Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
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Carlos Filipe Moreira e Silva

Gestão Comum de Recursos Rádio em Redes Sem Fios de Próxima Geração

Common Radio Resource Management in Wireless Heterogeneous Networks

"Try and leave the world a little better than you found it and when your turn comes to die, you can die happy in feeling that at any rate you have not wasted your time but have done your best."

— Robert Smith Baden Powell

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Common Radio Resource Management in Wireless Heterogeneous Networks

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Electrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Francisco Fontes.

Thesis submitted to the University of Aveiro for the degree of Master in Electronics and Telecommunications under the supervision of Professor Francisco Fontes.

o júri / the jury

presidente / president	**Professor Doutor Atílio Manuel Silva Gameiro** Professor Associado da Universidade de Aveiro
Vogais / Examiners committee	**Professor Doutor Fernando José Silva Velez** Professor Auxiliar da Universidade da Beira Interior (arguente principal)
	Professor Doutor Francisco Manuel Marques Fontes Professor Auxiliar Convidado da Universidade de Aveiro (orientador)

agradecimentos / acknowledgements

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palavras-chave Gestão de Recursos Rádio, Redes Heterogéneas, Redes Sem Fios, Rádio sobre Fibra Óptica

resumo

A tecnologia de sinais de rádio frequência sobre fibra óptica involve o uso de *links* ópticos para transportar os sinais desde a unidade central de processamento até aos *sites* remotos (e vice-versa). A centralização do processamento dos sinais de rádio frequência permite a partilha de equipamentos, alocação dinâmica de recursos e uma manutenção mais simplificada do sistema.

Embora o conceito de gestão comum dos recursos rádio tenha despertado grande interesse na comunidade científica em termos da melhor utilização desses recursos e de novos modelos de negócio, a verdade é que a sua implementação não tem sido fácil. A interligação entre diferentes componentes de rede, normalmente localizados em locais diferentes, introduz um grande atraso nas comunicações; por outro lado as implementações proprietárias e a escassez de informação global não satisfazem os requisitos de um ambiente extremamente dinâmico, como é o ambiente *wireless*. Uma topologia centralizada permite ultrapassar estas contrariedades, disponibilizando uma interligação eficiente entre as entidades locais e comuns de gestão de recursos rádio.

Nesta dissertação é apresentada uma nova arquitectura de gestão comum de recursos rádio, baseada no conceito de interligação entre diferentes tecnologias de acesso. Esta arquitectura faz a gestão dos recursos rádio de forma centralizada, onde os sinais rádio chegam sem qualquer pré-processamento. Essa arquitectura é avaliada com a implementação de um algoritmo simples de balanceamento da carga que segue a politica de minimização da interferência e aumento da capacidade.

As simulações com duas tecnologias de acesso, quando consideradas separas ou em agregado, mostraram um aumento do débito de pelo menos 51% para o mesmo valor de interferência enquanto que o erro de simbolo decresce pelo menos 20%.

keywords Common Radio Resource Management, Heterogeneous Networks, Wireless Networks, Radio over Fibre

abstract Radio over fibre technology involves the use of optical fibre links to distribute radio frequency signals from a central location to remote sites (and vice-versa). The centralisation of radio frequency signals processing functions enables equipment sharing, dynamic allocation of resources, and simplified system operation and maintenance.

Despite the unquestionable interest concept of common radio resource management from the point of view of resource usage and novel business models, its implementation has not been easy. The interworking between the different local radio resource management entities, usually located on different places will not satisfy the requirements of the wireless dynamic behaviour due to increase of delay in communication process, less information availability and proprietary implementations. A centralised topology can overcome the drawbacks of former wireless systems architecture interconnection by providing an efficient common radio communication flow with the local radio resource management entities.

In this thesis a novel common radio resource management architecture is presented based on the concept of inter-working between different technologies. This is a centralised architecture where the radio frequency signals are delivered to the central location through the optical links. The new architecture is evaluated with a common policy that minimises interference while the overall system capacity is increased. The policy is implemented through the load balancing algorithm.

The simulations of two radio access technologies when separately and jointly considered show that when the load balancing algorithm is applied the available throughput increases in at least 51% while the symbol error rate decreases at least 20%.

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List of Acronyms and Abbreviations

3G Third Generation

3GPP 3rd Generation Partnership Project

AAA Authentication, Authorization and Accounting

ABC Always Best Connected

AC Admission Control

AP Access Point

AWGN Additive White Gaussian Noise

B3G Beyond Third Generation

BER Bit Error Rate

BLER Block Error Rate

BPSK Binary Phase Shift Keying

BS Base Station

BSC Base Station Controller

CAC Call Admission Control

CC Congestion Control

CDMA Code Division Multiple Access

C/I Carrier-to-Interference

CMC Connection Mobility Control

COST COperation européenne dans le domaine de la recherche Scientifique et Technique

CPCH Common Physical Channel

CRRM Common Radio Resource Management

CU	Central Unit
CWmin	Minimum Contention Window
DPCH	Dedicated Physical Channel
DRA	Dynamic Resource Allocation
eNB	Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network Node B
E-UTRAN	Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network
FACH	Forward Access Channel
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FUSC	Full Usage Sub-Channels
FUTON	Fibre Optic Networks for Distributed, Extendible Heterogeneous Radio Architectures and Service Provisioning
GERAN	Global System for Mobile Communications/Edge Radio Access Network
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HCS	Hierarchical Cell Structure
HHO	Horizontal Handover
HoF	Handover Function
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISI	Inter-Symbol Interference
LB	Load Balancing
LC	Load Control
LRRM	Local Radio Resource Management
LS	Link Selection
LTE	Long Term Evolution

MAC	Media Access Control
MDB	Middleware Database
MIHO	Mobile Initiated Handover
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MRRC	Maximal-Ratio Receiver Combining
MT	Mobile Terminal
NB	Node B
NIHO	Network Initiated Handover
NRT	Non-Real Time
ns2	Network Simulator 2
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OVSF	Orthogonal Variable Spreading Factor
PC	Power Control
PDCP	Packet Data Convergence Protocol
PER	Packet Error Rate
PHY	Physical Layer Device
PS	Packet Scheduling
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAB	Radio Access Bearer
RAC	Radio Admission Control
RAN	Radio Access Network
RAT	Radio Access Technology
RAU	Remote Access Unit
RBC	Radio Bearer Control

RF	Radio Frequency
RLC	Radio Link Control
RNC	Radio Network Controller
RoF	Radio over Fibre
RRC	Radio Resource Control
RRM	Radio Resource Management
RRU	Radio Resource Unit
RT	Real Time
SCM	Service Connection Manager
SER	Symbol Error Rate
SF	Service Flow
SFID	Service Flow Identifier
SINR	Signal-to-Interference and Noise Ratio
SIR	Signal-to-Interference Ratio
SLA	Service Level Agreement
SNR	Signal-to-Noise Ratio
SPID	Subscriber Profile Identifier
SUI	Stanford University Interim
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TxOP	Transmit Opportunity
UMTS	Universal Mobile Telecommunications System
UPE	User Plane Entity
UTRAN	Universal Mobile Telecommunications System Terrestrial Radio Access Network
VHO	Vertical Handover
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

WP4 Work Package 4

CHAPTER 1

Introduction

ONE of the main trends in the mobile communications sector is the possibility to be connected anywhere, anytime, anyhow philosophy. This is the Always Best Connected (ABC) philosophy. It is based on the fact that several competing technologies, which have different requirements and capabilities can co-exist. This approach tries to select always the best network according to a set of requirements and perform the inter-system handover between them, when those requirements are not fulfilled.

Wireless communication systems are dynamic by nature. Dynamism comes from several factors: radio propagation impairments, traffic changes, interference conditions, or user mobility. Thus, the dynamic network behaviour demands for a dynamic radio resources management, which is carried out by the Radio Resource Management (RRM) mechanisms. This mechanism has associated a large number of parameters and quality/performance indicators that need to be set, measured, analysed and optimised.

Radio over Fibre (RoF) technology involves the use of optical fibre links to distribute Radio Frequency (RF) signals from a central location to Remote Access Units (RAUs) (and vice-versa). The centralisation of signals processing functions enables equipment sharing, dynamic allocation of resources, and simplified system operation and maintenance. Since switching, modulation, and other RF functions are performed at a central location, dynamic radio resource configuration and capacity allocation is feasible. In this context, Base Stations (BSs) are significantly simplified as they only need to perform optical-electronic conversion and amplification functions. Consequently, they may be more compact, cost-effective and easier to deploy. These bring major benefits in system installation and operational savings, especially in wide-coverage broadband wireless communication systems, with a high density of BSs. Therefore, in order to increase the radio capacity and minimise the interference, novel RRM algorithms and mechanisms shall be addressed, taking advantage of RoF centralised topology and increased number of RAUs that can be deployed.

Each RAU simply consists of basic RF converters, radiating elements or antennas, and electro-optical conversion modules, which greatly reduces the complexity of the cell-sites by concentrating all the signal processing capabilities in the Central Unit (CU). This characteristic allows the potential improvement/optimisation of existing and the deployment of novel joint processing, cross-layer and cross-system algorithms for distributed and heterogeneous wireless systems.

The scenario of an heterogeneous wireless environment with multi-mode terminals, where several Radio Access Technologies (RATs) coexist, introduces a new dimension into the RRM problem. Instead of performing the management of the radio resources independently for each RAT, an overall and global management of the pool of radio resources can be envisaged. The Common Radio Resource Management (CRRM) is the process envisaged to manage dynamically the allocation and de-allocation of radio resources within a single or between different radio access systems for the fixed spectrum bands allocated to each of these systems, achieving a more efficient usage of the available radio resources.

Up to now the CRRM concept, despite its unquestionable interest from the point of view of resource usage and novel business models, has not been easy to implement. The interworking between different Local Radio Resource Management (LRRM) entities, usually located on different places, which may greatly increase the delay and the message exchange overload, will not satisfy the requirements of wireless dynamic behaviour. Furthermore, the different implementations and proprietary software limit the communication process that do allow an efficient common management in the heterogeneous scenario. A centralised topology can overcome the drawbacks of former wireless systems architecture interconnection by providing an efficient CRRM communication flow with the LRRM entities.

Depending on the implementation, the CRRM may contain several functionalities such as: initial RAT selection, joint Admission Control (AC), joint Congestion Control (CC), cell selection and Vertical Handover (VHO) algorithms. Considering this top and integrated view of the available radio resources, an higher efficiency on its usage can be achieved, guaranteeing the planed coverage, the contracted Quality of Service (QoS) for each service and the planed blocking rate by limiting the user interference within the same cell or inter-cell interference

Due to the high capacity of optical fibre infrastructure, the main application was initially done at core backbone networks. In contrast, wireless networks were greatly affected by the propagation environments, thus they were mainly dedicated to low and medium data rate mobility scenarios. However, the dramatic drop in the cost of optical fibre networks and the advent of powerful signal processing capabilities for wireless communications have led to a natural convergence between these two previously independent technologies. Low cost optical fibre networks means that they can be extended with no problems almost to the end user, e.g., in fibre to the home applications. On the other hand, wireless technologies have created in the user a sense of freedom and mobility which together with the proliferation of advanced user terminals and processing algorithms have contributed to an explosive demand for faster and better wireless connections. Therefore, it seems natural to think about high speed wireless access radio technology combined with optical fibre networks in order to achieve the stringent requirements of next generation networks.

The propose of FUTON [18] project is the development of a hybrid fibre-radio infrastructure transparently connecting the RAUs to a CU where the joint processing is performed. This concept allows the development of virtual multiple transmission/reception antennas to achieve broadband wireless transmission and inter-cell interference cancellation. Furthermore, the fact that the management of several heterogeneous systems is co-localised enables the development of efficient procedures for a joint management of the radio resources.

1.1. Objectives

The objectives of this thesis may be summarised as:

1. Characterise the state-of-art about mechanisms of RRM and CRRM in heterogeneous wireless systems;
2. Study of the main problems in wireless networks regarding radio resources, namely interference, which limits coverage and the total admitted users[1]. The CRRM policy under study may be enunciate as: minimise interference and increase the overall system capacity (and, if possible, also coverage);
3. Propose a new architecture for CRRM which takes advantage of centralised information availability and joint processing while being compatible with 3rd Generation Partnership Project (3GPP) standards;
4. Implement an algorithm for the proposed CRRM policy, which is the Load Balancing (LB) algorithm;
5. Validate the CRRM architecture, evaluating the behaviour of the implemented algorithm for the studied CRRM policy that is proposed within the context of the new architecture.

1.2. Contributions

The main contributes for this thesis were achieved during the participation of the author in the European project FUTON. Namely in Work Package 4 (WP4) [19, 20].

1.3. Assumptions

The author assumes an heterogeneous wireless environment characterised as follows:

1 In this thesis users, sessions or service flows are often mentioned in an undifferentiated meaning.

- Different wireless technologies share the same geographical area, namely Universal Mobile Telecommunications System (UMTS) and Worldwide Interoperability for Microwave Access (WiMAX);
- Considering different Radio Access Networks (RANs), multiple cells with different radio access modes and operating on different frequencies may overlap and multiple cell layers (macro, micro, pico) will co-exist. This situation must be met otherwise the inter-system handover cannot be performed;
- It is assumed that every RAN already have their own LRRM entities for performance optimisation and radio management inside the RAN;
- The physical parameters and measurements can be obtained from terminals and somehow from the legacy (proprietary) networks;
- The terminals are multi-mode terminals, thus they can connect to different RATs.

1.4. Thesis Organisation

The thesis is organised in the following way:

Chapter 2: the state-of-art regarding RRM in different wireless and cellular networks is presented. In the end of this section it is presented the vision of 3GPP about CRRM, which is the followed approach in the thesis.

Chapter 3: the novel CRRM architecture is presented and described. The adopted principles regarding the design of CRRM solutions for the architecture are also stated in the section.

Chapter 4: in this chapter the author studies the interference problems inside multi-user technologies when it it necessary to access to the RF spectrum, namely Wideband Code Division Multiple Access (WCDMA) (which is the RAT used in UMTS) and Orthogonal Frequency Division Multiple Access (OFDMA) (which is the RAT used in WiMAX), both for downlink and uplink.

Chapter 5: the new architecture is evaluated in terms of CRRM for a particular scenario where two technologies, RAT1 and RAT2, are co-localised. The cell in the centre is the one under study, while the outer cells are interfering ones. The policy and the algorithm are implemented in a simulator. Finally, the discussion of results is done.

The thesis ends with the conclusions and possible future work.

CHAPTER 2

Local and Common RRM

THE RRM is a system level control of co-channel interference and other radio transmission characteristics in wireless communication systems, either cellular networks, wireless networks or broadcasting systems. RRM involves strategies and algorithms for controlling parameters such as transmit power, channel allocation, handover criteria, modulation scheme, and error coding scheme. The objective is to utilise the limited RF spectrum resources and radio network infrastructure as efficiently as possible. Furthermore, RRM concerns to multi-user and multi-cell network capacity issues, rather than point-to-point channel capacity.

In the protocol stack, RRM functions can be divided between the link (L2) and network (L3) layers, considering the information requirements, the target object and functions that are available. In figure 2.1 the example of UMTS radio interface is represented. The Radio Resource Control (RRC) entirely belongs to the control plane, hence it has no data information, only control information. It receives measurements from Media Access Control (MAC) and Physical Layer Device (PHY) layers and sends control information to Radio Link Control (RLC), MAC and PHY layers.

RRM may be static or dynamic: dynamic RRM schemes are considered in the design of wireless systems, in view to minimise expensive manual cell planning and achieve tighter frequency reuse patterns, resulting in improved system spectral efficiency. Dynamic RRM schemes adaptively adjust the radio network parameters to the traffic load, user positions, or QoS requirements. Some schemes are centralised, where several BSs and Access Points (APs) are controlled by a Radio Network Controller (RNC); others are distributed, either autonomous algorithms in terminals, BSs or wireless APs, or coordinated by exchanging information among these stations.

In [1] 3GPP introduced the concept of CRRM, which is further enhanced in [2]. That document starts like this: *In the future, the mobile network configurations will not be as simple as in nowadays. Multiple cells from different radio technologies will be overlapped in the same area and multiple layers will co-exist. In this complicated environment, multi-mode mobile*

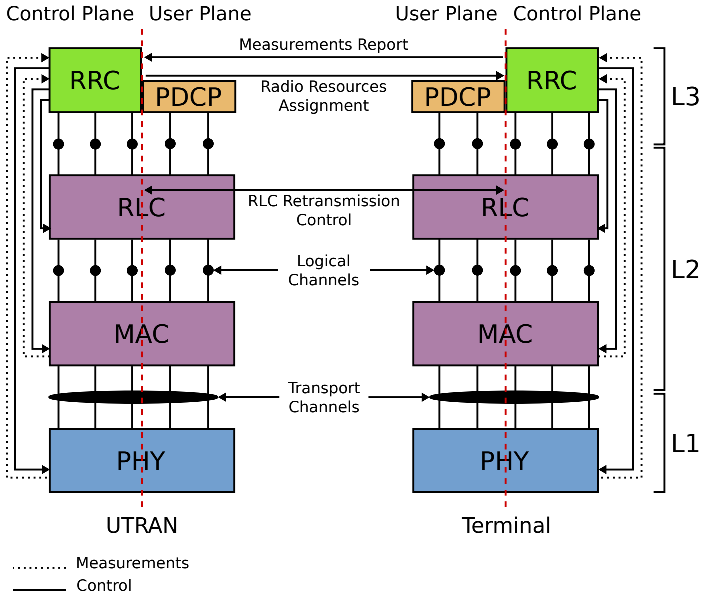


Figure 2.1.: UMTS radio interface: RRM blocks divided per L2 and L3

can be connected to different cell and unless there is knowledge about each cell it would be very difficult to optimise network performance and to manage resources efficiently. In addition, it would be reasonable to direct different services with different QoS classes to the most suitable radio accesses.

Further, 3GPP defines LRRM and CRRM entities and suggests three different topologies: CRRM integrated into every RNC/BSC, CRRM integrated only in some RNC/BSCs, and CRRM as a stand-alone server. The last option is the one that is explored in this thesis.

2.1. Overview of LRRM Techniques

In this section is provided an overview regarding the RRM techniques considered for legacy and new systems. Many of them are common to many technologies, while others are technology-specific.

2.1.1. Wireless Fidelity (WiFi)

Wireless Fidelity (WiFi), also known as IEEE 802.11 standard, does not originally include RRM techniques. However, the RRM techniques were required for industrial environments and offices, thus new standards had to be developed. The first was IEEE 802.11h, which has already been integrated into the full IEEE 802.11-2007 standard [26], and the newer IEEE 802.11k.

The working groups proposed three RRM techniques: dynamic channel assignment, dynamic transmit Power Control (PC), and load sharing [21].

Dynamic Channel Assignment

The performance of a network depends, in part, on the assignment of radio channels to each AP. The optimal channel assignment for a given Wireless Local Area Network (WLAN) should minimise the overlap between coverage areas of co-channel APs. This will enhance the performance of the network by reducing interference between co-channel APs.

The coverage areas, and therefore the channel assignments, are dependent on, among other things, the radio propagation environment; the radio propagation environment changes, which make impossible to be sure that the channel assignments valid at the time that network was designed will continue to be valid. With RRM techniques it is possible to dynamically adjust channel assignments accordingly.

There are 14 radio channels available at 2.4 GHz to use in IEEE 802.11b/g worldwide.

Dynamic Transmit Power Control

The dynamic transmit PC has the potential to reduce the effort involved in the site survey and design of a WLAN. It may be possible to carry out an abbreviated site survey and design process, placing APs in good, if not the best, locations (which provides a complete coverage without excessive coverage overlap) and allowing the dynamic transmit PC capability to make the necessary adjustments.

Furthermore, to facilitate the dynamic channel assignment, the dynamic transmit PC accommodates the changes in the propagation environment, and also compensates the lost coverage due to failed APs.

It can be used the inter-AP received signal strengths as a proxy for coverage overlap. The APs listen to each others signals, and the transmit power of each AP is set in a way that will achieve the desired signal strength at (and coverage overlaps with) other APs.

Until the year 2004, the transmit PC technique only affected the transmit power of APs (the downlink coverage area). The IEEE 802.11 standard does not provide a way for the WLAN infrastructure (e.g., an intelligent switch/AP combination) to control the transmit power of clients and, therefore, uplink coverage area.

Load Sharing

An AP and its associated clients share a limited bandwidth resource. This limitation implies that APs may become overloaded, which conducts to performance degradation.

However, since clients may be able to communicate quite successfully with two or more APs, redistributing associations among APs more or less uniformly so that no AP becomes overloaded may considerably enhance the network performance. Thus, if an AP is heavily loaded, it might not be the best candidate to accept a new association request. If such request is received and the RRM is running on the intelligent switch, which knows that a lightly loaded AP is also within radio range of the requesting client, it may decide that it is better for the requested AP to deny the association (and the association would be done with the lightly loaded AP).

2.1.2. Universal Mobile Telecommunications System (UMTS)

The RRM modules for UMTS are: AC, CC/LC, handover control, PC, and Packet Scheduling (PS) control. The functions for each of these modules are presented bellow.

Admission Control

AC handles all new incoming traffic checking whether new connections can be admitted to the system and generates parameters for them. It occurs when new connection is set up as well during handovers and bearer modification.

If the load of air interface increases excessively, the coverage area of the cell is reduced below the planned values, which is known as cell *breathing* (and QoS cannot be guaranteed). The breathing phenomenon occurs because Code Division Multiple Access (CDMA) technologies are an interference-limited system.

Admitting a new call always increases the cell load. In order to avoid overload situations, the AC will limit the increase of this load. The principle is to check the current load in the system plus the expected resource consumption of the new call against the AC threshold. The load estimation is applied both for downlink and uplink. The requesting bearer can be admitted only if the admission is made in both directions, otherwise it is rejected because of the excessive interference that it adds to the network. Although, as the AC techniques are applied separately for downlink and uplink, different AC strategies may be used in each direction.

In case the admission check fails, the basic strategy is to protect ongoing calls by denying the new user access to the system, since dropping is assumed to be more annoying than blocking.

Generally, the AC strategies can be divided into two types: power- and throughput-based AC strategy. In the first strategy, new users are not admitted if the new resulting interference level is above of the maximum uplink noise rise (*near-far* problem). In the second strategy, users are not admitted if the new resulting total load is higher than the threshold throughput value.

Congestion Control and Load Control

One important task of the RRM functionalities is to ensure that the system is not overloaded and remains stable. Furthermore, if the system is properly planned, and the AC works well, overload situations are exceptional.

However, due to mobility (especially of high data rate users) overload situations occur even if an efficient AC algorithm is used. When overload is encountered the CC (also known as Load Control (LC)) returns the system quickly and controllably back to the targeted load, which is defined in the radio network planning phase.

Some possible actions that can be used by the CC in order to reduce or balance load are:

- Decrease data rate of one or several services that are insensitive to delay;
- Inter-frequency or inter-system handover;
- Drop calls in a controlled way.

Handover Control

Handover is an essential component of mobile cellular communication systems. Mobility causes dynamic variations in link quality and interference levels, which sometimes require that a particular user changes its serving Node B (NB)[1].

The objectives of handover can be summarised as follows [13]:

- Guarantee the continuity of wireless services when the mobile user moves across the cellular boundaries;
- Keep the required QoS;
- Minimise the interference level of the whole system by keeping the mobile linked to the strongest NB;
- Roaming between different networks;
- LB.

Different types of handovers may be considered in UMTS:

- Soft/Softer handover (dedicated channels with the same carrier);
- Hard handover (shared channels or dedicated channels with different carriers);
- Inter-frequency handover;
- Inter-system handover (e.g., UMTS/GSM);
- Cell selection/reselection (inactive or idle).

1 NB is the name for BS in UMTS.

Power Control

PC is a necessary element in all mobile systems because of the battery life problem and safety reasons. In WCDMA systems, PC is essential because it optimises the system capacity by controlling interference and overcomes the near-far effect in the uplink.

For WCDMA systems and in the same direction (downlink or uplink), all users share the same channel (same carrier). Two terminals have different codes (Code Division Multiple Access) attributed by NB. In this sense, if one terminal increases its transmit power to reach the NB without being controlled, it will probably block other terminals that have lower transmit power.

The near-far problem in the uplink direction is well known in literature [38]. Signals from different terminals are transmitted in the same frequency band simultaneously and the spreading codes are not perfectly orthogonal. Without PC the signal coming from the nearest terminal to the NB may block signals from other terminal that are farer away from the NB; or farer way terminals would increase the transmit power, which would highly increase the noise of the system.

In downlink direction there is no near-far problem due to the one-to-many scenario. In this direction, PC is responsible for compensating the inter-cell interference suffered by terminals, especially those who are near the cell boundaries. Moreover, PC in the downlink is responsible for minimising the total interference by keeping the QoS at its target value.

There are mainly three types of PC algorithms in WCDMA systems:

Open loop PC: this relates directly to the path loss. As the name suggests, this control has no feedback. Thus, it simply sets the initial power at which the terminal should transmit. This initial setting happens via RRC signalling. The open loop PC is done in the terminal and RNC.

Outer loop PC: this relates to long term variations of the channel. A target Signal-to-Interference Ratio (SIR) is specified and if the received SIR is less than this target, the transmit power needs to be increased, otherwise it needs to be decreased. In practice, downlink target quality is in terms of transport channel Block Error Rate (BLER). BLER can be related to a target SIR. If the received SIR is less than the target then BLER is likely to be not met. Alternatively, if the BLER is more than the target, the transmit power has to be increased. This control is in the terminal and the RNC. This is also known as slow closed loop PC, because it happens at the rate of $10-100\,\text{Hz}$.

Inner loop PC: this is also known as fast closed loop PC. It happens at a rate of $1500\,\text{Hz}$ to combat fast fading and is done in the terminal and the NB. While outer loop control is set at RRC level and executed at L2, fast PC happens at L1 in order to meet the BLER target set by outer loop control. The effect of this control is that even in a fading channel, the received power is maintained constant so as to achieve the target BLER.

Packet Scheduling Control

The PS control monitors the system load and controls the existing data session scheduling in an efficient way.

It handles all Non-Real Time (NRT) traffic, deciding when a packet transmission is initiated and its bit rate. Moreover, PS control is also responsible to initiate the transport channel type, switching between common, shared and dedicated channels when necessary.

2.1.3. Worldwide Interoperability for Microwave Access (WiMAX)

The standards of the IEEE 802.16 family provide fixed and mobile broadband wireless access and promise to deliver high data rate services over large areas, based on complexity and flexibility management of the MAC and PHY layers. The IEEE 802.16 family is expected to improve the delivered QoS, namely when compared with UMTS [23].

Although IEEE 802.16 specifications define the signalling messages for the multiple access mechanisms and WiMAX Forum[2] streamlines the implementation of IEEE 802.16 standards, namely Mobile WiMAX also known as IEEE 802.16e, the RRM protocols and many aspects of network control and management are left unspecified on purpose for innovations by individual equipment vendors as a way to differentiate their products in the marketplace.

In Mobile WiMAX RRM algorithms include: Call Admission Control (CAC), adaptive transmission, and Horizontal Handover (HHO).

Call Admission Control

The CAC algorithm handles system overloading and satisfies the QoS by limiting the number of users in the system (i.e., deciding if new user shall be or not admitted to the network). The goals of CAC are related with satisfying the QoS requirements for admitted users, maximising the network capacity, and support fairness and priorities among users [7, 31].

The CAC schemes are based on Signal-to-Interference and Noise Ratio (SINR), interference, bandwidth, load, or system capacity [7, 31]. However, in [29, 32] the admission of new users is based on the analysis of the current status of active users queues.

In Mobile WiMAX network the most suitable scheme is the one that maximises network capacity, while satisfying QoS for all admitted users [16].

Adaptive Transmission

The adaptive transmission enables the adaptation of PHY layer parameters to the changes in the reception conditions.

2 `http://www.wimaxforum.org`

The adaptive transmission includes scheduling, adaptive modulation and coding, PC, and time-frequency resource allocation. In OFDMA with the multi-user diversity, adaptive resources allocation algorithms play an important role. The receiving conditions are dependent on sub-channels frequency, thus users can be assigned to sub-channels with the best receiving conditions, achieving multi-user diversity gain. These algorithms when performed in OFDMA networks are computational complex due to large degrees of freedom, and most of them do not perform a joint downlink and uplink optimisation.

For example, in the case of frequency diversity, the adaptation parameters are position of the frame boundary between the downlink and uplink subframes, coding and modulation schemes, and transmission power values of downlink and uplink Service Flows (SFs). Positions of service flows within the downlink and uplink subframes may be selected arbitrary. However, the optimisation for these service flows on the frame-by-frame basis shall be considered to achieve the desired QoS.

Horizontal Handover

HHO guarantees the continuous service by assigning a new serving BS to user in the cellular environment when the receiving conditions degrade. The receiving conditions are characterised by the signal level or SINR. Although, to guarantee the QoS requirements, not only the downlink and uplink receiving conditions shall be taken into account but also the load of the serving sector. New algorithms are an enhancement to the traditional algorithms, which only consider the signal level or SINR and not the load of sector, thus cannot guarantee the QoS requirements.

2.1.4. Long Term Evolution (LTE)

The text in this section is based on the last studies done in the scope of RRM functions for Long Term Evolution (LTE) technology [3, section 16.1], proposed by 3GPP, which is presented here as a reference in Beyond Third Generation (B3G) systems.

For LTE the set of RRM functionalities include: Radio Bearer Control (RBC), Radio Admission Control (RAC), Connection Mobility Control (CMC), Dynamic Resource Allocation (DRA) or PS, Inter-Cell Interference Coordination (ICIC), LB, inter-RAT RRM, and Subscriber Profile Identifier (SPID) for RAT/frequency priority.

Radio Bearer Control

The establishment, maintenance and release of radio bearers involve the configuration of radio resources associated with them. When setting up a radio bearer for a service, RBC takes into account the overall situation of resources in E-UTRAN, the QoS requirements of in-progress sessions and the QoS requirement for the new service. RBC is also concerned with the maintenance of radio bearers of in-progress sessions at the situation change of the radio resources due to mobility or other reasons. RBC is involved in the release of radio resources associated with radio bearers at session termination, handover or at other occasions.

Radio Admission Control

The task of RAC is to admit or reject the establishment requests for new radio bearers. In order to do this, RAC takes into account the overall resource situation in E-UTRAN, the QoS requirements, the priority levels and the provided QoS of in-progress sessions, and the QoS requirement for the new radio bearer request. The goal of RAC is to ensure high radio resource utilisation by accepting radio bearer requests as long as radio resources are available and at the same time to ensure proper QoS for in-progress sessions by rejecting radio bearer requests when they cannot be accommodated.

Connection Mobility Control

CMC is concerned with the management of radio resources in connection with idle or connected mode mobility. In idle mode, the cell reselection algorithms are controlled by the setting of parameters (thresholds and hysteresis values) that define the best cell and/or determine when the terminal should select a new cell. E-UTRAN also broadcasts parameters that configure the measurement and reporting procedures. In connected mode, the mobility of radio connections has to be supported. Handover decisions may be based on terminal and eNB[3] measurements. In addition, handover decisions may take other inputs, such as neighbour cell load, traffic distribution, transport resources and policies.

Dynamic Resource Allocation or Packet Scheduling

The task of DRA or PS is to allocate and de-allocate resources (including buffer, processing resources and chunks (resource blocks)) to user and control plane packets. DRA involves several sub-tasks, including the selection of radio bearers whose packets have to be scheduled and managing the necessary resources (e.g., the power levels or the specific used resource blocks). DRA typically takes into account the QoS requirements associated with the radio bearers, the channel quality information for terminals, buffer status, or interference situation. DRA may also take into account restrictions or preferences on some of the available resource blocks or resource block sets due to ICIC considerations.

Inter-Cell Interference Coordination

ICIC has the task to manage radio resources (notably the radio resource blocks) such that inter-cell interference is kept under control. ICIC is inherently a multi-cell RRM function that needs to take into account information (e.g., the resource usage status and traffic load

3 eNB represents NB in UMTS or BS generally speaking.

situation) from multiple cells. The preferred ICIC method may be different for downlink and uplink.

Load Balancing

LB has the task to handle uneven distribution of the traffic load over multiple cells. The purpose of LB is thus to influence the load distribution in such a manner that radio resources remain highly utilised and the QoS of in-progress sessions are maintained to the extent possible and call dropping probabilities are kept sufficiently small. LB algorithms may result in handover or cell reselection decisions with the purpose of redistribute traffic from highly loaded cells to underutilised ones.

Inter-Radio Access Technology Radio Resource Management

Inter-RAT RRM is primarily concerned with the management of radio resources in connection with inter-RAT mobility, notably inter-RAT handover. At inter-RAT handover, the handover decision may take into account the resources of involved RATs as well as the terminal capabilities and operator policies. The importance of inter-RAT RRM may depend on the specific scenario in which E-UTRAN is deployed. Inter-RAT RRM may also include functionalities for inter-RAT LB for idle and connected mode terminals.

Subscriber Profile Identifier for Radio Access Technology/Frequency Priority

The RRM strategy in E-UTRAN may be based on user's and usage specific information.

The SPID parameter received by the eNB via the *s1 interface*[4] is an index referring to user information (e.g., mobility profile, service usage profile and roaming restrictions). The information is specific to the terminal and applies to all its radio bearers.

This index is mapped by the eNB to a locally defined configuration in order to apply specific RRM strategies.

2.2. Overview of CRRM Techniques

In legacy cellular networks, each network is seen as a tight system and does not interact with other systems. Here the available Radio Resource Units (RRUs) are locally managed by the logical entity LRRM (e.g., the NB and RNC in UMTS).

In a B3G scenario, where several RATs co-exist, the management of the provisioned RRUs can be seen as a problem with different dimensions. Every RAT is based on a specific multiple

4 This interface connects the eNB to the MME/UPE in the E-UTRAN.

access mechanism, which exploits different orthogonal dimensions, such as frequency, time and code.

This heterogeneous scenario must also be seen as a new challenge in order to deliver services to users over an efficient and ubiquitous radio access thanks to coordination (joint processing information) of the available RATs. Thus, user may not only be served through the RAT that fits better to the terminal capabilities and service requirements, but also a more efficient use of the available radio resources can be achieved [17].

This overview will mainly focus on the 3GPP CRRM functional model which is the starting point for the new CRRM architecture proposal.

2.2.1. CRRM Main Functionalities

As shown in section 2.1, within the context of a single technology the RRM functions are more or less related with AC, CC, handover control, PC, and PS. In an heterogeneous environment, these functions can be donated as *common* (common AC, common PC, etc.).

In this scenario, the main CRRM function is related with collecting information from different LRRM entities (one per cell) and make decisions, namely the RAT selection, of the RAT that better fits according to policies.

When the terminal is switched on, an initial RAT selection is performed based on the available technologies and user's or usage profile. Then when a new request for a session exists and if there are not enough resources in that RAT the migration of the terminal connection to another serving RAT is the next step. However, if there is already an ongoing session, this migration process is called VHO and shall be seamless and fast enough.

The VHO provides mechanisms to rearrange traffic in a certain area, thus it may be useful for many reasons. Next some of those reasons are presented:

- LB;
- Services based on RAT;
- QoS improvements;
- Lack of coverage of current RAN;
- Avoid blocking users.

2.2.2. 3GPP CRRM Functional Model

The functional model assumed in 3GPP for CRRM operation [1, 2] considers the whole set of radio resources to be divided into radio resource pools.

Each radio resource pool consists in a set of resource units available in a set of cells, under the control of, e.g., a RNC in UTRAN or Base Station Controller (BSC) in GERAN.

Although, the 3GPP CRRM mechanisms are proposed to be mainly used in UMTS and Global System for Mobile Communications (GSM), the next description tries to extend the 3GPP concepts and apply them to any heterogeneous wireless scenario. For example, instead of referring the interface names (*cc-i/f* which connects CRRM entities and *rc-i/f* which connects CRRM and LRRM entities [2]), they will be referred generally as interfaces and the description will be focus their capabilities/functionalities.

Two types of logical entities are considered for the management of these radio resource pools:

LRRM entity: is the responsible for the management of resources in one radio resource pool of a certain RAN. This functional entity may involve many other different physical entities in the network. Although, it is usual to assume that the LRRM entity resides, e.g., in the NB and RNC for UMTS case, or eNB for LTE.

CRRM entity: is the responsible for the coordination and management of overlapping/neighbour radio resource pools controlled by different LRRM entities.

Each CRRM entity controls a number of LRRM entities and may communicate with other CRRM entities, which is useful for collecting information about other LRRM entities that are not under its direct control.

CRRM Architecture and Functions

In [2] three CRRM topologies are presented. However, has it already been said, this thesis is only focused in CRRM as a stand-alone server, like it is presented in figure 2.2.

The interactions between LRRM and CRRM involve mainly two types of functions: *information report* and *RRM decision support* functions. These two functions are not yet object of standardisation, but their main characteristics are described below:

Information report function: allows the LRRM entity to exchange relevant information (which can be dynamic or static) with its controlling CRRM. The reporting may be done periodically, event-triggered or at a given instant when explicitly requested by the CRRM entity [39] (see table 2.1).

The information exchange may also be done between CRRM entities to know the status of other LRRM entities that are not directly connected to the CRRM which requested the information. It is assumed that all this information is controlled by the RNC/BSC (UMTS/GSM).

Measurements within a cell may have different natures regarding their periodicity:

- Dynamic measurements: the current cell load, interference measurements, transmitted carried power, etc;

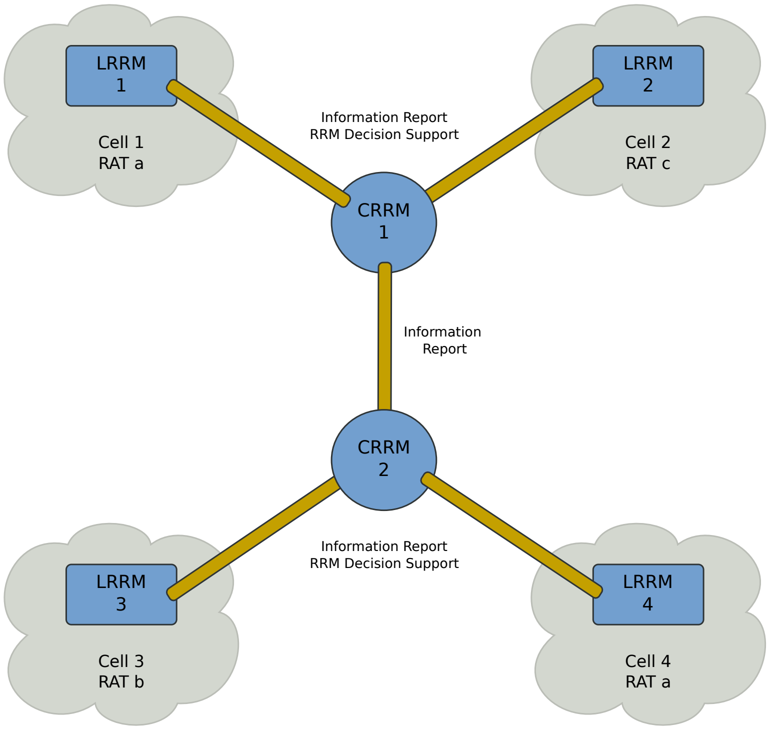


Figure 2.2.: 3GPP CRRM functional model

- Static information: the overlapping between cells or they belong to a different Hierarchical Cell Structure (HCS) layer, the cell capabilities (e.g., the number of available time slots) or the available QoS, etc.

RRM decision support function: is related with the way how LRRM and CRRM entities interact to take decisions. For example, it is possible that LRRM remains the master of each decision and CRRM only advises (and the contrary is also possible).

In a heterogeneous wireless scenario, the RRM functionalities for LRRM and CRRM are related with the interaction degree between these two entities, as it is presented in table 2.1. If the interaction degree begins to be higher, more functionalities may reside in the CRRM taking advantage of the global information availability.

Interaction degree	**CRRM entity functions**	**LRRM entity functions**
No interaction	No CRRM entity	Initial RAT selection Vertical handover Admission control Congestion control Horizontal handover Packet scheduling Power control
Low/hours (or days)	Policies definition	Initial RAT selection Vertical handover Admission control Congestion control Horizontal handover Packet scheduling Power control
Intermediate/minutes	Policies definition Initial RAT selection Vertical handover	Admission control Congestion control Horizontal handover Packet scheduling Power control
High/seconds	Policies definition Initial RAT selection Vertical handover Admission control Congestion control Horizontal handover	Packet scheduling Power control
Very high/milliseconds	Policies definition Initial RAT selection Vertical handover Admission control Congestion control Horizontal handover Packet scheduling	Power control

Table 2.1.: Interaction degrees between LRRM and CRRM entities

Approach based on CRRM Policies

As it was said, the parameters and information exchange over an open interface between LRRM and CRRM entities are not yet standardised. However, this topic is highly important because it would enable the policies exchange from CRRM entity to the LRRM entity.

In the proposal of [2] it is assumed that the CRRM entity only acts as an advisor, so the LRRM entities take the final decisions, but based on parameters adjusted by CRRM.

To choose the best target cell further information about the capacity/load situation of possible candidates is provided by the CRRM to the LRRM entity. For example, this information might be a relative ranking of cells.

For this policy-based CRRM, a loose coupling between CRRM and LRRM entities shall be adopted, which means that CRRM policies are valid in the LRRM entity for all handovers until the policy is changed by the CRRM entity. If the policy for a given cell is not changed for more that the time indicated by a certain time-out, then it is assumed that the CRRM entity has failed.

In case of CRRM entity failure it is assumed that the supported LRRM entities can continue with the last available policy, and after some time-out they can fall back to a predefined default policy. In the latter case, the network performance in the affected area would fall back to the case where no CRRM exists (see table 2.1).

While LRRM entities take fast decisions required for each access request or handover request, the CRRM entity works at a slower time scale and provides policies to the LRRM entities whenever an update is necessary. In this sense the frequency for a policy update depends on the traffic variations within the involved cells. The updating frequency can also be subject of configuration.

The CRRM policy approach describes the functional relationship between CRRM and LRRM by three functions:

- CRRM triggers LRRM to report measurement/load information or LRRM reports are initiated by the LRRM entity itself;
- CRRM can inform LRRM about CRRM related information (e.g., cell capacity and load situation of neighbour cells which are not under control of this LRRM);
- CRRM sets load targets for the LRRM functions for which the CRRM entity is responsible.

This can be obtained by the following four procedures:

- Measurement initiating procedure (CRRM initiated);
- Measurement reporting procedure (LRRM initiated);
- Neighbour cell information procedure (CRRM initiated);

- Load target setting procedure (CRRM initiated).

CHAPTER 3

Novel CRRM Architecture

As it was said before, in a heterogeneous scenario, different technologies coexist in the same region and their serving areas may be overlapped. In order to efficiently manage the available poll of resources, the 3GPP proposed a new logical entity, the CRRM, in addition to the already existed LRRM. Each considered LRRM is connected to a CRRM that receives measurements and takes decisions related with the global management of available RRUs.

Each RAT has its particularities in multiplexing users to access the RF spectrum limiting the interference between them. In WCDMA different users have different and orthogonal codes, since they all use the same frequency to transmit. In OFDMA based technologies, the available bandwidth is divided into orthogonal sub-carriers; these sub-carriers are grouped and form sub-channels, which are distributed among users.

With an appropriate management of the radio resources, the particularities of each RAT may be exploited and it is possible to limit the interference, increase capacity and coverage, increase energy efficiency and improve Quality of Experience (QoE) by delivering the agreed (between operator and user) QoS, the Service Level Agreement (SLA).

3.1. Architecture Description

In this architecture, the RRUs are dynamic and centralised managed by the RRM entities: CRRM is concerned with the common tasks and LRRM takes care of particular tasks within each considered RAT. It is considered three different types of LRRM, one per each different technology (WiFi, UMTS and WiMAX).

The CRRM concept in this thesis is aligned with the 3GPP CRRM functional model, presented in figure 2.2. However, this particular implementation tries to take advantage of the centralised information processing and the fact that LRRMs and CRRM are placement inside the same CU.

In order to deliver the agreed QoS per service, optimising the radio resource usage and impose the policies defined by the network operator, the CRRM will take advantage of VHO mechanism. Thus, in a new SF request, the service characteristics are determined, the actual radio resources are evaluated, a prediction of the new cell load is done admitting that the new request is accepted and, if it is above the cell load threshold, the considered request is transferred to other cell/RAT or it is blocked, otherwise it is accepted (if it is accordingly with the adopted policies).

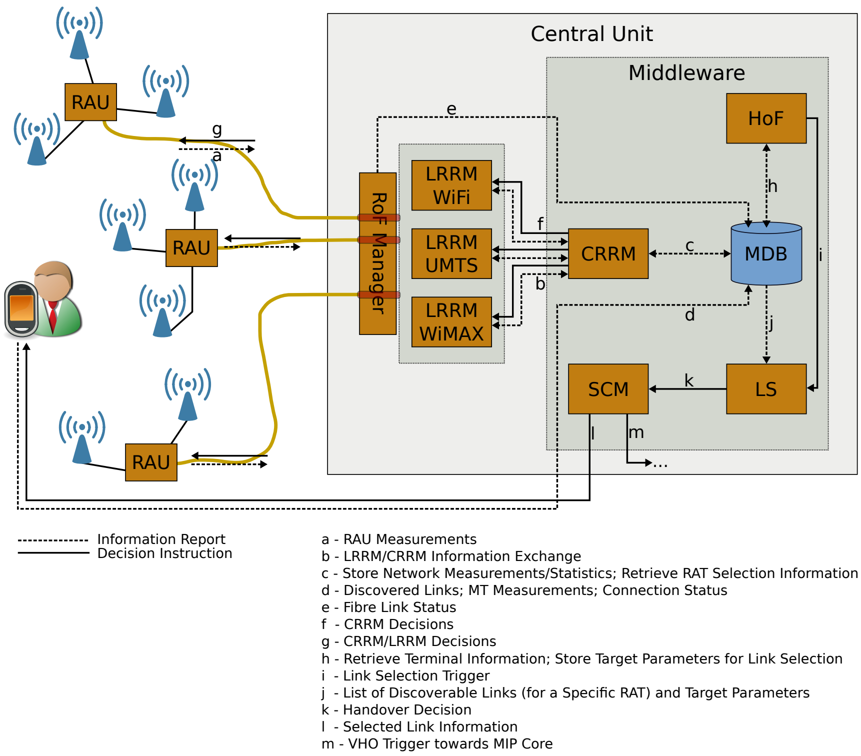


Figure 3.1.: Novel CRRM architecture

In figure 3.1 a general FUTON Middleware architecture, where the RRM entities take place, is presented. The CRRM architecture is described as follow: the Middleware Database (MDB) is the central point (the aggregation point) where the available information is stored (i.e., measurements either performed in the network side or by the terminal, the network statistics, profiles and policies); CRRM takes decisions to perform VHO based on policies defined by the operator and select the best available cell/RAT based on all available information retrieved from the MDB, concerning the global network stability and optimisation, interference mitigation, increase capacity and coverage; each LRRM manages the local RRUs based on the instructions that come from CRRM and the local information of its cells; RAUs are constituted by one or more antennas (not limited to a particular technology) and an optical-to-RF/RF-to-optical converter. The RAU measurements are performed by the PHY layer inside each CU that have to send them periodically or upon request to LRRM, which will forward them to the CRRM.

In this solution, two VHO decision points are defined: one at the Handover Function (HoF) and another one at CRRM. This is done because CRRM is related with the radio resource management reasons, while HoF is concerned with the link connection stability and SF QoS. The MDB is also the connection between these two points.

As two decision points are considered, it is easy to predict that two contrary decisions may be taken by the two modules regarding the migration of SFs to another serving cell/RAT. However, in this situation the final decision should be taken by the CRRM. The HoF is more concerned with a single connection or a SF and tries to provide the best QoS as possible and improve the QoE, so it will mainly use the terminal measurements to trigger the handover initiation (e.g., signal strength and application statistics). This type of handover is also known as Mobile Initiated Handover (MIHO). CRRM is concerned with radio network stability and performance. For that, it will mainly use the network measurements (e.g., current cell load) provided by the PHY layer of the CU and the network statistical information (e.g., blocked call rate or call drop rate in each cell/RAT) provided by the LRRM. This handover is known as Network Initiated Handover (NIHO).

When HoF triggers a handover, the CRRM can provide a list rank of the best candidate cells/RATs based on measurements and statistical information to the Link Selection (LS) that will take the final decision for the best suitable link in a certain cell/RAT. However, when CRRM triggers a handover due to network reasons, it is its function to specify the destination cell/RAT, and the LS shall only select the best link inside the specific RAT. In this sense, it is worth clarifying that the term link denotes either a particular RAT, link or channel within a particular RAT. The exact definition will depend on the final LS algorithm.

The goal of LS is to exploit all the information available in the MDB in order to select the best access technology, cell site, or modulation scheme, either for handover sessions or new incoming sessions, delivering the agreed QoS in the best possible way. After the link is selected, the Service Connection Manager (SCM) module will force the terminal to select that link. In this architecture the terminal shall also perform and store measurements in the MDB (that are presented in table 3.1).

MDB is where the measurements and network statistics are stored. It is also the connection point, the bridge, between the HoF, CRRM and all other entities.

Each RAU that serves a certain area is not limited to a particular RAT, and it may support different antennas for different RATs. The received radio signals are multiplexed and transparently transported without any information processing from RAUs to the CU through optical fibre. Each optical fibre in its edges is connected with an optical-to-RF/RF-to-optical converter. The RRM entities are only concerned with the radio part of the system, thus the optical part is seen as transparent. In this sense, the functionality of optical fibre is to deliver the radio signals either into the CU or RAUs. Furthermore, it is important to stress that it is not the scope of RRM entities to specify the interface that will map the cells/RATs/RAUs radio resources in each LRRM entity.

In this architecture, the RoF Manager plays an important role since it manages the optical part of the network. Its main responsibilities is to deliver the information if an optical link is available or not. This information is relevant in order to select a specific cell/RAT when a handover is triggered.

With this topology, there is a LRRM for each considered cell. The advantage is that each cell will in a first instant rely on its local RRM mechanisms to support the intra-RAT mobility. However, apart from the RRM activities between the BSs and terminals, the local radio management functionalities of the legacy RNC (the UMTS case) and BSs are now moved to the CU, which means that part of local radio management will be remotely done, which may be far away (introducing delays that can limit the decisions validity). This new scheme will not completely break the previous rules or policies defined by operators in the legacy systems (compatible with 3GPP standards); however, instead of being implemented in a distributed fashion (BSs and RNCs) they are centrally implemented in the CU.

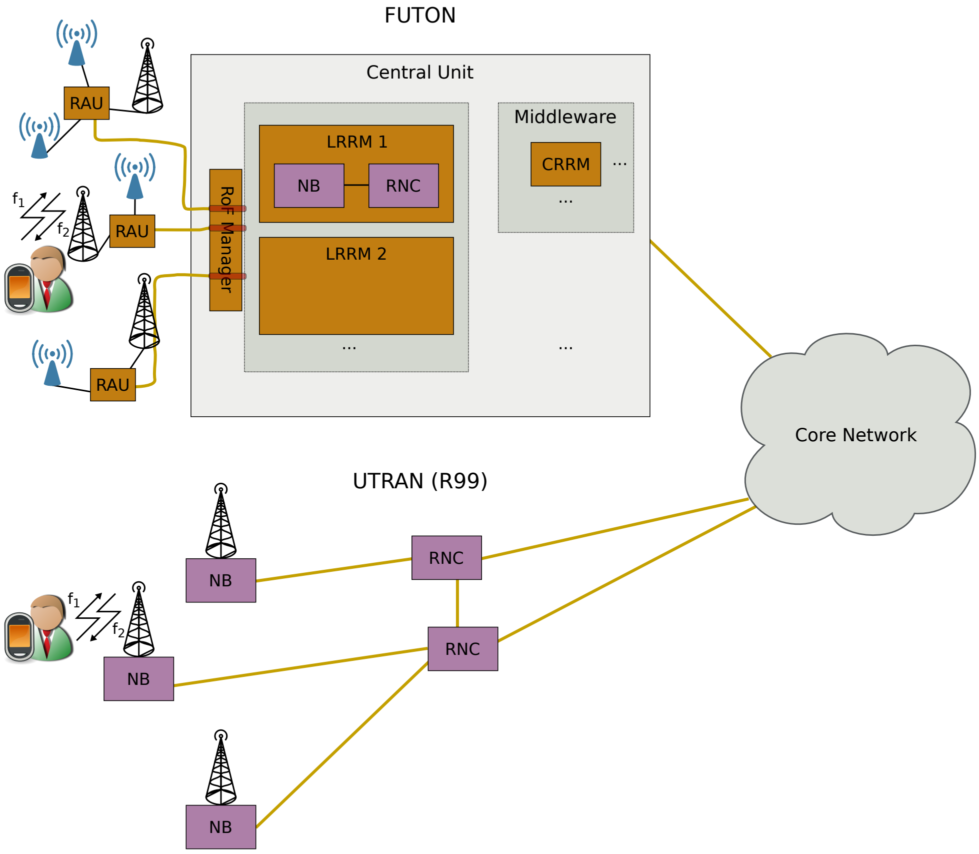


Figure 3.2.: LRRM placement in CU versus legacy system (UTRAN)

As it can be seen in figure 3.2, the NB and RNC functionalities are moved to the logical entity LRRM inside the CU. However, with the introduction of CRRM entity, the decision taken moves to the CRRM while the local implementation still remains in the LRRM.

3.2. Design Principles of CRRM

In this section it is described the concepts used to develop the presented CRRM architecture and its algorithms. In the end of this section, it is presented a small table that summarises the followed choices when designing the CRRM algorithms.

3.2.1. Functionalities of LRRM and CRRM Entities

RRM functionalities may be divided into two categories: network-based RRM and connection-based RRM [11]. Network-based RRM includes: AC, CC, and PS; and it applies to how users affect performance and network load. Connection-based RRM includes: handover control and PC; and it deals with the performance of the connection on an individual level.

Regarding the local and the common radio management functionalities, they are closely related with the interaction degree between LRRM and CRRM entities. Table 2.1 clearly divides those functionalities considering the interaction degree. Thus, if the interaction is considered low, more functionalities reside in the LRRM; however if it is considered very high, almost all functionalities reside in the CRRM entity (the exception is the PC that always reside in the LRRM).

One key aspect of this new architecture is the centralised information processing and decision taking at the CU. Since both LRRM and CRRM entities are placed in the same CU, they are close to each other which greatly reduces the delay in messages exchange. This closeness leads the interaction degree to be considered as high (seconds). This way, more RRM functionalities are considered common (reside at the CRRM), which may optimise the system due to the global information availability. In figure 3.3 the local and common radio management algorithms and functionalities are divided per entity.

Taking into account the scope of this thesis and the nature of supported technologies, some adjustments were done when comparing figure 3.3 with table 2.1, namely the initial RAT selection is done at the terminal side and the HHO is done by the LRRM. HHO is locally done between cells within the same RAT because it is envisaged the compatibility with the already deployed systems. Regarding the initial RAT selection, it is done in the terminal side because when it switches on no service has already been requested, so no radio management must be done. The following sections only consider the RRM techniques that make part of CRRM.

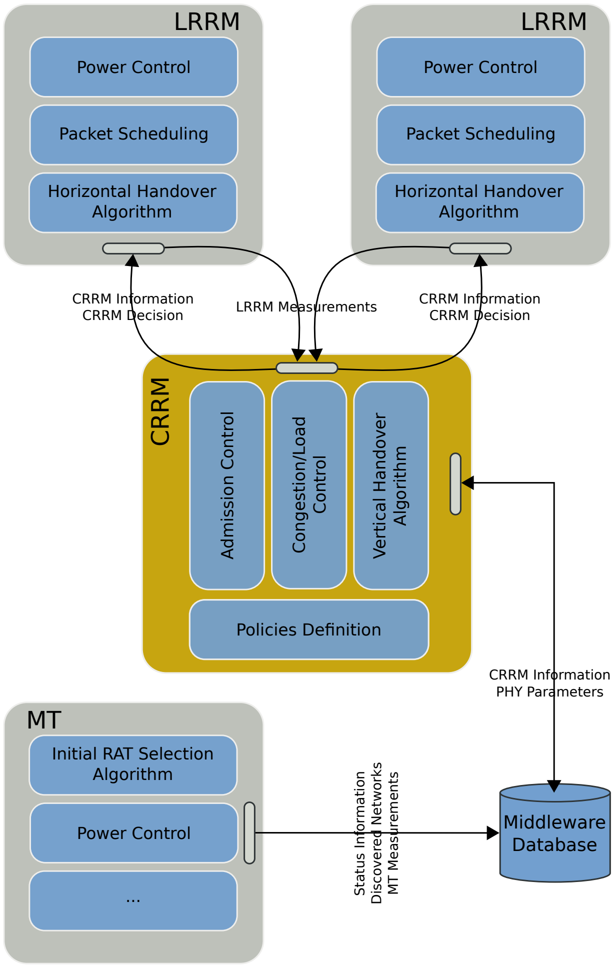


Figure 3.3.: RRM functionalities divided per entity

3.2.2. CRRM based on Vertical Handover

For an operator that owns sites with different RATs it would be useful to manage and distribute users among its infrastructure in a certain optimal way so that more users may be accommodated, while each of them would receive the contracted QoS per SF and, at the same time, limit interference and greatly reduce the congestion risk. Traffic balancing strategies based on VHO are one of the possible procedures to optimise the network without compromising QoS.

In legacy systems, the basic strategies for VHO are only motivated by coverage issues to guarantee the continuity of service. In B3G networks, more sophisticated strategies shall be adopted, taking into account not only coverage issues, but also the capacity criteria, the required QoS per service flow or service classes and the operator policies [24].

Here traffic shall be balanced according to load, interference, capacity, coverage and policy issues. The terminal must be able to discover which RATs are available and accessible, so mobility management and broadcast signalling are essential aspects of the CRRM approach. The terminals either scan the air interface periodically, or the networks themselves broadcast details of the available access networks.

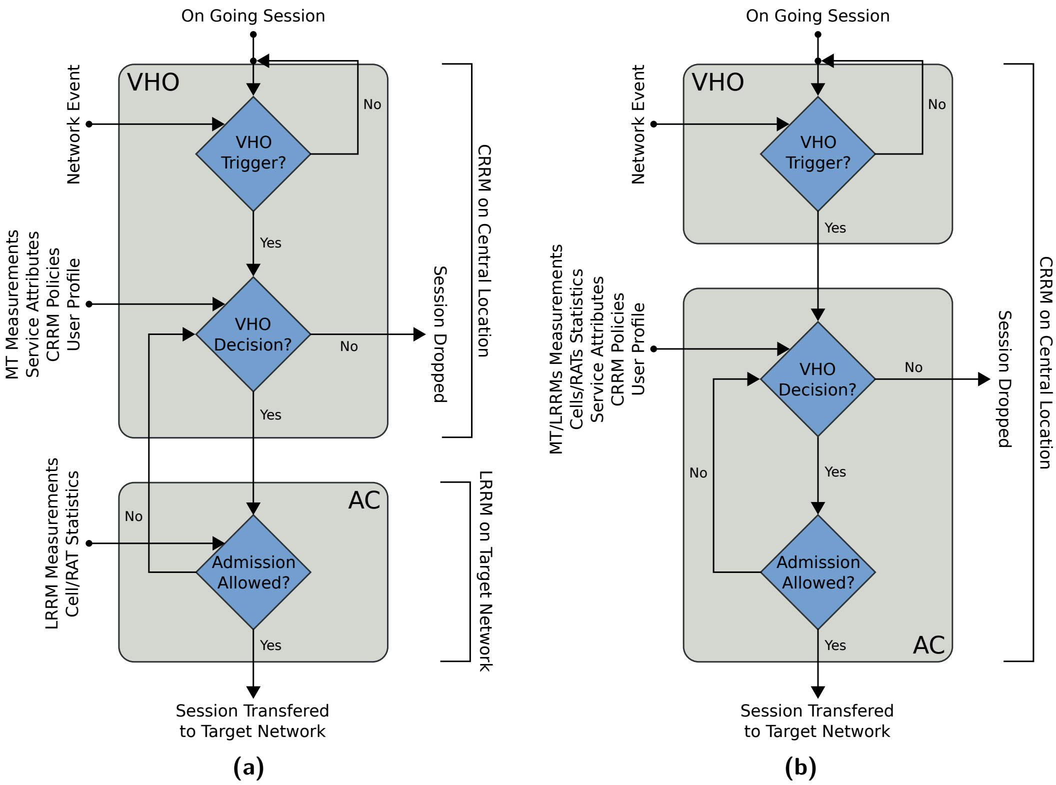


Figure 3.4.: VHO/AC in distributed and centralised fashion

Figure 3.4 illustrates in logical blocks the principles of VHO and its relation with AC algorithm either in a distributed fashion (a) or in a centralised fashion (b). The VHO algorithm has two important phases: first the decision to trigger the handover and prepare it, then the selection of the most suitable target cell/RAT to execute the handover to. The handover is triggered by a network event (NIHO), then the second phase may take into account various inputs such as measurements coming from terminal/network, service attributes, and statistics from the network.

In a distributed fashion, the AC is done at local level, thus once the target network for handover has been selected by the handover algorithm, the AC on that target network will check if the SF can actually be accepted. The LRRM has local information about the status of local network, thus it can determine if the session may or may not be admitted. If the answer is no, another network must be chosen, and so on. On the worst case scenario, all suitable networks will be questioned to admit that session. This process greatly increases the communication overhead and delay, which may not be acceptable for certain services. To reduce overhead and delay, the handover algorithm shall be defined to minimise the rejection done by AC.

In a centralised fashion, the AC is done at the CU. In this form, the CU knows the status of all connected cells/RATs, so it can be more efficient when the destination cell/RAT is chosen due to its global information availability. In this sense and trying to minimise the possible rejections the VHO selection and AC shall be made inside the same block.

The criteria to choose users (and their priority number) that perform the handover must be determined: it can be a service based criteria (e.g., speech users are queued to handover first) or resource based criteria (e.g., users consuming lot of resources are transferred first) or user based criteria (e.g., bronze users are queued first, then silver users, then gold users to handover) [25].

3.2.3. Admission Control

The radio resources in heterogeneous networks, as in all wireless networks, are limited. One of the basic radio management mechanisms used in wireless networks in order to find a suitable solution for QoS requirements is the AC. AC algorithms are used to ensure that admittance of a new flow into a resource constrained network does not violate the service commitments made by the network to the already admitted flows and does not bring the network into an overloaded situation. The goal of an efficient AC algorithm is to guarantee the QoS of the ongoing connections, while at the same time, efficiently use the available RF spectrum [28].

When the terminal switches on, it camps in the predefined network and at that time no service has already been requested. Whenever a service is requested or if a handover session arrives to a certain cell/RAT the AC algorithm is triggered and based on policies the SF is either admitted or rejected. If during the handover process the session cannot obtain a new channel in the new cell/RAT the session is dropped; if a new session cannot obtain a channel, then the session is blocked.

It is well known that handover sessions are more sensitive than regular sessions and should have priority against new sessions because dropping an existing session is undesirable, though blocking a new session is not very important as user can restart the session request [15]. For that reason, the handover and new sessions must be treated differently in terms of resource allocation and queuing. In the context of this thesis, new session and handover session are interpreted as follows:

New session: is a session request in a specific RAN without an ongoing service.

Handover session: is an ongoing session which has already established a SF and because there are insufficient resources in the current cell or a new service has been requested and the current cell cannot provide it, the session needs to be finalised in another cell/RAT. The handover sessions are usually assigned with higher priority than new sessions.

The main function of an efficient AC algorithm is to decide at a specific point in time if there is a cell/RAT that has the available resources to serve (to ensure the QoS requirements to) a new session request, which could be a brand new session or a handover session. The AC algorithm decisions must be made very carefully in order to avoid or minimise the following two events [33]:

Bad rejections: which occur when the algorithm rejects a session, although there is actually a cell/RAT that can meet the session requirements (there is enough capacity thus session can be allocated). In this case, capacity is wasted and revenues are not optimised.

Bad admissions: which occur whenever the algorithm accepts a session although there is not a cell/RAT that has the available capacity for the session. In this case, QoS guarantees are not provided and QoE is degraded.

Managing different cells/RATs, with different capacities and available QoS, admitting new requests are related with many parameters. For the proposed architecture the measurements/statistics are in table 3.1. However some other parameters may also be useful, as an example, let us consider the user speed and the throughput requirements of a requested service: to be admitted in a short area cell, user shall have low velocity and/or request very high data rate service; to be admitted in a wide area cell, user may have very high velocity, but also low data rate requirements. When a user has high mobility and high data rate requirements then the decision will be very critical, since admitting the user in a short area cell will result into many inter-cell handovers increasing load in many short area cells and also the overhead due to signalling messages used for the inter-cell handovers. On the other hand, admitting it in a wide area cell will cause problems either to the load of the wide area cell because the load will highly increase since the user requested a high data rate service, or to the user because he will receive the requested service with decreased quality due to the insufficient data rate [27].

There are several AC schemes: counter-based, statistics-based and measurement-based strategies. However, the fundamental concept behind AC schemes remains the same: when a service is requested, the session is admitted to the system only when the required load plus the associated load from the already admitted sessions is below the threshold value (see figure 3.5 for the UMTS case). Measurement-based systems are complex to implement as they operate in a Real Time (RT) manner. Counter-based methods are simple to implement and are often used in cellular networks. Statistical methods are considered the optimum solution in terms of complexity, system optimisation, and implementation [11].

Counter-based schemes generally under-provision the radio resource to ensure QoS. Consider a radio bandwidth divided up into R radio resource equivalent units, where R may correspond to a user bit rate R_b, and there are a finite number of units R^*. If there are N users in the system, the counter admission scheme will only admit the $N+1$ user if the total load plus the load of $N+1$ is less or equal to R^*, as it is written in equation 3.1.

$$\sum_{i=1}^{N} R_i + R_{N+1} \leq R^* \tag{3.1}$$

For example, considering a heterogeneous environment with WiFi and UMTS technologies. Typical bit rates associated with business and consumer users are 384 kbit/s and 128 kbit/s, respectively, for web browsing and e-mail services. Using a counter-based AC strategy to determine the number of terminals admitted into a UMTS or WiFi cell is a non-complex task. UMTS allocates radio bearers to users up to a maximum number and provides guaranteed bandwidth. Fair access in WLAN can be achieved by controlling the buffer size in the access point or changing the Transmit Opportunity (TxOP) and Minimum Contention Window (CWmin). Considering the saturated Transmission Control Protocol (TCP) throughput of WiFi to be 4.76 Mbit/s, the maximum number of admitted users is 12 and 37 for business and consumer users, respectively [11].

Due to its simplicity, this scheme is the one proposed to be used. However, there are several drawbacks with counter-based methods. These systems tend to have lack flexibility; simply looking at traffic and user types, it is clear the system utilisation is not maximised. Counter-based strategies ignore traffic and user behaviour, which can be statistically multiplexed to increase the number of users that can safely be admitted and maintain QoS requirements (statistical scheme).

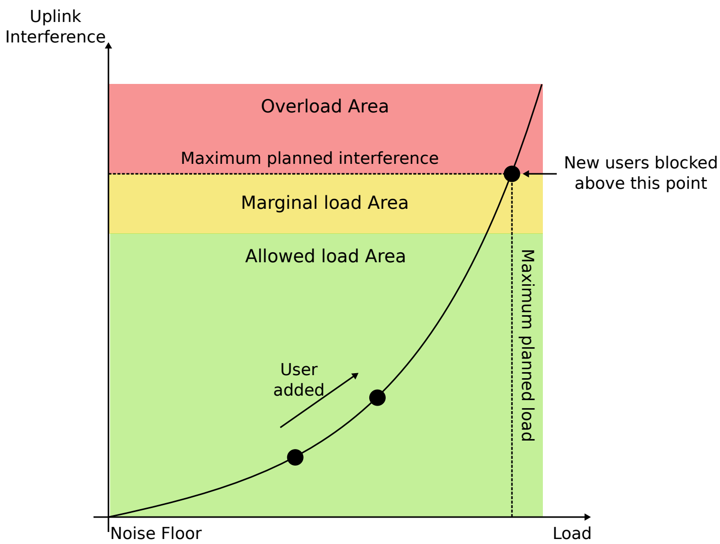


Figure 3.5.: AC and uplink interference in UMTS

3.2.4. Congestion Control

Network congestion happens when the total amount of traffic entering into the system within a predefined time interval is greater than the outgoing capacity of the system in the same time interval. In [30] a communication system is defined as congested whenever the communication services are affected in a way that is perceptible to their users. The CC (sometimes referred as LC) algorithms are not the mechanism mechanism to avoid network congestion and shall only be used if, for some reason, the AC algorithm does not properly work.

The CC algorithms are triggered in order to deliver the system to its stable state. The two main categories for these algorithms are the preventive or reactive load control [27]. The preventive load control ensures the network does not get overloaded and remains stable, while attempts to improve the overall system performance by redistributing users/flows/resources among the available cells/RATs. The reactive load control attempts to bring the load back to stable condition as fast as possible whenever a congestion situation is detected. The reactive load control algorithm, which is the proposed one, is divided in three phases:

Detection phase: the algorithm continuously monitors the network and periodically checks the load of the cells/RATs in order to detect an overload situation in any of them. It is considered that a cell/RAT is overloaded if the load factor is over the pre-defined threshold during a certain amount of time.

Resolution phase: this is the phase where the algorithm is trying to resolve the problem that causes the overload situation. Some of the actions that the algorithm performs to resolve the congestion situation is to deny all new requests, or handover sessions according to a defined criterion to another cell/RAT.

Recovery phase: after resolving the congestion situation, the algorithm enters in the recovery phase, where it tries to restore the QoS to the SF, which QoS was degraded in the resolution phase. A recovery algorithm is necessary, because the SFs shall see their QoS restored to the contracted SLA.

When thinking about the practical implementation of a CC algorithm, it is obvious that two different load values are required to identify when the algorithm has to enter the congestion resolution phase and when the algorithm can stop the congestion resolution phase. If the same threshold value is used for both entrance and exit, the load value after the congestion resolution would be very close to the threshold value which triggered the CC process. Therefore, a little change in the activity of the network would trigger the whole algorithm once again and the situation of the network would not be stable enough after congestion resolution.

The highest threshold value will be used to enter the congestion resolution process while the lowest one will be used to exit it. The lowest value is then used to trigger the congestion recovery phase, where flows whose QoS was degraded can recover it. However, this lowest value cannot be too low otherwise the congestion resolution process might reject or drop more users than necessary. As an example, for WCDMA systems a figure of 70% was introduced [12] and in [37] is said that the load factor should be in the interval of 40% to 80%. It should be noted that the threshold for the load criteria can be absolute or relative, if it is possible to compare directly the load of two systems.

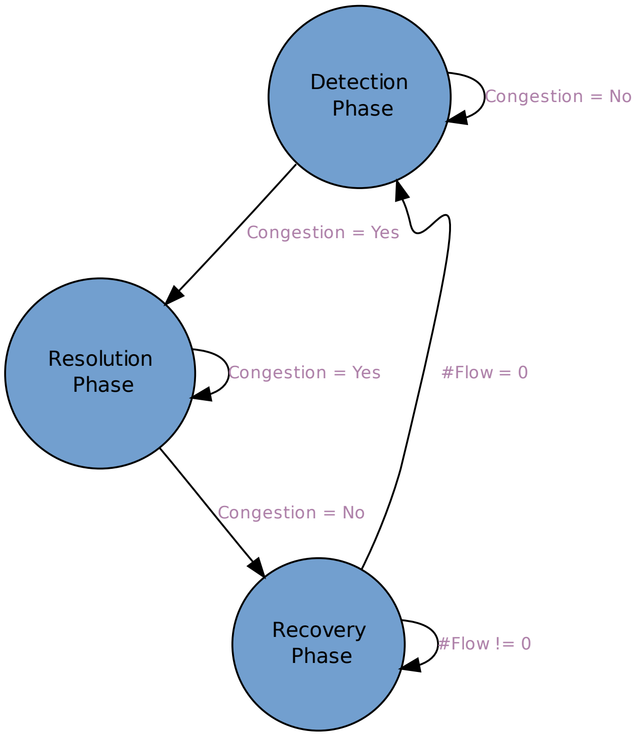


Figure 3.6.: Congestion control phases

3.3. Measurements and Statistical Information

Concerning the measurements and information gathering, RAUs do not have the ability to perform measurements thus the PHY layer of CU have to send periodically or on request messages containing useful information to LRRM unit, which will forward it to the CRRM. The efficiency and the delay will depend on the location of LRRM. The LRRMs are placed inside the CU, thus in principle the delay will only depend on the time that RF signals need to travel in the optical fibre from RAUs to the CU (the processing time is considered too low when compared with the travel time).

In order to reduce even more the delay, the PHY layer of CU sends information to LRRM periodically without any filtering and then LRRM sends that information to CRRM only on request. The terminal and network measurements and network statistics shall be available to CRRM in order to implement policies/algorithms and trigger network events. This information is stored in the MDB and is present in table 3.1.

Some of these parameters can be used to trigger the NIHO; those are the interference level, signal strength, Carrier-to-Interference (C/I) ratio and current cell load. Others, like cell load threshold, blocked call rate, dropped call rate and handover failure rate may be used to define/implement the CRRM policies, select the suitable cell/RAT and implement the AC and CC algorithms.

Parameter	Type	Who provides
Signal strength	RT	Terminal
Interference level	RT	Terminal
C/I ratio	RT	Terminal
BER/PER/Packet loss/SIR	RT	Terminal
Cell load	RT	LRRM
Cell load threshold	Fixed	Operator
Discovered networks	Dynamic	Network discovery
Fibre link status	Dynamic	RoF Manager
Blocked call rate	Dynamic	LRRM
Dropped call rate	Dynamic	LRRM
Handover failure rate	Dynamic	LRRM
Handover success rate	Dynamic	LRRM

Table 3.1.: Measurements and statistical information required by CRRM

3.4. Summary of Adopted Schemes

This section summarises the previous ones regarding the adopted schemes in the followed solutions for RRM techniques, which are network-based, taking into account the new CRRM architecture.

The schemes behind the RRM techniques shall be simple enough but at the same time deliver high robustness and feasibility. Table 3.2 presents the followed schemes for the practical definition and implementation of CRRM algorithms.

VHO	Centrally triggered
AC	Counter based
CC	Reactive LC

Table 3.2.: Adopted schemes for CRRM algorithms

CHAPTER 4

Radio Interference Scenarios

THIS chapter presents the radio interferences scenarios mainly focusing on the so-called radio intra-cell interference, which stands for the interference from users within the same cell, and the interference coming from outer cells, also called inter-cell interference, which reduces the coverage and capacity of the system and degrades the delivered QoS.

Here some radio interference scenarios in WCDMA and OFDMA based systems (e.g., UMTS and WiMAX, respectively) are studied. Interference mitigation is presented, namely the CRRM policies that will VHO users to other RAT with higher capacity or where the impact of users is less noticed than in the actual cell/RAT. This approach keeps the overall system in target values of load, while at the same time, increases capacity, and somehow the coverage.

Having described the scope and the main contents of this chapter let the author first proceed, in the next section, to present a review of the concept of interference in wireless systems.

4.1. Interference in Wireless and Cellular Networks

In contrast with wireline communication systems, where channels can be efficiently estimated, tracked, and equalized; reliable transmission of information through wireless channels represents a more difficult challenge. Wireless impairments such as fading, interference, refraction, reflection, and shadowing greatly degrade the quality of received signal [35]. Among these impairments, fading and interference are known to cause the majority of the degrading effects upon the received signals, which is the reason why they have a considerable attention within the research communities.

Fading is caused by the natural random and destructive contribution from different copies of the signal after travelling through a time-variant multipath environment. In comparison, interference is mainly caused by artificially created signals that coexist with the desired signal along the same physical dimension: code, frequency, space or time.

In wireless and cellular networks, the channel resources have to be reused because the electromagnetic spectrum is scarce, so it is impossible and impractical to assign a different channel to every possible connection. Additionally, radio waves rapidly fade with distance, thus users which are far enough can reuse the same channel at the same time, which is called frequency or channel reuse. Modern cellular systems are designed upon the basis of reusing channels in the space domain, thus they are said to be interference limited. It is worth pointing out that, unlike the problem of noise, which can be solved by simply increasing the transmit power, reducing interference cannot be achieved by such simple-minded technique because increasing power is directly translated into more interference to other users [10].

However, exploiting and combining the aforementioned physical dimensions or diversity sources together with smart PC techniques can lead to efficient interference mitigation or cancellation techniques. For example, in the frequency and code domains, this can be achieved by simply assigning a different band or code signature to different users, whereas in the spatial domain this can be done by either using the same channel at different locations (frequency or code reuse) or simply using different spatial directions (smart antennas and beam forming). In time dimension, e.g., the important areas of PS and AC algorithms aim to regulate the number of users or interferers that simultaneously transmit in the same network.

There are several kinds of interference depending on the type of communication system, the source of interference, and who is being subject to such interference. In the following sections, the author will only focus in intra-technology and inter-user interference; inter-system and inter-symbol interference will not be treated in the thesis.

Moreover, in order to have a clear understanding, interference power caused by users of the same cell is called intra-cell interference. The interference power resulting from connections in the co-channel cells is called inter-cell interference.

4.2. Interference in WCDMA Systems

The WCDMA is a wideband version of CDMA and is used as multiple access technique for UMTS. WCDMA systems typically have the cluster size one, which means that all senders are causing mutual interference. Due to the close proximity of intra-cell interferers, the intra-cell interference is usually greater than the inter-cell interference ($I_{intra} >> I_{inter}$). The transmitters are controlled by the PC in such a way that in ideal circumstances all signals received at the BS have the same power, thus preventing the near-far effects. If there are n transmitters in a cell, one of them always supplies the wanted signal, while the remaining $n-1$ contributes to the interference power.

In CDMA the loss of orthogonality of each user signature makes codes to interfere with each other, which represents the major impairment in CDMA systems. Such loss of orthogonality can be caused either by non-linearities or fast variations of the channel, among many others. Therefore, in CDMA systems more than in any other type of communication systems, the reduction of interference using accurate and fast PC, as well as an appropriate scheduling and access control are crucial for the correct performance of the system. It is worth mentioning that in most of the commercial CDMA systems, interference from neighbour cells is controlled by an appropriate spatial planning of the spreading sequences allocated to each site. This means that in CDMA there is not frequency reuse but instead code reuse.

Summarising, the intra-cell interference problem is solved with tight PC, code diversity and optionally with scheduling, whereas the other cell interference problem is dealt with a less tight PC and with code/spatial diversity.

4.2.1. System Capacity

In order to determine the capacity of a WCDMA network, it is essential to understand the capacity of a single WCDMA cell. It can be defined as maximum amount of communication traffic (in terms of bits) or services (in terms of number of simultaneous calls or SFs) that can be supported by the cell, while a more understandable voice capacity metric is referred to in Erlangs.

Since Third Generation (3G) the average cell capacity of a network, even if it is only assumed one type of service is not strait forward because it depends on various factors, such as, coverage, QoS requirements, type of application or the mix of applications, the network configuration, the characteristics of terrain where the deployment is done, or the mobility environment.

To support calls, UMTS R99 assigns Dedicated Physical Channels (DPCHs) for each call to carry the traffic (in Forward Access Channel (FACH) operation a Common Physical Channel (CPCH) is used). Hence, as an approximation, the cell capacity can be defined by the maximum simultaneous DPCHs assigned within a WCDMA cell. On each dedicated channel, the coding and modulation (hence the data rate) is fixed. However, as the radio channel condition changes, the terminal and BS adjust the transmit power on each DPCH to maintain a (constant) target Signal-to-Noise Ratio (SNR).

Since the size of a cell depends on the traffic in the network, the adopted planning for a WCDMA network is always only optimal for a certain volume of traffic. When traffic volumes are higher, large areas of overlapping occur; with very low traffic volumes the cells can shrink to such an extent that gaps occur in the radio coverage. Furthermore, the cells breathe differently for services that require different QoS, which shall be taken into account during the planning phase.

A higher E_b/N_0 ratio also means a smaller maximum range of radio coverage. Radio coverage for services with a high spreading factor is therefore higher than for services with a low spreading factor. Depending on the network planning, such high data rate services can only be used in the proximity of the BS, whereas services with a lower transmission rate, such as voice services, are available in the entire cell.

Uplink Capacity

Considering a cell in a WCDMA network, the upper bound of the uplink capacity, herein referred to as the pole capacity, N_{pole}, of a WCDMA carrier, can be estimated using the standard uplink capacity equation. This widely accepted formula (equation 4.1) is derived from the early CDMA literature and applies equally to WCDMA if variables are set properly.

$$N_{pole} = \frac{W/R_b}{E_b/N_0.\upsilon.(1+\alpha)} \tag{4.1}$$

Where W represents the spreading bandwidth of the system, fixed for UMTS R99 standard at 3.84 MHz; R_b is the Radio Access Bearer (RAB) bit (data) rate for the selected application; E_b/N_0 means the energy per bit to the total noise spectrum density ratio; υ is the voice activity factor; and α is the interference factor which is the ratio between the other cell interference power and the total received power of a user (it represents the inter-cell interference).

In addition to the target E_b/N_0 and R_b, equation 4.1 shows that the uplink cell capacity is also a function of υ and α. For the initial capacity estimation, the voice activity factor is normally set to 0.6, and the interference factor is normally set to 0.6.

The pole capacity is obtained by assuming that each terminal has infinite transmit power and the interference at the BS receiver goes to infinity. In practical systems, both terminal transmit power and the BS receiver allowed interference level are limited and the operating point is set well below the pole capacity.

$$N_{user} = N_{pole}.\eta \tag{4.2}$$

As example, for an Additive White Gaussian Noise (AWGN) channel a 3G voice service with $R_b = 12.2$ kbit/s, a target $E_b/N_0 = 5.1$ dB and considering the previous conditions, the pole capacity is 101. If the operational point, η, is set to 75%, the loading capacity, N_{user}, is 76.

Downlink Capacity

In the downlink as well, the pole capacity can be interpreted as the maximum capacity with infinite BS power. The downlink pole capacity is not easy to analyse, but can be approximately simulated by keeping a very small cell radius (close to zero coverage) and the capacity reaches a limit in the trade off between coverage and capacity.

A closed-form equation can also be derived for the downlink pole capacity by simplifying certain assumptions (equation 4.3).

$$N_{pole} = \frac{(1-\eta_{OH}) + W/R_b}{E_b/N_0.\upsilon.\left(\delta + I_{oc}/\hat{I}_{or}\right)} \tag{4.3}$$

Where η_{OH} is the percentage of the overhead channel power; I_{oc} represents the total interference power at terminal; $\hat{I}_{or}$ is the total downlink cell transmit power at the terminal; $I_{oc}/\hat{I}_{or}$ states the interference factor, which represents the inter-cell interference, but it is not usually the same as the uplink interference factor α (the $\hat{I}_{or}/I_{oc}$ is referred to as cell geometry); finally, δ is the orthogonality factor.

The downlink interference factor (or the geometry) is a location dependent value for each user in the cell. A very low interference factor (high geometry) is achieved for locations close to the cell transmission antenna, while for locations close to the cell edge, the interference factor will be high (low geometry). For capacity estimation, a medium value should be used.

For example, based on the minimum performance requirements specified for 3G, the maximum downlink target E_b/N_0 for voice service under different mobility channel conditions can be estimated using equation 4.3. Assuming an AWGN channel (orthogonality factor is 0.1), an interference factor of 0.3 (-5 dB), voice activity factor of 0.6 and the overhead channel power percentage of 25%, the pole capacity for downlink is 299.

In practice, since the downlink transmit power cannot be infinity and the cell radius cannot be zero, instead of using the pole capacity equation, the downlink capacity is normally evaluated using equation 4.4, where $E_{c,\mathrm{DPCH}}$ is the expected power on DPCH.

$$N_{user} = \frac{I_{or}.(1-\eta_{OH})}{\nu.E_{c,\mathrm{DPCH}}} \tag{4.4}$$

In UMTS the spreading codes of different cells are only quasi-orthogonal to one another. All senders in co-channel cells thus produce inter-cell interference. The main property of the spreading code is that they need to be orthogonal to each other or have a low correlation. Perfect orthogonal codes guarantee that the different DPCH do not cause mutual interference. In the following text only Orthogonal Variable Spreading Factor (OVSF) codes will be considered.

Each downlink DPCH is associated with a unique OVSF code and the total number of available OVSF codes in a WCDMA cell is fixed. Hence, the downlink cell capacity is assumed to be bounded by the total amount of OVSF codes available.

In the pole capacity analysis, the OVSF code limitation is not considered, thus it is assumed there is always a unique OVSF code available for all the calls in the cell. In reality this is not true. Therefore, to accurately evaluate the network capacity, it shall be always checked the cell capacity estimation against the OVSF code limitation.

For instance, the total number of available OVSF codes for the 12.2 kbit/s voice service is typically 125 OVSF codes (discounting the codes necessary to support the common control channels). So when the OVSF code limitation is considered, the downlink pole capacity for AWGN channel (which is 299) will never be reached.

4.2.2. Intra-cell Interference

The UMTS as defined by 3GPP may provide WCDMA two duplexing schemes: Frequency Division Duplex (FDD) or Time Division Duplex (TDD) both for downlink and uplink channels. This study is only focused in FDD mode for WCDMA because it is the most used. In FDD mode both downlink and uplink channels use different channel bands, e.g., 1920 – 1980 MHz for uplink and 2110 – 2170 MHz for downlink [9]. This separation of 30 MHz between both channels insures that there is no interference between them.

Furthermore, the use of direct sequence spread technique greatly reduces the effect of interference in communication in both uplink and downlink channels. The reduction is proportional to the relation W/R_b, where W is the chip rate and R_b is the bit rate of the session.

As shown in [22], the power P_k necessary for a session k to be able to communicate in a cell where the total received wideband power, including the thermal noise power in the BS, is given by I_{total} is represented in equation 4.5.

$$P_k = L_k . I_{total} \tag{4.5}$$

The total interference level is the sum of the interference noise with the power of all active sessions. When a new session is set active all other sessions will have to increase their transmit power because this new session will increase their interference value. The L_k (equation 4.6) is the load factor of session k, which has an activity factor of v_k, a certain $(E_b/N_0)_k$ and bit rate of R_k, and indicates the portion bellow the interference level that a session in WCDMA needs to arrive at the receiver to establish the link.

$$L_k = \frac{1}{1 + \frac{W}{(E_b/N_0)_k . R_k . v_k}} \tag{4.6}$$

The increase in the load value makes the overall noise, I_{total}, increase relative to the noise measured at the BS without any connection, P_N. This is expressed in equation 4.7.

$$Noise\_Rise = \frac{I_{total}}{P_N} = \frac{1}{1 - \eta_{UL}} \tag{4.7}$$

Where, at the BS, the total load value is $\eta_{UL} = \sum_{k=1}^{N} L_k$. When η_{UL} is close to 1, the corresponding noise rise approaches to infinity and the system reaches its pole capacity.

The noise rise makes all the sessions connected to a BS to increase their emitting power. In the AC is necessary to verify that the noise rise will not outage any of the active sessions. With the increase of the noise rise factor the coverage of the cell decreases, since the all terminals will increase their power to reach the BS. This continuous change in coverage area provided by each cell is called cell breathing. In order to keep the radio coverage and the continuity of the services in the network, it is necessary to keep the cell load bellow a certain threshold defined during the radio network planning phase.

4.2.3. Inter-cell Interference

In multiple cells coexistence scenarios, there are two inter-cell sources of interference, the co-channel interference and adjacent-channel interference.

Frequency reuse implies that in a given coverage area there are several cells that use the same frequencies. These cells are called co-channel cells and the interference from these cells is called co-channel interference. Unlike thermal noise which can be overcome by increasing the SNR, co-channel interference cannot be combated by simply increasing the carrier power of a transmitter because it increases the interference to neighbouring co-channel cells.

To limit the co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation [36]. Coordination and avoidance techniques may also be used. These techniques involve the coordination of the transmitters in time, space, power, code and frequency.

Interference resulting from signals which are adjacent in frequency to the desired signal is called adjacent-channel interference. Adjacent-channel interference results from imperfect receiver filters which allow nearby frequencies to leak into the passband. The problem can be particularly serious if an adjacent-channel user is transmitting in a very close range to a subscriber receiver, while the receiver attempts to receive a BS on the desired channel (near-far effect).

Adjacent-channel interference can be minimised through careful filtering and channel assignments. In [4] minimum values for the adjacent-channel leakage ratio and for the adjacent-channel selectivity are defined. Both these values are combined to give the adjacent-channel protection, which indicates the relation between the signal intended to the receiver and the adjacent-channel interference (table 4.1).

	Downlink	**Uplink**
Adjacent-channel leakage ratio	45 dB (BS)	33 dB (terminal)
Adjacent-channel selectivity	33 dB (terminal)	45 dB (BS)
Adjacent-channel protection	33 dB	33 dB

Table 4.1.: Minimum values of adjacent-channel leakage ratio, selectivity and protection for the first adjacent-channel

With a value of 33 dB of adjacent-channel protection and with a good frequency planning, the adjacent- and co-channel interference near the BS will be much smaller than the BS signal. However, with the terminal movement towards the edge of the cell, the interferer signal will increase and the BS signal will decrease. With adjacent cells transmitting in adjacent-channels, the adjacent-channel interference will have a dominant effect in the interference value.

For intra-to-inter cell interference ratio the value of 0.65 dB and for interference margin the value of 3 dB are usually used. However, in [22] it is shown these values are over dimensioned, specially for low density areas.

With the increase of sessions, n, in a cell the downlink transmit power at the BS will increase. The BS emits to all terminals at the same time, so terminals will suffer a noise rise from all others non-intended communications.

The BSTxP represents the BS transmit power for an average attenuation factor between the BS and terminal of $\overline{\mathrm{L}}$, an activity factor of v_k and noise spectral density of N_{rf} [22].

$$\mathrm{BST}x\mathrm{P} = \frac{\mathrm{N}_{rf}.\mathrm{W}.\overline{\mathrm{L}}.\sum_{k=1}^{\mathrm{N}} v_k \frac{(\mathrm{E}_b/\mathrm{N}_0)_k}{\mathrm{W}/\mathrm{R}_k}}{1-\overline{\eta_{\mathrm{DL}}}} \tag{4.8}$$

The N_{rf} value can be obtained from $\mathrm{N}_{rf} = k.\mathrm{T} + \mathrm{NF} = -174\,\mathrm{dBm} + \mathrm{NF}$ assuming $\mathrm{T} = 290\,\mathrm{K}$ and NF as the receiver noise figure at the terminal (typically $5-9\,\mathrm{dB}$).

The average load of the cell is given by equation 4.9. Where the $\overline{\alpha}$ is the orthogonality factor and $\overline{i}$ is the average value across the cell for the ratio of intra-to-inter cell interference.

$$\overline{\eta_{\mathrm{DL}}} = \sum_{k=1}^{\mathrm{N}} v_k \frac{(\mathrm{E}_b/\mathrm{N}_0)_k}{\mathrm{W}/\mathrm{R}_k} \left[(1-\overline{\alpha}) + \overline{i}\right] \tag{4.9}$$

From equation 4.8 it is possible to notice that an increase in the load of the cell will increase the transmit power, and consequently the inter-cell interference.

In uplink, the effects are similar to the ones already described but with a slightly different equations. In equation 4.10 the transmitted power by the terminal is represented and equation 4.11 shows the uplink load factor.

$$\mathrm{P}_k = \frac{1}{1+\frac{\mathrm{W}}{(\mathrm{E}_b/\mathrm{N}_0)_k.\mathrm{R}_k.v_k}}.\mathrm{I}_{total} \tag{4.10}$$

$$\eta_{\mathrm{UL}} = (1+i).\sum_{k=1}^{\mathrm{N}} \mathrm{L}_k \tag{4.11}$$

Where L_k is introduced in equation 4.6 and i measures the ratio of other cell to own cell interference.

4.3. Interference in OFDMA Systems

In the last few years, Orthogonal Frequency Division Multiplexing (OFDM) has become the promising transmission scheme in wireless communications due to its ability to combat the Inter-Symbol Interference (ISI) in multipath environments with large delay spreads. In this technique, a large number of closely-spaced orthogonal sub-carriers are used to carry data signals. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as Quadrature Amplitude Modulation (QAM) or Quadrature Phase Shift Keying (QPSK)) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

In a multi-user scenario, the traffic for each users is multiplexed using a time-frequency mapping. The multiplexed traffic then undergoes the OFDM modulation, which involves inserting unused carriers on either side of the data-bearing carriers, performing an Inverse Fast Fourier Transform (IFFT) and adding a cyclic prefix.

However its great improvements, OFDM is not immune to noise and interference. For example, the carrier frequency offset and phase noise may arise due to the imperfect and asynchronous nature of the oscillators at the transmitter and receiver ends, thus causing the signal at a particular sub-carrier being affected by the superposition of several other sub-carriers, which is known as inter-carrier interference. Inter-carrier interference in OFDM may also be caused by several other reasons such as channels with considerable variations along the duration of an OFDM symbol (i.e., time-selective channels), non-linearities of the channel transfer function, and environments where the delay spread of the channel considerably exceeds the length of the cyclic prefix.

When OFDM technology is used as multiple access technique, i.e., OFDMA, different users might be assigned with different sub-carriers (which form the sub-channels), as shown in figure 4.1. Therefore, inter-carrier interference is also known as inter-user or multiple access interference. In these cases, complex carrier frequency offset estimation, tracking, synchronization and scheduling schemes must be adopted in order to avoid errors in the information link.

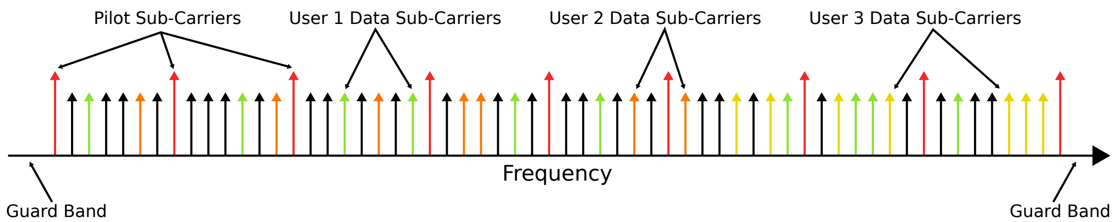


Figure 4.1.: OFDMA sub-carriers

The next interference analysis follows the IEEE 802.16 specification that can be found in [5]. In the initial working group release, in TDD mode, the standard supports 5 MHz and 10 MHz bandwidth allocations for each radio frequency channel. The available channel bandwidth is made up of sub-carriers each of which can be modulated individually with information. The number of sub-carriers available for assignment in the uplink and downlink are a function of the channel bandwidth, the frame size, and the uplink/downlink transmit ratio.

In Mobile WiMAX, the smallest unit of frequency-time allocation available is a slot which contains 48 data sub-carriers. The sub-carriers comprising a slot can be made up of adjacent sub-carriers or can be allocated in a distributed fashion throughout the available carrier space. In general, distributed carrier allocations perform better in mobile environments, while adjacent sub-carriers are better suited for fixed links. The number of slots assigned to a particular user per frame is a function of its data needs.

4.3.1. Intra-cell Interference

In OFDMA all the sub-channels are orthogonal to each other causing no intra-cell interference, however, in practice this is not so correct. In order to have orthogonal sub-channels, both the transmitter and receiver have to be synchronised, so that they both use the same symbol period. Any shift in the symbol period will affect the orthogonality of the sub-channels, causing intra-cell interference in the radio channel. This shift in time can be caused by movement in the transmitter or receiver and by limitations in the equipments at both BS and terminal to synchronise and generate the sub-channels at correct distance.

4.3.2. Inter-cell Interference

Channel planning in WiMAX systems can be performed in several ways. Channel allocation is left up to the service providers and is based upon the amount of available spectrum and the density of the users requiring service. When enough bandwidth is at hands, the channels can be allocated and reassigned among the available sectors in such a way as to minimise the co-channel interference at neighbouring sites. This procedure corresponds to the traditional form of channel planning where a channel frequency re-use factor can be picked to appropriately balance the trade off between spectral efficiency and interference. The interference between sectors operating on the same frequency is typically minimised through the use of directional antennas, sector spacing, and transmit PC in order to reduce the co-channel interference levels experienced by the users in the service area. Lower interference levels result in higher reliabilities and prevent the system from becoming interference limited.

However, to increase the WiMAX OFDMA performance, Multiple Input Multiple Output (MIMO) techniques have to be used. The MIMO techniques are divided into three groups: transmission diversity, beam forming and spatial multiplexing. Spatial multiplexing uses multiple antennas to send different information for the terminal, although it increases the maximum throughput it does not improve interference. The transmission diversity technique presented in the WiMAX standard is a 2Tx-1Rx Alamouti algorithm [8]. This technique allows a reduction of 14 dB in the SNR for a Bit Error Rate (BER) of 10^{-4}. The main advantage of this technique against the Maximal-Ratio Receiver Combining (MRRC) is that it requires 2 antennas at the BS and not in the terminal, keeping it small and simple.

Another MIMO technique is beam forming where the same signal is transmitted through multiple antennas placed at the BS or terminal. Changes in the phase and relative amplitude between the signals transmitted by each antenna creates directions where the combination of the signals is constructive and others in which it is destructive. With the increase of the number of antennas and/or by changing the antennas distances it is possible to create different transmission patterns. Beam forming does not increase the wanted signal power at the reception but it allows a decrease of interference signal to all others terminals.

The total transmit power in OFDMA of a BS, $\mathrm{BST}x\mathrm{P}$, is the sum of the power transmitted in all sub-channels (equation 4.12). The transmit power for each sub-channel will increase with the interference level, I_k, with the path loss, L_k, to the terminal, and with the number of used sub-channels for the session.

$$\mathrm{BST}x\mathrm{P} = \sum_{k=1}^{\mathrm{N}} \mathrm{SNR}_k.\mathrm{I}_k.\mathrm{L}_k.\mathrm{S}ub\mathrm{C}h_k \tag{4.12}$$

4.3.3. System Capacity

To approach the theoretical capacity of the system, WiMAX uses a combination of adaptive modulation schemes and coding ranging from 1/2 rate BPSK to 3/4 rate 64-QAM. In table 4.2 it is represented the SNR per each modulation using OFDMA technique in WiMAX.

Modulation	**Coding rate**	**SNR** (dB)	**Bits/symbol**
BPSK	1/2	3	0.5
QPSK	1/2	6	1
QPSK	3/4	8.5	1.5
16-QAM	1/2	11.5	2
16-QAM	3/4	15	3
64-QAM	2/3	19	4
64-QAM	3/4	21	4.5

Table 4.2.: Receiver SNR assumptions

The amount of error correction applied to each transmission is adjustable and can be changed depending on the required QoS and based on the reliability of the link between each user and BS. The higher modulation constellations offer a larger throughput per frequency-time slot but not all users receive adequate signal levels to reliably decode all modulation types. Users that are close to the BS that exhibit good propagation and interference characteristics (higher SNR) are assigned with higher modulation constellations to minimise the use of system resources. While users that are in less favourable areas (lower SNR) use the lower order modulations for communications to ensure data is received and decoded correctly at the expense of additional frequency-time slots for the same amount of throughput. Assigning modulations based on the link conditions increases the overall capacity of the system.

In a WiMAX systems, not all users use the same type of applications: browsing the web, e-mailing, sending/receiving video, downloading files, or using Voice over IP (VoIP) are activities that might be performed simultaneously within the population of users [34]. Each of these operations places varying demands on the system; some might require a higher data rate on download than on upload, while others are about evenly distributed. In order to predict capacity, users should be classified based on their demands and how much load they place on the system. For example, streaming video requires considerably more data rate than VoIP, so a user receiving video uses more system resources. At any given time there will be a mixture of services that are being requested and the system is able to support several voice users with the same resources it takes to serve one video user.

An alternate way of looking at capacity is to establish the load that a typical number of users place on a system and then determine at what point the load surpasses the ability to deliver of each sector. The number of system resources that are consumed in a given area depends on its demographics and the type of users that are present in that location (factors such as terrain and time of day can also affect demand). Additionally, in the case of WiMAX, the signal levels received at the terminal and BS are important since users that achieve better C/I ratios can be reached using higher order modulation schemes therefore consuming less of available slots in a given sector (table 4.2).

It can be useful to examine capacity in the extreme cases where a sector can achieve the maximum or minimum of both the number of supported users and spectral efficiency (bit/s/Hz) in a sector. The worst case occurs when all the users are at the edge of the coverage area of the cell and are only reachable by the lowest order modulation (BPSK with 1/2 rate coding) and at the same time have the greatest demand on the system. On the other hand, the most number of supported users and the best spectral efficiencies occur when all users are close to the BS (and can attain the highest order modulations; 64-QAM with 3/4 rate coding) and demand low data rate services like e-mail. Both of these cases are possible scenarios and all other cases that achieve varying numbers of sustained users and spectral efficiencies will fall in between these two extremes. The data rate that a sector should be able to deliver is therefore a random variable that is dependent on the distribution of the type of users in the service area as well as their achievable modulations. A similar argument can be made about the number of supported users in a sector which is also stochastic and is a function of the achievable modulation order as well as the distribution of the type of users over the coverage area.

4.4. WCDMA and OFDMA Interference Summary

From the analysis above, uplink and downlink interference analysis have to be approached and analysed differently. Downlink interference analysis can be computed or measured at each location in the service area and is therefore deterministic in nature. On the uplink, however, the randomness of the distribution of the users in the sectors introduces also a stochastic behaviour on the received C/I ratio at the BS. Channel planning, sub-channel allocations, as well as the use of frequency re-use factor zones all have effects on system wide interference levels. System capacity is dependent on the distribution of the users in the service area as well as the type of service that is requested. In systems that employ adaptive modulation such as WiMAX, capacity is also a function of the C/I ratio since higher modulation orders can achieve higher spectral efficiencies. Channel and, if necessary, sub-channel planning also has an effect on the data rate that can be supported per unit bandwidth.

Furthermore, it is easy to deduct that for both WCDMA (UMTS) and OFDMA (WiMAX) systems, the reduction in SNR for a connection and in the path loss from the BS to the terminal will reduce the total transmit power. This reduction in power will decrease the interference in adjacent cells, which is the inter-cell interference.

Finally, taking into account equation 4.12 and table 4.2, it can be seen that to limit the BSTxP the scheduler will have to use all the available space in the frames to use the smallest possible modulation. Thus some trade off is needed between overall system capacity and interference level to best allocate the resources to supply the customers with their data needs.

CHAPTER 5

CRRM Policies and Algorithms

THE CRRM policies shall be simple enough while at the same deliver high robustness. The simplicity is achieved in terms of implementation and when the message overhead is considered low.

In the heterogeneous environment (where various wireless systems coexist and their coverage range may be overlapped) the policies are adopted in order to select the best available RAT for AC, CC and VHO processes.

These policies, which are stored in a policies database (even in legacy networks), are defined by operators or according to the profile of users. The best available RAT can be related with the provision of best QoS, available/supported services, low costs, available bandwidth, profile, speed of the terminal, cell load, or business reasons.

Herein the focus is to reduce interference between users while migrating users (or service flows) between RATs, which, in principle, increases the overall system capacity.

Policies definition is seen as a higher level abstraction of the actions to be taken by the RRM entities. However, in order to be implemented, they need to be translated in algorithms. The algorithms and their evaluation is the focus of the next sections.

5.1. Load Balancing Algorithm for Technology Selection

The CRRM architecture presented in this work tries to exploit the available radio information to select the best RAT. The studied algorithm selects the RAT based on the load of each cell/RAT and it is depicted in algorithm 1. This is known as the LB algorithm and is the one that is used to ensure that the interference is reduced and the capacity is increased.

Require: 2 RATs (here referred as RAT1 and RAT2) and multi-technology terminal
Ensure: Either RAT1 or RAT2 is selected or the session is blocked/dropped

```
if The radio link in RAT1 and RAT2 supports the service then
   if There is enough capacity in RAT1 and RAT2 then
      if load in RAT1 > load in RAT2 then
         Select RAT2
      else
         Select RAT1
      end if
   else
      Use the available RAT or block/drop the service request if there is not enough capacity
   end if
else
   Use the available RAT or block/drop the requested service if none of the link supports
   the service
end if
```

Algorithm 1: General LB algorithm for RAT selection

5.1.1. Vertical Handover

In the AC the user is connected to the RAT that better satisfies the policy, which is the cell/RAT that has the smallest load. Although, wireless networks are dynamic and since the position of users in the cell will change along the time, it is necessary to insure that while moving in space the terminal continues to satisfy the policy. So the LRRM will be measuring the load of all the cells/RATs that are connected to it and store the values in the MDB.

The CRRM compares the values that are stored and if an overload situation is eminent the VHO is triggered. Then the VHO algorithm will evaluate the propagation conditions and the SLA in order to select a suitable cell/RAT to continue the service. The process starts with AC for the selected RAT and either the session is accepted or dropped. The AC can be unsuccessful when the new RAT does not have enough capacity to provide the requested QoS for the session.

In figure 5.1 a possible diagram for the VHO is presented. This diagram follows the new architecture proposed in chapter 3. However, if the selected cell has the same RAT as the original cell, the handover process is called HHO and it is made in the LRRM level. In this case, it is necessary to insure that this policy is also applied.

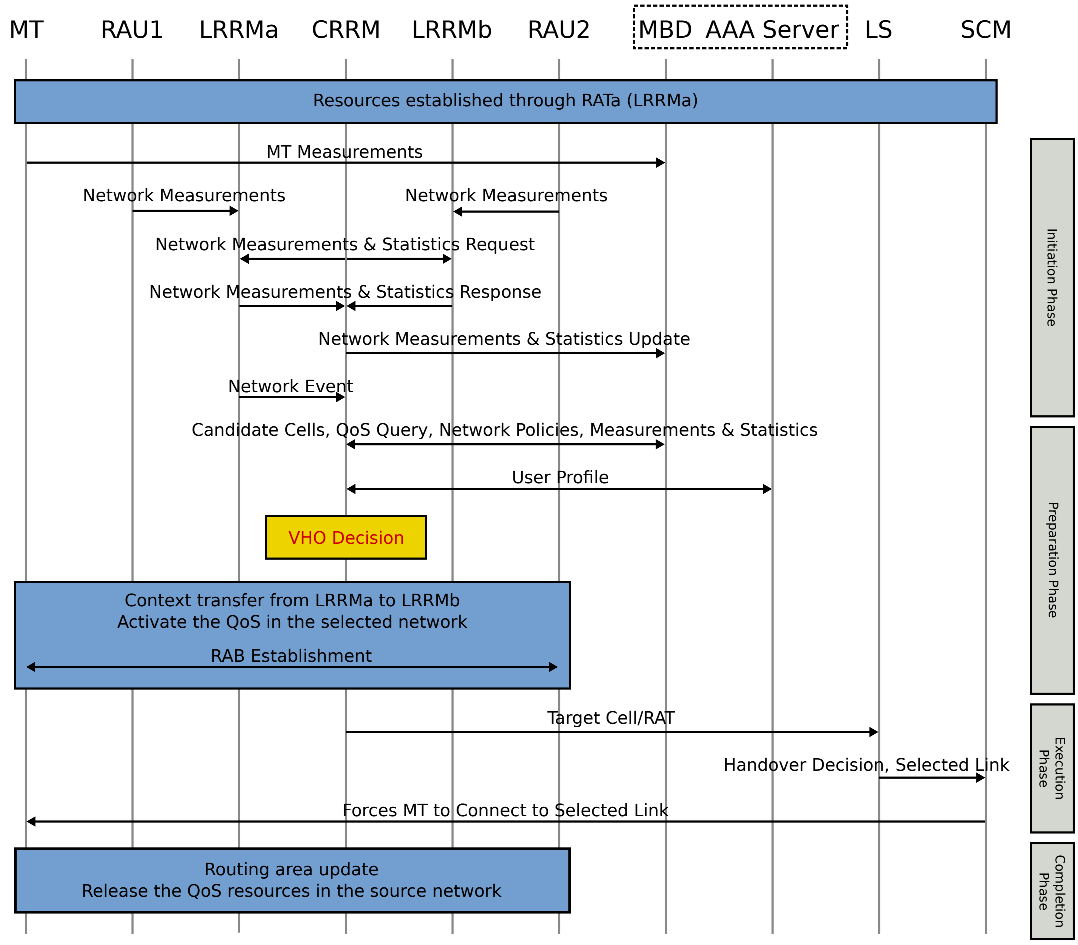


Figure 5.1.: Possible VHO process

5.1.2. Admission Control

All brand new sessions or VHO sessions arriving to the network have to be validated by the AC process, where it is chosen the best RAT. The criteria for the AC will change depending on the type of session to be admitted; if it is a new session the AC will try to chose the RAT that maximises the overall capacity, if it is a session in VHO the destination RAT may be already decided, or in case of CC the choice may not be the best RAT for the session but the one that can faster resolve the congestion situation. In all those cases, the AC has to confirm that the selected RAT has enough capacity to receive the session and maintain the agreed QoS for the sessions that are already active.

The AC has the function of authorise or deny session requests. This is done by evaluating the conditions of RATs, the requirements for QoS for the session, and policies. With the new proposed architecture, all decision entities remain in the same physical space, which greatly reduces the communication delay. In this sense, policies for the heterogeneous environment may be more efficiently applied.

The requests for session acceptance are either required by the terminal for a new session or by the VHO module when it is a VHO session. The AC starts to read the values from the MDB and thus evaluating the radio conditions of each possible candidates. In the case of a brand new session, the best possible RAT is chosen, which means that the load will be properly balanced and the interference is minimised. However, in the case of a VHO session, the AC will retrieve from the MDB only the parameters of the already chosen cell/RAT and admit or drop the session. If the session is accepted, the SCM instructs the terminal to connect to the selected cell/RAT.

Note that the cell/RAT designates the best available cell from a RAT for the terminal to connect. This is because in any place terminal will receive signals from multiple cells of the same RAT, and one of them must be chosen.

The AC will follow the process presented in figure 5.2. The measurements will come directly from the LRRM and terminal or they will be read from the MDB.

The process is described as follows:

Process starts : with the arrival of a session admittance request.

Arrival of a new session request : for every new request of SF, a request message has to be sent to the AC, and only after the choice of the best possible RAT is made, the admittance process is initiated.

Get list of RATs that support the service : it is only possible to provide a certain service if the RAT supports it.

Apply the policy and check capacity : apply the policy with the LB algorithm and guarantee that an overload situation will not happen. In this case, if a certain RAT is selected and it does not have the sufficient resources, then the RAT is removed from the list of RATs and the process starts again. If there is not any available RAT, the process finishes and the session is rejected.

Process finishes : the process successfully ends when the request is accepted and the connection is established; or the session request is blocked/dropped when there is no available RAT that covers the terminal area capable to provide the requested service.

The load estimation in this algorithm is critical. A bad guess may conduct the system to an overload situation or sub-utilisation. Next it is presented how this estimation is done in the UMTS and WiMAX cases.

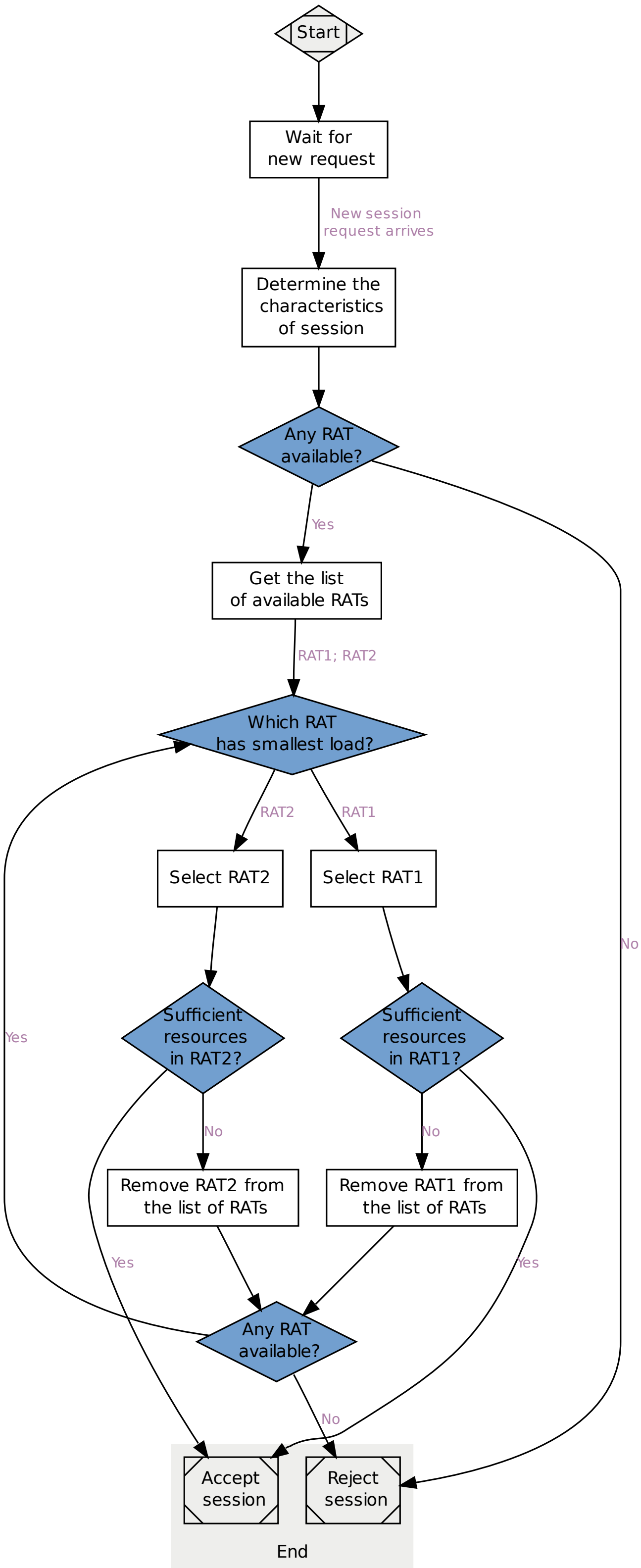


Figure 5.2.: AC process based on LB algorithm for RAT1 and RAT2

Estimation of Load in UMTS

In UMTS, as it was already seen in this thesis, for every new session accepted the overall noise increases, so it is necessary to confirm that both in uplink and downlink the noise rise will not outage any active session and the new session will be able to overcome the interference.

Besides the interference level, it is necessary to insure that the load of the cell does not exceed the maximum load value. Due to cell breathing, it is necessary to define a threshold value during the planning phase, so that a minimum coverage is kept.

The process used to accept a new session in UMTS for downlink has the following steps:

- Measurement of the downlink channel by the terminal and calculation of the needed power to communicate with it;
- Confirm that the transmit power in BS is enough for the new session and to accept the increase in power by the active sessions;
- Insure that the load will not exceed the pre-defined values.

As an approximation and in practical implementations it can be evaluated the number of occupied DPCHs against the total DPCHs.

In the uplink the steps are the following:

- Measurement of the total received power at the BS, I_{total}. This value includes the received power from the terminals connected to the BS and the interference power, either from other cells or from noise sources;
- Calculate the necessary transmission power for the terminal taking into account the necessary SNR for the requested service and the path loss;
- Estimation of the noise rise from equation 4.7 (the achieved value already includes the new session);
- Estimation of the load from the noise rise equation;
- Check that the load value does not exceed the maximum limit;
- Check for every active session that the new interference value at the BS will not block any of them from communicating in the uplink. This is done by calculating the new required transmission power necessary to reach the BS and checking that it will not be bigger than the maximum allowed value.

Estimation of Load in WiMAX

In WiMAX the load estimation will depend on the available capacity, which is used to estimate the performance of the data scheduler. However, since it has a granular structure to place the information, it is assumed that the scheduler will be able to use all the available resources. This means, that the scheduler will be able to place all information in the available slots, without free space, in each frame (see figure 5.3).

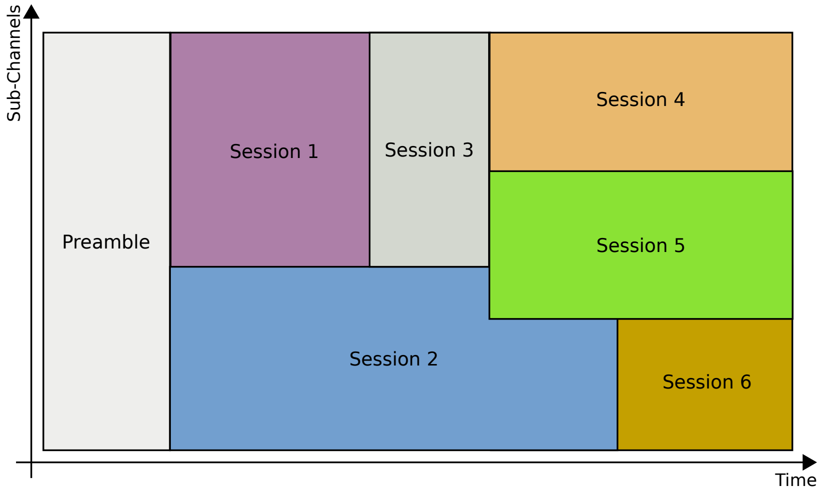


Figure 5.3.: WiMAX frame structure

So the overall capacity of WiMAX is 2 649 600 slots/s, using the Full Usage Sub-Channels (FUSC) mode, 10 ms frames and 3.5 MHz of bandwidth. For every new session that arrives it is calculated the amount of slots that the session requires and the amount of available slots. Due to adaptive modulation scheme the number of slots used by each session will vary with the SNR at the reception, where higher order modulations will spend fewer slots. If the session requires more slots than the ones that are available, it will be blocked.

5.1.3. Congestion Control

The CC will act when cell reaches an overload situation, this means that the load that cell is experiencing is above of the planned value. At this state the QoS cannot be maintained and some actions shall be done in order to restore the normal state.

Congestion situations may occur due to bad cell/RAT choices in the AC process or because of the dynamic behaviour of wireless and cellular environments; the load of the cell will increase too much if the sessions load in downlink or uplink overcomes the predefined values of load for UMTS or start demanding too much bandwidth in WiMAX.

When this happens the system has to act fast in order to avoid entering in a state where no session is able to communicate. The chosen actions to control the load may be different from RAT-to-RAT taking into account the technology particularities. For UMTS, in subsection 3.2.4, a group of actions to be applied by phases are suggested, trying in a first phase control the admission of new sessions and, in a last phase, sessions are dropped until the cell reaches a stable state.

In WiMAX with the increase of load, the packet scheduler will maintain the QoS of RT sessions and decrease the bandwidth for NRT sessions. The change of bandwidth can be done by changing the window given to each TCP connection. The criteria to choose the amount of bandwidth to reduce will be of economical source, but it should be defined a minimum bandwidth for every user. However, if this action is not enough to decrease the load, additional tasks, like disconnect some active sessions, shall be implemented.

In both RATs, the decision of dropping sessions is only made when there is no possibility to handover them.

5.2. Policies Evaluation

In the following text a CRRM algorithm that follows the policy to minimise interference and increase capacity is applied in a heterogeneous environment. Moreover, in the next sections the gains are presented and discussed.

5.2.1. Simulation Scenario Description

In figure 5.4 the simulation scenario is presented. In this scenario there are six interfering cells (C1, C2, C3, C4, C5 and C6) while the cell in the centre (C0) is being studied.

The cell in the centre (and all the outer interfering cells) have two co-localised technologies (which is the most common scenario in terms of money saves), one interference limited and another one contention (capacity) limited, RAT1 and RAT2, UMTS and WiMAX, and both RATs have the same coverage range.

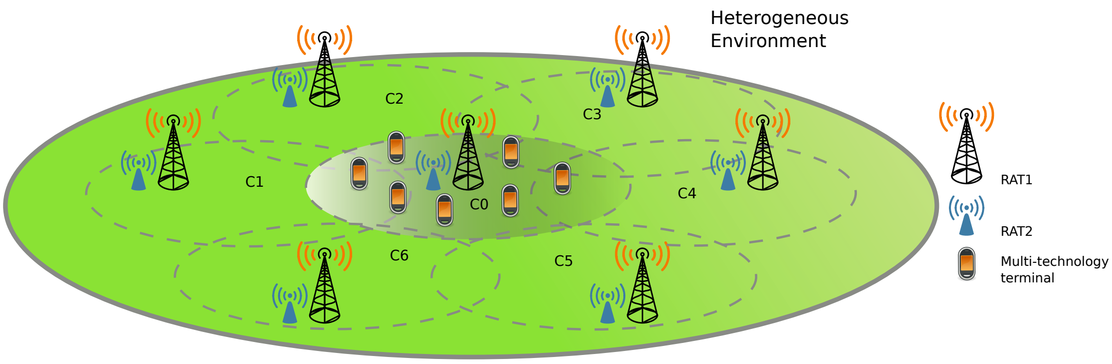


Figure 5.4.: The simulation scenario

The requests of sessions were simulated with the same application for all users. The rest of simulation parameters are presented in table 5.1.

Parameter	**Value**	
Studied cell	1 (cell in the centre)	
Interfering cells	6 (outer cells)	
Technologies	RAT1 (UMTS) and RAT2 (WiMAX)	
RATs relative position	Co-localised (cells overlapped)	
Number of users	50 (uniform distributed)	
Inter-site distance	1800 m	
BS transmit power	100 dBW	
Antenna type	Omni-directional	
Propagation model	Free-space	
CRRM algorithm	LB	
	RAT1	**RAT2**
Carrier frequency	1.8 GHz	3.5 GHz
Channel bandwidth	5 MHz	3.5 MHz

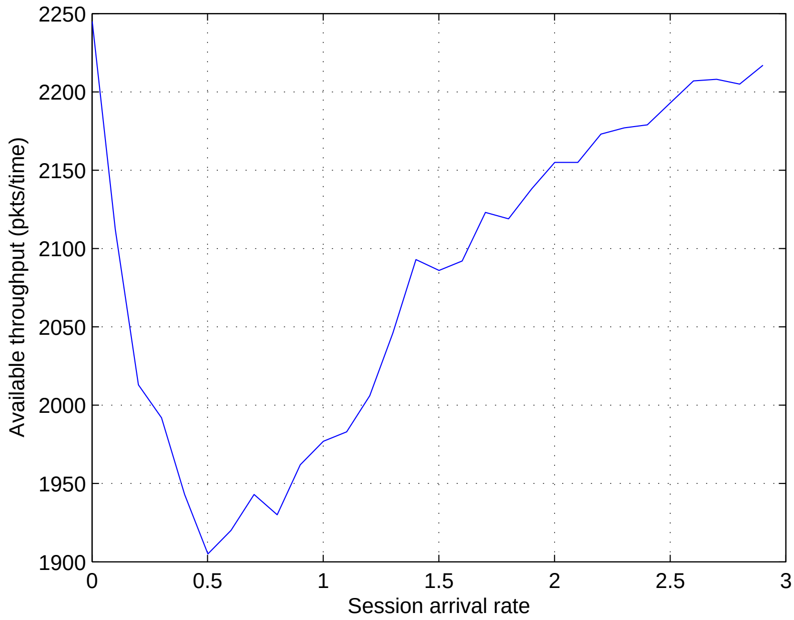
Table 5.1.: Simulation parameters

5.2.2. Achieved Results

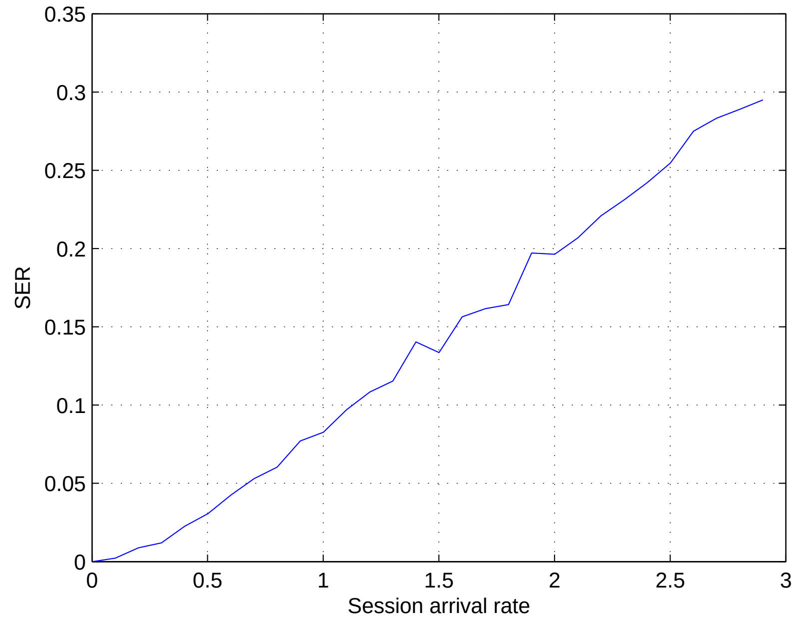
In this section the results from the simulations are presented. Let the author remember that the objective of these simulations is to achieve less interference and increase the overall capacity when the LB algorithm is applied.

Figure 5.5 and 5.6 show the available throughput and Symbol Error Rate (SER), respectively, when RAT1 and RAT2 are separately studied, which means there is no inter-connection between them. Figure 5.7 shows the available throughput and SER when the LB algorithm is applied. The available throughput represents the available resources within the cell, this is the total physical resources minus the occupied ones. All this results show in the x-axis the session arrival rate, which represents the sessions arrival during the simulation time. Furthermore, users are uniformly distributed in the cell.

Figure 5.8 represents the average throughput and figure 5.9 represents the average SER when users are localised in different positions within the cell. Cell centre means all users near the BSs of the cell under study, uniform distributed means that the distribution of users in the cell follows a uniform statistical distribution, and cell edge means that users are spread in the limit of central cell. The first and second bars represent RAT1 and RAT2, respectively, studied independently and the third bar represents the aggregated values for RAT1+RAT2 when the LB algorithm is applied.

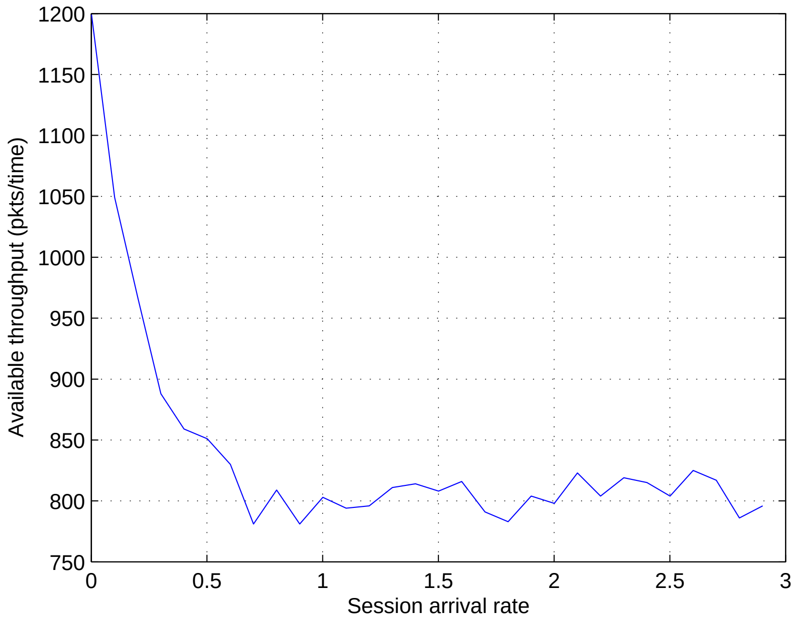


(a)



(b)

Figure 5.5.: Available throughput and SER for uniform distributed users in RAT1 without algorithm



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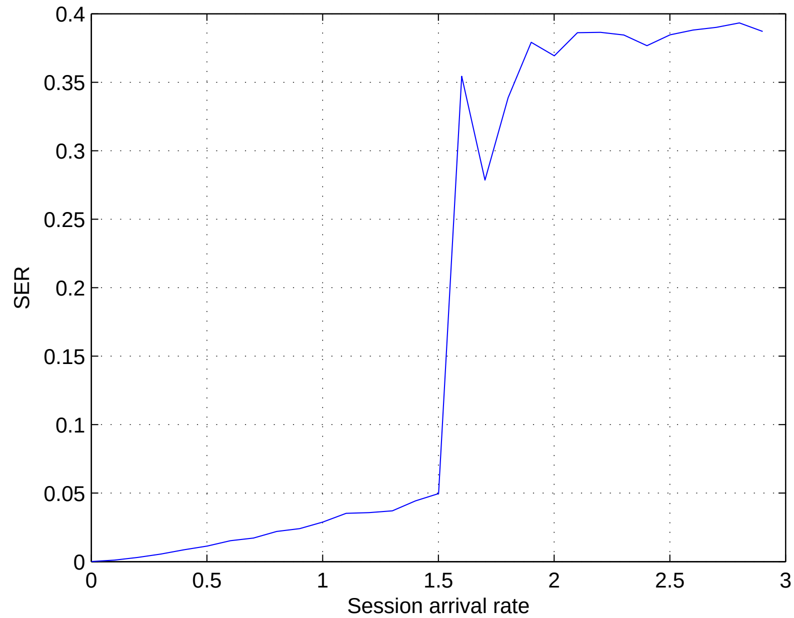
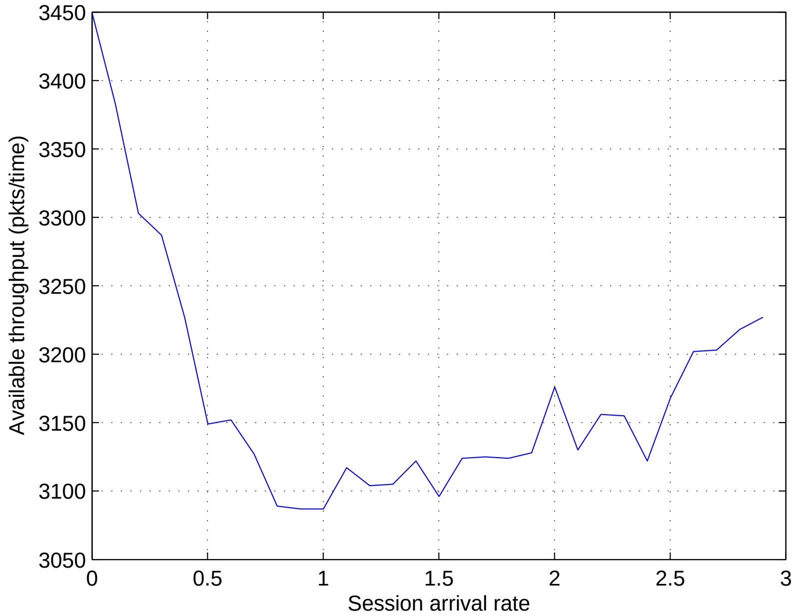


(b)

Figure 5.6.: Available throughput and SER for uniform distributed users in RAT2 without algorithm



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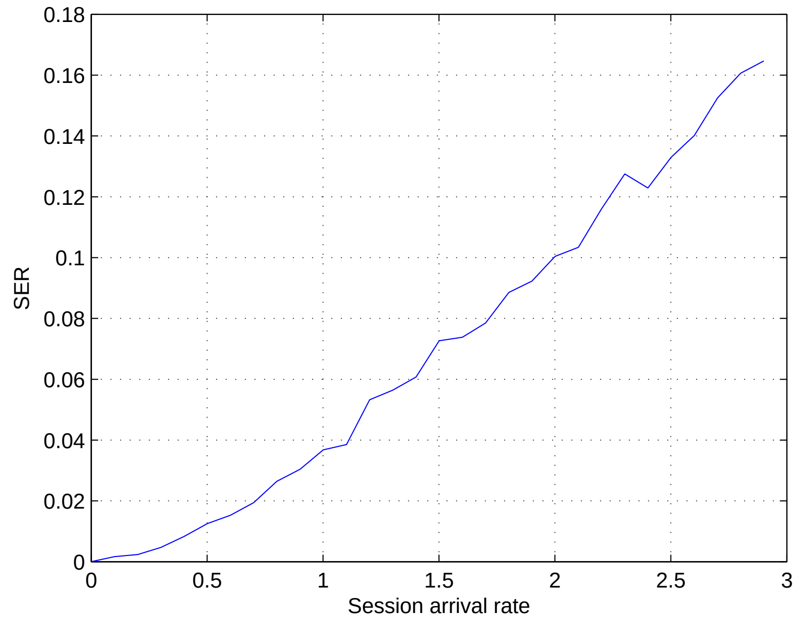

(b)

Figure 5.7.: Aggregated available throughput and SER for uniform distributed users in RAT1+RAT2 with CRRM LB algorithm

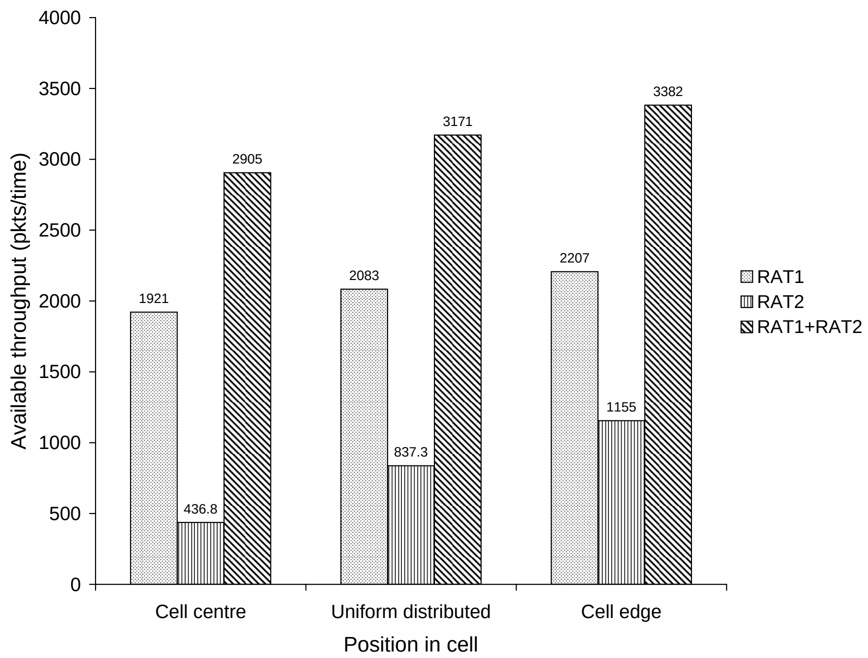

Figure 5.8.: Average available throughput for different positions in the cell

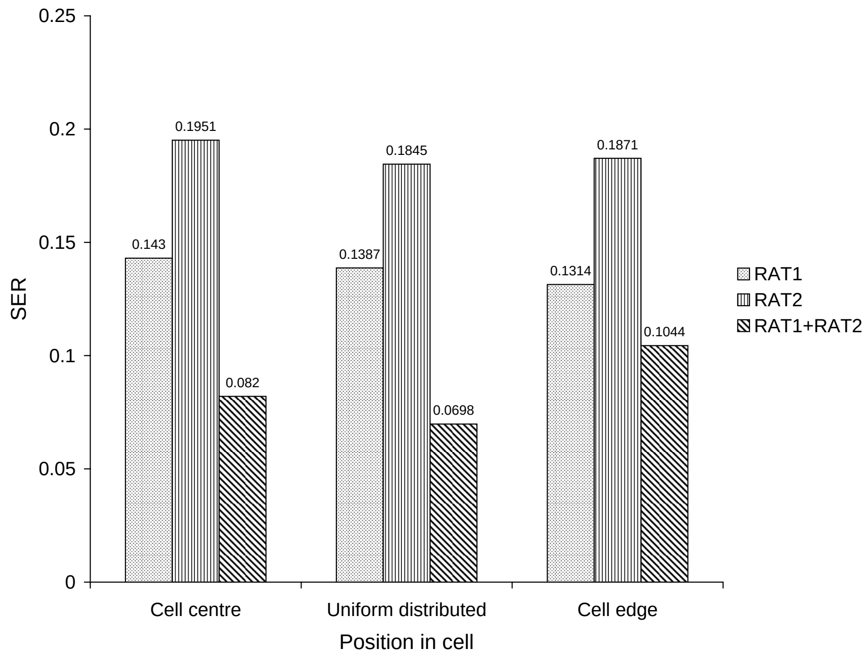

Figure 5.9.: Average SER for different positions in the cell

In table 5.2 it is presented the main gains in terms of available throughput and SER that were achieved when the cooperation between RATs is possible and the LB algorithm is applied.

	Cell centre	Uniform distributed	Cell edge
Available throughput	+51%	+52%	+53%
SER	-42%	-49%	-20%

Table 5.2.: Aggregated gains in percentage when the CRRM LB algorithm is applied to RAT1+RAT2

5.2.3. Discussion of Results

Regarding the results presented in subsection 5.2.2, it is possible to see that the available throughput is always higher in RAT1 than in RAT2, which means that in RAT1 there are less physical resources being consumed than in RAT2.

Regarding SER it is expected that the less congested RAT has less SER and the most congested RAT has the highest SER. For RAT1 SER ranges from 0 to 0.3 while in RAT2 the value ranges from 0 to 0.4. In fact, RAT2 is the one that has the lower values for the available throughput (more congested) thus it has higher SER when compared with RAT1.

When the LB algorithm is applied, it can be seen that the available throughput increases, while SER decreases; if the available throughput is higher it means that for the same interference level the capacity is increased; and if the SER is lower it means less collisions and less errors in the reception, thus a lower interference level is achieved.

When users move from the centre of the cell towards the cell edge the available throughput increases, both when RATs are individually considered or when they are aggregated, which means there are more resources being used in the cell centre than in cell edge. This result was expected because if the distance (between an user and BS) increases the path loss also increases, thus for the same level of SNR it is necessary to increase the transmit power, which also increases the interference level. However, for the same level of interference (the same transmit power), less QoS can be delivered to the users in the cell edge and more physical resources are be available. In this sense, users in the cell centre have high data rate services consuming more resources (less available throughput) than users in the cell edge (more available throughput). According to table 4.2, it is possible to see that for the WiMAX case if SNR value increases then higher modulations can be used, thus higher data rate services may be provided, and higher spectral efficiency is also achieved (which happens in cell centre).

On the other side, when the LB algorithm is applied the available throughput increases, as shown in table 5.2). It means that in average and for this particular scenario it is possible to allow the admission of more 26 users in the system for the same level of interference.

Furthermore, when users move from the centre of the cell towards the cell edge it is expected an increase in SER value. However, in the simulations the average SER was more or less constant when RATs where individually considered. For the aggregated simulations, the value of SER is higher when users are in the cell edge than in cell centre or uniform distributed.

When the algorithm is applied the value of SER is reduced, as it is depicted in table 5.2. On this case it can be concluded that even users in the cell edge see their QoS improved in at least 20% than when both technologies are separately considered.

CHAPTER 6

Conclusion

INTERFERENCE is the major limiting factor in the performance of wireless and cellular radio systems and it has been recognized as a major bottleneck in the increasing capacity and is often responsible for dropped and blocked sessions. The interference level is much related with the deployment scenario, namely the BS placement. The radio network planning of all RATs shall be analysed as a whole in order to take advantage of the CRRM solution.

The RoF solution to transport RF signals from remote sites to CU where the joint processing is done has demonstrated to be a profitable solution. Moving all processing equipment to a central location decreases the operational and maintenance costs, while enables the adoption of policies and algorithms that mitigate interference and increase capacity/coverage.

The proposed architecture, which is a generalisation of 3GPP CRRM functional model, and the solutions adopted for CRRM algorithms (see table 3.2), in conjunction with the LB algorithm have shown an increase of the available throughput for the same level of interference, which allows the admittance of more 26 users for the simulated scenario, and a decrease of 20% in the value of SER (i.e., less interference).

Coverage is very dependent of the scenario. In this case, no coverage enhancements were achieved because the cell radius is the same for both technologies and BSs are co-localised.

No adaptive modulation simulations were done, however from the interference analysis it is clear that the use of adaptive modulation results in an interesting limiting effect on system capacity. Users at the edge of coverage area are more likely to be using a lower-constellation modulation type which is less efficient in terms of frequency-time slot usage. This implies that BS need to be located within the areas where the majority of the users are found in order to maximise the number of them using the more efficient modulation types.

Although good results were achieved, the simulated RATs do not closely follow the standards, thus for UMTS only dedicated channels are simulated (DPCHs) while for WiMAX no adaptive modulation is implemented. Furthermore, it was only simulated VHO and AC on the downlink direction and all users are served with the same service.

As a future work, some enhancements in the simulation platform are required.

6.1. Future Work

As a future work, the author suggests the following:

- In the architecture define and implement the interfaces between different entities that take part in the RRM process;
- Improve the simulation platform adding at least adaptive modulation for WiMAX (and in this case better results shall be achieved);
- Simulate users with different services, following the service classes adopted for UMTS and WiMAX;
- Add other technologies to be simulated in the platform;
- Simulate the same scenario with other type of simulator, for instance Network Simulator 2 (ns2), and compare results.

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Appendices

APPENDIX A

Radio Propagation Model

THE wireless transmissions are subject of two major sources of propagation degradation, namely fading and interference. Fading is caused by propagation path loss and multipath phenomena. Multipath propagation may be frequency-selective leading to inter-symbol interference for high data rate transmission. On the other hand, in cellular radio, due to the reuse of frequencies for increasing the spectrum efficiency and system capacity, co-channel interference is the dominant interfering source.

A radio propagation model is an empirical mathematical formulation for the characterisation of a radio wave propagation as function of frequency, distance or other factors. Which means they are developed based on large collections of data for a specific scenario. For any model, the collection of data has to be sufficiently large to provide enough scope to all kind of situations that can happen in that specific scenario.

Researchers try to define a single model in order to predict the behaviour of propagation wave form for all similar links under similar constraints, between the transmitter and the receiver. Those models are typically used to predict the path loss. However, due to its complexity, the mobile radio propagation phenomena cannot be entirely described by a single model.

COST 231 [14] and SUI [6] loss models are some of the models used to predict the path loss in urban environment. However, here only the free path loss model is presented because it was the one used for the simulations that were done in the scope of this thesis.

A.1. Free Path Loss Formulation

Path loss is generally defined as the loss in signal between the transmitter and the reception station and may be due to many effects, such as free-space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption. Path loss is also influenced by terrain contours, environment (urban or rural, vegetation and foliage), air conditions, distance between the transmitter and the receiver, and the height and location of antennas. It is the major component in the analysis and design of the link budget of a telecommunication system.

Equation A.1 is the well-known free space loss model which only takes into consideration distance and frequency. Hence, this model is limited in its ability to accurately predict path loss in most environments.

$$\mathrm{L} = 32.44 + 20log(f) + 20log(d) \tag{A.1}$$

Where L (dB) is the path loss, f (MHz) the frequency and d (km) the distance[1].

From the equation A.1 and using a CRRM path loss algorithm [20], it is obvious that for the same distance to the BS the terminal is instructed to select the RAT that operates at lower frequency. For example, in an environment where UMTS and WiMAX coexist, WiMAX will be selected only when UMTS is fully occupied.

The equation A.1 does not include any component for antenna gains. It is assumed that the gain for each antenna is unity for both the transmitter and receiver. In reality, though, all antennas will have a certain amount of gain that will reduce the loss when compared to a unity gain system (see equation A.2). The values for the gains of antennas are relative to an isotropic source, i.e., an antenna that radiates equally in all directions.

$$\mathrm{L} = 32.44 + 20log(f) + 20log(d) - \mathrm{G}tx - \mathrm{G}rx \tag{A.2}$$

Where $\mathrm{G}tx$ and $\mathrm{G}rx$ are the gains of the transmitter and receiver antennas relative to an isotropic source (dBi).

1 "$log()$" means "$log_{10}()$".

APPENDIX B

Glossary of Terms

In order to have a better understanding, the meaning of some terms commonly used during this thesis are presented. Some of this terms may be already described in the main document, while others are only defined here.

Handover: also known as hand-off, refers to the process of transferring an ongoing call or data session from one BS where the terminal is associated to another (with the same or different RAT). In this process the RAN changes the radio parameters (e.g., codec or radio mode) used to provide bearer services, while maintaining a defined bearer QoS and minimum added system load.

Inter-system handover: an inter-system handover is the switching process between two different radio systems (e.g., UMTS/WiFi or WiMAX/UMTS). The radio networks may belong to the same or different operators. The term VHO is equivalent to the inter-system handover.

Intra-system handover: HHO is the same as intra-system handover. These kinds of handovers refer to the switching process between two different radio cells within the same system, with the same or different radio mode (i.e., intra-system intra-mode and intra-system inter-mode handovers).

Radio Resource Management (RRM): refers to network controlled mechanisms and architectures that support intelligent admission of calls, sessions, distribution of traffic, QoS, transmitted power aiming at an optimised usage of available radio resource, maximising the system capacity and coverage.

Common Radio Resource Management (CRRM): this is the architecture proposed by 3GPP to make UMTS and GSM/GPRS networks cooperate. It includes a CRRM entity, which is responsible for coordinating the individual LRRM entities of each RAT.

Radio link: it is a two point communication channel, that uses the electromagnetic spectrum by the means of a radio wave, from few kHz to many GHz. Besides using the same frequency, both sender and receiver have to use the same modulation, the bit coding, and the data encryption.

Legacy system: it is a piece of hardware or software that is being used for a long time. Even with new and improved versions the designers use legacy systems because of their critical importance in the system, or because of the huge investment necessary to upgrade it.

Service Flow (SF): a SF is a MAC transport service that provides unidirectional transport of packets on the uplink or on the downlink. A SF is identified by a 32-bit Service Flow Identifier (SFID). The SF defines the QoS parameters for the packets that are exchanged on the connection.

Radio Resource Unit (RRU): a RRU is the smallest division where information is placed. It is called slot in WiMAX and there are two possibilities for downlink: 48 sub-channels and 1 symbol or 24 sub-channels and 2 symbols. A slot is the time to send a symbol of the modulation, $1/\Delta f$ (where Δf is the distance in frequency between each sub-channel). The amount of bits in a slot is dependent on the used modulation.

Radio Access Network (RAN): it has many entities, e.g., in UMTS it is considered the NB plus RNC and it is called Universal Mobile Telecommunications System Terrestrial Radio Access Network (UTRAN). Each RAN implements a different technology to divide the radio resources for their users, which is called RAT. In cellular networks, the concept of RAT only makes sense within a cell.

Radio Access Technology (RAT): means the way SFs may access to the shared resource, the spectrum, in a way that interference is reduced. It may be based on time, Time Division Multiple Access (TDMA), frequency, Frequency Division Multiple Access (FDMA) and OFDMA, or codes, CDMA. For example, WiMAX implements OFDMA, while UMTS uses a version of CDMA, WCDMA.