data is predictably smaller. These asymmetric characteristics of data rate requirements anticipate an architecture that might take advantage of this fact to maximize overall network performance.

A potential approach to maritime CR-B-VHF networks implementation is a shore-based infrastructure, where each fixed node is implemented in a radio station. A central cognitive engine would compile and process the information collected by cognitive nodes, then central management information is disseminated and operationally managed by each node. The radio picture would be centrally built, according to information collected by each coastal station, where spectral usage can be associated to a location and, eventually, additional information that would help to estimate near future occupation of associated band. Afterwards, according to the respective spectra opportunities and adjacent node usage, each network node would implement its own spectral usage plan, which results in a correspondent local data rate.

The system architecture can be depicted as the octopus of Figure 3.3. The system brain is a central cognitive engine responsible for compilation and processing of information collected by cognitive nodes, and for network general management. This engine produces a recognized spectrum occupancy picture, identifying spectral opportunities in both time and space do-

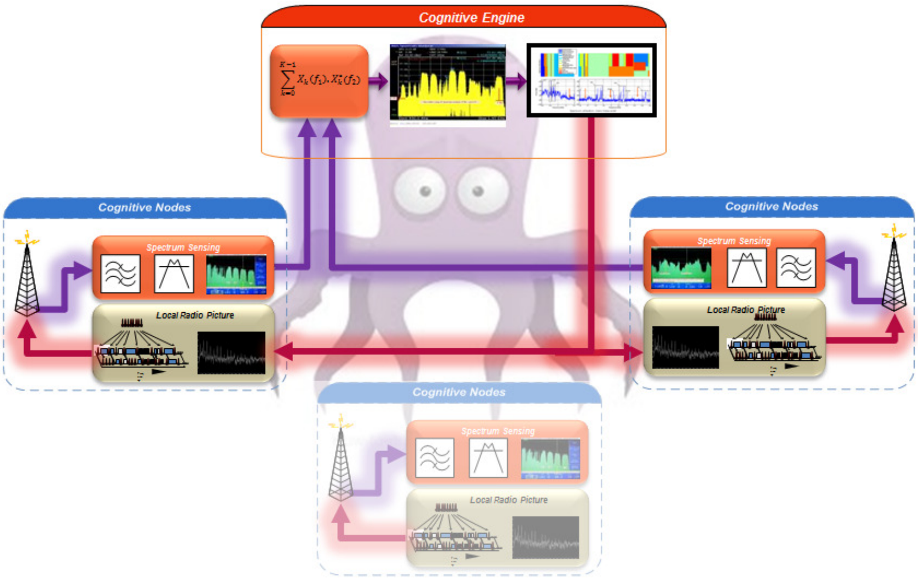


Figure 3.3: Maritime CR-B-VHF system architecture.

mains, and producing complementary information to support estimation of future occupation and associated capacity, in designated bands. Based on such information, a spectrum usage plan is produced for each cognitive node, and disseminated throughout the network nodes.

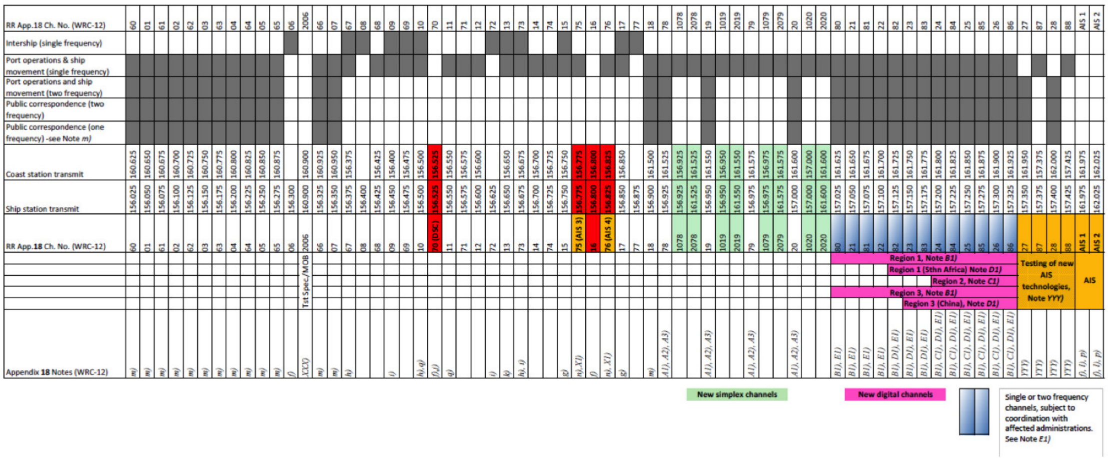
In brief, proposed CR-B-VHF solution has a significative potential to provide maritime broadband services and replace SATCOM operational use, within shore radio line of sight. Nevertheless, it depends on successful development of technological solutions to ensure detection and exploitation of spectrum opportunities in VHF band, which is critical to convince regulatory authorities to grant permission to operate and designate spectra for that opportunistic usage. In addition to that, practical deployments of this concepts depend upon systems envisage achievable performances, which are subject to previously referred conditions.

3.2.1 Eligible Spectrum

The complexity of frequency assignment/management in VHF band results, not only from the need of coordination between neighbor countries, but also due to diversity of stakeholders (namely government agencies, military and international organizations). It is particularly difficult to find and allocate spectrum for new services, especially contiguous spectra for broadband services. That is why proposed solution assumes that CR-B-VHF will use legacy assigned spectrum in an opportunistic basis, recognizing that any eligible spectra will not be contiguous.

Nevertheless, it is essential to identify eligible slots that might constitute spectra pool and the conditions of its opportunistic utilization. Therefore, at this point, we have to consider that CR-B-VHF concept can have multiple applications, within maritime environment, and consequently spectrum procurement and suppliers can have different precedence. For global applications, such as *e-navigation* related services, ITU and WRC have to be involved, either to allocate spectra or to provide guidance on spectrum assignment to national regulatory authorities, in order to coordinate worldwide availability of designated spectrum for opportunistic use in CR-B-VHF networks. The obvious candidate is the MMS allocated band, but there are other bands that might be taken into consideration (at least in theory) namely lower bands of former analogue TV. In any case, it is not expected that the amount of spectra, and its associated bandwidth, would be significative, but one can anticipate lengthy and complex processes. On the other hand, specific applications or ”national domains” of an Io(M)T would be considered within the scope of national regulatory authorities and, therefore, much simpler associated processes and better chances to have wider assigned bandwidths. Finally, for official networks applications (Navy, Coast Guard, Maritime Police, etc.), processes are even simpler and, in the limit, non-critical applications VHF assigned spectra can be fully used by opportunistic networks, as long as it follows regulatory bodies recommendations.

Curiously, MMS allocated spectrum is not completely assigned to maritime services. In fact, except for two most important channels in MMS, none of the other channels are exclusively allocated to MMS, and administrations are not obligated to allocate those remaining frequencies to maritime service [28]. Channel 16 (156.80 MHz) and channel 70 (156.525 MHz) are used for emergency, safety and security purposes, the former for telephony and the later for data supported in DSC and channels 75 and 76 (which are retained as guard bands around channel 16). ITU recommends that the use of channels for maritime mobile purposes, Figure 3.4 other than those indicated in the table of transmitting frequencies (Appendix 18 of Radio Regulations) shall not cause harmful interference to services which operate in accordance with that table and shall not prejudice the future development of such services.



RR App.18 Ch. No. (WRC-12)	Intership (single frequency)	Port operations & ship movement (single frequency)	Port operations and ship movement (two frequency)	Public correspondence (two frequency)	Public correspondence (one frequency) -see Note *m)*	Coast station transmit	Ship station transmit	RR App.18 Ch. No. (WRC-12)		Appendix 18 Notes (WRC-12)
60		■	■	■	■	160.625	156.025	60		*m)*
01		■	■	■	■	160.650	156.050	01		*m)*
61		■	■	■	■	160.675	156.075	61		*m)*
02		■	■	■	■	160.700	156.100	02		*m)*
62		■	■	■	■	160.725	156.125	62		*m)*
03		■	■	■	■	160.750	156.150	03		*m)*
63		■	■	■	■	160.775	156.175	63		*m)*
04		■	■	■	■	160.800	156.200	04		*m)*
64		■	■	■	■	160.825	156.225	64		*m)*
05		■	■	■	■	160.850	156.250	05		*m)*
65		■	■	■	■	160.875	156.275	65		*m)*
06	■						156.300	06		*f)*
2006						160.900	160.900	2006	Tst Spec./MOB	*XXX)*
66		■	■	■	■	160.925	156.325	66		*m)*
07		■	■	■	■	160.950	156.350	07		*m)*
67	■	■				156.375	156.375	67		*h)*
08	■						156.400	08		
68		■				156.425	156.425	68		
09	■	■				156.400	156.450	09		*i)*
69	■	■				156.475	156.475	69		
10	■	■				156.500	156.500	10		*h), q)*
70						156.525	156.525	70 (DSC)		*f), j)*
11		■				156.550	156.550	11		*q)*
71		■				156.575	156.575	71		
12		■				156.600	156.600	12		
72	■						156.625	72		*i)*
13	■	■				156.650	156.650	13		*k)*
73	■	■				156.675	156.675	73		*h), i)*
14		■				156.700	156.700	14		
74		■				156.725	156.725	74		
15	■	■				156.750	156.750	15		*g)*
75		■				156.775	156.775	75 (AIS 3)		*n), X1)*
16						156.800	156.800	16		*f)*
76		■				156.825	156.825	76 (AIS 4)		*n), X1)*
17	■	■				156.850	156.850	17		*g)*
77	■						156.875	77		
18		■	■	■	■	161.500	156.900	18		*m)*
78		■	■	■	■	161.525	156.925	78		*A1), A2), A3)*
1078		■				156.925	156.925	1078		
2078		■				161.525	161.525	2078		
19		■	■	■	■	161.550	156.950	19		*A1), A2), A3)*
1019		■				156.950	156.950	1019		
2019		■				161.550	161.550	2019		
79		■				161.575	156.975	79		*A1), A2), A3)*
1079		■				156.975	156.975	1079		
2079		■				161.575	161.575	2079		
20		■	■	■	■	161.600	157.000	20		*A1), A2), A3)*
1020		■				157.000	157.000	1020		
2020		■				161.600	161.600	2020		
80		■	■	■	■	161.625	157.025	80	Region 1, Note *B1)* Region 3, Note *B1)*	*B1), E1)*
21		■	■	■	■	161.650	157.050	21		*B1), E1)*
81		■	■	■	■	161.675	157.075	81		*B1), E1)*
22		■	■	■	■	161.700	157.100	22		*B1), E1)*
82		■	■	■	■	161.725	157.125	82	Region 1 (Sthn Africa) Note *D1)*	*B1), D1), E1)*
23		■	■	■	■	161.750	157.150	23	Region 3 (China), Note *D1)*	*B1), D1), E1)*
83		■	■	■	■	161.775	157.175	83		*B1), D1), E1)*
24		■	■	■	■	161.800	157.200	24	Region 2, Note *C1)*	*B1), C1), D1), E1)*
84		■	■	■	■	161.825	157.225	84		*B1), C1), D1), E1)*
25		■	■	■	■	161.850	157.250	25		*B1), C1), D1), E1)*
85		■	■	■	■	161.875	157.275	85		*B1), C1), D1), E1)*
26		■	■	■	■	161.900	157.300	26		*B1), C1), D1), E1)*
86		■	■	■	■	161.925	157.325	86		*B1), C1), D1), E1)*
27			■	■	■	161.950	157.350	27	Testing of new AIS technologies, Note *YYY)*	*YYY)*
87		■				157.375	157.375	87		*YYY)*
28			■	■	■	162.000	157.400	28		*YYY)*
88		■				157.425	157.425	88		*YYY)*
AIS 1						161.975	161.975	AIS 1	AIS	*f), l), p)*
AIS 2						162.025	162.025	AIS 2		*f), l), p)*

New simplex channels

New digital channels

Single or two frequency channels, subject to coordination with affected administrations. See Note *E1)*

Figure 3.4: Frequency arrangements for RR Appendix 18 [28].

According to [46], MMS in Portugal is assigned within frequency range of 156.050 MHz to 162.025 MHz, with channel separation of 50 KHz, as presented in Figure 3.5. The typical services, such as voice and DSC, are supported by bandwidths up to 25 KHz, using analogue or digital modulation schemes with transmitted power up to 25W. Despite channels 16, 70 and two AIS, there are several other frequency bands assigned to specific purposes, including nine full-duplex channels (2, 3, 4, 5, 61, 62, 63, 64 and 65) for experimentation of new technologies based maritime VHF systems. Therefore, excluding non-critical emergency, safety and security channels, there are 93 channels that might be eligible for opportunistic usage, which means 2.325 MHz.

Moreover, one might consider to complement the eligible pool of frequencies with analogue TV bands that have been released in the lower VHF band due to the digital TV allocations.

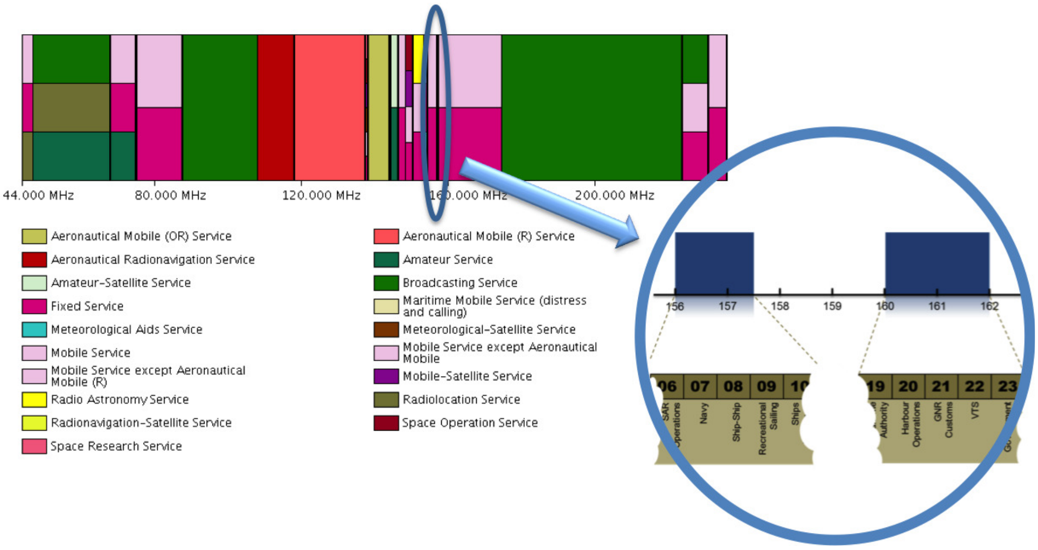


Figure 3.5: Maritime Mobile Service - Channel allocations for VHF Radio Services and Applications - Portuguese electronic National Table of Frequency Allocations (eNTFA) [40].

In fact, as presented in Figure 3.6, a considerable analogue TV spectrum is in vicinity of MMS, which have potential to be used in maritime communications, even with similar bandwidth allocations as in MMS, and may constitute a valid resource to upgrade the designated spectra for opportunistic usage. Such initiative would significantly increase the possibilities to maximize link availability and data rate, without assign considered spectra.

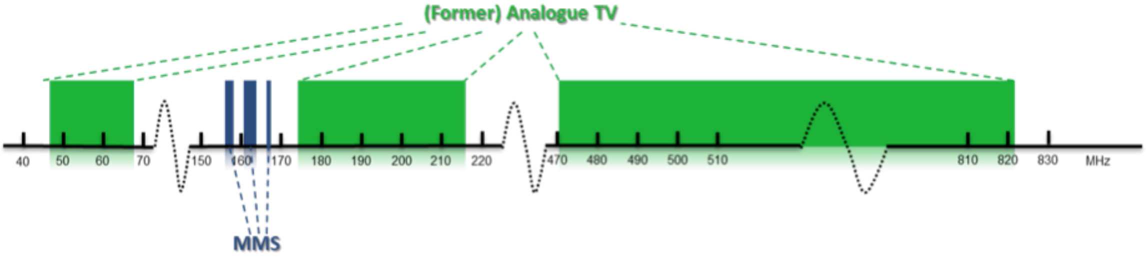


Figure 3.6: Former analogue TV assigned spectra.

Finally, CR-B-VHF systems have great potential for government areas. Opportunistic networks can be implemented, based on a pool of government assigned spectra, to support maritime information exchange between different authorities, including Navy, Coast Guard, Maritime Police, etc. The spectrum regulatory aspects, associated with details of internal management, can be simplified and decisions can be made within reasonable time frames, which simplify deployments and facilitate technological developments. In fact, there are some initiatives, at Portuguese Naval Research Center, related with spectrum management flexibilization and evaluation of CR deployment in Naval Forces, as the example of [T2].

3.2.2 Enabling Technologies

The implementation of CR-B-VHF claim for a set of demanding features that are currently topics of intensive research and are in the basis of some of the most important wireless systems. Those include a combination of recent advances in cognitive radio, multi-carrier modulation techniques and smart antennas, which support the design of a system that can benefit from spectrum opportunities and efficiently use them to deploy adaptive broadband capabilities over VHF radio channels. Nevertheless, specific characteristics of maritime incumbent users and operational environment require tuned and proper conception solutions.

Cognitive radio is a concept that has no reference architecture and can be differently interpreted. Therefore, practical implementations of CR might differ from each other, not only on operational context, but also at cognition level, i.e. degree of awareness and adaptation. Just to mention two examples: COGnitive radio systems for efficient sharing of TV white spaces in EUropeean context (COGEU), aims to take advantage of TV analogue switch-off by developing systems that leverage the favourable propagation characteristics of the TV white spaces through the introduction and promotion of real-time secondary spectrum trading and the creation of new spectrum commons regime [47]; and COgnitive RAdio for dynamic Spectrum Management (CORASMA), a program that is dedicated to the evaluation of cognitive solutions in the military context (Tactical Networks) [48]. In any case, the advantages and application areas of CR are tremendous and can be demonstrated and evaluated in a open federated test platform, which facilitates experimentally-driven research on advanced spectrum sensing, cognitive radio and cognitive networking strategies in view of horizontal and vertical spectrum sharing in licensed and unlicensed bands, developed under FP7-CREW project [49].

Notwithstanding, IEEE 802.22 standard is probably the most important implementation of CR concept [35]. The system is intended to be a point to multipoint system that uses CR techniques to share geographically unused spectrum allocated to the television broadcast service, on a non-interfering basis, to bring broadband access to low population density areas. One of the most interesting features of this standard is that end users perform spectrum sensing and send periodic reports to the base stations informing about spectrum occupancy status and the need for channel change. Additionally, it is flexible enough to dynamically adjust the bandwidth, modulation and coding schemes in order to explore more than one 6 MHz channel, through Orthogonal frequency-division multiple access. Despite the fact that investigation efforts have been focused in demonstrating solutions for the individual components and capabilities, such as spectrum sensing implementations [50] [51] [52] or allocation and management schemes [53], [54], rather than feasibility demonstrating of a complete CR, this has been the first worldwide effort to define a standardized air interface based on CR techniques for the opportunistic use of TV bands on a non-interfering basis.

Additionally, a cognitive radio prototype implementation, based on IEEE 802.11, is presented in [55]. The existing 802.11 implementation is considered as a starting point for the implementation, and on top of this, a management overlay takes care of network synchronization. The exchange of list of current available channels is considered to be a major challenge in the implementation, so it happens to be the main concern for this project.

We can provide numerous examples more, on implementations of CR for different applications. However, as far as we know, there are no available CR applications for maritime VHF band or CR prototypes for opportunistic usage of VHF band, except for implementation presented in [T1]. Literature refers investigation on maritime networks, but the focus is mainly on WiMAX bands or MANET subjects.

The convergence of digital radio and computer software grant permission to CR implementations in a platform called SDR. A basic SDR consists of a RF front end, a analogue-to-digital converter (ADC) and a general-purpose processor that runs specific software that can be reconfigurable, as depicted in Figure 3.7. Trend is to move ADC towards and antenna and eliminate RF hardware, as far as possible.

There are several available software development solutions to implement SDR, from paid applications to open-source, from specific (ex: amateur radio) to general purpose, as listed in [56]. Even though, GNU radio is the most popular toolkit for hobbyist, academic and commercial environments to support both wireless communications research and real-world radio systems [57]. It is free of charge and can be used with readily available low-cost external RF hardware to create SDR, or without hardware in a simulation-like environment. Furthermore, it has an comprehensive support organization, which includes a huge community of people involved in GNU Radio, based on annual conferences, online tutorials and documentation, forums, monthly conferences with developers, etc., that provides a decent backup for SDR implementers.

One of most important features of GNU radio, which makes it different from the rest, is the way it handles the samples between processing blocks. GNU Radio's core is based on a

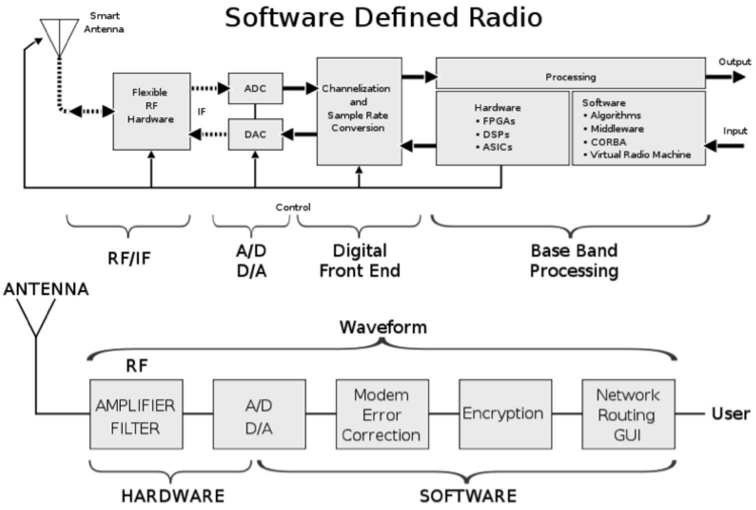


Figure 3.7: Basic architecture of a SDR [Author: Tuukkanen]

scheduler, which moves large amounts of samples stored in memory between blocks, instead of sample by sample, which is a very efficient manner of moving memory (memory copies) and is what makes it suitable for real time signal processing.

Despite simulation environment, GNU radio requires an external hardware radio peripheral in order to set up a complete radio system. This piece of hardware, often based in Field Programmable Gate Arrays (FPGA), is responsible for interfacing between host Digital Signal Processing (DSP) software application, Digital to Analogue Converter (DAC) andAnalogue to Digital Converter (ADC). Ettus Research, a National Instruments company, is one of the most important supplier of SDR platforms, namely the Universal Software Radio Peripheral (USRP) family of products (Figure 3.8), which are very popular due to its affordable price and instrumentation grade quality. The USRP was initially developed to address the hardware requirements of the GNU Radio project, so there is a strong connection between these two components of SDR [58], [59].

Succinctly, the technological platforms for CR-B-VHF implementation are available and with a maturity level that can be considered acceptable. Initially, a prototype can be implemented with a GNU radio toolkit and hardware peripherals, such as USRP presented in Figure 3.9, which can manage targeted frequency bands, with proper developed algorithms and taking advantage of available GNU radio dedicated processing blocks. In fact, an interest-

Figure 3.8: Three different USRP family products from Ettus Research [58].

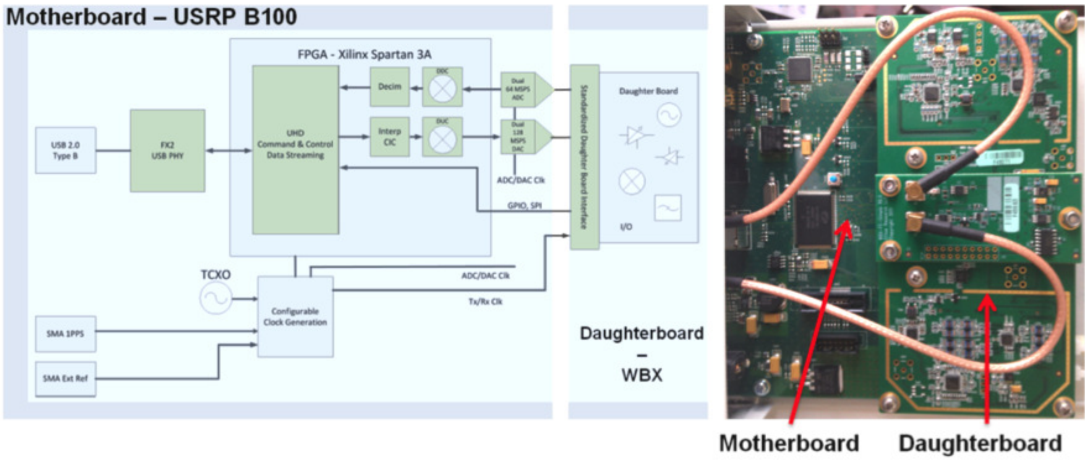


Figure 3.9: USRP B100 block diagram and USRP B100 with WBX daughterboard (50 MHz to 2.2 GHz) [58].

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ing example of an implementation of CR based on GNU Radio and USRP is described in [60] and [61], where, despite the lack of networking and cognitive aspects, adaptability features of an OFDM based physical layer together with a sensing component is demonstrated.

Another technological enabler for CR-B-VHF is a multi-carrier modulation scheme that can be able to take advantage of non-contiguous spectrum opportunities. OFDM is a multicarrier modulation technique that allows a transmission of a single data stream over a number of overlapping lower rate subcarriers, which are orthogonal to each other. It is very popular due to its straightforward implementation and its characteristics of high spectral efficiency, multipath delay spread tolerance, immunity to frequency selective fading channels [62]. It can be used as a modulation technique only, as is the case of IEEE 802.11 based local area networks [63], or as modulation and multiple access technique, as in fourth generation terrestrial networks (LTE) [64]. However, classical OFDM is intended to be used in contiguous spectrum, so in the case of non-contiguous portions of the spectrum it is required a variant of OFDM, called NC-OFDM [65], [66], which has similar limitations and drawbacks. Anyway, GNU Radio has its own OFDM implementation, providing some dedicated processing blocks for OFDM modulation and comprehensive documentation to develop own applications [67].

3.3 Feasibility Issues

The importance of maritime broadband VHF capacity has been addressed in previous chapter and it does not raise too much reluctance, while a CR based solution might not be as unanimous.

The evaluation of CR-B-VHF deployment requirements and its feasibility is critical to decide on any research and development. Generally speaking, broadband radio systems implementation requires spectrum, technology, licenses, infrastructures and financial support, otherwise it will not pass the wishful phase. In Figure 3.10, it is represented the set of system deployment enablers and their interdependency, so considering that:

- CR-B-VHF babisteps have to include a prototype and a proof of concept;
- existing VHF systems have been globally deployed in coastal areas;
- and investors interest depends ultimately on system performance;

feasibility analysis, in our case, can be reduced to the evaluation of spectrum availability and system performance.

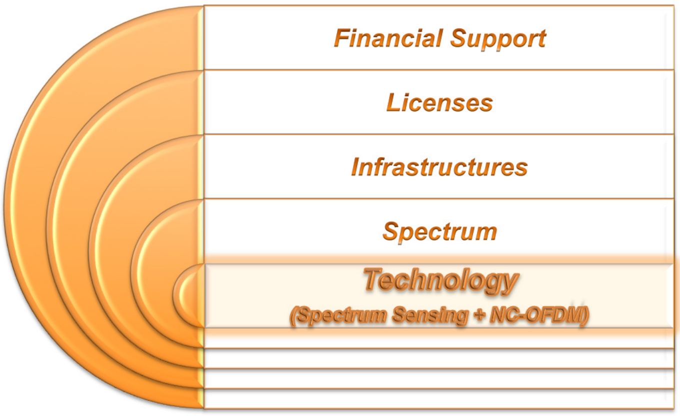

Figure 3.10: CR-B-VHF deployment enablers interdependency.

Essentially, main concerns about this proposed solution would be associated to practical issues, such as regulatory and standardization aspects related with spectrum management aspects and incumbents service interference protection; and implementation details related with spectrum sensing and NC-OFDM deployment. The former disquietude has no simple solution and is out of system designer's control, despite the fact that technological aspects can have an important role in decision making process associated to regulatory paradigm change. On the other hand, later issues can be played down through the implementation of a prototype that can demonstrate basic functionalities and document evidences that a CR-B-VHF system can be successful.

The feasibility and deployability of any cognitive radio based solution depend on evolution of current regulatory framework towards a more flexible and dynamic tool, focusing in spectrum efficiency rather then interference abolition. It is critical to include in regulatory and standardization processes some practical aspects, related with QoS enforcement, that ensure incumbents live operations and legacy systems coexistence. This essential aspect, is important to assure primary users harmful interference levels and to provide guidelines for opportunistic systems developers.

Moreover, practical interest of CR-B-VHF deployment depends on envisage performance of proposed solution and impact on incumbents. Those effects can be evaluated through the analysis of maximum achievable capacity and outage probability of primary service. Hence, considering that proposed solution would operate within 156-174 MHz frequency band, where each allocated 25kHz channel is assigned to a specific service, achievable capacity would be proportional, not only to the amount of eligible channels for opportunistic usage, and incumbents activity profiles, but also to the ability to manage non-license transmissions without harming operation of primary services. In other words, feasibility and performance of secondary networks depend on spectrum opportunities, their characteristics and systems capacity to exploit them. Unfortunately, system's designer cannot control former conditions, but available technology is able to support further developments to ensure later requirement.

In [T1], Capela described his implementation of proposed CR-B-VHF concept, considering a open sharing model for spectrum access. The developed prototype uses an USRP, as a radio front-end, and GNU radio software for digital signal processing and physical layer design, to support end-to-end Internet Protocol (IP) data communications. It relies on three functional blocks: spectrum sensor, which implements a multiuser energy detector; radio transceiver, which implements a NC-OFDM reconfigurable transceiver; and cognitive engine, which implements a middle layer between IP and physical layers (cognitive + MAC layer) and enables cognitive processing, network synchronization and coordination, as depicted in Figure 1.2. Essentially, radio architecture follows a master-slave topology, where shore based stations (masters) are responsible for spectrum usage control and policy enforcement, acting as network gateways, while afloat stations (slaves) must synchronize with masters to share spectrum sensing information and receive information about available radio resources and synchronization elements. Spectrum policy enforcement is implemented using a synchronization procedure (network synchronization), which uses a dedicated radio channel, so master stations can broadcast policy enforced radio transceiver settings among network users. A two-mode communication system was implemented: B-VHF mode, which uses the NC-OFDM transceiver over vacant spectrum bands; and SYNC mode, which uses a fixed allocated band for network synchronization. At the end, this implementation proved to be able to detect and adjust its transceiver settings for dynamic spectrum access [C7] and [C8].

Despite Capela's implementation worthiness, it cannot efficiently explore spectrum opportunities in an hierarchical access model with spectrum overlay, in dynamic environments. Primary exclusive access to spectrum requires an approach to spectrum sensing that maximizes opportunistic use efficiency and ensure acceptable levels of collision probability with incumbent's live services. In other words, spectrum sensing schemes shall be able to support operating modes where, secondary users are allowed to take advantage of spectrum, when primaries are not using it, but have to release it as soon as incumbents start to use it. A simple Carrier Sense Multiple Access (CSMA) scheme cannot provide such features, but is more then enough to support a successful proof of concept, as being defined.

A hierarchical dynamic access model requires a sensing algorithm that has to encompass the limited and unknown time dimension of spectrum opportunities. In other words, spectrum sensing algorithms have to deal with the fact that, from incumbents harmful interference perspective, detection of opportunities to operate includes not only the evaluation of the instant where secondary system can start to operate, but also the moment that has to stop its transmission, in that band. This highly demanding requirement introduces another relevant subject related to marine users activity profile in maritime services, which is not documented and eventually quite heterogeneous, around the world. This lack of information on incumbents' occupancy and transmission ratios profiles represents a serious limitation for spectrum sensing design, which requires to include temporal duration nature of spectrum opportunities.

In any case, there are two options to implement spectrum sensing, in a hierarchical dynamic access context. A classical approach, where sensing and transmitting are performed in half duplex, i.e. CR either senses or transmits in a given band, which results imposes an initial constraint to achievable capacity that results from required time-sharing between spectrum sensing and data transmission. This limitation, commonly referred as the *"sensing efficiency problem"*, imposes a trade-off between sensing accuracy and throughput and, therefore, limitations on maximum achievable capacity. Alternatively, one might consider to implement a full-duplex type of solution, where the CR simultaneously transmit and senses each considered frequency band. The spectrum efficiency gains are obvious, as well as the self-interference cancellation challenges. Such solution requires an effective scheme that might be able to detect low levels primary emissions, while transmitting in a closed antenna. The design issues associated to each one of these solutions are different and so the technical solutions to overcome them.

3.4 Concluding Remarks

The proposed system intends to take advantage of multiple available MMS assigned channels, each one with its own characteristics. Without loss of generality, it is assumed that 241 channels of 25KHz, in 156-162.025 MHz band, are technically available for opportunistic usage in a overlay scheme. Therefore, the achievable capacity of the combined use of such channels will depend on traffic activity profiles and occupancy probabilities associated to each channel.

Considering the achievements described in [C7] and [C8], essential feasibility issues can be summarized, at this stage, to the development of a spectrum sensing scheme that might be able to support opportunistic use of spectrum in a hierarchical dynamic access context. Such requirement would support prototype testing and proof of concept evaluation for eventual near future deployment.

Chapter 4

Detection of Spectrum Opportunities in Maritime VHF Band

Before addressing required spectrum sensing design, it is important to revise radio scene analysis background and understand maritime operational context, MMS assigned services and communications channel characteristics in order to approach detection of spectrum opportunities in a proper way. In typical maritime VHF communications operation scenarios, hidden node occurrences are likely to occur and spectrum opportunities in MMS assigned band are expected to be a set of non-contiguous holes. On the other hand, any mathematical analysis on maritime VHF communications requires a proper channel model, especially if one intend to obtain system operating parameters, based on optimization algorithms. Consequently, before addressing development of spectrum sensing schemes for hierarchical dynamic access modes, it is essential to prepare fundamental background.

The following analysis is organized as follows: radio scene analysis is addressed on Section 4.1, where spectrum opportunities and spectrum sensing concepts are presented, detectors characteristics analyzed and metrics are discussed; Section 4.2 is dedicated to maritime environment context, where operating characteristics are described, incumbents services are specified and channel model is characterized. In Section 4.3 is formulated the objective for any opportunistic system (and its associated constraints), characterized the role of spectrum sensing and identified the fundamental options to pursuit spectrum sensing design. Finally, Section 4.4 is dedicated to final remarks.

4.1 Radio Scene Analysis

Cognitive radio operation is based upon two main tasks in a closed loop: spectrum sensing and adaptation. During spectrum sensing, it is crucial to detect spectrum opportunities, estimate their power contents, and predict its availability to support high reliable communications. Therefore, radio scene analysis is about detecting and evaluating potential operating conditions.

Even so, radio scene analysis depends upon considered dynamic access model. In a spectrum overlay approach, which requires an exclusive operation in a given band, the search for spectrum opportunities is focused on detection of bands that have nothing but noise, while in a underlay approach, which allows concurrently primary and secondary operation with limited interference levels, the objective is to estimate noise and interference contents of a given band. Therefore, spectrum opportunities have different operational classification, depending on context.

Opportunities to operate might be classified into three types: black, grey and white spaces; depending upon interference power within a specific band. Black spaces correspond to spectrum highly occupied by high-power interferers, grey spaces are partially occupied by low-power interferers and white spaces are free of Radio Frequency (RF) interferers (except for ambient noise) [64]. Naturally, potential opportunities are associated with grey and white spaces category, while black spaces are only consider proper candidates for DSA if interferers (RF emitters) are switched off. Naturally, to categorize a given band, according to its ability to accommodate more RF emissions, it is necessary to determine the level of interference that can be added, without causing any degradation on incumbent receiver's performance.

However, the definition of allowable interference level, at primary receiver, in not a simple task. FCC Spectrum Policy Task Force introduced interference temperature concept [36], as a measure of power (noise plus interference), at receiver, per unit of bandwidth in order to define an accurate measure of RF noise and interference level in a frequency band of interest. The idea is to define an interference temperature limit where any transmission that would raise noise floor is considered to be harmful. The quantification of this threshold is essential, not only to detect existence of spectrum opportunities and its operating conditions, but also to protect incumbents from harmful interference. Nevertheless, the definition of this interference temperature limits might not be enough to ensure opportunistic usage of grey spaces.

Spectrum opportunities, a.k.a. spectrum holes, can be defined in a multidimensional region of frequency, time, space, angle, etc. Depending on incumbent's technique to access wireless channel, opportunities for secondary user might be in one of these domains or, in some cases, in a mixed domain. Thus, the first step is to understand what a spectrum hole is and how to recognize it.

4.1.1 Spectrum Opportunities

Usually, spectrum opportunities are defined as *"a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area"* [68], which implicitly indicate that spectrum opportunities are restricted to three dimensions. However, there are multiple other dimensions that have significant potential and are not much exploited in literature, such code, Angle of Arrival (AoA), etc. In fact, [69] and [70] changed the paradigm of spectrum space to be *''a theoretical hyperspace occupied by radio signals, which has dimensions of location, angle of arrival, frequency, time, and possibly others"*, but the available signal detection algorithms to exploit this "new" frontiers are far from being closed. There is significant and comprehensive published work approaching time, frequency and space, and scarce initiatives on other dimensions. Available spectrum sensing algorithms do not incorporate the capability to deal with signal that use spread spectrum, time or frequency hopping codes. Primary users that use spread spectrum signalling are difficult to detect as power is distributed over a wide frequency range, even though actual information bandwidth is much narrower [71].

Spectrum opportunities result from frequency bands capability to accommodate non-licensed transmissions without harming operation of primary users. Normally, opportunities to use licensed bands are classified either in terms of frequency or time domain. A spectrum hole in time domain corresponds to a period where a primary is not transmitting; a spectrum hole in frequency corresponds to a band where secondary can transmit without interfer with any primary (at adjacent bands), as represented in Figure 4.1. Keeping in mind that a frequency band may be available (free form primary transmissions) and a secondary transmitter can still cause interference to primary receivers operating in adjacent bands. Therefore, a spectrum hole, in frequency domain, corresponds to a band where secondary transmissions do not interfere with any primary receivers, independently of their operations bands.

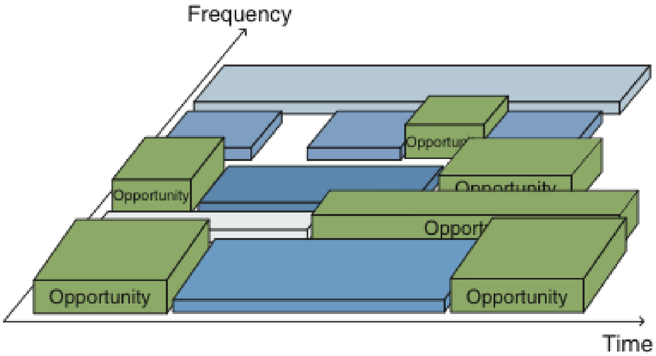

Figure 4.1: Spectrum opportunities in frequency and time domains [72].

Additionally, a spectrum hole can also be defined in space domain as a complementary area to the union of non-talk regions of all primary receivers, as represented in Figure 4.2. Spatial spectrum holes are associated with primary receiver harmful protection. In other words, secondary users are only allowed to transmit within areas that are far enough to cause interference to primary receivers. The secondary emissions will raise the noise plus interference floor and that may overcame the fading benefits that protect primary receivers from interference.

Recent advances in multi-antenna technologies, namely beamforming, allow multiple users to be multiplexed into the same channel at same time in the same geographical area, as represented in Figure 4.3. The consequence is a requirement for estimation of AoA to create new opportunities [72]. Recently, [73] proposed a scheme that exploits transmit beamforming to enable better spectral sharing between primary and secondary users, but, in general, the angle dimension has not been too much exploited for spectrum opportunities. Interesting enough, angle dimension has tremendous potential for maritime VHF applications.

Exploration of spectrum holes depends, firstly, on detection capacity. Since those opportunities are defined in hyper-planes whose axis represent domains like time, space, angle, polarization, coding, etc., it is crucial to have adequate tools to clearly identify holes in those domains. Ideally, a single tool would be appropriate to explore all domains opportunities but, in practical terms, the available tools are normally domain oriented. Typically, time and space holes oriented. In any case, evaluation of spectral occupancy requires information of frequency domain and consequently spectral estimation of incoming signals.

In addition to that, despite importance of information provided by spectral estimation to understand the radio picture, it does not provide any insight of spectrum dynamics. The inclusion of time variable in the analysis permits to explore RF environment dynamics and evaluate spectrum holes' existence. On the space domain side, the analysis of opportunities requires information regarding the spectrum footprint of each primary user within the range of cognitive radio network. These spectra footprint can be centrally built through the compilation of spectrum sensors data that permits a radio scene analysis, which is materialized in spectra non-interference regions definition. In other words, given that each incumbent has its own non-interference region, spectrum occupancy footprint characterization, and its associated protection area, would allow the identification of spectrum holes described by position, spectrum availability and maximum transmitted power allowed. Therefore, spectrum holes definition accuracy would be proportional to estimated primary user position, not only due its effect on emitter's position definition itself, but also due to its impact on transmitted power estimation.

4.1.2 Spectrum Sensing

The maximization of achievable capacity, fulfilling incumbents live operations and legacy systems requirements, is the essence of sensing design problem. Therefore, finding spectrum opportunities for operational usage is far from being a simple and static spectral estimation. Spectrum sensing involves detection of spectrum holes and its spectrum resolution, estimation of spatial directions of incoming interferes and signal classification [72]. These tasks have several sources of uncertainty, from channel randomness to device and network-level uncertainties [74], which require different type of approaches and, at certain stage, a balance of trade-offs that determine feasibility of any system.

The major challenges for spectrum sensing are associated to randomness and range of uncertainties of communication channel. The fading and shadowing may hide on-going licensed operations and induce secondary users to wrongly conclude that a white space was found. Multipath fading is the result of constructive/destructive addition of multiple replicas of primary transmitted signal, while shadowing is due to obstacles attenuation within transmitter and receiver path. Either one or both may lead to deception of primary user

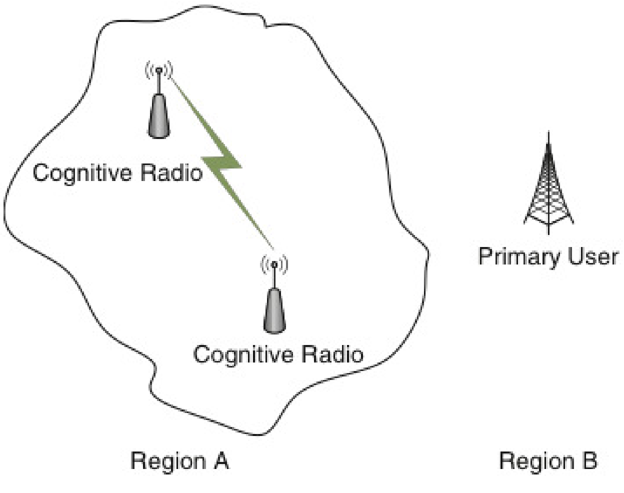

Figure 4.2: Spectrum opportunities in space domain [72].

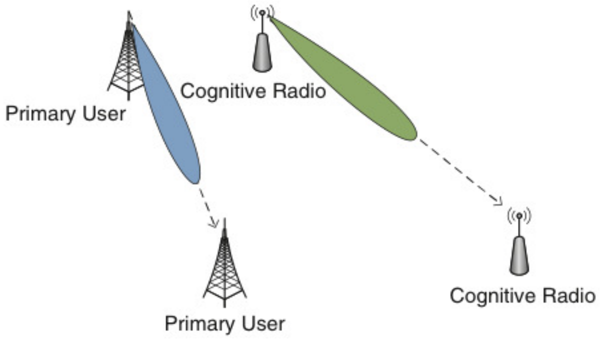

Figure 4.3: Spectrum opportunities in angle domain [72].

existence. Therefore, the detection of a low strength signal does not necessary mean that the primary system position is out of secondary users interference range, a deep fade or obstacles shadowing may be affecting the primary's signals recognition. One of the key challenges of spectrum detection is to distinguish a faded or shadowed primary signal from a spectrum hole [74]. Particularly in multipath environments, where path loss, shadowing and deep fading generates fluctuations in the power level of received signals. To overcome these limitations, several research studies have been published [75], [76], [77], [78], [79] and [80], where the proposed solutions exploit spatial diversity through either cooperative and distributed systems or multiple antenna systems.

If one considers an underlay access model, spectrum sensing is far more complex, due to complexity associated to definition of allowed interference at primary receiver. Allowed interference depends upon radio detection sensitivity, which requires an estimation of noise power, subject to significant random errors. Any under-estimation of noise power would cause a miss detection of weak signals, due to low sensitivity of receiver. On the other hand, the maximum distance from primary receiver, at which incurred interference is still considered harmful, depends upon transmitted power of secondary user and interference tolerance of primary receiver. This tolerance, associated to detection sensitivity of receiver, depends on characteristics of interfering signal (e.g. signal waveform, continuous/intermittent) and has to be translated to a threshold defined by regulators [74]. Additionally, an increasing of opportunistic utilization of licensed bands will add an uncertainty related with the nature and amount of secondaries operating in that bands which may result in an aggregate-interference prohibitive for incumbents operation.

Spectrum sensing focus is not just on detector itself, but on its algorithm implementation scheme. Even after getting access to a spectrum opportunity, CR must maintain band sensing in order to determine whenever primary user starts to transmit. Take advantage of idle spectra in an opportunistic basis demands high spectrum sensing accuracy and efficiency capacities. Additionally, it is necessary to include a good channel availability estimation and the ability and flexibility to access multiple, non-contiguous portions of spectra, each one with its own activity profile, which brings up an optimization problem far more complex than in a single broadband channel. The feasibility and deployability of any opportunistic system results from compromises that depend on spectrum opportunities, their characteristics and systems capacity to exploit them.

Signal Detectors

The reliability of spectrum hole identification is close connected to spectrum sensing algorithm that is used to perform the search. Widely speaking, white spaces require spectrum sensing, while grey spaces demand for spectrum estimation. Anyway, the most important component of a spectrum sensing scheme is naturally its signal detector. Depending upon implementation requirements, different detectors may perform differently and present diverse advantages and drawbacks, as well.

If one is focusing on white space detection (i.e. a band that has nothing but white noise), the available spectrum sensing techniques might be divided in two groups of methods: those that do not require any information about incumbent signals and the ones that require knowledge of some features of incumbent signals. In the first group, a.k.a. blind sensing, one may include energy and maximum eigenvalue detection based methods, while matched filters, waveform and cyclostationary based detection are classified in the second group.

Blind sensing techniques like energy or maximum eigenvalue based detection are simple and low cost. Energy detectors, like radiometers, measure the energy in a band, for a given timeframe, and compare it with a threshold [81], [82]. Logically, this solution would not provide the ability to discriminate between primary users and noise, especially for small values of Signal-to-Noise Ratio (SNR) and the precision of measurement is proportional to the evaluate time. Alternatively, maximum eigenvalue based techniques are available to overcame the drawback of noise uncertainty presented by energy detectors. In this case, it is performed the auto-correlation of received signal and the eigenvalues of correlation matrix are used to distinguish incumbent signal from noise, since the values are different.

Nevertheless, one may claim that for known primary signals it is possible to exploit the spectral correlation characteristics of communication signals and use a dedicated feature detector to address this issue. In any case, field of application would be limited to considered primary signals, which would increase detector complexity. When primary signal is well understood, optimal detector, in stationary Gaussian noise, is a matched filter followed by a threshold test [83]. Although, it requires coherent detection and demodulation of received signals, which for opportunistic use of primary bands would incur in an impractical cost and complexity. The selection of optimum threshold, due to noise variance, represents an additional issue. On the other hand, in waveform based sensing it is considered a training patterns set used by primary users to synchronize or be acquired by secondary users. Given that training patterns are known, spectrum sensing is performed through the correlation of received signals with these copies of primary patterns [84].

Moreover, to take advantage of an inherent property of digital modulated signals it is possible to use cyclostationarity feature [85]. Due to spectral redundancy, caused by periodicity, signals exhibit correlation between widely separated spectral components [86], [87] that easily allow distinguishing signals from noise, even in low SNR environments. Noise is a wide sense stationary random process while the modulated signals have built-in features, due to sine wave carriers, spreading sequences, etc., which can be used as features [88] for the evaluation of spectral correlation function to detect (cyclostationarity of) signals [89]. The main advantage of cyclostationary approach is its capability of signal classification and the ability to distinguish co-channel interference, but requires awareness about cycle frequencies of incumbents.

All the above-mentioned techniques approaches are appropriate for white spaces and their

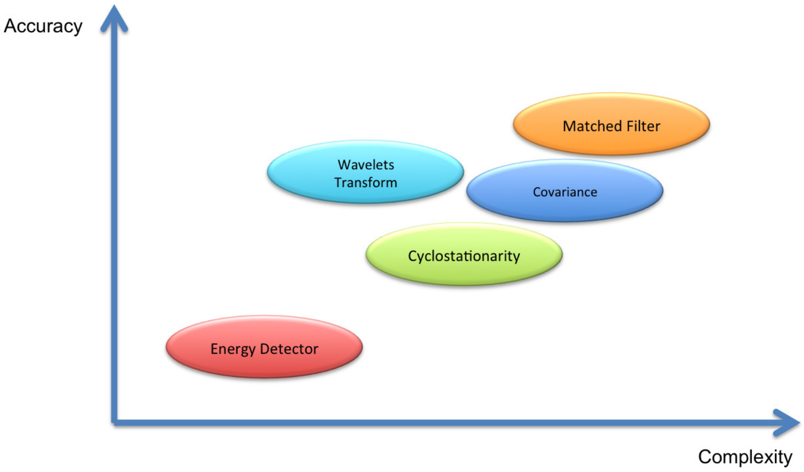

Figure 4.4: Complexity *versus* accuracy of spectrum sensing techniques.

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accuracy as a function of complexity is presented in Figure 4.4. However, if one intend to enlarge the scope of spectrum sensing to bands that contains noise and interfering signals, commonly designated as grey holes, a spectrum estimation capability must be considered. Spectrum estimation methods are divided in parametric, which requires modelling of stochastic process of interest, and non-parametric, which bypasses the need of modeling and uses stochastic process directly. Typically, due to unreliable nature of wireless communications channels the non-parametric methods are the preferred choice [90].

The Multi-Taper Method (MTM) is a non-parametric method introduced by Thomson [91] for climate data analysis, which was considered for CR applications for the first time by Haykin [90]. Since then, several published research studies like [92], among others, confirmed the significance and performance of MTM in CRN. For example, [90] comprehensively explored the foundations of the application of MTM to CR signals and applied the background theory to set an experimental study of spectrum sensing using data collected from communication media amenable to CR, while [92] investigated the principles and performance of MTM based detection in single and multiple-user scenarios. Basically, the published research refers to MTM as a reliable algorithm, which provides high spectral resolution in both average power and frequency, and it is computationally feasible in real time. In practical terms, MTM is used to estimate the power spectra with a nearly optimal performance for wideband signals, providing similar results to maximum likelihood power spectrum density estimator ([90] referring to [93]), but with a lower computational cost.

Additionally, MTM provides the means to determine direction of reliable communication link through the space-time processing capability and, combined with Loève transform, allows time-frequency analysis that provides cyclostationarity information about received signals [90]. To estimate the power spectrum of RF stimuli, as a function of frequency, one of the attractive characteristics of MTM is its ability to perform space-time processing [90]. This sense of direction that can be included in the analysis is provided through the engagement of a set of sensors to seek for interfering signals along different directions. Finally, another attribute of MTM, among several [94], is its aptitude to mitigate the estimation problem associated with bias-variance dilemma, which results in the loss of information due to tapering (windowing), through the utilization of orthogonal tapers (Slepian sequences) to decrease the leakage. In conclusion, MTM is considered to be a robust integrated multifunction signal processor, which extends the dimensions of spectrum sensing to time, frequency and space.

The advantages of MTM over periodogram, regarding bias and variability, are significant. In [56] it is presented an example of a wide-sense stationary Auto Regressive (AR) process, presented in Figure 4.5 to show the effects of bias and variability in the periodogram. As depicted in Figure 4.6, even when it is used a Hamming window to taper the AR, periodogram Power Spectral Density (PSD) estimates still demonstrate bias and variability, regarding AR true PSD, while in the case of MTM, the produced PSD estimate present significantly less bias and variability.

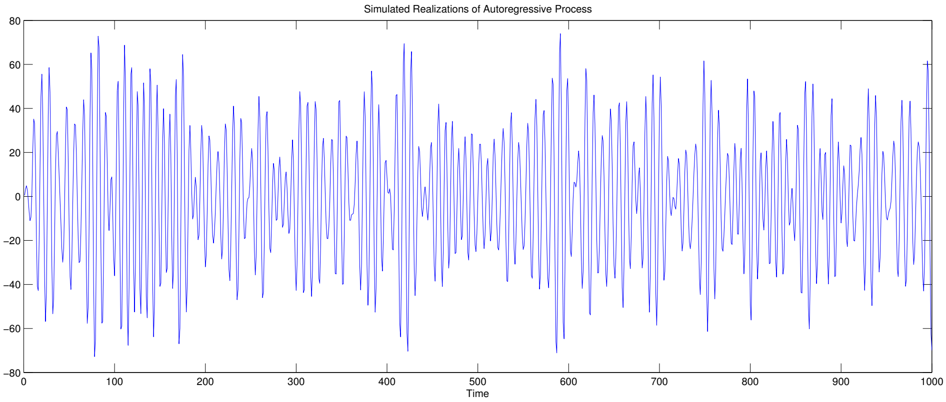

Figure 4.5: Simulated realizations of AR Process.

Several other methods have been proposed in literature, like wavelet approach to perform wideband spectrum sensing [95], or a novel idea of radio classification based sensing [96], [76], [77], [97], [98], where several features are extracted from received signal and used to identify the most possible transmitting system by employing various classification methods and technologies [92].

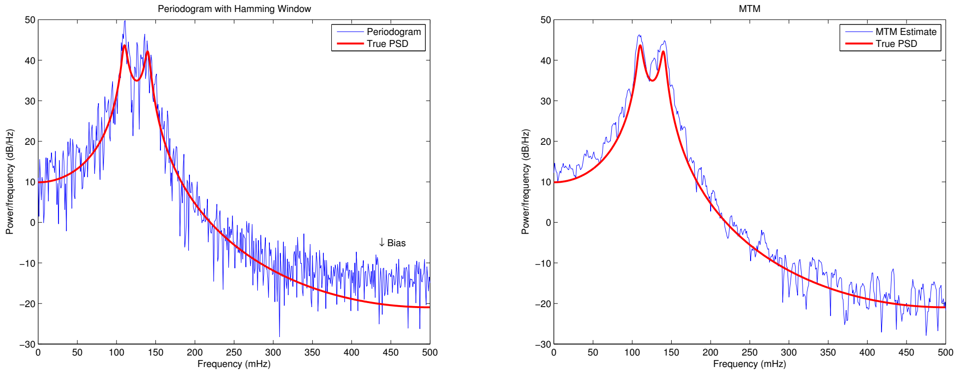

Figure 4.6: Comparison of AR true PSD with periodogram and MTM estimated PSD.

Independently from detection algorithm, there are different approaches to implement spectrum sensing functionalities. In fact, there are several options for spectrum design, depending

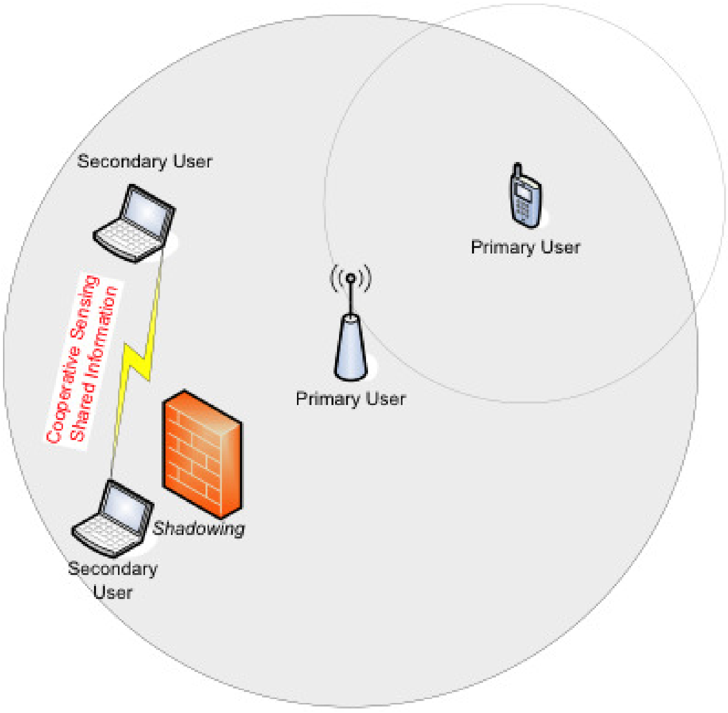

Figure 4.7: Cooperative sensing concept.

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on incumbents and deployed secondary systems, which can be divided according to detection target: either primary transmitters or receivers. Former cases include local sensing [99] and cooperative sensing [79], while later detection goes from reactive to proactive sensing.

Local sensing corresponds to independent nodes that compile information and evaluate opportunities independently from CRN. However, in order to allow better sensing performance, it is required that users should guaranteed to experience independent fading. Otherwise, it is not possible to overcome the effects of multipath fading, noise/interference level variation with time and location and time dispersion of channel. Thus, main objective of cooperative sensing is to share information between CR and combining results from various measurements to mitigate the mentioned problems, as represented in Figure 4.7. The cooperative approach is normally the appointed solution for fading, shadowing and hidden node issues in spectrum sensing and can be widely found in published research, like [80], [100] and [101].

The implementation of a cooperative spectrum sensing method requires functionalities normally associated to Media access Control (MAC) layer and an architecture that may be centralized or distributed. In centralized cooperative sensing, a central node compiles data from sensors, evaluate potential opportunities and broadcast information about available bands to CRN. In a word, central node is responsible for all the tasks. In contrast, distributed cooperative sensing is characterized by information sharing among sensors and individual decisions about available bands, without any control from a central node.

Complementary, there are two ways of combining the methods of measurement: hard decision and soft decision. In hard decision combining, each sensor evaluates, for instance, signal energy, in a band, compares it with a detection threshold and decides whenever a primary user is present. For soft decision combining, shared information is not limited to band availability. The information about measurement reliability is included in shared information regarding observed signal energy. The sensors send full observation measurement of signals energy to those who requested that information. According to [102] and [103], the probability of missed opportunity is minimized through the combination of soft information, while performance is equivalent between hard and soft when the number of cooperating uses is high [80].

Naturally, the overhead associated to cooperation process increases with the number of cooperating nodes. Therefore, there is a trade-off between detector processing and cooperation that minimizes total sensing overhead. The optimal point is reached when sensing is optimized as a result of trade-off between sensing time and throughput, as have been addressed in [104] and [105].

Both local sensing [99] and cooperative sensing [79] are centred in primary transmitters detection. However, main purpose of spectrum sensing is to avoid interference with primary receivers. It is perfectly acceptable a simultaneous transmission of primary and secondary users, as long as this does not result in interference at primary receiver. Actually, this is the principle of space opportunities, represented in Figure 4.2. Hence, we can make a change on paradigm and concentrate all the effort on primary receiver detection and get focus on interference avoidance on that. To perform this task, there are two types of available schemes: reactive schemes, which sense spectrum if secondary user needs to transmit, and the proactive schemes, which anticipate the need of spectrum sensing.

In [106], Zhao et al. introduced a proactive spectrum sensing method to detect primary receivers indirectly, exploiting the Close-Loop Power Control (CLPC) policy, which has been widely used in wireless systems [107]. The basic idea of this technique is to find spectrum holes through the observation of possible power fluctuations of primary signal (due to CLPC in primary systems) when CR sends a sounding signal. It is simple to realize when a CR is close to a primary receiver, since changes in power of primary transmitter are proportional to interference environment changes introduced by sounding signal from CR. Obviously, sounding signal power must be carefully selected in order to assure that it does not cause any interference at primary receiver. In other words, sounding signal power must be within primary receiver threshold tolerance.

Sensing Metrics

As presented, there are different methodologies to deal with spectrum opportunities detection, each one presenting its own advantages and drawbacks. For a given system and scenario, there is an optimal choice that maximizes the probability of detection of spectrum opportunities and minimizes the fear of harmful interference for incumbents. The way to find such method relies on the definition of criteria that allows, not only an evaluation of detection capacity's, but also the risk of interference with primary services. In other words, comparison of sensing strategies requires metrics to quantify performance with respect of spectrum opportunities detection and safety granted to primary users.

The need for metrics to quantify detection performance is not new. Digital radio receivers have been characterized by ROC, a curve that plots probability of miss detection (P_{md}) as a function of probability of false alarm (P_{fa}) [108], for a fixed sensing time and fixed operating SNR. Alternatively, receiver characterization may be expressed in terms of sensitivity, i.e. operating SNR that satisfies a given P_{md} and P_{fa}. The overhead for a detector is measured by the sensing time, i.e. amount of processed samples, required to achieve a P_{md}, P_{fa} at a given SNR.

Accordingly, sensing strategies comparison can be performed through traditional metrics, of sensitivity (ROC) complemented with required time to sense, to deal with imposed overhead, for a given fading intensity. The awareness for offered protection/safety (P_{md}) to primary uses and performance (throughput), which may be achieved by secondary system, is provided by a trade-off between, previously mentioned, four metrics (P_{md}, P_{fa}, time to sense and SNR). False alarms causes waste of spectrum opportunities, while miss detections would result in primary service outage. Therefore, accurate modeling of channels and operating conditions are essential to evaluate performances of spectrum sensing strategies and support design, where detector selection is only a part of an implementation deployment scheme.

Nevertheless, evaluation analysis results have to be carefully interpreted, since traditional metrics couples internals of sensing with communication strategy used, once opportunities have been found, as discussed in [109]. The outcome of traditional metrics approach is a complete system model, because sensitivity and P_{md} are related with primary user level of protection, while P_{fa} is related with secondary user performance. The point is the suitability of a comparison at complete system level, when the objective is an evaluation/design of sensing algorithms. In other words, an evaluation performed at sensing level itself should not be expanded to system upper layers. This should not be a problem for time domain opportunities, but in different domains, it might be not so straightforward.

The comparison of sensing algorithms should be performed at sensing layer itself and should accommodate modelling uncertainties that can significantly affect sensing overall capacity. Bearing these in mind, Tandra et al. [109] introduced two new metrics to assess the recovering of spectrum opportunities in space: weighted probability of area recovered, to measure overall sensing performance, decoupling primary users; and an approach to quantify the fear of harmful interference, in a worst-case scenario, where probability of interference is maximized. It is quite simple to intuit metrics for a problem of identifying time domain opportunities, but the development of correspondent metrics, for a problem of recovering spectrum opportunities in space, it is not a trivial exercise. Naturally, other dimensions of spectrum opportunities, such as code, angle, etc., would require future development of appropriate metrics, as well.

4.2 Maritime Environment Context

A successful evaluation of circumstances associated to detection of spectrum opportunities in maritime VHF band requires an environment context characterization. Particularities on maritime operational environment, such as maritime traffic patterns and geographical relative positions (of network nodes), or VHF communications features and ranging, are fundamental aspects to take into consideration in opportunistic systems development. In addition to that, if one intend to detect incumbent services in MMS assigned band, it is essential to understand their spectral footprints and operational characteristics. Finally, mathematical formulations and simulations, associated to sensing algorithms development and performance analysis, requires a decent model for maritime VHF channel.

This section is dedicated to maritime context characterization and analysis. The objective is to provide sufficient information to conceive practical application of radio scene analysis concepts to opportunistic systems that operate in maritime VHF band.

4.2.1 Operating Characteristics

In typical maritime VHF communications scenario, each primary transmitter can interact with any receiver located within a circular area, centered on transmitting antenna, with a radius defined by radio horizon. Specifically, in VHF band, refraction effect acts as an extender of Line-Of-Sight (LOS) and is antenna height dependent. For atmosphere factor of 4/3, the radio horizon, later referred as Radio Line-Of-Sight (RLOS), is given by

$$RLOS \approx 4.12\sqrt{h_r} + 4.12\sqrt{h_t} \qquad [\text{km}] \tag{4.1}$$

where(h_t) (h_r) represent transmitting and receiving antenna heights, respectively.

Any shore based VHF network, intended for full littoral coverage (as in the case of VTS or GMDSS), has to be deployed to ensure a complementary coverage areas (footprints) of each coastal station, as in cellular communications. A journey along a coastline is supported through handovers between adjacent stations across multiple footprint areas, as long as ship and coastal stations remains within RLOS (typically, 30 to 40 nautical miles). Considering that conventional maritime VHF communications transmitted power is 25W (in some cases it is authorized a 50W for shore based stations), radiostations coverage are normally limited by radio horizon.

Fortunately, maritime traffic is controlled in most coastal waters, which simplifies shore based systems deployment. In the cases of traffic at busy confined waterways or around capes, IMO has defined *"traffic separation schemes"* as plans that organizes traffic proceeding in opposite or nearly opposite directions by means of a separation zone or line, traffic lane, etc. [110]. Essentially, the objective is to help reduce and manage head on situations for the streams of opposing traffic, manage crossing situation arising while entering or coming out of port and provide directives regarding safe distance from the installations of offshore activities. Most of these shipping lanes are established near shore, as in the Portuguese case (Figure 4.8), which provides an extra assistance on shore based maritime systems coverage planning.

Within this context, it is expectable that maritime VHF networks must deal with hidden node problem. Hidden nodes issues occur in wireless networks that adopt a star topology with an access point and when nodes are out of range of each other and within the range of the access point. Hence, collisions occur if those two nodes start to send packets simultaneously to access point, corrupting received data. This is a well-documented problem in 802.11 networks and is likely to occur in MANET.

There are several solutions for this issue, mostly at data link level. The IEEE 802.11 uses a Request-To-Send /Clear-to-Send (RTS/CTS) handshaking implemented in conjunction with Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme, while WiMAX standards assign time slots to individual stations to prevent multiple nodes from sending simultaneously and ensure fairness even in over-subscription scenarios. Other approaches can be considered, namely token passing or polling strategies. Regarding opportunistic systems, hidden node problem represents an extra challenge for spectrum sensing, but in the space domain. As previously mentioned, cooperative sensing is a typical solution appointed to these cases, but beamforming is also a option to take into consideration, especially for transmission purposes.

In the case of maritime VHF, primary services footprints are binded to coastal radio-stations and ships footprints, according to assigned services. In other words, since in MMS each channel is assigned to a service, each station can be a primary user on the multiple

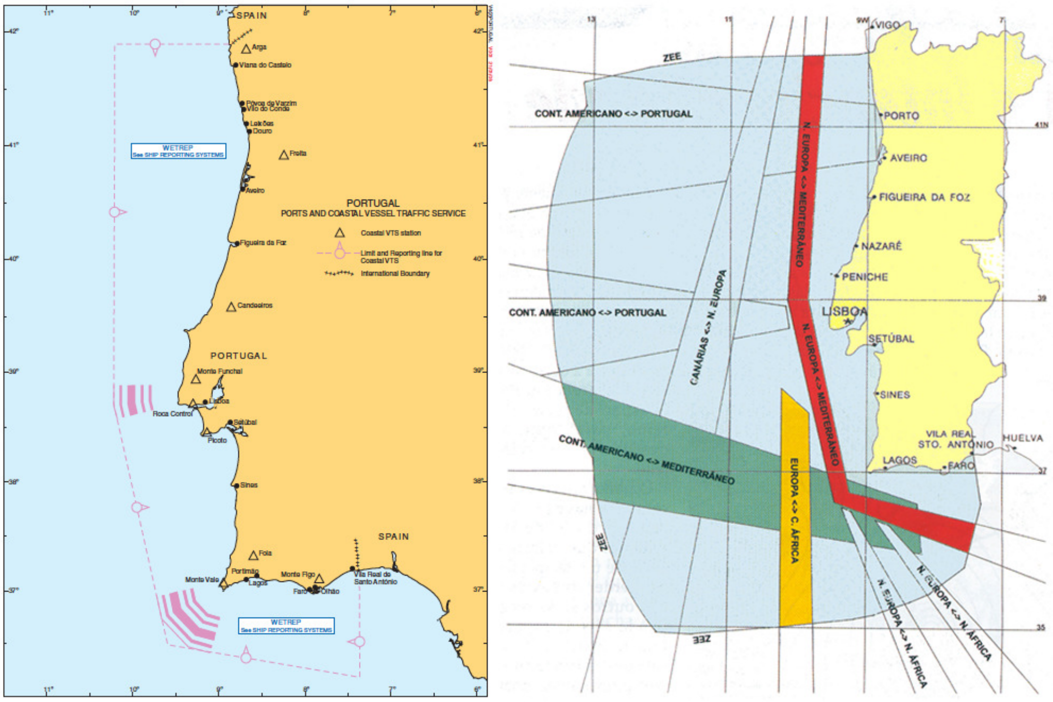

Figure 4.8: Portuguese Traffic separation schemes along the Portuguese continental shore.

channels that its operational condition allows it to operate, which means that, in the limit, a primary service footprint can be the summation of all ship and shore stations. Therefore, an application that can merge AIS information and an estimation of RLOS for each station, in a geographical information system, can provide an interesting perspective of potential primary service area and can be included in spectrum sensing algorithms to support measures to overcome hidden node problems.

A shore based opportunistic network is composed by two types of nodes, fixed (coastal stations) and mobile (ships); each on with different characteristics and functionalities. Firstly, one should consider that antenna heights of shore based radiostations normally exceed ship's installations, i.e. RLOS for ship-to-shore VHF links are larger then ship-to-ship. Secondly, in infrastructure mode, all mobile nodes connect to shore based nodes (access points), which requires more functionalities from coastal stations, while in ad-hoc mode, nodes have similar functionalities and participate in routing by forwarding data for other nodes. Finally, data exchange and performance requirements might not be symmetric, given that information consumption is on ship's side. These asymmetric characteristics of data rate demanding might anticipate an architecture that might take advantage of this fact to maximize overall network performance and release pressure on afloat spectrum sensing capacity.

From shore based secondary stations perspective, incumbent's activity can be detected whenever primary users are located within RLOS, as in case of *Primary Station A* and *Primary User B* in Scenario A, depicted in Figure **??**. Therefore, spectrum opportunities area, for operating channels of *Primary Station A* and *Primary User B*, can defined by orange circle, represented in the same picture. Unfortunately, *Primary User A* and *Primary Station B* are considered hidden nodes, which can transmit without detection, by *Secondary Station*, but can potentially generate interference at *Primary Station A* and *Primary User B*, respectively,

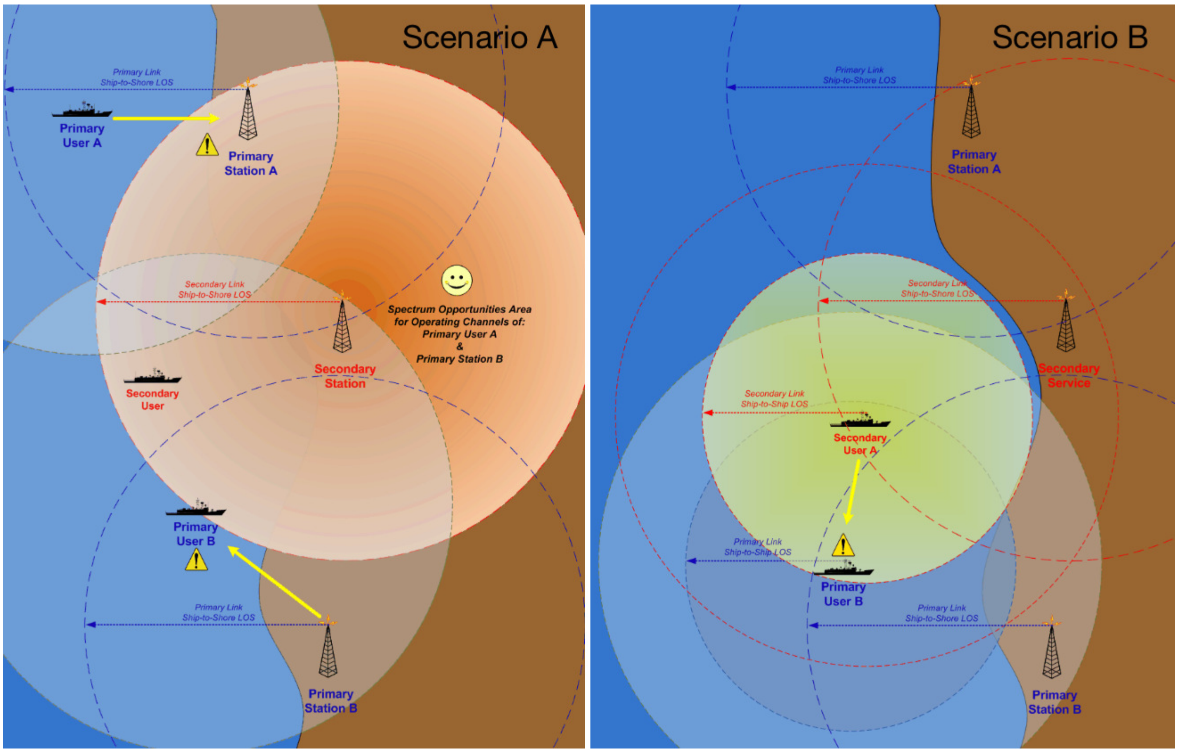

Figure 4.9: Operating scenarios for potential hidden node problems.

in case of simultaneously service operation.

On the other hand, in the case of Scenario B, presented in Figure **??**, *Secondary Station* can take advantage of operating channels of *Primary Station A*, *Primary Station B* and *Primary User B*, without causing any interference. However, if *Secondary User A* does not have any spectrum sensing capacity and uses the same pool of spectrum, as *Secondary Station*, potential interference can occur at *Primary User B*. Again, this is a typical case of hidden node that requires appropriate spectrum sensing measures or an asymmetric approach to shore based network architecture.

Regarding environment dynamics, typical ship's cruise speed of 14 knots (40 km/h) result in a "quasi-static" operating context. In other words, mobile station's low velocity causes a relatively small rate of variability of spectrum occupancy, as a function of emitter position. Hence, for an initial analysis on spectrum opportunities, one may consider static primary users. Naturally, once a secondary user start to take advantage of spectrum opportunities, it is necessary to accommodate primary's dynamics to guarantee tolerable interference level and seek for new opportunities in spatial domain.

4.2.2 Incumbents Services

Despite spatial perspective of spectrum opportunities, time-frequency characteristics of incumbents' services are critical for secondary systems deployment. Essentially, maritime VHF communications are narrowband, mostly assigned to a specific system, and operate circuit (channel) switching. Each MMS channel is assigned to a specific usage, so mariners select their operating channels according to the instantaneous operational needs. In this paradigm, there is no primary user, but a primary service, which can be used by multiple marine users, according to operational requirements. Hence, occupancy of a communications channel varies according to assigned service and amount of users, so service characteristics dictates the amount, duration and frequency of demands of each user and user density conditionates the overall traffic volume. Consequently, primary channels availability profiles are specific for each channel and depend on shipping traffic density, associated to geographic location.

Moreover, spectrum opportunities depend on primary services and its traffic activity profiles, which explicitly focus on frequency and time domains. Typical incumbent services have been described in Chapter 2 and their supported radio systems present spectrum characteristics depicted in Figure 4.10. Radiotelephony equipment is able to transmit and receive standard IMO class G3E/F3E emissions on designated channels. The DSC equipment operates with IMO class G2B emissions on channel 70 and AIS transponders are required to support bit rate of 9600 bps, based on Gaussian Minimum Shift Keying (GMSK) data packets in a bursty mode.

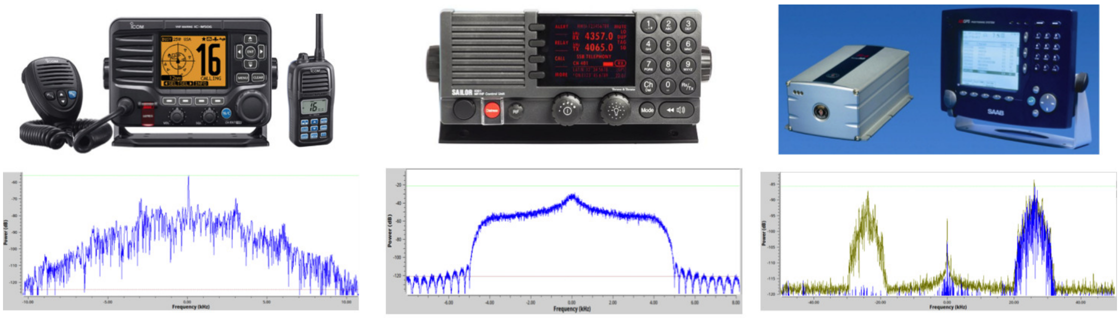
Analogue Telephony **DSC** **AIS**

Figure 4.10: VHF telephony signals (FM), DSC and AIS power spectrum density from synthesized signal with GNU Radio [T1].

However, an accurate global information on MMS channels activity profiles, namely probability of being idle (P_{off}) and transmission rate (β), are difficult to obtain. In spite of natural constraints associated to surveys, national allocations may vary from a country to another, as exemplified in Figure 4.11 [111], [112], [113], [114], [115], [116]. As previously mentioned, except for two most important channels in MMS, none of the other channels are exclusively allocated to MMS, and administrations are not obligated to allocate those remaining frequencies to maritime service [28]. Therefore, any investigation or survey on 156-174 MHz band in one country cannot be simply extrapolated to another country, because assigned channels traffic might be antipodal.

In any case, it is possible to perform national surveys and try to have an insight of maritime services activity. In fact, in [T3] it is presented an endeavor to obtain statistics on MMS assigned spectrum, within Lisbon coast and port area, in order to estimate channels activity profiles. The proposed analysis assumes a relationship between the amount of ships obtained in AIS system (within RLOS) and the traffic on MMS assigned channels and normalizes it with channel 16 traffic. The idea is to obtain a way to estimate MMS assigned channels activity profiles in other regions, based on AIS databases information obtained online. Such transformation is not trivial to accurately obtain and requires enough data to validate mathematical models. Unfortunately, collected data was not sufficient to obtain a

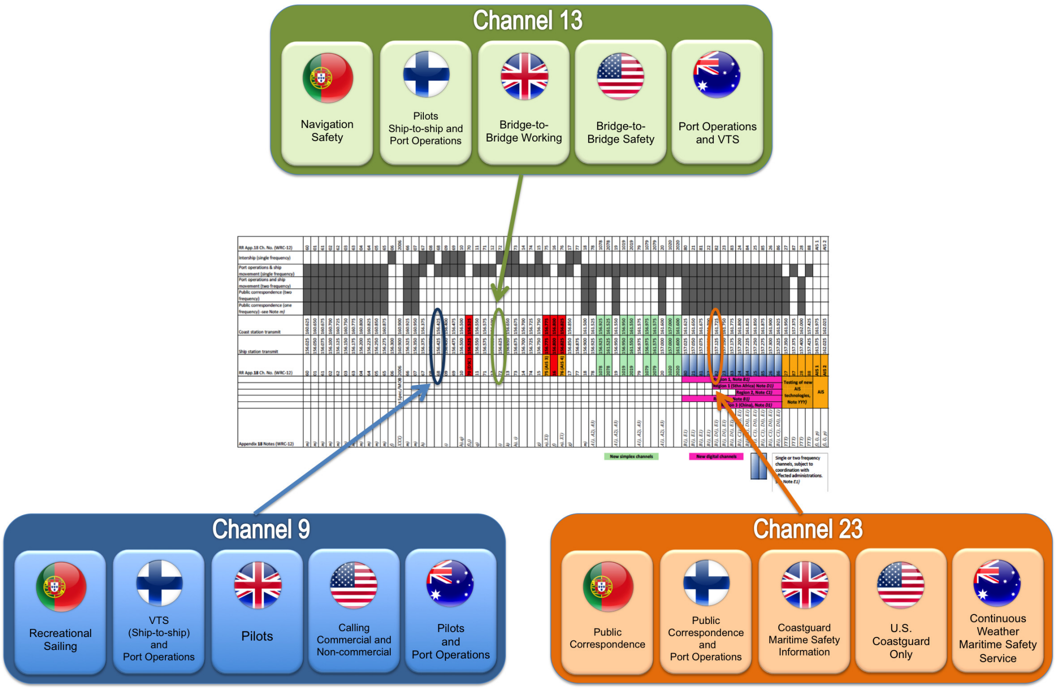

Figure 4.11: Example of differences in MMS assigned channels.

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robust algorithm that ensure low error estimation intervals, but some survey results provide interesting information.

For illustration purposes, it is presented, in Figure 4.12, some survey data results obtained on a cruise between Portuguese Naval Academy (Escola Naval) and Cascais area, during a working day in May 2015. Excluding 158.050 to 160.600 MHz and 162.650 to 169.400 MHz frequency bands, which are assigned to terrestrial mobile service, it can be observed that channel occupancy does not reach 50% of the time. Actually, during the afternoon period, average probability of occupancy is below 30%. Regarding transmission periods, it has been observed, during morning period, for Channel 16, a total of 1.240 transmissions with an average duration of 3.6 seconds. Note that Channel 16 is used for distress, safety and calling, that is why call duration are reduced. In any case, these facts are even more relevant if one consider that Lisbon-Cascais area includes ports and anchorage approaches and several marinas, which is particularly demanding in terms of VHF communications. Certainly, transit areas, away from port would present values of occupancy significantly lower.

Practical consequences of inappropriate secondary activity are noise floor level rising and an increase in primary service outage probability. Since most of the MMS assigned services are analogue telephony based, there is a need for a characterization of common understanding of *"restrictions on incumbents achievable capacity"*. An analogue modulated voice signal can be understandable, even with very low SNR levels, but this does not means that such kind of quality of service can be acceptable as a standard. In digital world, service outage is synonym of unintelligible, but in analogue voice services such definition might not be as consensual.

The service outage definition for analogue voice services is not simple. Even voice intelligibility level is a subjective issue. Many marine radios for VHF band have specifications where sensitivity performance of a radio receiver is expressed in terms of Signal-to-Noise And

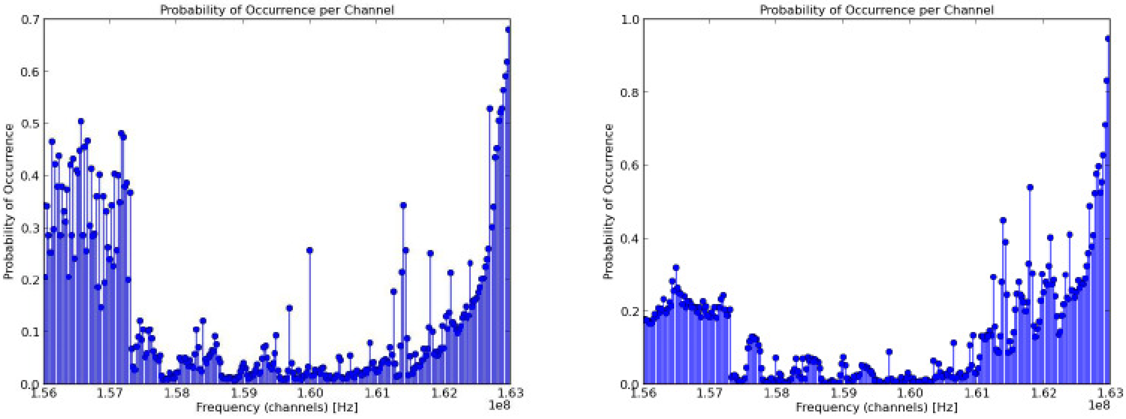

Figure 4.12: Survey results of spectrum occupancy probability, for 156 to 163 MHz frequency band, obtained in a cruise between Escola Naval and Cascais area, during a working day in May 2015. Left graph presents 8h to 12h period and right graph presents 12h to 17h period [T2], [T3].

Distortion ratio (SINAD). Basically, SINAD is a measurement to quantify degradation of a signal by unwanted or extraneous signals including noise and distortion and is used to express sensitivity of receiver. Receiver sensitivity is often specified in terms of the signal level at the antenna input necessary to produce audio output with a particular SNR. Normally, a SINAD value of 12 dB is taken, as this corresponds to a distortion factor of 25%, and a modulating tone of 1 kHz is used. A typical specification might be that a receiver has a sensitivity of 0.25 μV for a 12 dB SINAD. Obviously, the lower input voltage, needed to achieve a given level of SINAD, the better receiver performance. In any case, sensitivity is not exactly the dual of digital communications service outage.

In spite of this definition constraint, it is possible to pursue with protective measures for incumbents. A secondary system has two ways of managing interference in their approach to opportunistic usage of spectrum. Either adopt an exclusive use of spectrum paradigm, avoiding any kind of interference with incumbents, or accept concurrent primary and secondary transmissions, as long as interference generated by both transmissions is below any acceptable level, which corresponds to different DSA strategies. As previously mentioned, in early stages of CR-B-VHF maturity, a conservative approach, such as overlay, would be more appropriate, so for the sake of current analysis it is assumed that incumbents are supposed to exclusively use the assigned spectrum. Therefore, primary service outage probability (P_{out}) is defined in terms of concurrent primary and secondary transmission probability. In other words, instead of defining P_{out} as a probability of having a Signal-to-Noise-plus-Interference-Ratio (SNIR), at primary receiver, bellow its required value to provide defined QoS, we defined it as a probability of collision (P_c).

Within this context, a definition of primary services acceptable levels might be not that complex. If one think in a typical MMS half-duplex analogue voice call, specifically in the time between push-to-talk activation moment and initiation of standardized voice procedures, it is possible to contend that MMS stakeholders would agree on a certain acceptable overlapping time, between primary user and a secondary interference, mainly caused by an increasing on Probability of Miss Detection (P_{md}) in opportunistic system spectrum sensing. It is reasonable to accept that this gap might be able to accommodate a significative collision time tolerance to ensure both systems operation. Anyway, such definitions require regulatory and standardization procedures, which raise a whole area of discussion.

4.2.3 Channel Model

The radiowave propagation path over the sea behaves differently from an equivalent over land, because atmospheric conditions over the sea are the dominant influence on propagation characteristics. Depending on atmosphere conditions, radio links may be affected by phenomena of refraction (including ducting), reflection, diffraction and scattering. The troposphere, which is the lower layer (< 10Km) of the atmosphere, is the most important region for VHF communications and is also where all weather occurs [117].

Normally, maritime VHF radio links are affected by refraction effect, which acts as an extender of radio horizon, multipath fading, caused by strong reflections on sea surface, as shown in Figure 4.13, and scattering, whose intensity depends on sea state. Such adverse conditions post several challenges in detection process accuracy and performance, not only because refraction (ducts) can allow signals to propagate for very long distances beyond the geometric horizon, but also in a consequence of strong destructive interferencies. Appropriate modeling of such phenomena has to accommodate not only channel fading severity, but also provide flexibility to incorporate dynamic characteristics of maritime environment.

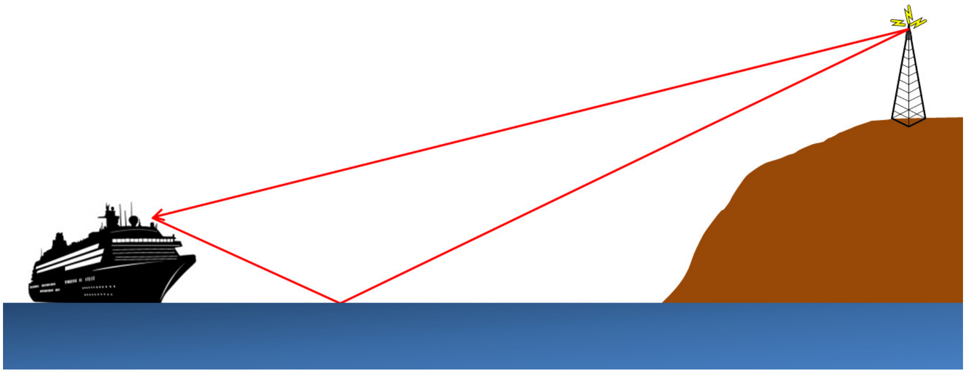

Figure 4.13: Maritime radio links are affected by multipath fading, caused by strong reflections on sea surface.

Refraction occurs whenever there is a change in refractive index of atmosphere. Abnormal weather conditions cause a dramatic change in refractive index of atmosphere, leading to a ”super refraction” phenomenon that ”bends” propagation wave path towards earth, which results in a radio horizon extension. In extreme cases, it leads to ”ducting” phenomenon, where signals can propagate over enormous distances beyond normal horizon, or to a ”sub-refraction” phenomenon, where radio wave path bending is less than normal, thus shortening radio horizon and leading to an increase in path loss [118].

The multipath fading is caused by reception of multiple replicas of transmitted signal, coming from any direction of arrival with different amplitudes and phases, which result in a serious lost of power. In a typical maritime VHF radio link, consisting of a direct path and a sea reflected path, as shown in Figure 4.13, the path loss depends on relative amplitude and phase relationship of two paths propagated signals. Reflection coefficient (Γ), defined as the ratio of amplitude of reflected wave to amplitude of incident wave, provides useful information regarding the amount of energy that is expected to be received from reflected path. Classical formulas, derived first by Fresnel in 1816, give reflection coefficients for horizontal and vertical polarization as a function of dielectric constant and conductivity of ground substance. In Figure 4.15, it is presented the reflection coefficient of sea water at three frequencies, as a function of grazing angle (angle between the incident ray and its projection on the horizontal reflecting plane) [119].

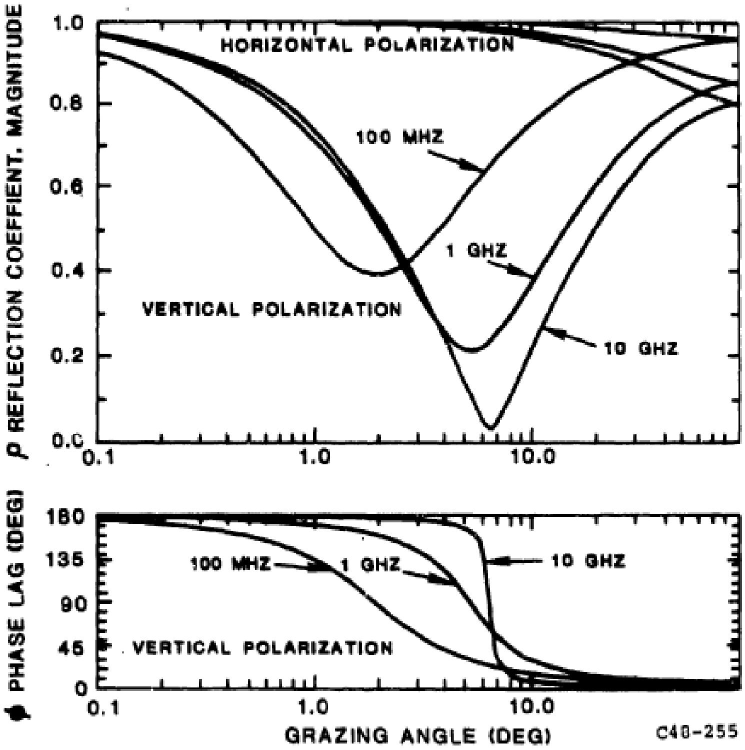

Figure 4.14: The reflection coefficient as a function of the grazing angle for sea water. The relative dielectric constant is 80 and the conductivity 5.0 mhos/m. Separate curves are shown for frequencies of 100 MHz, 1 GHz, and 10 GHz [119].

In 1970, Algor [120] performed some experiments, in Atlantic, to analyse signal levels and fading characteristic at various distances and frequencies (30, 140 and 412 MHz), taking meteorological conditions into consideration. Interesting enough, and despite the usual decrease in signal strength as distance increases, as depicted in Figure 4.15, study concludes that [117]: higher frequencies have greater fading range and faster fluctuation in level; fading range is not a function of distance, signal level varies more at higher frequencies but for a fixed frequency, the variation of fading does not change accordingly with increase in distance; fading range may increase with increased sea and wind states; fading at one frequency is essentially uncorrelated with fading at other frequencies, with certain uncommon exceptions; fading can be divided into two components, fast and slow which both may have different causes.

Nevertheless, in the cases where reflected surface is not smooth, scattering of the radiowave

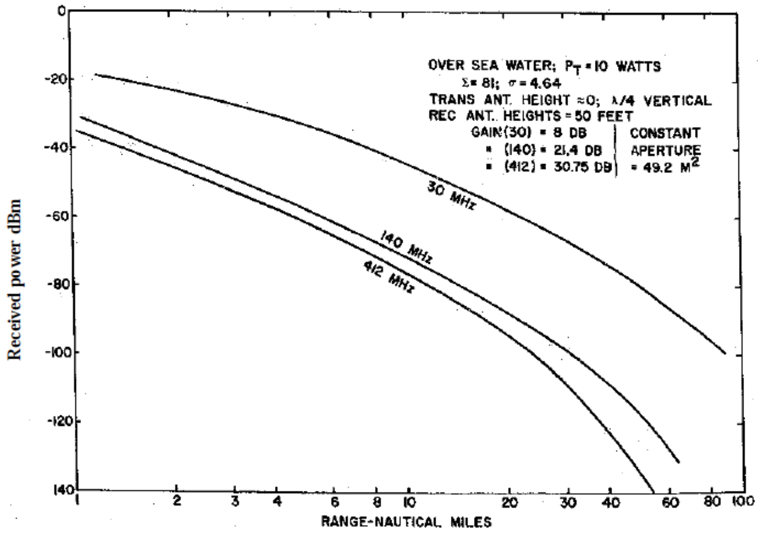

Figure 4.15: Normalised propagation signal strength against various distances [121].

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will occur and power is retransmitted in all directions. In the case of sea surface, whose roughness is random and highly correlated with weather conditions, the maximum reflected power will be in the direction of specular reflection. Even though, sea state may change such condition and scattering might be significative enough to reduce power retransmission in receiver direction.

The Rayleigh criterion is based on simplistic model that takes into consideration the interference between received replicas of a radiowave that has been reflected in multiple surface scatters. Hence, Rayleigh roughness parameter Υ expresses the difference in phase between two rays with grazing angle Φ reflected from surface scatters, separated by a wave (RMS) height deviation h and is given by:

$$4\pi\,\frac{h}{\lambda}\,sin(\Phi) < \Upsilon, \tag{4.2}$$

where λ represents the radiowave wavelength.

Additionally, in [122], it is presented a general criterion for a surface to be considered as rough, based on impact on path length variations. A surface is considered to be rough if is texture characteristics cause variations in the path length of more than an eighth of a wavelength, as depicted in Figure 4.16.

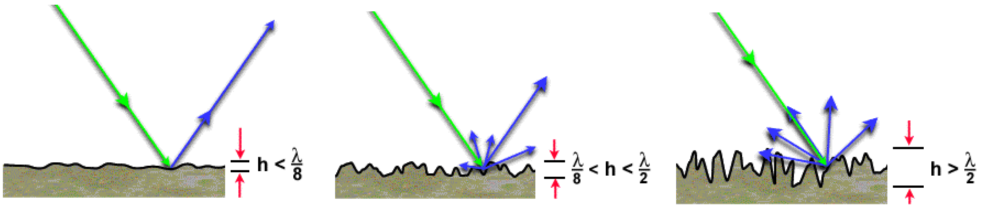

Figure 4.16: Roughness effect on reflected radiowaves.

In any case, it is possible to take advantage of Britain's Admiral Sir Francis Beaufort developed scale (1805), presented in Figure 4.17, to estimate wind speeds and its effects, and envisage scattering effects on sea surface, based on weather conditions.

Figure 4.17: The Beaufort scale [http://www.delta-s.org].

The channel model, for maritime VHF band, has to consider the absence of shadowing in communications links (normally stations have LOS) and comprehend sea surface as a unique source of reflections, with different level of scattering. In [123], ITU assumed that amplitude distribution of sea reflected signals follows a Nakagami-m distribution [124], also known as Rice-Nakagami distribution, which is general enough to describe most of fading phenomena, including Rayleigh fading. The Nakagami-m distribution is able to model a significant diversity of fading channels, simply through a definition of shaping parameter m. Hence, sea surface reflection can be modeled by treating received SNR as a Nakagami-m random variable (γ), which Probability Density Function (PDF) is defined by

$$f_{Nak}(\gamma) = \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} exp\left(-\frac{m\gamma}{\bar{\gamma}}\right) \tag{4.3}$$

where $\bar{\gamma}$ is γ average and m parameter can be used to characterize either more or less severe fading conditions, from no fading ($m = \infty$) to one-sided Gaussian ($m = 0.5$), namely Rayleigh ($m = 1$) or Rice ($m = 2$) [124], as presented in Figure 4.18.

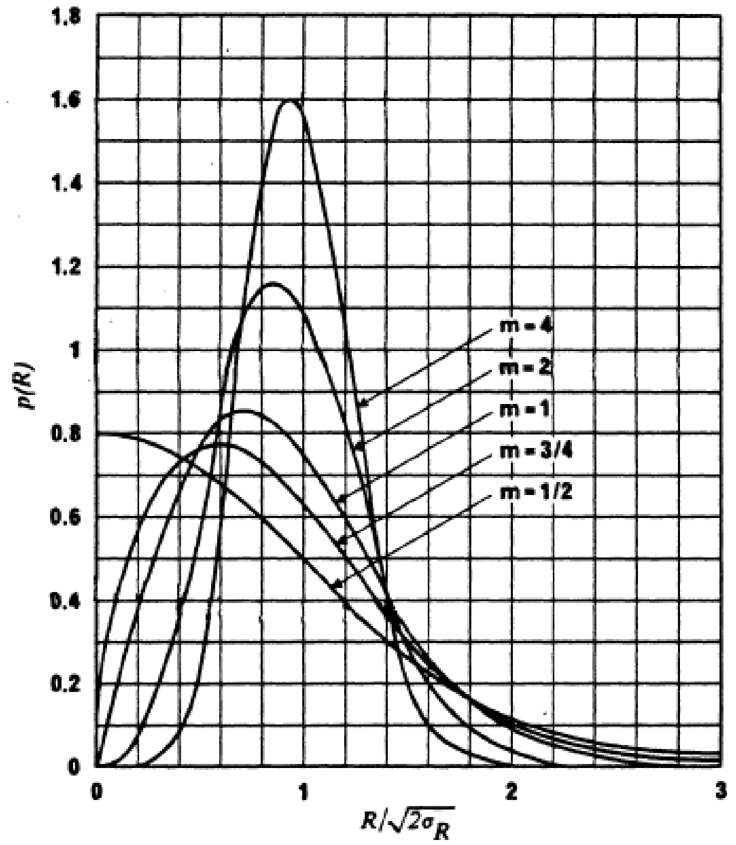

Figure 4.18: An example of the m-distribution using "m" as a parameter, as presented in [124], where R represents the amplitude of the reflected signal and σ_R is the value of reflected signal.

Furthermore, Rice factor (K) defined as a ratio of LOS received power to scattered power, can be used to characterize different sea conditions, where surface reflection has different contribution to received signal at secondary sensor. Using the following relation between K and m, one can classify typical scenarios, as those presented in Table 4.1, where sea conditions might conditionate multipath fading and consequently detection performance.

$$m = \frac{(K+1)^2}{(2K+1)} \tag{4.4}$$

Sea Conditions	Wave height (m)	Considered K
Flat	0-1	0
Moderate	1-3	10
Rough	3-5	100

Table 4.1: Suggested Rice factor for maritime links

4.3 Sensing in MMS Assigned Spectrum

Despite the fact that throughput is the ultimate goal for network users, in opportunistic systems context, the most important figure of merit is the capacity to take advantage of spectrum opportunities. As a matter of fact, that is the only variable that can be controlled by system designers, given that performance depends, not only on capacity to explore spectrum opportunities, but also on spectrum opportunities availability and characteristics. The maximization of achievable capacity, fulfilling incumbents live operations and legacy systems requirements, is the essence of sensing design problem.

In the case of opportunistic systems operating in MMS assigned spectrum, the ability to manage non-license transmissions without harming operation of primary services is especially critical, due to multiple non-contiguous and narrowband nature of channels. In fact, practical interest of a CR-B-VHF system deployment depends on talent to find the so-called opportunities to operate and explore them efficiently, which requires an accurate detector and a appropriate spectrum sensing algorithm.

In perfect conditions, maximum achievable capacity of a secondary link (C_s) depends on channel bandwidth (BW), its availability (P_{off}) and on SNIR at secondary receiver.

$$C_s = P_{off}\mathbf{E}\Big[BWlog_2(1 + SNIR)\Big] \tag{4.5}$$

However, secondary receiver is not ideal, i.e. probability of false alarm (P_{fa}) is not 0 and probability of detection (P_d) is not 1, so concurrently primary and secondary transmissions are potentiated. Practical results of such situation are a decrease on primary and secondary networks capacity, caused by a diminution on SNIR. Different factors might result in errors on channel availability estimation, most of them translated in spectrum sensing parameters associated to both state estimation accuracy itself and implementation strategy.

Hence, for inaccurate spectrum sensing, the capacity of a secondary service is now given by a summation of two capacities: one that corresponds to transmission in absence of incumbents C_0 and another that results from miss detection of incumbent's activity (still valid as long as it does not exceed the required outage probability) that concurrently occurs with its transmissions C_1:

$$C_s = P_{off}(1 - P_{fa})\,C_0 + P_{on}(1 - P_d)\,C_1 \tag{4.6}$$

where

$$\begin{aligned} C_0 &= \mathbf{E}\Big[BWlog_2(1 + SNR)\Big] \\ C_1 &= \mathbf{E}\Big[BWlog_2(1 + SNIR)\Big] \end{aligned} \tag{4.7}$$

with SNIR and SNR representing the signal-to-noise ratios with and without incumbent's interference, respectively.

In the case of multiple non-contiguous bands operation, additional features are required to concatenate individual channel capacities, which result in some constrains and limitations on achievable capacity, mostly introduced by multiple band spectrum sensing scheme. Essentially, there are two options for multiple band sensing: wideband and sequential sensing.

Wideband sensing requires a single sensing transceiver, uses identical observation and transmission times over all bands, without considering each individual channel characteristics, and demands high speed analogue-to-digital converters [125]. Alternatively, *sequential sensing* enables adjustment of sensing parameters to each spectral band characteristics, because it senses each channel individually. Unfortunately, this requires multiple transceivers. There are natural advantages and disadvantages associated to the application of each of those schemes [126], which depend on specific application.

On the other side, challenges associated to secondary usage of spectra, in a hierarchical dynamic access model, impose detection of spectrum holes, opportunistic transmission and monitorization of frequency bands availability, in order to avoid further incumbent's harmful interference. Even after getting access to a spectrum hole, the opportunistic user must maintain band sensing in order to determine whenever primary user starts to transmit. In cases where transmission and sensing cannot be performed concurrently, sensing has to be periodically interleaved with the data transmission. The sensing period determines the amount of time that secondary user will be unaware of a reappearing primary user and hence may harmfully interfere with it [74]. An efficient opportunistic usage of spectrum resources is about trade-off management, between maximization of capacity and primary service outage probability requirements. This paradoxical challenge requires awareness for opportunity occurrence, as soon as primary services turned off, and preciseness in interference avoidance, as incumbent services start to operate. Incumbent's spectra have to be monitored to detect idle/busy state transitions in order to start/stop secondary transmission, without causing warmful interferences.

The cognitive process, represented in Figure 3.1 starts each iteration with probing of radio environment to collect a radio frequency stimulus and finishes it with a transmitted signal. However, there are no requirements for time-sharing in these operations. In other words, spectrum sensing period might be followed by a transmitting time, but it can also be performed concurrently. The former case corresponds to, what can be called as, HDS scheme, where spectrum sensing is performed in a dedicated time slot, without any secondary transmission. The later case, designated by FDS, as opposed to HDS, requires a self-interference cancellation scheme, because detection is performed in the presence of self-transmission signal.

Consequently, further limitations on throughput would result from time domain characteristics of sensing (i.e. HDS or FDS). HDS imposes a trade-off between sensing accuracy and throughput which results in limitations on the maximum achievable capacity, even though, optimization problem should be focus on finding the optimal parameters for periodic sensing that maximize throughput within acceptable levels of interference. In the case of FDS, self-interference cancellation scheme inaccuracies would raise SNIR and P_{md}, which decreases spectrum efficiency.

Sensing design problem is about defining the parameters that are required to achieve a maximization of achievable capacity, fulfilling primary service outage probability. One of the most important parameters to be defined is the detection threshold (Λ) to be used for detection. According to operating conditions, detectors have associated ROC and optimal thresholds to be applied. Moreover, depending on time domain characteristics of sensing (i.e. HDS or FDS), there might be other required optimal parameters, namely sensing time (t_s) and transmitting time (t_T), in the case of HDS.

4.4 Concluding Remarks

Maximum achievable capacity of an opportunistic system depends, not only on primary channels availability characteristics (P_{on} and P_{off}), but also on detectors capacity. Despite the fact that later constraint is expressed in terms of a ROC, this capacity should include all the process associated to exploitation of spectrum opportunities. In other words, P_d and P_{fa} are related to spectrum sensing algorithm and not just associated to detector performance. Depending on sensing design approach, overall detection capacity (P_d and P_{fa}), are more or less connected with individual detector's P_d and P_{fa}.

In any case, at this point, detection of spectrum opportunities in maritime VHF band has been characterized and fundamental aspects, related with operational context of incumbents, has been presented and discussed. The maritime VHF channel has been modeled and achievable capacity of a secondary system has been formulated in terms of primary channels availability characteristics and ROC. Therefore, it is time to address spectrum sensing design in its different time domain characteristics, i.e. HDS and FDS.

Chapter 5

Half-Duplex Sensing in Maritime VHF Band

In HDS, the design focus is on optimal sensing cycle that maximizes achievable capacity of opportunistic system, fulfilling primary service harmful interference levels. Hence, the optimization problem has to include an objective function, centered on maximization of achievable capacity, and a set of constraints that take into consideration the requirements of incumbents. In the case of CR-B-VHF, restrictions associated to multiple non-contiguous spectra have to be included, as well. Presumably, optimal sensing cycle is not independent from considered detector, neither from primary services activity profiles.

The initial approach to HDS for CR-B-VHF has included four phases. Firstly, a quadratic detector has been selected for narrowband signal detection in the VHF band, instead of commonly used energy detector, due to its expected superior performance, so mathematical analysis should be performed in order to derive closed form expressions for ROC over Nakagami-m fading channels, to be used in optimization problem. Secondly, a MMS spectrum survey campaign has to be performed to obtain statistically significant data to support estimation of channel activity profiles, based on AIS information, and optimization results. Thirdly, a set of optimal parameters would be obtained and experimentally validated in order to calibrate the models. Finally, a parametric nonlinear regression models would be used to estimate optimal parameters and performances for arbitrary environments, for the cases where primary services activity profiles are not available, but AIS information can be accessed online.

Unfortunately, such plan could not be fulfilled. The MMS spectrum survey campaign has been frustrated due to several contingencies, which included several weeks corrupted data and logistic difficulties to collect data outside Lisbon area. In fact, this unsuccessful endeavor has been on the basis of research initiatives presented in [T3]. Eventually, the lack of required field data compelled to simulation alternatives, which might anticipate the conviction that HDS is not the best solution for CR-B-VHF and drove towards development of SCD for FDS.

Nevertheless, an analytic formulation has been performed for quadratic detector and closed form expressions have been derived for ROC over Nakagami-m fading channels, for both single and multiple combined received signals. Diversity gain analysis has been performed, for cases of insufficient antenna separation and limited amount of processed branches, and overall detection performance has been estimated. These achievements are highly relevant, not only for analytical solution of optimization problems, but also for benchmarking.

Furthermore, spectrum efficiency optimization problems have been analyzed, for single 25 kHz channel and multiple channels aggregation, and dependency of prior information on primary channels activity profiles has been discussed. Finally, simulation and parametric nonlinear regression models have been used to estimate performance of arbitrary aggregation of multiple channels, when field information is scarce. All of this work is presented in the following sections. The lack of field data on MMS channels activity profile statistics prevent validation and attainability analysis on simulation results, but presented framework would allow further developments for any other applications.

The remainder of the chapter is organized as follows: in Section 5.1 we present HDS algorithm and sensing design problem, proposing a hybrid wideband/sequential sensing for detection in multiple non-contiguous narrowband channels; Section 5.2 is dedicated to mathematical modeling of detection in maritime VHF band, where closed form expressions for quadrature ROC, over Nakagami fading channels, are derived. Sensing cycle optimization is discussed in Section 5.3; and Section 5.4 concludes the chapter with final remarks.

5.1 Half-Duplex Sensing

In HDS, the multiple spectrum access control, which enables spectrum exclusive access to incumbents, is performed though synchronous interruptions on secondary operation to evaluate primary activity occurrences. Hence, it is assumed a time-sharing between spectrum sensing and transmission, as represented in Figure 5.1. From sensing perspective, transmitting slots are blind periods, similar to half-duplex communications, where secondary system cannot be aware of primary activity. On the other hand, from throughput perspective, sensing and synchronization periods are overhead costs that reduce system's performance. This results in a classical trade-off between interference and transmission: longer observation periods would represent higher accuracy in primary activity detection and consequently less harmful interference with incumbents; but longer sensing times implies lower transmission time and obviously lower throughputs. The definition of these sensing parameters is critical for opportunistic system maximum achievable capacity.

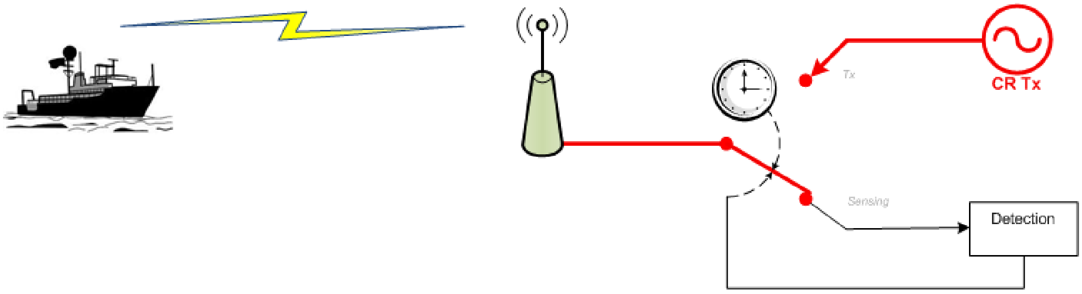

Figure 5.1: Half-Duplex sensing algorithm

The optimization of spectrum sensing, which intend to solve both sensing efficiency and interference avoidance problems, have been addressed in several published research, namely [127], [128] and [129]. The objective is to find optimal parameters for periodic sensing, specifically observation (t_{sens}) and transmission (t_T) times, which permit a maximization of throughput, with acceptable levels of interference. In the following analysis, it is considered an approach, similar to [129], where the maximization of achievable throughput is used as objective function, for a sensing cycle flexible and adaptive.

Generically, sensing design problem is focused on optimal parameters for periodic sensing, described in Figure 5.2. The solution provide optimal values for t_T, t_{sens} and detection threshold (Λ) that maximize the spectrum usage efficiency of a secondary network, while maintaining probability of simultaneous transmission with incumbents (collision probability) bellow a threshold (P_c).

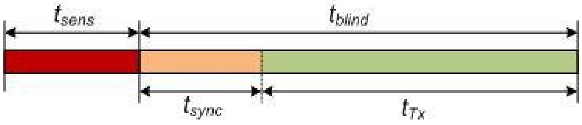

Figure 5.2: Sensing Cycle.

The objective function, formulated as follows, incorporates the spectrum usage efficiency degradation:

$$\max_{t_T, t_{sens}, \Lambda} C_{eff} = \frac{t_T}{t_T + t_{sens}} C_s \tag{5.1}$$

where C_s represents the achievable capacity in (4.6).

Furthermore, several constraints need to be taken into account, namely detector characteristics (ROC), sensing blindness during transmission, primary services quality of service and channel occupancy profile. Essentially, a concurrently transmission of secondary and a primary users occurs when: primary user is ON ($\mathcal{PR}_{on}$) and secondary system miss detects it; or primary user is OFF ($\mathcal{PR}_{off}$) and secondary system detects its idleness and start to use its frequency band, but, during secondary blind period, a primary user starts to operate. Therefore, the condition to ensure an acceptable probability of collision with primary service (P_c) is formulated as follows:

$$P_{on}\big(1 - P_d\big) + P_{off}\big(1 - P_{fa}\big)\big(1 - e^{-\beta t_T}\big) \leq P_c \tag{5.2}$$

where P_{on} and P_{off} represents primary channel probabilities of being busy and idle, respectively, and β is the primary transmission rate.

The problem constraints, summarized in (5.2), point out areas that have to take into account in modeling setup, which include: communications channel; signal detector ROC; spectrum availability and incumbents' utilization profile. Unfortunately, none of these factors are deterministic and even random variables are difficult to model. As a consequence, optimization solution has an additional uncertainty that depends on models accuracy.

The absence of detection capacity during transmission period is supposed to be counterbalanced by incumbent activity profiles statistics and acceptable probability of collision with primary service. Presumably, sensing cycle design must accommodate the fact that opportunistic system is blind during transmitting period, but the probability of having primary activity, during this period, is within harmful interference tolerance of incumbents services.

The application of such concept take (implicitly) for granted that either primary activity profiles statistics are accurate or harmful interference tolerances are not restrictive.

The inaccuracy of channel occupancy statistics data, or its dynamics over time, results in sub-optimal sensing parameters with consequences in system performance, which affects capacity and harmful interference. In fact, it might lead to unacceptable opportunistic operation, either due to poor throughput or violation of regulatory context of dynamic spectrum access strategies. An obvious solution, to overcome inaccuracy of incumbents activity profiles statistics, is to impose additional restrictions on P_c, but even in this case, the outcome of optimization process might not be as one would expect.

Ideally, opportunistic systems would use real time channels availability information to find optimal t_{sens} and t_{blind} that maximize throughput, or as an alternative, that channels availability statistics would be well know and barely change over time. In practice, one can count on roughly estimations of channels statistics, which have to be used as initial guesses. The optimal radio operating conditions are difficult to encounter, especially in dynamic environments where prior information on primary users activity is required to fine-tune the sensing cycles. Unless an opportunistic network has a dedicated subsystem for real time channel availability parameters estimation, inadequate estimation of channels availability parameters would be a generic starting point for a secondary system setting.

Despite primary activity profile parameters, (5.2) includes another critical feature for overall optimization results, which is the ROC of considered detector. The challenges associated to detection process does not cease with detector selection, its characteristics and modeling preciseness have significant impact on secondary system performance and harmful interference on primary services. The ROC has multiple dependencies, namely SNR and communications channel, so precision of models and real world conditions degree of matching make a significative difference in system design and on achievable performance.

Signal detection has been the subject of an enormous amount of research, with a comprehensive body of work on detection theory, digital communications and fading channels [130]. However, due to the fact that vast majority of cases of spectrum sensing is performed in contiguous spectrum, most of the documented detection process requirements are centred in detector itself and so the addressed problems. That is not the case for spectrum sensing in multiple non-contiguous spectra.

The detection of primary activity in multiple non-contiguous narrowband channels, over a wide frequency at a time, requires compromises. Especially, in cases with requirements for time-sharing between sensing and transmitting operations. The proposed solution for detection in HDS is a mixed compromise of wideband and sequential sensing. As presented in Figure 5.3, wideband sensing in performed in non-contiguous channels by multiple narrowband detectors at the same time. One of the advantages of this approach is related with optimization of solution to maximize spectrum usage efficiency, by using individual detection thresholds according to each channel activity profile. Further benefits, associated with synchronization of sensing cycles, are addressed later in this chapter. Now, the choice for narrowband detectors can be addressed separately, but taken into account its massive implementation complexity in a software defined radio platform.

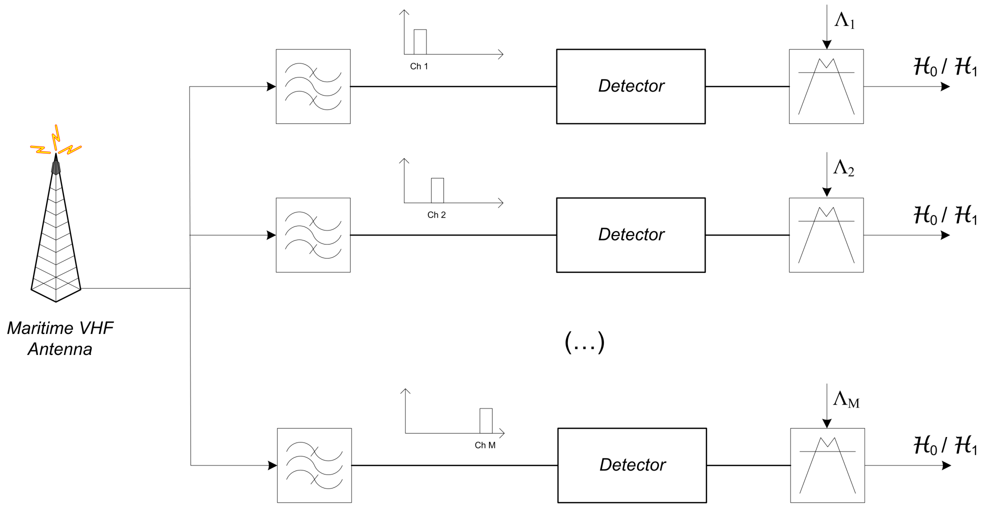

Figure 5.3: Wideband sensing in multiple non-contiguous narrowband VHF channels.

5.2 Detection of Narrowband VHF Signals

Recently, energy detectors have drawn a lot of attention, due to its simplicity, low requirement for information on the signals to be detected, and applicability to wideband signals [131] [132]. Several published work provide comprehensive analysis on energy detection performance, mostly concentrated in the cases of non-LOS (Rayleigh) or LOS with strong reflection components (Rice). The detection of unknown deterministic signals by an energy detector was firstly introduced by Urkowitz [131], and then followed by Kostylev [132], which extend the problem to fading channels. Digham *et all* [99] derived a closed form expression for the probability of detection (P_d) over Nakagami-m fading channels, and presented an analysis for $m = 1$ (Rayleigh fading), using square law combining schemes. Alouini and Simon [133] provided a unified framework for performance analysis of digital communications over fading channels, which collects several research in this area and provides interesting tools to address figures of merit such as probability of bit error, symbol error rate and outage probability.

Alternatively, instead of assuming unknown signals and modelling them as samples of a random process, one can significantly improve the detection of well characterized narrowband signals, as those from MMS, by using a quadratic detector. Since most of MMS channels operate analogue modulated voice, a quadratic receiver would be able to provide appropriate data for an effective detection. In [134], Whalen addresses narrowband signals with unknown amplitude and phase over Rayleigh fading and presents an analysis for quadratic detector, which is referred as an analytical and tractable form to evaluate the performance of envelope detector for most cases of interest. Despite the fact that Rayleigh fading does not properly model typical maritime VHF LOS links, one can take advantage of formulated detection problem for Additive White Gaussian Noise (AWGN), presented in [134] and derive the adequate expressions for quadratic detector ROC over Nakagami-m fading. In any case, energy detector should be used as a benchmark, for comparison purposes in the same operating conditions.

Hence, detection problem, in the case of MMS narrowband signals, is reduced to the investigation of presence of a narrowband signal with random parameters, as in [134], assuming that received signal is corrupted by AWGN with zero mean and spectral density $N_0/2$, over the entire frequency range of interest. Furthermore, primary signal period $(2\pi/\omega_c)$ is considered to be very much shorter than the time duration T of the signal, the phase is supposed to be a random variable, uniformly distributed over the interval $(0, 2\pi)$ and amplitude is modeled, in this case, as a Nakagami-m random variable, which is considered to better describe the randomness of fading maritime channel, as proposed in Chapter 4.

The detection of MMS primary signals can be expressed as a binary hypothesis problem, where $\mathcal{H}_0$ and $\mathcal{H}_1$ represent the chance of primary user be idle or active, respectively

$$r(t) = \begin{cases} n(t) : & \mathcal{H}_0 \\ Asin(\omega_c t + \theta) + n(t) : & \mathcal{H}_1 \end{cases} \tag{5.3}$$

where A represents the signal received amplitude , ω_c is the carrier frequency, θ is the received phase and $n(t)$ represents noise component, assumed to be AWGN with zero mean and variance σ^2.

5.2.1 Quadratic Detector

Considering a quadratic detector, as presented in Figure 5.4, where more than one decision sample of signal is available at the receiver at different time intervals. As referred in [134], this is conceptually the same as dealing with single pulses on a set of N received signal vectors, so each of those decision samples contains information regarding the presence/absence of primary user.

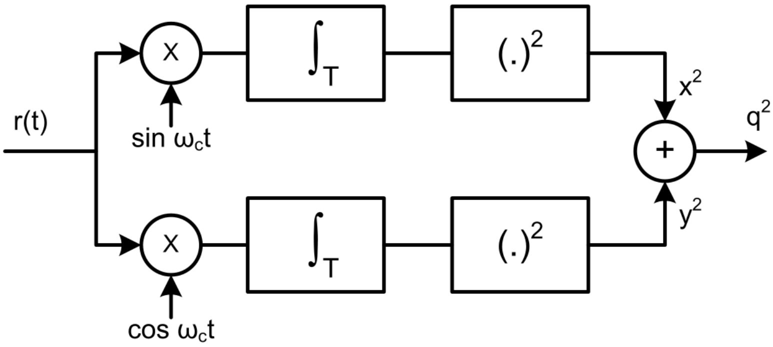

Figure 5.4: Quadratic Receiver

Hence, to obtain the expressions of ROC in AWGN for quadratic detector, as in [134], the statistic $Q = \sum_{i=1}^{N} q_i^2$ can be normalized to

$$G = \sum_{i=1}^{N} q_i^2/\sigma_T^2 \tag{5.4}$$

where $\sigma_T^2 = N_0T/4$ and $q_i^2 = x_i^2 + y_i^2$, defining

$$\begin{aligned} x_i &\triangleq \int_0^\infty r_i(t)\sin\omega_c t dt \\ y_i &\triangleq \int_0^\infty r_i(t)\cos\omega_c t dt \end{aligned} \tag{5.5}$$

When the primary signal is present, for a given θ, the expected values for x_i and y_i are $(AT/2)\cos\theta$ and $(AT/2)\sin\theta$, respectively.

On the other hand, the normalized statistic G is non-centrally distributed chi-square (χ^2) with $2N$ degrees of freedom an has a non-central parameter, given by

$$\nu = \frac{NA^2T^2}{4\sigma_T^2} = 2N\frac{E}{N_0} = 2N\gamma \tag{5.6}$$

Considering now that distributions for G are

$$\begin{cases} p_0(G) = \frac{1}{2^N\Gamma(N)}G^{N-1}e^{-G/2} & : \mathcal{H}_0 \\ p_1(G) = \frac{1}{2}\left(\frac{G}{\nu}\right)^{(N-1)/2} exp\left(-\frac{G}{2}-\frac{\nu}{2}\right)I_{N-1}\left(\sqrt{G\nu}\right) & : \mathcal{H}_1 \end{cases} \tag{5.7}$$

it is possible to derive, as in [134], the probability of false alarm (P_{fa}) and the P_d, respectively, as

$$\begin{aligned} P_{fa} &= \int_\Lambda^\infty p_0(G)dG = 1 - \int_0^\Lambda p_0(G)dG = 1 - \int_0^\Lambda \frac{G^{N-1}e^{-G/2}}{2^N\Gamma(N)}dG = \\ &= 1 - I\left(\frac{\Lambda}{2\sqrt{N}}, N-1\right) \end{aligned} \tag{5.8}$$

and

$$\begin{aligned} P_d &= \int_\Lambda^\infty p_1(G)dG = \int_\Lambda^\infty \frac{1}{2}\left(\frac{G}{\nu}\right)^{(N-1)/2} exp\left(-\frac{G}{2}-\frac{\nu}{2}\right)I_{N-1}\left(\sqrt{G\nu}\right)dG = \\ &= \mathcal{Q}_N\left(\sqrt{2N\gamma}, \sqrt{\Lambda}\right), \end{aligned} \tag{5.9}$$

where $I(u,p)$ is Pearson's form of the incomplete Gamma function, Λ is the threshold and $\mathcal{Q}_M$ is the generalized Marcum Q-function, defined as:

$$\mathcal{Q}_M(\alpha,\beta) = \int_\beta^\infty z\left(\frac{z}{\alpha}\right)^{M-1} exp\left(\frac{z^2+\alpha^2}{-2}\right)I_{M-1}\left(\alpha z\right)dz \tag{5.10}$$

Now, to obtain the probability of detection for quadratic detector over Nakagami fading, it is necessary to average the P_d, obtained for AWGN, over the PDF of instantaneous value of γ, which is considered to be modeled as Nakagami-m random variable:

$$\bar{P_d} = \int\limits_0^\infty P_d(\gamma) f(\gamma) d\gamma \tag{5.11}$$

where $f(\gamma)$ is defined as:

$$f(\gamma) = \Big(\frac{m}{\bar{\gamma}}\Big)^m \frac{\gamma^{m-1}}{\Gamma(m)}\, exp\Big(-\frac{m\gamma}{\bar{\gamma}}\Big), \qquad \gamma > 0, \tag{5.12}$$

and $\bar{\gamma}$ represents the mean value of γ.

Hence,

$$\bar{P_d} = \int\limits_0^\infty P_d(\gamma) f_\gamma(\gamma) d\gamma = \int\limits_0^\infty \mathcal{Q}_N\Big(\sqrt{2N\gamma}, \sqrt{\Lambda}\Big) \left(\frac{m}{\bar{\gamma}}\right)^m \frac{\gamma^{m-1}}{\Gamma(m)} e^{\left(-\frac{m\gamma}{\bar{\gamma}}\right)} d\gamma, \tag{5.13}$$

and operating a change of variables $x = \sqrt{2N\gamma}$, differential become

$$d\gamma \;=\; \frac{x}{N} dx \tag{5.14}$$

and consequently,

$$\begin{aligned} \bar{P_d} &= \int\limits_0^\infty \mathcal{Q}_N\Big(x, \sqrt{\Lambda}\Big)\, \frac{1}{\Gamma(m)}\, \left(\frac{m}{\bar{\gamma}}\right)^m\, \Big(\frac{x^2}{2N}\Big)^{m-1} exp\Big(-\frac{m}{\bar{\gamma}}\,\frac{x^2}{2N}\Big)\, \frac{x}{N}\, dx \;= \\ &= \int\limits_0^\infty \mathcal{Q}_N\Big(x, \sqrt{\Lambda}\Big)\, \frac{2}{\Gamma(m)}\, \left(\frac{m}{2N\bar{\gamma}}\right)^m\, x^{2m-1}\, exp\Big(-\frac{m}{2N\bar{\gamma}}\, x^2\Big)\, dx \;= \\ &= \frac{2}{\Gamma(m)}\, \left(\frac{m}{2N\bar{\gamma}}\right)^m \int\limits_0^\infty \mathcal{Q}_N\Big(x, \sqrt{\Lambda}\Big)\, x^{2m-1}\, exp\left(-\frac{m}{2N\bar{\gamma}}\, x^2\right)\, dx \end{aligned} \tag{5.15}$$

Taking advantage of integral tables, presented in [135], namely

$$\int\limits_0^\infty \mathcal{Q}_N\Big(b_1 x, b_2\Big) x^u exp\left(-\frac{v^2}{2}x^2\right) dx = G_1 + G_M \tag{5.16}$$

where:

$$\begin{aligned} G_1 &= \int\limits_0^\infty \mathcal{Q}\Big(ax, b)\Big) x^{2N-1} exp\left(-\frac{p^2}{2}x^2\right) dx = \\ &= \frac{2^{N-1}(N-1)!}{p^{2N}} \frac{a^2}{p^2+a^2} exp\left(-\frac{b^2}{2}\frac{a^2}{p^2+a^2}\right) \left[\sum_{k=0}^{N-1} \epsilon_k \frac{p^2}{p^2+a^2} L_k\Big(-\frac{b^2}{2}\frac{a^2}{p^2+a^2}\Big)\right] \end{aligned} \tag{5.17}$$

with:

$$\epsilon_k = \begin{cases} 1, & k < N-1 \\ 1+\frac{p^2}{a^2} & k = N-1 \end{cases} \tag{5.18}$$

and

$$G_M = \sum_{k=1}^{M-1} \frac{\Gamma\left(\frac{u+1}{2}\right)\left(\frac{b_2^2}{2}\right)^i exp\left(\frac{b_2^2}{2}\right)}{i!} \, {}_1F_1\left(\frac{u+1}{2}; i+1; \frac{b_1^2 b_2^2}{2\left(v^2+b_1^2\right)}\right) \tag{5.19}$$

where $L_i(.)$ represents the Laguerre polinomal of degree i and ${}_1F_1(.;.;.)$ is the congruent hypergeometric function.

After some manipulations and the following mapping:

$$\begin{cases} N \;=\; m \quad\quad \mathit{and} \quad\quad u \;=\; 2m-1; \\ p^2 \;=\; \frac{m}{N\bar{\gamma}} \quad\quad \mathit{and} \quad\quad v^2 \;=\; \frac{m}{N\bar{\gamma}}; \\ a \;=\; 1 \quad\quad \mathit{and} \quad\quad b_1 \;=\; 1; \\ b \;=\; \sqrt{\Lambda} \quad\quad \mathit{and} \quad\quad b_2 \;=\; \sqrt{\Lambda}; \end{cases} \tag{5.20}$$

then

$$\begin{aligned} G_1 = \frac{2^{m-1}(m-1)!}{\left(\frac{m}{N\bar{\gamma}}\right)^m} \left(\frac{N\bar{\gamma}}{m+N\bar{\gamma}}\right) exp\Big(-\frac{\Lambda}{2}\,\frac{m}{m+N\bar{\gamma}}\Big) \Bigg[\left(\frac{m+N\bar{\gamma}}{N\bar{\gamma}}\right)\left(\frac{m}{m+N\bar{\gamma}}\right)^{m-1} \times \\ \times L_{m-1}\Big(-\frac{\Lambda}{2}\,\frac{N\bar{\gamma}}{m+N\bar{\gamma}}\Big) + \sum_{k=0}^{m-2}\left(\frac{m}{m+N\bar{\gamma}}\right)^k L_k\Big(-\frac{\Lambda}{2}\,\frac{N\bar{\gamma}}{m+N\bar{\gamma}}\Big)\Bigg] \end{aligned} \tag{5.21}$$

and

$$\begin{aligned} G_M = \sum_{k=1}^{M-1} \frac{\Gamma(m)\left(\frac{\Lambda}{2}\right)^i exp\left(-\frac{\Lambda}{2}\right)}{2i!\left(\frac{m+N\bar{\gamma}}{2N\bar{\gamma}}\right)^m} \, {}_1F_1\Big(m; i+1; \frac{N\bar{\gamma}}{2m+2N\bar{\gamma}}\,\Lambda\Big) = \\ = \Gamma(m)\, 2^{m-1}\left(\frac{N\bar{\gamma}}{m+N\bar{\gamma}}\right)^m exp\left(-\frac{\Lambda}{2}\right) \sum_{i=1}^{N-1} \frac{1}{i!}\, {}_1F_1\Big(m; i+1; \frac{N\bar{\gamma}}{m+N\bar{\gamma}}\,\frac{\Lambda}{2}\Big). \end{aligned} \tag{5.22}$$

Alternatively, G_1 and G_M can be expressed as:

$$\begin{aligned} G_1 &= \frac{2^{m-1}\Psi(m-1)!}{\left(\frac{m}{M\bar{\gamma}}\right)^{m}} exp\left(-\Phi\frac{\Lambda}{2}\right)\left[\frac{\Phi^{m-1}}{\Psi}L_{m-1}\left(-\Phi\frac{\Lambda}{2}\right)+\sum_{k=0}^{m-2}\Phi^{k}L_{m-1}\left(-\Phi\frac{\Lambda}{2}\right)\right] \\ &\text{and} \\ G_M &= \Gamma(m)2^{m-1}\Psi^{m} exp\left(-\frac{\Lambda}{2}\right)\sum_{i=1}^{M-1}\frac{1}{i!}\left(\frac{\Lambda}{2}\right){}_1F_1\left(\frac{u+1}{2};i+1;\frac{b_1^2b_2^2}{2\left(v^2+b_1^2\right)}\right), \end{aligned} \tag{5.23}$$

with

$$\Psi = \frac{M\bar{\gamma}}{m+M\bar{\gamma}} \qquad \text{and} \qquad \Phi = \frac{m}{m+M\bar{\gamma}} \tag{5.24}$$

Consequently, the probability of detection for M decision samples of narrowband signals, with unknown amplitude and phase, in Nakagami-m channels, is

$$\begin{aligned} \bar{P_d} &= \frac{2}{\Gamma(m)}\left(\frac{m}{2N\bar{\gamma}}\right)^{m}\left(G_1+G_N\right) = \\ &= \frac{(m-1)!}{\Gamma(m)}\Psi\; exp\left(-\Phi\frac{\Lambda}{2}\right)\left[\frac{\Phi^{m-1}}{\Psi}\;L_{m-1}\left(-\Psi\frac{\Lambda}{2}\right)\;+\;\sum_{k=0}^{m-2}\Phi^{k}\;L_{k}\left(-\Psi\frac{\Lambda}{2}\right)\right]+ \\ &+\left(\frac{m}{M\bar{\gamma}}\right)^{m}\;\Psi^{m}\; exp\left(-\frac{\Lambda}{2}\right)\sum_{i=1}^{M-1}\frac{1}{i!}\left(\frac{\Lambda}{2}\right)\;{}_1F_1\left(m;i+1;\Phi\frac{\Lambda}{2}\right) \end{aligned} \tag{5.25}$$

The analysis of ROC provides a good perception for sensing capacity behavior of quadratic detector, under MMS primary users operating conditions. It is important to understand the performance sensibility, in terms of probability of miss detection ($P_{md} = 1 - P_d$) and P_{fa}, for variations in fading intensity, received SNR level and amount of processed samples, to design spectrum sensing schemes that can solve both sensing efficiency and interference avoidance problems. Specially because, in opportunistic systems, the sensing is one of the few variables that can be controlled by system designers.

In the following paragraphs, we present complementary ROC (P_{md} versus P_{fa}) for quadratic detector over Nakagami-m fading channels, for different fading intensity levels, SNR levels and amount of processed samples, and compare it with an energy detector, which ROC expressions are derived in [99]. Despite the obvious differences in detection process itself, energy detector can be considered as an interesting benchmark to appreciate the influence of sensing time, i.e. amount of processed samples, and anticipate the throughput impact, given that sensing cycle acts as an additional factor to decrease P_d. Hence, three scenarios have been defined and modeled through the shaping parameter m, as defined in Table 4.1.

The fading intensity is modeled through the parameter m of Nakagami PDF, which is computed based on Rice factor K. In Figure 5.5, it is presented a comparison of complementary ROC for energy and quadratic detectors over Nakagami fading, for different fading intensity levels. For a given SNR ($\bar{\gamma} = 12\text{dB}$) and a fixed number of processed samples ($N = 10$), the improvement afforded by the quadratic detector is more decisive when the reflected component of the received signal is less significant, and varies from more than one order of magnitude, in P_{md}, for Ricean fading, to almost four orders of magnitude for $m = 8$. On the other hand, in Ricean channels, for a given amount of processed samples, the higher the received signal energy (SNR), the better the performance, as one would expect and depicted in Figure 5.6.

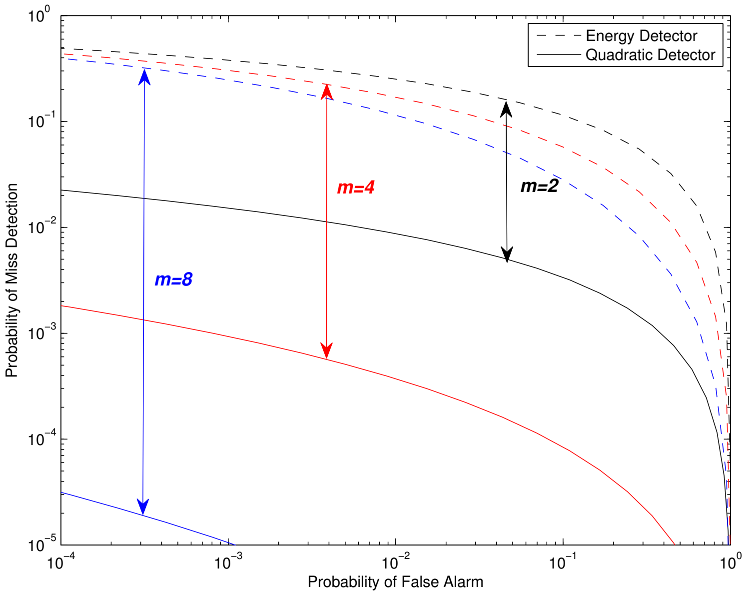

Figure 5.5: Complementary ROC curves for energy and quadratic detectors, for different sea conditions, i.e. fading intensity, considering a fixed number of processed samples ($N = 10$) and SNR = 12 dB.

Alternatively, one can address the effect of collected samples, for a fixed SNR, in the detector's performance. In Figure 5.7 , it is presented the complementary ROC for Ricean fading ($m = 2$), which corresponds to a scenario where a strong reflection in sea surface is captured by secondary sensor receiver. For a given SNR, the fewer the amount of collected samples, the better the performance of energy detector, while in the case of quadratic, the effect is other way around.

5.2.2 Diversity Gain Analysis

Conceptually, a CR-B-VHF network has a central cognitive engine that compiles and processes information collected by the cognitive nodes, then central management information is disseminated and operationally managed by each node. The radio picture would be centrally built, according to the information collected by each coastal station, where spectral usage can be associated to a location and, eventually, additional information that would help to estimate

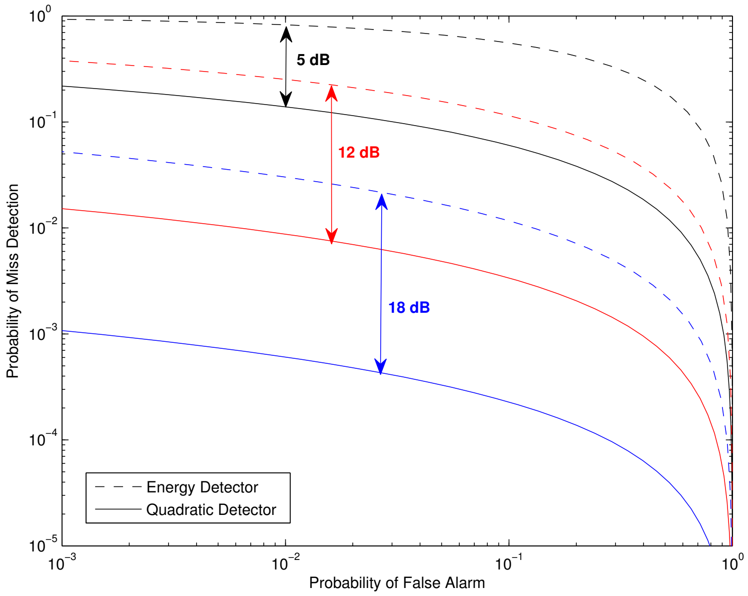

Figure 5.6: Complementary ROC curves for energy and quadratic detectors, for Ricean fading $(m = 2)$ and $N = 10$, considering different values SNR.

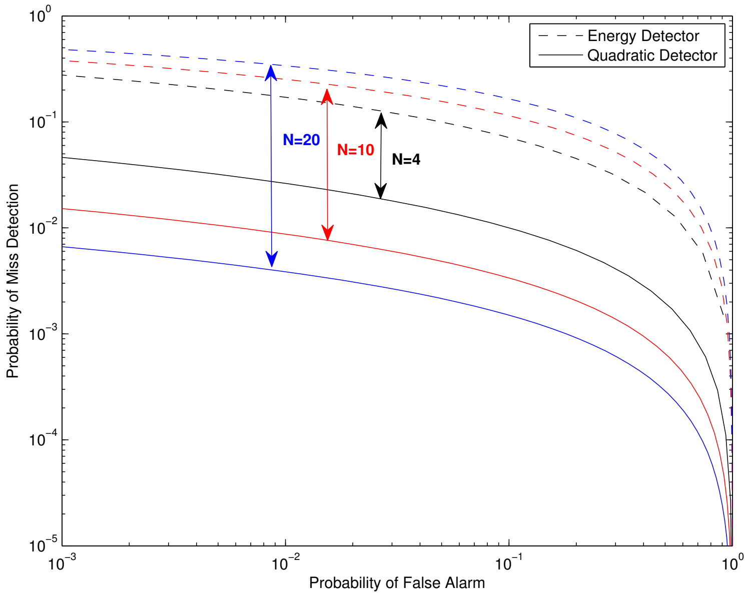

Figure 5.7: Complementary ROC curves for energy and quadratic detectors, for Ricean fading $(m = 2)$ and SNR=12dB, for different number of collected samples (N).

near future occupation of the associated band. Afterwards, according to the respective spectra opportunities and adjacent node usage, each network node would implement its own spectral usage plan, which results in its own local data rate.

Opportunistic networks would benefit from a combination of multiple received replicas of primary user emissions. The information redundancy, provided by antenna diversity (at same site and/or at distinct sites), is specially useful to mitigate the effects of multipath fading, exploiting the low probability of concurrent deep fades in the several diversity branches. The idea behind this concept is to take advantage of the signal information, received redundantly from more than one antenna, to increase the overall SNR. However, diversity gain depends on the cross correlation between branches, and is, naturally, upper bounded by the case of independent signals. In practice, insufficient antenna separation, due to space constraints in radio sites (VHF signal's wavelength $\sim$ 2 m), and a limited number of processed branches (due to the distance between coastal radio stations) are the main causes for diversity gain limitations. In fact, it is reasonable to consider that in real opportunistic systems each primary user would normally be detected by, at most, two stations and that a site will not possess more than two antennas. In any case, diversity deployment based on multiple co-site antennas or on interconnected radio stations, must be justified by a resulting significant improvement in detection performance. The break-even point is not easy to quantify, due to dynamic nature of maritime ecosystems, but this does not avoid the need for such a cost-benefit analysis.

Let us consider the case where the decision statistic is obtained by Square Law Combining (SLC) L diversity branches (further particularized for $L = 2$), and assumed slowly varying flat fading channels, where each replica of the signal is perturbed by AWGN with variance σ^2. Since the outcome of each quadratic detector branch (q_i) is a chi-square variable with $2N$ degrees of freedom [134], the SLC decision statistic

$$Q_{slc} = \sum_{i=1}^{L} q_i^2/\sigma^2 \tag{5.26}$$

is a chi-square with $2LN$ degrees of freedom and non-central parameter $\sum\limits_{i=1}^{L} 2N\gamma_i = 2N\gamma_t$. Hence, the probability of detection associated to a SLC, for AWGN, becomes:

$$P_{d_{slc}} = \mathcal{Q}_{LN}\left(\sqrt{2N\gamma_t}, \sqrt{\Lambda}\right). \tag{5.27}$$

The probability of detection over Nakagami channels can now be obtained by averaging (5.27) over the joint Nakagami PDF of instantaneous value γ_t:

$$\bar{P}_{d_{slc}} = \int\limits_{0}^{\infty} \mathcal{Q}_{LN}\left(\sqrt{2N\gamma_t}, \sqrt{\Lambda}\right) f_{\gamma_t}(\gamma_t) d\gamma_t \tag{5.28}$$

Unfortunately, obtaining the joint PDF of several paths in the case of different fading severities is not trivial. However, an alternative approach, based on Moment Generating Function (MGF), can provide, in some cases, a simple and elegant closed form solution for similar problems [133] by representing the Marcum Q-function [136], as a contour integral:

$$\mathcal{Q}_k(\alpha,\beta) = \frac{1}{2\pi j}\oint_{\Delta} \frac{exp\left[\frac{\alpha^2}{2}\left(\frac{1}{z}-1\right)+\frac{\beta^2}{2}\left(z-1\right)\right]}{z^k(1-z)}dz \tag{5.29}$$

Hence, the $P_{d_{slc}}$ can be rewriten as

$$\bar{P}_{d_{slc}} = \frac{e^{-\frac{\Lambda}{2}}}{2\pi j}\oint_{\Delta} \frac{e^{\frac{\Lambda}{2}z}}{z^{LN}(1-z)}\Big[\int\limits_0^{\infty} e^{(\frac{N}{z}-N)\gamma_t} f_{\gamma_t}(\gamma_t)d\gamma_t\Big]dz \tag{5.30}$$

where the MGF of the output γ_t is represented by

$$M_{\gamma_t}(s) = \int\limits_0^{\infty} e^{-s\gamma_t} f_{\gamma_t}(\gamma_t)d\gamma_t. \tag{5.31}$$

Consequently, the probability of detection of a primary signal affected by AWGN over Nakagami fading channels, processed through L different branches of N samples each, and combined as mentioned, is given by

$$\bar{P}_{d_{slc}} = \frac{e^{-\frac{\Lambda}{2}}}{2\pi j}\oint_{\Delta} \frac{e^{\frac{\Lambda}{2}z}}{z^{LN}(1-z)} M\left(\frac{N}{z}-N\right)dz. \tag{5.32}$$

Let us now apply this general solution to two typical cases.

L i.i.d. Nakagami Channels

This is the case where antennas are sufficiently far apart (site diversity or antenna diversity) to guarantee uncorrelated fading between branches. This scenario is most easily found in the case of site diversity, due to typical space and implementation constraints of multiple antennas in the same radio site. This uncorrelated branches case provides an upper bound for diversity gain. The PDF for L i.i.d. Nakagami branches is similar to (5.25), with mL replacing m, $L\bar{\gamma}$ instead of $\bar{\gamma}$ and NL instead of N. Hence,

$$\bar{P}_{d_c} \;=\; \bar{P}_{d_{multipulse}}, \qquad \begin{cases} m \;=\; L \\ \bar{\gamma} \;=\; L\,\bar{\gamma} \\ N \;=\; L\,N \end{cases} \tag{5.33}$$

$$\begin{aligned} \bar{P}_d = \frac{(L-1)!}{\Gamma(L)}\,\Psi\; exp\left(-\Phi\frac{\Lambda}{2}\right)\left[\frac{\Phi^{L-1}}{\Psi}\;L_{L-1}\Big(-\Psi\frac{\Lambda}{2}\Big)\;+\;\sum_{k=0}^{L-2}\Phi^k\;L_k\Big(-\Psi\frac{\Lambda}{2}\Big)\right]+ \\ +\left(\frac{L}{L\,N\bar{\gamma}}\right)^L\;\Psi^L\;exp\left(-\frac{\Lambda}{2}\right)\sum_{i=1}^{L\,N-1}\frac{1}{i!}\;\left(\frac{\Lambda}{2}\right)\;{}_1F_1\Big(L;i+1;\Phi\frac{\Lambda}{2}\Big) \end{aligned} \tag{5.34}$$

with

$$\Psi = \frac{M\bar{\gamma}}{L+L^2\,N\bar{\gamma}} \qquad \text{and} \qquad \Phi = \frac{L}{L+L\,N\bar{\gamma}} \tag{5.35}$$

In the considered case of $L = 2$, the performance is equivalent to a single antenna, with reduced fading and increased received SNR, both by a factor of 2, as:

$$\begin{aligned}\bar{P_d} = \frac{(L-1)!}{\Gamma(L)}\,\Psi\, exp\left(-\Phi\frac{\Lambda}{2}\right)\left[\frac{\Phi^{L-1}}{\Psi}\,L_{L-1}\left(-\Psi\frac{\Lambda}{2}\right) + \sum_{k=0}^{L-2}\Phi^{k}\,L_{k}\left(-\Psi\frac{\Lambda}{2}\right)\right]+ \\ + \left(\frac{L}{L\,N\bar{\gamma}}\right)^{L}\Psi^{L}\,exp\left(-\frac{\Lambda}{2}\right)\sum_{i=1}^{L\,N-1}\frac{1}{i!}\left(\frac{\Lambda}{2}\right)\,{}_1F_1\left(L;i+1;\Phi\frac{\Lambda}{2}\right)\end{aligned} \tag{5.36}$$

with

$$\Psi = \frac{L\,N\bar{\gamma}}{L + L^2\,N\bar{\gamma}} \qquad \text{and} \qquad \Phi = \frac{L}{L + L\,N\bar{\gamma}} \tag{5.37}$$

Two Correlated Branches with Nonidentical Fading

The scenario of two correlated branches with nonidentical fading corresponds to dual diversity reception over correlated Nakagami-m channels. This is a typical situation of antenna diversity in a radio site, with insufficiently separation. Using (5.27) and the Moment Generating Function (MGF) of the combined SNR variable [133]:

$$M(s) = \left[1 - \frac{\bar{\gamma_1} + \bar{\gamma_2}}{m}s + \frac{((1-\rho)\bar{\gamma_1}\bar{\gamma_2}}{m^2}s^2\right]^{-m}, \tag{5.38}$$

where $\bar{\gamma_1}$ and $\bar{\gamma_2}$ represent the average received SNR in each branch and ρ represents the correlation factor between branches, and since

$$M\left(\frac{N}{z} - N\right) = \left[\frac{m^2z^2}{Az^2 - Bz + C}\right]^{m}, \tag{5.39}$$

where:

$$\begin{aligned} A &= m^2 + 2m(\bar{\gamma_1} + \bar{\gamma_2} + 4\bar{\gamma_1}\bar{\gamma_2}(1-\rho) \\ B &= 2m(\bar{\gamma_1} + \bar{\gamma_2}) + 8\bar{\gamma_1}\bar{\gamma_2}(1-\rho) \qquad , \\ C &= 4\bar{\gamma_1}\bar{\gamma_2}(1-\rho) \end{aligned} \tag{5.40}$$

The probability of detection can be written as,

$$\bar{P}_{d_{slc}} = \frac{m^{2m}e^{-\frac{\Lambda}{2}}}{2\pi j}\oint_{\Delta} f(z)dz. \tag{5.41}$$

By Cauchy's Residue Theorem,

$$\oint_{\Delta} f(z)dz = 2\pi j\sum_{r=1}^{n} Res(f, z_r), \tag{5.42}$$

$f(z)$ can be expressed as

$$f(z) = \frac{e^{\frac{\Lambda}{2}z}}{(z-\theta_0)^m(z-\theta_1)^m z^{2(N-m)}(1-z)}. \tag{5.43}$$

Since, in practical terms, $N-m \geq 0$, the contour integral in (11) contains m order poles at θ_0 and θ_1, and $2(N-m)$ poles at the origin, which corresponds to a residue function representation of

$$\bar{P}_{d_{slc}} = m^{2m} e^{-\frac{\Lambda}{2}} \big[Res(f,\theta_0) + Res(f,\theta_1) + Res(f,0)\big] \tag{5.44}$$

where, $Res(f,\theta_0)$, $Res(f,\theta_1)$ and $Res(f,0)$ can be represented, respectively, as

$$\begin{aligned} Res(f,\theta_0) &= \lim_{z\to\theta_0} \frac{1}{(m-1)!} \frac{d^{m-1}}{dz^{m-1}} \Big(\frac{e^{\frac{\Lambda}{2}z}}{(z-\theta_1) z^{2(N-m)} (1-z)} \Big) \\ Res(f,\theta_1) &= \lim_{z\to\theta_1} \frac{1}{(m-1)!} \frac{d^{m-1}}{dz^{m-1}} \Big(\frac{e^{\frac{\Lambda}{2}z}}{(z-\theta_0) z^{2(N-m)} (1-z)} \Big) \\ Res(f,0) &= \lim_{z\to 0} \frac{1}{(2(N-m)-1)!} \frac{d^{2(N-m)-1}}{dz^{2(N-m)-1}} \Big(\frac{e^{\frac{\Lambda}{2}z}}{(z-\theta_0)(z-\theta_1)(1-z)} \Big) \end{aligned} \tag{5.45}$$

Two Identically Distributed Branches with Constant Correlation

The MGF for D identically distributed branches with constant correlation is presented in [133], as

$$M(s) = \Big(1 - \frac{\bar{\gamma}(1-\sqrt{\rho}+D\sqrt{\rho})}{m} s\Big)^{-m} \Big(1 - \frac{\bar{\gamma}(1-\sqrt{\rho})}{m} s\Big)^{-m(D-1)} \tag{5.46}$$

Considering $D = 2$ for the case of two antenna diversity in a radio station site, the required MGF become:

$$M\left(\frac{N}{z} - N\right) = \frac{\Omega}{z^{-2m}(z-\theta_0)^m (z-\theta_1)^m} \tag{5.47}$$

where:

$$\begin{aligned} \Omega &= \Big[\frac{m^2}{m^2 + 2mN\bar{\gamma} - N^2\bar{\gamma}^2(\rho-1)}\Big]^m \\ \theta_0 &= \frac{N\bar{\gamma}(1+\sqrt{\rho})}{m + N\bar{\gamma}(1+\sqrt{\rho})} \\ \theta_1 &= \frac{N\bar{\gamma}(1-\sqrt{\rho})}{m + N\bar{\gamma}(1-\sqrt{\rho})} \end{aligned} \tag{5.48}$$

Therefore, the probability of detection can be written as,

$$\bar{P}_{d_{slc}} = \frac{\Omega e^{-\frac{\Lambda}{2}}}{2\pi j} \oint_{\Delta} f(z) dz \tag{5.49}$$

Based on Cauchy's Residue Theorem,

$$\oint_{\Delta} f(z) dz = 2\pi j \sum_{r=1}^{n} Res(f, z_r) \tag{5.50}$$

Hence $f(z)$ can be expressed as

$$f(z) = \frac{e^{\frac{\Lambda}{2}z}}{(z-\theta_0)^m (z-\theta_1)^m z^{2(N-m)}(1-z)} \tag{5.51}$$

Since $N - m \geq 0$, the contour integral in (11) contains m order poles at θ_1 and θ_1, and $2(N-m)$ poles at origin, which corresponds to a residue function representation of

$$\bar{P}_{d_{slc}} = \Omega e^{-\frac{\Lambda}{2}} \left[Res(f,\theta_0) + Res(f,\theta_1) + Res(f,0) \right] \tag{5.52}$$

5.2.3 Diversity Advantages

Naturally, real maritime VHF systems would take advantage of diversity, even considering potential restrictions to dual branches ($L = 2$), if that would bring detection benefits. The point is that detection capacity gains must overcome diversity implementation and processing costs. In other words, an installation of multiple antennas in a radio station or a data link between radio stations, with their associated imbroglio, must represent a significant improvement in detection performance, otherwise it is an absurd. Obviously, the break-even point is not easy to quantify, due to randomness nature of maritime ecosystem, namely primary users activity profiles and the need for periodic sensing, which are key variables in the detection efficiency equation.

On the other hand, one cannot expect to envisage detection performance requirements through a simple analysis of P_d. Although major cause of disturbances in performance of primary systems is due to inaccuracy in opportunistic system's spectrum sensing process, its effects are a function of incumbent's activity characteristics, ROC and service operating requirements. The probability of miss detection, which results in secondary transmission during incumbents operation with consequences in SNIR and eventually in primary service outage, is not only dependent on detector's ROC, but also on sensing cycle time. Therefore, the intended comparison analysis has to be performed in relative terms and order of magnitude. In other words, the diversity gain has to be seen as a tendency, instead of an absolute value.

In Figure 5.8, a complementary ROC is presented, for different levels of correlation between processed diversity branches (the arrows represent fading intensity variation, from $m = 2$ to $m = 4$). As expected, performance is upper and lower bounded by the i.i.d branches and no-diversity cases, respectively. However, there is an interesting phenomena of performance tendency inversion, for lower values of P_{fa}, when the correlation is higher. Specifically, for lower fading intensity, the performance of SLC for $\rho = 0.6$ is worst then in no-diversity case. This event can be better perceived in Figure 5.9, where the degradation in detector's performance became abrupt, for slight increases in branches correlation, in the vicinity of $\rho = 0.5$, for $m = 8$ and around $\rho = 0.6$, for $m = 2$ and $m = 4$. This information might be important for correlation threshold delimitation in diversity deployment decision making.

The fading intensity is modeled through the shaping parameter m of Nakagami-m PDF, for the three scenarios defined in Table 4.1. In Figure 5.8, it is presented a comparison of complementary ROC for energy and quadratic detectors over Nakagami fading, for different fading intensity levels. For a given SNR ($\bar{\gamma}$) and amount of processed samples ($N = 10$), the improvement of quadratic detector is more decisive when the reflected component of received signal is less significant and goes from more than one order of magnitude, in P_d, for Ricean fading, to almost five orders of magnitude for Nakagami $m = 8$.

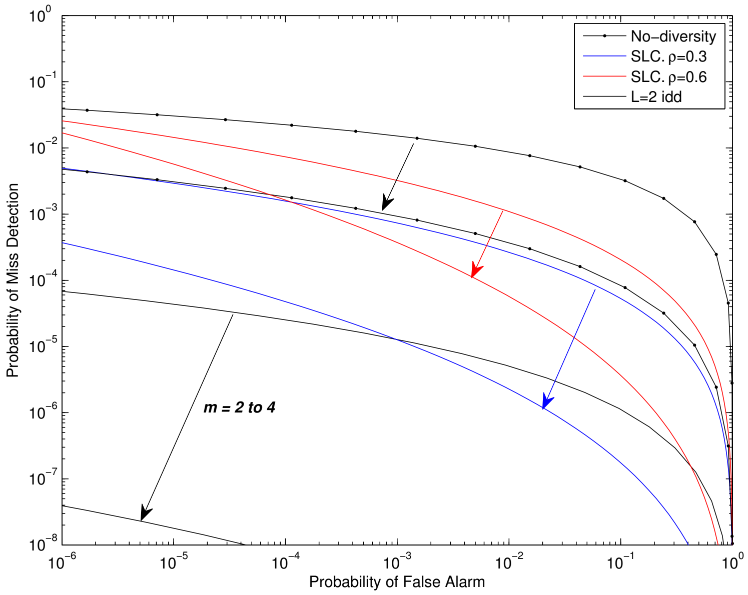

Figure 5.8: Complementary ROC curves comparison for different diversity techniques, considering different fading severity values, $N = 10$ and SNR=12 dB.

Alternatively, it is analyzed the effect of the collected samples, for a fixed SNR, in the detector performance. In Figure 5.10, it is presented the complementary ROC for Ricean fading ($m = 2$), which corresponds to a scenario where a strong reflection in sea surface is captured by secondary sensor receiver. For a given SNR, the fewer the amount of collected samples, the better the performance of energy detector, while in the case of quadratic, the effect is other way around.

Finally, Figure 5.11 presents the dependency on SNR. As expected, higher SNR correspond to better detection capacity.

5.3 Sensing Cycle Optimization

Despite Shannon considerations and channels availability, performances of HDS based solutions are conditioned by accuracy of data and models that have been used in optimization solution. The estimation of primary channels availability characteristics is critical for optimization problem resolution, to determine the most favorable parameters t_{sens}, t_{blind} and Λ. Additionally, the amount of required samples (N) and considered threshold (Λ) are system parameters that conditionate the P_d and P_{fa} and consequently the overall performance.

The signal detector and channel model definition have a significant impact on overall solution, since they are important inputs for sensing cycle problem. The imperfections on spectrum availability evaluation may result in supplementary constraints, on achievable capacity, which are not caused by primary activity itself, but by misapprehension of channel conditions. There are different factors that might result in errors on channel availability estimation, most of them related to signal detector, and its associated ROC, and channel modeling.

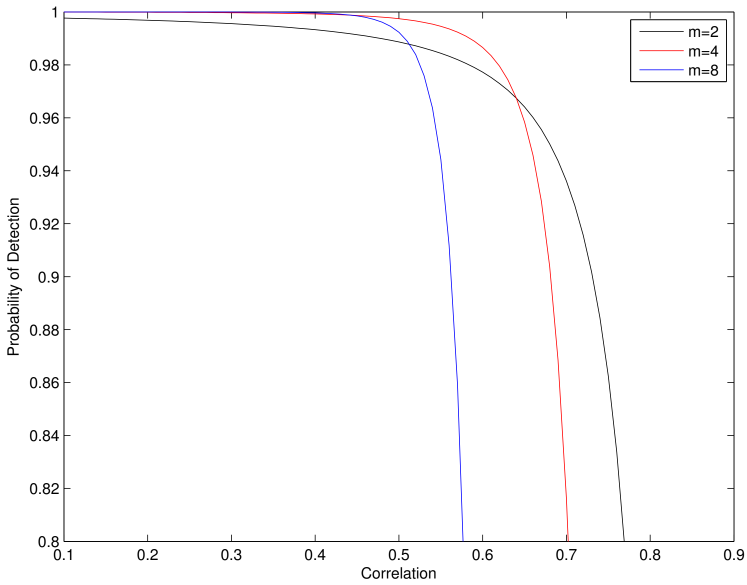

Figure 5.9: Dependency of P_d on correlation (ρ) of processed branches, for different fading intensity. It is assumed a diversity for $L = 2$, $N = 10$ and SNR=12dB.

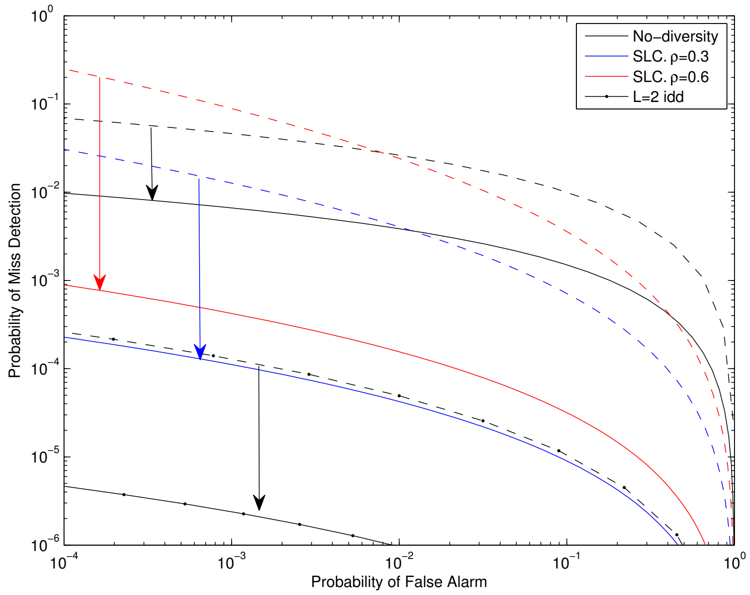

Figure 5.10: Dependency on on number of collected samples of complementary ROC curves of quadratic detectors for different diversity conditions. Assuming Rician fading and SNR=12dB, the arrows point the behavior of detection performance when N goes from 4 to 20 processed samples.

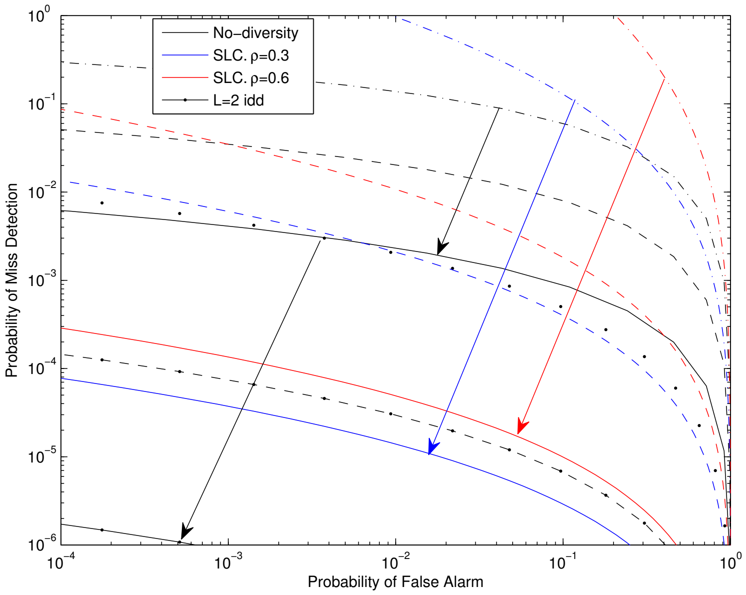

Figure 5.11: Dependency on SNR of complementary ROC curves of quadratic detectors for different diversity conditions. Assuming Rician fading and $N = 10$, the arrows point the behavior of detection performance when SNR goes from 5 to 10 and further to 15 dB.

Incumbent's activity profile statistics became even more relevant for simultaneous opportunistic operation in multiple non-contiguous channels. For a given number of channels, there are many possible combination values of β, P_c, P_{on}, P_{off} and primary received SNR, all of which may result in different performances. Prior information on incumbent's services occupancy statistics, and its invariability over time, are critical for the "optimality" of provided solution, since opportunistic system cannot detect any emissions, while it is transmitting. During this period, primary services would be interfered and eventually disrupted, if channel availability statistics and dynamics are not taking into account on sensing cycle design.

In the following section we address sensing cycle optimization problem from two perspectives. Firstly, it is considered an opportunistic usage of a single 25KHz channel, which is scarce for an CR-B-VHF network, but allows an analysis of fundamental characteristics of HDS and sensing cycle design for contiguous (wider) spectrum. Secondly, it is assumed a multiple channels aggregation, where each channel incumbents has their own activity profiles.

5.3.1 Single 25kHz Channel

The analysis of an opportunistic usage of a single 25 kHz channel can provide a good awareness for potential throughput and an interesting perception for optimization process variables. Performance is a function of multiple variables, where primary services characteristics, channel model and sensing design play an important role.

Considering that sensing cycle optimization is a multidimensional problem, it is difficult to perform a generic analysis and impossible to plot all variable dependencies. Essentially, optimization problem involves the following variables: ROC, which includes P_d, P_{fa}, Λ, N, m and received SNR; primary services activity profiles, which includes P_{off} and β; P_c; and secondary received SNR (associated to achievable capacity). Obviously, it is required to assume specific values, in many dimensions, to investigate dependencies on two or three other variables and try to infer general performances.

The following exercise intend to obtain optimal parameters for periodic sensing for a 25kHz channel, which maximum allowable P_c is 1%, primary received signal is SNR = 10dB and sampling rate of 1 Mega samples per second (Msps), and an order of magnitude for effective achievable capacity (C_{eff}), as a function of channel availability (P_{off}) and primary service transmission rate (β), for two values of capacity obtained during simultaneous transmission of CR and a primary user.

The C_{eff} can be normalized by single channel achievable capacity, assuming that simultaneous transmission results in a fraction of capacity η, as:

$$\hat{C}_s = \frac{C_s}{C_0} \text{ and } \frac{C_1}{C_0} = \eta \tag{5.53}$$

.

Hence, normalized capacity becomes:

$$\bar{C}_{eff} = \frac{t_T}{t_T + t_s}\left[P_{off}(1 - P_{fa}) + P_{on}(1 - P_d)\eta\right] \tag{5.54}$$

Under these conditions, we can compute optimal parameters for sensing cycle, i.e. t_{sens} and t_T, as a function of P_{off} and β, over a Ricean channel (m =2). Figure 5.12 depicts obtained sensing times t_{sens} values, while Figure 5.13 shows the values for t_T. As expected, sensing time is barely affected by β, but decreases as P_{off} increases. Given that t_{sens} is proportional to N and detection capacity is related with the amount of processed samples, for a given service interference tolerance, when the probability of primary users operation requires low probability of detection. On the other hand, transmission times decrease exponentially with increasing of primary services transmission rate increases and P_{off}. The former effect is intuitive, since high primary transmission duty cycles would require smaller opportunistic blind periods, to ensure interference requirements, but later consequence is not that obvious. For the value of β, high values of P_{off} would represent higher probability of a primary user start to transmit during a blind period, which demands for a t_T decreasing, in order to fulfill defined P_c.

5.3.2 Multiple Channels Aggregation

In the case of combined opportunistic usage of multiple non-contiguous channels, optimization problem is far more complex. The accuracy-throughput trade-off is complemented with additional compromises, due to different activity profiles of considered channels. Different spectral bands have different optimal sensing cycles, so an optimal combined use of multiple channels would necessarily results in multiple suboptimal operation.

Therefore, optimization problem has to be redefined to include aggregate operation of multiple channels. Assuming a wideband sensing scheme, as represented in Figure 5.3, optimization solution would provide values of t_T, t_{sens}, for a single sensing cycle, and individual

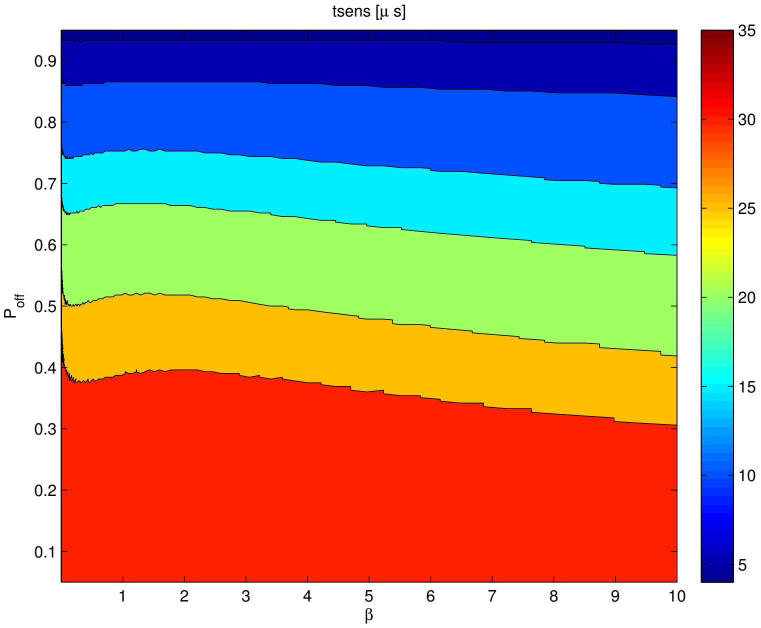

Figure 5.12: Sensing time (t_{sens}) in μs, as a function of P_{off} and transmission rate (β), for a Quadratic Detector in Ricean channel, for a received SNR = 10 dB. It is assumed Pc of 1% and a sampling rate of 1 Msps.

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detection thresholds (Λ_i) for all considered channels, which maximize spectrum usage efficiency. Naturally, required compromises to setup a common sensing cycle, in order to maximize overall performance, would result in a reduction on individual channels usage efficiency.

Hence, optimization problem has to incorporate each individual channel constraints in order to obtain minimum t_T that would fulfil all requirements, which can be formulated as:

$$t_{T_i} \leq -\frac{1}{\beta_i} \ln \big[1 - \frac{P_c - P_{on_i}(1 - P_{d_i})}{P_{off_i}(1 - P_{fa_i})}\big]. \tag{5.55}$$

Consequently, t_T has to be selected, from values that maximize capacity, by

$$t_T = min(t_{T_i}). \tag{5.56}$$

The result is an objective function, formulated as follows:

$$\max_{t_T, t_s, \Lambda_i} C_{s_{eff}} = \frac{t_T}{t_T + t_{sens}} \sum_{i=1}^{M} C_{s_i}(\Lambda_i), \tag{5.57}$$

where $C_{s_i}(\Lambda_i$ represents the achievable capacity of each channel, considering individual threshold values (Λ_i).

Again, due to multiple dimension of this problem, we present an analysis based on a specific case of multiple channels aggregation. It is assumed a set of seven channels with arbitrary P_c and primary users activity profiles, which are detected at secondary receiver with an aleatory SNR. The objective is to determine individual optimal parameters and correspondent values

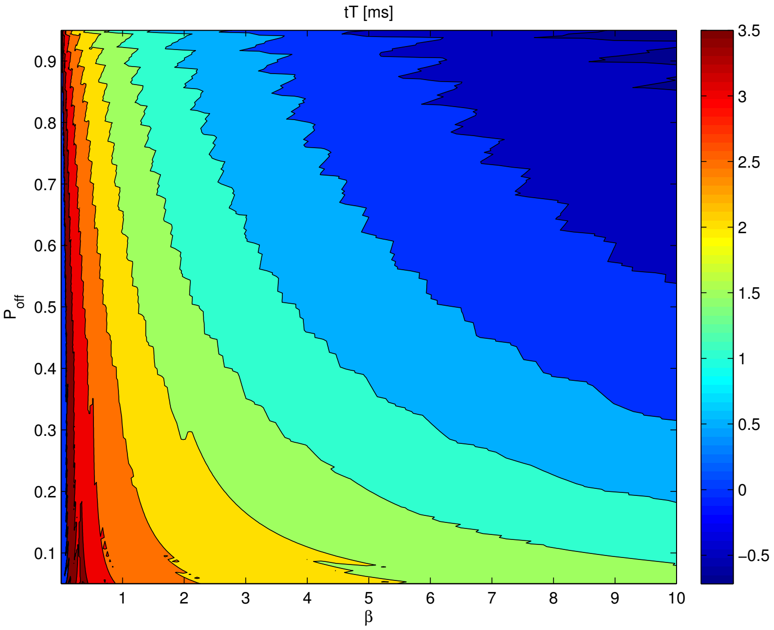

Figure 5.13: Transmission time (t_T) in ms, as a function of P_{off} and transmission rate (β), for a Quadratic Detector in Ricean channel, for a received $SNR = 10dB$. It is assumed Pc of 1% and a sampling rate of 1 Msps.

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in an aggregated situation and address differences and lost capacity associated to required compromises.

In Table 5.1 it is presented the individual characteristics of each one of considered channels and the optimal parameters for its opportunistic exploitation (t_{sens}, t_T and Λ) and its associated achievable capacity. Additionally, it is showed the optimal parameters for their aggregate opportunistic exploitation, which has different values, and the achievable performance that is slightly lower (98.62%).

Apparently, despite differences in sensing cycle parameters, combined capacity of an opportunistic usage of multiple channels, with different characteristics, is equivalent to a summation of individual (optimal) performances. In fact, that is the case for ideal operation, since sensing times are negligible, when compared with t_T. However, multiple channel aggregation becomes difficult to manage for small discrepancies introduced in each of the channels characteristics. Eventually, the impact would be on primary services disruption probability.

5.3.3 Estimation for an Arbitrary Aggregation Channels

The performance evaluation of opportunistic systems requires more than particular cases analysis. It is important to have a perspective of general behavior of certain figures of merit, even in approximate way, and a sense of achievable capacity of an arbitrary aggregation of channels. The multiple dimension of problem is obviously a limitation, but it would be important to have a mean to estimate C_{eff}, based on simple data on eligible channels, as the considered amount of channels and their average P_{off}. Despite the simplicity, and associated

Table 5.1: Sensing Parameters for Seven Channel Aggregation

	P_{off}	β	P_c	SNR [dB]	t_{sens} [μ s]	t_T [m s]	Λ	$\bar{C}_{eff}$
Ch.1	0.9	1	1%	8	16	5.189	65.5	0.897
Ch.2	0.8	2	5%	12	2	3.266	30	0.804
Ch.3	0.7	3	2%	10	10	3.71	48	0.699
Ch.4	0.6	3.5	10%	14	2	2.306	48.5	0.609
Ch.5	0.7	4	3%	10	6	3.006	35	0.7
Ch.6	0.2	8	1.5%	8	40	3.167	117	0.198
Ch.7	0.4	6	2%	13	6	2.586	36	0.4
Aggregation	0.9	1	1%	8	30	2.428	106.5	4.248 (98.62%)
	0.8	2	5%	12	30	2.428	120	
	0.7	3	2%	10	30	2.428	111	
	0.6	3.5	10%	14	30	2.428	120	
	0.7	4	3%	10	30	2.428	120	
	0.2	8	1.5%	8	30	2.428	88.5	
	0.4	6	2%	13	30	2.428	36	

errors, this kind of achievable capacity estimation can provide interesting indications for feasibility analysis purposes and benchmarks for spectrum sensing design.

Simulation and parametric nonlinear regression models can assist a search for a closed form expression to estimate C_{eff}. In this kind of regression analysis, a set of simulated data, for random combinations of MMS channels with aleatory amount of channels and activity profiles, are modeled by a function that is a nonlinear combination of model parameters and depends on a minimum amount of independent variables. The data is fitted by a method of successive approximations that uses non-linear model and least squares. Naturally, such approach has associated errors, which can be impracticable for some analysis, but would provide an order of magnitude, when field information is scarce. The idea is to obtain a set of optimal parameters, and their correspondent performance values, for a significant number of trials and use a parametric nonlinear regression model to fit the data (C_{eff}) with a reasonable number of predictor variables.

Initially, it has been assumed an operating scenario and used Monte Carlo simulation to obtain optimal normalized achievable capacity ($\hat{C}_{eff}$), while randomly assign availability parameters (P_{off}), transmission rates (β) and maximum probability of collision (P_c) to each one of eligible channels. Afterwards, it has been used a parametric nonlinear model to represent the relationship between $\hat{C}_{eff}$ and predictor variables (amount of channels and their average P_{off}), following a typical work-flow: import data, fit a nonlinear regression, test its quality, modify it to improve the quality, and make predictions based on the model.

Simulation and Data Fit

The considered data should consist of error-free independent variables (explanatory variables), x, and their associated observed dependent variables (response variables), y. If the problem has many independent variables, it might not be feasible, nor necessarily provides any added value, to model dependent variables as a function of all independent variables. The focus has to be on a subset of independent variables that might be able to explain a significant amount of variation in dependent variable. In other words, one should select the opportunistic systems context elements that explain a significant amount of variation in y.

Hence, the starting point has been a set of simulation trials, using quadratic detector in Nakagami $m = 2$ channels, to obtain solutions for sensing efficiency problem that would provide a relationship between $\bar{C}_{eff}$ and:

- Summation of all channels P_{off};
- Average probability P_{off};
- Standard deviation of P_{off}.

Monte Carlo simulations have been performed assuming normalized capacity for an amount of 25 KHz channels up to 300 and $\eta = 0.1$; primary services characteristics within the following intervals: $P_{off} = [0.5 \;\; 0.95]$, $\beta = [0.1 \;\; 1.2]$ and $Pc = [0.01 \;\; 0.1]$; average primary users received SNR= 10 dB and sampling rate of 1 Msps.

Afterwards, a parametric nonlinear regression model is used to fit the data, due to its capacity to represent the relationship between a continuous response variable and one or more continuous predictor variables in the form:

$$y = f(X, B) + \epsilon, \tag{5.58}$$

where: y represents observations of response variable; f is a function of X and B that evaluates X along with vector b to compute prediction for the corresponding y; X represents predictors; B represents unknown parameters to be estimated; and ϵ represents independent, identically distributed random disturbances.

Hence, it was considered the following response function:

$$\hat{C}_{eff} = \frac{b_1 \; M}{E\big[P_{off}\big]^{b_2}} \tag{5.59}$$

where $E[.]$ represents expected value operator and M is the number of considered channels. Afterwards, a data fit process has been computed in MATLAB, producing the estimated coefficients b_i, and its associated error statistics, presented in Table 5.2.

b(i)	Estimated Coefficient	SE	tStat	pValue
b1	0.262476	0.0001199	2188.15815	0
b2	0.923763	0.0006202	1489.46347	0

Table 5.2: Estimated Coefficients for Quadratic Detector in Ricean Channels

In spite of expression simplicity and limited amount of independent variables, data fit process present interesting error statistics, which can be summarized in the following metrics: Standard Error (SE), "t" statistic (*tStat*) and pValue.

The SE of the model is the estimated standard deviation of the errors, apart from the degrees of freedom adjustments. It represents the average distance that the observed values fall from the regression line, so it provides an overall measure of how well the model fits the data. Therefore, small values of SE represent observed values cluster fairly closely to the regression line, which is the case, as observed in Table 5.2.

The *tStat* is computed by dividing the estimated value of the parameter by its SE and can seen as a measure of precision for regression coefficient. The larger the absolute value of tStat, the less likely actual value of the parameter could be zero. Again, presented values are quite decent.

Finally, *pValue* indicates the probability that a coefficient is *not* statistically significant. It is obtained by comparison of *tStat* with values in the Student's t distribution, which describes how the mean of a sample, with a certain number of observations, is expected to behave. In this case, small values (zero) of pValue means that variable really influences dependent variable (C_{eff}).

Additionally, there are further metrics that allow us to measure how strongly each independent variable is associated with C_{eff}. The results of data fitting process, presented in Table 5.3, provide important indications regarding errors and estimation capacity of presented function.

	Quadratic Detector
Initiating vector	[0.1 1 0.5]
Number of observations	26276
Error degrees of freedom	26274
Root Mean Squared Error	0.206
R^2	0.988
Adjusted R^2	0.988
F-statistic vs. zero model	2.04e+08
p-value	0

Table 5.3: Simulation results for Nakagami-$m = 2$

The root mean squared error is a residual standard error, which indicates roughly the average difference between C_{eff} values of individual observations and predictions of C_{eff} based on regression. Hence, the value of 21%, presented in Table 5.3, indicates an interesting accuracy on prediction capacity of (5.59), taking into consideration that the objective is to have an order of magnitude.

On the other hand, R^2 indicates the amount of variance of C_{eff} that is explained by independent variables. It measures how well the regression model fits the data, so it is an important metric to take into consideration when regression equation is used to make accurate predictions. In this case, obtained results are even more encouraging, since 98.8% of C_{eff} is explained by M and $E[P_{off}]$.

Finally, adjusted R^2 gives the percentage of variation explained by only those independent variables that in reality affect the dependent variable. As expected, all the considered independent variables contribute for C_{eff} variations.

Model Diagnostics

Regression diagnostics are methods for determining whether a regression model fit to data adequately represents the data. Normally, procedures involve both graphical and formal statistic tests to evaluate the assumptions of regression and are crucial to avoid faulty conclusions on examination of quality and adjust of fitted nonlinear model [137]. There are several methods and numerical tests to assess the overall impact of an observation on the regression results [137], addressing the following: unusual and influential data, heterosckedasticity and multicollinearity.

The unusual and influential data correspond to single observations that are substantially different from the others, which can have a significant impact on regression analysis results. There are three different kind of such data [137]:

- Outliers: observation with large residual, i.e. an observation whose dependent-variable value is unusual given its values on the predictor variables. It might indicate a sample peculiarity or may indicate a data entry error or other problem;
- Leverage: observation with an extreme value on a predictor variable, i.e. observation that is far from the mean of that variable. These points can have an effect on the estimate of regression coefficients.
- Influence: observation that substantially changes the estimate of coefficients if it is removed.

Partial leverage plots are an attempt to isolate the effects of a single variable on the residuals [138]. The leverage provides a sense of distance associated to observations, and it measures measure of how far an independent variable deviates from its mean. In Figure 5.14 it is presented a leverage plot for considered data fit process, which, despite a single point, does not show any significant diversion. Hence, it is useful to take a look on Cook's distance plot to investigate if it is worth to remove it from the model.

Cook's distance is a commonly used estimate of the influence of a data point when performing least squares regression analysis. In a practical ordinary least squares analysis, Cook's distance can be used in several ways: to indicate data points that are particularly worth checking for validity; to indicate regions of the design space where it would be good to be able to obtain more data points. In this case, Cook's distance plot, presented in Figure 5.17, show that diversed point is not significant enough to be excluded.

The objective of finding a expedited procedure to estimate an order of magnitude of achievable capacity, of an opportunistic system that uses HDS to take advantage of MMS assigned channels, has been achieved. The proposed function (5.59) has a significant root mean squared error (20%), associated to the obtained predictions, but has a decent capacity to estimate capacity, based on the amount of considered channels and their average P_{off}. This interesting analysis tool can be useful in different domains.

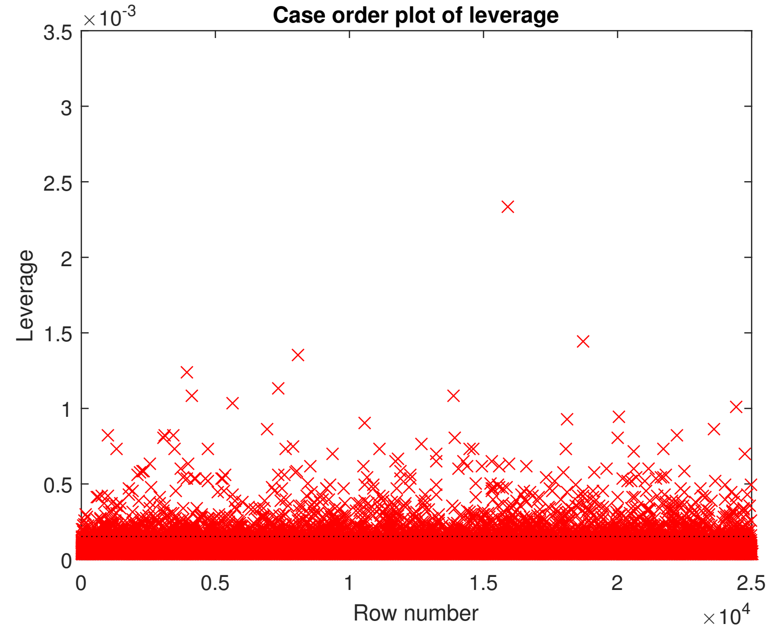

Figure 5.14: Leverage plot.

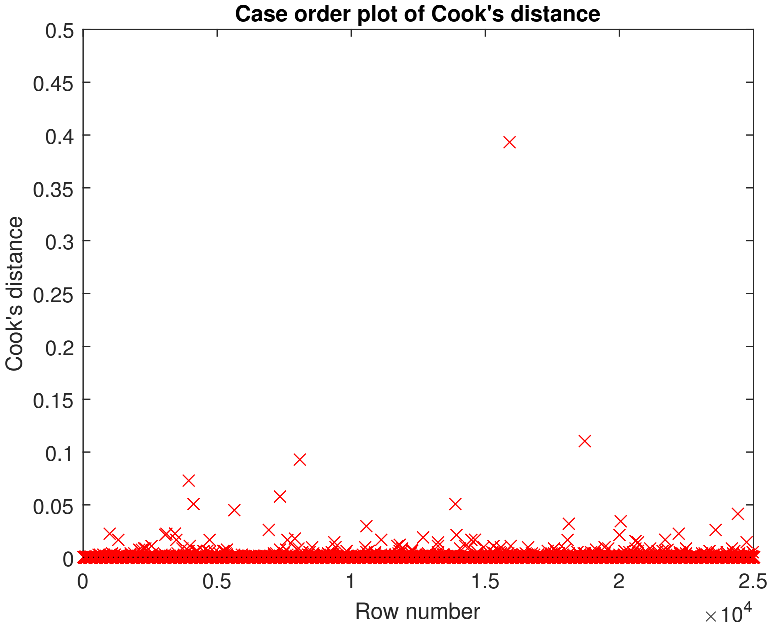

Figure 5.15: Cook's distance plot.

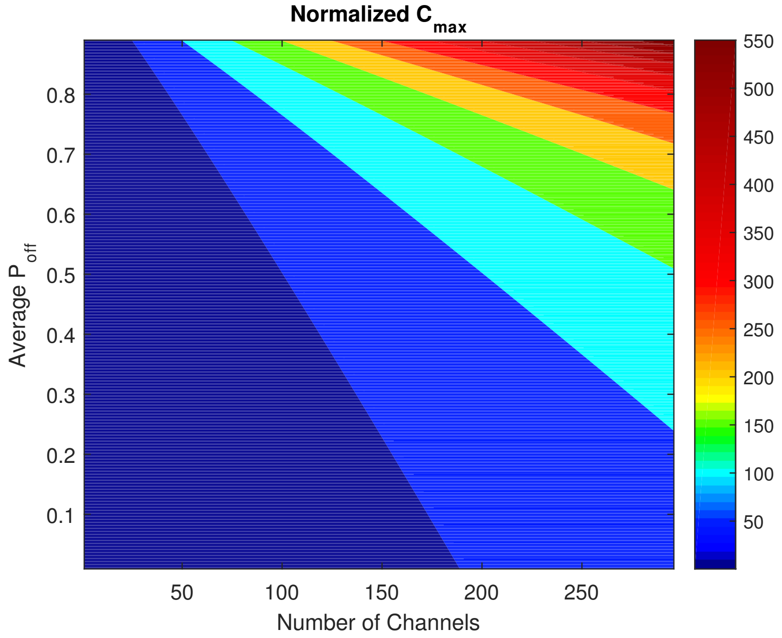

Figure 5.16: Estimated order of magnitude of envisage normalized capacity, for a opportunistic system that uses HDS to take advantage of MMS assigned channels, based on the amount of considered channels and their average P_{off}.

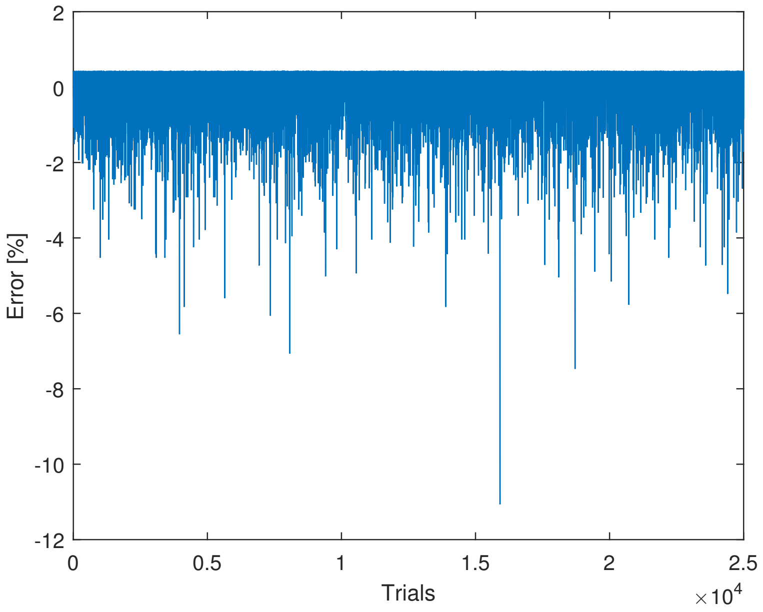

Figure 5.17: Estimated prediction errors for envisaged performance.

5.4 Concluding Remarks

The spectrum exclusive access of primary users requires that opportunistic systems suspend transmission to avoid harmful interference. In a HDS approach to hierarchical dynamic access model, sensing design is focus on find optimal parameters for periodic sensing, which requires not only accurate models for channel and detector's performances, but also statistically significative characterization of primary services activity profiles. The success of a HDS deployment depends on exactitude of such variables, because they are critical for optimization solution that maximizes the achievable capacity fulfilling interference constraints.

In the current chapter, we have presented an analysis on narrowband signal detection in the maritime VHF band, from an implementation perspective. The derived closed form expression for quadrature detector ROC over Nakagami channels and the framework to obtain ROC for practical diversity deployments, constitute interesting tools to model detection of maritime VHF signals over different sea conditions. Additionally, we proposed a multiple non-contiguous narrowband channels detection based on a mixed compromise of wideband and sequential sensing, where multiple quadratic detectors operate simultaneously. Unfortunately, accurate detectors models are not enough for HDS design.

The answer for the optimization problem requires incumbents traffic activity profiles and occupancy probabilities associated to each channel. However, statistics on maritime services are difficult to obtain, not only due to survey logistics and associated costs, but also due to different national assignments on MMS allocated spectrum. Even though, there were some initiatives, within the scope of this work, to obtain data on maritime incumbents, while detection modeling was on-going, but regrettably it was not possible to successfully come to an end.

The major challenge on HDS design is the low tolerance of narrowband spectra for inefficient use. In other words, opportunistic advantage, taking out of each narrow bandwidth channels, cannot manage to have too much overhead associated to sub-optimal exploitation. Hence, it is necessary to have either *à priori* information on primary services activity profiles or an adaptive system that learns while it is operating. In any case, a expedited procedure to estimate an order of magnitude of achievable capacity is an important feature for feasibility analysis and benchmarking.

Chapter 6

Full-Duplex Sensing in Maritime VHF Band

In dynamic environments, prior information on incumbents activity, required to fine tune sensing cycles, is difficult to encounter. Ideally, a cognitive radio would take advantage of real time channels availability information to find optimal t_{sens} and t_T that maximize throughput. Unfortunately, a realistic best effort ambition would ask for decent channels availability statistics, which barely change over time. In practice, one can count on roughly estimations of channels statistics, which have to be used as initial guesses. Consequently, HDS operational exploitation of time opportunities tend to be inefficient, not only because it requires a sensing time overhead, but also due to introduction of additional tolerances to compensate availability statistics inaccuracy, in order to fulfill primary services disruption constraints.

Alternatively, one might consider to implement a FDS scheme, which would be able to perform spectrum sensing and opportunistic transmission, simultaneously, in a given frequency band. In addition to channel profile statistics independence, such sensing scheme has the advantage of not being conditioned by the amount (or nature) of sensed channels. As previously mentioned, synchronous interruption of CR transmission supposes an optimization process for wideband sensing (non-continuous channels) that requires compromises, due to different channels activity profiles and disruption tolerances constraints, which has consequences in overall performances. In practice, FDS overcomes the exploration efficiency dependency on channels data accuracy and the compromises due to different activity profiles and service disruption tolerances.

The FDS concept is not new and has been drawn some attention after full-duplex radio proposal in [139]. Even though, to the best of our knowledge, there is no published experimental results of FDS for cognitive radio applications. Anyway, we propose a novel FDS scheme, based on a SCD, which presents significant advantages, regarding HDS, namely performance, flexibility and adaptability. Briefly, the idea is to use two sensing antennas and evaluate spectral coherence of received signals during opportunistic usage of channels. In a properly designed system, spectral coherence of self transmitted signals is close to 1 and will drastically decrease (ideally to zero) whenever primary user starts to use assigned band. The detection of incumbents activity, during opportunistic operation, is performed through spectral coherence evaluation of received signals. Given that coherence function provides a frequency domain measure of two signals similarity, the idea is to control self interference in such a way that spectral coherence of incoming self signals is maximized, in the absence of primary transmissions, but would suffer a significant decompensation with any primary activity. These requires not only a self interference control scheme, but also a way to enable spectral coherence discrimination.

In the following sections it is presented the foundations for a novel proposed SCD, its deployment analysis and its experimental validation. The remainder of the chapter is organized as follows: in Section 6.1 its is introduced the fundamentals on FDS and briefly exposed the state of the art in this area; Section 6.2 is dedicated to detection of narrowband VHF signals, where we present the spectral coherence, as a frequency domain tool to measure similarity of two signals, and present the proposed concept of SCD and discuss its working principles, dynamic range issues and envisage deployment challenges, such as Self Interference Control (SIC), fading and primary users azimuth effects; the FDS concept development and experimentation is addressed in Section 6.3, where FDS algorithm and developed prototype are described, test bed is characterized, experimentation results are discussed and evaluated; Finally, Section 6.4 concludes the chapter with final remarks.

6.1 Full-Duplex Sensing

The FDS concept assumes that spectrum sensing and opportunistic transmission are performed simultaneously. The detection paradigm is completely different from HDS, where any channel occupation, detected during observation period, is assumed to be caused by a third party. In this case, after starting to take advantage of a spectrum opportunity, CR shall be able to detect concurrently primary transmissions. The spectrum exclusive access to incumbents is enabled by asynchronous interruptions of CR operation, whenever primary users activity is detected, as depicted in Figure 6.1.

The advantages of FDS are quite obvious, but its deployability post a set of interesting challenges. The convenience, regarding spectrum use efficiency and independence of prior information on primary activity profile statistics, makes FDS tailored for narrowband maritime channels applications. It gives permission to take advantage of full period of primary services inactivity, since it would be possible to detect incumbent's start/stop transmission instant, which is particularly relevant in dynamic environments where prior information on primary users activity is difficult to obtain. Nevertheless, a FDS scheme requires the implementation of adequate tools to mitigate self interference effects and enable detection of primary signals, which are several orders of magnitude below uncontrolled self received signals.

Recent breakthroughs in full-duplex radio [139], and its potential combination with CR, give rise to a couple of initiatives in FDS. Ahmed et al. [140] addressed the potential of adaptive directional transmissions to improve the performance over half and full-duplex systems, Yang et al. [141] proposed a correlation based least square algorithm to cancel out self-interference, followed by a phase difference based spectrum sensing scheme, in Gaussian noise. Yan and al. [142] used an energy detector with correlation based channel estimation algorithm to cancel self interference, where weighted energy detector is proposed, in which samples at the end of the sensing period are assigned bigger weights. Anyway, despite performance merits, none of those approaches are designed for non-contiguous wideband sensing, nor have presented experimental results that would demonstrate their practical capacity.

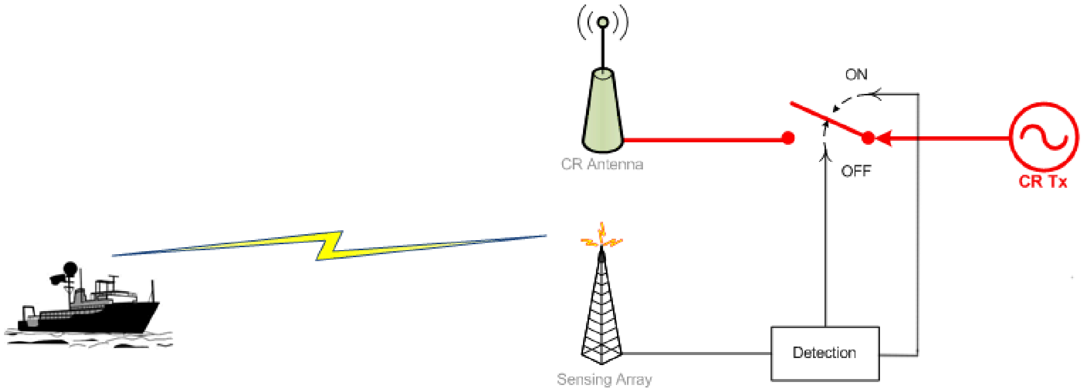

Figure 6.1: Half-duplex sensing basic scheme.

Typically, proposed solutions for FDS are based on full-duplex wireless communications concept [139], where radio is operating at a given band. Conceived CR systems sense and transmit in a contiguous frequency band, which has, in most cases, several MHz bandwidth. On the other hand, presented solutions are based on simulation results, which might exhibit additional problems on implementation phases. The challenges in CR-B-VHF context are different, it requires a narrower band sensing capacity, but a detection aptitude to evaluate activity on multiple non-contiguous narrowband channels.

6.2 Detection of Narrowband VHF Signals

The classical approaches to signals detection are focused on amplitude of RF stimuli, which in the case of FDS represents a double challenge. Despite the need for information regarding noise power to determine threshold, in FDS, detection methods have to deal with superimposed primary and self signals, due to simultaneous transmission occurrences. Nevertheless, in full duplex radio, presented in [139], in-band full duplex Wi-Fi radios simultaneously transmit and receive on a single antenna, at the same channel (continuous 80 MHz bandwidth), using analog and digital cancellation techniques to reduce self interference up to receiver noise floor, and therefore ensure that there is no degradation on received signal. Experimentation proved that design works robustly in noisy indoor environments, and provides close to the expected theoretical doubling of throughput in practice.

In a CR-B-VHF system, the need for non-contiguous narrowband spectrum sensing and typical maritime VHF radio transmitting power (25W) recommend that detector for FDS should avoid signals amplitude evaluation and search for a different feature. Hence, we propose a spectral coherences based detector that uses two sensing antennas and frequency domain tools to examine the relationship between two received signals [143]. Given that linear processes correspond to spectral coherence equal to one and uncorrelated processes correspond to zero values, it would be possible to distinguish between self received signals (low fading) and a combination of self plus primary received signals, which are affected by different kind and fading severity. In addition to immunity to noise uncertainty, which avoids the need for noise power estimation to determine the threshold, such method is well suited for non-contiguous narrowband spectra, due to scalability of the concept.

The spectral coherence is an interesting frequency domain tool to measure the similarity of two signals, providing analogous information to conventional correlation coefficient in statistics. Hence, given two non-stationary processes $x(t)$ and $y(t)$, which corresponding time-frequency representations are $X(\tau, f)$ and $Y(\tau, f)$ respectively, the time-frequency cross spectrum between them can be defined as

$$S_{xy}(\tau, f) = X(\tau, f)\, Y^{*}(\tau, f) \tag{6.1}$$

where auto-spectra are given by

$$S_x(\tau, f) = |X(\tau, f)|^2 \tag{6.2}$$

and

$$S_y(\tau, f) = |Y(\tau, f)|^2. \tag{6.3}$$

Moreover, it is possible to evaluate a time-frequency based coherence to identify significant frequency-domain correlation between two time series, as

$$R^2_{xy}(\tau, f) = \frac{\left|S_{xy}(\tau, f)\right|^2}{S_x(\tau, f) S_y(\tau, f)}. \tag{6.4}$$

Usually, the procedure for time-frequency coherence estimation is based on a series of repeated trials, recorded simultaneously. Hence, considering the following set of K trials:

$$\{x_1(t), x_1(t), ...x_K(t)\} \qquad \text{and} \qquad \{y_1(t), y_1(t), ...y_K(t)\}, \tag{6.5}$$

where time-frequency representations are calculated for each trial, one can obtain an estimation of time-frequency based coherences, as

$$\hat{R}^2_{xy}(\tau, f) \;=\; \frac{\left|\hat{S}_{xy}(\tau, f)\right|^2}{\hat{S}_x(\tau, f) \hat{S}_y(\tau, f)}, \tag{6.6}$$

where

$$\begin{aligned}
\hat{S}_x(\tau, f) \;&=\; \frac{1}{K} \sum_{k=1}^{K} \left|X_k(\tau, f)\right|^2 \\
\hat{S}_y(\tau, f) \;&=\; \frac{1}{K} \sum_{k=1}^{K} \left|Y_k(\tau, f)\right|^2 \qquad (6.7) \\
\hat{S}_{xy}(\tau, f) \;&=\; \frac{1}{K} \sum_{k=1}^{K} X_k(\tau, f)\, Y^{*}_k(\tau, f)
\end{aligned}$$

Furthermore, an intuition for spectral coherence behavior can be provided as in [144], expressing $\hat{R}_{xy}(\tau, f)$ in polar coordinates

$$\hat{R}_{xy}(f) \;=\; \frac{\left|\sum_{k=1}^{K} A_k(f)\, B_k(f)\, exp\big(j\Delta\phi_k(f)\big)\right|}{\sqrt{\sum_{k=1}^{K}\left|A_k(f)\right|^2}\,\sqrt{\sum_{k=1}^{K}\left|B_k(f)\right|^2}}, \tag{6.8}$$

where $A_k(f)$ and $B_k(f)$ represent the resulted amplitudes of non-stationary processes $x(t)$ and $y(t)$, respectively, for k^{th} trial, and $\Delta\phi_k(f)$ represents the phase difference between the two processes at frequency f, for k^{th} trial.

Assuming identical amplitudes of both considered signals in a set of K trials, $\hat{R}_{xy}(f)$ can be simplified to an expression that involves phase differences only, as

$$\hat{R}_{xy}(f) \;=\; \frac{1}{K}\sum_{k=1}^{K} exp\big(j\Delta\phi_k(f)\big). \tag{6.9}$$

Now, according to (6.9), if two signals have constant phase differences, at a given frequency, across K trials, the coherence value would be equal to 1, as depicted in Case A of Figure 6.2, which means that signals have strong coherence between them. In the case of low severity fading, there will be slight random differences in relative phases, which would result in discrepancies in phase differences across K trials and consequently in coherence values, which will be lower than 1, as presented in Case B of Figure 6.2. Finally, if two signals experiment random phase differences, over K trials, as a result of high severity fading contributions, the coherence values decreases towards zero, as shown in in Case C of Figure 6.2.

Coherence is a measure of phase consistency between signals, at a given frequency f, which has a tremendous potential for FDS, as long as self received signals can be controlled (power and fading) to maintain high coherence levels to ensure that high fading of primary channel would provide the characteristics to distinguish incumbents transmission. The CR transmitting antenna proximity allows a phase control and a reduced fading impact on self received signals, thus, the coherence value might be handled to be maximized. On the other hand, received primary signals that result from direct and sea reflected paths, which after superimposition with self received signals, would impact relative phase differences. Naturally, such impact would be proportional to the relative amplitudes, between self and primary signals. Therefore, given that primary received signals are low power, there is a need for an auxiliary scheme that might be able to reduce the effects of self interference signal (CR transmission), and its disturbing consequences in incumbent detection process. Actually, one might contend that design and implementation of such "auxiliary" scheme is the essence of this type of FDS detector.

Most of the challenges, associated to FDS, are centered on SIC. A SIC scheme is required to provide an adequate relationship between self and primary received signals amplitude, as well as, a rigorous control on self received signals phase. The discrimination of two narrowband sources, concurrently transmitting in the same frequency band, when one of those sources might be very weak, is not trivial. That is why practical implementation of FDS has just been tackle in literature.

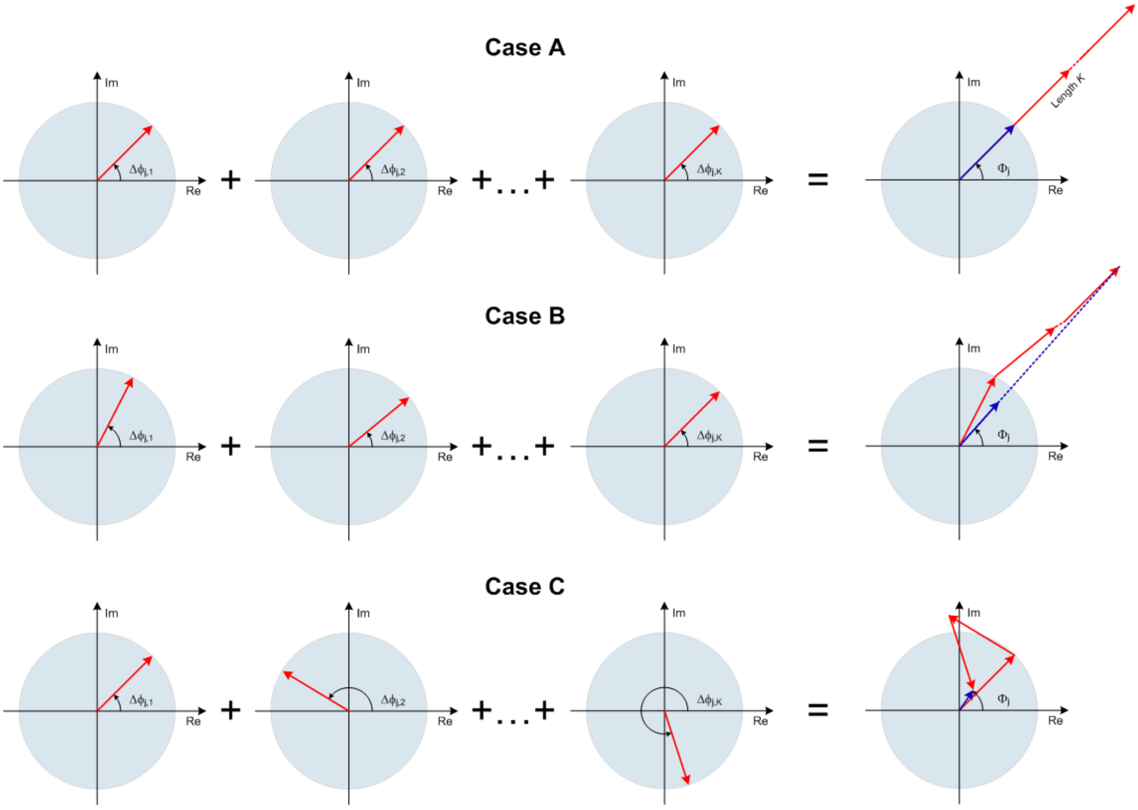

Figure 6.2: Examples of spectral coherence behavior for two non-stationary processes, assuming identical amplitudes in a set of K trials. The polar plots represent each k^{th} trial and the resulted $\hat{R}_{xy}(f)$ for three cases: Case A represents a no fading scenario; Case B assumes a low severity fading scenario; and Case C is scenario where both of non-stationary processes are highly affected by fading.

6.2.1 Spectral Coherences Detector

The proposed SCD takes advantage of dependency and correlation characteristics of random variables. Noise and fading diversity that both, self and primary, signals suffer throughout their way, from transmitting antenna to each one of sensing antennas, will have a correspondent impact on random processes relationships and consequently on spectral coherence value. Despite dynamic range issues, it is expected that self transmitting antenna position and proximity to sensing antennas would permit a decent linear dependency between received signals. Afterwards, when primary user starts to transmit, the superposition of self received signal with multiple replicas, reflected in sea surface and get over different kind of delays and fading severity, would disturb significantly the previous relations between collected samples of random processes, providing the means for detection.

Actually, spectral correlations have been used for several applications, from climate analysis to neuroscience, namely to obtain cyclostationarity related information. Thomson's formulated framework [145], for estimating spectral correlations, can be used to measure spectrum similarity to its neighbors. It combines Loève transform, for dealing with non-stationary processes, and MTM, for resolving the bias-variance dilemma, through the use of Slepian sequences, as presented in [90] and depicted in Figure 6.3 a).

The combination of MTM with Loève transform enables time-frequency analysis and thereby reveal the property of cyclostationarity [90], which is equivalent to the Fourier-theoretic framework presented by Gardener in [146] and [75]. The MTM has several advantages, which have been discussed in Chapter 4, and Loève transform is a second-moment description of a non-stationary process that provides information regarding physics responsible for its generation. The idea is to compute a multitaper Fourier transform, at two different frequencies, f_1 and f_2, using k^{th} Slepian taper and evaluate the spectral correlation of the process at f_1 and f_2. The multiplying factors $exp(-j2\pi f_1 t)$ and $exp(j2\pi f_2 t)$, presented in [90], play similar frequency shifting roles as the factors $exp(-j\pi\alpha t)$ and $exp(j\pi\alpha t)$ of Gardner's formulation [146]. Both theories perform similar signal processing operations on their inputs, but Fourier theory assumes that stochastic process is cyclostationary, whereas the Loève theory applies to any nonstationary process regardless of whether it is cyclostationary [90].

Now, one can take advantage of Thomson formulated framework and adapt it to recognize primary emissions during opportunistic systems operation. Instead of investigate signal's behavior at two different frequencies f_1 and f_2 and evaluate spectral correlation of the process at f_1 and f_2, as presented in Figure 6.3 a), we propose to examine the behavior of two sensor received signals at same frequency and analyze their correlation, as represented in Figure 6.3 b). The objective is to benefit from accuracy, resolution and reliability provided by Thomson approach to evaluate the presence of signals from different sources at the same frequency band.

The spectral estimation accuracy is essential for SCD performance. Considering that in wireless communications, channels are quite unreliable and difficult to model, the preferable choices for spectral estimators are the non-parametric methods. Among them, MTM have been proved to be appropriate for CR applications due to its performance in real time and spectral resolution in both average power and frequency [91].

Anyway, considering that $x_1(t)$ and $x_2(t)$ are the received signals at sensing antennas 1 and 2, respectively, then eigenspectra of each sensor received signal, $x_i(t)$, can be computed through Fourier transform of the tapered data sequences($w^{(k)}[n]$):

$$X_i^{(k)}(f) = \sum_{n=0}^{N-1} x_i[n] w^{(k)}[n] e^{-j2\pi fn} \tag{6.10}$$

Furthermore, considering the tutorial exposition of MTM, presented in [90], the demodulation of a RF stimuli frequency band allows a representation of a time-series $\{x[n]\}_{n=0}^{N-1}$ in baseband. Hence, given that, Slepian sequences, denoted by $\{w^{(k)}\}_{n=0}^{N-1}$, are computed based upon the following eigen equation:

$$\mathbf{K}\mathbf{w}_k = \lambda_k \mathbf{w}_k \tag{6.11}$$

where the $(i,j)^{th}$ entry of Toeplitiz matriz K is defined by:

$$k_{i,j} = \frac{sin\big(2\pi W(i-j)\big)}{\pi(i-j)}, \quad i,j = 1,2,...,N, \tag{6.12}$$

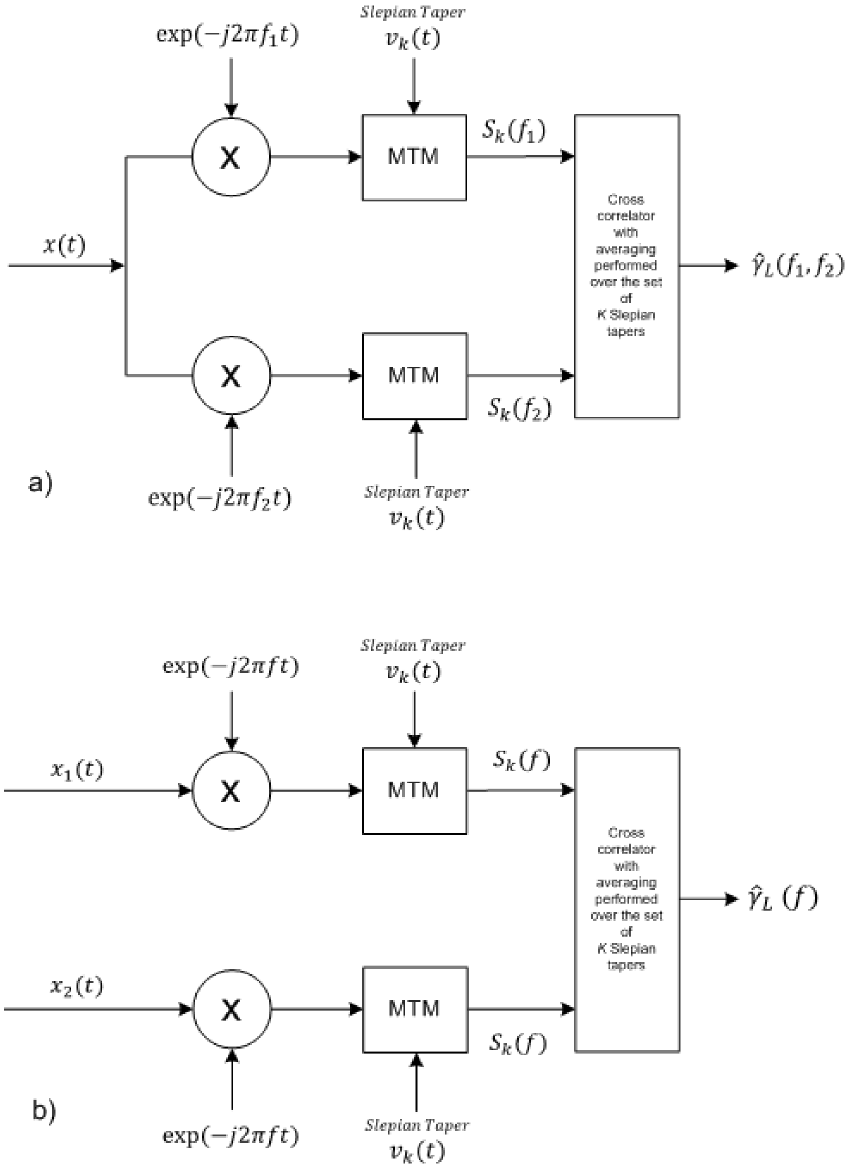

Figure 6.3: Spectral correlation: a) Thomson's approach to cyclostationarity evaluation [145]; b) proposed adaptation to evaluate sensor received signals similarity.

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the eigenvalues, which range follows between 0 and 1, are organized in descending order such that: $\lambda_0 \geq \lambda_1 \geq ... \geq \lambda_{N-1}$, so the first $K \approx \lfloor 2NW \rfloor$ of them clearly dominate (close to 1), while the rest are negligible. Figure 6.4 present an example of four initial windows, for $N = 512$ and $NW = 2.5$.

The tapers of lower order have much stronger energy concentration capability than their higher order counter parts, which results in a good spectral estimation based on the first K tapers only. If the number of tapers increases, the eigenvalues decrease, causing eigenspectra to be more contaminated by leakage. However, eigenvalues counteract this effect by reducing weighting applied to higher leakage eigenspectra [90].

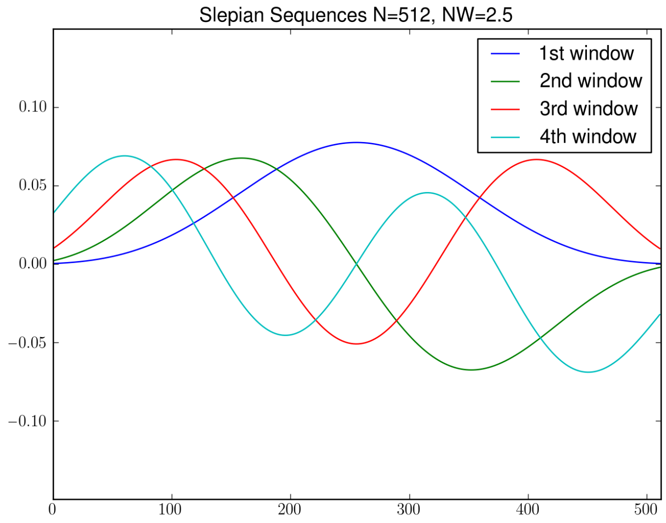


Figure 6.4: Example of Slepian sequences (four initial windows), for $N = 512$ and $NW = 2.5$.

Hence, spectral estimate might be obtained by:

$$\hat{S}_i(f) = \frac{\sum_{k=0}^{K-1} \lambda_k |X_i^{(k)}(f)|^2}{\sum_{k=0}^{K-1} \lambda_k} \tag{6.13}$$

and Loève spectral coherences can be computed as:

$$\hat{\gamma}_L(f) = \frac{1}{K} \sum_{k=0}^{K-1} X_1^{(k)}(f) X_2^{(k)}(f) \tag{6.14}$$

where, $X_1^{(k)}(f)$ and $X_2^{(k)}(f)$ represents the Fourier transform of tapered data sequences, computed through MTM, for sensing array 1 and 2, respectively.

Ussually, Magnitude Squared Coherence (MSC) is the preferred form to express spectral coherence, which can be obtained by

$$MSC(f) = \frac{\left|\hat{\gamma}_L(f)\right|^2}{S_1(f) S_2(f)} \tag{6.15}$$

.

Thereby, the proposed solution for SCD is depicted in Figure 6.5. The idea is to control CR received signals at sensing arrays in order to have highly correlated received signals, i.e. MSC values close to 1, in absence of primary service. Hence, any primary user transmission, would disturb phase relations of received signals (correlation) and consequently its spectral coherence, decreasing its MSC value, as exemplified in Figure 6.6.

One of the several advantages of SCD is the simplicity to perform detection on multiple non-contiguous channels. The evaluation of spectral coherence, between two sequences, is independent of their spectral contents, so it can be used for spectrum sensing in multiple

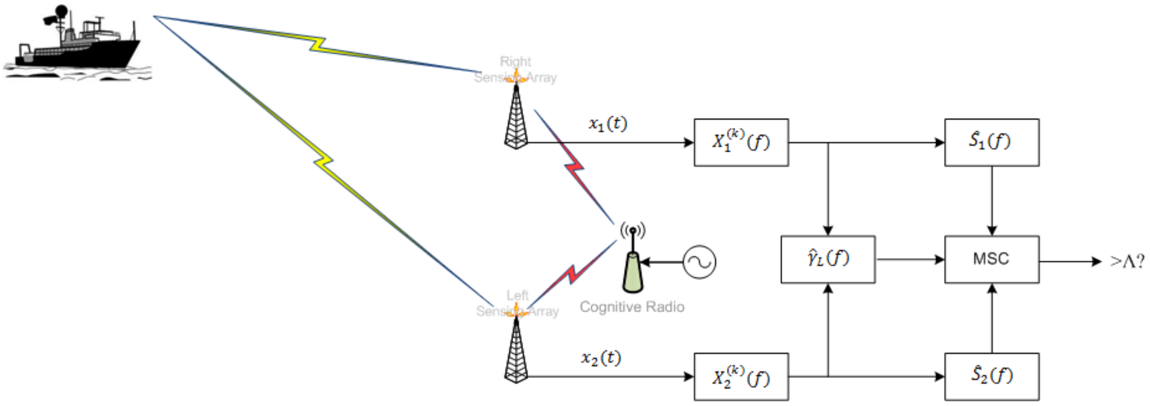


Figure 6.5: Proposed architecture for SCD, with a CR antenna and two sensing arrays. The threshold level, Λ, for MSC value, would support decision on primary user operation.

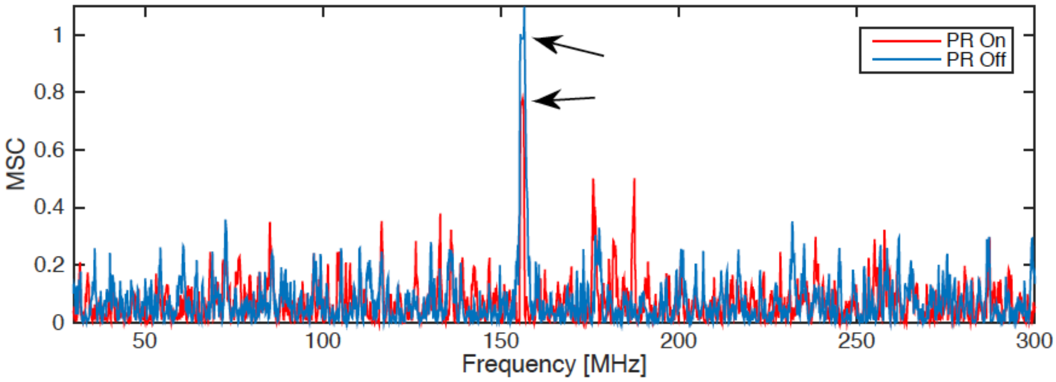


Figure 6.6: Simulation example: MSC values for secondary operation ($\mathcal{PR}_{off}$) and concurrently operation, of primary and secondary, users ($\mathcal{PR}_{on}$).

channels, as the example presented in Figure 6.7. The simulated spectrogram presents the MSC values for an opportunistic usage of three MMS channels of 25 KHz, using SCD based FDS. It can be observed in the waterfall diagram that, at the center of each channel footprint, MSC varies according to primary users activity.

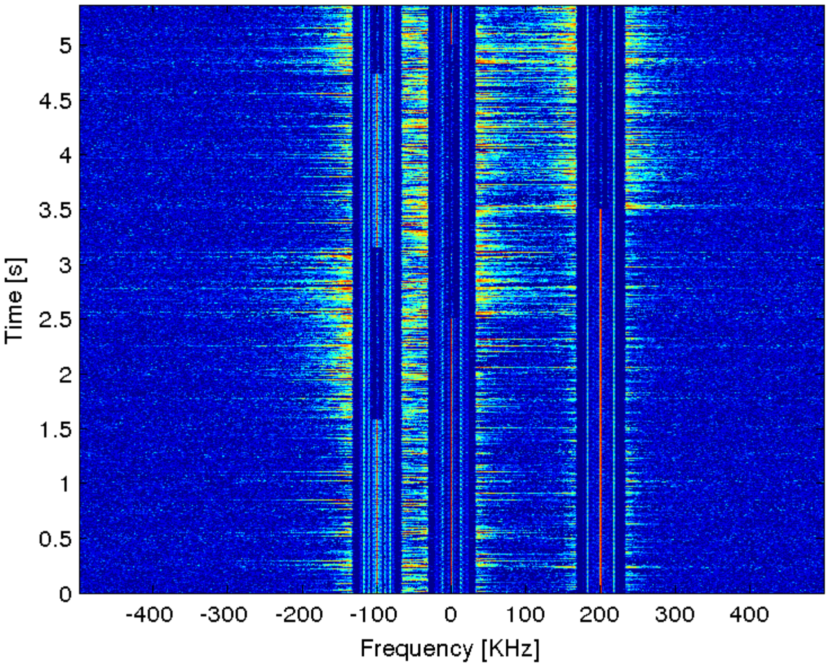


Figure 6.7: Waterfall of MSC values for simulated opportunistic usage of three 25 KHz channels.

The detection problem, in FDS, can be expressed as a binary hypothesis problem, where $\mathcal{H}_0$ and $\mathcal{H}_1$ represent the cases where of primary service is inactive ($\mathcal{PR}_{off}$) or active ($\mathcal{PR}_{on}$), respectively. Hence, considering $x_1(t)$ and $x_2(t)$ as the received signals at sensing arrays 1 and 2, respectively, which for the sake of simplicity can be represented by sine waves. Under $\mathcal{H}_0$ ($\mathcal{PR}_{off}$), received signals, generically represented by $x_i(t)$, correspond to attenuated versions of self transmitted signals, which amplitude and phase are represented by random variables a_i and θ_i, respectively. On the other hand, under $\mathcal{H}_1$ ($\mathcal{PR}_{on}$), received signals, would correspond to attenuated versions of self transmitted signals superposed with primary user received signals, which amplitude and phase are represented by random variables b_i and ϕ_i, respectively, as in

$$x_i(t) = \begin{cases} a_i \, cos(\omega_c t + \theta_i) : & \mathcal{H}_0 \\ a_i \, cos(\omega_c t + \theta_i) \; + \; b_i \, cos(\omega_c t + \phi_i) : & \mathcal{H}_1 \end{cases} \tag{6.16}$$

where ω_c represents the carrier frequency.

The sum of the two equal-frequency sine waves, under $\mathcal{H}_1$, is given by

$$x_i(t) = \begin{cases} a_i\, cos(\omega_c t + \theta_i) : & \mathcal{H}_0 \\ \alpha_i\, cos(\omega_c t + \Theta_i) : & \mathcal{H}_1, \end{cases} \tag{6.17}$$

where:

$$\begin{aligned} \alpha_i \;&=\; \sqrt{\Big[a_i cos(\theta_i) \;+\; b_i cos(\phi_i)\Big]^2 \;+\; \Big[a_i sin(\theta_i) \;+\; b_i sin(\phi_i)\Big]^2} \\ \Theta_i \;&=\; tan^{-1}\left[\frac{a_i sin(\theta_i) \;+\; b_i sin(\phi_i)}{a_i cos(\theta_i) \;+\; b_i cos(\phi_i)}\right]. \end{aligned} \tag{6.18}$$

Therefore, for different operating conditions, cross-power spectra are given by:

$$\mathcal{H}_0 : \begin{cases} S_{x_1} = \mathcal{F}\{x_1[k]x_1^*[n-k]\} = \mathbf{E}\Big[|a_1|^2\Big]\delta(f-f_c) \\ \\ S_{x_2} = \mathcal{F}\{x_2[k]x_2^*[n-k]\} = \mathbf{E}\Big[|a_2|^2\Big]\delta(f-f_c) \\ \\ S_{x_1x_2} = \mathcal{F}\{x_1[k]x_2^*[n-k]\} = \mathbf{E}\Big[a_1a_2^*\Big]\delta(f-f_c) \end{cases} \tag{6.19}$$

$$\mathcal{H}_1 : \begin{cases} S_{x_1} = \mathcal{F}\{x_1[k]x_1^*[n-k]\} = \mathbf{E}\Big[|\alpha_1|^2\Big]\delta(f-f_c) \\ \\ S_{x_2} = \mathcal{F}\{x_2[k]x_2^*[n-k]\} = \mathbf{E}\Big[|\alpha_2|^2\Big]\delta(f-f_c) \\ \\ S_{x_1x_2} = \mathcal{F}\{x_1[k]x_2^*[n-k]\} = \mathbf{E}\Big[\alpha_1\alpha_2^*\Big]\delta(f-f_c) \end{cases} \tag{6.20}$$

where $\mathbf{E}[.]$ represents the expected value, $\mathcal{F}\{.\}$ denotes the Fourier transform, S_{x_1} and S_{x_2} represent the auto-power spectra density of $x_1(t)$ and $x_2(t)$ respectively, and $S_{x_1x_2}$ is the cross-power spectra density between $x_1(t)$ and $x_2(t)$.

Therefore, correlation coefficient (MSC) , for f_c is given, generically, by:

$$\begin{aligned} MSC &= \frac{\Big|\mathbf{E}\big[a_1a_2^*\big]\Big|^2}{\mathbf{E}\big[|a_1|^2\big]\mathbf{E}\big[|a_2|^2\big]} \;:\; \mathcal{H}_0 \\ \\ MSC &= \frac{\Big|\mathbf{E}\big[\alpha_1\alpha_2^*\big]\Big|^2}{\mathbf{E}\big[|\alpha_1|^2\big]\mathbf{E}\big[|\alpha_2|^2\big]} \;:\; \mathcal{H}_1. \end{aligned} \tag{6.21}$$

The detection is now based on the analysis of MSC value for f_c. Despite fading and noise, a_1 and a_2 are expected to be linearly dependent, which would result in a MSC = 1, under $\mathcal{H}_0$. By contrast, α_1 and α_2 are composed by two nearly linear dependent random variables (a_1 and a_2), superimposed by extra random variables that are affected by different kind of fading. The result is a pair of random variables, α_1 and α_2, that are independent or uncorrelated, forcing MSC value towards zero. This is the foundation for SCD working principle.

6.2.2 Received Signals' Dynamic Range

The capacity of a SCD depends on its competency to obtain highly discriminated MSC values for different incumbent's operational status. In other words, the difference between SCD detector MSC outputs, corresponding to primary operation ($\mathcal{PR}_{on}$) and idle incumbent service ($\mathcal{PR}_{off}$), should be as high as possible to enable a good detection. Ideally, self received signals should generate MSC output values close to 1 ($\mathcal{PR}_{on}$) and combined, self and primary received, signals should push these values towards zero ($\mathcal{PR}_{off}$). Unfortunately, in practice, both of these conditions require high power received signals, which is simple to achieve for self signals, but unlikely to obtain from incumbents received signals.

Additionally, due to working principle of SCD, dynamic range is another issue to take into consideration, in detectors performance. The amplitude differences, between self and primary received signals have impact on primary signal capacity to cause a drastic decrease on (high) MSC value. Given that MSC is a measure of similarity between two received signals, if the amplitude of primary received signals is very low, as compared to self received signals, the superimposed signals would be very similar to the original self received signals, which are planned to be balanced (controlled amplitude and phase), and consequently MSC value would hardly change. In other words, the amplitude ratio of primary and self received signals is critical for primary signal capacity to offset coherence (of self received signals) and, thereby, for SCD sensibility. Therefore, detection of primary weak signals requires low power self received signals (that implies low MSC values), which results in smaller differences in MSC output values and, consequently, in potential detection errors.

Considering that, in real operational scenarios, self received signals power tend to be high and received incumbents signals are usually low power, it is important to characterize SCD dynamic range and understand its role on performance to support further design. The detection of primary weak signals, in the presence of nearby (self) strong ones, represents an interesting challenge for system's designer that has to be evaluated, prior to any deployment tentative. Since SCD responsiveness is not independent from difference between primary received signal and self interference, it is important to quantify an order of magnitude for such interval and its associated performances, in order to perceive context constraints. This exercise would provide feasibility indicators and references for further developments on SCD support systems, namely SIC schemes.

We define a figure of merit to characterize SCD detector performance according operational conditions, called *Primary-to-Self signal Ratio* (PtSR), and perform a set of GNU radio based simulations that intend to address detector's performance, for primary FM and BPSK modulated signals, in different conditions. Considering that SCD is designed to be a full-duplex detector, the operating self received power is a system parameter, so it is convenient to "normalize" primary received power to this value. Briefly, self received power will dictate the average value of MSC output value, for $\mathcal{PR}_{off}$, and PtSR will restrict its deviations (for $\mathcal{PR}_{on}$).

Nevertheless, real scenarios stochastic processes cannot be fully reproduced in computer software, such as MATLAB or GNU radio, due to minor dependency and/or correlation between generated random variables, which are negligible in most applications, but in this case have an important impact. Unavoidably, as deducted by (6.4), noise and channel fading are major contributors for signals coherence value, their weight and random characteristics will dictate independence and correlation between received signals and ultimately the detection capacity. Therefore, generated random variables characteristics have impact on final results and their acceptability to mimic reality, Even though, simulations can provide good indications for a qualitative analysis and a important guidance for designers.

The objective of proposed analysis is to evaluate the role of PtSR and modulation scheme in overall SCD performance, and the relative dependencies of self and primary received powers. Hence, a simulator has been implemented in GNU radio, where it is considered a CR transmitter that opportunistically operates a 25 KHz channel with a BPSK modulated signal and a primary transmitter that uses the same channel with two different modulation schemes: a 6 KHz bandwidth FM modulated voice signal, as presented in Figure 6.8, and a 25KHz bandwidth BPSK modulated signal, presented in Figure 6.9. The channels, for two sensing antennas, are modeled with AWGN sources, with different seeds and amplitudes; Rician fading random variables, with different seeds, Rician factors (K) and normalized maximum doppler ($fD * Ts$); and different variable delays. The SCD algorithm has been implemented in GNU radio, using "off-the-shelf" blocks from GNU radio toolboxes and developed "MTM Spectrum Estimator" and "Loeve SC" blocks, which source code is included in Appendices A and B.

A brief note on presented simulation results throughout this section, in figures, left column presents snapshots of received power spectra, for the different investigated conditions, while right column depicts correspondent MSC values, when self signal is continuously transmitting and primary signal transmission is triggered by a square wave of 0.2 Hz and a duty cycle of 50% (PR Tx).

Essentially, within this context, dynamic range is about detector's performance behavior for a given PtSR, but it is also important to understand the effect of absolute signals received power. These issues are evaluated through a set of simulations for primary FM and BPSK modulated signals, for two cases: fixed PtSR value and different self received power and fixed self received power and different PtSR. Given the amount and diversity of variables involved, we are not addressing all combinations, because such exercise would be tedious and worthlessly. Even though, a sense of detector's line of action, for PtSR variation, is an important instrument for designers. Therefore, the idea is to understand main contributions for different performances and the impact of PtSR, for different primary signal modulation schemes.

The first scenario has been focused on investigation of signals received absolute power influence on detector's performance, for two different primary modulated signals. It was considered three different received power levels, for both self and primary signals (FM and BPSK), and a fixed PtSR = 1. Presented Figures 6.10a and 6.10b, show received power spectra of simulated signals (self and primary received signals) and obtained MSC values at SCD, for different self received signals SNR.

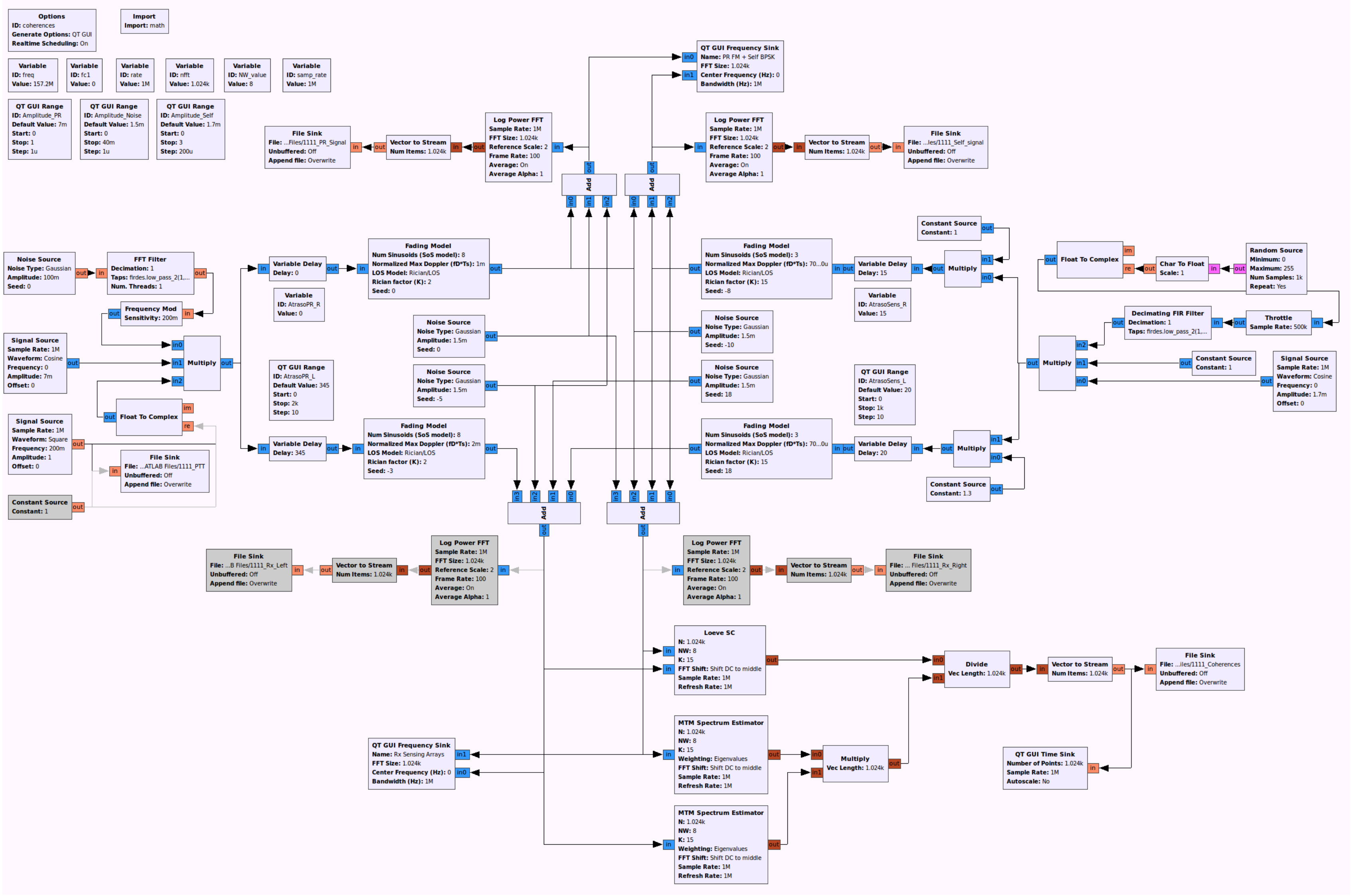


Figure 6.8: GNU Radio simulator for a SCD based FDS, where primary user is operating a 6 KHz bandwidth FM modulated voice signal.

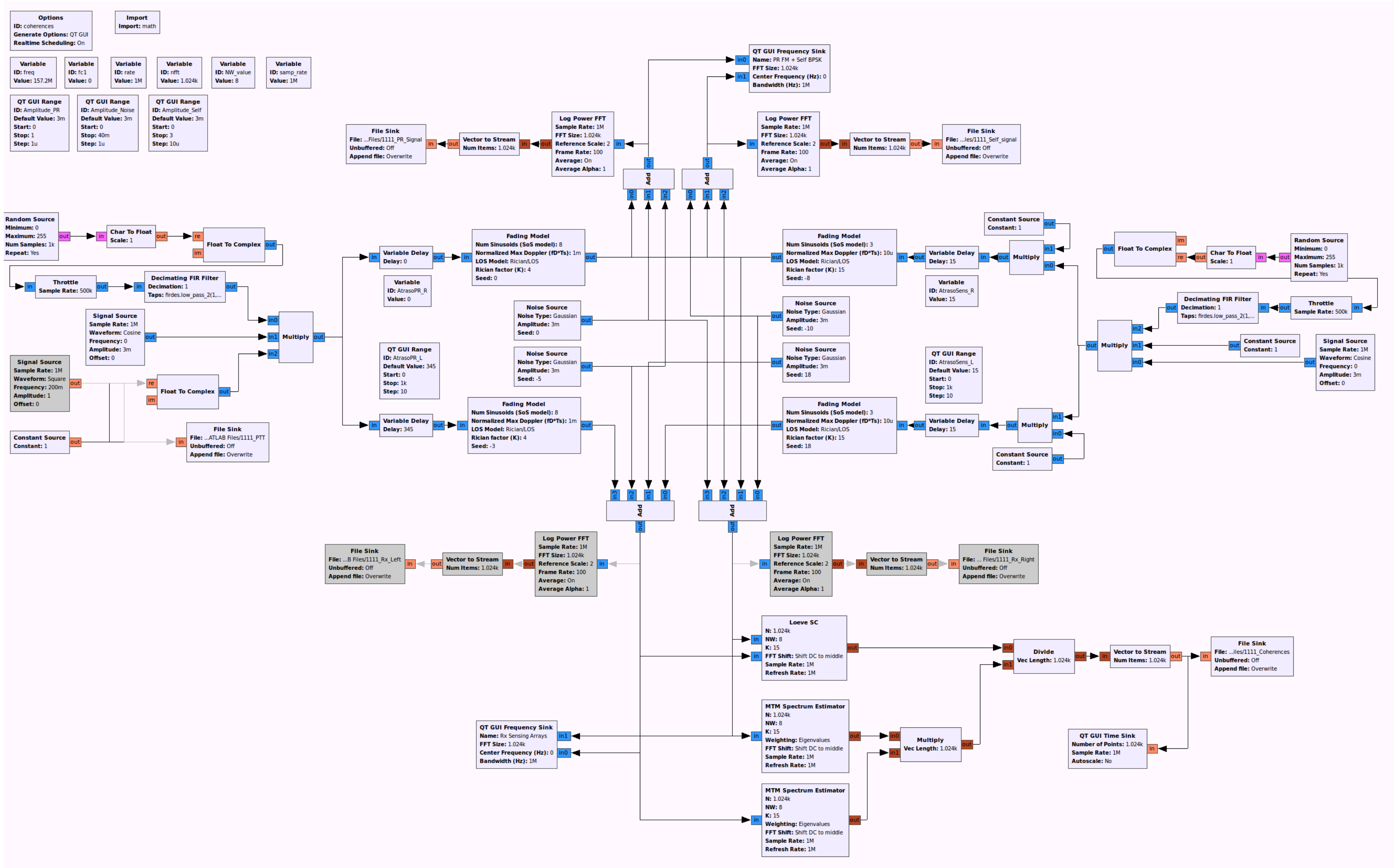
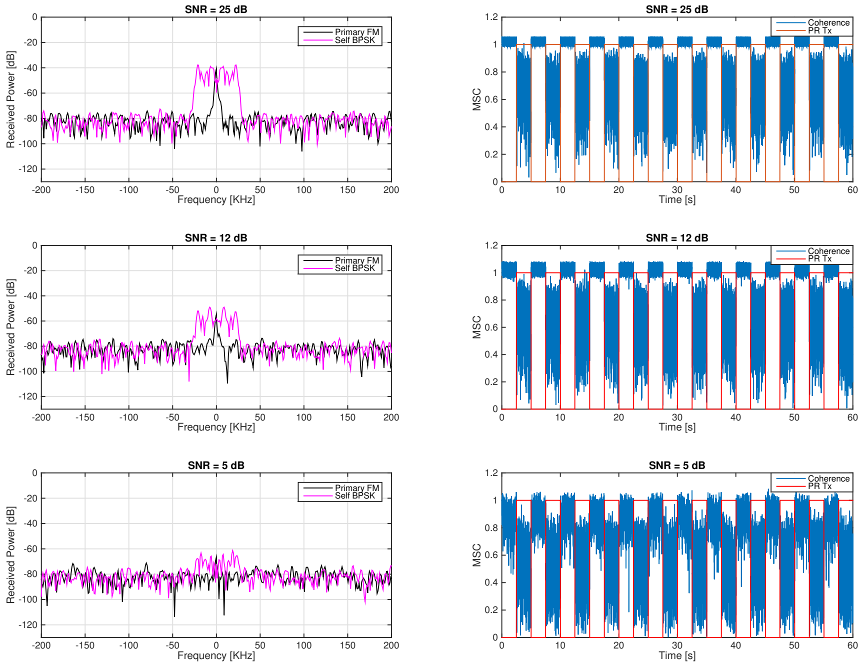
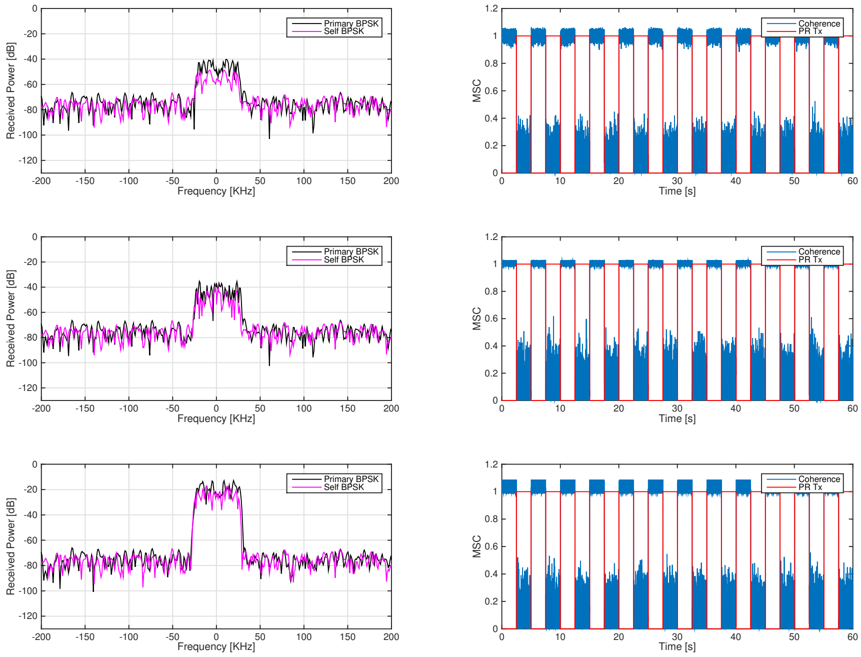


Figure 6.9: GNU Radio simulator for a SCD based FDS, where primary user is operating a 25KHz bandwidth BPSK modulated data signal.



(a) Primary FM Modulated Signal



(b) Primary BPSK Modulated Signal

Figure 6.10: Simulation results for different self received power (SNR), ensuring the same PtSR. Simulated signals correspond to a self BPSK modulated signal and indicated primary modulated signal.

Figure 6.10a presents the simulation results for different primary and self received signals power, ensuring the same PtSR. The self received signal is a 25KHz BPSK modulated signal and primary received signal is a 6 KHz FM modulated signal. It was assumed a good delay control on self received signals, in both sensing antennas, and an offset position of primary user (different delays on both primary received signals). The channel was modeled with a $K = 4$, for CR antenna-to-sensing antennas path, and a $K = 15$, for primary antenna-to-sensing arrays path. The considered sample rate was 1 Msps and discrete period $N = 1024$. Identical simulations have been performed for a case of primary 25KHz BPSK modulated signal, whose results are presented in Figure 6.10b.

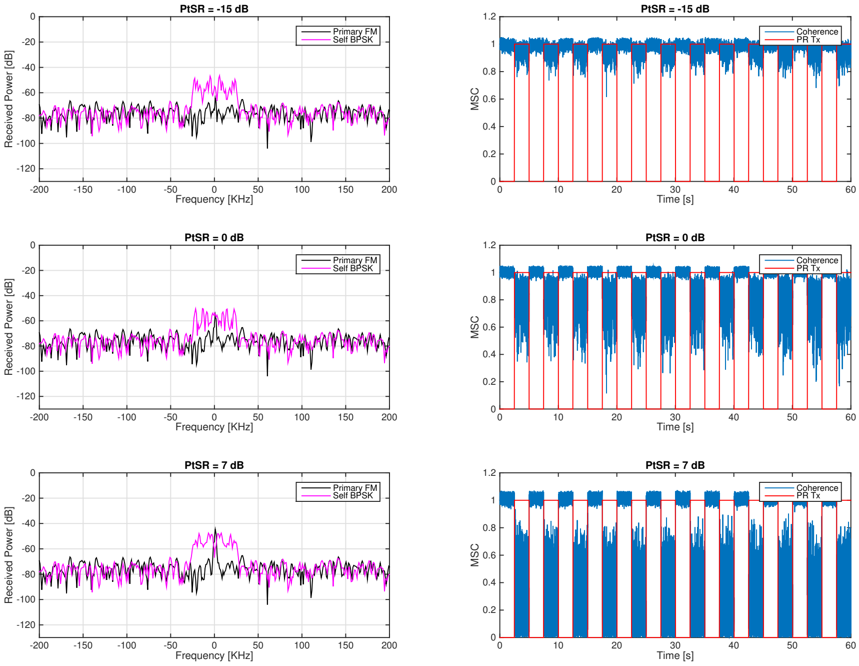
The simulation results point out that, for fixed PtSR, after a certain level of received power, performance is independent from signals absolute power and for both primary signals modulated schemes. The maximization of MSC value for $\mathcal{PR}_{off}$ requires enough power on self received signals in order to mitigate fading effects, so once the minimum power requirements are satisfied, the performance becomes nearly independent from signal's absolute power level. Even though, primary BPSK modulated signals present a better capacity to disturb MSC values and it is expected a better performance in those cases.

On the contrary, variations on PtSR are expected to affect significantly detection capacity. Again, a set of GNU radio based simulations have been performed to evaluate the impact of PtSR, for primary FM and BPSK modulated signals. In Figure 6.11a, it is presented the simulations results for a fixed self received power and different PtSR, when primary signals are FM modulated. One can confirm what has been stated, regarding the ability to differentiate MSC values, correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, which increases as PtSR increases, due to improvement on primary signal capacity to disturb MSC value. Therefore, in cases of low PtSR, it is expected a degradation on detectors performances, due to lack of primary signal aptitude to push down MSC value. Such capacity is more significant in the case of primary BPSK modulated signals, as presented in Figure 6.11b.

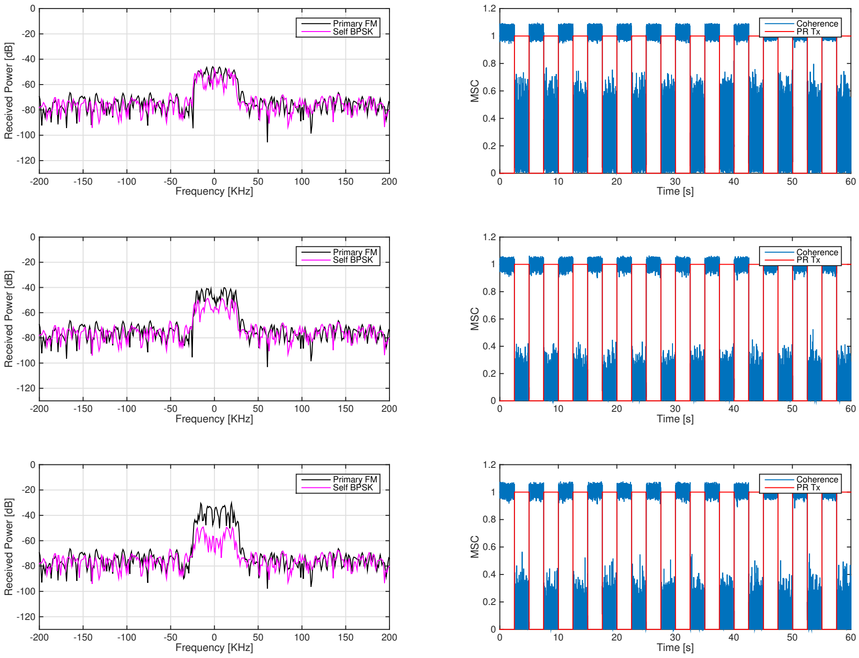
Additionally, a fine-tune investigation is performed for PtSR ≤ 1. The self received power is again fixed and PtSR varies between 0 and 1. In Figures 6.12a and 6.12b, are presented the simulation results for primary FM and BPSK modulated signals, respectively. Interesting enough, for $\mathcal{PR}_{on}$, PtSR increasing has the following effects: in the case of primary FM signals, MSC mean value decreases and variance increases, while in the case of primary BPSK signals, both MSC mean value and variance decrease. Therefore, performance for primary BPSK signals is expected to be considerable better than in FM cases.

In resume, simulation results showed that PtSR is critical for ability to differentiate MSC values, correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, and consequently for overall SCD detector performance. The self received signals power is important to setup a reference value on MSC as close as possible to one, with a minimum variance. Afterwards, for a given PtSR, signals received absolute power barely influence on detector's performance, but primary signal bandwidth and modulation scheme is an important issue to take into consideration. The 25 KHz BPSK modulated signals have higher capacity to disturb self received MSC, than equivalent 6KHz FM modulated primary signals.

The PtSR is the main contributor distinguish MSC relative to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. For values of PtSR ≥ 1, the expected performance is outstanding, while it is exponentially degraded as PtSR assumes values smaller than one. Unfortunately, in normal conditions, it is

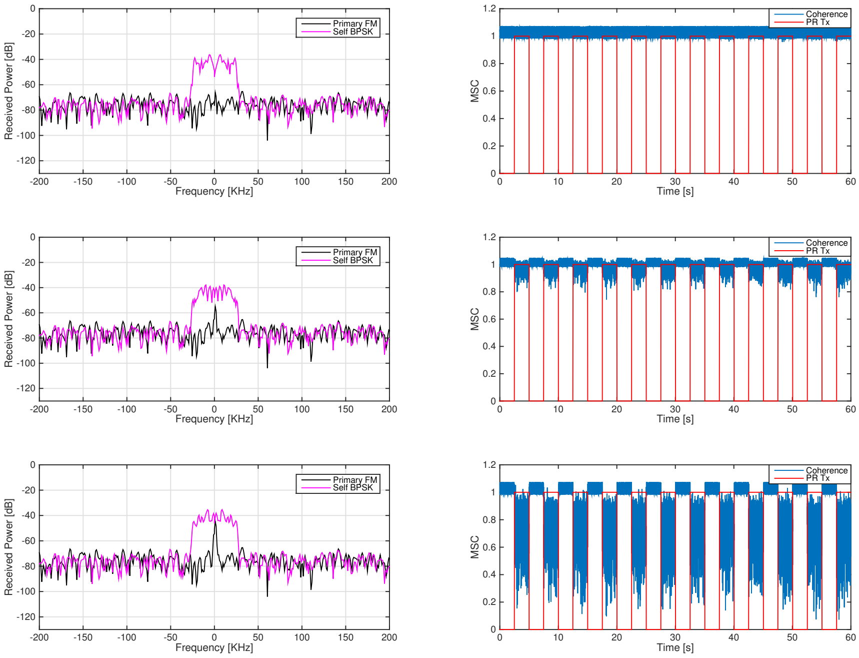


(a) Primary FM Modulated Signal

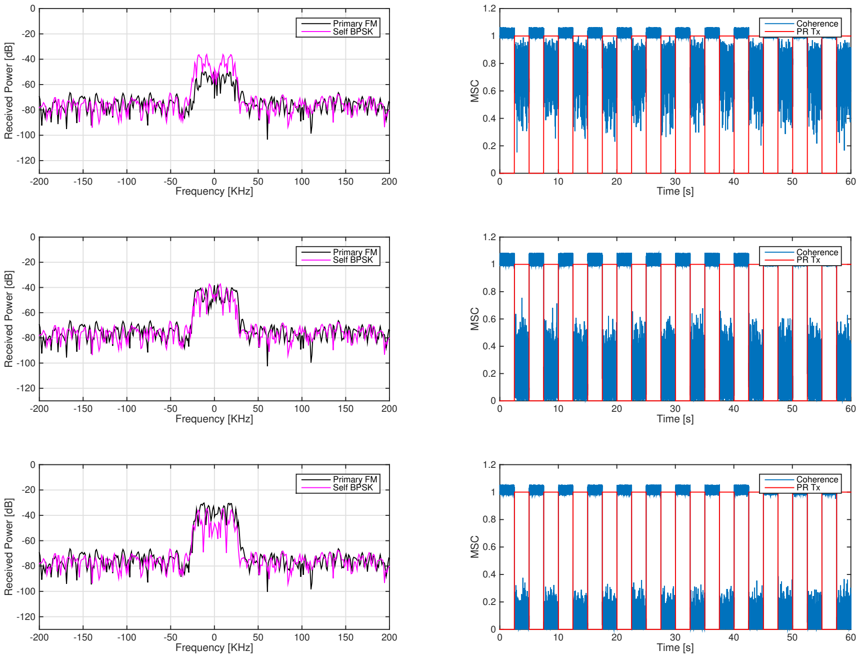


(b) Primary BPSK Modulated Signal

Figure 6.11: Simulation results for different PtSR values: fixed self received signal and different primary signals powers.



(a) Primary FM Modulated Signal



(b) Primary BPSK Modulated Signal

Figure 6.12: Simulation results for $PtSR$ values between 0 and 1, for fixed self received signals power and indicated primary modulated signal.

not expected that primary signals received power would be higher than self interference, but it is possible to post it as a requirement for the SIC scheme.

Despite the lack of general benchmarks, this analysis sorted out important indications for SIC designers, regarding received signals dynamic range. For instance, it revealed that evolution on MMS towards digital channels does not restrain SCD utilization in opportunistic systems, given that performance is expected to increase with bandwidth and digital modulation schemes.

6.2.3 Deployment Challenges

The operation principle of a SCD is very simple. It assumes that it is possible to obtain a MSC value close to 1, for self received signals only ($\mathcal{PR}_{off}$), so, any third party transmission, in the same frequency ($\mathcal{PR}_{on}$), would cause a decrease on MSC, grant permission to detection mechanism to stop opportunistic transmission, as depicted in Figure 6.1. Ideally, an appropriate setup of sensing antennas would allow a maximization of self received signals spectral coherence (for $\mathcal{PR}_{off}$), and empower a drastic decrease on MSC value when extra random processes (primary signals), affected by different kind of fading and, therefore, independent and/or "highly" uncorrelated, are superimposed with self received signals and "destroy' their linear dependency. In practice, detection capacity depends on designer's capacity to maximize the difference between MSC values that correspond to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, rather than have high or low MSC values.

In fading channels environment, it is more difficult to ensure linear dependency of two non-stationary processes (received signals) than to obtain independent or uncorrelated processes. Even in the case of self received signals, where amplitude (power) and phase are controlled, it is not possible to obtain a stable measure of MSC value equal to one. Normally, MSC values will change, within a variance interval, as a result of channel conditions and noise effects, which are more or less significant according to signals received power. On the other hand, as exposed in previous section, one should not take for granted that it is possible to ensure a drastic decrease in MSC value, for $\mathcal{PR}_{on}$, no matter how weak primary signals might be. Consequently, there is a paradox for system designer: considering that primary received signals are likely to be low power, than self received signals have to be large enough to maximize MSC value, for $\mathcal{PR}_{off}$, and minimize its variance, but low enough to ensure an adequate PtSR, for dynamic range purposes. The solution for such problem is the secret for a successful implementation of a SCD.

In the current analysis we address SCD responsiveness and envisage deployment issues that implementors need to take into consideration, both from designer controlled and non-controlled issues perspective. The objective is to expose problems and challenges, discuss feasibility and draw a set of guidelines to assist designers in the implementation of SCD based solutions. Due to SCD dependency on adopted solution for SIC, any initiative to provide general benchmarks or absolute references would be worthless and even performance analysis has to be considered within a context.

Essentially, a FDS scheme based on SCD requires a deployment of a SIC scheme to ensure appropriate levels of self received signals amplitude and phase, in order to maximize the difference between MSC values that correspond to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. The outcome of such cancellation scheme depends not only on system designer talent to manage self and primary signals, but also on its proficiency to understand maritime operating environment and channel fading related challenges.

Similarly to the previous section, GNU radio based implementations are used to simulate normal and extreme cases that can provide a sense of detector behavior for each variable. Firstly, we address the aspects that can be controlled by designer, i.e., self cancellation scheme, and then we investigate the operating environment and channel conditions. The objective is to derive a set of guidelines to assist designers in the implementation of SCD based solutions.

Self Interference Control

A SIC scheme is a fundamental component of any FDS implementation and an enabler for SCD, because it ensures adequate amplitude and phase on self received signals. In other words, SIC is responsible for received signal's dynamic range and spectral coherence control. Accordingly, there are two functional requirements to be fulfilled: self interference cancellation (control) and self spectral coherence control. The former has several options and an extensive literature, follow after full-duplex radio proposal [139] and associated to 5G development, while the later is specific for the proposed SCD.

The main challenges associated to received signal's dynamic range issues (addressed in the previous section) are related to fulfillment of PtSR requirements to distinguish MSC values, relative to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, and can be resumed to a significant attenuation on self received signals. Classical approaches to signals cancellation include three mitigation levels: passive isolation, through the usage of separate antennas for transmission and sensing; active cancellation, through spatial filtering (beamforming); and subtractive analog and/or digital cancellation, through the processing of a combination of received signal and properly adjusted self transmitted signal. Recently, several authors address radio self interference cancellation problematic and proposed solutions based on all-analog cancellation, as in [147], all-digital cancellation, as in [148], active cancellation, as in [149], RF cancellation, as in [150] and [151], or non linear distortion supression, as in [152], just to mention a few examples. Anyway, the objective in most proposed cases is to cancel self transmitted signal and all distortions in order to enable in-band full duplex operation, as proposed in [139], rather to reduce self interference contribution to received signals that are tested for spectral coherence. Even though, it is possible to take advantage of such developments to fulfill identified PtSR requirements.

Furthermore, self coherence control is critical for SCD operation, due to the fact that detection of primary activity is based on disturbance on coherence value of (nearly) linear dependency of self received signals, caused by superimposed uncorrelated primary signals. In addition to self interference reduction, SIC should be able to ensure a stabilization of MSC value, for $\mathcal{PR}_{off}$, as close to 1 as possible, in order to separate MSC values for $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. The identified MSC requisite demands an amplitude and delay control of self received signals to minimize fading effects on signals correlation, keeping high values of coherence with minimum variance. Afterwards, the effect of received primary signals on MSC is a function of channel conditions (fading) and noise, which is out of designer's control. Therefore, performance of a SCD depends on designer's capacity to ensure conditions for a maximization of MSC, for $\mathcal{PR}_{off}$, and grant permission, through an appropriate dynamic range, to sudden change on that value, for $\mathcal{PR}_{on}$.

Essentially, SCD performance would be optimal if one could manage to have self received signals with the same phase at both sensing antennas, within the same order of magnitude of primary received signals. Unfortunately, some, or even none, of those conditions cannot be ensured for all operational conditions. The objective of this section is to carry out an evaluation on impact of imperfect interference control, specifically, the role of phase discrepancies on self received signals in MSC outcome and on overall performance. Again, GNU radio based simulations have been used to assess amplitude and phase variations and envisage their impact on detection capacity.

The previously presented simulators and setups have been used to investigate the variations in MSC caused by different delays on self received signals. As expected, the phase differences in self received signals have an immediate impact on obtained MSC value, not only for $\mathcal{PR}_{off}$, but also for $\mathcal{PR}_{on}$, as depicted in Figures 6.13a and 6.13b. The simulation results revealed a decrease on maximum achievable MSC, for $\mathcal{PR}_{off}$, with direct impact on MSC values for $\mathcal{PR}_{on}$, which range cannot be distinguishable from $\mathcal{PR}_{off}$, with obvious consequences on detection capacity.

Furthermore, simulations point to the fact that maximization of MSC, for $\mathcal{PR}_{off}$, is the better way to obtain a decent discrimination between $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. The lack of phase control is critical for spectral coherence of self received signals and to draw a distinction between $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, based on MSC value. Such conclusions are valid for both FM and BPSK modulated primary signals.

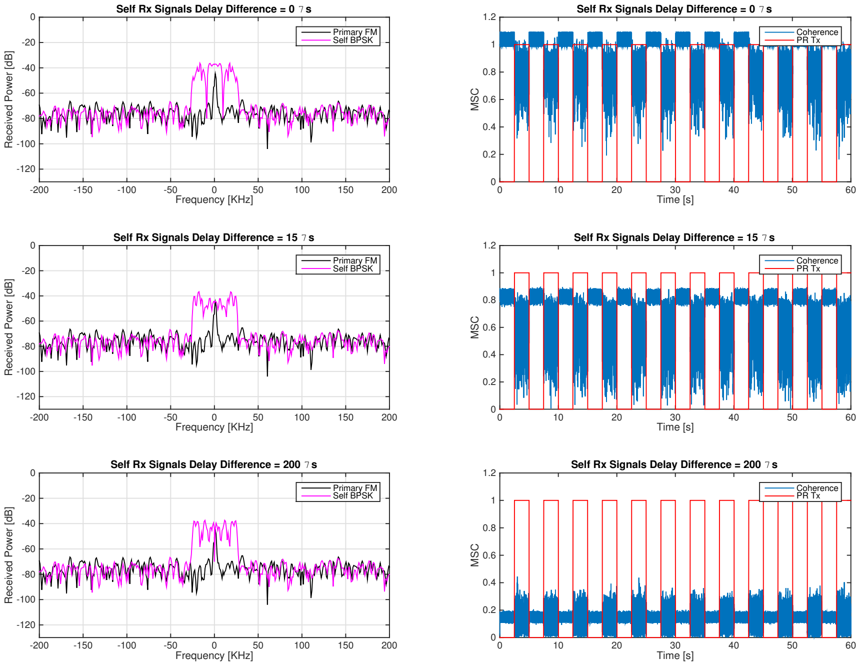
The relative phase of self received signals is an important issue to take into consideration in any SCD deployment. Nevertheless, due to CR proximity to sensing arrays, it is technically possible to manage delay control at low cost. Beamforming, spatial positioning of antennas, analog and digital processing are some of available schemes that might be used, separately or conjointly, to support maximization of MSC of self received signals.

Fading Effect

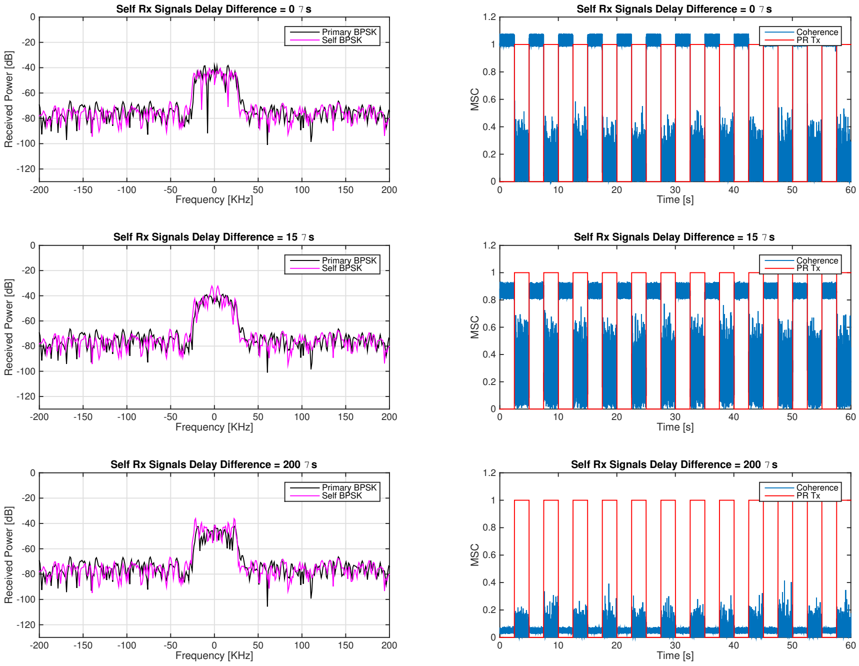
The sea state, characterized by statistics that includes wave height, period, and power spectrum, has a repercussion on roughness of scattering surface and consequently on multipath fading. Depending on swell, received signals might exhibit more or less contributions from reflections in sea surface, which can be modeled by parameter m of Nakagami PDF, as proposed on Chapter 4. Therefore, it is pertinent to evaluate the proposed solution behavior for different sea conditions, i.e. different fading intensities, as previously presented in the case of quadratic detector.

In Figures 6.14a and 6.14b, it is presented the simulation results, for primary FM and BPSK modulated signals, in cases where primary channel is affected by different fading intensity levels. Starting with a situation where (flat) sea conditions allow a strong reflection in surface and a significant contribution of reflected path ($K = 2$), which corresponds to a worst case scenario, simulation evolved towards cases where scattering reduce contribution of reflected path to overall primary received power ($K = 5$ and $K = 15$). Essentially, fading severity in primary channel has a slight influence in MSC values, and consequently, on SCD detection capacity.

Despite its relevance in communications channel, fading effect does not improve significantly the primary signal capacity to disturb MSC of received signals ($\mathcal{PR}_{off}$). Actually, a minor improvement, in detection capacity, can be noticed for FM modulated signals, but in the case of BPSK such effect is unheeded. The role of primary signal in SCD detection process is associated to a phase discompose on received signals, therefore, the relationship level of primary received signals phase (incongruence) has a limited scope. This fact might

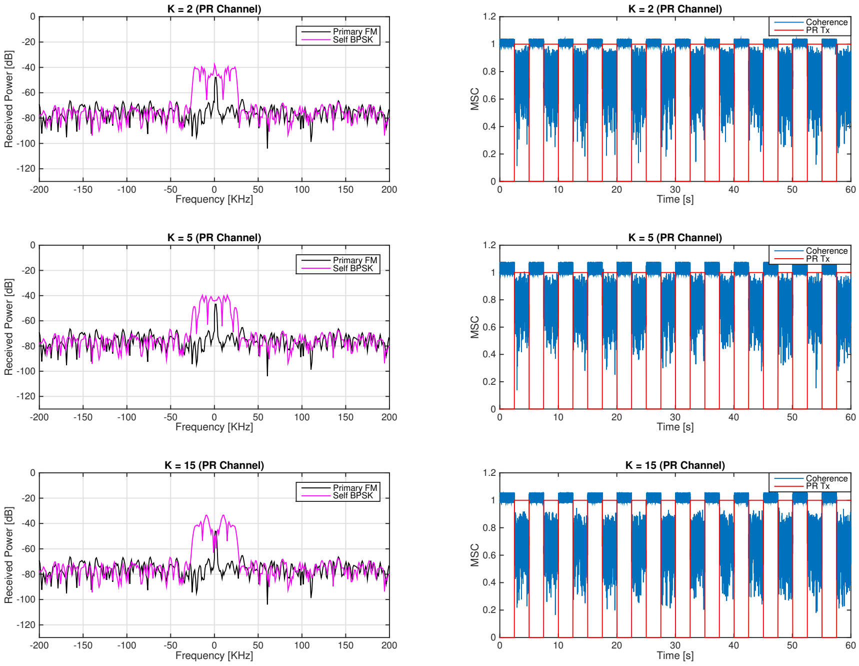


(a) Primary FM Modulated Signal

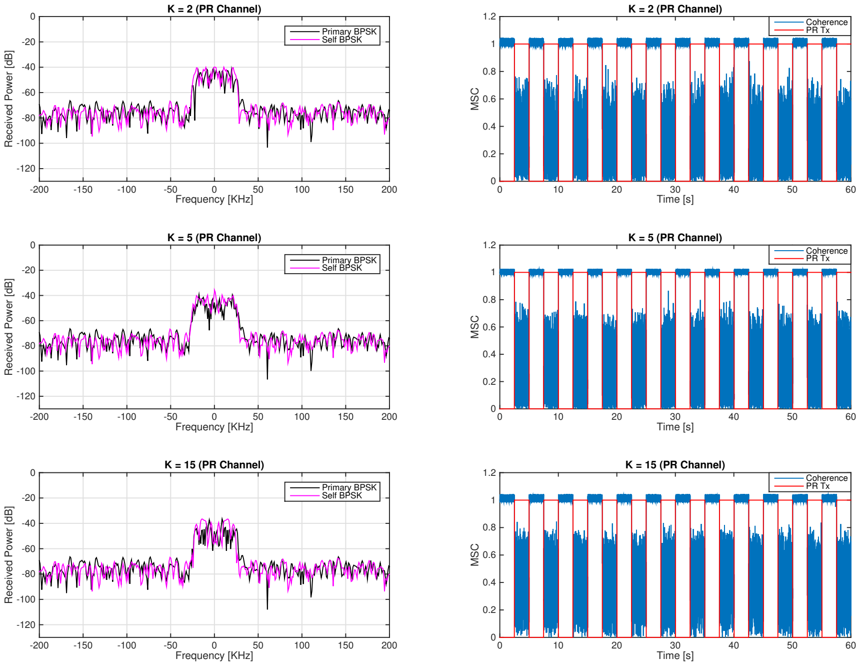


(b) Primary BPSK Modulated Signal

Figure 6.13: Self received signals delay comparison: simulation results for different delays in self received signals, at each sensing antennas, for indicated primary modulated signals.



(a) Primary FM Modulated Signal



(b) Primary BPSK Modulated Signal

Figure 6.14: Primary channel fading effect comparison: simulation results for indicated primary modulated signals over different fading intensity levels (K).

justify the results obtained in Figures 6.14a and 6.14b.

On the other hand, fading effect on self signals path is expected to be a relevant concern. The maximization of MSC (for $\mathcal{PR}_{off}$) requires a good control on relative phase of self received signals, as previously discussed, and fading is well known for being responsible for significant phase changes. Simulation results, presented in Figures 6.15a and 6.15b, evidence the consequences of fading on self received signals phase balance. These repercussions are naturally, more notorious for $\mathcal{PR}_{off}$, but indirectly affect $\mathcal{PR}_{on}$ cases.

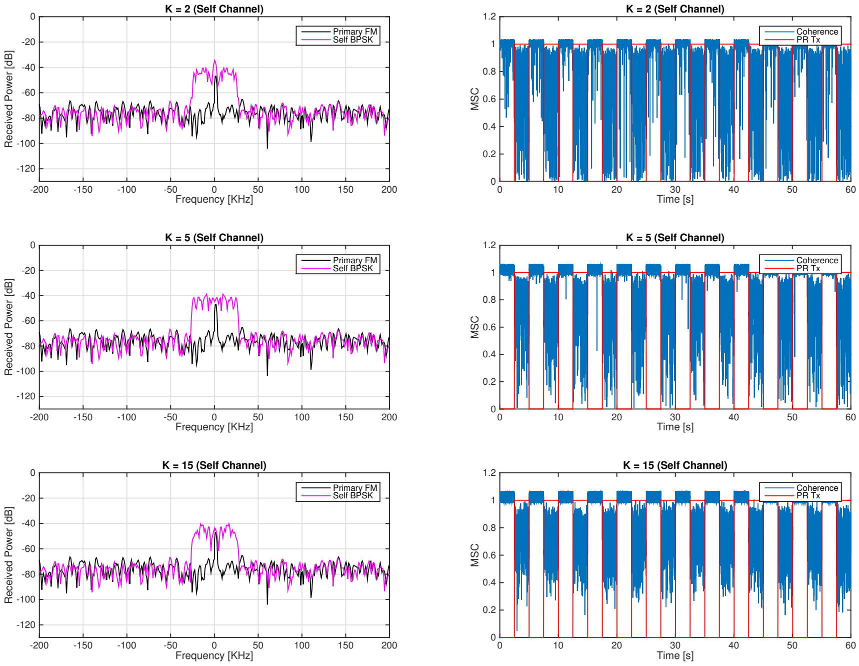
Complementary, it is opportune to briefly address doppler shift caused by ships motion, given that time-varying fading causes inter-carrier interference in multi-carrier modulation schemes, namely OFDM. In maritime environment, mobile station's velocity is relatively slow, for instance a typical vessel speed of 14 knots is equivalent to seven meters per second. Therefore, maximum doppler frequency (fD), which is a ratio of the speed of the mobile user and the wavelength of the carrier, for maritime VHF band would represent a value between 3 and 4 Hz.

In Figures 6.16a and 6.16b, it is presented the simulation results, for primary FM and BPSK modulated signals, when primary user is moving. It is considered three scenarios, where primary transmitter located in a stopped vessel and in a vessel that sails at 14 and at 40 knots. Considering a sampling frequency of 1 MHz, the correspondent normalized maximum doppler difference ($fD * Ts$) would be 0, 3μ and 10μ, respectively. Depicted results show that typical vessel speeds (up to 18 knots) do not provide relevance increasing in performance, due to additional decorrelation factor provided by doppler shift.

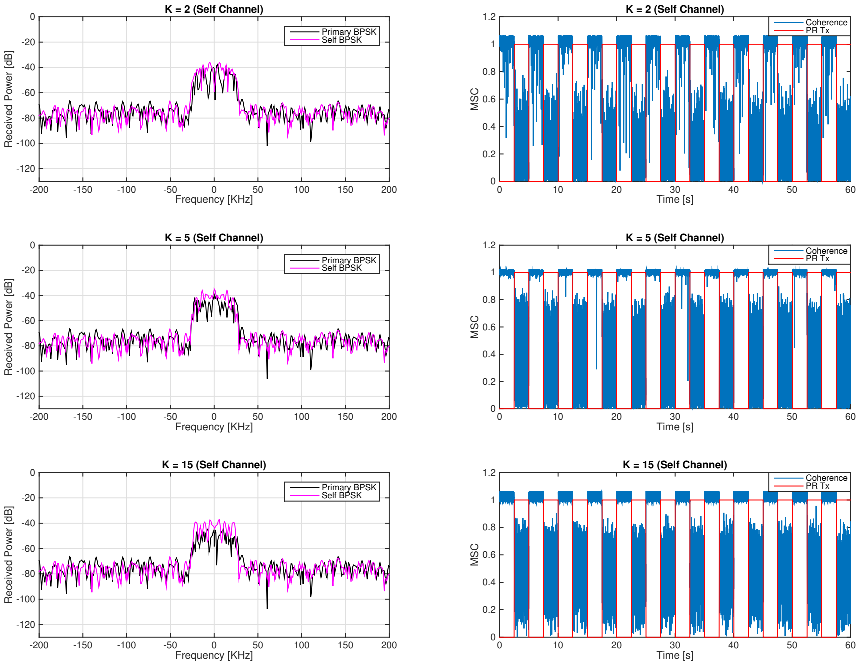
Primary User Azimuth Effect

Despite the fact that MSC value, for $\mathcal{PR}_{on}$, is mainly caused by noise and fading effects on primary received signals, it is reasonable to consider that primary user location, specifically a position with the same distance to both sensing antennas (bisecting line), might be a singularity for SCD performance. In fact, since beamforming is one of the available techniques to control self interference, it is possible that performance could be influenced by primary transmitter relative position, i.e, primary azimuth. However, maritime area of operations would be covered by complementary coastal stations and ships main activity occurs (typically) beyond 3 nautical miles range, which provide enough chance to deploy an opportunistic system that would mitigate eventual low angles undermost performance. Stations diversity and cooperative sensing can provide significant improvement on detection capacity, specially in cases where performance is a function of antennas direction.

In any case, simulation results can provide a rough indication on SCD behavior for different path delays on primary received signals, which is equivalent to have different primary user azimuth. Interesting enough, even in the case of equal delays, in both primary received branches (at both sensing antennas), results indicated that SCD performance is not affected, both for FM and BPSK modulated primary signals, as presented in Figures 6.17a and 6.17b, respectively. The justification might rely on differences in fading effects that impact each one of propagation paths.

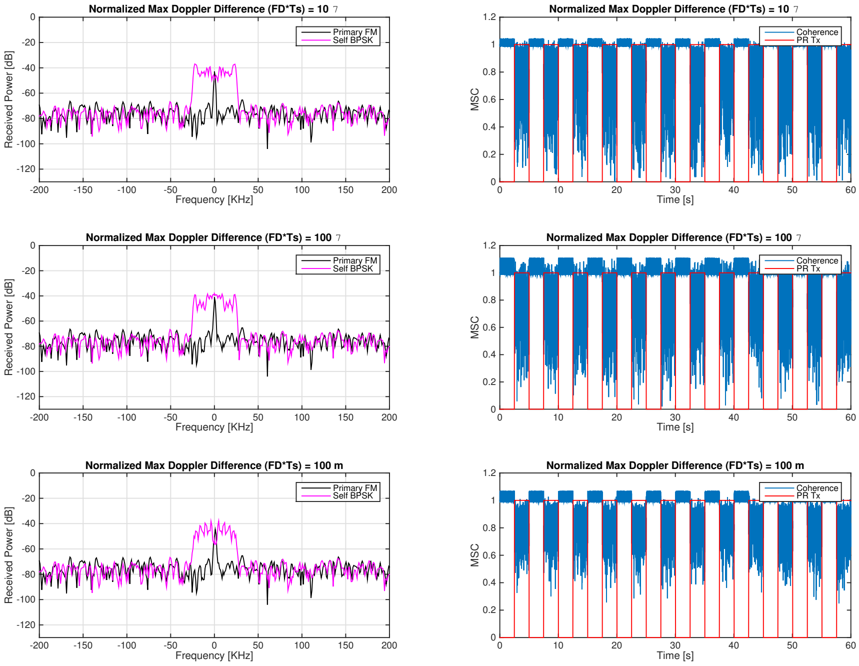


(a) Primary FM Modulated Signal

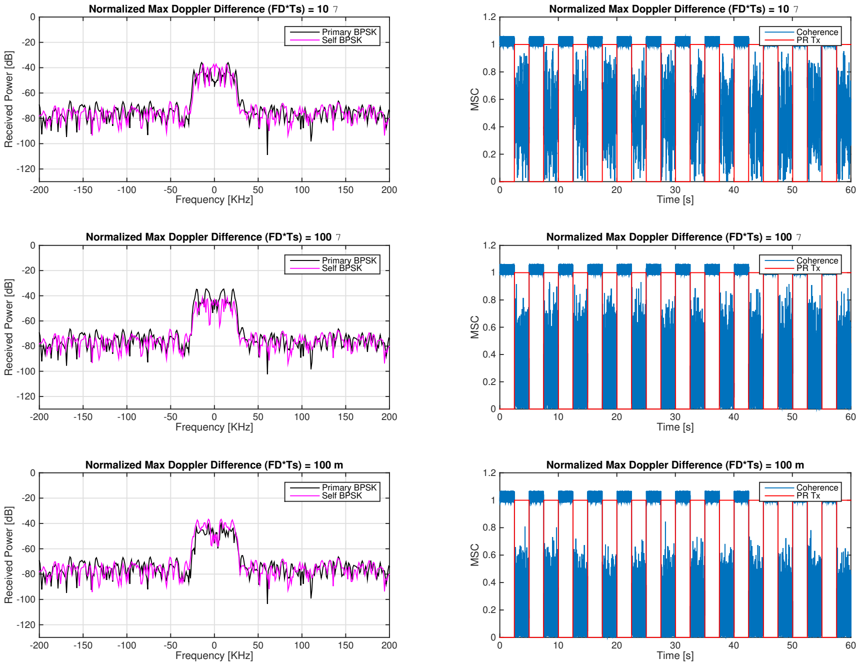


(b) Primary BPSK Modulated Signal

Figure 6.15: Self channel fading effect comparison: simulation results for indicated primary modulated signals over different fading intensity levels (K).

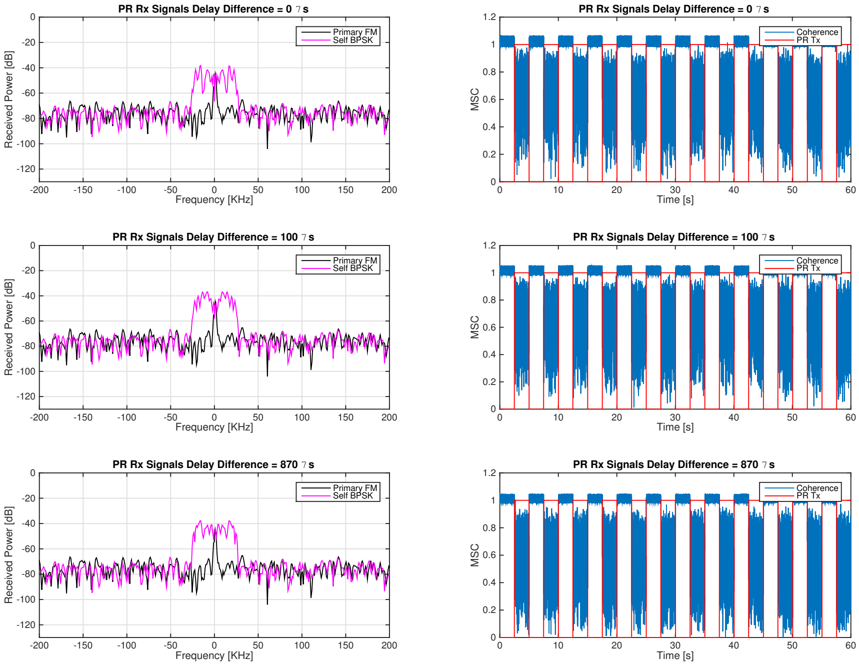


(a) Primary FM Modulated Signal

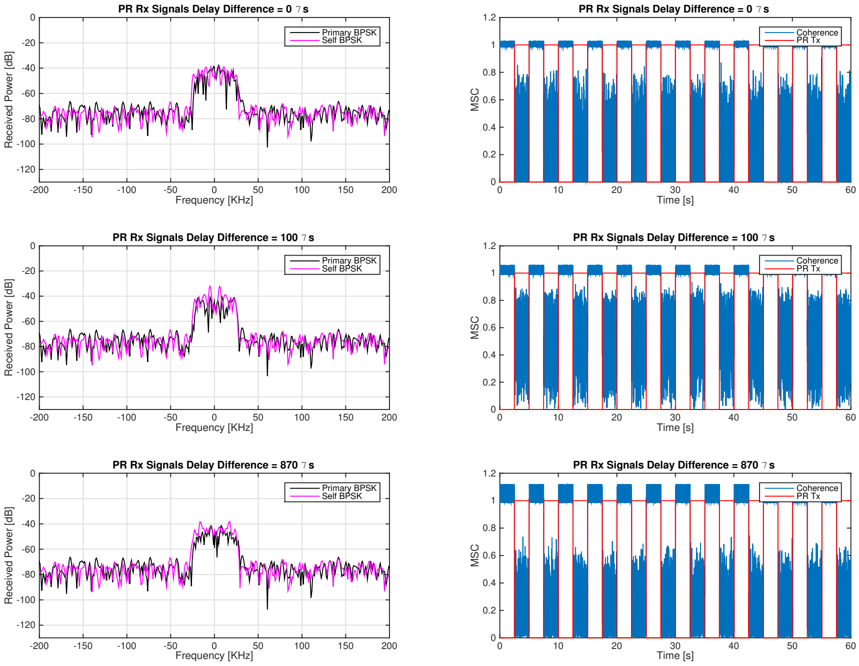


(b) Primary BPSK Modulated Signal

Figure 6.16: Doppler shift effect: simulation results for different $fDTs$, in Ricean fading, considering different vessel speeds and indicated primary modulated signals.



(a) Primary FM Modulated Signal



(b) Primary BPSK Modulated Signal

Figure 6.17: Primary azimuth comparison: simulation results for different path delays on indicated primary modulated signals, which is equivalent to have different azimuths to transmitter.

6.3 FDS Concept Development & Experimentation

The performance of FDS is difficult to characterize in abstract, due to its dependency on considered detector and SIC scheme. Despite HDS, which is focused on "sensing efficiency problem", FDS deployment can have multiple approaches and consequently several potential metrics to characterize overall performance. Even though, after previous analysis on SCD deployment challenges, it is essential to evaluate FDS operation to have a better sense for implementation details, recognizing that obtained outcomes are biased by specificity of adopted solution for SIC, which is definitively a major constraint for FDS performance. Additionally, for the sake of detection capacity evaluation, it is important to obtain some reference values to be compared with equivalent HDS performances.

Nevertheless, considering that current thesis objectives include feasibility analysis of CR-B-VHF concept and deployability of a SCD based solution for FDS, a reasonable demonstration of viability of SCD would be acceptable and, at this stage, an important milestone given the presented state of the art. Therefore, we have had architected a feasible solution, implemented a test bed and performed experimentation tests to validate the concept, in order to support both objectives: demonstrate deployability of SCD based solution for FDS and provide benchmarks to enable performance comparison with correspondent HDS.

The adopted methodology followed best practices, as those presented in [153], [154] and [155], namely an approach known as Concept Development and Experimentation (CD&E) [156], [157], to develop the concept, build up a prototype and demonstrate it experimentally. The previously discussion on FDS and SCD proposal supported the required framework within which further presented solution has been developed, and might constitute a baseline. Even though, since CD&E process employs an iterative spiral development, it is possible to pursuit improvements on this baseline according to a framework, adapted from [158], that involves progress through steps, where each iteration includes: determination of new objectives, alternatives and constraints; alternatives evaluation; identification and resolution of risks; prototyping development; testing; requirements validation; and benchmarking.

Experimentation, in this case, has two main purposes: confirm the hypothesis, providing formal validation that deployability of SCD based solution for FDS will achieve its desired aim; and provide opportunities to discover new challenges and courses of action, and indication for new experimentation. Despite the fact that former purpose is the main objective of this initiative, later goal is important in a future work context. As referred in introduction, this thesis work triggered several other initiatives, namely within Naval Research Center, which would anticipate further developments on similar topics, thus, prototypes and experimentation results are always good sources for research. Real, or near-real, environments provide a good insight for operational context and an opportunity to include extra sources of uncertainty, which are not available from other means, such as simulations.

The objective of this initiative was to build up a prototype that can be used for experimentation, in support of last phase of above mentioned CD&E process, be able to sustain theoretical considerations on SCD and allow validation of simulation outcomes. Considered solution is based on Ettus URSPs, GNU radio software and two Moxom antennas, which radiation patterns are far from being optimal, but can ensure proposed proof of concept. Complementary, a test bed has been implemented to evaluate the prototype in scenarios that can replicate maritime operational conditions and adversities, despite the lack of an ocean surface. The experimental tests have been focused on detection performance for different setups, which might be extrapolated for other situations.

6.3.1 Prototype Development

The deployment of a FDS scheme has two main conceptual constraints: CR sampling frequency and SIC. The former limitation has an impact on maximum sensing bandwidth, which in MMS should not be a problem, while later factor is definitively a major restriction for FDS performance. Even though, in the case of SCD, SIC has to ensure both amplitude and phase control, the former for dynamic range issues and the later for discrimination of MSC values, correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. Therefore, prototype development has to accommodate such requirements and incorporate adequate features to maximize detection performance.

Keeping in mind the foundations for FDS and SCD, experimental demonstration requires the implementation of a prototype that includes enough features to enable concept validation. Hence, it is assumed that exploitation of MMS opportunities, with a CR, requires a sensing block that can provide On/Off signal triggers to enable/disable secondary transmission on a given band. Therefore, proposed FDS algorithm is based on two detectors: a combined double quadratic detector, for CR transmitter enabling, and a SCD, for CR transmitter disabling. As presented in Figure 6.18, designed CR sensing block provides two actuators for radio module: an enabler for opportunistic usage (in considered spectrum), in the cases of CR system start up or after incumbents channel release, and a disabler of CR transmissions, when concurrently operation, of CR and primary users, occurs. Since FDS operation is based on the later feature, we dedicated the experimental trials to the validation of this component.

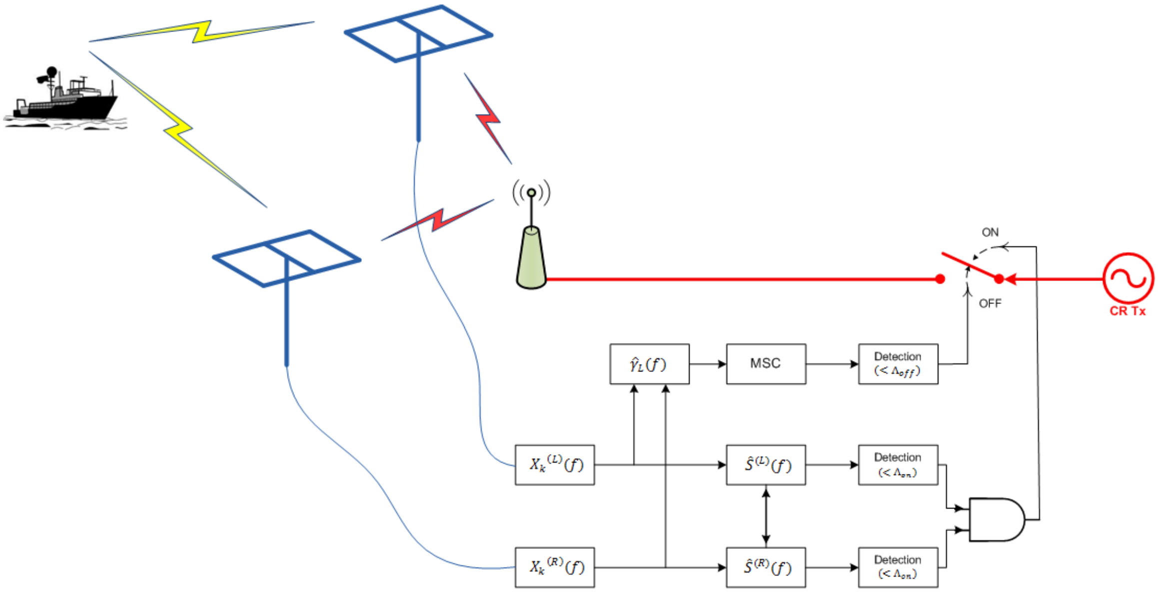


Figure 6.18: Full-Duplex sensing algorithm.

Furthermore, it is expected that MSC values at SCD output, correspondent to both $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, would have a substantial degree of variation, i. e. superimposed high frequency components, as shown in simulation results. Therefore, one can consider to apply a low pass filter, with a proper time constant (τ), to MSC block (Figure 6.18), prior to detection, in order to minimize variance and ensure a proper operation for a given threshold.

Frequently, in ordinary operation of telephony channels, which is far the most common service in MMS, there is a delay between push-to-talk button depress and operator starts to talk, so any concurrently transmission, of primary and opportunistic user, within this time frame, will not, in practice, result in a incumbent service disruption. Thus, the introduction of a low pass filter in SCD detector will potentially delay opportunistic system turn On/Off by a factor of 3 to 5 τ, which in rigorous terms would decrease spectrum opportunistic usage efficiency and increase the probability of primary service disruption. In practice, low pass filter with τ values of $10\mu s$ or even 1 ms, as depicted in Figure 6.19, would be irrelevant for services operation, but can make a whole difference in detection performance, as further demonstrated.

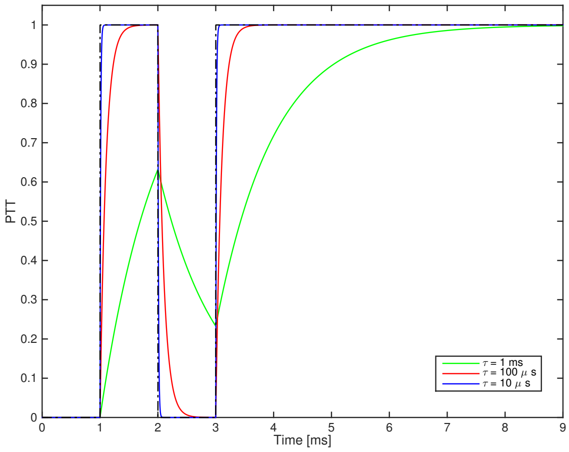
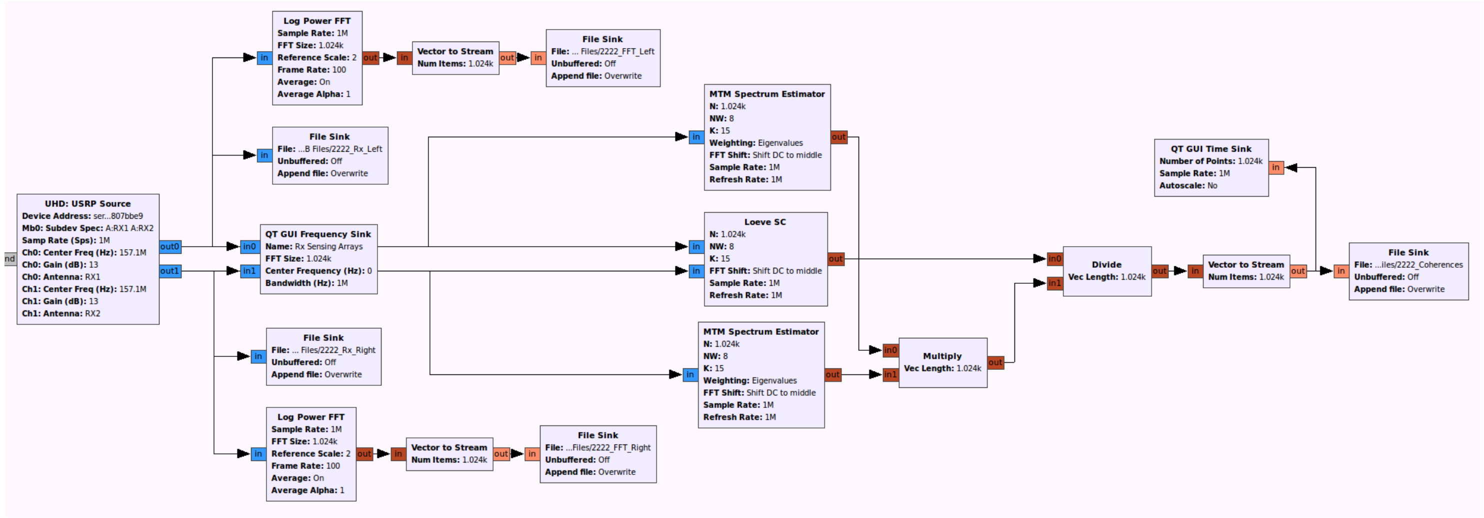


Figure 6.19: Time constants (τ) for difference low pass filters and their impact on opportunistic system turn On/Off delay.

As previously mentioned, technological support for FDS implementation is based on GNU radio software, which architecture is presented in Figure 6.20, Ettus URSPs, a wavelength monopole and two sensing arrays. Furthermore, a USRP B100 with WBX daughterboard, as presented in Figure 3.9, has been used for interfacing and DAC/ADC purposes. Finally, a SIC scheme has been designed and built on an adjustable structure with a vertical monopole for CR and two directional arrays for sensing.

Investigation performed in section 6.2 provide primordial information for SIC design, so the considered approach assumed a minimum self interference cancellation capacity and a rigorous phase control on self received signals. Due to USRPs limited transmission power (100 mW), subtractive cancellation has not been considered, due to the fact that passive isolation and beamforming would be enough to fulfill PtSR requirements. However, future operational deployments have to include additional features, as discussed in subsection 6.2.3, to reduced



UHD: USRP Source
Device Address: ser...807bbe9
Mb0: Subdev Spec: A:RX1 A:RX2
Samp Rate (Sps): 1M
Ch0: Center Freq (Hz): 157.1M
Ch0: Gain (dB): 13
Ch0: Antenna: RX1
Ch1: Center Freq (Hz): 157.1M
Ch1: Gain (dB): 13
Ch1: Antenna: RX2

Log Power FFT
Sample Rate: 1M
FFT Size: 1.024k
Reference Scale: 2
Frame Rate: 100
Average: On
Average Alpha: 1

Vector to Stream
Num Items: 1.024k

File Sink
File: ... Files/2222_FFT_Left
Unbuffered: Off
Append file: Overwrite

File Sink
File: ...B Files/2222_Rx_Left
Unbuffered: Off
Append file: Overwrite

QT GUI Frequency Sink
Name: Rx Sensing Arrays
FFT Size: 1.024k
Center Frequency (Hz): 0
Bandwidth (Hz): 1M

File Sink
File: ... Files/2222_Rx_Right
Unbuffered: Off
Append file: Overwrite

Log Power FFT
Sample Rate: 1M
FFT Size: 1.024k
Reference Scale: 2
Frame Rate: 100
Average: On
Average Alpha: 1

Vector to Stream
Num Items: 1.024k

File Sink
File: ...Files/2222_FFT_Right
Unbuffered: Off
Append file: Overwrite

MTM Spectrum Estimator
N: 1.024k
NW: 8
K: 15
Weighting: Eigenvalues
FFT Shift: Shift DC to middle
Sample Rate: 1M
Refresh Rate: 1M

Loeve SC
N: 1.024k
NW: 8
K: 15
FFT Shift: Shift DC to middle
Sample Rate: 1M
Refresh Rate: 1M

MTM Spectrum Estimator
N: 1.024k
NW: 8
K: 15
Weighting: Eigenvalues
FFT Shift: Shift DC to middle
Sample Rate: 1M
Refresh Rate: 1M

Multiply
Vec Length: 1.024k

Divide
Vec Length: 1.024k

Vector to Stream
Num Items: 1.024k

QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 1M
Autoscale: No

File Sink
File: ...iles/2222_Coherences
Unbuffered: Off
Append file: Overwrite

Figure 6.20: SCD implementation in GNU Radio. Collected data is saved on a file (File Sink) for offline analysis.

self interference, which transmitting power are expected to go up 25W. Additionally, self coherence control, which is specific for SCD deployment and independent from PtSR issues, has been assured through a manufactured antenna assembly that permits an adequate relative positioning of all units and a rigorous distance, between transmitting antenna and sensing arrays, in order to control received phases. Figure 6.21 shows the layout of antenna assembly, which includes adjustable screws that permit a fine tune on distance between antennas.

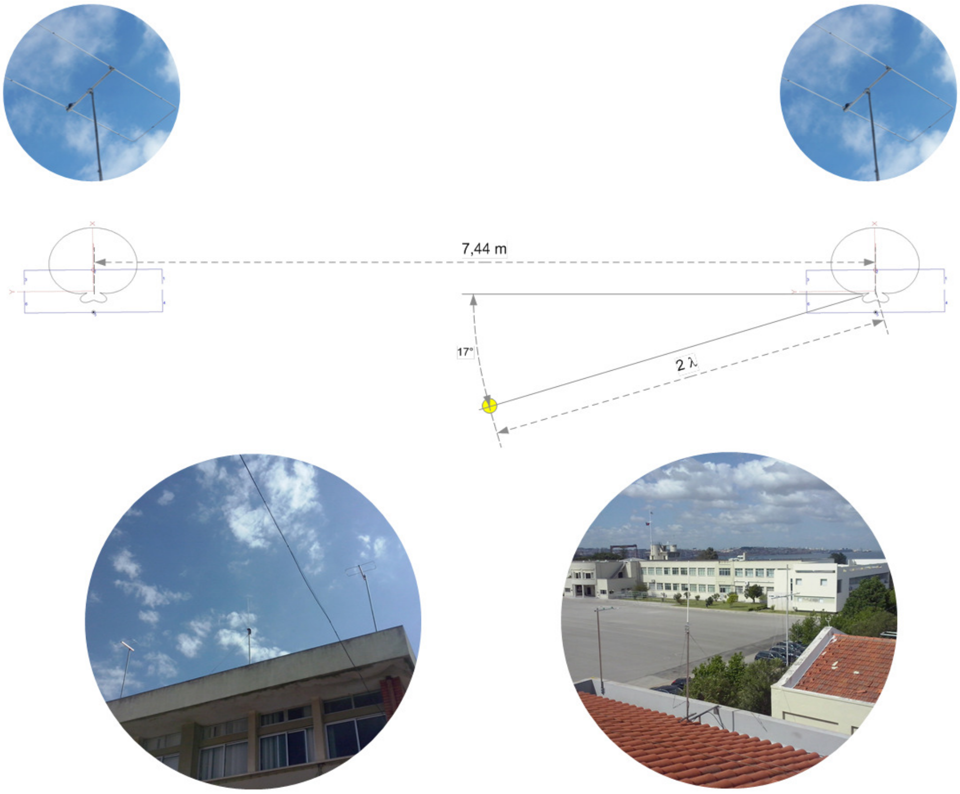


Figure 6.21: SIC antennas layout

The antenna setup includes a CR transmitting/receiving antenna and two sensing arrays, as depicted in Figure 6.21, where CR antenna is a wavelength vertical monopole, for maritime VHF band, and sensing arrays are directional, with a minimum in CR antenna azimuth. Nevertheless, considering maritime CR-B-VHF system architecture, presented in Chapter 3, it is expected that, in most cases, shore based radio stations would operate in a sector of 180°, so there is a significant degree of freedom to design an array with a decent spatial filtering of self interference signals. In any case, for the sake of current demonstration, it has been considered to use Moxom antennas, which radiation patterns, presented in Figure 6.22, can provide, not only the required isolation, between CR and sensing antennas, but also appropriate radiation patterns to maximize opportunistic link footprint (monopole) and control azimuth gain of sensing arrays, thus ensuring proposed proof of concept.

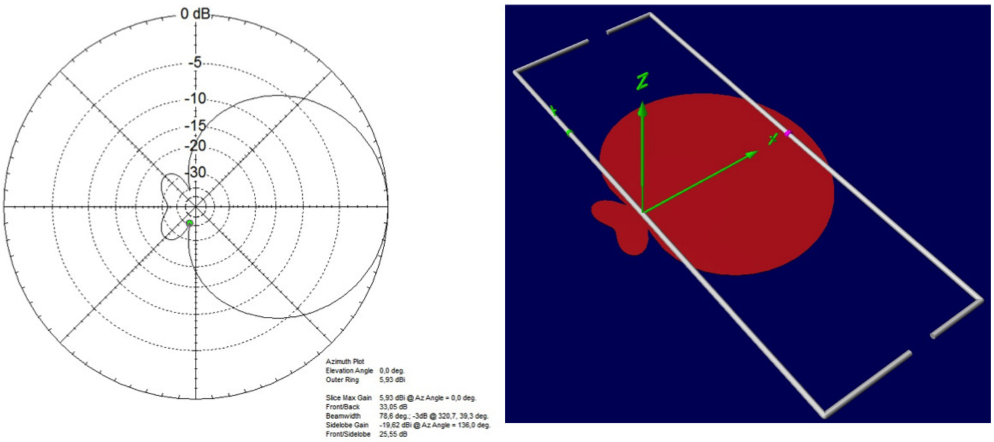


Figure 6.22: Moxom antennas radiation pattern.

6.3.2 Cognitive Radio Test Bed for Maritime Applications

Practical evaluation of developed prototype requires a test bed with minimum conditions to mimic fundamental challenges of operational context. Unfortunately, maritime environment experimentation post significant logistic and financial constraints, which can result in time and scope limitations that jeopardize entire initiatives. There is a compromise, between test practicability and scenario adequacy, which has to be considered pragmatically. As a result, a test bed has been implemented at Escola Naval, which environment is depicted in Figure 6.23.

Despite the lack of a sea water surface, ”ships” (primary users antennas) proximity and existence of several buildings, testing conditions clearly provide enough maritime analogous radio challenges to ensure a decent variety of experiments. In addition to wide parade ground, clear LOS links (in different azimuths) between antennas and transmission power control, it is possible to perform trials with real maritime VHF radios and with GNU radio based implementations for FM modulated voice and BPSK modulated data.

The testing facility setup considered a scenario of a coastal radio station and three ships located in different azimuths. A monopole (CR Tx) and two sensing arrays (blue rectangles) have been installed in order to emulate an shore based opportunistic system and a set of monopoles at three sites (Tx Site 1 to 3) that would represent primary users locations. The idea is to take advantage of different azimuths and distances to evaluate spatial impact and different fading on detection and play with transmitters power to pretend different distances from sensing arrays.

As represented in Figure 6.24, opportunistic system is implemented in GNU radio and uses USRPs for sensing and transmitting, while primary systems can be deployed through a maritime VHF radio or GNU radio implementations of FM and BPSK modulated signals. It is considered that CR transmitter opportunistically operates a 25 KHz channel with a BPSK modulated signal and a primary transmitter that uses the same channel with a 6KHz bandwidth FM modulated voice signal or 12.5 KHz BPSK modulated signal. The bandwidth restriction of 12.5 KHz, in the case of primary BPSK signals, results from USRP power constraints, which cannot ensure an adequate received power level to perform tests with

Figure 6.23: Testing environment in Escola Naval.

25KHz from antennas locations. Interesting enough, the main constraint in this setup is power: maritime VHF radios have only two available power options (1 and 25 W) and USRP have output power limitations. Consequently, CR transmitted power is not enable to test full scale dynamic range response (PtSR) and weak primary signals have to be simulated with GNU radio implementations only.

The GNU radio implementation of test bed components for FDS experimentation is presented in Figure 6.25. Essentially, FDS algorithm is depicted in the bottom part of figure, while upper part refers to CR, which continuously transmits random data with a BPSK modulator.

6.3.3 Experimentation Tests

Experimentation is the best way to evaluate performance and system design constraints. In this case, the focus is on viability of SCD based FDS and performance indicators, rather than absolute values. The objective is to carry out a feasibility analysis on SCD, based on experimentation trials that can point out aptitudes and limitations to draw guidelines for further developments on system components. Given that practical overall FDS outcome is highly conditioned by deployed solution, it is essential to address field testing and its outcomes

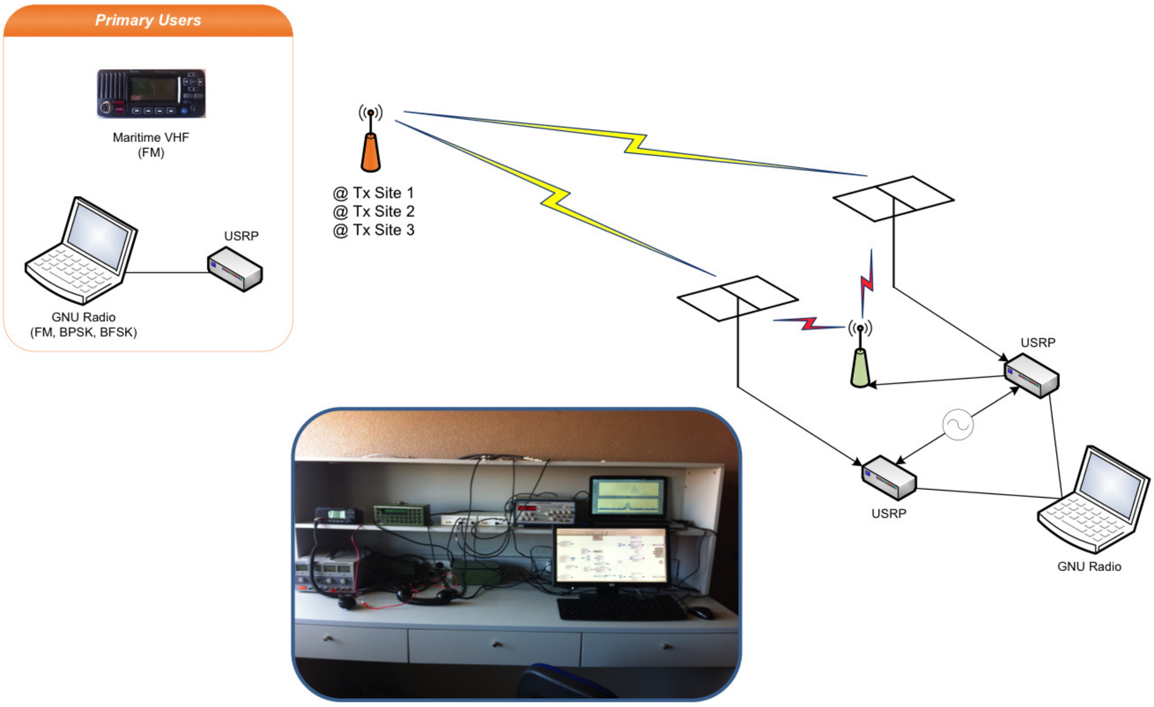


Figure 6.24: Test bed: Radio assets architecture for opportunistic system and primary systems.

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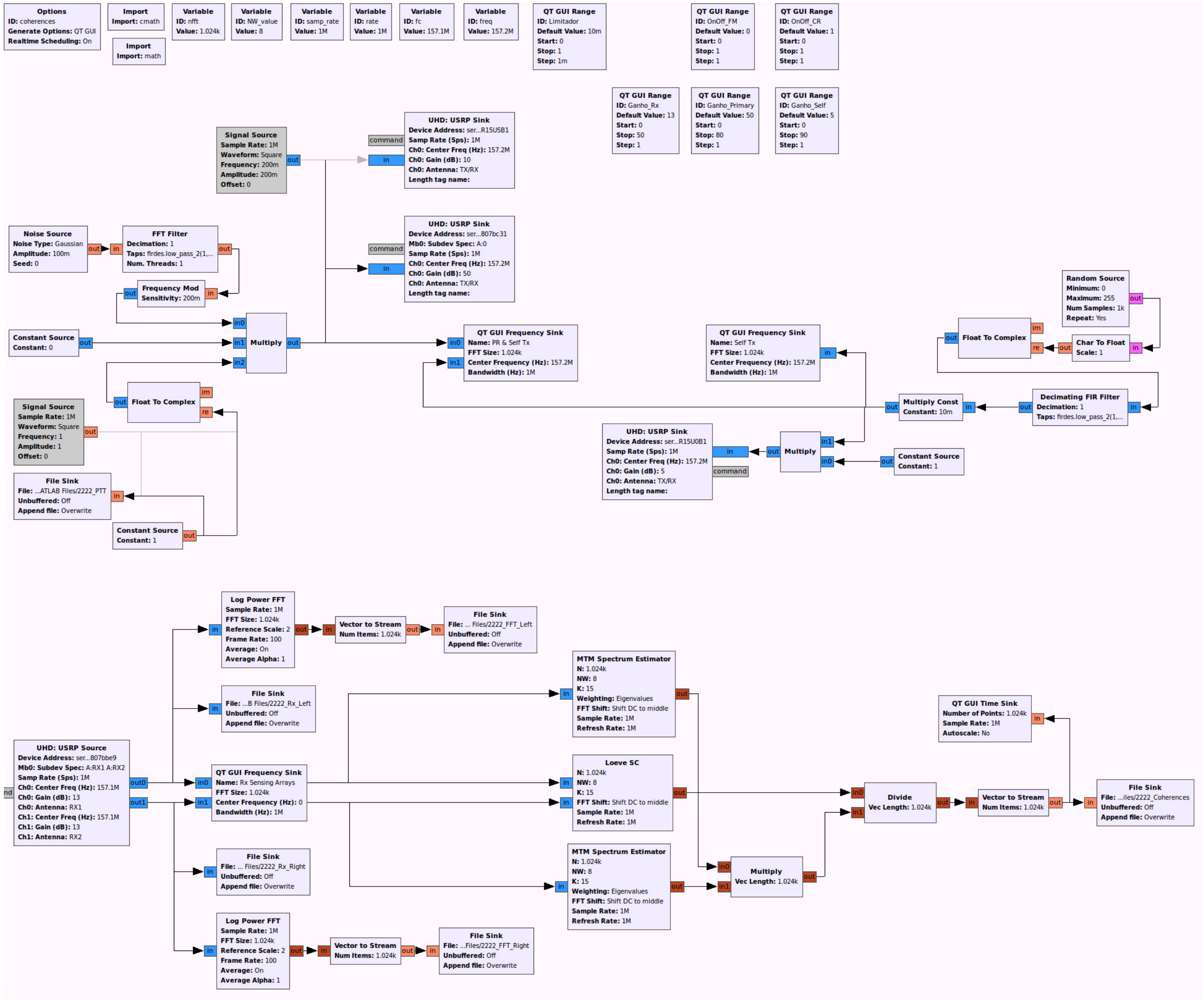
in such a way that implemented SIC scheme impact can be as neutral as possible.

The assessment metrics that has been considered was ROC, not only do to its universality, but also to have a simple way to compare performances with reference values of energy and quadratic detectors, for similar conditions. Taking primary received signal power and a PtSR, as referential parameters, results comparison become transparent to SIC scheme. Note that, in those field tests, CR transmission power is not an issue, so it can be reduced to accommodate required values and ratios.

The main aspects to measure out are naturally associated with identified sensor dynamic range, SIC effectiveness and primary user azimuth effects. Hence, three locations, for primary transmission, have been defined, as presented in Figure 6.23, in order to have an interesting variety of testing conditions and overcome power control limitations. Additionally, it was consider to use short wires for antennas, with maritime VHF radios, to have an extra degree of freedom in transmission power reduction.

The detection and false alarm inventory requires synchronization between FDS detector and primary user transmission, in order to ensure rigorous evaluation of events. For high power levels, the duty cycle of primary service has a clear footprint on MSC value, like in the example presented in Figure 6.26. During CR operation, a SCD operation checking procedure has been performed with a maritime VHF radio transmitting 1W (FM) without antenna (for a dummy load), located in laboratory bench, which is located in the deck bellow sensing arrays. The result has been recorded and presented in Figure 6.26, where, due to high received power, it is possible to obtain a clear picture of push-to-talk duty cycle of primary radio. However, for lower received power cases, it is not expected to have such clear



Options
ID: coherences
Generate Options: QT GUI
Realtime Scheduling: On

Import
Import: cmath

Import
Import: math

Variable
ID: nfft
Value: 1.024k

Variable
ID: NW_value
Value: 8

Variable
ID: samp_rate
Value: 1M

Variable
ID: rate
Value: 1M

Variable
ID: fc
Value: 157.1M

Variable
ID: freq
Value: 157.2M

QT GUI Range
ID: Limitador
Default Value: 10m
Start: 0
Stop: 1
Step: 1m

QT GUI Range
ID: OnOff_FM
Default Value: 0
Start: 0
Stop: 1
Step: 1

QT GUI Range
ID: OnOff_CR
Default Value: 1
Start: 0
Stop: 1
Step: 1

QT GUI Range
ID: Ganho_Rx
Default Value: 13
Start: 0
Stop: 50
Step: 1

QT GUI Range
ID: Ganho_Primary
Default Value: 50
Start: 0
Stop: 80
Step: 1

QT GUI Range
ID: Ganho_Self
Default Value: 5
Start: 0
Stop: 90
Step: 1

Signal Source
Sample Rate: 1M
Waveform: Square
Frequency: 200m
Amplitude: 200m
Offset: 0

UHD: USRP Sink
Device Address: ser...R15U5B1
Samp Rate (Sps): 1M
Ch0: Center Freq (Hz): 157.2M
Ch0: Gain (dB): 10
Ch0: Antenna: TX/RX
Length tag name:

Noise Source
Noise Type: Gaussian
Amplitude: 100m
Seed: 0

FFT Filter
Decimation: 1
Taps: firdes.low_pass_2(1,...
Num. Threads: 1

Frequency Mod
Sensitivity: 200m

UHD: USRP Sink
Device Address: ser...807bc31
Mb0: Subdev Spec: A:0
Samp Rate (Sps): 1M
Ch0: Center Freq (Hz): 157.2M
Ch0: Gain (dB): 50
Ch0: Antenna: TX/RX
Length tag name:

Constant Source
Constant: 0

Multiply

QT GUI Frequency Sink
Name: PR & Self Tx
FFT Size: 1.024k
Center Frequency (Hz): 157.2M
Bandwidth (Hz): 1M

QT GUI Frequency Sink
Name: Self Tx
FFT Size: 1.024k
Center Frequency (Hz): 157.2M
Bandwidth (Hz): 1M

Random Source
Minimum: 0
Maximum: 255
Num Samples: 1k
Repeat: Yes

Float To Complex

Char To Float
Scale: 1

Float To Complex

Signal Source
Sample Rate: 1M
Waveform: Square
Frequency: 1
Amplitude: 1
Offset: 0

Multiply Const
Constant: 10m

Decimating FIR Filter
Decimation: 1
Taps: firdes.low_pass_2(1,...

UHD: USRP Sink
Device Address: ser...R15U0B1
Samp Rate (Sps): 1M
Ch0: Center Freq (Hz): 157.2M
Ch0: Gain (dB): 5
Ch0: Antenna: TX/RX
Length tag name:

Multiply

Constant Source
Constant: 1

File Sink
File: ...ATLAB Files/2222_PTT
Unbuffered: Off
Append file: Overwrite

Constant Source
Constant: 1

Log Power FFT
Sample Rate: 1M
FFT Size: 1.024k
Reference Scale: 2
Frame Rate: 100
Average: On
Average Alpha: 1

Vector to Stream
Num Items: 1.024k

File Sink
File: ... Files/2222_FFT_Left
Unbuffered: Off
Append file: Overwrite

MTM Spectrum Estimator
N: 1.024k
NW: 8
K: 15
Weighting: Eigenvalues
FFT Shift: Shift DC to middle
Sample Rate: 1M
Refresh Rate: 1M

File Sink
File: ...B Files/2222_Rx_Left
Unbuffered: Off
Append file: Overwrite

QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 1M
Autoscale: No

UHD: USRP Source
Device Address: ser...807bbe9
Mb0: Subdev Spec: A:RX1 A:RX2
Samp Rate (Sps): 1M
Ch0: Center Freq (Hz): 157.1M
Ch0: Gain (dB): 13
Ch0: Antenna: RX1
Ch1: Center Freq (Hz): 157.1M
Ch1: Gain (dB): 13
Ch1: Antenna: RX2

QT GUI Frequency Sink
Name: Rx Sensing Arrays
FFT Size: 1.024k
Center Frequency (Hz): 0
Bandwidth (Hz): 1M

Loeve SC
N: 1.024k
NW: 8
K: 15
FFT Shift: Shift DC to middle
Sample Rate: 1M
Refresh Rate: 1M

Divide
Vec Length: 1.024k

Vector to Stream
Num Items: 1.024k

File Sink
File: ...iles/2222_Coherences
Unbuffered: Off
Append file: Overwrite

File Sink
File: ... Files/2222_Rx_Right
Unbuffered: Off
Append file: Overwrite

MTM Spectrum Estimator
N: 1.024k
NW: 8
K: 15
Weighting: Eigenvalues
FFT Shift: Shift DC to middle
Sample Rate: 1M
Refresh Rate: 1M

Multiply
Vec Length: 1.024k

Log Power FFT
Sample Rate: 1M
FFT Size: 1.024k
Reference Scale: 2
Frame Rate: 100
Average: On
Average Alpha: 1

Vector to Stream
Num Items: 1.024k

File Sink
File: ...Files/2222_FFT_Right
Unbuffered: Off
Append file: Overwrite

Figure 6.25: GNU Radio implementation of test bed components for FDS evaluation.

transitions, which recommends detection synchronization.

Additionally, due to fundamentals on SCD operation, it was considered to perform detection in an intermediate frequency of 100 KHz. Essentially, its has been verified that coherence detection of baseband signals under-performs modulated signals. The carrier presence in (CR) digital modulated signals provides an extra attribute to balance/unbalance MSC value.

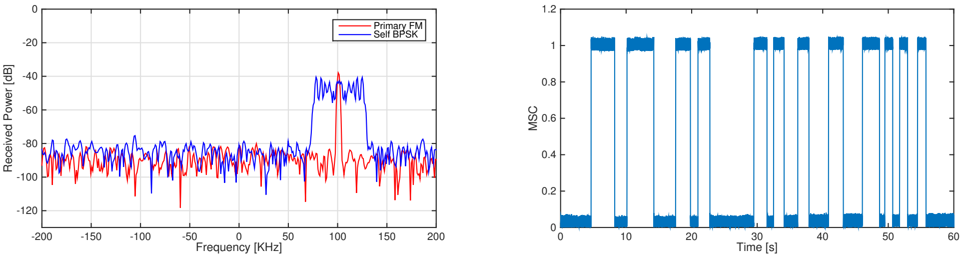
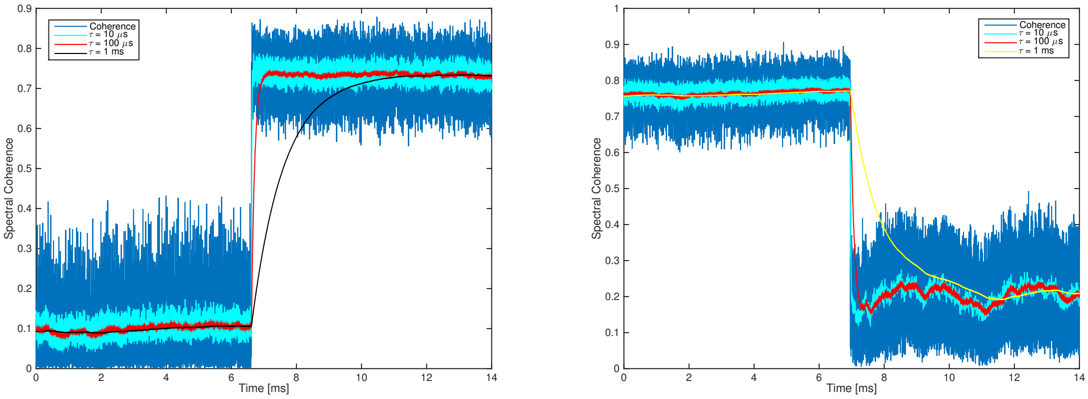


Figure 6.26: SCD operation checking procedure, for a maritime VHF radio, with dummy load, transmitting 1W (FM) from lab bench.

There are several available options to synchronize primary transmission with detection, most of then introducing extra complexity that is dispensable. The adopted procedure is quite simple: manual start/stop synchronization, by two radio operators, enables simultaneous CR and primary radio operation periods of 60 seconds, interleaved by CR only operation periods of the same duration. Given that data recording has been started after confirmation of radio transmission, as long as each trial record finishes before radio transmission, there is no need for additional synchronization. These allows data recording for multiple periods (and transitions) exclusive and concurrent operation of, CR and primary, radios on a single channel, using the same or different modulation schemes.

In the following paragraphs, we present experimentation results that have been collected for primary transmitters located in three different locations. Several combinations of primary and self received powers have been used for both primary FM and BPSK modulated signals, considering that opportunistic system is operating a 25KHz bandwidth BPSK modulated signal. Presented results include snapshots of received power spectrum and spectral coherence values correspondent to unfiltered MSC at SCD output and filtered versions with low pass filters with $\tau = 10\mu s, 100\mu s$ and 1 ms. The idea is to compare performance (depicted in ROC graphs) of SCD when spectral coherence is filtered and transitions on $\mathcal{PR}_{on}/\mathcal{PR}_{off}$ and $\mathcal{PR}_{off}/\mathcal{PR}_{on}$ are delayed, which effect is depicted in Figure 6.27. Moreover, for comparison purposes, all the ROC graphs have plotted curves for energy (black dashed line) and quadratic (black line) detectors, in Ricean channels (Nakagami $m = 2$) and received SNR $=10dB$.

Regarding ROC curves, presented in the same figure, it is introduced a set of additional plots that correspondent to low pass filters where transition points are not considered in P_{md} and P_{fa} calculation (labeled as Cut). The idea is to exclude, from detection counting, the points that correspond to instantaneous transitions, in order to reflect numerically what would be the practical result of detection capacity. Anyway, this is simply for the sake of distinction between a numerical counting and what can be expected in a practical observation.



(a) $\mathcal{PR}_{on}/\mathcal{PR}_{off}$ transition

(b) $\mathcal{PR}_{off}/\mathcal{PR}_{on}$ transition

Figure 6.27: The MSC filtering effect on SCD output: unfiltered output (blue) variance can be minimized using a low pass filter with a time constant τ.

Primary User at Transmitter Site Nr.1

In this experiment, a maritime VHF radio has been used, to transmit FM modulated voice signals with 1W (minimum selected power). Given site proximity, two short wires have been used as antennas, as presented in Figure 6.28, in order to reduce primary received signals power. The objective of this setup is to evaluate prototype performance for different PtSR in a context of wide primary user azimuth and enabling parade ground reflection, as presented in Figure 6.23.

For a fixed primary received power of -52 dB, it has been considered a set of values for CR transmission power in order to have -5 $\leq$ PtSR $\leq$ 20 dB. Figure 6.29 presents snapshots of received power spectrum, MSC values obtained for several trials and their associated ROCs, correspondent to unfiltered MSC at SCD output and three different time constants, for low pass filter. A brief note on spikes observed in MSC plots ($\mathcal{PR}_{on}$) to clarify that those have been resulted from power supply fluctuations, which occasionally occurred during tests, due to external overloads.

The field tests confirmed what has been stated before, regarding self received power. Fading and delay control imperfections on self received signals decrease average value of MSC, for $\mathcal{PR}_{off}$, and increase variance, so self received signals power is the way to overcome such inconvenience, and contribute for a better discrimination of MSC values correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. On the other hand, for $\mathcal{PR}_{on}$, PtSR is the main cause of MSC disturbance. Severe fading and delay (and amplitude) difference of primary received signals break coherence of self signals and such preponderance is proportional to PtSR. However, the combination of these behaviors can produce interesting and unexpected results, when primary signals received power is enough to bias MSC.

Surprisingly, or not, best performances do not correspond to higher PtSR, as one initially might anticipate. In fact, is the other way around. Considering that PtSR increase is based on a reduction of self received power, instead of being caused by an increasing on primary signals, the reduction of MSC average and increasing of variance caused an overlap on MSC values

Figure 6.28: Maritime VHF radio with short wire acting as an antenna, for transmitting power control.

correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, which prevent a clear separation of values by a threshold. Despite the fact that high values of PtSR reduce the MSC mean and variance, for $\mathcal{PR}_{on}$, such effect cannot counterbalance the reduction of MSC average and increasing of variance ($\mathcal{PR}_{off}$), which results in a detection capacity degradation. In any case, performances are clearly better than expected values for energy and quadratic detectors, operating in Ricean fading with an SNR = 10dB. Specially for practical purposes (suppressed transition samples), it is possible to draw a separation line for MSC values that correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$.

Afterwards, primary received power is reduced to -70dB, by using a very short wire for antenna purposes, and previous trials are repeated. Obtained results, showed in Figure 6.30, present similar behavior, but performance is naturally much worse. As in the previous case, PtSR increases by reducing self received power, so detection capacity increases as PtSR decreases, until it reaches a break point, where primary signal is unable to destabilize MSC value and push down its value. In this case, there is a combination of negative impact of mean and variance on MSC values for $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, which result in MSC values overlap, for both primary operational conditions. The first set of trials (PtSR = -20dB) corresponds to a situation where self received power is enough to ensure a high MSC mean value and reduced variance, for $\mathcal{PR}_{off}$, but reduced primary received power, i.e. PtSR, is not enough to disturb spectral coherence of self received signals. The performance is obviously poor. On the other hand, as self received power is reduced, the average value of MSC is also decreased and variance increases, causing a significant overlap on MSC values for $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. Even though, filtered versions of MSC can steel be separable, for $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$.

These experimentation outcomes revealed an interesting fact regarding signals' spectral coherence. Despite simulations indications, the matter-of-fact is that MSC of received signals tend to be low, due to noise and fading effects. Typically, most of the simulated events have presented an high degree of spectral coherence, which has been, more or less, biased by uncorrelated contributions. Nevertheless, overall values tend to be relatively high. On the contrary, experimentation revealed that spectral coherence values tend to be low. Even in the case of self received signals, where transmitting (CR) and receiving (sensing) antennas are

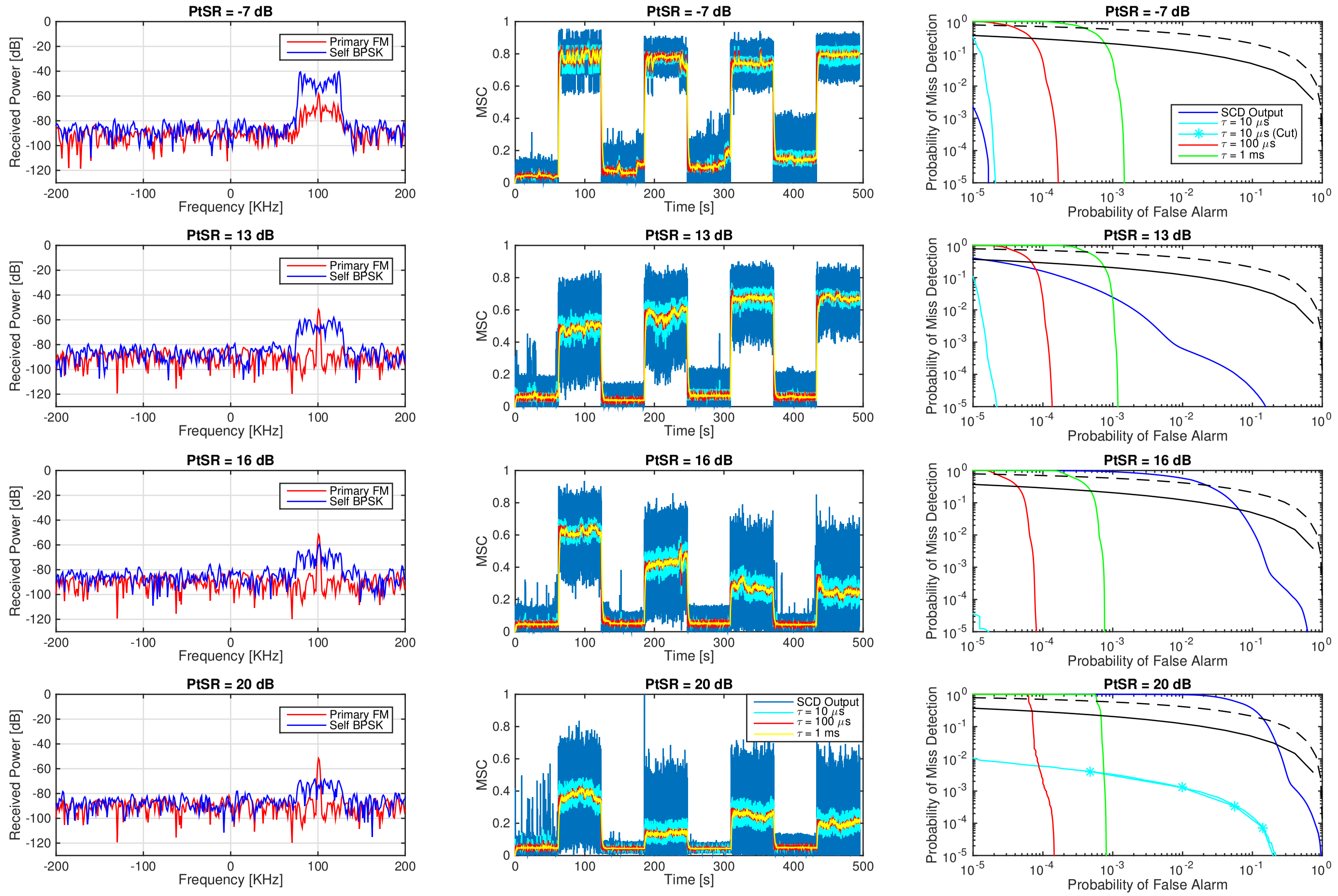


Figure 6.29: Tx Site Nr.1: Spectrum snaphots, coherences values and ROCs, for a maritime VHF radio, transmitting on a short wired antenna and using FM modulated voice signals of 6KHz.

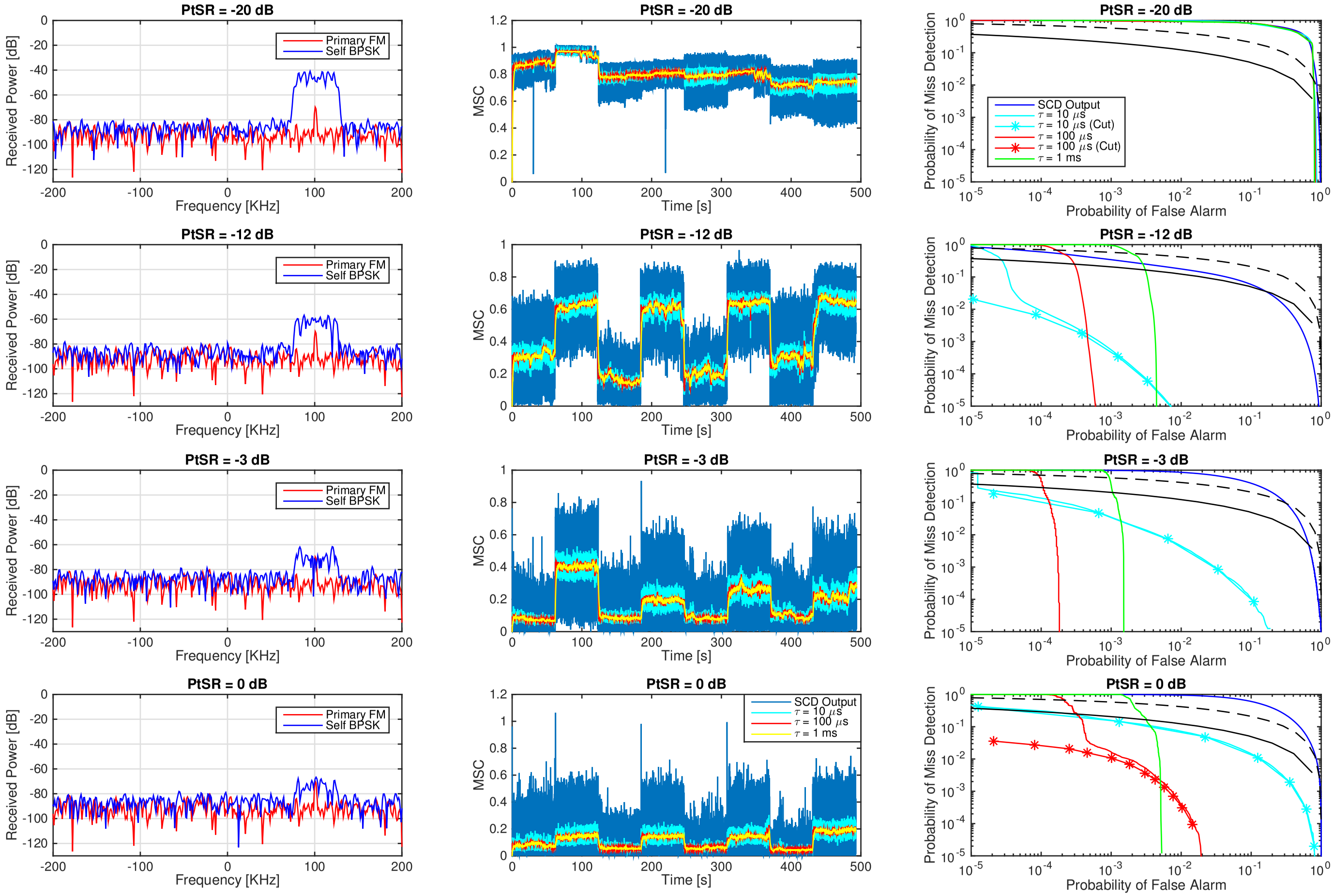


Figure 6.30: Tx Site Nr.1: Spectrum snaphots, coherences values and ROCs, for a maritime VHF radio, transmitting on a very short wired antenna and using FM FM modulated voice signals of 6KHz.

very close, fading effects have to be defeated with power. Typically, during $\mathcal{PR}_{off}$, practical response indicated average MSC lower than 1 and significant variance and in primary signal presence ($\mathcal{PR}_{on}$), MSC tend to be close to zero, with a variance that is proportional to primary received power.

A final remark on curves that correspond to filtered MSC values, which do no appear in presented plots. The practical consequences of such filtering is a perfect detection of primary activity, so the P_{md} and P_{fa} are always zero.

Primary User at Transmitter Site Nr.2

The Tx Site Nr.2, represented in Figure 6.23, has been deployed to grant permission to investigate primary user azimuth effect on detection performance. Unfortunately, it was not possible to install antenna, exactly, in the bisecting line of sensing arrays, but the angle is not far from 90°. In any case, angular difference and close distance to prototype transmitting antenna provide good enough conditions to understand desired effect.

An USRP has been used to transmit FM modulated voice signals (6 KHz) and BPSK data (12.5 KHz) in order to simulate weak primary signals. Sensing arrays proximity requires a good power control and maritime VHF radio minimum selectable transmitting power is far to high. On the other hand, USRP and GNU radio allowed experimentation trials using digital data, despite power limitations that imposed 12.5 KHz bandwidth.

Previous experiment has been repeated for this site with slight differences is settings. The primary received power was fixed in -70 dB and prototype transmitting power has been tuned in order to obtain a PtSR between -12 dB and 3 dB. The fading effect is expected to be different, not only because the distances are quite different, but also due to environment context, within radio path. Despite builds around, in the former case, there is a clear LOS and a parade ground between primary antenna and sensing arrays, while in this case antennas are roof mounted, in two different buildings very close to each other, as depicted in Figure 6.23. This evidence would highlight any primary azimuth effect on detection performance, caused by small difference in primary signals propagation paths.

Curiously, trials results, presented in Figures 6.31 and 6.32, showed no azimuth effect. Despite the clear improvement in detection performance, associated to less severe fading effects, there are no indications of detection capacity degradation due to primary azimuth. Fading effects seem to overcome any delay match that potentially would be verified in the case of propagation paths equivalence.

Another interesting observation is the practical effects of fading severity. Previous and current trials experienced difference fading channels. In the former, propagation channel conditions potentiate many reflected paths with equivalent gains, while the later, due to antennas location (roof top) and proximity, is less susceptible to such diverse contributions. As observed in ROCs presented in Figures 6.30 and 6.31, detection capacity is highly correlated with fading severity. In any case, such scenarios are far from reproducing a maritime typical propagation environment, in terms of fading severity, but can provide good indications regarding expected performances and have the merit of representing (quite) worst cases.

Additionally, a set of trials have been performed using 12.5 KHz bandwidth BPSK modulated signals, at primary user side. In this case, primary received signals amplitude has been reduced to -77 dB, to counteract higher potential of broader digital modulated signals

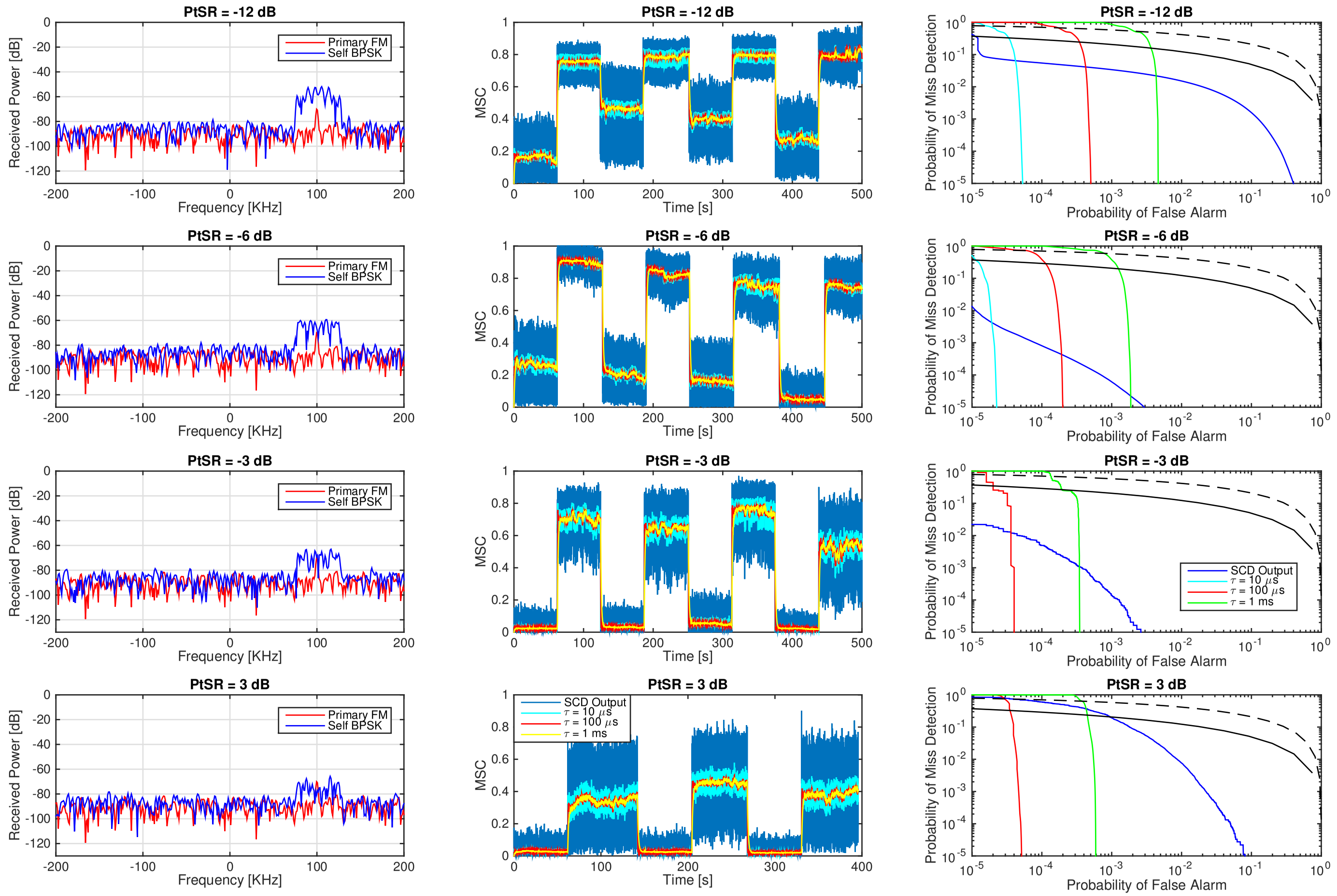


Figure 6.31: Tx Site Nr.2: Spectrum snaphots, coherences values and ROCs, for a GNU Radio and USRP implementation of FM modulated voice signals of 6KHz, using a monopole antenna.

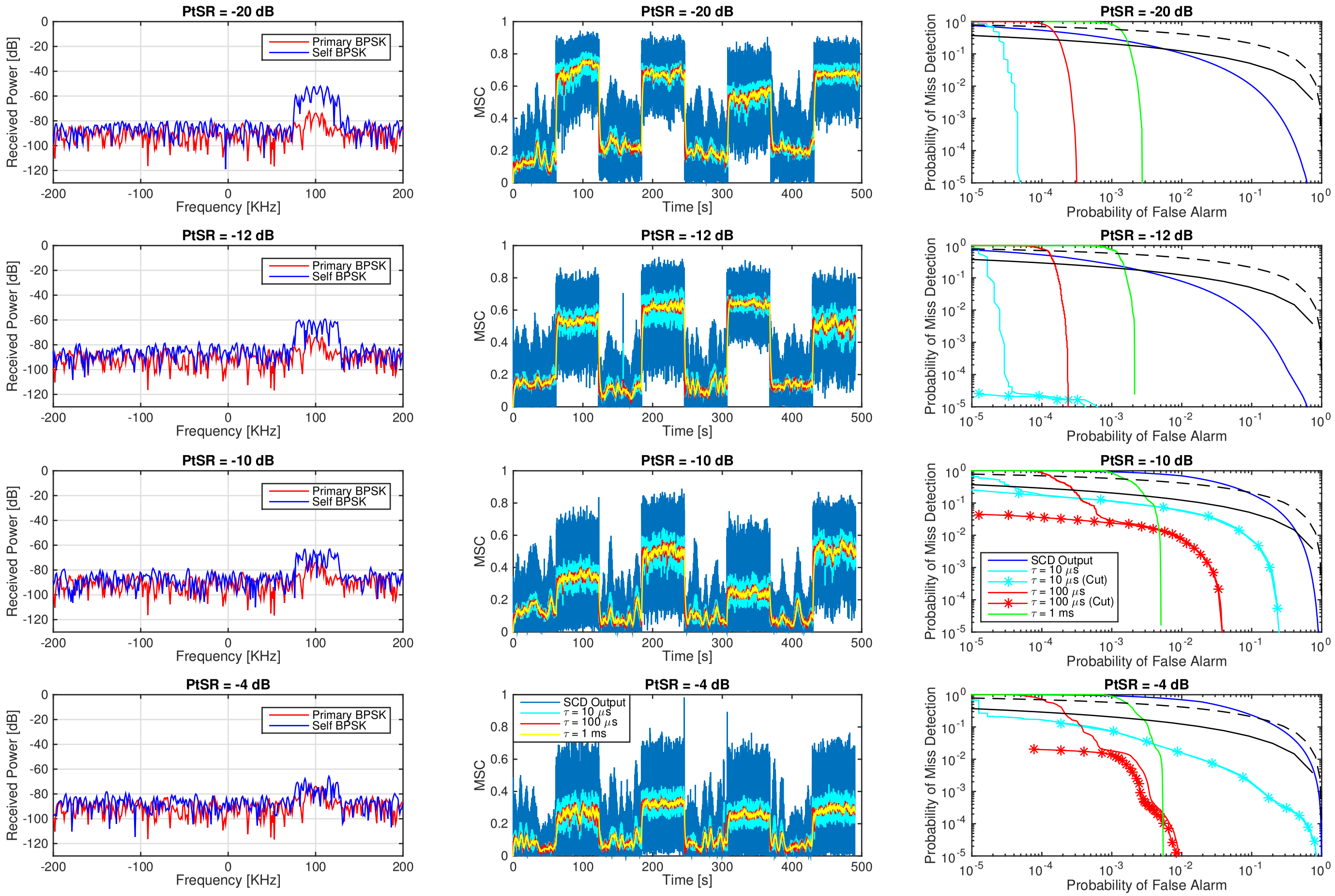


Figure 6.32: Tx Site Nr.2: Spectrum snaphots, coherences values and ROCs, for a GNU Radio and USRP implementation of BPSK modulated signal with 12.5KHz bandwidth, using a monopole antenna.

to disturb MSC values. The several experiments that have been performed, for PtSR values between -4 dB and -20 dB, showed no relevant effect that would be assigned to primary user azimuth effect, as presented in Figures 6.32. On the other hand, performance had suffered some degradation, as compared with previous experiments, due to lack of primary received power to disturb consistently MSC of self received signals, during $\mathcal{PR}_{on}$.

Primary User at Transmitter Site Nr.3

The last set of trials intend to evaluate performance for an offset primary location, close to prototype transmitting antenna and a primary FM modulated signal with a received power of -62 dB. The objective is to obtain complementary data to compare performances with a equivalent tests, in the other sites, exploring -4 dB $\leq$ PtSR $\leq$ 12 dB. As observed in Figure 6.33, overall performance is similar to those presented for Tx Site Nr.1, but worst than equivalent in Tx Site Nr.2.

6.3.4 Performance Analysis

The presented experimental results confirmed the potential of SCD based FDS for CR applications, particularly for the implementation of CR-B-VHF systems. Despite the advantages of FDS, regarding efficiency and independency of prior information on incumbents operation statistics, SCD testing provide good indication on superior performance, not only due to clear discrimination between $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, but also as compared with classical energy and quadratic detectors. This fact, by itself, is relevant enough to pursuit a FDS solution for CR-B-VHF deployment.

The usage of a low pass filter, with an adequate τ to the targeted primary services, to discard high frequency components of measured MSC, proved to be a fundamental asset to improve detection capacity, which might be "perfect" for several operational conditions. As revealed in experimentation trials, filtered version of MSC, correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, hardly ever overlap, which allows a "near perfect" separation between busy and idle state of incumbent services. Providentially, for multiple channels detection, it is possible to use different τ for each channel, according to its specific service and associated characteristics.

Fortunately, MMS primary services provide outstanding conditions to take advantage of filtering effects. The fact that most, if not all, of MMS use 25W, as a fixed transmitting power, makes RLOS as only constraint for detection of incumbents activity, for the most of common operational scenarios. In other words, seldom MMS users, within RLOS, do not achieve substantial received signals SNR. On the other hand, analogue voice services have appreciable tolerance to interference, which, in addition to inoperative time between push-to-talk activation and initiation of standardized voice procedures, provide interesting conditions that empower detection and undermine service disruption. By contrast, digital modulated primary services, do not benefit from those operational advantages, but presented better detection performances.

The deployed FDS scheme, based on SCD, presented excellent experimental results, specially when it is compared with envisage theoretical upper bounded performances of energy or quadratic detector based HDS, for equivalent conditions. The presented ROC curves, in the

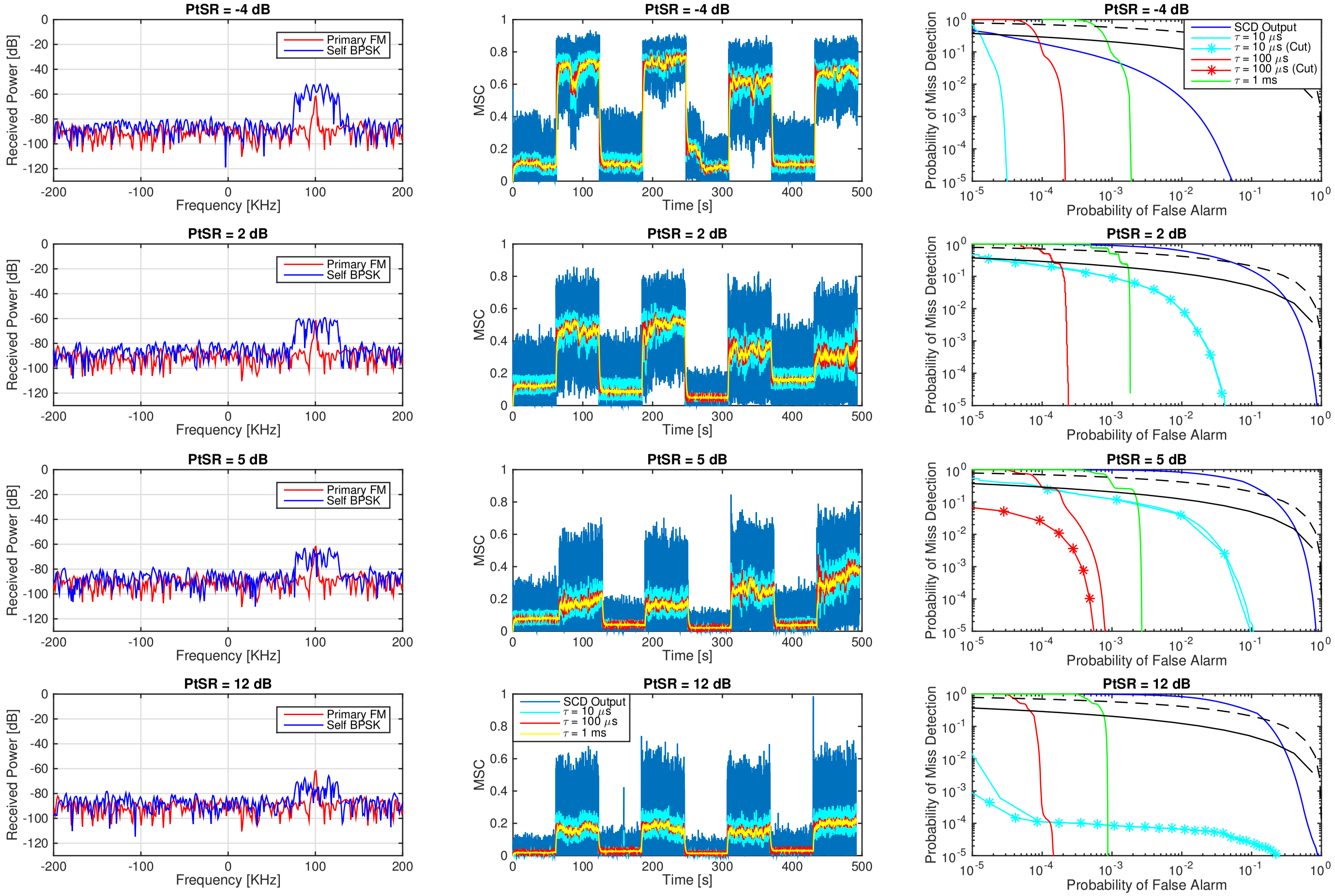


Figure 6.33: Tx Site Nr.3: Spectra and Coherences values for a VHF radio (FM) with a monopole antenna. - 9

various graphs, for energy and quadratic detectors in Ricean channels and received primary signals SNR=10dB, represent what would be an upper bound for an HDS, using the same detector. In the case of a HDS, one should consider an additional detection penalization, due to time sharing of sensing and transmitting times. Despite other advantages, these outcomes are decisive for a designation of FDS as a preferable choice for CR-B-VHF.

In the previous section, we presented the experimental results obtained in a set o tests and discussed the operational context and setup of each one. The focus of examination has been on prototype behavior for different setting conditions. Moreover, it is interesting to evaluate obtained results from universal metrics point of view, instead of being centered in experimentation context variables. Hence, in the following paragraphs, it is carried out a qualitative analysis on prototype performance, based on criteria that can be easily converted in common metrics, for comparison purposes. The most important aspects to be evaluated are definitely: absolute power; PtSR; fading; and modulation scheme effects. Therefore, experimentation data has been collected according to analysis focus and re-plotting for reader benefit. The objective is to condense in the same picture all the required data to support current discussion.

The experimental coherence values does not follows, exactly, the simulated ones, event though, general behavior does not differ significantly. Figure 6.34 presents experimental results for different testing, where PtSR are kept approximately constant and primary SNR assumes the following values: 5, 15 and 25 dB. The lower the self and primary SNR, the higher the MSC variances, for both $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, and consequently less aptitude to distinguish primary operation without errors.

The effect of low pass filter has a prime importance to overcome MSC oscillations, associated to low power signals. Hence, despite the case of unfiltered MSC, performance is similar for all filtered MSC values, since it is possible to separate MSC values correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, for most of filtered values. Even for Primary SNR = 5dB, it is possible to draw a separate line (threshold) between MSC values, for $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. The exception is $\tau = 10\mu s$, which performs worst that the other filtered MSC, but significantly better than energy (dashed black plot) and quadratic (black plot) detectors for twice the SNR (10dB).

The importance of PtSR in SCD performance has already been emphasized. As it stands, its effects are resumed through an analysis of SCD performance for two different situations, where primary signals assume similar SNR. In the first case, which experimental results are presented in Figure 6.35, it is considered that PtSR is bellow 1. Implicitly, this means that self received signal power has a better capacity to maximize spectral coherence, for $\mathcal{PR}_{off}$, than primary received signal power to push it down (towards zero), for $\mathcal{PR}_{on}$. Therefore, one can expect good performances, as long as primary received power overcome break even point to disrupt the balance of self received signals coherence.

On the other hand, there is a second case, where considered PtSR values can be greater than one, as presented in Figure 6.36. In this case, primary signal power has a better capacity to push down spectral coherence, for $\mathcal{PR}_{on}$, than self received signals to rise it up, for $\mathcal{PR}_{off}$. Consequently, the variances of MSC, correspondent to $\mathcal{PR}_{on}$, are expected to decrease, as PtSR increases. Again, performances are expected to be very good, for PtSR ≥ 1 as long as self received power is enough to reduce MSC variance for $\mathcal{PR}_{off}$.

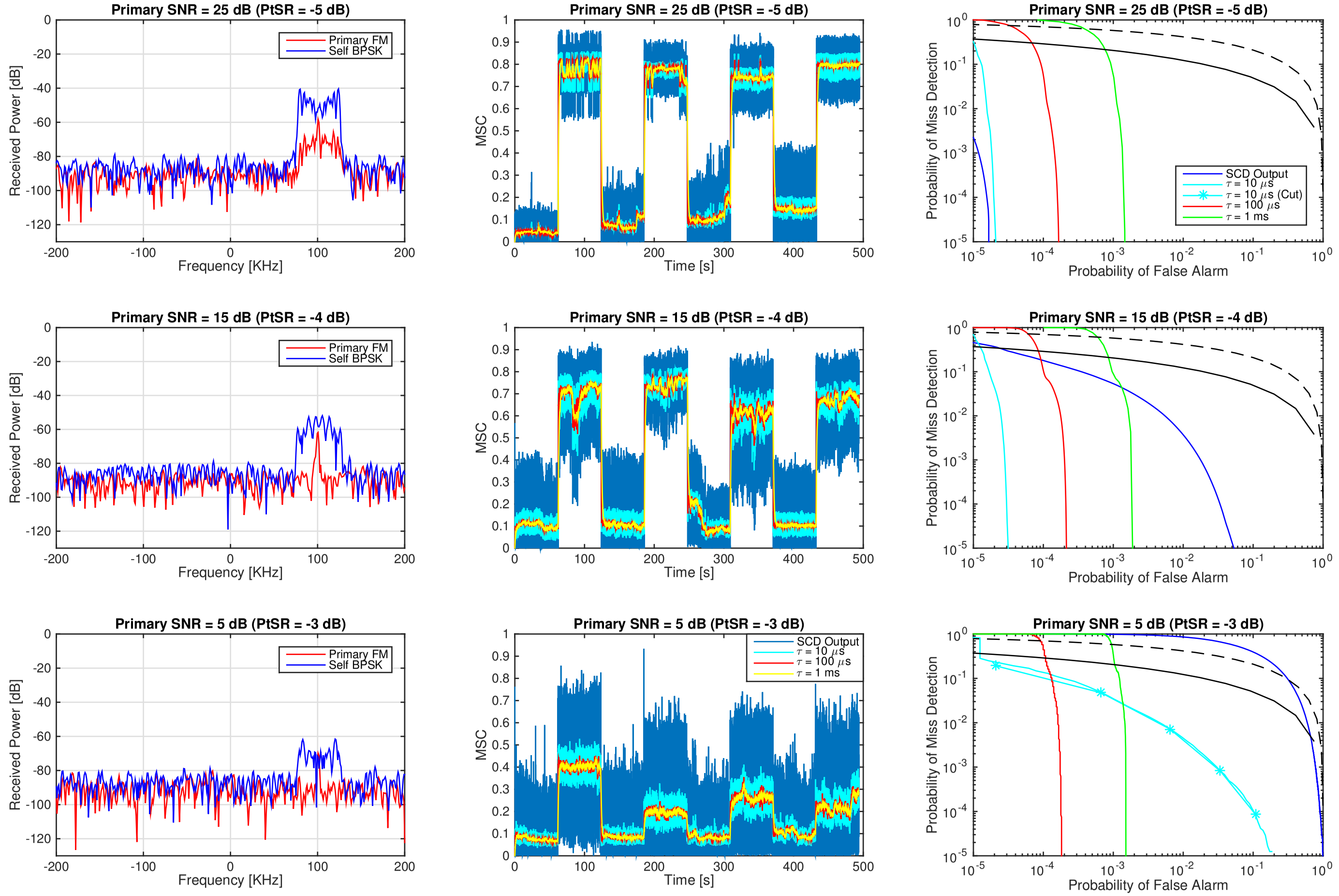


Figure 6.34: Experimental results for different primary SNR and fixed PtSR.

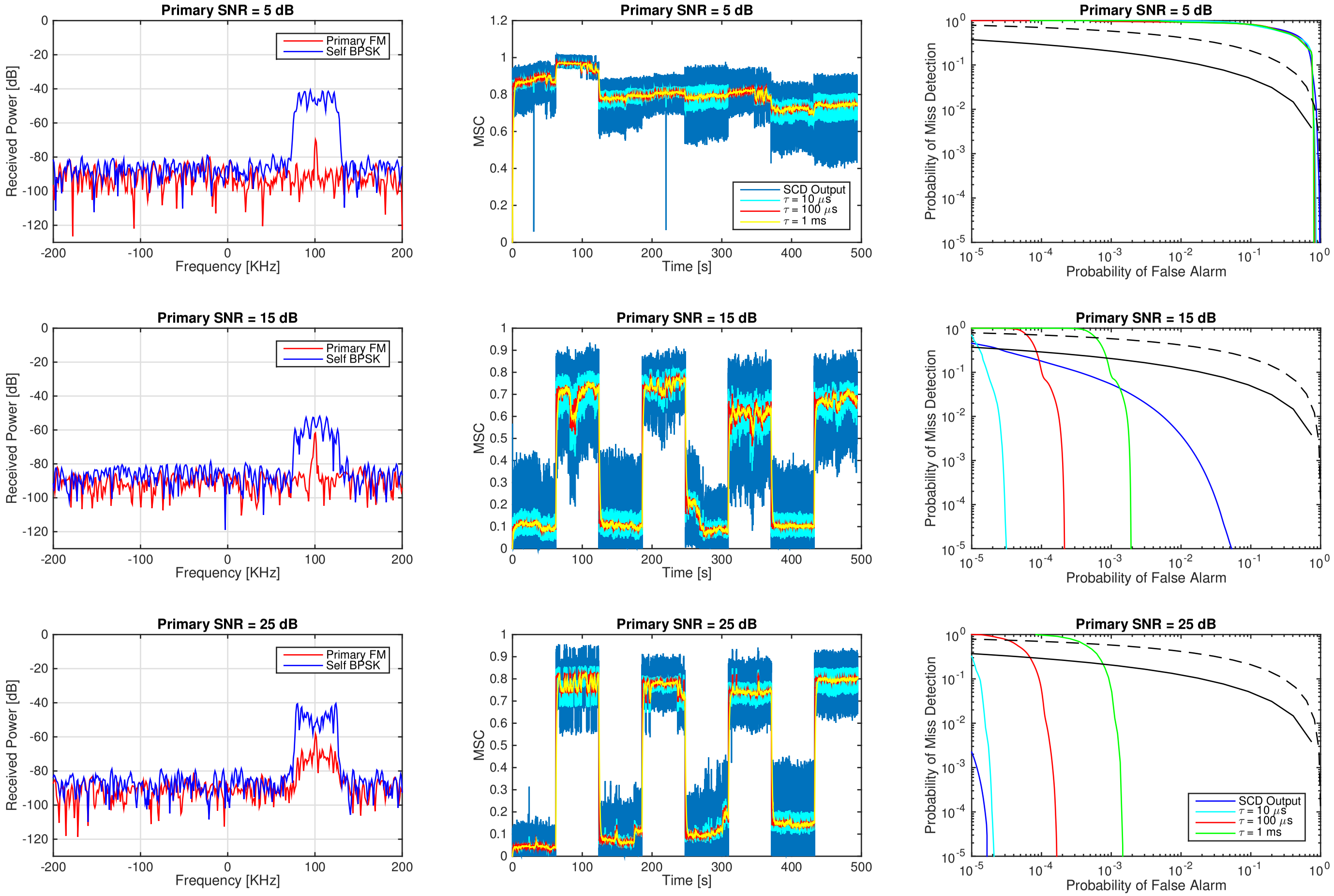


Figure 6.35: Experimental results for different primary SNR for PtSR bellow 1.

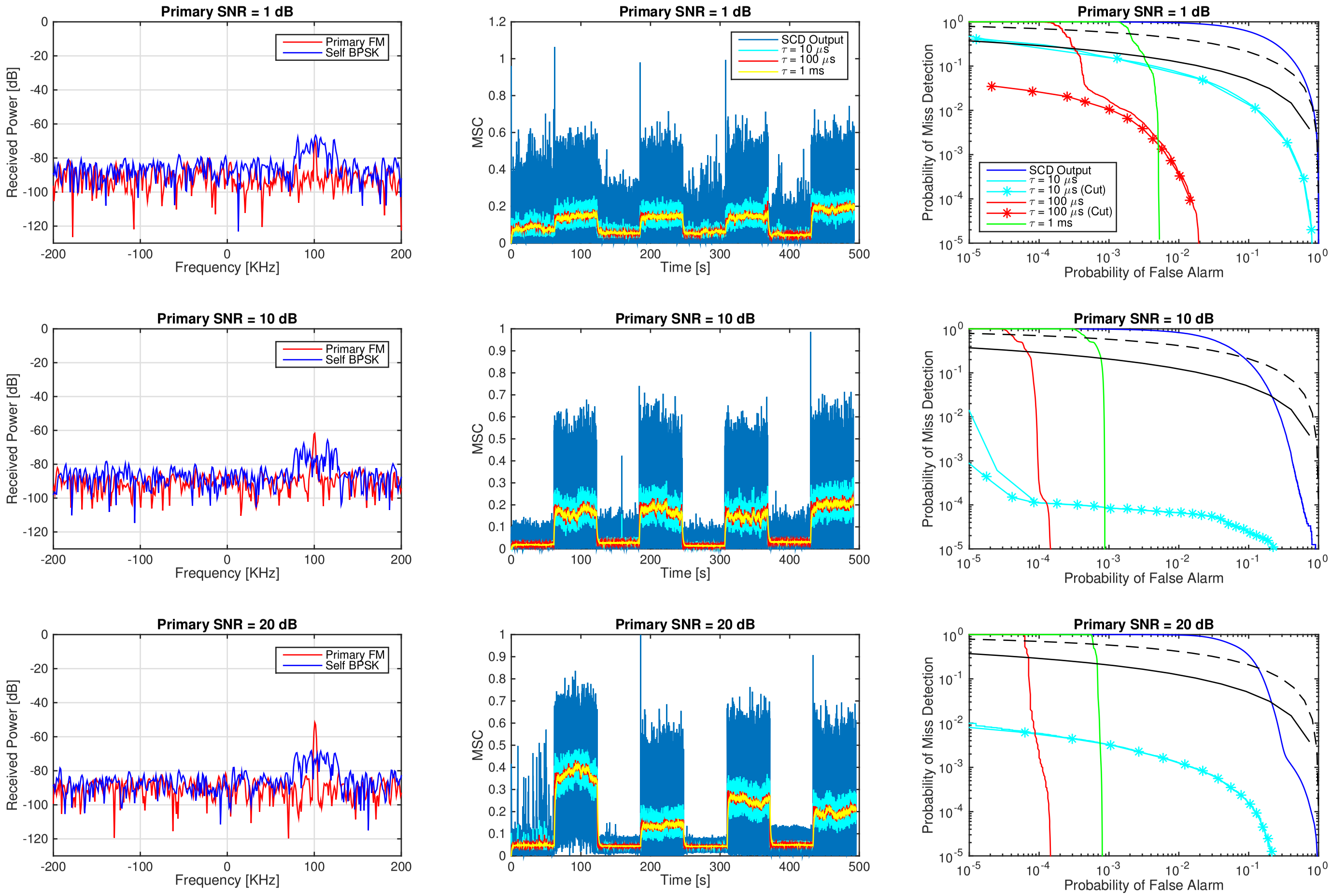


Figure 6.36: Experimental results for different primary SNR and PtSR.

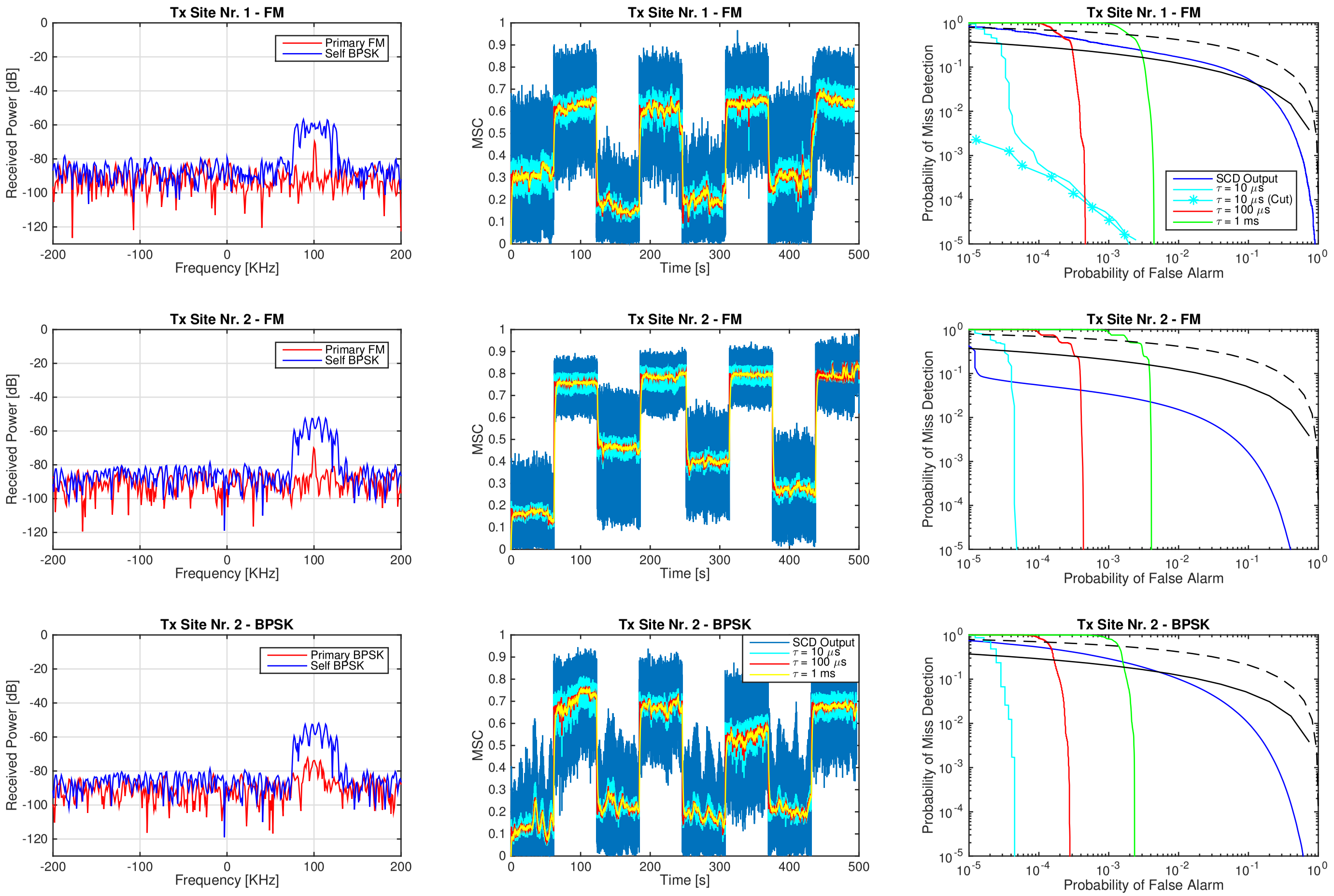


Figure 6.37: Experimental results for different fading conditions and difference primary signals modulation scheme.

In any case, filtering would solve most of the problems and one should not anticipate any detection problems, as long as self or primary received power are strong enough to restrain MSC variance.

Finally, in Figure 6.37, it is presented a comparison of experimental trials obtained in different Tx Sites and for different modulation schemes. The two upper rows correspond to similar set ups at two different radio sites, and the obtained performances are slightly different, due to different fading conditions. Even though, proper filtering of MSC values would eliminate the differences in performances. Moreover, last two rows correspond to different primary modulation signals, transmitted from the same radio site. Again, performance is similar, for filtered MSC, despite lower received power in BPSK (primary) modulated signal. In brief, these results confirmed what have been stated for fading and modulation effects on performance.

6.4 Concluding Remarks

A novel SCD has been proposed for FDS, based on spectral coherences evaluation of received signals at two sensing antennas. Essentially, spectral coherence is a measure of phase consistency, so if one can manage to control self received signals (at sensing antennas) in order to maintain a high degree of similarity between them, it is possible to detect third party emissions, while transmitting at the same frequency bands, through an evaluation of MSC value. The required (linear) dependency of self received signals is expected to be achieved through proximity of transmitting and sensing antennas, which allows a decent phase control and a reduced fading impact. Any concurrent transmission, at the same frequency band, will superimpose a set of extra random variables, affected by different kind of fading (independent or just uncorrelated), which result in a lost of dependency on received signals, pushing MSC towards zero. The detection capacity of a SCD depends on its proficiency to associate MSC values to different operational conditions.

Anyway, expected performance of a FDS scheme, based on SCD, depends on spectral estimator of SCD and on SIC design. The considered spectral estimator has an obvious impact on the overall evaluation of interest signals, namely spectral accuracy and resolution in both average power and frequency, and on practicability of real time implementations. The SIC design has to ensure adequate amplitude and phase on self received signals to enable SCD proper operation. Therefore, it has to accommodate an appropriate dynamic range on self and primary received signals (PtSR), which is associated to a self interference cancellation, as well as an accurate self signals coherence control.

The spectral estimation requirements are fulfilled with a proposed adaptation of Thomson's framework for cyclostationarity evaluation. It takes advantage of a combination of MTM with Loève transform, where MTM deals with bias-variance dilemma and provide high spectral resolution and superior performance in real time processing, while Loève transform adapts the non-stationary processes in order to produce the best possible basis for its expansion. The MSC is used as a parameter to decide whenever opportunistic system has to release the spectrum, as an incumbent service starts to operate.

Presented analysis on envisage deployment challenges addressed comprehensively the SIC problematic and appointed it as a key feature for FDS overall performance and a critical enabler for SCD operation. Despite full-duplex radios applications, where the SIC focus is on self interference cancellation, a SCD requires an appropriate reduction on self interference in order to fulfill PtSR and a coherence control to maximize MSC value, for $\mathcal{PR}_{off}$. The objective is to maximize the differences in MSC values, correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$.

Experimental tests validated the proposed solution for FDS in maritime VHF band and revealed that SCD has tremendous potential for CR applications. The complementary usage of a low pass filter, to discard high frequency components of measured MSC, has been proved to be an outstanding solution to improve performance. An adequate τ design, according to the targeted primary services, can provide "perfect" detection for most of operational conditions, and it is possible to use different τ for each of the multiple opportunistic channels that are being used. The SCD based FDS is definitely the preferable choice for CR-B-VHF.

Chapter 7

Regulatory and Standardization Issues

Current regulatory framework is not prepared for emerging radio communications technologies so governing issues are still an active area of discussions. Spectrum under-utilization and scarcity are incontestable facts, intensifying a common understanding that DSA is the only viable strategy to overcome identified problems. In any case, there is an obvious need for an evolution on regulatory framework, not only because current model does not promote efficient use of spectrum, but also because cannot support other vectors of regulatory mission, namely the detach of barriers throughout telecommunications sector and the support of business.

In this chapter we address evolution of regulatory framework towards a more flexible and dynamic management process, centering the discussion on regulatory and standardization issues associated to the application of CR concepts to maritime VHF band. Practical aspects, related with Quality of Service (QoS) enforcement to ensure incumbents live operations and legacy systems coexistence, namely figures of merit, are also tackled. Eventually, some of the presented proposals might contribute for paradigm change in specific cases, such as government agencies, Navy, Coast Guard or Maritime Police, which can manage their own assigned spectra, and can take advantage of less complex and bureaucratic decision processes to materialize a flexibilization on spectrum management and an improvement on spectrum utilization efficiency. Actually, in [T2], it is addressed an evolution on Portuguese Navy spectrum management towards a dynamic paradigm and the introduction of CR technology to support it. These can also apply to international organizations, such as NATO, where coalition operations require efficient spectrum management. Obviously, this subject is too complex to be wrapped with this exercise, but we expect to contribute for on-going discussions, which, hopefully, will enable VHF based maritime broadband services in a near future.

The remainder of the chapter is organized as follows: in Section 7.1 we discuss the role of CR in spectrum scarcity mitigating processes, namely in the support of DSA; Section 7.2 is dedicated to the challenges and opportunities associated to an evolution on regulatory framework and Section 7.3 addresses the practical aspects related with the deployment of a spectrum allocation strategy, namely operational caveats such as QoS enforcement, metrics and equipment certification. Final remarks are presented in Section 7.4.

7.1 The need for Dynamic Spectrum Management

The opportunistic usage of spectrum is probably the most important endeavor to overcome spectrum scarcity. Despite DSA addresses the fundamental issues and enable feasible implementations of required features, it cannot be appointed as a model for spectrum access policy without the technological support to enable governance models deployment. This is particularly important, not only to provide a reliable solution to handle radio environment challenges and opportunities, but also to offer an unquestionable answer to all spectrum stakeholders, regarding its capacity to deal with interference and ensure live operations requirements. In fact, the key for spectrum efficient usage does not reside on management strategy definition merit, but on the quality and possibility to implement it.

The principles of DSA are associated to the need of taking advantage of inactive spectrum segments through opportunistic access to radio spectrum bands that are not being used. Curiously, Mitola [3] proposed the concept of CR, which is exactly an approach to increase spectrum efficiency exploring frequency bands capacity to accommodate non-licensed transmissions, without harming operation of incumbents. The development of CR concept presents an extraordinary opportunity to implement a set of functionalities that are vital for opportunistic usage of spectrum and consequently decisive to increase the efficiency of electromagnetic radio spectrum usage and overcome its scarcity.

Naturally, the expected efficiency improvement is proportional to the level of cognition functionalities available in the implementation. This means that a CR ability to exploit inactive frequency bands will depend upon its faculty to find the so-called opportunities to operate and consequently on its spectrum sensing techniques capabilities. Therefore, one cannot think in CR as a silver bullet for all the problems, not only because the technology is not mature enough, but also because the radio communications stakeholders are not ready for the application of such disruptive mind set approach. Anyway, the discussion shall not be centered in the problem, but focused on the solution. In other words, the recurrent issue is not the spectrum scarcity, but the lack of capacity to implement an efficient and effective DSA scheme. Apparently, CR represents the searched aptitude to successfully implement DSA, so the empowering of its deployment should be also on governance and policy side.

7.2 Evolution of Regulatory Framework

The regulatory framework for radio spectrum management has two basic processes: allocation and assignment. The spectrum allocation is an international cooperative process where frequency bands are devoted to a specific use or service. The frequency assignment, mainly a National Regulatory Authority (NRA) role, is a licensing process of spectrum to a specific user or purpose. Any change in defined frequency allocation scheme requires consensus-based decisions at international level, which are associated to time frames of decades and obviously difficult to accomplish. At national level, the modifications are less bureaucratic and potentially not so complex to materialize. The overall global framework for the use of spectrum, governed by ITU RR, is foreseen to be quite stable, specifically regarding MMS allocations. Therefore, in the presented discussion, it is assumed that will be no significant changes at international level. However, it is expected that national frameworks might evolve towards a more dynamic management approach, which is in the foundations of the following reflection.

Considering that, none of the 156-174 MHz channels are exclusively allocated to MMS, each NRA can choose which service(s) to license in the band, given that the degree of compatibility between services shall be taken into consideration to minimize harmful interference. Moreover, NRA can allow frequency bands to be used for other purposes, providing that does not cause harmful interference to any service that is operating under an allocation in the RR. Under those circumstances, it is possible to conceive different ways of doing business and anticipate a change in national regulatory paradigms. Actually, FCC published a new framework [159], which abolished the actual spectrum management model in large parts of spectrum, and evolved towards a dynamic model. Thus, in the present discussion we intend to address the required changes in regulatory framework that would answer to maritime community demands for broadband services and support emerging technologies and information exchange requirements. Additionally, it is important to discuss the associated opportunities and challenges of such intention and present an evolutional model to implement it.

7.2.1 New Policy Definition

The change in regulatory paradigm is an essential transformation to enable the deployment of DSA and an inevitable step towards mitigation of spectrum scarcity problems. However, the simple definition of a dynamic access based principle is not enough to characterize a governance model. For instance, interference control is a complex endeavor that needs to be enforced to ensure protection of primary systems. Eventually, the regulatory foundations need to be revisited and the fundamental objectives readdressed, to evaluate different possibilities to fulfill requirements, accommodate user demands and promote industry innovation, as represented in Figure 7.1.

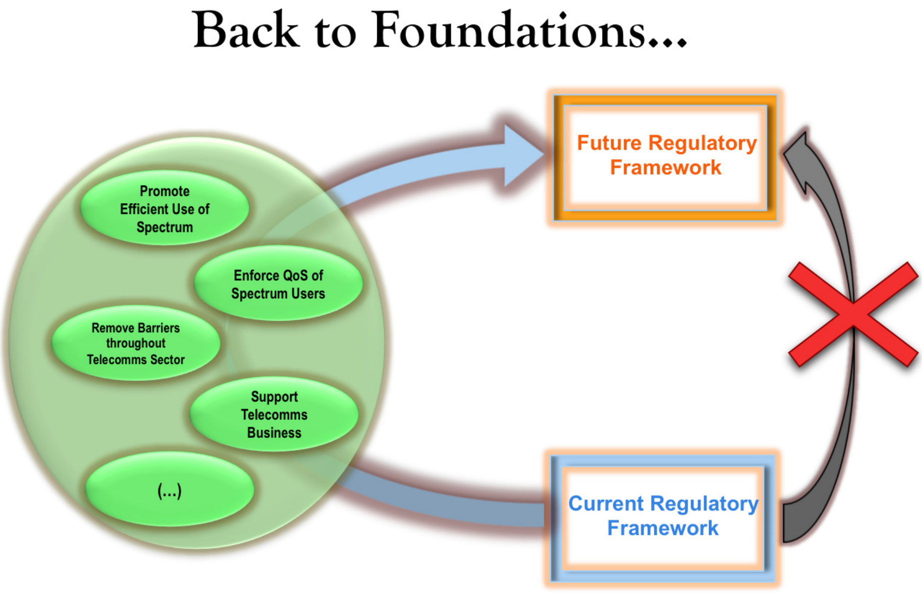


Figure 7.1: Paradigm change requires an evolutionary process that might need to re-address regulatory foundations to progress towards a new framework.

The basis of a flexible regulatory environment, which might be able to accommodate dynamic utilization of spectrum, must include a well-defined command and control concept with two components: policy and enforcement. A spectrum access priority policy should translate the idea of agility and temporary allocations into a policy and rules that specify the way (allowed) users get access to the spectrum.

Generically, the eligible techniques to rule spectrum access are priority and contention based. In a priority based spectrum access control, the users are classified according to their privileges to explore spectrum: incumbents (or primary) are frequency band assigned users, while opportunistic (or secondary) users are unlicensed users that are allowed to use allocated spectrum as long as they do not harmful interfere with on-going operations of primary users. In a contention based access control, all the users have the same priority to get access to spectrum and compete for the resources (eventually) at same time. Mixed options are, of course possible, with contention being used within privilege classes. Complementary, this policy might have an evolution process that goes from exclusive use and interference free spectrum to priority based shared spectrum and mitigation of interference to appropriate QoS levels. The second component of command and control model is an enforcement program that is addressed later in this chapter.

Another key issue is the definition of cooperation level between primary and secondary users. The general principle considers that secondary unlicensed users are allowed to use assigned spectrum, as long as they do not interfere with primary users, but it is not explicitly assumed any kind of cooperation. The underlay paradigm, where primary and secondary users do not cooperate, has the merit of independence and permits a shorter deployment time, being usually considered a natural choice. However, in the case of multiple secondary users, it does not incorporate any means to control that aggregated interference generated is kept below a certain threshold, since primary receivers are passive and may be located in the vicinity of secondary transmitters. Alternatively, one may include some sort of symbiotic co-operation where, for instance, primary user trades the relaying of its transmissions by secondary operation [160] or some other type of cooperation within overlay paradigm. In any case, the choice of spectrum sharing strategies can have a significant impact in the overall spectrum efficiency, but it also implies different level of cognition and implementation complexity, which leads to different challenges, as well.

Despite the obvious advantages at efficiency level, the evolution of regulatory framework, in the case of MMS, presents additional opportunities regarding change management and field deployment. In MMS, most of frequency bands are assigned to a service, instead of a specific user. It is common to have multiple users getting access to a frequency in a maritime band, without any kind of precedence or supervising in a contention type of scheme. In fact, such situation constitute, in practice, some sort of early deployment of DSA similar concept, which constitutes an opportunity for a new paradigm transition phase. Considering that disruptive processes need transition plans and evolution strategies that are not compatible with "big bang" approaches, any migration process should promote a smooth evolution without disturbing current operations or delaying start ups based on new concepts. In this context, a transition plan to introduce new practices in MMS bands would be highly simplified.

7.2.2 Enforcement Mechanism

In addition to spectrum access priority policy, it is essential to establish a course of action to ensure its enforcement, which naturally includes a set of metrics, procedures and organizations to guarantee their practical implementation. Harmful protection does not necessary means interference abolition, providing that communications link conditions are appropriate to ensure the required QoS. In other words, interference is allowed whenever it does not affect the fulfillment of the minimum requirements for service provision. Conceptually, the incumbent QoS assurance is built on the basis of a trustful relationship between primary and secondary users in a shared spectrum venture. In the past, the fear of harmful interference has resulted in the exclusiveness of spectrum usage for most of bands and restrictions on out of band interference. The QoS was guaranteed through a regulatory policy enforcement based on auditing practices, which were supposed to guarantee that only assigned users could use the corresponding frequency bands. The focus of QoS assurance was definitely on interference abolition. In the future, the new spectrum access paradigm will change the focus towards maximization of usable capacity. Depending on the communications service type, different SNIR may result in the same system performance. In other words, interference free and concurrently usage of spectrum (with acceptable levels of interference) may produce the same practical results, in terms of incumbent service provision QoS, but with obvious differences in terms of spectrum efficiency. The key point is the definition of a service interference tolerance that needs to be preserved an its associated evaluation metrics, as resumed in Figure 7.2.

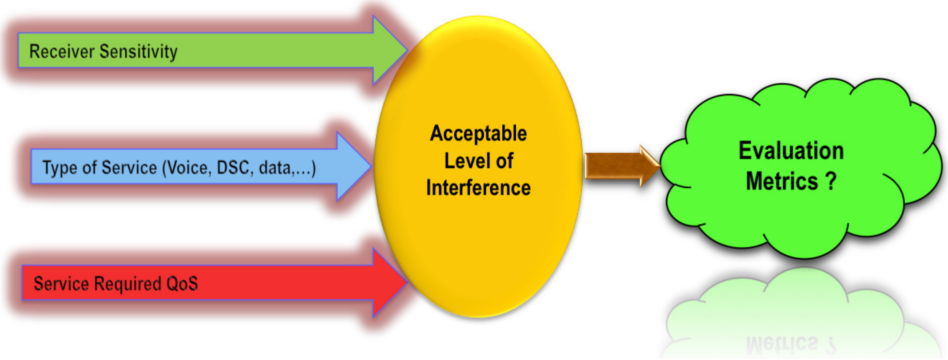


Figure 7.2: Enforcement mechanism requires the definition of a service interference tolerance that needs to be preserved an its associated evaluation metrics.

Similarly to classical regulatory framework, a policy definition and a set of well-defined rules are not enough to guarantee the interference at proper levels. The enforcement is critical to guarantee spectrum access, in compliance with allocation and assign criteria, and important to overcome user's concerns. Even so, in the case of DSA, the fact that interference is allowed, as long as it does not compromise the incumbent's system performance, post an additional challenge, which make a huge difference in auditing operations and on harmful interference verification and enforcement, as summarized in Figure 7.3. It is critical to come up with a framework that can be able to handle this new way of doing business, specifically, it is essential to address practical aspects that are fundamental for the effectiveness of regulatory authorities in their spectrum policy execution.

Recently, FCC Spectrum Policy Task Force [36] has recommended a paradigm shift in interference assessment, introducing a new metric, called interference temperature, which is intended to quantify and manage the sources of interference in a radio environment. The idea is to characterize a worst case scenario, where a primary receiver is able to support the defined QoS and specify the interference temperature limits that cannot be exceeded [44], for each frequency band. Eventually, such approach, conceptually interesting, might be difficult to apply to real systems, without any further developments. In any case, normalization and standardization requirements, such as reference values, thresholds and metrics, are critical to create a common understanding of criteria for operational requirements, spectrum access conditions, users relationships and regulatory authority roles.

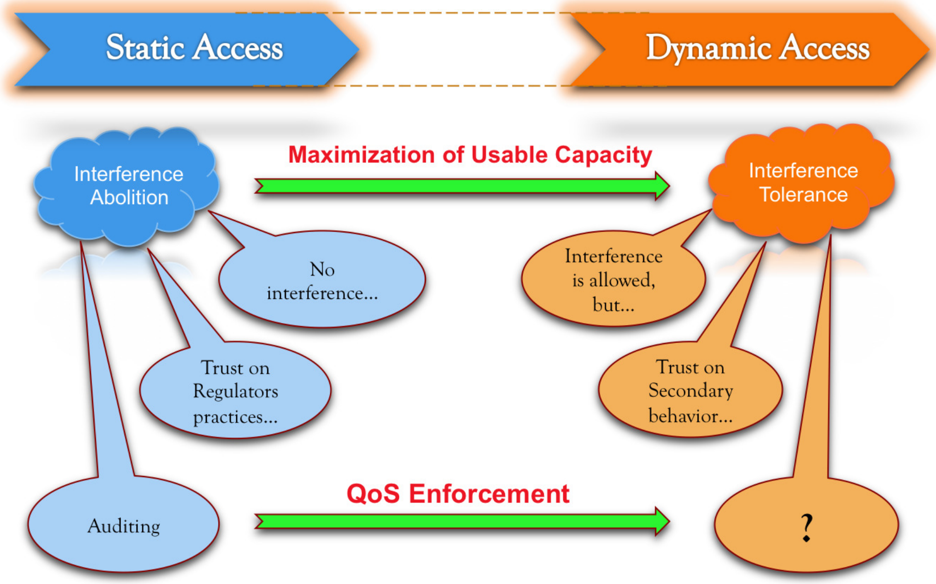


Figure 7.3: In the new paradigm, what will be the corresponding auditing operations?

Additionally, in a DSA environment, where users rights to transmit are distinctive and spectrum access control is decentralized, the policy enforcement based on spectrum auditing can be really challenging. From a regulatory perspective, it is critical to be able to perform identification, classification and localization of spectrum users to control interference levels, assure incumbents rights and conciliate demands. Those capabilities are not trivial to implement and continuously support, because in most cases, opportunistic users are difficult to register and log. Therefore, in addition to inevitability of metrics definition, regular policing of spectrum use would benefit from prior to market entry equipment certification, according to operation normalization procedures and parameters, as depicted in Figure 7.4. Such procedure would endorse metrics fulfillment compliance mitigating the probability of unintentional interference and facilitating spectrum use policing.

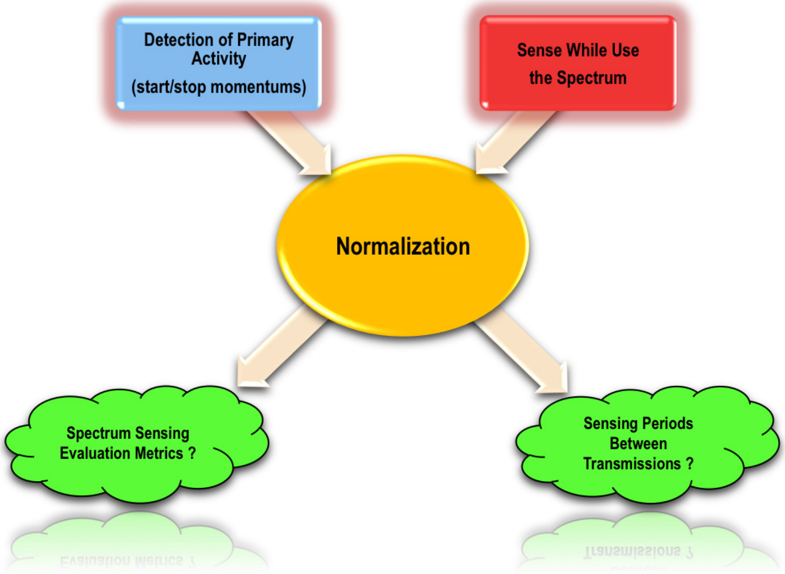


Figure 7.4: In the new paradigm, what will be the corresponding auditing operations?

7.2.3 Transition Plan

Considering the general constraints and opportunities associated to spectrum management paradigm change and the technological state of the art, the incremental spiral approach, as represented in Figure 7.5, is definitely the appropriate strategy for an evolution of regulatory framework. Not only because a migration of this nature cannot be performed in one step, but also due the maturity level of enable technology, stakeholders, regulation and standardization. This process has to be performed through incremental steps of functionalities, where each stage should be carefully is designed, implemented, tested and evaluated. Furthermore, new iterations have to be planned, taken into consideration the lessons learned from previous phases, and according to the level of technological maturity and expansion of applied spectrum.

Initially, a pilot implementation is a good approach to large-scale proof of concept. For instance, a set of field tests might be performed in VHF channels assigned to new technologies. Furthermore, the process can be expanded to the opportunistic use of spectrum on carefully selected non-critical analogue voice assigned channels. Actually, this manoeuvre does not present significant risks for incumbent operations, even in early stages of cognition maturity of secondary radios, because analogue voice services have a good tolerance to noise and interference. Nevertheless, pilot testing need to be carefully documented, considering comprehensive communication and change management plans, to ensure that all stakeholders would positively impact the process. This methodology would permit quick wins and potentiate concepts consolidation, increasing users' confidence in process development.

Subsequently, a set of initial spirals has to be planned, each one with an associated cognitive (radio) maturity level and applied portion of spectrum. The development governance has to be performed, taken into consideration the practical results of each spiral, because it requires large-scale implementation testing, which is difficult to emulate in laboratory. Even-

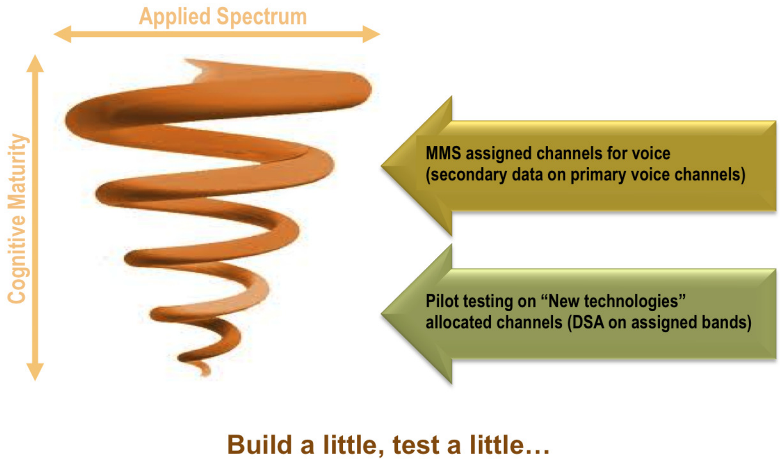


Figure 7.5: Incremental spiral approach to evolution of regulatory framework.

tually, at low levels of cognition, the deployments may include beacons to help the searchers and some sort of "spectrum access on demand" based on geolocation and databases to find white spaces in the area. Subsequently, new cognition functionalities, with detection algorithms more capable and complex, could be deployed and validated.

7.2.4 International Coordination

The envisage CR-B-VHF networks can potentially be implemented all over the world. Nevertheless, the scope and applied spectrum might vary between countries. Actually, these do not constitute a problem, from regulatory perspective, since MMS assigning channels is a NRA responsibility. The only aspect that needs to be taking into consideration is the fact that some ships may need to roam between CR-B-VHF networks operated from different countries. In this case, it is necessary to implement a control mechanism to support roaming, which can be conceptually similar to cellular communications implemented solutions. Anyway, international coordination is required to avoid disturbances in spectra, from adjacent countries, that are not applying the same concepts to common frequency bands.

Furthermore, regulatory policy coherence is highly recommended, not only to harmonize and combine QoS enforcement, but also to facilitate technological developments and equipment interoperability. These efforts would also potentiate operational issues, regarding system?s exploration and support, namely prevention of harmful interference and guarantee of incumbent's rights, within overlapping footprints of different nations. Complementary, it might also be consider to include such international coordination within ITU activities, similarly to other frequency bands, like high frequency, given the potential of maritime B-VHF networks to have transnational coverage and roaming between nationally explored networks.

7.3 Deployment Challenges

The major challenge for a DSA strategy deployment is definitely the QoS enforcement. Firstly, it is necessary to build-up a common understanding criteria for the definition of operational requirements, spectrum access conditions, (incumbents/opportunistic) users relationships and regulatory roles. Additionally, it is crucial to ensure that policy is implemented and followed. Moreover, the maximization of usable capacity is in the basis of opportunistic use, changing paradigm from interference abolition to interference tolerance. The consequences of such transformation, associated to an inevitable decentralized spectrum control access and an unavoidable difficulty to register and log opportunistic users have also a significant impact on QoS enforcement practices and procedures. Such challenging context needs to be characterized in terms of performance of each stakeholder in order to be represented with adequate metrics that would allow spectrum survey and user's scrutiny, as summarized in Figure 7.8.

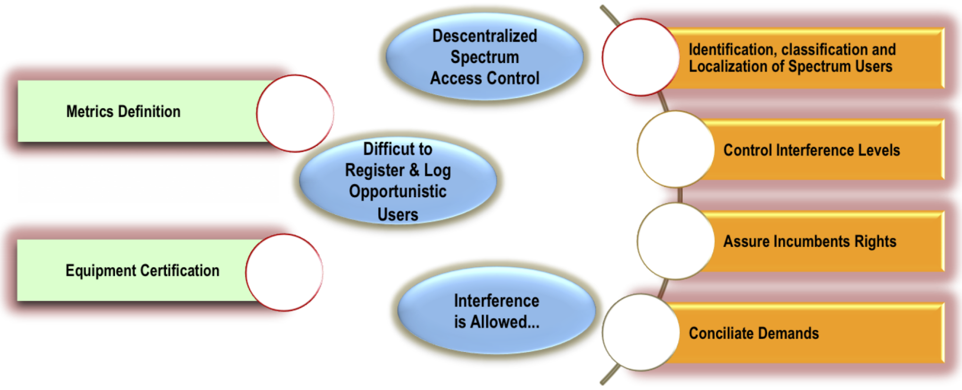


Figure 7.6: Deployment challenges associated to a dynamic management strategy.

Dynamic and unpredictable environments are not simple to characterize, particularly in terms of evaluation metrics. In a CR based DSA scenario there are basic operational areas that need to be addressed, namely primary and secondary utilization of spectrum and their relationship. On primary side, the Acceptable Level of Interference (ALI) depends upon primary receiver sensitivity value, communication service and its respective QoS. Therefore, it is necessary to characterize and quantify each one of those requirements and find the appropriate metrics to relate them and their effect on interference level. Furthermore, on the secondary side, the most critical issues are the spectrum sensing capability, its implementation and performance. Moreover, it is not only the detection of primary activity, its start and stop momenta, but also the monitoring of any primary activity while secondary is using the spectrum. The evaluation metrics of such performances and its practical application to real systems are critical to prevent harmful interference and ensure incumbents rights. Finally, it is necessary to detail interactions, procedures and grading between primary and secondary users and between secondary's themselves, the later depends upon spectrum access policy.

7.3.1 Primary Users' Figures of Merit

In a context of opportunistic use of spectrum, metrics such as reference values and thresholds are very important, not only to establish a common understanding criteria for spectrum users coexistence, but also to support regulatory rules enforcement. Concepts such as operational requirements, spectrum access conditions, primary/secondary users relationships and regulatory authority regimentation need to be translated in values that can be measure and compared in order to enforce spectrum management policy and assure service level requirements. The QoS enforcement is a clincher to control interference levels, ensure incumbents rights, conciliate demands and resolve disputes. Actually, this condition is essential for incumbents support to any evolution towards DSA and opportunistic use of spectra, given that their live operations depend on ALI assurance. Inevitably, the fact that spectrum might be used in opportunistic basis has potential impact on incumbent systems, which might limit services performances. Hence, such possibility needs to be addressed and quantified in metrics that allow an evaluation of interference harmful protection.

The practical consequences of inappropriate secondary activity are noise floor level rising and an increase in service outage probability, which directly restricts incumbent's achievable capacity. The threat, for primary service, might intensify as a consequence of cumulative noise and risk of interference, depending on the amount of secondary service users within coverage area of primary network. Essentially, this effect is due to aggregate interference and to increase on probability of miss detection in secondary spectrum sensing, which results in secondary transmission during incumbents operation and rising on outage probability of live services. The inaccuracy in spectrum sensing process is probably the major cause of disturbances in performance of primary systems. Anyway, the consequences of such inconvenient events depend upon the incumbent services' ALI, which is a function of users activity (duty cycle), service operating requirements and ROC.

In an interference tolerant context, it is necessary to characterize each incumbent minimum operating requirements, namely its availability and reliability, in order to support the QoS assurance process. Unfortunately, most of MMS assigned bands (if not all) have no explicit operational requirements (QoS) for supported services, probably because it is implicitly considered the best effort reached within an interference free environment. In the future, these aspects need to be rectified upfront. Depending on type of service, and its associated performance demands, ALI might vary. For most of MMS services, typically analogue voice, the operating requirements are quite permissive, but in the case of digital services, such as DSC and AIS, admissible interference constraints are definitely more restrictive. Obviously, primary receiver's probability of miss detection and probability of false alarm, characterized in ROC, are critical for systems behavior, especially under low SNIR. Finally, in addition to miss detection probability, aggregate interference is also a function of primary users activity, which, in MMS, is quite atypical. Depending on assigned band, even for the same type of service, the traffic profile might be completely different. For example, channel 16 has an activity profile quite different from channel assigned for recreation sailing voice communications. Nevertheless, all of those effects and consequences need to be related with primary's QoS requirements, specifically Service Level Requirement (SLR).

Thus, the challenge is to express incumbent's SLR into metrics that would be able to support primary QoS enforcement and facilitate opportunistic systems design. The SLR, which are typically specified in terms of availability, reliability and performance, need to be translated into metrics that, ultimately, point to an ALI that would be measured and enforced. Hence, the natural course involves operational conditions managing by controlling SNIR level that would allow the incumbents service to operate according to SLR. On the other hand, service outage probability and achievable capacity are assenting ways to evaluate the consequences of secondary activity. For both, the assessment is based on the analysis of radio environment conditions and its ability to fulfill service requirements. In other words, these examinations intend to verify how often the SNIR at primary receiver is below a certain threshold. Apparently, SNIR would be the natural metric to assure ALI and SLR, but it might not be enough to characterize SLR. Eventually, it can be representative of primary service performance, but it is not sufficient to give evidence of availability and reliability requirements, due to lack of time dimension characterization. Therefore, ALI might need to incorporate, not only interference limitations, but also a time domain component that might be able to express the environment dynamics.

In any case, primary services' figures of merit should be able to provide overall information regarding primary services performances. As depicted in Figure 7.7, spectrum sensing inaccuracy and density of secondary users raise noise floor, which cause impact on primary services achievable capacity and outage probability. Therefore, these two later metrics might be used as a common criterion for spectrum users coexistence.

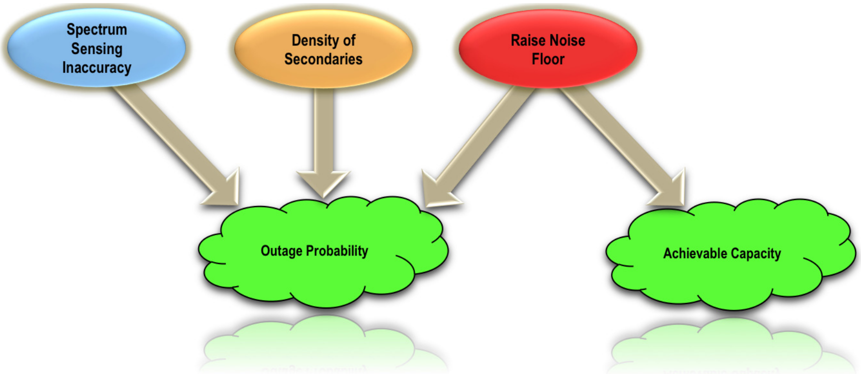


Figure 7.7: Incumbents systems figures of merit.

7.3.2 Secondary Users' Figures of Merit

The purposes of secondary users related metrics are slightly different from incumbents. While primary services metrics are associated to regulatory policy enforcement, secondary service metrics intend to measure the ability of secondary users (systems) to fulfill regulatory roles and act as indicators of feasibility and effectually of deployments. The success of opportunistic systems depends on their ability to exploit inactive frequency bands. Specifically, it depends upon secondary's capability to find the so-called opportunities to operate and consequently on its spectrum sensing techniques capabilities. Therefore, the capability to detect and classify spectrum holes, within accurate levels of spectral resolution, to estimate the direction of arrival of interferers and to do it in real time, is definitely a critical asset. On the other hand, there are radio environment characteristics that determine operating conditions of opportunistic systems, independently of its own performances, namely detection sensibility and processing or incumbent's activity profiles. Ultimately, these constraints would limit achievable performances in such a way that secondary deployment might be not interesting and/or rewarding. Hence, there are two categories of metrics for secondary services that need to be addressed and quantified, which may be generically designated as compliance and performance metrics.

The harmful interference depends on secondary capacity (and behavior) to detect primary activity and carry out spectrum sensing while opportunistically uses the spectrum. The primary activity detection requires a spectrum sensing algorithm that, not only be able to detect the presence of primary transmissions and overcome the effects of attenuation, fading and shadowing, but also to perform it in appropriate time frames in order to maximize spectrum holes achievable capacity. Specifically, it is critical to detect, as accurate as possible, the start/stop momenta of primary transmissions. Therefore, the minimization of harmful interference implies some sort of normalization with reference values for detection performance. In any case, it is not simple to define a benchmark for detection performance, but it is more difficult to come up with spectrum sensing evaluation metrics, as already have been addressed in Chapter 4.

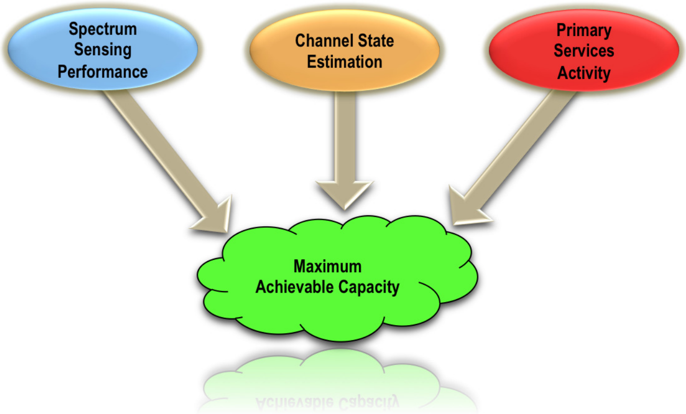


Figure 7.8: Opportunistic systems figures of merit.

The maximum achievable capacity of an opportunistic network is able to summarize the interest and incentive for its deployment, acting as a single benchmark for viability analysis. The secondary systems performances depend not only on its own faculty to exploit spectrum holes, but also on spectrum holes occurrences and characteristics. As previously mentioned, spectrum sensing algorithms shall be able to detect primary start/stop transmissions instants, as soon as possible, to minimize the harmful interference and maximize time of opportunistic usage. On the other hand, channel state estimation play an important role in situation analysis, providing information to define spectral availability and channel characteristics, like noise floor statistics and channel capacity, allowing dynamic adaptation and/or reconfiguration of transmitted signal to maximize link throughput. In the learning process, it is crucial to detect spectrum holes, estimate their power contents, and predict its availability to support high reliable communications. Thus, radio scene analysis includes the detection of spectrum holes and the evaluation of noise floor and traffic statistics that will be used as inputs for adjustments in power and spectrum management. Additionally, it is required another input, which provide an estimation of channel capacity and allow coherent detection. Nevertheless, incumbent's traffic profile characteristics, namely transmission time and duty cycle, might preclude opportunities in such a way that it is not possible or effective to use them. For instance, primary bursty traffic, with short transmission time and small times between transmissions might be useless at all. In conclusion, radio scene analysis competence will determine the achievable capacity of a secondary network, which ultimately is decisive for its deployment decision.

7.3.3 Equipment Certification

Trust is the foundation of primary-secondary users' relationships in a DSA based scenario. Obviously, this confidence conception needs to be regulated and enforced, not only because secondary users require guidance and assistance to avoid harmful interference, but also because incumbents demand for support of their live operations QoS. One potential enabler for interference handling, and consequently, a front line for an implementation of a sureness aptitude would again be equipment certification, prior to its market entry, as represented in Figure 7.9. Understandably, the probability of unintended harmful interference is clearly mitigated, when a certified secondary system intends to take advantage of opportunistic spectra. In fact, incumbents QoS enforcement may start with a compliance verification of secondary systems.

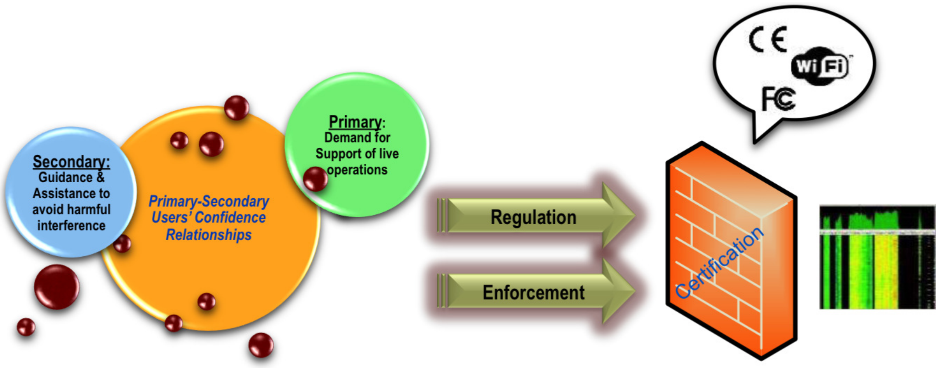


Figure 7.9: The role of certification.

However, the establishment of a worldwide certification capacity requires an international level of coordination, which might be equivalent, in complexity, to spectrum management processes. There are well known industry joint ventures and non-profit organizations that have been proved to be successfully in their missions of connectivity, interoperability and quality assurance of enabled products. Wi-Fi Alliance [161] is probably one of the most successful experiences in this area. However, those types of association based certification initiatives and their driving effects, are highly dependent upon the amount of members, their industry footprint and the amount of deployed systems/equipment. In the case of maritime CR-B-VHF communications, probably neither the amount of members, nor its industry footprint would be a problem. Eventually, the drawback of a Wi-Fi Alliance similar initiative, for maritime VHF, would be the potential amount of target terminals. Nevertheless, and even though a hypothetical worldwide equipment certification would not substitute the need for auditing operations and other policy enforcement initiatives, it would definitely be an importance complementary tool.

7.4 Concluding Remarks

The practical interest of maritime B-VHF services is easily recognizable and so is spectrum unavailability, either in MMS assigned spectrum or VHF spectrum in general. DSA and CR are pointed as decisive strategies to increase efficiency of electromagnetic radio spectrum usage and overcome its scarcity. The journey is definitely challenging, so every step should be carefully considered and based on criteria of feasibility, support and coexistence with legacy systems. However, similarly to other technological achievements, maritime B-VHF may end up in a situation where technological progress is far more intense than its equivalent in regulatory policy and plans.

Definitely, currently regulatory framework it is not only inadequate for emerging radio communications concepts and technologies, but also a potential barrier to its deployment. It is necessary to evolve towards a more flexible and dynamic approach to spectrum management, comprehensively preparing the transition phase and involving stakeholders. The path from exclusive use and interference free spectrum towards priority based shared spectrum and mitigation of interference to appropriate QoS levels is complex, but is essential to support users' needs and increasing demand for information exchange. Vital aspects such as QoS enforcement and operational livelihood depend upon the definition of adequate metrics and processes that goes from auditing activities to eventual equipment certification. The role of regulatory agencies is crucial in this process, to promote discussions, mediate processes and support solutions. The regulatory paradigm shift is inevitable, so the question is how its agenda will impact the systems under development.

The presented analysis intended to contribute for discussion on real need for regulatory framework evolution, specifically in maritime VHF bands, focusing the arguments on the solution, instead of the problem. The paradigm change encompasses a new policy definition, an enforcement mechanism and a transition plan. For all of those constituents it is necessary to identify an appropriate solution and a way to implement it, taking into consideration the existing environment. In the current analysis, we have been centered in the identification of challenges and opportunities associated to the maritime environment, addressing potential tracks for further investigation. It is now necessary to evaluate the feasibility of such courses of action and hand up with specific solutions for each case.

Chapter 8

Conclusions and Future Work

Despite the fact that non-SATCOM broadband systems would represent an important role on current maritime communications diversity, performance and cost, the most important value added to maritime community is their capacity to drive a paradigm change in information sharing at sea. A dramatic evolution on command and control, safety and security domains can be expected with a change at information centricity level. Currently, node centric entities collect, integrate, analyze and present, independently, the required information. In the future, if maritime communications enable it, information can be addressed in a network centric paradigm, focusing on information services provision. Such transformation would shape the maritime operations, allowing a consolidation of *e-navigation* and ITS, a massive deployment of autonomous vehicles and a federation of maritime based embedded computing like devices ecosystem, in a Io(M)T.

The proposed CR-B-VHF framework can support broadband services to current mariners' requirements, but is focused on future challenges of maritime community infostructure. Obviously, achievable performance depends on available spectrum for opportunistic usage. It is assumed that a significative portion of MMS assigned spectrum is eligible for this purpose, but that will depend on further regulatory authorities decisions. We have addressed regulatory framework evolution and practical aspects associated to regulatory and standardization, namely QoS enforcement within dynamic management models, and expect to contribute for on-going discussions on this subject. Nevertheless, decisions have to be made at some point, and hopefully, arguments as those presented will prevail.

Additionally, CR-B-VHF concept can be used to specific applications, as in the government area. For example, authorities can take advantage of their assigned spectrum and "autonomy" to manage it, and adopt dynamic access approaches to enable opportunistic use by CR-B-VHF network. Navy, Coast Guard and Maritime Police can benefit from this kind of initiatives, within national territories' area, due to their official status and competences, and dependency on SATCOM for broadband access. In those cases, CR-B-VHF "time to market" would be almost immediate, and just depending on technology availability.

The proof of concept of CR-B-VHF has been divided in two phases, so the following independent tasks have been assigned to fulfill experimental objectives: implementation of CR-B-VHF concept on a prototype, focusing on complete cognitive communication system and integrating essential processing components to achieve dynamic spectrum access, network integration and over-the-air network synchronization, with a spectrum sensing module that supports essential features to allow system validation; and development of a spectrum sensing scheme that considers a hierarchical spectrum access model and maximizes opportunistic spectrum usage efficiency, ensuring acceptable levels of harmful interference with incumbent's services. The former task has been accomplished within [T1] and later task has been presented within the scope of current thesis. Both of these assignments have been successfully bring to completion, which grant permission to demonstrate CR-B-VHF framework suitability, feasibility and deployability.

The spectrum sensing for opportunistic systems that operate within hierarchical access model requires a feature that would support spectrum exclusive access to incumbents. Such multiple spectrum access control requirement implicate secondary transmission suspension whenever primary service starts to operate. Hence, considered design options followed normal approaches to multiple access techniques: either use synchronous or asynchronous interruptions of transmission. In other words, two different solutions for spectrum sensing were investigated: half-duplex and full-duplex sensing.

In HDS, it is consider a time-sharing between sensing and transmission, where a synchronous interruption of transmission is performed according to defined sensing cycle time. This solution is adequate for cases of well characterized primary activity profiles, since it is based on optimization of sensing cycle parameters, i.e sensing and transmitting times, that maximize achievable capacity, which have primary activity statistics, such as P_{on} and its transmission rate, are included in constraints. Unfortunately, despite several efforts, the characterization of MMS incumbents is not simple, as referred in [T2] and [T3], not only because its requires a significant and diverse amount of spectrum surveys data, but also because administrations are not obligated to assign MMS allocated band for maritime services, which results in a mismatch of services from one country to another. Consequently, HDS has been found to be a solution that cannot achieve significant levels of spectrum efficient opportunistic use, in an hierarchical spectrum access model, due to its dependency on primary services operating statistics accuracy. The narrowband channels achievable throughput, in opportunistic use, is highly sensitive to overheads, so the introduction of tolerance coefficients, to fulfill incumbents harmful interference protection, associated to primary statistics data inaccuracy, has a considerable impact in the overall performance.

Alternatively, one can perform sensing and transmission simultaneously, i.e. in a full-duplex way, avoiding prior required information for optimization processes. A novel SCD has been proposed for FDS, based on spectral coherences evaluation of received signals at two sensing antennas. Since spectral coherence is a measure of phase consistency, if one can manage to control self received signals (at sensing antennas) in order to maintain a high degree of similarity between them, it is possible to detect third party emissions, while transmitting at the same frequency bands, through an evaluation of MSC value. The superimposition of primary signals, affected by multipath fading, will disrupt dependency of self received signals, pushing MSC towards zero. Therefore, detection capacity of a SCD will depend upon designer's competency to maximize the differences in MSC values, correspondent to $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$, i.e., highly conditioned by spectral estimator accuracy and resolution, and SIC proficiency.

The considered solution to fulfill spectral estimation requirements has been a proposed adaptation of Thomson's framework for cyclostationarity evaluation. It takes advantage of a combination of MTM with Loève transform, where MTM deals with bias-variance dilemma and provide high spectral resolution and superior performance in real time processing, while Loève transform adapts the non-stationary processes in order to produce the best possible basis for its expansion. The SIC design has to ensure adequate amplitude and phase on self received signals to enable SCD proper operation. Therefore, it has to accommodate an appropriate dynamic range on self and primary received signals (PtSR), which is associated to a self interference cancellation, as well as an accurate self signals coherence control.

The experimental results confirmed the potential of SCD based FDS for CR applications, particularly for the implementation of CR-B-VHF systems. The deployed FDS scheme presented excellent experimental results, specially when it is compared with envisage theoretical upper bounded performances of energy or quadratic detector, for similar conditions. Despite the advantages of FDS, regarding efficiency and independency of prior information on incumbents operation statistics, SCD testing provide good indication on superior performance, due to clear discrimination between $\mathcal{PR}_{off}$ and $\mathcal{PR}_{on}$. Despite other advantages, these outcomes are decisive for a designation of FDS as a preferable choice for CR-B-VHF.

In conclusion, the main contribution of this thesis work is the CR-B-VHF framework and the demonstration of its suitability, feasibility and deployability. The presented relevancy analysis provides an overview of the state of the art on maritime business and its associated support CIS systems, and prospects future requirements and applications for low-cost broadband access. The developed solutions for detection and exploitation of multiple non-contiguous narrowband spectrum opportunities in maritime VHF band, and their envisage performances, opens perspectives about attainability of opportunistic B-VHF systems and their future deployment. Finally, the discussion on regulatory and standardization issues intend to contribute for a shared problem solving, providing an end user perspective of hierarchical spectrum access.

The relevancy of non-SATCOM services and the demonstrated potential of CR-B-VHF recommend further related research initiatives that can contribute for the implementation and testing of a pre-industrial prototype. Unfortunately, it was not possible to integrate developed FDS module in the implemented prototype [T1], to perform full system testing. Even though, that activities are planned for a near future, in order to close the first spiral of development, conceived under CD&E doctrine. Afterwards, further spirals should be planned, in a bottom-up approach to systems engineering, consolidating sensing, transmission and CR links synchronization, before address upper layers.

The following phase shall include the integration of a 25 W power amplifier in prototype. The USRP limited transmitting power (100 mW) prevent experimentation trials at sea, so the increasing in radio power is an essential feature for any further initiatives. Additionally, SIC scheme has to be re-designed in order to ensure an appropriate PtSR, in accordance with radio higher power. The introduction of a cancellation module with an higher degree of self interference reduction requires to take advantage of analogue and digital cancellation techniques, and, eventually, replace Moxom antennas by other sensing array design, which might be able to provide an higher spatial filtering.

Furthermore, it is necessary to address CR links synchronization, from a FDS perspective. In other words, since FDS uses asynchronous interruptions of CR transmission, it is necessary to provide real time spectrum usage picture to all CRN nodes, in order to make sure that transmitting and receiving node are synchronized in the same operating spectra. A dedicated channel, as proposed in [T1], might be a good starting point, but it is necessary to evaluate operational conditions and asymmetric nature of links to decide on the appropriate architecture.

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Appendices

Appendix A

Python Code for GNU Radio Block: ”MTM Estimator”

```
from gnuradio import gr
from gnuradio import blocks
from gnuradio import fft
import specest_gendpss
import specest_swig

## Estimates PSD using Thomson’s multitaper method
# @param[in] N: Length of the FFT
# @param[in] NW: Time Bandwidth Product usually is of value 2, 2.5,
         3.0, 3.5, or 4
# @param[in] K: Numbers of Tapers to use. K should be smaller than
         2*NW
# @param[in] weighting: Which type of weighting to use for the
        eigenspectra. Choices can be ’unity’,’eigenvalues’ or
                adaptive class mtm(gr.hier_block2):
    ””” Estimates PSD using Thomson’s multitaper method. ”””
    def __init__(self, N=512 , NW=3 , K=5, weighting=’adaptive’,
         fftshift=False, samp_rate = 1, rate = 10):
        gr.hier_block2.__init__(self, ”mtm”,
                gr.io_signature(1, 1, gr.sizeof_gr_complex),
                gr.io_signature(1, 1, gr.sizeof_float*N))
        self.check_parameters(N, NW, K)

        self.s2v = blocks.stream_to_vector(gr.sizeof_gr_complex, N)
        self.one_in_n = blocks.keep_one_in_n(gr.sizeof_gr_complex *
        *N, max(1, int(samp_rate/N/rate)))
        self.connect(self, self.s2v, self.one_in_n)

        dpss = specest_gendpss.gendpss(N=N, NW=NW, K=K)
        self.mtm = [eigenspectrum(dpss.dpssarray[i], fftshift) for
         i in xrange(K)]
```

```
        if weighting == 'adaptive':
            self.sum = specest_swig.adaptiveweighting_vff(N,
            dpss.lambdas)
            self.connect_mtm(K)
            self.connect(self.sum, self)
        elif weighting == 'unity':
            self.sum = blocks.add_ff(N)
            self.divide = blocks.multiply_const_vff([1./K]*N)
            self.connect_mtm(K)
            self.connect(self.sum, self.divide, self)
        elif weighting == 'eigenvalues':
            self.eigvalmulti = []
            self.lambdasum = 0
            for i in xrange(K):
                self.eigvalmulti.append(blocks.multiply_const_vff
                ([dpss.lambdas[i]]*N))
                self.lambdasum += dpss.lambdas[i]
            self.divide = blocks.multiply_const_vff
            ([1./self.lambdasum]*N)
            self.sum = blocks.add_ff(N)
           #self.connect_mtm(K) #--> doesn't take into account
            self.eigvalmulti !!!!!!
            self.connect_mtm_eig(K)
            self.connect(self.sum, self.divide, self)
        else:
            raise ValueError, 'weighting-type should be: adaptive,
            unity or eigenvalues'


    def connect_mtm(self, K):
        """ Connects up all the eigenspectrum calculators. """
        for i in xrange(K):
            self.connect(self.one_in_n, self.mtm[i])
            self.connect(self.mtm[i], (self.sum, i))

    def connect_mtm_eig(self, K):
        """ Connects up all the eigenspectrum calculators. """
        for i in xrange(K):
            self.connect(self.one_in_n, self.mtm[i])
            self.connect(self.mtm[i], self.eigvalmulti[i],
            (self.sum, i))
```

```
    ## Checks the validity of parameters
    # @param[in] N: Length of the FFT
    # @param[in] NW: Time Bandwidth Product
    # @param[in] K: Numbers of Tapers to used
    def check_parameters(self, N, NW, K):
        ””” Checks the validity of parameters. ”””
        if NW < 1: raise ValueError, ’NW must be greater than or
        equal to 1’
        if K < 2:  raise ValueError, ’K must be greater than or
        equal to 2’
        if (N % 1): raise TypeError, ’N has to be an integer’
        if N < 1:  raise ValueError, ’N has to be greater than 1’


## Computes the eigenspectra for the multitaper spectrum estimator:
# data ——> multiplication dpss ——> FFT ——> square ——>
output eigenspectrum
# @param[in] dpss: the dpss used as a data taper
class eigenspectrum(gr.hier_block2):
    ””” Computes the eigenspectra for the multitaper spectrum
    estimator:
    data —> multiplication dpss —> FFT —> mag–square —>
    output eigenspectrum ”””
    def __init__(self, dpss, fftshift=False):
        gr.hier_block2.__init__(self, ”eigenspectrum”,
                gr.io_signature(1, 1, gr.sizeof_gr_complex*
                *len(dpss)),
                gr.io_signature(1, 1, gr.sizeof_float*len(dpss)))
        self.window = dpss
        self.fft = fft.fft_vcc(len(dpss), True, self.window,
        fftshift)
        self.c2mag = blocks.complex_to_mag_squared(len(dpss))
        self.connect(self, self.fft, self.c2mag, self)
```

Appendix B

Python Code for GNU Radio Block: ”Loeve SC”

```
from gnuradio import gr
from gnuradio import blocks
from gnuradio import fft
import specest_gendpss
import specest_swig

## Estimates PSD using Thomson’s multitaper method
# @param[in] N: Length of the FFT
# @param[in] NW: Time Bandwidth Product usually is of value 2, 2.5,
      3.0, 3.5, or 4
# @param[in] K: Numbers of Tapers to use. K should be smaller than
      2*NW
# @param[in] weighting: Which type of weighting to use for the
      eigenspectra. Choices can be ’unity’,’eigenvalues’ or
      adaptive
class loeve(gr.hier_block2):
    ””” Computes Loeve Spcetral Coherences ”””
    def __init__(self, N=512 , NW=3 , K=5, fftshift=False,
        samp_rate = 1, rate = 10):
        gr.hier_block2.__init__(self, ”loeve”,
                gr.io_signature(2, 2, gr.sizeof_gr_complex),
                gr.io_signature(1, 1, gr.sizeof_float*N))
        self.check_parameters(N, NW, K)

        self.s2v1 = blocks.stream_to_vector(gr.sizeof_gr_complex,
        N)
        self.s2v2 = blocks.stream_to_vector(gr.sizeof_gr_complex,
        N)
        self.one_in_n1 = blocks.keep_one_in_n(gr.sizeof_gr_complex
        *N, max(1, int(samp_rate/N/rate)))
```

```
        self.one_in_n2 = blocks.keep_one_in_n(gr.sizeof_gr_complex
        * N, max(1, int(samp_rate/N/rate)))
        self.connect((self, 0), self.s2v1, self.one_in_n1)
        self.connect((self, 1), self.s2v2, self.one_in_n2)

        dpss = specest_gendpss.gendpss(N=N, NW=NW, K=K)
        self.mtm1 = [eigenspectrum(dpss.dpssarray[i], fftshift) for
         i in xrange(K)]
        self.mtm2 = [eigenspectrum(dpss.dpssarray[i], fftshift) for
         i in xrange(K)]

        self.multipliers = [blocks.multiply_vcc(N) for i in
         xrange(K)]

        self.sum = blocks.add_vcc(N)
        self.divide = blocks.multiply_const_vcc([1./K]*N)
        self.c2mag = blocks.complex_to_mag_squared(N)
        self.connect_loeve(K)
        self.connect(self.sum, self.divide, self.c2mag, self)

    def connect_loeve(self, K):
        """ Connects up all the eigenspectrum calculators. """
        for i in xrange(K):
            self.connect(self.one_in_n1, self.mtm1[i])
            self.connect(self.one_in_n2, self.mtm2[i])
            self.connect(self.mtm1[i], (self.multipliers[i], 0))
            self.connect(self.mtm2[i], (self.multipliers[i], 1))

            self.connect(self.multipliers[i], (self.sum, i))


    ## Checks the validity of parameters
    # @param[in] N: Length of the FFT
    # @param[in] NW: Time Bandwidth Product
    # @param[in] K: Numbers of Tapers to used
    def check_parameters(self, N, NW, K):
        """ Checks the validity of parameters. """
        if NW < 1: raise ValueError, 'NW must be greater than or
        equal to 1'
        if K < 2:  raise ValueError, 'K must be greater than or
        equal to 2'
        if (N % 1): raise TypeError, 'N has to be an integer'
        if N < 1:  raise ValueError, 'N has to be greater than 1'
```

```
## Computes the eigenspectra for the multitaper spectrum estimator:
# data ——> multiplication dpss ——> FFT ——> square ——>
output eigenspectrum
# @param[in] dpss: the dpss used as a data taper
class eigenspectrum(gr.hier_block2):
    ””” Computes the eigenspectra for the multitaper spectrum
     estimator:
    data —> multiplication dpss —> FFT —> mag–square —>
    output eigenspectrum ”””
    def __init__(self, dpss, fftshift=False):
        gr.hier_block2.__init__(self, ”eigenspectrum”,
                gr.io_signature(1, 1, gr.sizeof_gr_complex*
                len(dpss)),
                gr.io_signature(1, 1, gr.sizeof_gr_complex*
                len(dpss)))
        self.window = dpss
        self.fft = fft.fft_vcc(len(dpss), True, self.window,
        fftshift)
        self.connect(self, self.fft, self)
```