Universidade de Aveiro
2013

Departamento de
Electrónica, Telecomunicações e Informática

Muhammad Alam

Estratégias de Design de Camada Intermédia e Cooperativa para Redes Sem Fios Energeticamente Eficientes

Inter layer and Cooperative Design Strategies for Green Mobile Networks

Programa de Doutoramento em Informática

das Universidades do Minho, Aveiro e Porto

Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
2013

Muhammad Alam

Estratégias de Design de Camada Intermédia e Cooperativa para Redes Sem Fios Energeticamente Eficientes

Inter layer and Cooperative Design Strategies for Green Mobile Networks

Universidade de Aveiro Departamento de
Electrónica, Telecomunicações e Informática,
2013

Muhammad Alam

Estratégias de Design de Camada Intermédia e Cooperativa para Redes Sem Fios Energeticamente Eficientes

Inter layer and Cooperative Design Strategies for Green Mobile Networks

Dissertação apresentada á Universidade de Aveiro para cumprimento dos requisitos necessá rios á obtenção do grau de Doutor em Informática, realizada sob a orientação científica do Doutor Jonathan Rodriguez Gonzalez do Instituto de Telecomunicações.

Apoio financeiro da FCT com a
referência SFRH/BD/67027/2009.

O júri / The jury

Presidente / President	**Dr. Armando da Costa Duarte** Professor Catedrático da Universidade de Aveiro (por delegação da Reitora da Universidade de Aveiro)
Vogais / Examiners committee	**Dr. Joaquim Arnaldo Carvalho Martins** Professor Catedrático, Universidade de Aveiro
	Dr. Rui Luís Andrade Aguiar Professor Associado com Agregação, Universidade de Aveiro
	Dr. Charalabos Skianis Professor Associado com Agregação, University of the Aegean, Grécia
	Dr. Rui Carlos Mendes Oliveria Professor Associado, Universidade de Minho
	Dr. Marília Pascoal Curado Professora Auxiliar, Universidade de Coimbra.
	Dr. Paulo Jorge Coelho Marques Professor Adjunto, Escola Superior de Tecnologia, Instituto plitécnico de Castelo Branco
	Dr. Jonathan Rodriguez Gonzalez Professor Auxiliar Convidado, Universidade de Aveiro (orientador)

agradecimentos / acknowledgements

First of all, I thank all mighty GOD for giving me the strength to accomplish this work. I would like to express my deepest gratitude to my parents and my family for their love, encouragement and constant support.

I would like to express my sincere gratitude to my supervisor, Professor JONATHAN RODRIGUEZ, for his guidance and support during my studies. I am also thankful to CLÁUDIA BARBOSA for taking care of the financial, travel and other administrative affairs.

I would like to express my kind gratitude to FCT (Fundação para a Ciência e a Tecnologia), MAP-i PhD Program, Instituto de Telecomunicações Aveiro, University of Aveiro and C2POWER project for providing financial support and this valuable opportunity to pursue PhD. and accomplish this degree.

I would like to express my gratitude to my colleagues Dr. Ayman Radwan, Dr. Michele Albano, Dr. Shahid Mumtaz and Du Yang for their useful discussions, strong intuition, and collaborative research work. I am grateful also to the rest of 4TELL group at IT who helped me by providing valuable feedback within their areas of expertise.

I would like to express my deepest gratitude to my brother Alamgir Khan and Faheem Jan and all my friends especially Fazal M, Kazi, Wael, Firooz, Vahid, Hugo Cirrose, Mariana, Alexandra B, Rui P, Rui T, Tiago T, Sanaz, Volga, Tania, for their constant help and encouragement.

Finally, I would like to express the deepest appreciation to the president of the PhD committee and the examiner for honoring me with their presence and taking the time to evaluate my work.

Palavras-chave Redes cooperativas, Comunicaçãoes eficientes energeticamente, Perceção de contexto, Descoberta de nós em redes, Comunicaçãoes heterogéneas.

Resumo

A promessa de uma experiência realmente móvel é de ter a liberdade de deambular por qualquer sítio e não estar preso a um único local. No entanto, a energia requerida para manter dispositivos móveis conectados á rede, num período extenso de tempo, o mesmo rapidamente se dissipa.Na realidade, a energia é um recurso crtico no design de redes sem fios, uma vez que esses dispositivos são alimentados por baterias. Para além disso, dispositivos móveis multi-standard permitem que os utilizadores desfrutem de elevadas taxas de dados com conectividade omnipresente. No entanto, as vantagens adquiridas pelas múltiplas interfaces, imputa uma despesa, sendo essa um consumo maior de energia, numa era onde os dispositivos móveis têm de ser energicamente complacentes. Esta preocupação é reafirmada pelo facto de que a vida da bateria é uma das principais razões que impede os utilizadores de usufruir e utilizar de servios de multimédia mais avançados nos seus dispositivos, numa base frequente. De forma a assegurar a entrada no mercado para serviços da próxima geração, eficiência energética tem de ser colocada na vanguarda do design de sistemas. No entanto, apesar de esforços recentes, funcionalidades que cumpram os requisitos energéticos em tecnologias "legacy" ainda estão nos seus primórdios e novas abordagens disruptivas são requeridas, juntamente com abordagem de design interdisciplinar, de forma a aproveitar a poupana energética das diversas camadas protocolares. Uma bordagem promissora são os sistemas de cooperaão inteligente, que exploram não sáo contexto da informaão, mas também as entidades que são igualmente capazes de formar uma coligação e cooperam de forma a atingir um objectivo comum. Migrar a partir destas referências, esta tese investiga como é que este paradigma tecnológico pode ser aplicado para reduzir a potência e consumo de energia em redes móveis. Para além disso, introduzimos uma dimensão de poupana energética adicional, para adopção de design de camadas intermédias, de forma a que as camadas de protocolos sejam concebidas para trabalhar em sinergia com o sistema anfitrião, ao invés de independentemente, para aproveitamento de energia. Neste trabalho, nós exploramos o contexto da informaão, cooperação e design de camadas intermédias para desenvolver blocos de construção energicamente eficientes e tecnologias agnósticas para redes móveis. Estes habilitadores (enablers) tecnológicos incluem um nó de descoberta de energia eficiente e cooperação de curto alcance para poupana energética em aparelhos móveis, complementado com agendamento inteligente, energicamente consciente, de forma a promover a poupana de energia do lado da rede. Analiticamente e simultaneamente, foram obtidos resultados e verificados em laboratório, num modelo de hardware protótipo. Resultados demonstram que pode ser obtido uma poupana energética acima dos 50%.

Keywords Cooperative Networks, Green Communication, Context Awareness, Node Discovery, Heterogeneous Communication

Abstract

The promise of a truly mobile experience is to have the freedom to roam around anywhere and not be bound to a single location. However, the energy required to keep mobile devices connected to the network over extended periods of time quickly dissipates. In fact, energy is a critical resource in the design of wireless networks since wireless devices are usually powered by batteries. Furthermore, multi-standard mobile devices are allowing users to enjoy higher data rates with ubiquitous connectivity. However, the benefits gained from multiple interfaces come at a cost in terms of energy consumption having profound effect on the mobile battery lifetime and standby time. This concern is reaffirmed by the fact that battery lifetime is one of the top reasons why consumers are deterred from using advanced multimedia services on their mobile on a frequent basis. In order to secure market penetration for next generation services energy efficiency needs to be placed at the forefront of system design. However, despite recent efforts, energy compliant features in legacy technologies are still in its infancy, and new disruptive architectures coupled with interdisciplinary design approaches are required in order to not only promote the energy gain within a single protocol layer, but to enhance the energy gain from a holistic perspective. A promising approach is cooperative smart systems, that in addition to exploiting context information, are entities that are able to form a coalition and cooperate in order to achieve a common goal. Migrating from this baseline, this thesis investigates how these technology paradigm can be applied towards reducing the energy consumption in mobile networks. In addition, we introduce an additional energy saving dimension by adopting an inter-layer design so that protocol layers are designed to work in synergy with the host system, rather than independently, for harnessing energy. In this work, we exploit context information, cooperation and inter-layer design for developing new energy efficient and technology agnostic building blocks for mobile networks. These technology enablers include energy efficient node discovery and short-range cooperation for energy saving in mobile handsets, complemented by energy-aware smart scheduling for promoting energy saving on the network side. Analytical and simulations results were obtained, and verified in the lab on a real hardware testbed. Results have shown that up to 50% energy saving could be obtained.

Contents

List of Abbreviations

2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
AF	Amplify-and-forward
AP	Access Point
APSD	Automatic Power Save Delivery
BSS	Basic Service Set
BP	Beacon Period
BPST	Beacon Period Start Time
BS	Base Station
BER	Bit error rate
CAM	Context Aware Module
CAM	Constant Awake Mode
CAS	Context Aware Scheduling
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
Cx	Context

CxEF Context Extraction Function

DF Decode and Forward

DL Down Link

DP Data Period

DS Distribution System

DVB-H Digital Video Broadcasting

EE Energy Efficiency

eNB enhanced Node B

EPC Evolved Packet Core

EPS Evolved Packet System

E-UTRAN Evolved Universal Terrestrial Radio Access Network

FDD Frequency Division Duplex

GHz Gigahertz

GPS Global Positioning System

HO Handover

HSPA High Speed Packet Access

IBSS Independent Basic Service Set

ICT Information Communication Technologies

IE Information Element

IEEE Institute of Electrical and Electronics Engineers

LCC Logical Link Control

LTE Long Term Evolution

LTE-A Long Term Evolution-Advanced

MAC Medium Access Control

Max C/I	Maximum Carrier to Interference ratio
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MS	Mobile Station
MSDU	MAC Service Data Unit
MT	Mobile Terminal
OFDM	Orthogonal Frequency Division Multiplexing
P-GW	Packet Data Network Gateway
PANs	Personal Area Networks
PF	Proportional Fair
PHYs	physical layers
PSM	Power Save Mode
PSMP	Power Save Multi Poll mode
QoS	Quality of Service
RAT	Radio Access Technology
RF	Radio Frequency
RR	Round Robin
RTS	Request to Send
RSS	Received Signal Strength
Rx	Reception
S-GW	Serving Gateway
SAE	System Architecture Evolution
SOFDMA	Scalable Orthogonal Frequency Division Multiple Access
SE	Spectral Efficiency

SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal to interference ratio
SM	Spatial Multiplexing
SNR	Signal to Noise Ratio
TA	tracking area
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TIM	Traffic Indication Map
TFC	Test Fixture Controller
Tx	Transmition
UE	User Equipment
UGS	Unsolicited Grant Service
UMTS	Universal Mobile Telecommunications System
UL	Up link
VHO	Vertical Handover
VoIP	Voice Over IP
W	Watt
WLAN	Wireless Local Area Networks
UWB	Ultra-wideband

List of Figures

List of Tables

Chapter 1

Introduction

This chapter introduces the research contributions in this thesis. Initially, the motivation for the research challenges in this work are introduced providing the impetus for the objectives. Furthermore, the chapter provides the scientific contribution in this thesis followed by the organization of the thesis.

1.1 Introduction

The current 4G vision envisages higher data rates and multi standard radio interfaces (UMTS, LTE, Wi-Fi, DVB-H, Bluetooth, etc) to provide users with a continuous connection. However, state of the art multi standard devices have high power requirements for maintaining two or more radio interfaces. In addition, advanced imaging features (camera, high-definition display, etc.) and GPS/Galileo receivers will increase considerably the power demand of 4G handsets. This rise in power requirements combined with ergonomical trend towards smaller handset devices will cause handset devices to become " hot " since the transfer of heat is proportional to the surface area. Effectively this will give way to two consequent effects: firstly, the temperature of the casing of the device can increase such that it becomes too hot to handle; and secondly the high temperatures make the electronic components unreliable and more likely to fail. In [1] and [2], it is envisaged that short-term solutions to overcome hot devices is active cooling. Even though active cooling is not an attractive solution for users and manufacturers, recent works have started studying the performance of fans within mobile phone architectures [3]. From the mobile manufacturers perspective the energy consumption problem is critical, not only technically but also taking into account the market expectations from a newly introduced technology. This is in fact becoming a key concern: there exists a continuously growing gap between the energy consumption of emerging radio systems and what can be achieved by:

- Battery technology evolution.
- Scaling and circuit design progress.
- System level architecture progress.
- Thermal and cooling techniques.

In terms of battery technology, capacity is finite and the progress of battery technology is very slow, with capacity expected to make little improvement in the near future. In [4] it is claimed that battery capacity has only increased by 80% within the last ten years, while the processor performance doubles every 18 months following Moore's law. In terms of power consumption we have moved from a relatively low 1-2 W range in the first generations to around twice in 3G mobile devices. The perspective for the future does not look encouraging in this aspect, as one could easily expect another doubling in the power demand for 4G and beyond devices.

Therefore, one of the biggest impediments of future wireless communications systems is the need to limit the energy consumption of the battery-driven devices so as to prolong the operational times and to avoid active cooling. In fact, without new approaches for energy saving, there is a significant threat that the 4G mobile users will be searching for power outlets rather than network access, and becoming once again bound to a single location. Some authors describe this effect as the energy trap of 4G system [5].

Another challenge of future wireless radio systems is to globally reduce the electromagnetic radiation levels to have a better coexistence of wireless system (less interference) as well as a reduced human exposure to radiation leading to the so called Green Wireless technologies [6]. In this context, in September 2008 the European Parliament adopted a resolution on the mid-term review of the European Environment and Health Action Plan which highlights the health risks posed by emissions from mobile phones. It notes, in this respect, that the limits on exposure to electromagnetic fields are obsolete and should be amended, because they do not take into account recent developments in new wireless technologies, like multi-standard devices. Low-power communication can potentially contribute to ameliorate public concerns about health issues related to mobile communication.

In typical terminals of cellular systems (e.g., 2G, 3G) up to half of the power consumption comes from communications-related functions like baseband processing, Radio Frequency (RF) and connectivity functions [1][5]. Therefore any reduction in the power consumption in these functionalities will have a substantial impact on the battery lifetime. The importance of this problem has already motivated advanced solutions and communication protocols designed to allow dedicated switch off periods for power saving purposes and increase battery lifetime (e.g. [7]). In general these techniques sacrifice Quality of service (QoS) to save power. Based on the above facts, there is a clear need for new disruptive strategies to address all aspects of power and energy efficiency from the user devices through to the core infrastructure of the network and how these devices and equipment interact with each other.

1.2 Energy Saving Modes in Legacy Wireless Systems

In this section we briefly explain the key energy saving features introduction in legacy wireless communication systems.

1.2.1 WiMAX

Worldwide Interoperability for Microwave Access (WiMAX) is based on the IEEE 802.16 standard [8], which is also called Broadband Wireless Access. The main idea of WiMAX is to make broadband access more widely and cheaply available through a standard for wireless metropolitan area networks. The 802.16 includes two sets of standards: 802.16-2004 (802.16d) [9] for fixed WiMAX and 802.16-2005 (802.16e) [10] for mobile WiMAX.

The IEEE 802.16d, which provides fixed point-to-multi point broadband wireless access service, utilizes OFDM 256-FFT. It supports both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) services. The latter delivers full duplex transmission, if desired. IEEE 802.16e, based on the early WiMAX standard 802.16a, adds mobility features to WiMAX in the 2 to 11 GHz licensed bands. IEEE 802.16e provides fixed wireless and mobile Non Line of Sight (NLOS) applications, by enhancing the OFDMA (Orthogonal Frequency Division Multiple Access).

WiMAX is a possible candidate replacement for cellular technologies such as GSM and CDMA or an overlay to increase capacity. WiMAX has also been considered as a wireless backhaul technology for 2G, 3G and 4G networks.

The original WiMAX standard (802.16) specified a physical layer operating in the 10 to 66 GHz frequency range. 802.16a, updated in 2004 to 802.16-2004, added specifications for the 2 to 11 GHz band. 802.16-2004 was updated by 802.16e-2005, which uses Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) as opposed to OFDMA version with 256 sub-carriers (of which 200 are used) in 802.16d.

The IEEE 802.16 MAC protocol design is driven by the need for point-to-multipoint broadband wireless access providing high bit rates, both in the uplink and downlink. Users may require a variety of services which include TDM voice and data, IP connectivity and voice

over IP (VoIP). Consequently, the 802.16 must accommodate both continuous and burst traffic with QoS provisioning.The request-grant mechanism is designed to be scalable, efficient, and self-correcting. IEEE 802.16 access system is designed to efficiently handle multiple connections per terminal, multiple QoS levels per terminal, and a large number of statistically multiplexed users. It combines the advantage of a wide variety of request mechanisms, balancing the stability of contentionless access with the efficiency of contention-oriented access.The MAC protocol definition also includes a privacy sub-layer that provides authentication of network access and connection establishment to avoid theft of service, and provides key exchange and encryption for data privacy. Mobility management is defined through IEEE 802.16e-2005 standard, which provides the definitions of signalling mechanisms for tracking mobile stations (MSs), while moving away from the coverage of one BS towards the vicinity of another.
The extended mobility offered by IEEE 802.16e standard requires a mechanism for managing the limited energy of the mobile terminal, which is normally powered by rechargeable battery. To effectively manage this limited power, the standard specifies a sleep mode operation.Sleep mode is a state in which the MS is effectively turned off and becomes unavailable for predetermined periods. Sleep Mode is intended to decrease the power usage of MSs. Implementation of sleep mode is optional for MSs and mandatory for BSs. Sleep Mode has two parameters: Sleep-interval and Listening-interval. The Sleep-interval is the time duration from the point the MS enters sleep mode until it returns to awake-mode. This interval is negotiated with the serving BS. The Listening-interval is the time duration during which the MS has to decide whether to stay awake or go back to sleep, after waking up. This time is also used to balance the delay difference between the air-link and peer-to-peer traffic (e.g. TCP session).
WiMAX defines three power-saving classes, based on the manner in which sleep mode is executed.

- Power Save Class 1 mode: the sleep window exponentially increases from a minimum value to a maximum value. Class 1 mode is typically used, when the MS has best-effort and non-real-time traffic.

- Power Save Class 2 mode: The sleep window has a fixed-length. Class 2 mode is used for UGS (Unsolicited Grant Service).

- Power Save Class 3 mode: One-time sleep window is allowed. Class 3 mode is typically used for multicast traffic or management traffic, when the MS knows when the next message is expected.

WiMAX has various benefits in terms of coverage, self installation, power consumption, frequency re-use and bandwidth efficiency. 802.16e also adds full mobility support. Most commercial interest is in the 802.16d and 802.16e standards, since the lower frequencies used in

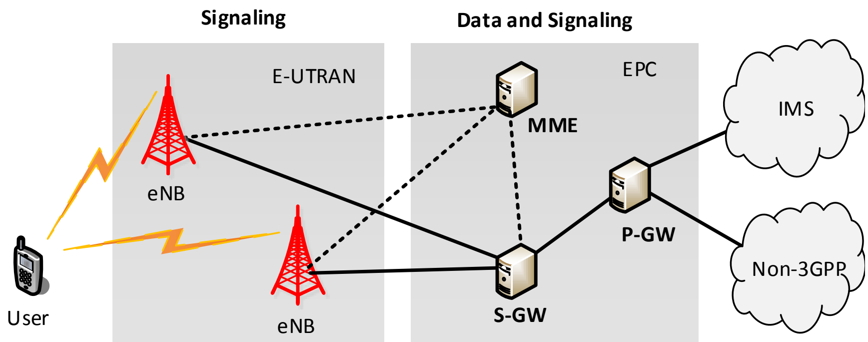

Figure 1.1: UTRAN and EPC architecture.

these variants have better propagation characteristics in terms of signal attenuation and therefore give improved range/coverage and in-building penetration/propagation. Some commercial networks are already operating throughout the world, using certified WiMAX equipment compliant with the 802.16d standard.

1.2.2 LTE

The Long Term Evolution, (LTE), and System Architecture Evolution, (SAE), are specified by 3GPP in parallel with High Speed Packet Access (HSPA). HSPA is being deployed all over the world; while the first LTE network has started operation in December 2009 [11]. The Evolved Packet System (EPS), objectives are to define a system architecture which enables all-IP services. The EPS is divided into the Evolved Universal Terrestrial Radio Access Network (e-UTRAN), and Evolved Packet Core (EPC). The e-UTRAN is composed by several evolved-Node Bs (eNB), which are individually responsible for the radio connection management to the User Equipment (UE) as shown in figure 1.1. The EPC connects the e-UTRAN with other 3GPP and non-3GPP networks. The components of the EPC are responsible for mobility management, authentication and packet handling. Specifically, their functionalities include:

- Mobility Management Entity (MME): responsible for the UE authentication and registration, for the selection of the P-GW and S-GW. After the registration of the UE the MME is also responsible for the mobility management, both in idle and active modes. In Idle mode it will keep track of the TA and in the Active mode it will manage the handover procedures.

- Serving Gateway (S-GW): responsible for packet routing and forwarding between the eNBs and the PGW, it is the mobility anchor for intra-3GPP handovers. Charges the UL and DL by UE, PDN and QoS Class Identifier (QCI).

- Packet Data Network Gateway (P-GW): This is the interface between the 3GPP and non-3GPP networks and the EPS. Manages the IP addresses by assigning one for each active UE, and by reducing the IP header to a compressed header, thus reducing the overhead in each transmission. Taking advantage of being the only point of the SAE where IP packets are processed, it sfilters packet data based on operator policies and does virus detection. It is also able to apply higher level charging, for example charge a user for each URL it accesses.

The LTE Air Interface is based on OFDMA for downlink and SC-FDMA for uplink taking into account both TDD and FDD modes. Moreover, it exploits Multiple Input Multiple Output (MIMO) and Smart Antennas techniques that has the capacity to deliver up to 100Mb/s for mobile users, and up to 1Gb/s for nomadic.
The LTE UL implements a slow power control procedure. Opposite to CDMA, where the transmission power in the UL channel is controlled to reduce interference, in LTE the intra-cell interference is greatly reduced by using the OFDMA. Nevertheless, power control in the UL is still used to decrease the power consumption of the UE.
The power control is done by continuously changing the number of subcarriers used by each UE. In this way, the spectral power density (power/hertz) can be controlled. In each UL frame, the optimum no of subcarriers and transmission time are chosen, taking into account the amount of information the UE needs to transmit.
In order to specifically conserve battery level, LTE supports the use of enhanced discontinuous reception mode (DRX), where the terminals alternate between idle and off mode, when no packet reception and transmission are required. There are two DRX modes: the RRC idle DRX mode and the RRC connected DRX mode [12]. In either mode the SGW will buffer the packets for the UE, when in the off period of the DRX mode, and subsequently forward them when the UE changes to idle mode. In both modes the DRX will start Twait (drx-InactivityTimer) after the last packet delivery. Then the UE will have a period of time where it is listening for packet arrival, Ton (onDurationTimer), and a period where it is off. This cycle will repeat until the arrival of a new packet, or when the UE needs to send a packet. The DRX cycle is shown in figure 1.2. The choice of the DRX period will affect the performance of delay sensitive services; the DRX can achieve very high power saving gains, but this introduces higher delays. Besides DRX, LTE brings from 2G/GSM the discontinuous transmission (DTX). In DTX during a conversation session, the UE detects the moments where the user is not talking and it sends a SID packet to the target UE. This will indicate to him that no speech is being made from the other party, and will generate comfort noise. This enables a reduction in the transmission period, increasing the battery life and reducing the intra-cell interference.

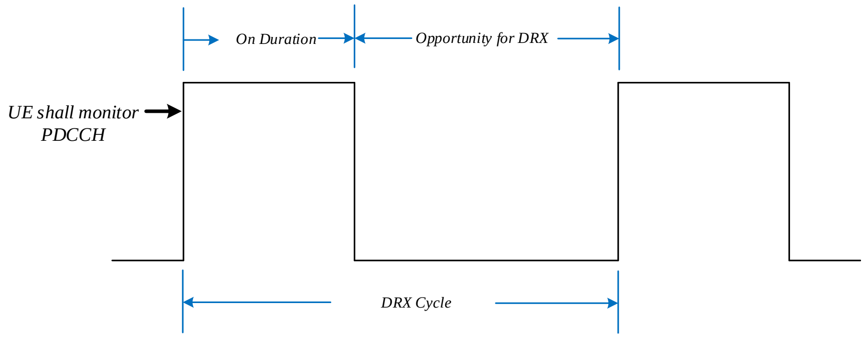

Figure 1.2: DRX cycle.

1.2.3 WLAN

Wireless Local Area Networks (WLANs) is a generic term that refers to the IEEE 802.11 communications standard for the wireless networks originally intended to provide connectivity instead of wired LANs (IEEE 802.3). The IEEE 802.11 standard [25] specifies information about the Medium Access Control (MAC) and Physical Layer (PHY) in order to provide wireless connectivity to devices which may be portable or handheld, or which may be mounted on moving vehicles within a local area [13]. Each IEEE 802 standard specifies the lowest two layers of the OSI model. Each version of the standard splits the Data Link layer in two sub-layers, namely Logical Link Control (LCC) and Medium Access Control (MAC). While each 802.X standard is specified in order to use the same IEEE 802.2/LCC encapsulation, the MAC defines the set of rules on how to access the medium, where as the PHY defines details on packet transmission and reception.

The basic building block of an 802.11 LAN is the Basic Service Set (BSS) that can be seen as the coverage area within which each station remains connected. In contrast, an Independent BSS (IBSS) consist of only two stations able to communicate directly. This kind of configuration is called an ad hoc network. Each station joins the BSS in a dynamic way using a synchronization procedure, moreover, no assumptions about the relative physical position of the BSSs are done in the standard. The Distribution System (DS) in an architectural component that supports interconnecting BSSs. While an Access Point (AP) is a component that has STA functionality and enables access to the DS. The Extended Service Set (ESS) is the union of the BSSs that are connected via a DS. The ESS does not include the DS and it appears to the Logical Link Control as an IBSS network. This means that a station is able to move among BSSs transparently to the LLC. A portal is the logical point that provides service in order to connect a non-802.11 LAN to the DS. Obviously, it is possible to have both functionality of AP and portal in one device.

The MAC sub-layer covers every physical layer and defines systems for the transmission of the

user data over the air. It provides the interaction with the wired network backbone and with different physical layers each of which works with different technologies and at different transmission speeds. For this reason it can be seen as the key of the 802.11 specification. Moreover, it makes use of a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in order to minimize the number of packets due to collisions.
Wireless LANs are typically used by mobile applications and where battery power is a scare resource. The 802.11 standard directly addresses the issue of Power Saving and defines a whole mechanism to allow stations to go into sleep mode for long periods of time without losing information. The main idea behind the Power Saving Mechanism is that the AP maintains an updated record of the stations currently working in Power Saving mode, and buffers the packets addressed to these stations until either the stations specifically require to get the packets by sending a polling request, or until they change their operation mode. The AP also transmits periodically (as part of its Beacon Frames) information about which Power Saving Stations have frames buffered at the AP, so these stations should wake up in order to receive one of these Beacon Frames, and if there is an indication that there is a frame stored at the AP waiting for delivery, then the station should stay awake and send a Poll message to the AP to get these frames.
Multicasts and Broadcasts are stored by the AP, and transmitted at a pre-known time, where all Power Saving stations that wish to receive this kind of frames should be awake. As wireless devices operate, their physical layers can be considered to be in one of five states:

- Off : The only power consumption is leakage current, but coming out of the off state can take a long time.
- Sleep/Standby : The device may be consuming as little as 175 μW and can wake quickly unless the main crystal is turned off.
- Listen: The device is listening for a packet to arrive, so most of the radio receiver must be on. State-of-the-art power numbers for WLAN devices in this mode is 110 mW.
- Active Rx : Similar to the listen state, but use of additional circuitry may push power consumption for WLAN (802.11g).
- Active Tx : In the transmit state, the device's active components include the RF power amplifier, which often dominates in high-power transmit systems. State-of-the-art power consumption for an 802.11g WLAN device is 450 mW at 15 dBm Tx power.

These wireless physical states are used in combination to create wireless protocol modes:

- Searching for a network

- Connected but idle
- Media traffic flow
- Max-throughput traffic flow

The IEEE 802.11 standard specifies how communication is achieved in a WLAN environment. Since handheld devices or battery powered laptops are likely to be operating in this environment, battery life is an important point to consider. In the IEEE 802.11 part of the standard is dedicated to describing Power Save Mode (PSM) that is a feature used in order to allow devices to extend battery life. Powering down the transceiver can lead to great power saving in the device side. For this reason IEEE 802.11 based its Power Save mechanism on the opportunity to set the station in two states; Power-Saving Mode (or dozing) when the transceiver is off, and the other is awake mode in which the transceiver is on. Since all the radio traffic must go through the AP which has access to a power supply, it has a key role in power saving by buffering traffic dedicated to various stations. Every station that has buffered MSDUs frames in the AP are identified in a Traffic Indication Map (TIM) which will be sent as part of the beacon frame. A station that operates in PS mode will periodically listen for beacon frames in order to observe pending buffered frames.
The 802.11n Std. has defined two new mechanisms for the Power Save Mechanism: Spatial Multiplexing Power Save and Power Save Multi-Poll. The spatial multiplexing (SM) power save mode allows the station to power down all the antennas but one. It operates in two different ways called static and dynamic operation. In the static SM power save mode, the station uses only one antenna becoming substantially equal to an 802.11a/g device. The AP is notified about the SM power save mode of the station, and will send only a single spatial stream to this station. In the dynamic SM power save mode, the station operates with only one antenna as in the previous case, but in this mode of operation, the station can rapidly enable its additional radios when it receives a frame waiting in the AP buffer. In this mode of operation, the AP sends a RTS to the station in order to wake up its radios, then the station responds with a CTS. The station can return to SM power save mode sending a management frame to the AP. The Power Save Multi Poll mode (PSMP) has been introduced in order to extend the Automatic Power Save Delivery (APSD) mechanism defined in 802.11e. PSMP uses the same concept of APSD for delivery-enable and triggering, but extends the ability of the station to schedule the frames that it transmits as the trigger for delivering the downlink frames. The scheduling mechanism is used in order to reduce the contention between stations and between a station and the AP and consequently the time spent by the stations in backoff.
In a real-world Wi-Fi network, several characteristics must be taken into consideration to reduce power and battery consumption, including the decreasing modulation rate as a user

device moves away from the access point.

1.2.4 UWB-WiMedia

The WiMedia Alliance is non-profit industry trade group that promotes the adoption, regulation, standardization and multi-vendor interoperability of Ultra-wideband (UWB) technologies. WiMedia's UWB is based on a fully-distributed network architecture operating in the frequency range 3.1 - 10.6GHz using Orthogonal Frequency Division Modulation. The frequency range is divided into channels to permit co-existence of several groups of nodes in the same area. The radio range can be up to 30 meters in free space, but is typically 3-10 meters depending on the environment and frequency of the channel selected for operation. Transmit power levels are constrained by varying national regulatory requirements, but are typically less than -40dBm/MHz in Europe.
There is no central coordination between nodes, which dynamically associate themselves to clusters as they come within range of each other. Nodes use a MAC layer protocol to join and cooperate with their peers in a non-disruptive manner and to negotiate and allocate air-time for data transmission. Prior to making any transmission, nodes follow a discovery procedure to identify and synchronize with any nodes already operating within range. By exchanging short beacon frames, nodes are able to identify and discover each other with a duty cycle as low as 0.4%. Networks may be independent or overlapping and a node may simultaneously be a member of more than one network. Networks dynamically reorganize themselves as nodes move or become obscured. The resultant topology can be an interconnected set of networks, encompassing the entire node population. This adaptive aspect has three main advantages.

- Spatial reuse of the bandwidth in neighboring networks.
- Bandwidth sharing or reservation in a controlled fashion in each network.
- Robustness in the face of changes caused by node motion, node failure and node insertion/removal.

Distributed networks formed by devices are called beacon groups. Devices operating in a beacon group transmit regular beacon frames. Devices always listen for an existing beacon group, before transmitting in order to discover, identify and select the most suitable beacon group to join. Devices then synchronize with any nodes already operating within range.
Air-time is partitioned into superframes of 64 ms duration. The first part of the superframe is a designated Beacon Period (BP) and is reserved for the exchange of beacon frames, the remainder - the data period (DP) - is available for devices to exchange data frames by negotiating for and subsequently following a selection of Medium Access Policies. The beginning

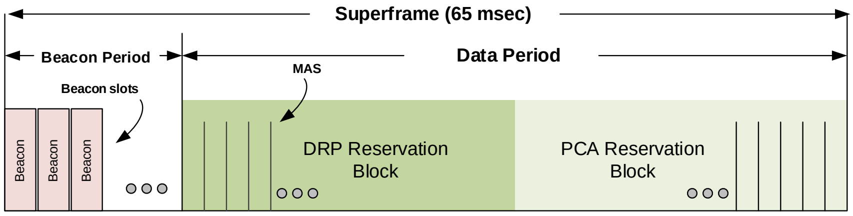

Figure 1.3: Super Frame Structure.

of a superframe is called the Beacon Period Start Time (BPST). The size of the BP expands and contracts as devices join and leave the beacon group. The BP is sub-divided into 85 μs beacon slots and the DP is divided into 256 Medium Access Slots (MAS) as shown in figure 1.3. Coordination of devices within radio range is achieved by the exchange of beacon frames. These are short periodically transmitted frames, which enable device discovery, support dynamic network organization, and provide support for mobility. In addition, beacons provide the basic timing for the network and carry reservation and scheduling information for accessing the medium. Beacon frames are always transmitted at the lowest rate to help ensure the best possible reception by all neighboring devices. Information Elements (IEs) are defined for particular types of information. Devices can include IEs in their beacons at will. The inclusion of specific IEs may be requested by inclusion of the Probe IE in the requestors beacon. MAC and PHY Capabilities IEs indicate support for optional facilities.

WiMedia aims to maximize battery lifetimes for mobile devices. Mechanisms are defined to allow devices to turn off or reduce power for relatively long periods of time. Several modes of operation are supported:

- Active : devices transmit and receive beacons in every superframe.
- Hibernation : devices neither transmit nor receive for multiple superframes.
- Partial Hibernation : devices turn off their radios for portions of each superframe. Typically this kind of hibernation takes place during those parts of the superframe being used by other devices for data frame exchange.

If all devices could enter hibernation mode at the same time, the first device to wake would need to scan for at least one superframe, which could negate any hibernation energy saving. Two or more devices could also become active together and create different BPSTs, which would incur significant protocol overhead to re-align them. To overcome these obstacles, devices cooperate in selecting devices to act as hibernation anchors, such that every device is either in the radio range of an anchor or is itself an anchor. The selection mechanism minimizes the number of anchors and rotates the anchor role so that devices share the burden of remaining in active mode. Beacon IEs specify when and for how long devices will hibernate.

1.3 Motivation

The energy required to keep mobile devices connected to the network over extended periods of time quickly dissipates which affects the promise of a truly mobile experience. In fact, energy is a critical resource in the design of wireless networks, since wireless devices are usually powered by batteries. Battery life time has been identified by TNS report [14] as the number one criteria for the majority of the consumers purchasing a mobile device. Reaffirming this, concern with depleting battery is one of the top reasons why consumers do not use advanced multimedia services on their mobile devices more frequently. The momentum towards energy conservation is also driven by international consortiums in a bid to place tighter control on global greenhouse gas emissions. It is estimated that Information Communication Technologies (ICT) contribute with 2% to 2.5% of the global greenhouse gas emissions. And with the expansion of the ICTs in developing countries, the total figure of carbon emissions will continue to grow to an estimated 2.8% of total global emissions by 2020 [4].
The market need for energy efficient devices is synergy with the political drive towards environmental impact has placed energy consumption at the forefront of system design. Although legacy technologies have each tackled energy saving towards taking a step to reducing the operational expenditure in the network, the reductions don't go far enough. Cognition and cooperation are seen as promising technologies that have shown good performance in different applications. Cognition for cognitive radio has been extensively applied towards enhancing spectrum efficiency exploiting the concept of opportunistic radios and spectrum pooling. Cooperation has also been considered only for improving wireless link capacity or coverage extension. Despite the extensive studies on cognitive radios and cooperation between MTs, these two disruptive emerging technologies have scarcely been used for the purpose of energy saving.

1.4 Objective

The complexity of heterogeneous wireless networks and the necessity for multi-mode and 'content' capable handsets have provided the impetus for new design requirements in terms of power efficiency to ensure that battery life time, environmental and operational expenditure targets can be met.
In this context, the main objective of this thesis is to research, develop and demonstrate en-

ergy saving mechanisms for multi-standard wireless mobile devices and networks, exploiting the combination of promising technologies such as cognitive radio and cooperative strategies while still enabling the required performance in terms of data rate and QoS to support active applications.
The thesis focuses on the power and energy that is consumed in the wireless transmission and reception process, i.e, on the wireless subsystem of the mobile devices without considering any power or energy consumption issues in the other mobile phones functionalities (display, memory, camera, etc).
In particular, this thesis investigated the following mechanisms to promote energy savings in future emerging wireless devices:

- Context based short-range cooperation for energy savings using advanced low-power short range communications to achieve power efficiency at mobile devices and save battery lifetime.
- Investigate and demonstrate the potential of context based cooperative techniques based on advanced short range communications energy efficient mobile wireless devices.
- Context based radio resource management for energy saving while ensuring the desired QoS by users.

As a consequence, this thesis should contribute to the existing research trends migrating from a purely network centric approach to network user centric where devices are now seen as pool of network resources for cooperation.

1.5 Thesis Contribution

This PhD thesis mainly contributes towards providing analytical, simulation and test bed based results to understand the contribution of context aware and cooperation as technology agnostic approaches for energy saving. The thesis considers UWB, WiFi, WiMAX ,and LTE-Advanced system as the technology platforms for testing our energy efficient approaches.
The results of this thesis have been published in book chapters, journals and conference proceedings listed below:

- **Book Chapters**

  1. Muhammad Alam, M. Albano, A. Radwan, J. Rodriguez "Context Based Node Discovery Mechanism for Energy Efficiency in Wireless Networks Green Commu-

nication for 4G Wireless Systems, ISBN: 9788792982056, River Publishers March 2013.

2. Muhammad Alam, M. Albano, A. Radwan, J. Rodriguez “Throughput Fairness Analysis of Reservation Protocols for WiMedia MAC Green Communication for 4G Wireless Systems, ISBN: 9788792982056, River Publishers March 2013.

3. Muhammad Alam, Shahid Mumtaz, Jonathan Rodriguez “Resource Allocation and Energy Calculation in WPANs based on WiMedia MAC Green Communication for 4G Wireless Systems, ISBN: 9788792982056, River Publishers March 2013.

- **Scientific Journal Papers**

1. Muhammad Alam, M. Albano, A. Radwan, J. Rodriguez, “CANDi for Energy Saving and Facilitating Short-range cooperation” Transactions on Emerging Telecommunications Technologies, ISSN 2161-3915,2013, Doi 10.1002/ett.2763.

2. Muhammad Alam, Du Yang, Jonathan Rodriguez, Raed A. Abd-Alhameed “Secure Device to Device Communication in LTE-A IEEE Communications Magazine, Vol. 52, no. 4, April 2014.

3. Muhammad Alam, Shahid Mumtaz, Firooz B. Saghezchi , Ayman Radwan, Jonathan Rodriguez “Energy and Throughput Analysis of Reservation Protocols of Wi Media MAC.” Journal of Green Engineering 3: 363-382.

4. Muhammad Alam, Peter Trapps, A. Radwan, J. Rodriguez, “Context-aware Cooperative Testbed for Energy Analysis in beyond 4G Networks (Accepted with minor revision Telecommunication Systems Journal)

5. Muhammad Alam, Du Yang, Shahid Mumtaz, Kazi M.S. Huq, Jonathan Rodriguez “Context Aware Resource Allocation for Energy Saving in LTE-A (Submitted to annals-of-telecommunications journal Springer)

- **Scientific Conference Papers**

1. Muhammad Alam ; Radwan, Ayman; Rodriguez, Jonathan; , “On the significance of context information in node discovery,” Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2012 IEEE 17th International Workshop on , vol., no., pp.302-306, 17-19 Sept. 2012.

2. Muhammad Alam, M. Albano, A. Radwan, J. Rodriguez, “Context Based Node Discovery Mechanism For Energy Efficiency In Wireless Networks Proc. IEEE ICC, Ottawa Canada, June 10-15, 2012.

3. Muhammad Alam, Shahid Mumtaz, M. Albano, A. Radwan, J. Rodriguez "Throughput Fairness Analysis of Reservation Protocols of WiMedia MAC" 8th International Conference on Innovations in Information Technology (Innovations'12) March 18-20, 2012, Al Ain UAE.
4. M. Albano, Muhammad Alam, A. Radwan, J. Rodriguez, "Context aware node discovery for facilitating short-range cooperation, Proc. of the 26th WWRF Meeting, Qatar, Doha, 11th-13th April 2011.
5. Muhammad Alam, M. Albano, A. Radwan, J. Rodriguez, "Context parameter prediction to prolong Mobile Terminal battery life, Proc. of the 1st International Workshop on Cognitive Radio and Cooperative Strategies for Power Saving, 6th International Mobile Multimedia Communications Conference (MOBIMEDIA 2010), Lisbon, Portugal, September 6-8, 2010.

1.6 Organization of the Dissertation

The PhD dissertation is organized as follows:

Chapter 2: Literature survey and Proposed Context Based Architecture. The main objective of this chapter is to provide the motivation behind this dissertation. The chapter begins with state-of-the art on node discovery, cooperative communication and radio resource management from an energy-efficient perspective. Besides presenting a comprehensive survey, we also highlighted the main challenges and major short comings of the existing work on these topics. The presented survey gives an in-depth knowledge and provides the motivation to exploit the benefits offered by promising technologies such as context aware and cooperative techniques for the purpose of energy saving.

Chapter 3: Context Based Architecture for Energy Saving
In this chapter, we discuss the different types of context information related to wireless communication and categorize it into mobile terminal and network related context. Furthermore, we provide a context based architecture for energy saving which can identify and manage context information for energy saving approaches. The proposed architecture provides the platform for exploiting our context based approaches pertaining to node discovery, cooperation and radio resource management for energy saving.

Chapter 4: Context-aware Node Discovery for Short Range Cooperation
In this chapter, we detail the latest innovations on lightweight node discovery mechanisms for WPANSs. In the first instance, we identify the benchmark performance; in that nodes can either be connected to a cluster or a solitary node, where knowledge of the neighboring devices are required to choose a suitable node for cooperation. This currently requires exhaustive

search approaches resulting in the radio interface being always "ON". We advance this by proposing new energy efficient discovery mechanisms that are essential for latching onto the benefits of cooperative mechanism. We present a context based beaconing mechanism both for node discovery and cooperative cluster formation. We exploit the available beacon Information Elements (IEs) of UWB propose a new Context Extraction Function (CxEF). The chapter is concluded by analytical and simulation results.

Chapter 5: Demonstration of Context and Short-range Cooperation for Energy Saving.
This chapter presents the analysis of energy consumption of heterogeneous cooperative communications based on context information. The presented results are achieved by implementing context and cooperation on a testbed platform using intelligent and programmable nodes. The demonstrative testbed comprises a WiFi Access Point, which provides WiFi coverage in the infrastructure mode, as well as nodes capable of communicating through short-range Ultra-Wideband (UWB) WiMedia. The testbed includes a context aware module that provides and stores information related to different nodes in the system. The chapter shows how context information can be used to save energy of mobile devices and extend their battery lifetime using short-range communications. The testbed is used as a proof-of-concept for the practical implementation of the proposed concept.

Chapter 6: Context Aware Resource Allocation for Energy Saving in LTE-A.
In this chapter, we are utilizing context information in the scheduling process as traditional packet scheduling algorithms are mainly designed for increasing spectral efficiency (SE) and do not consider energy saving. We propose an inter-layer design approach, to what we refer to as Context Aware Scheduling (CAS). An information model for context awareness along with a context aware framework for resource management is presented. CAS is simulated via a system level simulator and the results obtained shows that considerable amount of energy is saved by utilizing context information compared to conventional scheduling approaches.

Chapter 7: Conclusions and Future work.
This chapter provides the summary of the overall thesis and the main goals achieved.

Chapter 2

Literature survey

The main objective of this chapter is to provide the ambition for the proposed approaches in this dissertation. The chapter presents state-of-the art on node discovery, cooperative communication,radio resource management, and context aware systems with emphases on their shortcoming towards energy saving.

2.1 State of the Art

2.1.1 Node Discovery

Node discovery is a research topic that has been widely investigated, but most current results apply only to Personal Area Networks (PANs). Initially all the nodes are unaware of each other's presence, so node discovery is the initial state for joining and building an ad-hoc network. Given node mobility in PAN and the dynamics of the applications [15], nodes will join or leave the network during application's lifetime, and radio links will be greatly affected. To cope with this dynamicity, the network should be able to quickly reconfigure itself without the user's intervention. Thus, the mechanisms for the discovery of neighbors, the creation of connections, the scheduling of transmissions and the formation and re-configuration of the network topology should be seamless and energy efficient.
The simplest procedure for node discovery can be initiated by broadcasting a message and waiting for the neighbors response. The node discovery process seems to be simple, but in reality, considering different discovery criteria and requirements, is a complex problem. The node discovery protocols can be divided into asymmetric and symmetric protocols. Standard Bluetooth employs asymmetric protocols for node discovery. In asymmetric protocols the slave devices synchronize their clocks to the master, following the discovery protocol: nodes enter either the Inquiry or the InquiryScan state and finally perform the paging process. In

Bluetooth asymmetric protocols all the nodes have pre-assigned roles, which decide which nodes will discover other nodes and which nodes, will be waiting to be discovered. The other option for discovery are the symmetric protocols, in which the node can be both discovering nodes and waiting to be discovered. Each node will compete for the access to the communication channel. As the nodes are not aware of the presence of each other, there is a greater chance of collision. This collision can be direct (two nodes transmit to each other at the same time) or Secondary (nodes are unaware of each other and transmit at the same time) [16]. Frequency hopping as used in Bluetooth and randomized back off protocols [17] for single broadcast channel as implemented in wired networks are used to deal with the problem of collision.

Probabilistic symmetric protocols for node discovery have been proposed in [18] [19] [20], to cope with the collision problems related to symmetric approaches. In [20], with a probability of p, a node sends packets to discover other nodes and with $1 - p$ listens to the wireless medium to be discovered by other nodes. A node gives up hearing other nodes if it does not discover other nodes in a specified time period. In [18] the authors proposed several probabilistic node discovery protocols. A node can be in one of two states: talking (T) or listening (L). The state of each node is determined by the node discovery protocol run at that node. In the Random Protocol (RP in this section) each node decides at random whether to talk or to listen, and tries to minimize collisions by forcing nodes to switch from talking to listening with certain probability. Other proposed protocols are the Answering Protocol (AP), in which a node will immediately answer if it receives a message from another node, and Listen after talking protocol , in which the node shifts to the listen mode after sending a message. Conditional Protocol (CP), which is the combination of AP and LP, and Sleep Protocol (SP), which is used to save energy and avoid collisions, are two other protocols that are proposed by the authors. These protocols are suitable for a limited number of nodes and also they lack adaptability, and their behaviour is static. A family of probabilistic protocols called Birthday protocols for neighbours discovery in static ad hoc networks for energy saving has been proposed in [19]. A node can be in transmit, listen or energy saving state. During the transmission state a node is broadcasting a discovery message, listens for a message in the listening state and remains idle consuming zero energy in the energy saving state.

Node and neighbour discovery is also performed by the Hello protocol, which is more suitable for neighbour discovery in ad-hoc networks [21]. Each node builds a neighbourhood tables through the periodic exchange of Hello messages and nodes can also exchange their position. The parameters like Hello packet period, its transmission power, activity/inactivity (duty) period duration and energy consideration have a big impact on the performance of the protocol and of the discovery process.

A Polling-based MAC called PMAC protocol is proposed in [22], and it addresses the problem of neighbour discovery with directional antennas. PMAC exclusively uses directional antennas for the transmission and reception of all the frames. PMAC facilitates the discovery of one-hop neighbours and it uses polling for the maintenance of links to the discovered neighbours until they move outside the possible radial range of the node's antenna. At the scheduled time, the transmitter and the receiver nodes point their antenna beams towards each other and carry out the communication. An analytical study supported by simulations shows the efficiency of the protocol in term of capacity enhancement in the context of mobile ad hoc networks. Also the work described in [21] uses two types of protocols , the Direct-Discovery algorithm in which the node is discovered by receiving the hello message, and the Gossip-Based algorithm in which the node broadcasts information about its neighbourhood when it receives a hello message. Analytical and simulation results show the efficiency of the Gossip-Based algorithm in terms of delay.

Most of the approaches discussed do not consider the energy saving during the node discovery process and suffer from a number of shortcomings. The energy aware Hello protocol studied in [23] typically requires some form of reliable broadcast system which makes them very expensive in terms of energy consumption, because some nodes have to perform unnecessary broadcasting, or to wait for a long time in the listening state. Considering the distributed approaches to node discovery, and in particular to SDD, it must be noticed that it introduced good features in the discovery process. On the other hand, the signal acquisition time of the physical layer impact the performance parameters of the SDD protocol, which are the discovery time, the node join-time, the node leave-time and the data transmission time. Information like the current link used for routing and the service data unit that needs to be forwarded are sent from the link layer to the network layer. The SDD-based approaches suffer from the long time that the node has to spend while performing discovery time, the node join-time, the node leave-time and the data transmission time. In general, having a special channel, based on long-distance communication technologies to exchange context information can enhance the node discovery efficiency. The communication channel is more expensive than short-range communication and the resulting power consumption can be higher, but the shorter time needed to perform the node discovery can result in lower energy consumption, hence contributing to the energy saving capabilities of the system.

2.1.2 Cooperative Communication

Cooperative communication depends on relay based communication in order to boost the performance of the transmission. Each node transmits its own data, while it can also act as a cooperative agent (relay) to transmit other node's data. A simple cooperative communication system consists of a source, a relay and a destination node. The source node broadcasts the message to the relay nodes, which will process and forward the received message to the destination. The destination node receives messages from both the source and the relay and consequently enhances the signal to noise ratio (SNR), resulting in an improved performance [24, 25, 26]. Cooperative communication evolved in several different flavors e.g. Decode and forward (DF) [27], Amplify-and-forward (AF) [28], coded cooperation method [29] and a number of variations of these relaying protocols. In the AF (also called scale and forward) method, the relay node amplifies the received signal from the source node and forwards it to the destination node. There is no decoding involved in the AF method by the relay node. On the other hand, in the DF method, the relay decodes and detects bits from the source, and then retransmits these bits to the destination. Another method is coded cooperation which integrates cooperation into the channel coding [26]. In coded cooperation, the source and relay nodes use different codes for conveying messages. Adopting such a method increases the complexity, but can obtain higher diversity gain. Single or multiple relays can be used in cooperative communication. In single relay cooperation, the source has only one option to relay its information to the desired destination as considered in [30],[31]. In multiple relays cooperation [32], each source has more than one relay available as options to forward its data to the destination. In the case of a decentralized network, the source node selects the relay node while in a centralized network the central entity (node or base station) can help the source node to choose the relay. In single RAT (Radio Access Technology) cooperation both source and relay node use the same technology which is widely used in ad-hoc wireless networks. On the other hand, in multiple technology cooperation, the source node can send the information via one technology, while the relay node uses a different technology to forward the information to destination.

An interesting and challenging direction of the cooperative communication is the use of devices carrying multiple interfaces which forms the heterogeneous networks. In fact, very few works in the literature have addressed context based heterogeneous cooperation using short range technologies in combination with medium or long range. Most of the existing work either followed the simple relay based cooperation using standard relaying techniques or the cooperation based on hybrid relaying concept, where MT adaptively changes its relaying techniques e.g. AF/DF etc. For instance, in [33] the work is based on a combination of different cooperation selection technique: decode-forward (DF) and amplify-forward (AF), non-orthogonal amplify-forward and dynamic decode-forward and non-orthogonal amplify-forward and compress-forward. Similarly, the work presented in [34, 35, 36, 37, 38, 39, 40, 41] are based on adaptive relaying techniques or using a combination of the relaying protocols without considering multiple interfaces. For instance, in [41] the proposed protocol adaptively

determine the transmission mode according to channel conditions by considering single technology and analytical results. In the context of cooperative heterogeneous wireless networks, a work is presented in [42] but limited to only call blocking/dropping probabilities. A game theoretical method is proposed in [43] to model packet forwarding in relay networks. Similarly, in [44] a model of cooperation in ad hoc networks, based on evolutionary game theory is presented, but again, only analytical results are provided.
On the other hand, some recent works have considered heterogeneous cooperative communications. For instance, in [45] the authors have investigated the use of multiple radio access technologies (RATs) to improve the energy efficiency in cooperative networks. Similarly, efficient resource utilization and spectral efficiency optimization in heterogeneous cooperative networks has been investigated in [46],[47]. Although the above mentioned works do consider multiple technologies for cooperation, but the results are either analytically proven or based on simulations. A detailed survey covering the classification and various possible types of cooperative communications with its pros and cons is presented in [48]. Based on its application to wireless communication, cooperative communication is not only used for improved throughput and coverage, but also widely considered for energy savings of mobile terminal and overall network. In [49], it has been shown that cooperative communication contributes considerably to an extended battery life time. In fact, in cooperative wireless communication, the path to the BS or destination node is divided into shorter links which results in lower transmission power and contributes to energy savings of the network [50],[51]. Similarly, energy efficient relay selection protocols for cooperative communications are reported in [52, 53, 54, 55].

2.1.3 Resource Management

The energy efficiency of a system, defined as the amount of information bits per unit energy (b/J) is often used as a figure of merit. The energy efficiency determines the required amount of energy to meet the service requirements such as spectral efficiency, fairness, etc. Energy efficiency is not only a topic that is driving future research trends, but has been given significant attention in the design of LTE-A, which is expected to provide 1 Gbps in downlink. The question arises on how to transmit more data whilst the power remains constant and consumes less energy.Ideally, we need to find an approach that will try to adapt a dirty channel that constitutes multipath interference, fast fading, multi-user interference, and other sources of noise pollution into an Additive White Gaussian Noise (AWGN) channel, whilst maintaining the power consumption. The ideal way to increase capacity along with energy efficiency is by minimizing the transmission distance between the transmitter and receiver antenna, which create the dual benefits of higher quality link and more spatial reuse. This is the idea behind the small cell paradigm i.e. ultra-dense networks, which is now seen as a way forward for enhancing capacity in future networks e.g. Beyond 4G, 5G. An alternative way to reduce energy deals with interference management that controls which users are scheduled for transmission. An approach used in LTE-A is known as coordinated multipoint transmission, that increases the energy efficiency by centralizing and coordinating the transmission between a cluster of cells to mitigate interference. Furthermore, current research trends point towards the concept of low power nodes coupled with high power macro base stations to construct so called ultra-dense network to obtain further gains in coverage and capacity. Due to their short transmit-receive distance, home base stations can greatly lower transmit power and achieve a higher SINR. This translates into improved reception and higher capacity, leading to an enhanced spectrum and energy efficiency.

Another aspect of optimizing service and system performance of interference management relates to Radio Resource Management (RRM) and scheduling. The notion of RRM is concerned with overseeing the distribution of radio resources to different users, or different classes of users, and attempts to strike a balance by catering for user requirements while achieving profitability for the network operator. Given the scarcity of radio resources, RRM frameworks are designed to maximize the number of services in a cost-effective manner, but new challenges lie in how these can be extended to provide better interference management and energy efficiency. Different functionalities take part in RRM frameworks: for instance, admission control judges whether or not a call can be admitted into the network; scheduling addresses the priority assigned to each user based on satisfying some objective functions; and provisioning attempts to recognize demand patterns in the network such as long-term resource distribution satisfying the operator's objectives. All of these can be further extended towards higher QoS, energy efficiency and fairness.

In terms of scheduling, this function assigns the resource allocation priority to each user according to a predetermined criteria. There are typically three main scheduling policies: Round Robin (RR), Maximum Carrier to Interference ratio (Max C/I) and Proportional Fair (PF). RR allocates equal resources to all users, regardless of their current channel condition. On the other hand, Max C/I scheduling aims at maximizing the total cell throughput by considering CQI values fed back to eNB from the UEs. This leads to unfairness, as users that are further away from eNB (or have bad channel conditions) will not be allocated a fair share of the radio resources. The PF algorithm, [56], tries to provide fairness by increasing the priority of a mobile user who has a relatively low value of the C/I ratio. Several variations of the Proportional Fair scheduler, including a channel adaptive version, have been investigated in [57].

When the mobile devices are powered on unnecessarily for an extended period of time they consume useful battery which is considered one of the main reasons for energy consumption in both infrastructure and ad hoc networks. This problem is tackled by the introduction of proper sleep or idle modes of the mobile devices which is reported in [58],[59]. Therefore, to take advantage of the sleep or idle modes for energy saving, 3GPP [60] has standardized discontinuous Transmission (DTX) and Discontinuous Reception (DRX). Similarly, in [61] the study presented evaluates several different parameter settings for LTE's DRX, and attempts to discover a reasonable trade-off between VoIP performance and terminal battery life. But these mechanisms only contribute to energy saving only by extending the UE sleep time while ignoring the consideration of context information in the scheduling process. For instance, to guarantee the QoS for real-time flows and also to minimize energy consumption of mobile devices a work is presented in [62]. The scheduling problem is formulated as an integer linear program to minimize the total number of active frames to save energy consumption. The presented work adopts the scheduling process to contribute only to the mobile terminal's sleep time thus ignoring the context information e.g. battery remaining for application in use etc. A detail survey is presented on opportunistic scheduling in [63]. Opportunistic scheduling is considered to take advantage of the available information such as the channel quality and other QoS parameters (i.e., throughput, delay, and jitter) that consents the scheduler to the proper transmission resources for user [63]. An opportunistic scheduling mechanism in [64] aim to minimize the overall transmission power. Energy effcient and low complexity scheduling mechanisms for UL cognitive cellular networks has been presented in [65], with a comparison of round robin and opportunistic scheduling for energy efficiency. It has been proven that round robin is more energy efficient than opportunistic scheduling while providing the same QoS. Furthermore, existing schedulers mostly rely on either single parameter e.g. channel quality, throughput etc.[66][67][68], or a combination of more than one parameters, e.g. traffic type, channel quality or QoS metrics (jitter, delay) etc. But still these works are limited and do not go beyond the existing state of art work for terminal's context consideration in scheduling process.

2.1.4 Context Aware systems

The term context appeared for the first time in [69] where the context is introduced as location, identities of nearby people, objects and changes to those objects [70]. This representation of context was widely applied and used in early research. Active Badge Location System which is considered the first context based application was introduced in [71]. It was an infra-red technology based system and was able to find the location of users and to forward phone calls to a telephone close to the active user. In the mid 90's location-aware applications were introduced and considered exploiting context information; such works can be found in [72], [73], [74]. Beside the location information, context has been widely categorized and used in the last decade.

One popular way to carry out classification is based on the context dimensions. The authors in [75] and [76] classified it as external and internal context while the work presented in [77] classified context as physical and logical context. The external context dimension, in this work, refers to context measurable by hardware e.g. light, sound, mobility etc., while the internal dimension is referred as users interaction with the system or inferred from the user's monitoring activities, i.e. work context, tasks, user behavioural activities etc. This kind of context is also referred as logical context. According to [78], most of the existing context aware systems apply physical context information. The example of the logical context information using systems are Watson Project [79] and IntelliZap Project [80] which provide information by extracting knowledge from the users behaviours e.g. content read out of opened web pages, documents, etc.

Context aware systems use context management which deals with:

- Context sensing as a tool to obtain context information from external and internal resources;
- Context discovery as a mechanism to find and access relevant context sources;
- Context filtering for further use in different modules of the systems;
- Context dissemination for efficiently propagating the context to ensure availability and re-usability.

The context sensing or acquisition is important in the design of context management architecture. The context acquisition depends on the purpose of the context aware system and specifies the sources from which the context has to be collected. The following three different approaches have been used by Chen in [81] to acquire context:

- **Direct sensor access:** In this approach, the devices directly sense or collect the desired information from sensors or sources. The target devices can be sensor, smart phones, PDAs, laptops etc.
- **Middleware infrastructure:** In this approach, the software design uses techniques of encapsulation to separate business logic and graphical user interfaces. The middleware based approaches work on a layered architecture to hide low-level sensing details.

- **Context server:** This approach permits multiple clients access to remote context data sources. Once the data is collected from primary sources, it is then stored on single or multiple servers to facilitate concurrent multiple access.

Furthermore, three basic context management models are presented in [82] which are: Widgets, networked service, and blackboard model. Widgets are derived from GUI elements and provide a public interface for a hardware sensor [83]. The networked service models resemble the context server architecture and provide more flexibility. The blackboard model represents a data centric view and by means of asynchronous communication shared media is posted to the blackboard.

The context information needs to be represented and modelled to easily manipulate and to reduce the overhead of adding new types of information. The context information representation models can be classified into six different categories, namely Key-value models, markup scheme models, graphical models, object oriented models, logic based models and ontology based models [84]. Key-value pairs form a simple tuple of information and are assigned a unique key in order to allow easy lookup by applying a matching algorithm. Markup scheme models incorporate a hierarchical data structure of markup tags, attributes and content. Graphical models which are based on the Unified Modelling Language (UML) are mainly used for a picturesque description of a context model [85]. Most commonly used and powerful models are Object oriented and offer capabilities of inheritance, reusability and encapsulation. Access of contextual information is provided by well-defined interfaces [86][87]. Logic based models typically comprise facts, expressions and rules. The information is inferred by means of general probability, description, functional or first-order predicate logic. Ontological modelling intends to capture an abstract conceptual vision of the world and the relations between the entities could also be described by object oriented methods. Due to its unambiguousness performance ontology based models are considered best [88][89][90], but the querying process becomes slow in resource constraint mobile devices.

Exploiting context-aware systems and obtaining the desired goals depends on the user's requirements and special conditions that can allow these systems to work. For instance, in the deployment of network, the conditions can be local or remote and include the number of users, the available resource, the type of devices (mobile, stationary etc.) and capabilities of devices participating to form the network etc. The context aware system exploits these available information types and feeds systems which can provide benefits to all the devices which are part of the group. For this reason, the context information management systems require the design of multiple layered conceptual structures which can exploit and make use of the available information. Multiple layered conceptual architecture that exploits context information by using context interpreting and reasoning functionalities has been presented in

[91] and [92].
A middleware based system called Service-Oriented Context-Aware Middleware (SOCAM) has been introduced in [93]. SCOAM uses centralized servers which collect the context information from distributed context providers. SCOAM was mainly used as extensible centralized middleware architecture for building rapid prototyping of context-aware mobile services. A peer-to-peer architecture named Context Toolkit is presented in [94]. Although the Context Toolkit is a peer-to-peer framework, but it still needs a centralized discovery module where distributed sensor units, interpreters and aggregators are registered in order to be found by client applications. Another example of context aware system is CORTEX based on the Sentient Object Model [95] and designed for the development of context-aware applications in an ad-hoc mobile environment.
From the above literature review it is evident that there is sufficient work in the field of context aware systems, but most of these systems have still not stepped out of the laboratory into the real world. Furthermore, there are very few projects specifically focusing on exploiting the context information for energy saving of mobile devices or overall network systems. With the large scale availability of multi-slandered mobile devices, it is much demanding now to harness the benefits offered by the context awareness especially for energy saving.

2.2 Conclusions

This chapter presents the state of the art on node discovery, cooperative communication, radio resource management and context based systems. There are ample examples for node discovery mechanisms available in the literature, however asymmetric protocols can suffer from excessive scanning while asymmetric protocols have greater probability of collision as the nodes are not aware of their neighbours. In addition, legacy wireless nodes typically have energy efficient modes of operation, but little attention has be directed towards how these features can be exploited appropriately. Furthermore, the SOA study on cooperative communications and radio resource management have been presented and the major shortcomings have been identified providing the baseline for our work. For heterogeneous cooperative networks, we first introduced the basic concepts and then related works that focuses on systems that maximize the efficiency of wireless network in terms of throughput and energy savings but do not consider context information. Furthermore, State of the art work on conventional scheduling depicts that RR schedules each MT equally but do not considers parameters such as channel condition, Max C/I can maximize throughput but can lead to unfairness while PF tries to provide a more balanced solution. Although conventional scheduling algorithms are most commonly used but do not exploit context information. In the last part, a detailed literature study was presented on context aware systems. A number of previous works have shown how the context is sensed, modeled and harvested for different applications. However, few works have tackled context-aware systems for energy saving applications.

Chapter 3

Context Based Architecture for Energy Saving

This chapter discusses the different types of context information related to wireless communication and its categorization. Moreover, we provide a new context based architecture for mobile terminals and network which we proposed in C2POWER project [96], and will be utilized throughout this thesis as a platform for providing source context for the proposed node discovery in chapter 4 and for energy aware scheduling in chapter 6. In addition, the context framework in synergy with cooperation will be demonstrated in chapter 5.

3.1 Context Parameters Structure

This section describes the structure of the context information that is considered by our context-enabled MT and Network for enabling energy saving mode to support future emerging applications. The context information used has been broadly categorized as Network context, and MT context.

3.1.1 Network context

There are four categories of network context information that are taken into account by the context management system as depicted in the figure 3.1 .

- **Security**: defines the security level of the network access, that is fundamental to the user to decide whether he is interested into accessing the RAT; moreover this set contains the type of security mechanism the network is using. Security context is set by

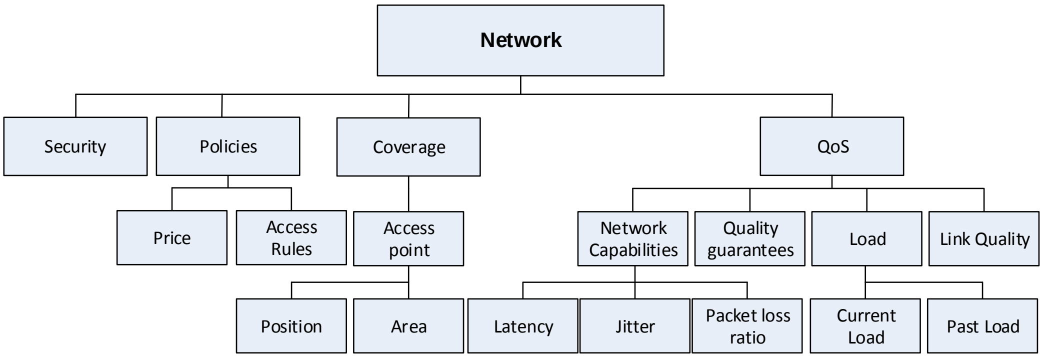

Figure 3.1: Context structure for the contexts owned by the network.

the network operators when the network is deployed.

- **Policies**: Another context information, which is set by operators and rarely modified, belongs to the policies category. It depends mainly on agreements between the end-user and the access provider, and on agreements between different operators. This context information is about the access rules regarding a given network for a user registered with another provider, and the **price** charged for accessing the network. The information gathered can be utilized in the business model or in price based preferences.

- **Coverage**: The category of coverage comprises more elements that are usually static, and it provides the information about the coverage of the network and the coexistence of different networks. In particular, this data contains **access point** parameters, which are used to infer the different networks covering certain locations.

- **QoS**: Both static and dynamic data exist in the QoS context category, that describes the maximum and current capabilities of the network. Static aspects regarding QoS are related to the maximum **network capabilities**, like for example the latency and bandwidth related to the technology for internet access, and the quality guarantees that the network can provide by using resource reservation protocols. The QoS that can be provided at a given time depends mostly on the current **load** of the base station. Hence the context module maintains both current load and load history. Using the logs about past load, the context module can perform some level of load estimation for the time the MT wants to be relayed. Another dynamic information used to evaluate the QoS provided by the network is the **link quality** of the connection between the MT and the

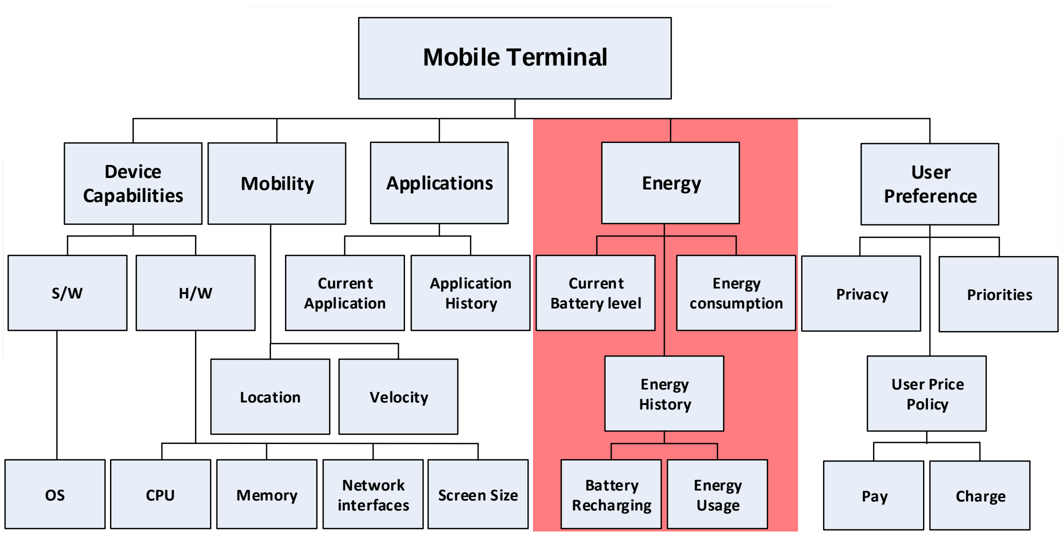

Figure 3.2: Context structure for the contexts regarding the Mobile Terminal.

network, that can be expressed by RSS, CIR, SIR, BER, etc.

3.1.2 Mobile Terminal Context

Five categories of MT context information have been identified as shown in figure 3.2 and elaborated as follows.

- **Device Capabilities**: Context information about **device capabilities** is composed of data describing the device itself, comprising both **hardware** and **software** (CPU, operating system, memory, display capabilities), with a particular focus on the network interfaces. These data are usually constant over time.

- **Mobility**: Most of the other context information change over time e.g. Mobility context provides information about the current location of the MT and its **velocity** (comprising speed and direction of mobility). This information is used to predict future location of MTs, and can be used to determine if short-range cooperation can be useful for energy saving. Moreover, a network can also use this context information about MT mobility to predict its own load, based on MT going in and out of its coverage.

- **Application**: The application category contains information about applications currently in use by the MT, which determine the QoS requirements. Moreover, a log of application history is maintained, to profile the common use of the MT, and predict the behavior of the user on short term basis.

- **Energy**: It can be seen in figure 3.2, a pivotal context category in our design is the energy component. The energy category comprises the current battery level, the rate of **energy consumption**, and **energy history** of the terminal. Energy history provides quantitative data on energy usage at different times of the day and the frequency of battery recharging. The energy information is used to predict the user needs for energy consumption on the short and medium term.

- **User preferences**: The last category of context information related to MT's context is user preferences, which are a set of parameters that are defined by the user, to specify what the user wants or expects from its interaction with the system. The user can set his **priorities** to be energy saving, price minimization or performance maximization. These user preferences can be a complex structure that bears data for different scenarios. For example, even for a user mainly concerned with energy saving, his priorities can be considered to be temporarily shifted to "performance maximization" if the user is executing an emergency call. Another issue considered in user preferences is the **privacy** that is desired by the user. In fact, some parts of the context information are used to profile the way the MT is used, to be able to predict the future needs of the user, and this implies logging data about user behavior. Hence there is a trade-off between user's privacy and the prediction capabilities of the system, that would not be able to function at full power without collecting data about the user behavior. Finally, the user can select a different profile for the **user price policies**, to decide how much the user is willing to *Pay* during energy saving collaboration, and how much money/privileges the user will *Charge* to relay other MTs' traffic. This information sets two profile functions, since the quantity of money the user is willing to pay or wants to receive depends on how much the user values its own energy, which depends on the current energy level and the prediction of the user behavior regarding future usage and battery recharging in the short term.

3.2 Context Based Architecture for Energy Saving

In order to enable full application of the proposed approaches e.g. context based node discovery, cooperation and radio resource management for energy saving, a completely new approach towards the functional architecture has been proposed. In a heterogeneous environment, the MT manages different types of RATs requiring different sets of context information

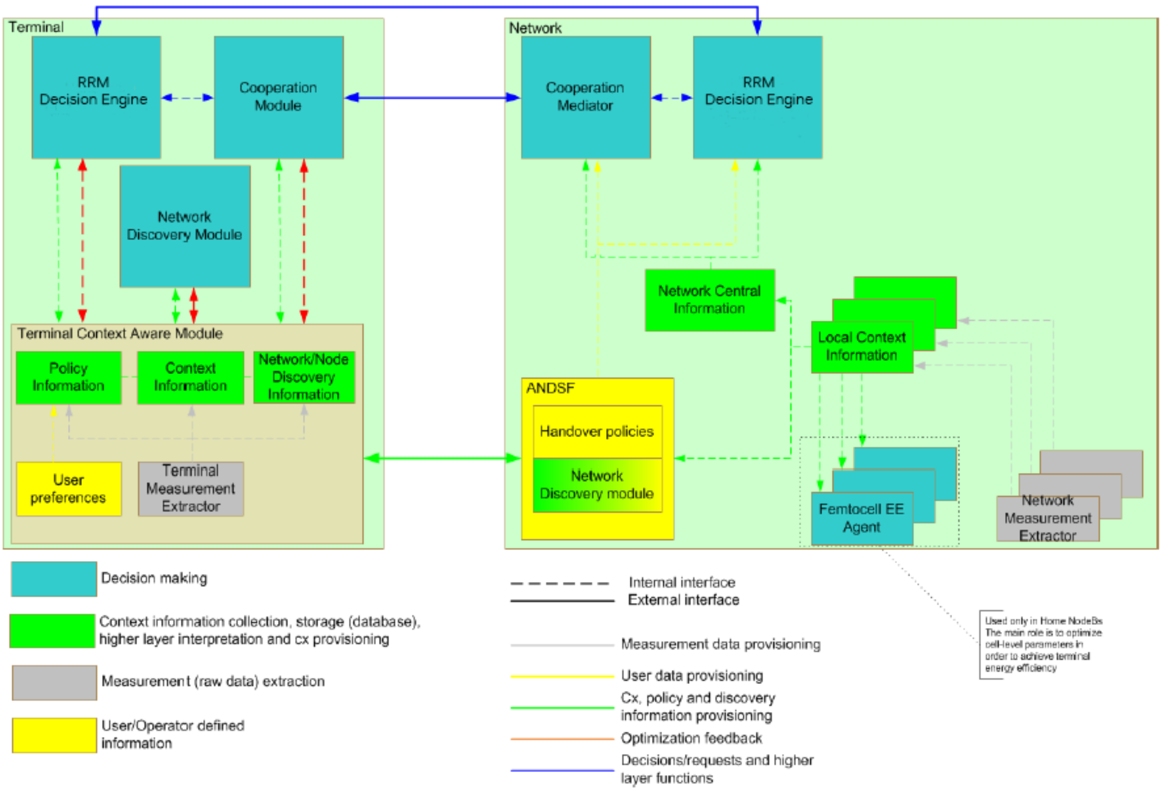

Figure 3.3: Context Based Architecture for Energy Saving.

depending on the technology in use. MTs in legacy systems are typically connected to the same RAT all the time, and always require the same set of context information. Therefore context enabled MTs can access different RAT, requiring the introduction of context elements that permit access to context information from multiple sources which operate on different standards. Due to the different sets of context information, the proposed architecture need to provide the quick delivery of context information and the components need as important design requirements to access all the required context information. The context based architecture is shown in figure 3.3.

3.2.1 Context Based Mobile Terminal Architecture

The above presented context management architecture is implemented to achieve the goal of energy efficiency by using context and cooperative strategies. The context based mobile terminal architecture is shown by figure 3.4. The global function is the Terminal Context Aware Module (TCAM), that obtains and provides information from and to the access network and other cooperative MTs in the vicinity. TCAM is at the core of the terminal context architec-

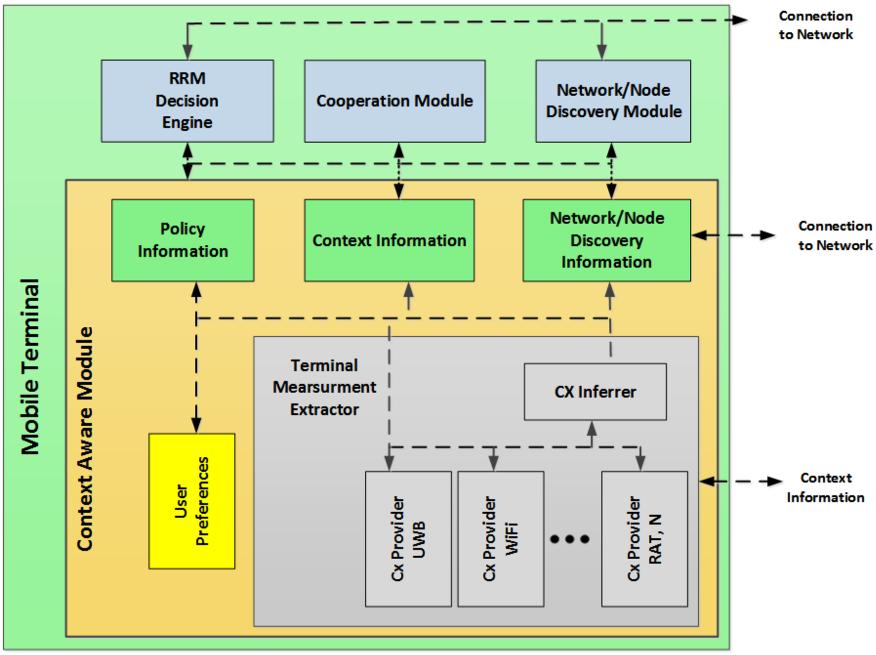

Figure 3.4: Context Based Mobile Terminal Architecture

ture functionalities, supporting the implementation of energy efficiency policies in partaking terminals. TCAM hosts all those functions that are required to collect and organize information fragments and then to derive (infer) and understand the context in which a terminal operates. The information collected from multiple interfaces in TCAM is further provided to different modules, thus making the algorithms working in a technology agnostic way. Within the TCAM, a number of functions are needed to provide all the features and tasks that are required to provide context information to the various surrounding modules.The individual tasks or sub-modules in the TCAM include three mechanisms that collect and refine context information fragments (i.e. Policy Information, Network/Node Discovery Information and Context information sub-module) and two functions that provide basic information about the user (i.e. User Preferences) and the terminal state (i.e. Terminal Measurement Extractor). The sub-modules include:

- **Context Information (CI)**: The context information sub-module collects information about the terminals operational state (e.g. RSSI, used bandwidth, CSI), as well as information are extracted and refined by the Policy Information, Network/Node Discovery Information sub-modules. The CI sub-module uses these information to infer higher layer context descriptions, that are then stored in its own (inherent) database or is provided to the different context consumers (ANDM, HDE, NDM, CM). Examples of the information inferred by the CI include battery consumption rate, future terminal

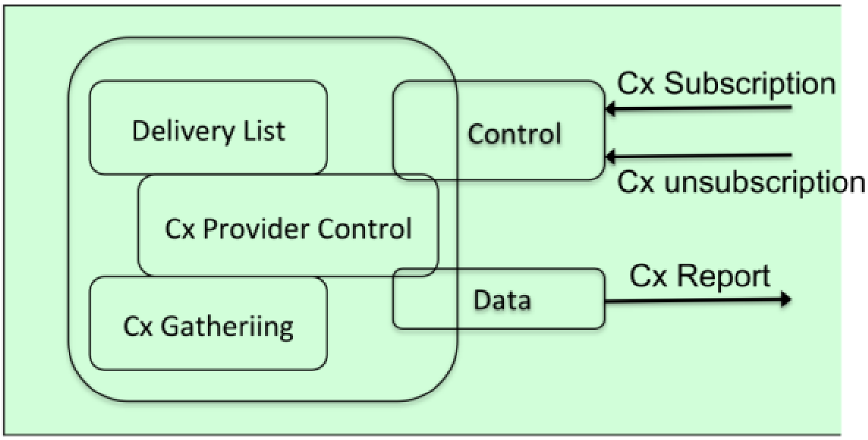

Figure 3.5: Cx Provider

location, power needed for transmission or cost of current air interface/access system usage.

- **Policy Information (PI)**: The policy information module interprets any information that is related to user settings and usage and uses information/context inferred by the CI to build a set of policies (such as handover or power management policies) that are stored and maintained in a database within the system. Policies limit the range of possible decisions that can be made specifically related to cooperation, network/node and radio resource management.

- **User Preferences (UP)**: User preferences are brought together and derived from usage patterns, and by collecting user defined information (or settings) regarding the preferred networks or information about restricted networks, the range of technologies or strategies that are allowed to be implemented (e.g. cost saving over battery saving), etc.

- **Network/Node Discovery Information (NDI)**: The network/node discovery information module collects and refines information about the networks (or) nodes in the target terminals (nodes) neighborhood that can be used as access points or relays. The context or node discovery information is derived from data provided by TME and/or is pulled/pushed from the network via the ANDSF. Depending on the scenario, the information of this module may be obtained in different ways; in cooperative scenarios, it can also be collected from other nodes. If there are clusters of nodes in the scenario, the cluster member lists describing nodes in the vicinity are updated. Information in the NDI module can be shared with other terminals that belong to the same cluster.

Within the TCAM, we have the Terminal Measurement Extractor (TME), that measures and collects raw data and operation parameters of the actual terminal. These parameters may be obtained directly from within the terminal, or indirectly via sensors collecting information on the radio environment. Terminal information (raw data) may describe battery power level, processing power requirements, inter-RAT (Radio Access Technology) cell list, RSS, etc. The measurement extractor determines how spectrum scanning should be performed and it considers the scanning strategies determined by the Network/Node Discovery Module (including frequency bands to be monitored, access networks that are restricted, duration of the listening/scanning period, etc.). Terminal Measurement Extractor has two elements, the Cx Providers and the Cx Inferrer.

- **Cx Providers:** The Cx provider is the source of the raw Cx information which is obtained directly from sensors or radio interfaces. Cx provider functional model is presented in 3.5 which has two interfaces and three functional blocks.
  The two interfaces are:

  - **Control Interface** is responsible for exchange of the subscription and unsubscription instructions from the Cx elements that require Cx information. When subscribing, the Cx element identifies the required Cx information and the Cx subscription profile. The Cx subscription profile specifies the required Cx information, the frequency of reporting, and other parameters that may be required to configure the Cx Provider. The Cx element has to unsubscribe, when the Cx information is not required anymore.
  - **Data Interface** is used for the return of the Cx reports with the required Cx Information. Based on the subscription profile, the Cx provider reports the Cx Information either periodically, one-time, or based on a trigger (which can be a certain threshold).
    The Cx provider has three functional components:
  - **Delivery List** stores the subscription profiles of Cx elements, which include the required Cx information, the Cx report address and the frequency of Cx reply.
  - **Cx Provider Control** manages the whole operation of the Cx provider. It determines, based on the information in the delivery list, when it is necessary to turn on/off sensors or radio interfaces.
  - **Cx Gathering** is the functional block of the sensor itself. Based on the instructions from Cx Provider Control, the Cx Gathering will operate to generate the requested Cx information. The Cx Gathering component encapsulates all the

functions required to produce the Cx information, by sensing or measuring certain values.

Depending on the Cx information, the Cx Provider will supply the group of Cx Inf associated to interfaces as shown in table 3.1.

Table 3.1: Examples of Cx Providers

Cx Provider	Description	Context information
Long Rang Cx Provider	This Cx Provider interacts with the long range technologies e.g. LTE, WiMAX etc. interfaces to supply the associated Cx information.	LTE/WiMAX SNR, Cell ID, Track Area, MaxTxP etc.
Short Rang Cx Provider	This Cx Provider interacts with the short range technologies e.g. UWB, Bluetooth etc. interfaces to supply the associated Cx information.	UWB/Bluetooth Neighbors list,battery levels, Willingness to cooperate etc.
GPS Cx Provider	This Cx Provider returns the geolocation of the MT.	Position.

- **Cx Inferrer:** The Cx Inferrer, shown in figure 3.6, is the element in the architecture that adopts the role of the Cx Manager in the Information model. The entity collects pieces of information, aggregates them and computes higher level Cx information. The higher level Cx information can be extracted from one or multiple Cx providers by using pattern recognition, processing of past data, or using other techniques to have a better view of the state of the UE.
  The Cx Inferrer constitutes two stages. In the first stage, red background in figure 3.6, the Inferrer subscribes Cx information from multiple Cx Providers. In the second stage, green background in figure 3.6, the gathered Cx information is used as input for the higher level Cx information computation. With the computation of the higher level Cx information, the Cx Inferrer will wait for subscriptions to the Cx information from the devices. Two examples of Cx Inferrers are:
  Battery level Prediction: The MT saves a log of the battery level over time. The battery level prediction over short time is an extrapolation of the current trend, based on the last measurements (between 2 and 10). The prediction is used to determine if the MT needs to apply energy saving technique to function for the length of current applications. The long term prediction is based on the mean trend over longer periods of time (a number of days). The battery level prediction is used to assess if the MT is

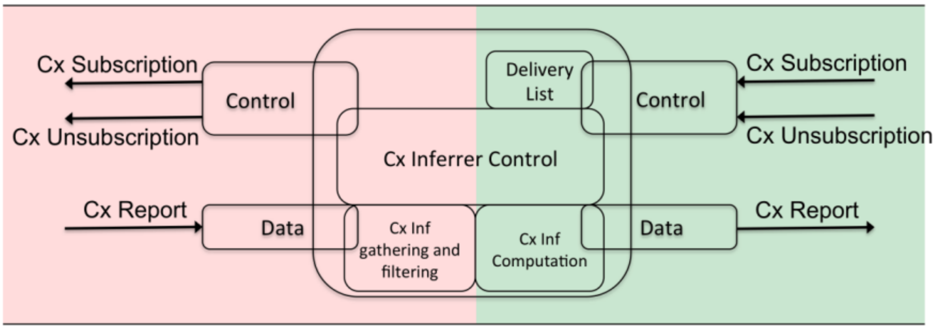

Figure 3.6: Cx Inferrer

a candidate to offer cooperative relaying to other MTs.
Positioning: Real-time positioning information is useful for the energy efficient algorithms and hence this module is responsible to provide the DB with time-stamped positioning context. This context can be either position information coming from a GPS or statistics from the terrestrial network (like received SNR, timing information such as power delay, or angle of arrival), which is used into a positioning algorithm to calculate the position of a MT. Such positioning algorithms help avoiding the use of the GPS, which is an extensive energy consuming procedure. Previous time-stamped positioning information is used to calculate mobility/movement information, which can be used to predict future position of MT.

- The Radio Resource Management Decision Engine (RRMDE) module receives the decisions related to context based radio resource management for energy saving.

- Information about terminal settings and available nodes is used by the Network/Node Discovery Module (NDM) to make more targeted searches for available access networks or nearby nodes that might be used in the implementation of any handover or other energy saving strategy.

- The Cooperation Module (CM), like NDM, uses terminal context information to search for terminal counterparts and to negotiate with them to implement multihop collaboration policies. Both NDM and CM instantiate, or at least negotiate instantiation of, energy efficiency decisions.

3.2.2 Context Based Network Architecture

In the network functional architecture, the Cooperation Mediator, the Radio Resource Management Decision Engine and the ANDSF access the Network Central Information to retrieve the required Cx information. All three elements can exchange Cx information and

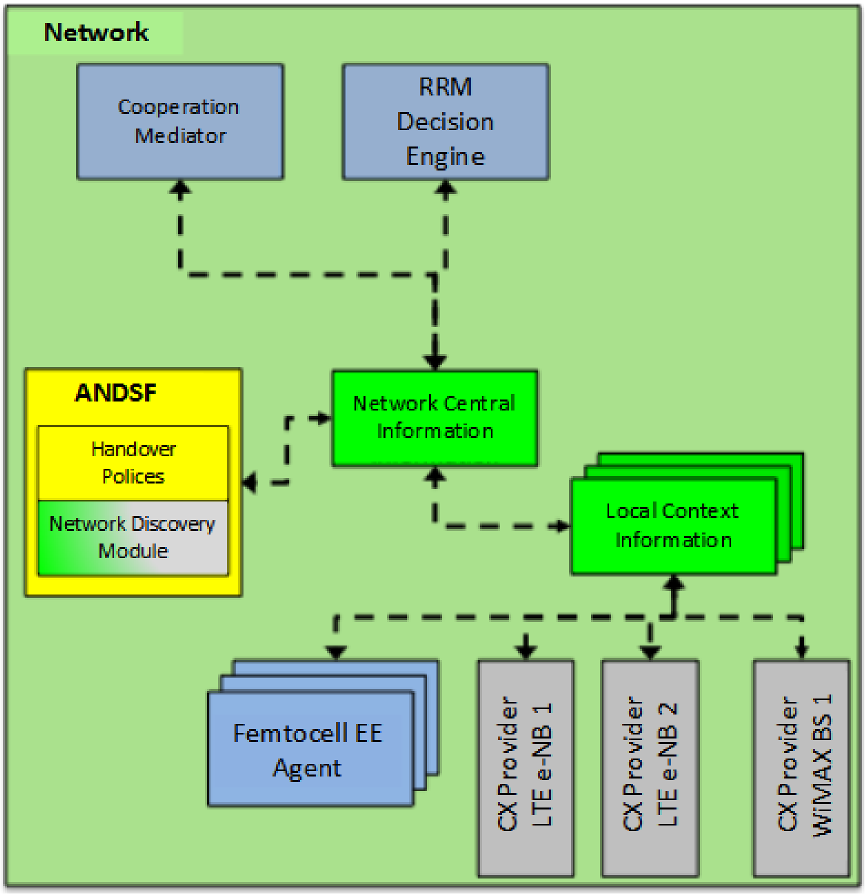

Figure 3.7: Context Based Network Architecture

decisions with the terminals. The challenge imposed by the extraction of Cx Information on the network side is the dispersion of the Cx sources. The Cx information information is accessed, stored, processed and delivered from multiple Cx providers. In the layered structure of the network functional architecture, the Cx Information is collected from Cx providers and placed at BSs and other network entities at the local Cx Information. The Local Cx information then transmits the Cx Information to the network Central Information. At the network Central information, the Cx information is transmitted to the three elements upon request. The ANDSF supplies the UE with Cx information regarding HO Policies, allowing the operator to manage the decision process and optimize overall network performance. The ANDSF also provide the UE with Cx information to help in the network and node discovery processes.

- Local Context Information: responsible for gathering e.g. cell capacities, cell load, backhaul load from Network Measurement Extractor(s), which is (are) located in the Access Network under supervision of the module. The Local Context Information is located in 3GPP networks in Access Network (RNC, eNodeB) and in untrusted non-3GPP networks in ePDG.

- Network Measurement Extractor: responsible for providing information related to the network load, cell capacities, cell load. The module shall be located in the access network, for: 3GPP it can be either Base Station or RNC and in trusted/untrusted non-3GPP access it shall be located in access point (AP in WiFi case and BS in WiMAX) It is also worth pointing out that in case of untrusted non-3GPP access the measurements obtained from NME will need to be adapted to common standard and evaluated in respect to reliability, therefore it is up to network decision making algorithm to decide how to include this information.

- Cooperation Mediator: responsible for the mediation between Cooperation Module (located in the relaying UE) and Cooperation Module (located in the service requesting UE). Cooperation Mediator allows ePDG to negotiate with the relaying UE on behalf of the UE which requests the service. Cooperation Mediator is responsible for: triggering the authentication (from 3GPP AAA Server) of the requesting user and determining the IP-CAN (IP Connectivity Access Network) type (used to determine the proper charging rate for the UE which requests the service). Two IP-CAN types are to be distinguished: 1) access through a relaying UE, 2) untrusted non-3GPP IP access (e.g. WLAN hotspot). In case the ePDG oriented variant 2 is used, the Cooperation mediator is also responsible for handling of the IP-CAN session modification on behalf of the relaying UE.

- Radio Resource Management Decision Engine: responsible for the radio resource scheduling utilizing the context information. The RRMDE receives the context information related to the network from Network Central Information module and MT context information from RRMDE module on MT side. RRMDE uses context information that are ignored in conventional scheduling for energy saving.

- Femtocell EE Agent: is implemented as a part of HNB (Home NodeB). Its purpose is to optimize parameters and processes available at HNB (e.g. could be SIR target in outer loop power control in LTE, optimize DRX cycle and inactivity timer) in order to provide improvement in energy consumption to the users connected to Femtocell. HNB context parameters are the input for the optimization process.

- Access Network Discovery and Selection Function(ANDSF): collects and provides ISMP (Inter-System Mobility Policy) and AND (Access Network Discovery) information to the terminals, where ISMP and AND has been specified by 3GPP. The AND information that is provided by this element should be extended to include mobile terminals that are willing to cooperate (relay connection) and information of base stations/access points power class/transmission power (if possible to be collected and spread to users). In order to support node discovery process, node location information could also be included; a positioning method (e.g. GPS or network based solution like measurement of Time-Of-Arrival) can be applied for the purpose.

- Network Central Information: collects information from Local Context Information modules, works as a centralized source of information to Handover Decision Engines.

3.3 Conclusion

In this chapter, we presented a context based architecture geared towards energy saving in the future emerging network and devices by exploiting context based node discovery, cooperative relaying and radio resource management. Although, these approaches have demonstrated the potential for energy saving, the energy reductions do not go far enough in the absence of context. Therefore, context information can be used to provide more intelligent decisions regarding node discovery, cooperative cluster formation and RRM for energy saving. In the first instance, this chapter provides a taxonomy of the context parameters related to both the MT and network. Moreover, we then present a context architecture that provides a framework that dictates how context information can be extracted, filtered and managed for energy saving. Terminal Context Aware Module (TCAM) is the core of MT context architecture and is responsible for generating high level context processed from the raw context extracted by the Context Providers and the Inferrers. Network context architecture has Cooperation Mediator, RRMDE and ANDSF modules responsible for exchanging context and decisions with the terminals. The generic architecture is given here, however this solution is customized to provide specific context based solutions for node discovery, cooperation and radio resource management in the following chapters.

Chapter 4

Context-aware Node Discovery for Short Range Cooperation

In this chapter, we detail the latest innovations on lightweight node discovery mechanisms for wireless personal area networks (WPANs). Specifically, we identify the benchmark performance for node discovery which requires exhaustive search for nodes in the near vicinity resulting in the radio interface being always "ON". We advance this by proposing a new energy efficient discovery mechanism based on cooperative mechanism. We present a context based beaconing mechanism both for the node discovery and cooperative cluster formation. We exploit the available beacon Information Elements (IEs) of UWB and have proposed a new Context Extraction Function (CxEF). Beyond this, we also present a detailed representation of bit mapping for energy and cooperation in beacons. The chapter is concluded by simulation results, which demonstrates the potential energy saving that can be achieved using the proposed node discovery algorithm based on Context Awareness.

4.1 Introduction

Energy is a critical resource in battery-powered mobile devices and the number one criteria for the majority consumers purchasing a mobile device [14]. Energy to keep mobile devices connected to the network over extended periods of time quickly dissipates. Furthermore, advanced multimedia services are power hungry and poses strict limitations on battery lifetime that users are reluctant to use these services for an extended period of time. To trim down the energy consumption of legacy and future emerging handsets, there are a number of international research initiatives such C2POWER [97], GREEN-T [98], GREENET [99] among others, that aim to reduce the holistic energy consumption using an interdisplinary and mutlidisplinary design approach.

Context information is seen as a promising approach towards taking a significant step towards energy efficient handsets. Alternative views applied on context lead to different definitions and different levels of applicability e.g. in [100] the author defined "context" as "location identities of adjacent people, objects and changes to those objects". In wireless communications, context is broadly related to two main categories: mobile terminal (MT) and network. The context related to network covers security, policies, coverage and QoS while MT context comprises device capabilities, mobility, application in use and support, energy and user preferences. Context and its categorization for wireless communication is well particularized in [101]. The fundamental objective of context is presented in [102]: "context-awareness is not only to assist in providing to end users at anytime, anywhere, with any media, but specifically to communicate the right service at the right time in the right manner." A number of European Union (EU) funded projects have explored context based communication by exploiting benefits offered by context information. Examples of these are: SPICE [103], C-CAST [104], MobiLife [105], OPUCE [106] and ongoing projects C2POWER [97], GREEN-T [98] and GREENET [99]. In particular, the C2POWER project uses cooperation as a mean of providing energy efficient topologies based on combining short-range with long-range communications using an intermediate proxy for relaying. However, this requires exhaustive search for scanning available nodes in the near vicinity for creating the relay network, which overrides the benefits obtained by using short-range. In this work, we go beyond this by proposing the Context Aware Node Discovery (CANDi) paradigm that exploits context to ensure efficient node discovery. For instance, with conventional discovery a node can discover nearby nodes with considerable amount of overhead, but it still lack information about the best available node for communication. However, the context based approach not only enables data transmission to the desired destination, but also provides the opportunity for the discovered node to become a member of the cooperative communication cluster, where each member of the network shares information for achieving a common goal resulting in efficient utilization of network resources. The benefits offered by cooperative communication are highlighted in [107] and includes higher throughput, lower delays, reduced inference, network scalability, lower transmitted power, opportunistic use, redistribution of network energy and bandwidth. Context information plays a vital role to ensure the benefits of cooperative communications are pronounced.

The Node discovery process is the initial step to start a cooperative communication network. Energy saving in node discovery is handled either by the proper MAC duty cycles or by protocols that use different antennas such as directional or omni-directional antennas to efficiently discover nodes with less overhead and thus saving time and resources. Most of the node discovery protocols that follow the MAC duty cycle are based on conventional scanning which is expensive in terms of energy because the node either spends a long period of time in the "listening" state or performs broadcasting, which is more energy consuming than smart scanning. To conserve energy, MAC protocols with proper sleep/wake duty cycle have been proposed for wireless networks, providing a balance between sleep and wake time of mobile terminals. Although suitable duty cycles contribute to conserve energy, keeping a node in sleep mode weighs down a network or part of a network [108]. Furthermore, even an efficient duty cycle cannot contribute effectively to the discovery of other node or networks because the node is unaware of when to turn on its radio interface to locate a cooperative node. Moreover, sometimes a node is in the vicinity of a cluster or a node might be unsuitable for cooperation. As stated earlier, the problem of node discovery has also been investigated extensively by using directional and omni-directional antennas. The use of directional antennas in static ad hoc networks for node discovery is reported in a number of research articles [109][110], while its use in mobile ad hoc networks is addressed in [111][112]. In the absence of context information the directional antenna in the node discovery has the edge over omni-directional communication such as low interference and high directional gain, due to high signal to interference and noise ratio (SINR), resulting in high data rates and an extended communication range on a given transmission power [113].

Ultra Wideband (UWB) is a possible candidate for short-range communication technology since it offers a number of advantages [114][115]. UWB MAC channel time is divided into superframes which have a time length of 65536 microseconds and are divided into 256 Medium Access Slots (MAS) with a time duration of 256 microseconds each. The three major subdivisions of the superframe are: the beacon period that starts at the beacon period start time (BPST); the beacon slots, and the media access slots. The beacon frame of UWB consists of a number of IEs and synchronization parameters [116]. There are a number of available fields in the beacon frames that can be modified or new fields that can be proposed to exchange novel kinds of information e.g. energy level of a MT. In this work, we exploit UWB for short-range scenario and modify the beacon frame to embed our own fields to facilitate both the discovery and the cooperation processes. Two distributed channel access mechanisms, prioritized channel access (PCA) and distributed reservation protocol (DRP), are used for ad hoc connectivity by WiMedia [117]. We have created an extraction function that extracts the information, maps the semantic information onto values, and forwards them to specified modules of the node.

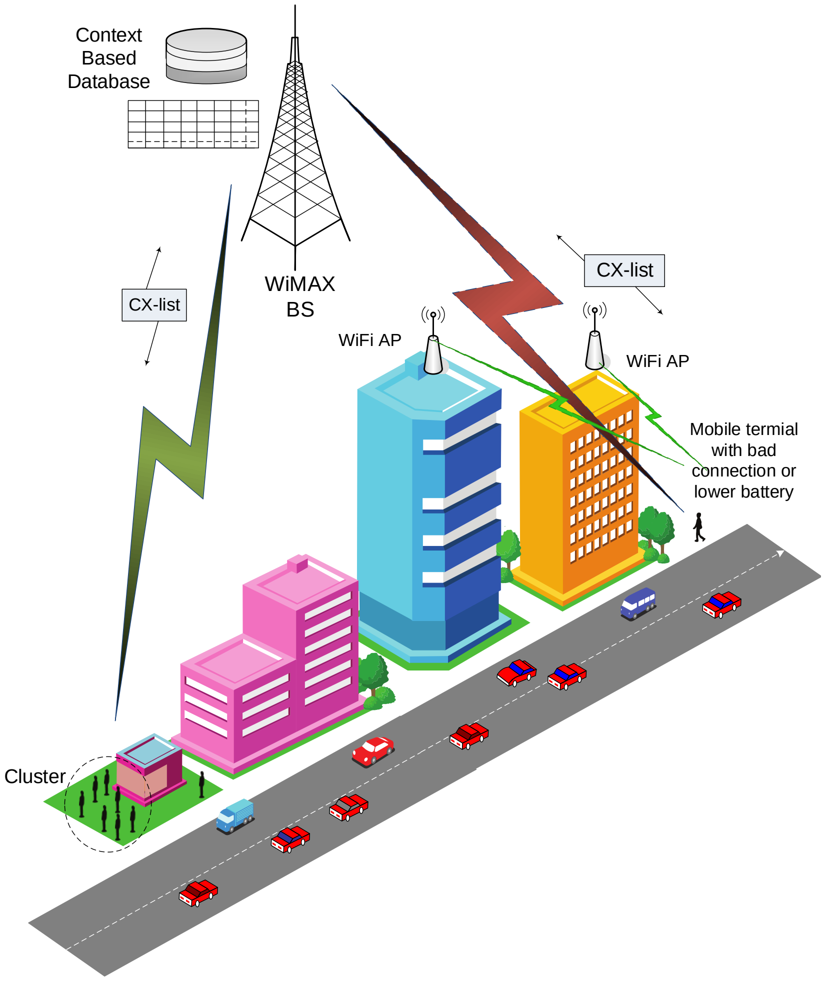

Figure 4.1: Network scenario representing WiMAX and Wi-Fi facilitates the short range UWB in the node discovery process.

4.2 Scenario

The proposed network scenario for simulations is shown in figure 4.1 and involves MTs that can communicate either through a long range network (e.g. WiMAX, LTE, etc.) or a short range network (e.g. UWB, Bluetooth, etc.). We consider WiMAX, Wi-Fi and UWB in our work as specific use-case technologies; however our approach is technology agnostic and can have general validity for future emerging technologies, such as LTE-A. The scenario covers cluster discovery and cooperation instantiation for a mobile terminal that is in search of a network or device. The cluster is based on the centralized approach, where the clusterhead is the centralized coordinating entity. Our approach uses the context information about the cluster e.g. location of cluster, battery levels of member devices, and willingness to cooperate. Furthermore, inside the cluster we defined two groups of member devices: a group consisting of devices that are considering switching to the hibernation state to save their energy, i.e. once a device is in hibernation mode it will not be considered as a candidate for cooperation; and a second group consisting of the devices in active mode that could be interested in cooperating with the external devices depending on their battery levels and willingness to cooperate. As represented in figure 4.1, a cluster connected with the BS and the clusterhead of these clusters (in case of multiple clusters) sends cluster information to the BS or AP so that, when a device looks for short range connectivity, the BS or AP can provide information about the nearby cooperative clusters. The information is then utilized by the MT to connect to the devices in an energy efficient way. For exchanging the context list (Cx-list) inside the cluster and with the BS or AP we consider that the clusterhead collects the Cx-list and periodically or on demand sends it to BS or AP as well as to the other cluster members.

4.3 Proposed Mechanism

For node discovery and cooperation in the aforementioned scenarios, we propose a mechanism that will facilitate the short range searching to allow a device to find its nearby cluster node and choose the optimal node for communication and cooperation.

4.3.1 Overall Algorithm

In the proposed algorithm, besides low signal-to-noise ratio we are considering other contextual information which has not been utilized so far, neither in the node discovery nor the cooperation process. Both the discovering MT and the clusterhead are connected to a WiMAX BS or Wi-Fi AP. Once the battery level (BL) of the MT reaches a threshold battery level (BLth), it triggers the BS for a Cx-list of nearby co-located short range networks. The Cx-list is the list of context information that the clusterhead sends to the same BS for future connectivity with nearby devices and contains a number of useful information e.g. members of the cluster willing to communicate, battery levels, current transmission power, cluster ID (in case of multiple clusters), etc. The Cx-list is constructed by the clusterhead and floats via WiMAX to the discovering device. The embedded information allows the searching MT to understand important characteristics of the clusterhead or of its members e.g. battery level, channel information, etc. The context information is used for three main purposes:

- Creating a list of possible co-located MTs that are willing to cooperate.
- Facilitating the communication: the exchanging of reserved channels, location, etc. is used to direct the scanning, without having to check the presence of MTs on different channels.

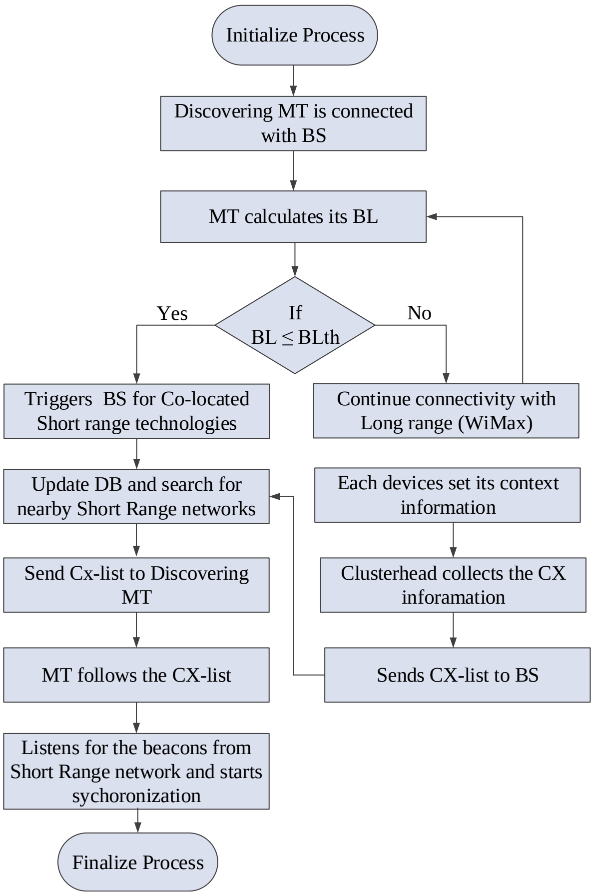

Figure 4.2: Flowchart of the proposed algorithm.

- Setting up a rendezvous with other MTs: The timing information can be used to know in advance when the next superframe will start. The timing information will be used to shorten the active mode (transmission and reception) phase, starting just a little before the probable start of the superframe, to take into account the delay in receiving this synchronization information from the WiMAX or Wi-Fi.

The flowchart of the algorithm is shown by figure 4.2.

4.3.2 Context Information management at MAC layer

Context awareness for energy saving is considered the core of the approach allowing terminals to become cognitive in nature and be responsible for their own decisions. In particular, we consider that a MT needs information on a number of features, settings and preferences/policies of the networks or nodes the terminal wants to connect to. The extracted context information, related to networks or other nodes, is used at different layers to make possible different operations and thus contributes to energy savings. Figure 4.3 shows our

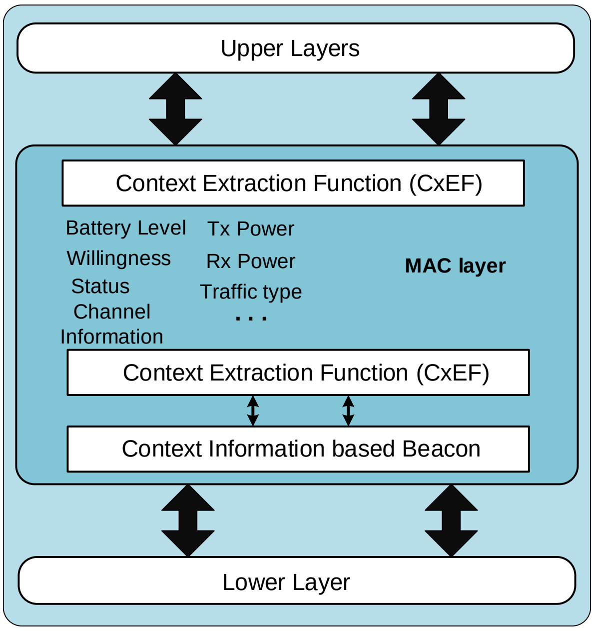

Figure 4.3: Context information management at MAC layer.

context based management MAC layer for the MT and demonstrates how the context list is constructed and how the information is extracted from the context list received from other member devices. When the beacon frames are received at the MAC layer the context extraction function (CxEF), as shown in figure 4.3, extracts the queries into bits, matches them to the defined values and then forwards the extracted information. The extracted context can be further utilized in different layers of the protocol stack for further actions such as the use of battery level information in energy efficient routing or VHO, which are beyond the scope of this chapter. On the other hand, if we want to construct the Cx-list and embed the information in the beacon frame, the CxEF extracts the context information from upper layers and inserts it in the beacon according to the requirements. The CxEF provides the functionalities of a sub-layer and extracts the context information independent of the underlying technologies.

4.3.3 Proposed WiMedia Beacon

This approach proposes to modify the superframe of the short-range communication protocol. Instead of basing the communication of beacons on contention access, we propose to insert in the beacon a superframe map, bearing information about which part of the beacon slot is reserved by remote terminals. This way, by using context information exchanged via long-range technologies, the devices will be able to know in advance when they have to send their beacon to the cluster or its members to complete the rendezvous. The rest of the beacon

Table 4.1: Willingness IE format.

Octet 1	1	1
Willingness	Length	Element ID

Table 4.2: Format for willingness status field.

b7-b2	b0-b1
Reserved	Status

slots will be used via PCA, to welcome devices that are not exchanging context information via long-range technologies. In this way, we will be able to speed up the insertion of devices that use context information in the cluster, while allowing other MTs into the cluster via the conventional beacon exchange. The clusterhead adds a field to the superframe at the beginning of the first beacon to inform all the devices that some of the beacon slots are reserved for devices that are using context information. Then, the clusterhead sends a number to MT via the BS or AP, indicating which beacon frame was reserved for the discovering MT.

4.3.4 Representation of Willingness in Beacon

Each mobile device sends its battery level and the willingness to cooperate to the clusterhead or other neighbor devices to exploit the proposed IEs in order to take energy-efficient decisions. An example of IE for willingness is shown in table 4.1 and the format of the field containing the Willingness status is reported in table 4.2. The status of willingness depends on the battery level. The willingness for cooperation of the device is represented by two bits as:

00 $\rightarrow$ not willing to cooperate.
01 $\rightarrow$ willing to cooperate and to be relayed.
10 $\rightarrow$ willing to relay.
11 $\rightarrow$ willing to cooperate both as relay and relayed.

4.3.5 Representation of Energy in Beacon for Cooperative communication

This section discusses our approach to integrate energy and willingness encoding into the beacon frame. In the previous section, we have shown different fields in the transmitted beacon packets, representing different levels of willingness to relay and to be relayed. The energy level is either a percentage of the maximum energy level, an estimation of the battery life time, or a future consumption prediction based on the current profile. On the other hand, in the case of node discovery for energy saving, the point of knowing the energy level of a unit

Table 4.3: Battery level IE format.

Octet 1	1	1
Battery level	Length	Element ID

Table 4.4: Battery level field format.

b7-b4	B3-b0
Reserved	Battery Status

and its willingness to cooperate is to evaluate if it should act as a relay or a source. Thus, for the purpose of saving energy we devise a way to encode all this information in a small number of bits which are used by a MT to map its energy level, depending on its willingness to relay or to be relayed as shown in figure 4.4. Depending on its energy level the MT can choose to be a relay, relayed or can be both used as relay or be relayed as represented a, b and c in the figure 4.4. The proposed battery level IE is shown in table 4.3 and 4.4. Let us consider three different MTs, that have got three different goals, and are described graphically in figure 4.4 by a, b and c. If a unit wants to be a relay (see figure 4.4.a), the ranges of energy that will be mapped to the lowest values will be smaller, to ensure that the MT is considered as a candidate for relaying. On the other hand, if a MT wants to be relayed (see figure 4.4.b), the energy levels mapped to the lowest values will be larger. The result is that, when the system will compare the two MTs' energy levels, it will assign the role of relay to the one that encoded its energy level to a higher number, and of source to the other. Figure 4.4.c shows a more balanced energy coding, where a MT wants to cooperate and is willing to act both as a relay and a source.

An example of the representation of the battery level is given in table 4.5. The encoded value is the next percentage value larger than the battery level. For example, if a unit wants to be a relay, and its energy level is 25% of maximum battery level, it will encode it as "0101", since it is higher than 23% but it is lower than 28%.

4.3.6 Context based cluster formation

According to the derived requirements and provisioned algorithm, nodes self-organize into one-hop clusters to exploit the energy saving capabilities of short-range cooperation. The cooperation actually occurs whenever nodes determine that energy saving is feasible. In general, it provides an energy saving benefit without jeopardizing any required QoS. In cluster formation, each node is required to:

- Discover$< ProposedBeacon >$ distributed by neighbouring nodes

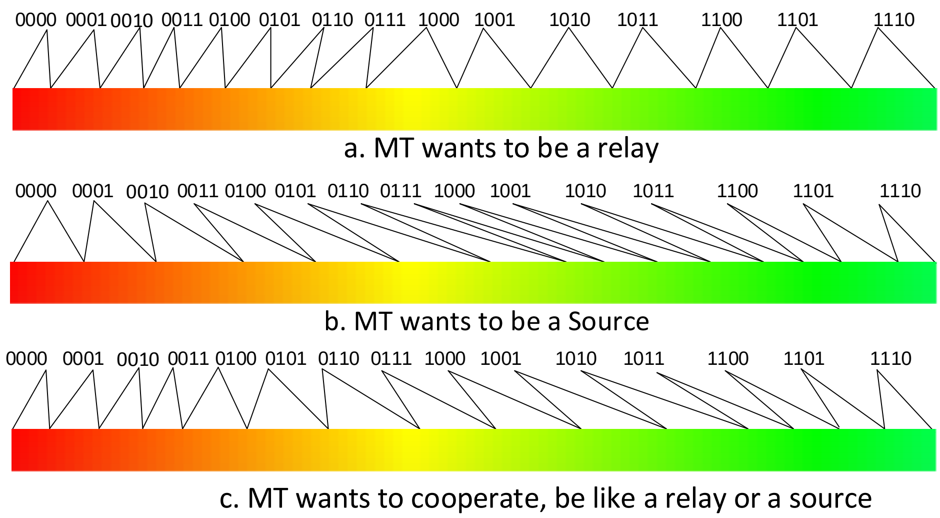

Figure 4.4: MT's energy and role mapping in cooperation.

Table 4.5: Battery level representation.

Bits	Basic representation	Relay	Source	Both
0000	6%	4%	8%	4%
0001	13%	9%	17%	9%
0010	20%	14%	26%	14%
0011	26%	18%	34%	19%
0100	33%	23%	43%	26%
0101	40%	28%	52%	35%
0110	46%	32%	60%	45%
0111	53%	39%	67%	54%
1000	60%	48%	72%	63%
1001	66%	56%	76%	71%
1010	73%	65%	81%	80%
1011	80%	74%	86%	85%
1100	86%	82%	90%	90%
1101	93%	91%	95%	95%
1110	100%	100%	100%	100%
1111	not willing	notwilling	notwilling	notwilling

- Broadcast its own $< ProposedBeacon >$ to allow other nodes to read its information.

A cluster is formed once a node receives a number of valid beacon frames from at least one neighbour node. The clusterhead is elected based on the context information embedded in the beacon frame e.g. energy level, willing to cooperate, etc. as elaborated in the previous sub sections. Once this basic functionality is running, mobile nodes become aware of the devices in their vicinity. Then, each node maintains its neighbourhood membership list, which contains information on the node addresses and their advertised context information. In case the beacon is received for the first time, the sender of the beacon is added to a neighbour list. Every further beacon reception triggers an update of entries in the neighbour list. The information carried by the beacons indicates available underlying technologies, channel conditions or currently supported data rates. Furthermore, the advertised capabilities of each member node can be further utilized for energy saving cooperative strategies.

4.4 Mathematical model for the proposed Mechanism

The model is based on the following assumptions:

1. Each node has a unique MAC id.
2. The discovering node is mobile and the members of the cluster have limited mobility.
3. Each node has a transceiver that can transmit and receive signals. The transmission and reception power of each node is fixed.
4. Nodes are equipped with directional antenna which can be used for both directional reception and transmission.
5. Each node is assuming a normal MAC behavior with 50 % sleep and active mode.

Let us define

- $E_{\mathrm{x}1}$ is the energy consumption of node X without context information.
- $E_{\mathrm{x}2}$ is the energy consumption of node X using context information.
- $E_{\mathrm{x}A}$ is the energy consumption during active mode.
- $E_{\mathrm{x}S}$ is the energy consumption during sleep mode.
- Es is energy savings.

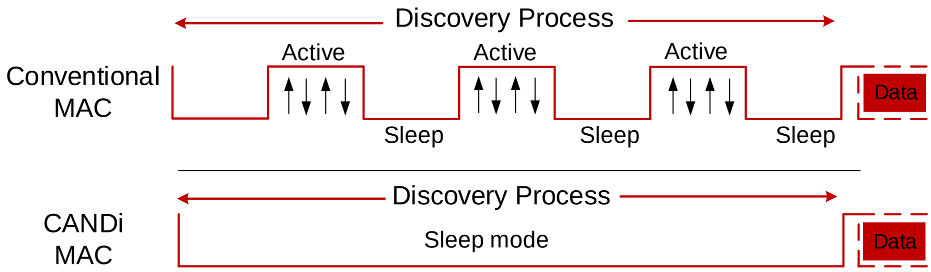

Figure 4.5: Comparison of conventional and CANDi MAC.

- Gs is the energy gain.
- E_{ND} is the energy cost of node discovery with optimal probability.
- F_{ND} is the fraction of neighbor discovered.

As shown in the network scenario, user X moves towards the cluster and periodically performs scanning. During the scanning process, user X switches between active and sleep modes. By the above definitions, the energy consumption without context information is shown in equation 4.1.

$$E_{\mathrm{x1}} = \frac{N}{2}(E_{\mathrm{xA}} + E_{\mathrm{xS}}) \tag{4.1}$$

Where $E_{\mathrm{xA}} = E_T + E_R$, $E_T = P_T * T_{BeaconPacket}$, $E_R = P_R * T_{BeaconPacket}$, P_T is the transmission power, P_R is the reception power, $T_{BeaconPacket}$ is the time to transmit one beacon packet and N is the number of switches of user X's MAC modes between active and sleep. The value of N depends on user speed towards the cluster or cooperative node and the distance between them. For instance, if the user is near to the cooperative cluster then the value of N will be smaller, otherwise the value of N will high. Similarly, if the speed of user is high, it will reach the cooperative cluster faster and the value of N will be smaller.
On the other hand, CANDi uses context information and turns on its interface once the user is in the coverage area of the nearby cluster or cooperative node. The energy consumption of the node using context information is shown in equation 4.2.

$$E_{\mathrm{x2}} = E_{\mathrm{xS}} \tag{4.2}$$

From equation 4.1 and 4.2 the energy saving is

$$Es = \frac{N}{2}E_{\mathrm{xA}} + E_{\mathrm{xS}}\left(\frac{N-1}{2}\right) \tag{4.3}$$

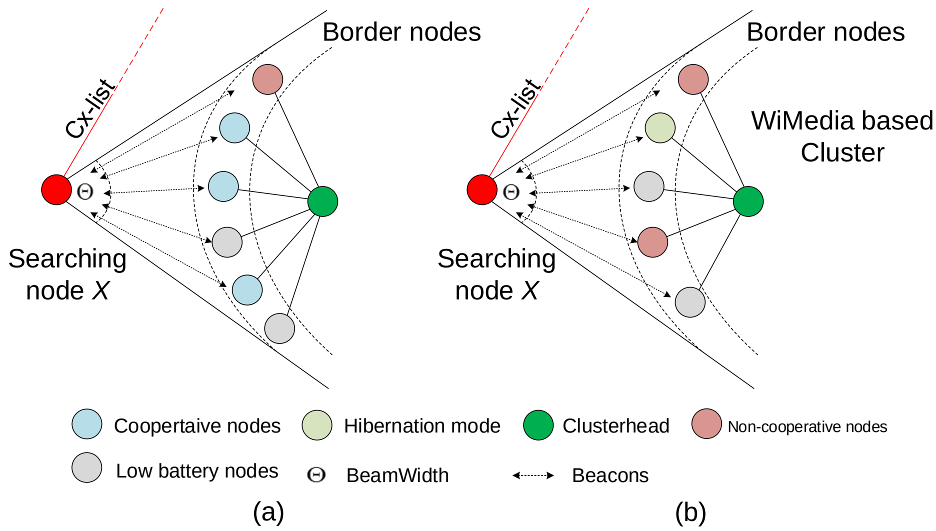

Figure 4.6: (a) Discovering node encounters all type of nodes on the border (b) Discovering node encounters only with non-cooperative nodes on the border.

From equation 4.1 and 4.3 the energy gain is

$$Gs = 1 - \frac{2}{N\left(1 + \frac{E_{\mathrm{xA}}}{E_{\mathrm{xS}}}\right)} \tag{4.4}$$

Now consider node X reaching the coverage area of the cluster. Inside the cluster we define cooperative and non-cooperative nodes (low battery, in hibernation mode, not willing to cooperate) as shown in figure 4.6. Due to mobility, the nodes can change their place and there can be all types of nodes on the border as in figure 4.6 (a), or only the non-cooperative nodes as in figure 4.6 (b). Node X can discover only the cooperative nodes (nodes with considerable battery level and willing to cooperate) as the low battery level, non-cooperative and hibernation mode nodes are exempted from discovery process.

Let's consider *k-1* are the border nodes of the cluster one hop from user *X*. Since node *X* can discover any of the border nodes, we will find out the probability and energy cost of the discovery process of user X using directional antenna.

The probability $P_{\mathrm{x,j}}$ that node X discovers a particular border node j is calculated by first conditioning on the probability that node *X's* beam covers j:

$$\begin{aligned} P_{X,j} = {} & P\left(Xsbeamcoversj\right) * \\ & P\left(Xdiscoversj|Xsbeamcoversj\right) \end{aligned} \tag{4.5}$$

Since the antenna is approximated by a circular sector, the direction is calculated as:

$$C = angle/totalarea = \Theta/2\pi \tag{4.6}$$

Where Θ is the angle that defines the direction within the range $0 \leq \Theta \leq 2\pi$, 2π is the area of network, $\frac{\Theta}{2\pi}P_t$ is the transmission probability in the direction of the antenna. The process of discovery following the Bernoulli stochastic process is

$$P\left(X\, discovers\, j|X's\, beamcoversj\right) = 1 - P_t \tag{4.7}$$

$$P\left(X's\, beam\, covers\, j\, in\, the\, specified\, direction\right) = \frac{\Theta}{2\pi}P_t(1 - \frac{\Theta}{2\pi}P_t)^{k-2} \tag{4.8}$$

$$P_{X,j} = \frac{\Theta}{2\pi}P_t\left(1 - \frac{\Theta}{2\pi}P_t\right)^{k-2}(1 - P_t) \tag{4.9}$$

Since each node has to transmit or receive beacons in a time slot t so the probability that node X discovers node j within time t time slot is given by :

$$P_{x,j}\left(t\right) = 1 - \left(1 - P_{x,j}\right)^t \tag{4.10}$$

We are interested in finding the optimum probability P_t of node X discovering a neighbor j within t time slots:

$$\frac{dP_{X,j}\left(t\right)}{dP_t} = 0$$

Then according to [118], after differentiating, node X can discover any of the border nodes with the optimal value of p_t as follows

$$P_t = \frac{\left(2 + (k-1)\right)\frac{\Theta}{2\pi} - \sqrt{\left(\left(2 + (k-1)\right)\frac{\Theta}{2\pi}\right)^2 - 4k\frac{\Theta}{2\pi}}}{\frac{k\Theta}{\pi}} \tag{4.11}$$

As shown in figure 4.6 the border nodes can be non-cooperative and represented as k_{NC}. The nodes that are available for node X to discover are $k - 1 - k_{NC}$ and the optimal value P_t to discover the nodes that are willing to cooperate is given be the equation 4.12 and 4.13.

$$P_t = \frac{\left(2 + (k - 1 - k_{NC})\right)\frac{\Theta}{2\pi} - \sqrt{\left(2 + (k - 1 - k_{NC})\right)\frac{\Theta}{2\pi} - \frac{4\Theta}{2\pi}(k - 1 - k_{NC}) - \frac{4\Theta}{2\pi}}}{\frac{\Theta(k-1-k_{NC})}{\pi} + \frac{\Theta}{2\pi}} \tag{4.12}$$

$$P_t = \frac{(2+(k-1-k_{NC})\frac{\Theta}{2\pi} - \sqrt{(2+(k-1-k_{NC})\frac{\Theta}{2\pi} - \frac{4\Theta}{2\pi}(k-k_{NC})}}{\frac{\Theta(k-k_{NC})}{2\pi}} \tag{4.13}$$

The required number of attempts for node discovery is $1/P_t$ and E_{xA} is the energy cost during active mode as defined earlier, then the energy cost for node discovery, E_{ND}.

$$E_{ND} = \frac{\mathrm{E_{xA}}}{p_t}$$

$$E_{ND} = \frac{\mathrm{E_{xA}}.\frac{k\Theta}{\pi}}{(2+(k-1)\frac{\Theta}{2\pi} - \sqrt{(2+(k-1)\frac{\Theta}{2\pi} - 4k\frac{\Theta}{2\pi}}} \tag{4.14}$$

CANDi reserves channel for the discovering node and all the member devices of the network know this information. The energy consumption increases as the node spends more time in the backoff mode and reattempts periodically as shown in the figure 4.7 and represented by the following equation.

$$C_{Attempts} * E_{Attempt} = E_{Total} \tag{4.15}$$

For validation, the results are obtained from the model by calculating the fraction of neighbors discovered by the node X in a time slot t are compared with the simulations results as shown in figure 4.15. Our model works on the assumption that no two nodes can discover neighbors in the same time slot e.g. if node X discovers j in a time slot t then another node from $k-1$ cannot use the same slot for discovery. There are $k-1-k_{NC}$ neighbor nodes for node X to discover in time slot t. The fraction of neighbors discovered by node X within time t is given by

$$F_{ND} = \frac{\sum_{n=1}^{\min(t,k-1-k_{NC})} nP_t(n,t)}{k-1-k_{NC}} \tag{4.16}$$

P_t, given in equation 4.13, maximizes the probability of a successful transmission in a time slot t considering both the cooperative and non-cooperative nodes. This P_t also maximizes the fraction of neighbors discovered within a given amount of time represented in equation 4.16. For validation we obtained results using equation 4.16 and compared with the simulation results. To represent the analytical results, the transmission probability is obtained from equation 4.13 by substituting the value of K=10 and $k_{NC} = 3$. The obtained results are shown in figure 4.14 and figure 4.15 and further elaborated in the results section.

4.5 Simulations Set Up

CANDi has been simulated using OMNeT++4.0 [119], an open source simulator. We installed the Numbat WiMAX/Mobile IPv6 framework for OMNeT++ [120] for long range

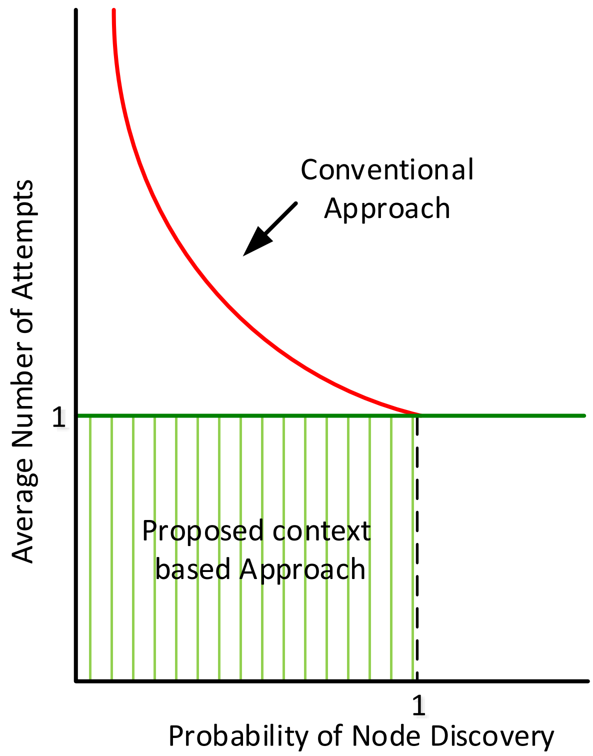

Figure 4.7: Probability comparison of node discovery by context based approach and conventional discovery approach.

simulation results. For energy calculation we used the Energy Framework of OMNeT++, which is a collection of modules that allows flexible and extensible modeling of battery consumption of wireless devices [121]. From the existing modules available in OMNeT++, we used SimpleBattery module which is a simple linear battery model that provides a common interface to all battery using devices. The battery status of each device records time series with events and results that are published in a vector. The resolution depends on battery's publishDelta value set in the main program. We set its value to 0.1 , which means that after each 0.1 seconds the battery data is recorded in a file which shows the energy consumption in different events. The simulation consists of a cluster of 10 nodes and a searching node. The discovering node is given different mobility models and tries to find the cluster by using both context based discovery and conventional scanning. The simulation setup parameters and values are shown in table 4.6.

4.5.1 Results And Discussion

In the proposed scenario, if the discovering node doesn't find any cooperative node or cluster and continues its connection with the long range technology, it will drain out battery

Table 4.6: Simulations set up.

Parameters	Value
Simulation Area	500 m x 500 m
Short range Technology	UWB
Long range Technology	WiFi ,WiMAX
Battery module	Omnet++ 4.0 Simple battery
Nodes in the cluster	10
Mobility Models	Constant Speed, Linear Mobility ,Rectangular (Defined areas)
Node speed	2m/s
Node update interval	1s
Number of nodes	10-100
Cx-list size	32,64,128,256,512 bytes
Initial node Battery	7mAh
Voltage	3.3 V
Maximum transmission power (UWB)	1 mW
Backoff time	0.0003 s
SIFS	0.00019 s
Time from RX to TX mode	0.00018 s
Time from RX to Sleep mode	0.000031 s
Time TX to RX mode	0.00012 s
Time TX to Sleep mode	0.000032 s
Time Sleep to RX mode	0.000103 s
Time Sleep to TX mode	0.000203 s

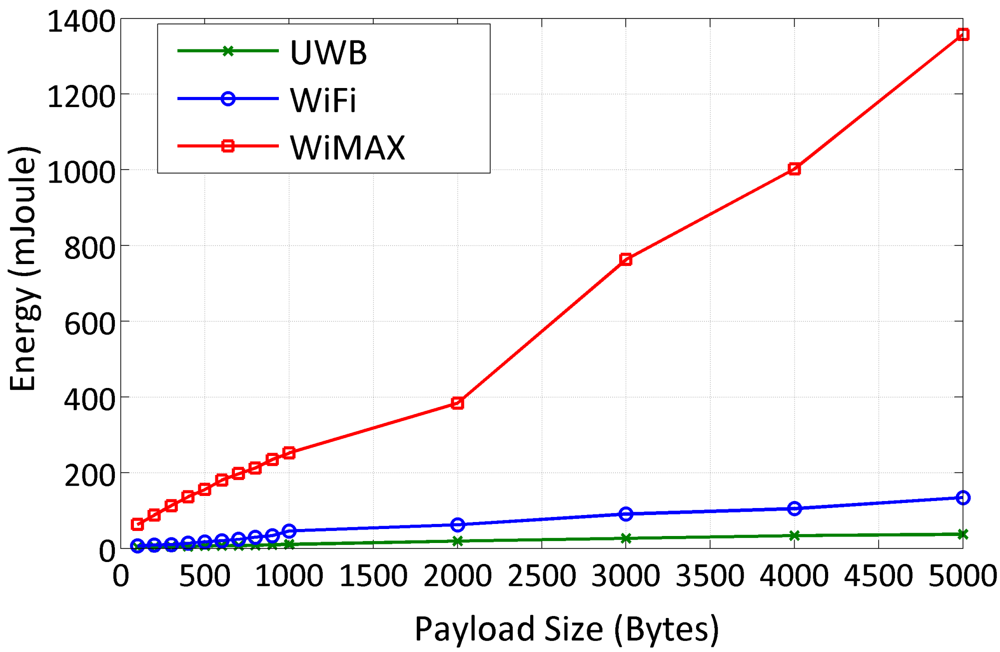

Figure 4.8: Energy consumption of different payload sizes over UWB, Wi-Fi and WiMAX.

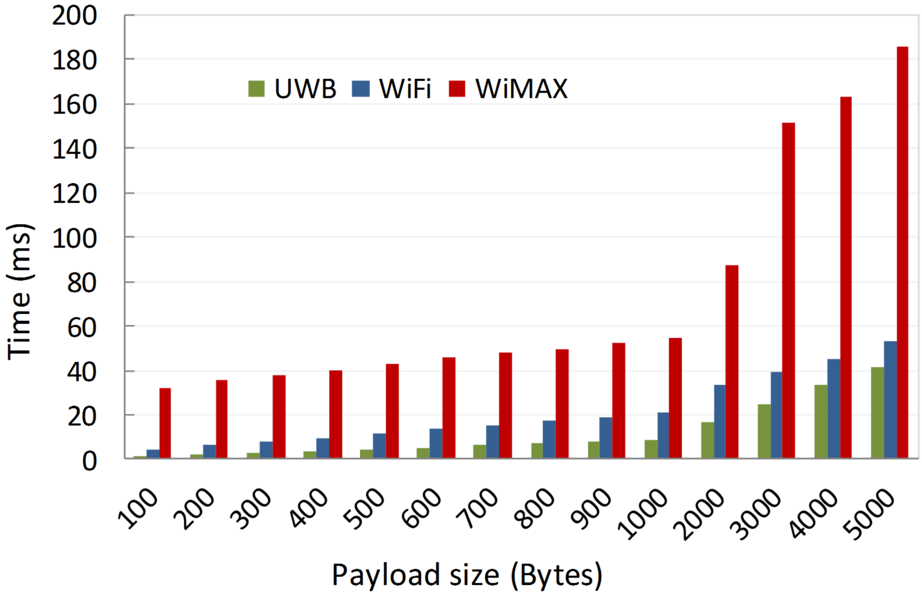

Figure 4.9: Transmission time of UWB, Wi-Fi and WiMAX with data payload size.

very swiftly. Figures 4.8 and 4.9 represent the motivation behind the use of short range technologies for energy saving and serves also to validate our energy saving mechanism by using WiMAX and Wi-Fi as the long range technology facilitating short range UWB in node discovery process. We have generated a series of traffic events with different data payload size and checked the energy consumption in UWB, Wi-Fi and WiMAX.

Figure 4.9 shows that the long range communication is expensive in terms of energy consumption. Mobile terminal energy consumption also depends on the data rates, payload size and the distance between the communicating devices. Since UWB offers high data rates, the transmission time is much less when compared to Wi-Fi and WiMAX, and the result in figure 4.9 shows that the transmission time is proportional to the data payload size.

Turning on the short range interface at the exact location once the discovery node is in the coverage area of the short range cooperative cluster is important, as the node has to consider the communication delay of the context list. We performed a series of simulations to check the period of time, during the discovery process, when the beacon packets success rate is zero and when its success rate is almost 100%. As depicted in figure 4.10, the beacon packets success rate is 0 when the node is not in the coverage area, but once it starts to touch the boundaries of the cluster the success rate rises and reaches its peak value in 5 seconds. For optimal connectivity the discovery node has to switch on its short range interface and receive the fresh context list during these 5 seconds. The coverage area of the UWB, considered in

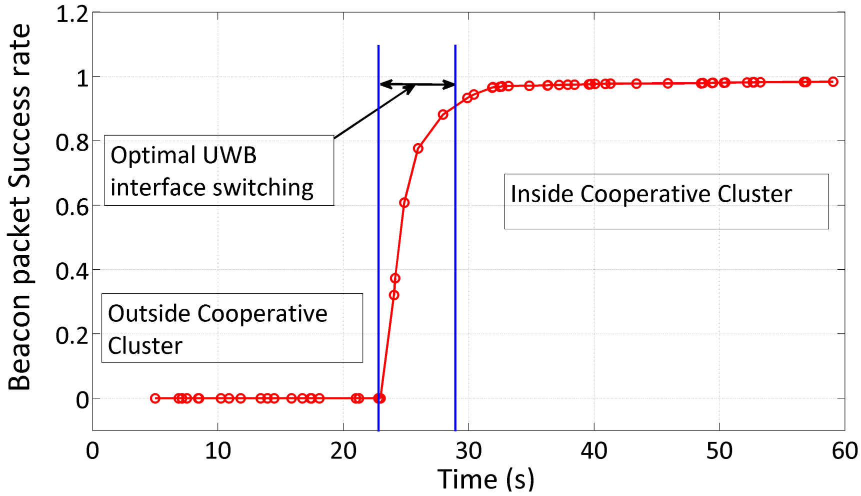

Figure 4.10: Beacon packet success rate and optimal point to switch on UWB interface.

this case, is exactly 10 m.

To facilitate the searching node's discovery of a cooperative node or cluster, the clusterhead in each cluster gathers the information about all the member nodes in a context list and sends it to the WiMAX or Wi-Fi. The context information flows over WiMAX or Wi-Fi connection and is received by the searching MT. Figure 4.11 shows the energy consumption of the context list versus sizes over UWB, Wi-Fi and WiMAX. We have varied the size of Cx-list from 32 to 512 bytes to check the energy consumption trend so as to validate our mechanism. The result shows that the energy consumption for different sizes of Cx-list of WiMAX and Wi-Fi is higher than UWB, but still negligible compared to the overall energy gain of the mechanism.

The time to discover the cluster varies with different mobility models, and this is the time that we consider in the context based discovery to keep the short range interface off and save energy. The energy consumption of node discovery with different mobility models is shown in figure 4.12. We have used constant speed, linear and rectangular (defined areas) mobility models. The node's power has been kept constant to 1mW and the speed to 2 m/s.
Figure 4.13 shows the energy consumption of the node when it scans blindly without context information to find a cooperative cluster, and with context based scanning. A series of simulations have been performed to record the average time when the node is in the coverage of short range technology. Despite having a MAC that has reasonable duty cycle of sleep and active mode, the energy consumption of the node in the discovery process is high. The figure shows that the context based discovery process saves a considerable amount of energy.

The analytical and simulation results of CANDi are shown in figure 4.14. The fraction of discovered nodes is high in the case of analytical results as we are not considering the Cx-list delay over WiMAX or Wi-Fi compared to the simulation results. In the simulation

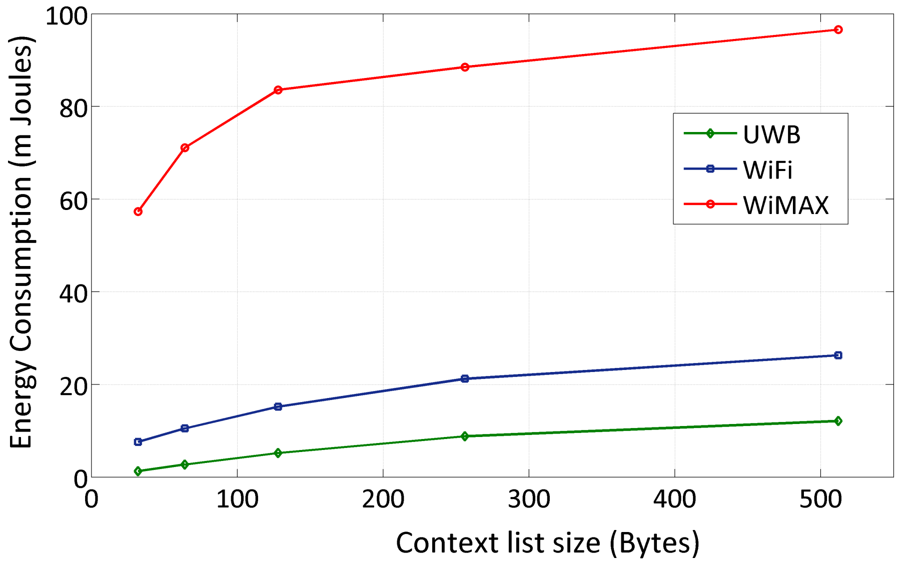

Figure 4.11: Energy consumption comparisons of Cx-list via UWB, Wi-Fi and WiMAX.

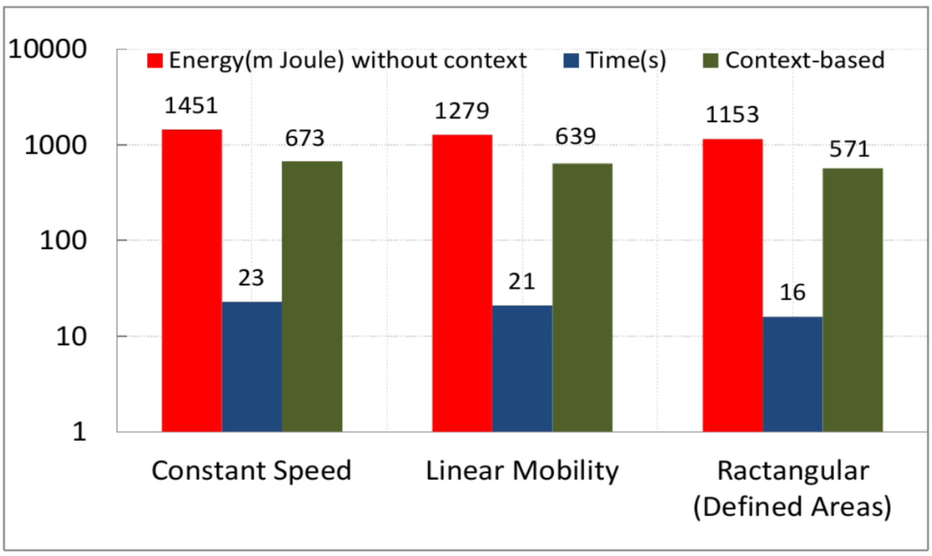

Figure 4.12: Energy cost and time to discover first node with and without context information using different mobility models.

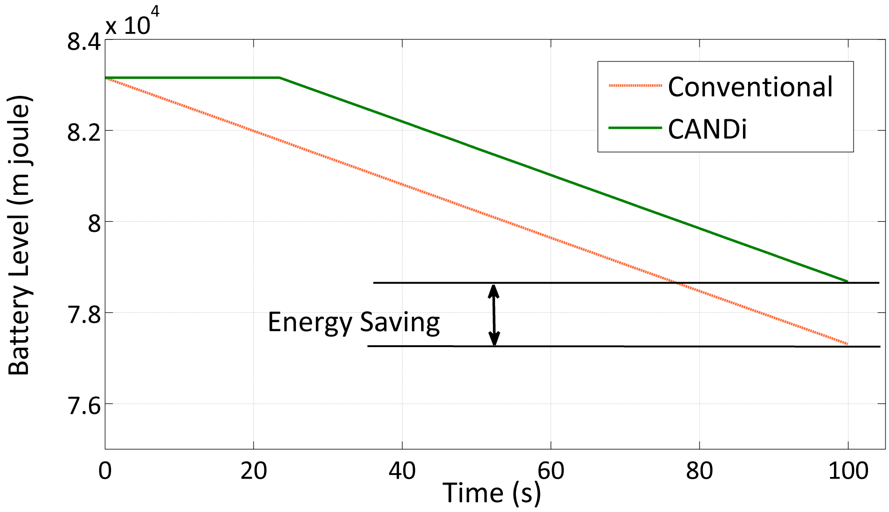

Figure 4.13: Energy consumption of scanning process of both CANDi and conventional scanning.

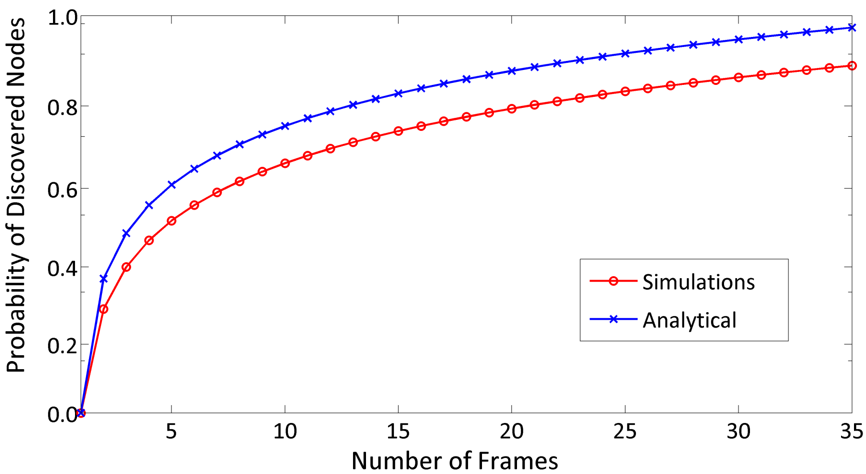

Figure 4.14: Analytical and simulation results comparison of CANDi.

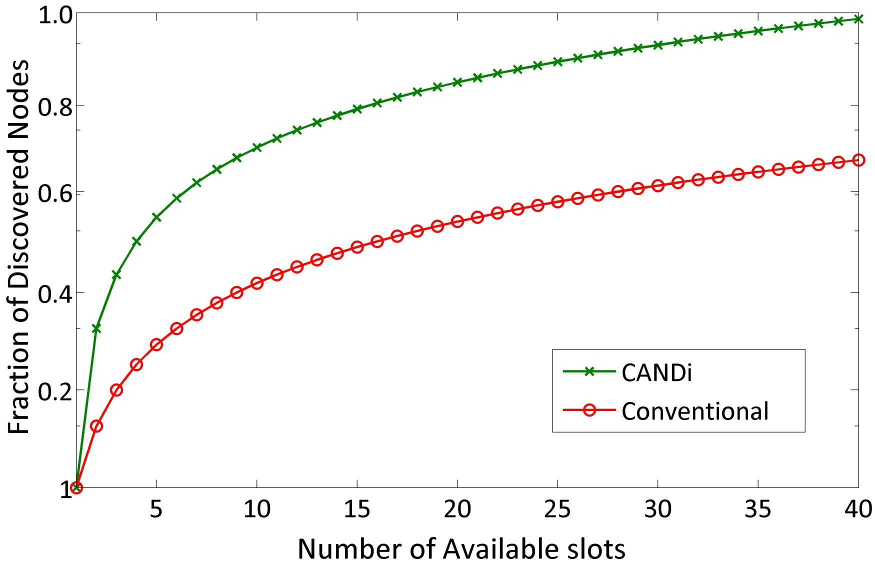

Figure 4.15: Simulation results comparison of CANDi with conventional node discovery.

results, we consider the re-transmission of lost beacon packets, the node back-off modes and the delays of the context list from WiMAX. As a result, the fraction of the discovered nodes is less when compared to the analytical results. In conventional discovery, the channel is not reserved for the incoming node to the system. Furthermore, in the case when the beacon period is saturated, then the discovering node has to wait for a considerable amount of time and periodically re-attempt to find free channels. In the proposed context based discovery, channels and the MASs are reserved for the incoming nodes. This facilitates the discovery process and helps the member nodes of the cluster to be aware of the incoming nodes to the system resulting in fast synchronization. Due to context facilitation, the proposed algorithm discovers more nodes with the same amount of available frames when compared to the conventional discovery process as shown in figure 4.15.

Figure 4.16 shows a comparison of the cumulative distribution function (CDF) of the number of attempts to discover nodes by CANDi and conventional protocols in a scenario of 10 connected nodes. CANDi follows the Cx-list information to access the reserved channel, and in more than 90% of attempts it discovers neighbors in the first attempt. Although the probability of discovery diminishes in denser clusters, where the number of nodes exceeds 50, it is still much higher than the conventional approaches, thus validating our protocol.
Conventional based discovery mechanisms periodically switch MAC status between active (transmission and reception) and sleep (idle and sleep) modes. Since, these protocols are not considering any prior knowledge for discovery, the energy consumptions are high. On the other hand, CANDi based nodes use context based scanning to become active and start

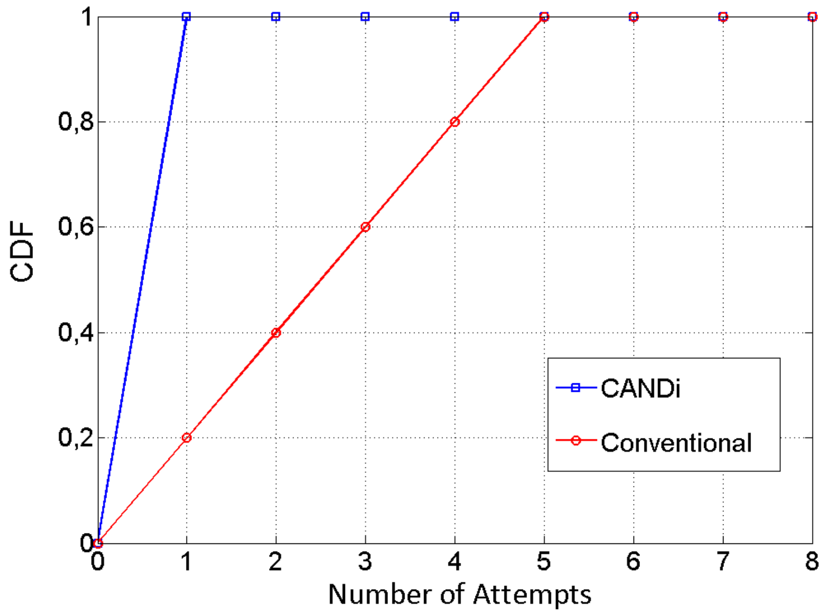

Figure 4.16: CDF of number of attempts by CANDi and conventional protocol.

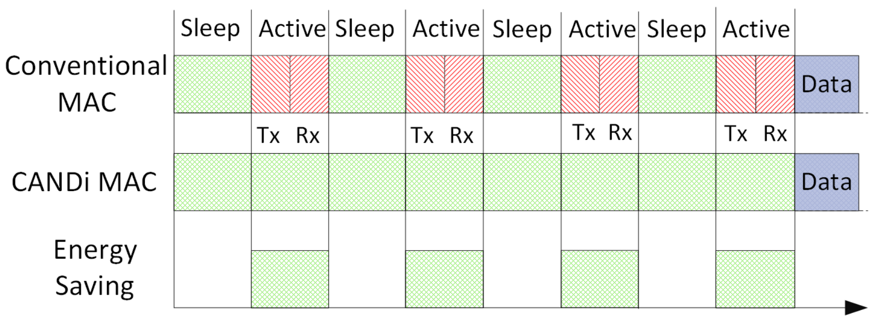

Figure 4.17: Energy consumption comparison of MAC layer during scanning process.

communication at the time when they reach the coverage area of the cluster. Thus, the unnecessary scanning is avoided by manipulating the context information received from the guided long range technology which leads to high energy saving. The energy cost and the ensued saving by using both CANDi and conventional scanning process with proper duty cycles is depicted in figure 4.17. Clearly, CANDi saves 50% energy in the node discovery process when compared to conventional discovery.

4.6 Conclusions

In this chapter, we presented a novel context based node discovery mechanism called CANDi and demonstrated its application for energy efficient node discovery in UWB, under the coverage of WiMAX and Wi-Fi. To make use of the available beacon IEs of UWB, we have proposed new IEs representing the energy level and willingness of nodes to cooperate, which contributes towards cooperative cluster building. We have shown how the context list is constructed and how the information is used at MAC layer. The context aware module is implemented to facilitate the discovery of neighbouring clusters by providing information about nodes in the vicinity of the searching MTs. By means of analytical modeling and simulations we have shown that CANDi contributes to energy saving in the discovery process and extends the MTs overall lifetime. As shown in the results, CANDi saves 50% energy in the node discovery process compared to conventional algorithms.

Chapter 5

Demonstration of Context and Short-range Cooperation for Energy Saving

The complexity of heterogeneous wireless networks in synergy with battery powered mobile devices is driving new stringent requirements in terms of power efficiency to ensure that battery life, environmental and thermal criteria can be met. Modern mobile devices are equipped with multiple interfaces, which allow them to exploit the benefits offered by heterogeneous networking environments, but on the other hand, battery power is liable to drain swiftly. In this chapter, the analysis of energy consumption of heterogeneous cooperative communications based on context information is presented. The presented results are achieved by implementing the proposed algorithms on a hardware testbed platform developed in [97]. The demonstrative testbed comprises a WiFi Access Point, which provides WiFi coverage in the infrastructure mode, as well as nodes capable of communicating through short-range Ultra-Wideband (UWB) WiMedia. The testbed includes a context aware module that provides and stores information related to different nodes in the system. The testbed is used as a proof-of-concept to show how context information can be used to save energy of mobile devices using short-range communications. More details results can be found online in the C2POWER deliverable in [122].

5.1 Introduction

Battery life time has been identified by TNS report [14] as the number one criteria for the majority of the consumers purchasing a mobile device. The concern with battery depletion is one of the top reasons why consumers do not use advanced multimedia services on their mobile devices more frequently. The motivation for reducing energy consumption is also driven by international consortiums in a bid to place tighter control on global greenhouse gas emissions. It is estimated that Information Communication Technologies (ICT) contribute with 2% to 2.5% of the global greenhouse gas emissions. And with the expansion of the ICTs in developing countries, the total figure of carbon emissions will continue to grow to an estimate 2.8% of total global emissions by 2020 [123]. Due to the increasing demand for energy saving, it would be interesting to investigate how techniques, such as context-aware and heterogeneous cooperative communications, can contribute to the energy savings of wireless communications.

Context awareness is a key feature of any cognitive radio, where understanding of the operational environment and situation state is crucial towards reasoning and decision making in resource allocation. One major challenge in the mobile system is to implement a module capable of extracting context information from the surroundings, and exploiting this for energy saving strategies for UEs. To accomplish this, it is necessary to establish a common understanding of the definition of context in our system. Context, in general, can be seen as higher level knowledge, derived from an aggregation of information or modes of parameters describing the operational environment, including information such as time, geographical location etc. This higher level knowledge is derived in a context engine. Operational context is closely linked to the actual application domain and the range of applicable situation, while environment information is dependent upon the actual use case. Context may include information about UE, network and applications. Information that forms the context can be placed into two basic categories: Information about the device itself (radio interfaces, battery capacity, maximum transmission power, processing power etc.) and information about the network (cell load, cell capacity, QoS guarantees etc). Context itself is an aggregate of such individual pieces of information, which are collected from various types of sources, including physical sensing of the radio environment, equipment data sheets, optimization policies, etc. Context information and context-awareness are now widely used in telecommunication and other related fields e.g. in short range communication [124], heterogeneous networks [125], wireless mesh network [126] etc.

On the other hand, cooperation technologies have been developed with the goal of enhancing the individual and/or group wireless link capacity. However, in today's information world there is a rich ecosystem of mobile technologies available for use. There are the cellular technologies like LTE, UMTS, etc; and the short range technologies like Bluetooth, UWB, WiBree, etc. This fact creates a great number of opportunities for cooperation with the intent of energy saving in mobile communications. Cooperative communication results in improved communication capacity, high speed and high performance. Furthermore, cooperative communication reduces the battery consumption resulting in extended network life time; it has been demonstrated to maximize the throughput and increase the stability region for multiple access schemes [127]. Cooperative communication also contributes to the enlargement of the transmission coverage area of both cellular and ad hoc networks. As a result, interest in cooperative wireless communication grew rapidly in the last decade, and the technology is continuously evolving in multiple directions.

Previously proposed systems and mechanisms, despite offering energy savings, limit their focus towards one technology only, i.e. the energy saving mechanisms in each wireless systems fail to consider the availability of alternate technology options in the near vicinity. Our proposed system advances beyond the current state-of-the-art by breaking with the non-cooperation paradigm, and proposing energy saving strategies that exploit more than one technology simultaneously. The main goals of this chapter is two fold: we aim to design and test a context based relay selection policy based on the fundamental architecture in chapter 3, and beyond that we aim to take algorithmic experimentation a step further by demonstrating the notion of context and short-range cooperation for energy saving. We implement context and cooperation on a hardware testbed, operating in real practical scenarios. For proof of concept, WiFi and UWB are the technology test-cases where conclusive results will be used to provide general design guidelines for cooperative scenarios which can be applicable to other technologies.

5.2 Scenarios

5.2.1 Scenario 1

Figure 5.1 presents the testbed based analysis scenario for a coffee shop, office or indoor heterogeneous cooperative communication. The two nodes in this configuration (scenario 1) are referred to as Originator and Intermediate. The Originator and Intermediate nodes are multi-mode nodes, equipped with UWB and WiFi and connected with Test Fixture Controller (TFC). The TFC acts as Context Aware Module (CAM) and is responsible for providing the context information and calculations of power and energy consumptions. The power consumption of the CPU, WUSB and WiFi radio modules on each node is measured, displayed and recorded whilst the Originator Node is performing the data transfer across the network from the AP. A USB analyzer is used to monitor the on-Air UWB traffic and to verify that traffic is being routed over the UWB radio via the Intermediate node. The Originator is connected with WiFi and when its battery level goes down, it receives the context information from the CAM; based on the context information it then tries to connect to the Intermediate node via UWB. After connection establishment, it sends the data via the Intermediate node

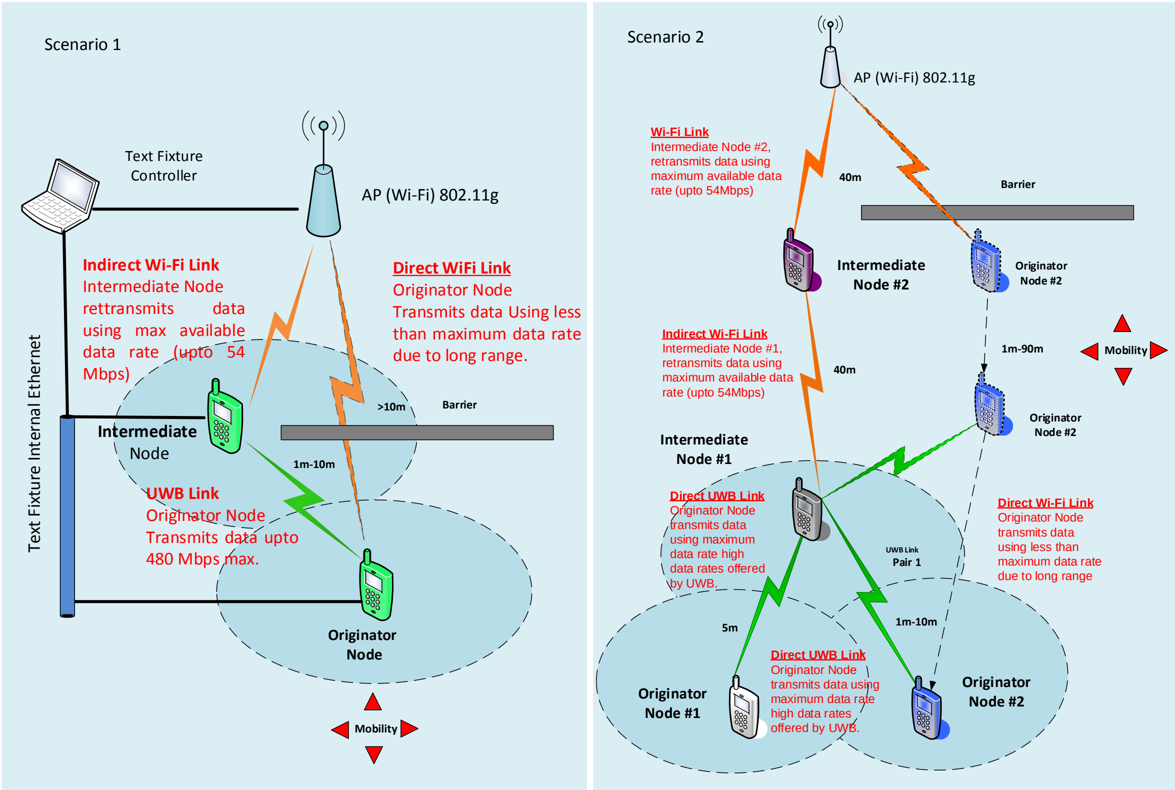

Figure 5.1: Testbed test scenarios.

to the WiFi access point (AP).

The scenario involves a data transfer of 200MByte for 300s and the measurements are undertaken using two scenarios:

- DIRECT- where the data is transferred from the Originator to the AP using only the WiFi.
- RELAY- where the data is transferred via the Intermediate node using the UWB radio between the nodes and then from the Intermediate node to the AP using the WiFi radio.

5.2.2 Scenario 2

Scenario 2, on the right side of figure 5.1, represents the multiple relays configuration. In total 4 nodes are involved in communication: two Originator nodes and two Intermediate nodes. Similar to scenario 1, the Originator and Intermediate nodes are multi-mode nodes and equipped with UWB and WiFi interfaces. These nodes are connected with TFC which acts as Context Aware Module (CAM) and is responsible for providing the context information and calculations of power and energy consumptions. Due to communication barrier, or low battery level the Originator node 2 has poor channel. Based on the internal context information the originator node 2 searches for the nearby available nodes for cooperation. The Originator node 2 has been provided random mobility and can change its location covering more wide area (upto 100m). Both Originator node 1 and 2 has a UWB link with Intermediate node 1, while intermediate nodes communicate via WiFi connection. The scenario 2 also involves a data transfer of 200MByte for 300s and the measurements are undertaken by direct and relay based communication.

5.2.3 Radio module power configuration

The WiFi radio module selected for the multi-mode nodes is a COTS dual band Ralink 802.11g and is configured for 2.4 GHz operation which is most widely used. The current implementation uses 802.11g WiFi in the 2.4 GHz band and UWB operating in WiMedia Band Group 3 (6336-7920 GHz). In order to determine and select the most optimal power saving mode, some investigations were undertaken in the RF screened room before any of the formal test runs. The WiFi radio module is configured in one of the three modes that directly affect power consumption.

- Constant Awake Mode (CAM) is the normal mode for machines where power consumption is not an issue. CAM mode keeps the radio powered up continuously.

- Power Save Mode (MAX-PSP) is recommended for devices where power consumption is a major concern, such as small battery powered devices. Power Save Mode causes the Access Point to buffer incoming messages. The Wireless Adapter must wake up periodically and poll the Access Point to see if there are any messages waiting. This has a big negative impact on throughput.

- Fast Power Save Mode (Fast-PSP) switches between PSP and CAM based on network traffic. When retrieving a high number of packets, Fast-PSP Mode will switch to CAM to retrieve the packets. Once the packets are retrieved, it switches back to PSP mode. This has a small impact on throughput, around a 20% reduction.

Based on the testing, the WiFi driver configures the WiFi radio for fast-PSP mode, as it gives the best combination of high throughput and low power consumption. A summary of the measured power consumption figures for the WiFi Radio for each power mode is shown in table 5.1.

Table 5.1: WiFi radio power summery (Direct scenario)

WiFi Radio Mode	Idle Power (mW)	Avg. Radio Power (mW)	Active Power (mW)	Avg. Through-put Mbps	Peak Through-put Mbps	Duration to transmit 200 MB.
CAM	620	857	760-1220	14.50	18.70	116s
Fast-PSP	134-600	727	900-1220	14.20	18.50	118s
MAX-PSP	134-550	950	900-1220	1.87	5.70	898s

5.3 Proposed Context Based Relay Selection Mechanism

5.3.1 Relay Selection Algorithm

The proposed context based relay selection algorithm is depicted in figure 5.2. MT collects its internal context information from CAM and checks its battery level (BL) or SNR value with threshold values. Lower BL level and SNR trigger MT to pledge the cooperation process. Moreover, context information related to the MTs in the vicinity is stored in CAM and the optimal relay section process is propped up by context information. BL, SNR and Willingness (W) of the neighbor nodes are compared with the pre-defined threshold values and the optimal relay is selected to start the cooperation process.

5.3.2 Proposed Beacon Frame Structure

The testbed implemented frame named as the C2P frame is shown in figure 5.3 and reflects the variety of purposes it is used for. The C2P frame consists of a header which defines: the message type, addressing type (either 1 for Unicast or 0 for Multicast), supported RATs (the technologies which are available to the mobile node) and supported cooperative strategies (the cooperative strategies available to the user of the mobile node). After the header, the C2P frame contains a Destination address field, which shall utilize the MAC address of the destination device or the multicast MAC address (agreed by the nodes in the cluster) of the cluster or the broadcast address. The rest of the C2P frame contains a payload specific to each of the cooperative strategies that are employed. The proposed C2P frame yields not only the exchange of information between neighbouring devices, but also enables the creation of more complex networking forms such as clusters that enable application of energy saving schemes in cooperative manner.

Apart from the utilization of application specific payload of beacon frames in WiMedia and WiFi, there are situations where it might be beneficial to change the transport scheme of C2P

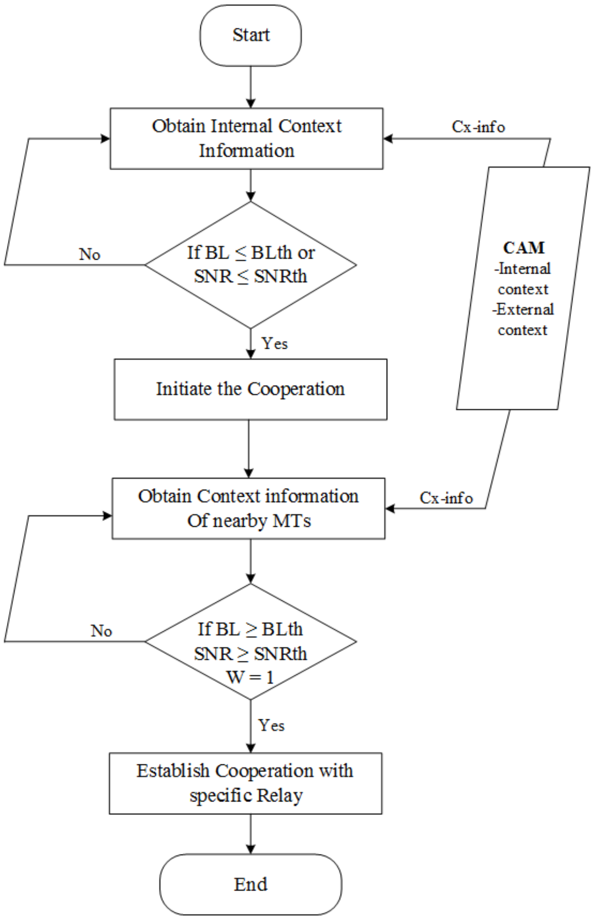

Figure 5.2: Flowchart of the proposed context based relay selection.

frames based on the characteristics of the underlying technology. First of all, such situation occurs when the application specific payload of beacon frame is already utilized by other applications or by excessive inclusion of Information Element (IE congestion). Second, C2P frames based application might be utilized by a technology, which does not support beacon frame exchange, for example Bluetooth4. In both situations, C2P based application is required to perform frame adaptation, so that C2P frame is exchanged through the payload of data frames. In this particular situation, a multi-mode layer is required to provide mechanisms that enable users to choose which short-range technology is utilized to exchange multi-mode frames (by default WiMedia or 802.11 in such precedence are assumed if available). The adaptation function shall insert multi-mode frames into appropriate transport frames. If applicable, the adaptation function should also reserve data channel as well as read incoming multi-mode frames from the same technology. In case of IE congestion, multi-mode enabled device should either refrain from distributing C2P frames (there is no space in each of the consecutive beacon frames to include user specific data) or include into the beacon a pointer

2 bytes				8 bytes	n bytes
C2P Frame header				Destination address	Payload
3 bits	1 bit	6 bits	6 bits	64 bits	8*n bits
Message type	Addressing type	Supported RATs	Supported Cooperated strategies	MAC address	Defined for corresponding cooperation strategy

Figure 5.3: Distributed C2P beacon frame structure.

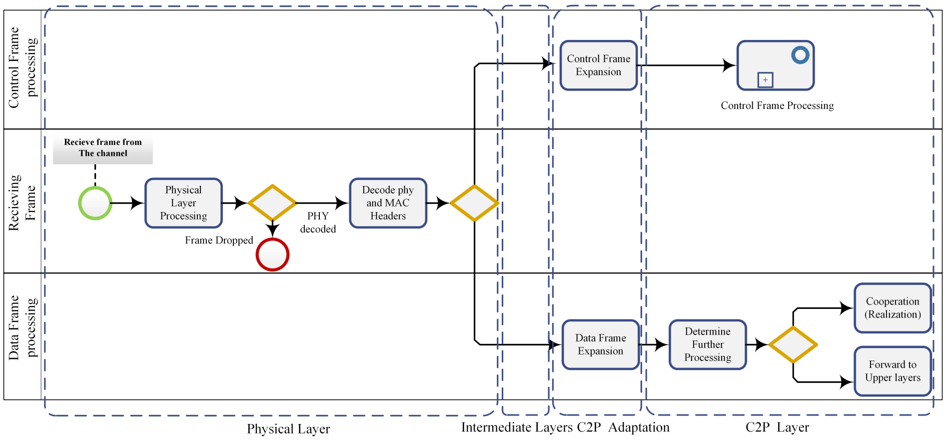

Figure 5.4: Frame processing within multi-mode network device.

frame that indicates that the C2P Distributed Management frame will be included into the data frame payload. The pointer frame should have a separate Message Type and its value should replace the C2P frame payload.

5.3.3 Frame Processing

Based on the presented layered model, we now analyze the frame processing scheme of the proposed context based architecture available in a multi-mode testbed device. Each layer of the protocol stack encapsulates the out-going packet with its own header, thereby connecting to its peer layer on other devices, which can subsequently expand the received packet and read the included information. However, the proposed system does not generate its own control frames; instead it utilizes vendor specific information in the beacon frames already available in the technology. Figure 5.4 presents a frame processing scheme for a device equipped with our proposed system capabilities. The figure illustrates a set of key processing steps in a network; when a new frame is received from the channel, it is decoded in the PHY and MAC layers, which is outside of the multi-mode application. At this stage the frame can be dropped due to RSSI being below the received threshold, unrecognized type or un fixable errors. As an alternative, one can utilize maximum ratio combining, which requires the incorrectly received frames to be stored and combined with others to benefit from multiplexing gain. At that point, the frame is passed to the adaptation layer which determines whether it is a control or data frame.

5.4 Mathematical Analysis

In this section we present our energy analysis using multi-mode nodes (WiFi and UWB) in context based cooperative relaying. Let TD be the time allocated to the transmission of data packet D. Each time slot is assumed to be fixed. Since, each node is equipped with two interfaces WiFi and UWB; we define the data rate offered by the UWB and WiFi as R_u and R_w respectively. The time spent by the originator node to send the packet D via UWB to the intermediate node is

$$T_{org} = \frac{D}{R_u} \tag{5.1}$$

Similarly, the time spend by the intermediate node to send the data packet D to the WiFi access point (destination) is

$$T_{\text{int}} = \frac{D}{R_w} \tag{5.2}$$

Since the size of the data that the originator or intermediate node is sending is known, then size of each packet over WiFi or UWB is

$$D = \frac{T_D \, R_w}{N} \tag{5.3}$$

Where N is the total number of available slots.
From equation 5.1 and 5.3 we can get

$$\begin{aligned} T_{org} &= \frac{T_D \, R_w}{N \, R_u} \\ &= \frac{T_D}{MN} \end{aligned} \tag{5.4}$$

Where

$$M = \frac{R_u}{R_w}$$

M Represents the ratio between the two transmission rates e.g. UWB and WiFi. Since $R_u > R_w$ then the time required for the transmission of same data over relay link is less than the direct link.

We now calculate the energy consumed by using direct WiFi connection and relaying the information via the intermediate node. It is known that:

$$E = P_T \times T \tag{5.5}$$

Where E is the energy consumed, PT is the power of transmission and T is the total time. Let P_u be the transmit power of originator node using UWB, we then calculate the energy consumed as

$$E_u = P_u \times T_{org} = \frac{P_u \, T_D}{M \, N} \;\; Joules \tag{5.6}$$

Similarly the energy consumed by using the WiFi Link is

$$E_u = P_w \times T_{org} = \frac{P_w \, T_D}{M \, N} \; Joules \tag{5.7}$$

The intermediate node receives the packets from Originator node by using UWB ,and then by using WiFi, it sends the data to the AP. To achieve the desired QoS by using WiFi we denote the achieved data rate as R_w , then the time spent in the transmission of D packets

$$T_D = \frac{D}{R_w} \tag{5.8}$$

Where $T_D = T_{\text{int}}$. The intermediate node performs the cooperation and receives the packets via UWB, and then performs the coding to get the desired QoS , and send it via WiFi ; thus the total energy consumed is given as follow

$$E_{c,\text{int}} = P_{c,w} \times T_D = \frac{T_D P_{c,w}}{R_w N} \tag{5.9}$$

Where $P_{c,w}$ is the power consumed by the intermediate node in WiFi mode to achieve R_w date rate. The cost of relaying in cooperation mode is given as

$$E_{coop} = E_{org,\text{int}} + E_{c,\text{int}} \tag{5.10}$$

Where $E_{org,\text{int}}$ is the energy consumed by the relay node in processing the packets sent by the originator nodes over UWB. The cooperation has an associated cost because useful battery is consumed to perform the cooperation. Therefore, the cooperation gain G is the ratio of energy consumed in cooperation mode to the non-cooperation mode.

$$\begin{aligned} G &= 1 - \frac{E_{coop}}{E_{non-coop}} \\ &= 1 - \frac{E_{org,\text{int}} + E_{c,\text{int}}}{E_{c,\text{int}}} \\ &= \frac{E_{org,\text{int}}}{E_{c,\text{int}}} \end{aligned} \tag{5.11}$$

Since $E_{org,\text{int}} = E_u$ then

$$\begin{aligned} G &= \frac{N.\frac{P_u T_D}{NM}}{T_D P_{c,w}} \\ &= \frac{P_u}{M P_{c,w}} \end{aligned} \tag{5.12}$$

The power saving gain from the energy consumed is calculated as follows

$$\begin{aligned} G_p &= \frac{E_u}{E_{c,\text{int}}} \\ &= \frac{\frac{P_u T_D}{NM}}{\frac{T_D P_{c,w}}{N R_w}} \\ &= \frac{R_w P_u}{M P_{c,w}} \end{aligned} \tag{5.13}$$

Again, the power saving mainly depends on the transmit power consumed by UWB and WiFi and also the data offered data rates.

5.5 Results and Discussions

This section presents the results of tests conducted on the C2P Node in an open office environment for both the direct and relay scenarios at various ranges from the AP.

5.5.1 Power measurement analysis

The power consumption of the CPU, WUSB and WiFi radio modules on each node is measured for a fixed duration of 300s, which is considered to be long enough to allow the file transfer to complete for all test cases. The Telemetry Controller generates a set of time-stamped log files of the measured power consumption of the CPU, WiFi and WUSB radio modules in each DUT. Four files are generated in total, two for the Originator node and two for the Intermediate node, grouped into sets - one for the DIRECT scenario and one for the RELAY scenario. The Originator generates a tabularized log of data throughput,

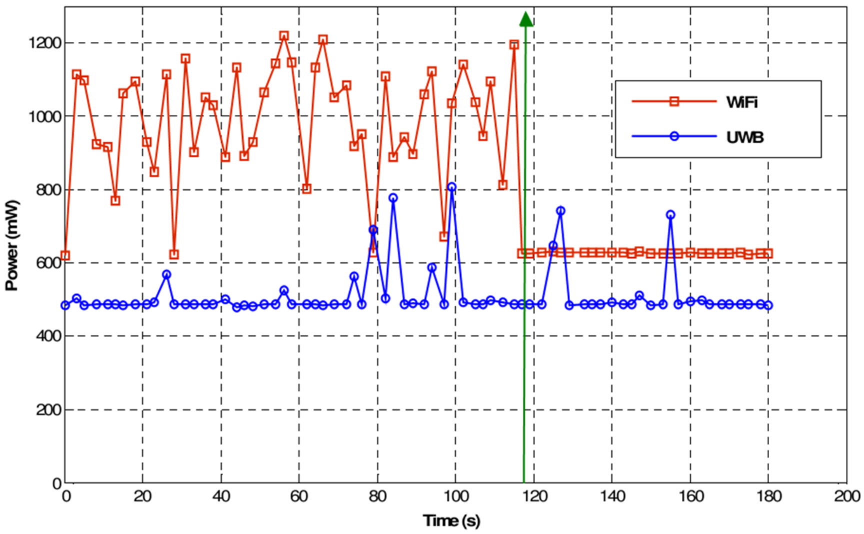

Figure 5.5: Originator node power consumption of WiFi (CAM mode) in direct scenario.

time-stamped at 1 second intervals.

Figure 5.5 and 5.6 compare the power consumption of the two radio interfaces in the DIRECT scenario for WiFi CAM and Fast-PSP modes. The idle power of the WiFi radio (Blue line) in the CAM mode is 620mW. The active power when transmitting is roughly the same as the CAM mode at 1200mW, however, the idle power of the WiFi radio in the Fast-PSP mode is only 135mW, waking up periodically to 620mW. Both modes, CAM and Fast-PSP, take time duration of 118s to transfer the same amount of data. Although, CAM provides best connectivity from the users perspective, the idle power consumption of Fast-PSP mode is very low compared to the CAM mode which can contribute to the energy savings of the terminal. UWB power consumption is almost the same in both scenarios.

The power consumption of WiFi radio operating in MAX-PSP mode is shown in figure 5.7. Devices operating in MAX-PSP go to sleep mode once it receives information that no data is available for that station. The device turned off its transmitter for 10 beacons and wakes up to listen for the 11th beacon. This process will continue until there is data available for the station to transmit or receive. Due to this periodic switching between sleep and wakeup modes, we can see the file transfer takes a very long time to complete; 900s as opposed to the 118s for the other two modes. Furthermore, it can be seen that the frequent switching off the radio results in a poor trade-off between power and throughput. Based on the testbed results, Fast-PSP is selected as a practical choice for the wireless testing in the energy calculations as it provides optimal battery life and network performance.

Central Processing Unit (CPU) of mobile terminals consumes considerable amount of energy which is neglected in most of the previous analysis. We include CPU power consumption

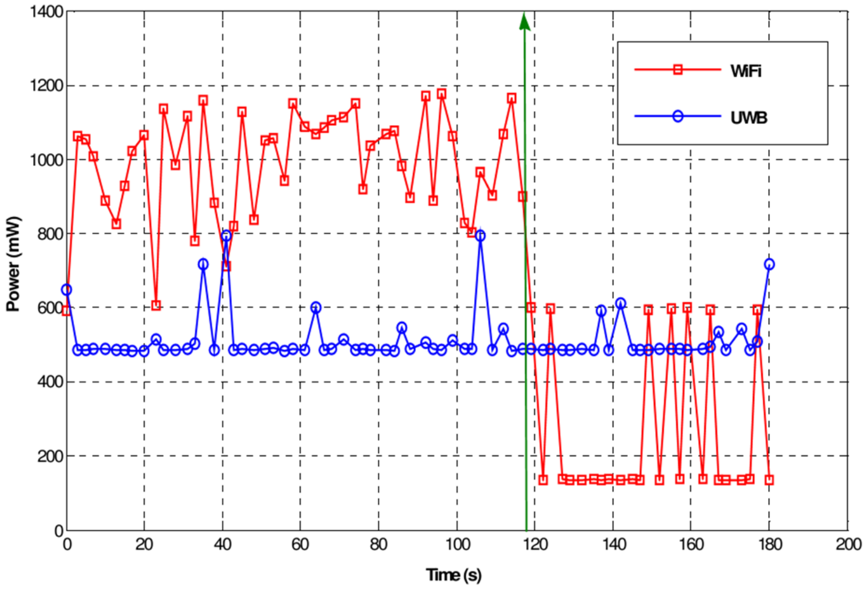

Figure 5.6: Originator node power consumption of WiFi (Fast-PSP) in direct scenario.

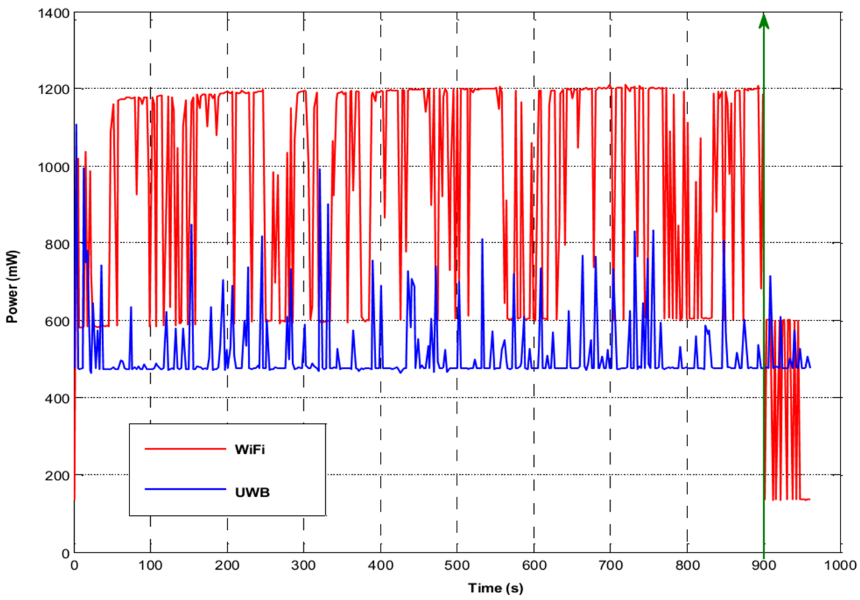

Figure 5.7: Originator node power consumption of WiFi (MAX-PSP) in direct scenario.

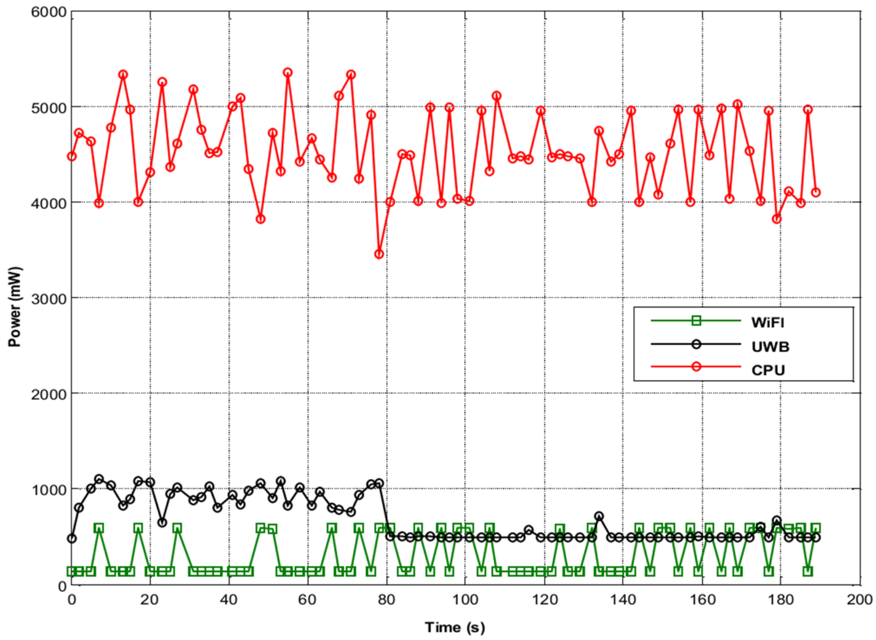

Figure 5.8: Power Consumption of the testbed's radios and CPU in relay scenario.

as part of power analysis in cooperative communication as shown in figure 5.8. Power consumption of the node, considering the radio interfaces (WiFi and UWB) and CPU is shown in figure 5.8. As depicted in the figure, the power consumption of CPU is much higher than the radio interfaces.

5.5.2 Energy measurement analysis of scenario 1

This section presents energy analysis of the testbed nodes used in direct and cooperative heterogeneous communications. From the previous section it is determined that Fast-PSP mode of WiFi is the most suitable for energy savings and used in the rest of energy analysis tests.

Figure 5.9 shows the energy usage (UWB, WiFi and CPU) in both the direct and relay scenarios in the fixed duration scenario (300s). The direct link between Originator node and the AP is experiencing bad channel conditions which results in low data rate. Since each node has a context-aware module which provides information related to the available devices in the vicinity, the originator node decides to cooperate with the Intermediate node to achieve better energy efficiency by relaying its data on the short range UWB. The energy consumption is first calculated for the direct case where the Originator node uses direct connection with AP to send data. While in the relay case, the Originator node sends data to intermediate node via UWB link which then sends it to the AP via WiFi connection. As we observed in the previous

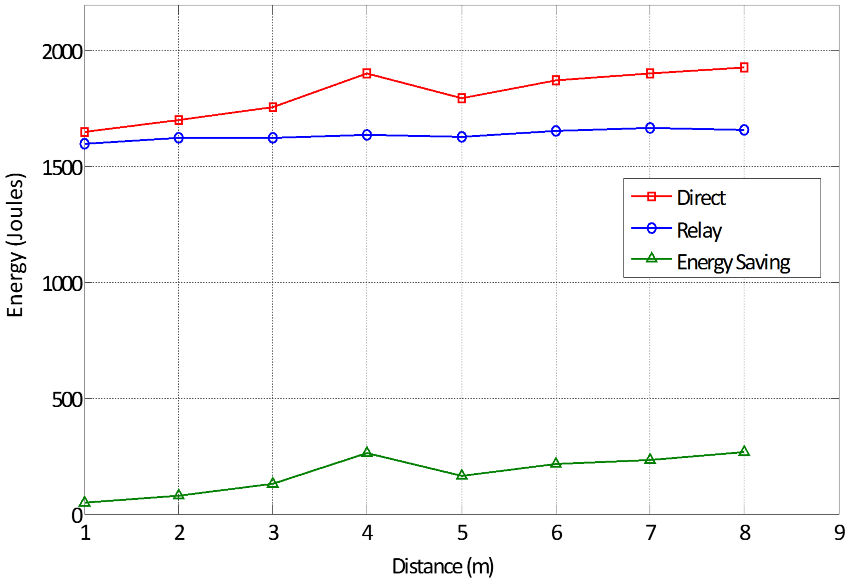

Figure 5.9: Energy consumption comparison of direct and relay scenario (Fixed Durations 300s).

section the power consumption of WiMedia is much lower than that of WiFi, and UWB can provide a data rate up to 480 Mbps; hence, UWB saves energy via cooperation. It is clear that more energy is consumed in the direct scenario compared to relay based communication. The total energy savings is also depicted in the figure 5.9.

Similarly, figure 5.10 shows the energy consumption comparison of direct and relay communication for a file transfer of 200 MB. Initially the energy saving is less when the Originator node is at a shorter distance from the AP, in both direct and relay scenarios, but at a distance of 4m and beyond a considerable amount of energy is saved via relay based communication. At a distance of 1m the energy saving is 13.96% which gradually increases and reaches 68.64% at a distance of 8m. In comparison to the fixed time duration scenario (300s), high energy saving is achieved in fixed size data transfer scenario. For instance, 68.64% energy is saved at a distance of 8m in fixed data scenario compared to 13.97% in the fixed time duration scenario.

The previous figures, 5.9 and 5.10, depicted the energy consumption and savings of the whole testbed node (interfaces and CPU). While, figure 5.11 shows the total radio (WiFi and UWB) energy consumed by the DUT over the duration of the test measurement period of 300s. Considering heterogeneous cooperative communication in comparison to direct communication, the total radio energy saving, in the relay scenario increase from 17.28% at a distance of 1m to 45.13% at distance of 8m. Considering as an example of energy consumption, the radio interfaces (WiFi and UWB) consumes 541.53 joules of energy at a distance of 8 m in di-

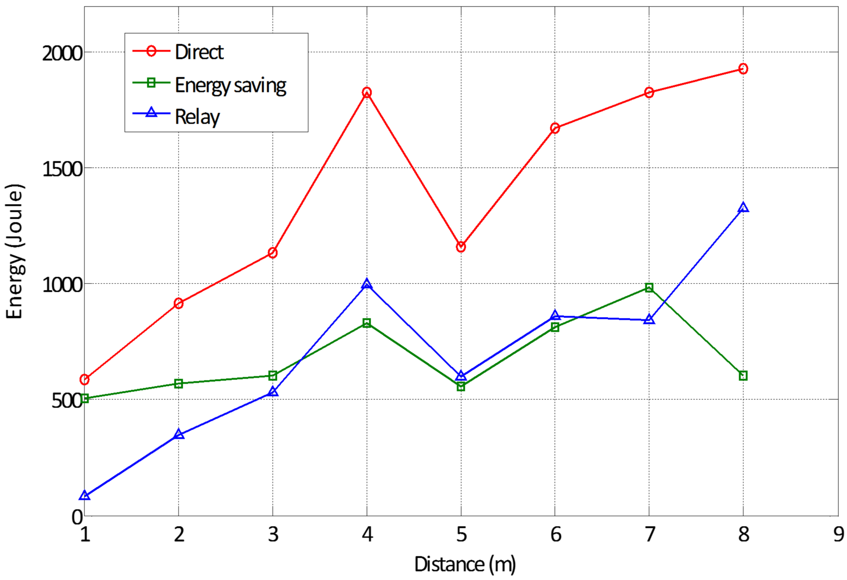

Figure 5.10: Energy consumption comparison of direct and relay scenario (200MB File Transfer).

rect communication compared to 244.38 joules of energy in case of heterogeneous cooperative communication. Clearly, transmitting via the RELAY path offers a distinct advantage as it utilizes the faster UWB radio which offers greater bandwidth and more power efficiency consequently saving energy.

The total radio energy (WiFi and USB) consumed by the DUT for the duration of the 200Mbytes file transfer is shown in figure 5.12. The total energy saving of the interfaces in heterogeneous cooperation is more in fixed data scenario compared to the fixed time duration scenario. For instance, at a distance of 1m from AP, the energy savings of the radio interfaces in cooperative communication is 31% which further increase to 75% at a distance of 8m. There is a sudden boost in energy savings at distance of 4m due to more favorable propagation conditions. Viewed from this perspective, transmitting via the relay path offers a distinct advantage and an even greater saving which increases with distance from the AP.

Based on the analytical calculations and testbed results, the energy gain comparison with respect to distance is depicted in figure 5.13. As we can see from equation 5.12, the energy gain mainly depends on the values of the transmit powers of UWB and WiFi and the data rates offered by both technologies. Since, UWB offers high data rate (54-480 Mbps) at lower power consumption (100-300 mW) compared to WiFi, higher energy gain is achieved by using UWB compared to WiFi. Moreover, energy gain increases both analytically and via the testbed results when the Originator node moves away from AP. At shorter distance from the destination (AP in this case) the gain is very small which signifies that there is no

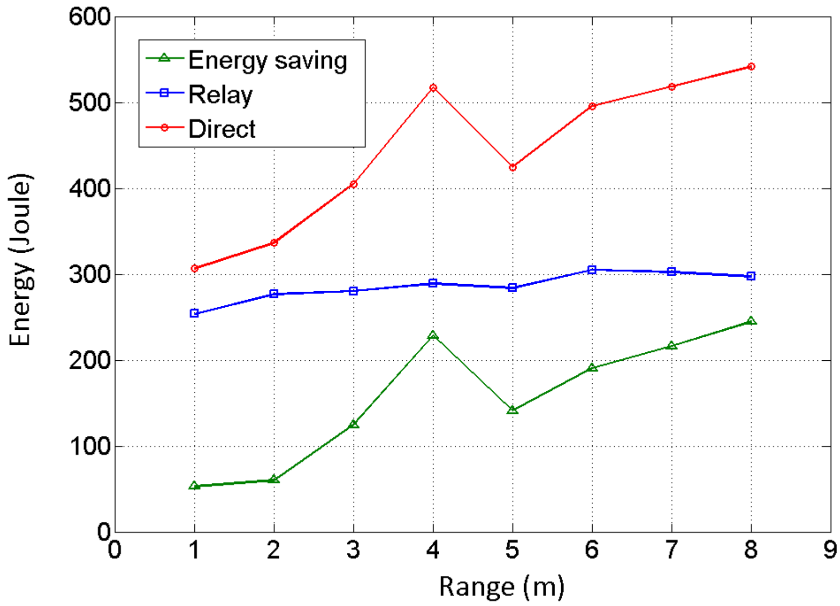

Figure 5.11: Total radio energy consumption comparison of direct and relay scenario (Fixed durations 300s).

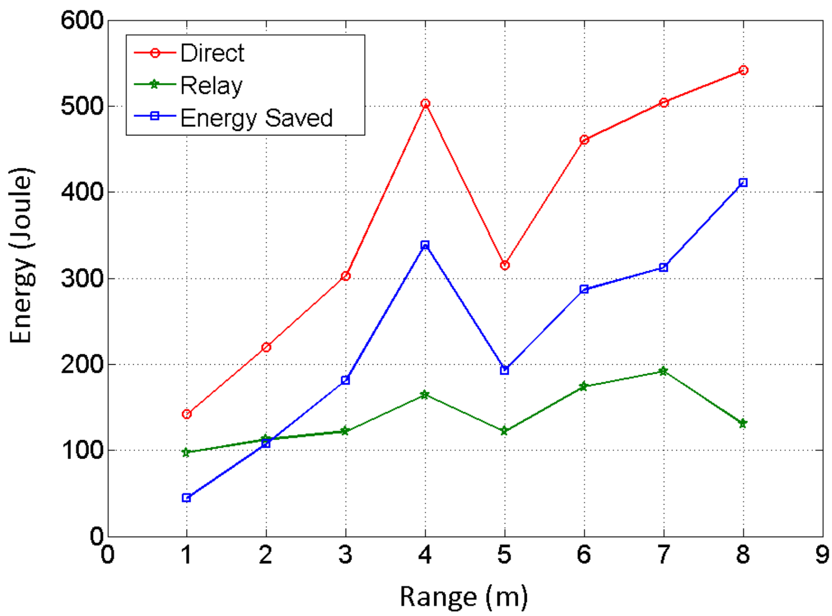

Figure 5.12: Total radio energy consumption comparison of direct and relay scenario (200MB File Transfer).

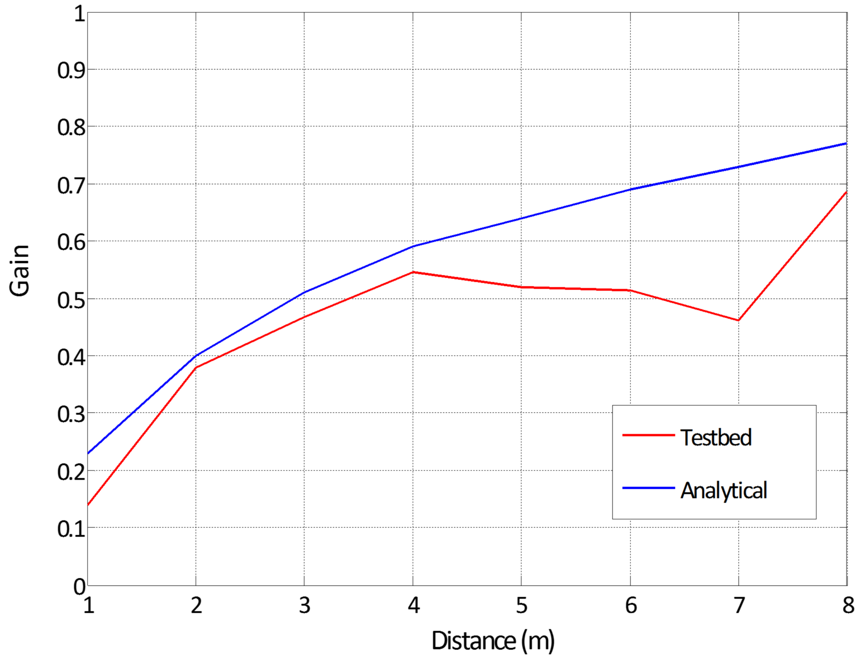

Figure 5.13: Energy gain comparison analytical and testbed.

need to apply cooperative strategies. On the other hand, with an increase in distance from the destination, the channel can experience interference and leads to bad channel quality thus requiring cooperative communication. Furthermore, it can be seen that the analytical gain is more in line with the real testbed results, although the analytical calculations are not considering the interference and other propagation parameters.

5.5.3 Energy measurement analysis of scenario 2

Figure 5.14 show the energy consumption with respect to the Originator Node for both the DIRECT and RELAY scenarios over the fixed time period (300s). Extrapolating from the two curves, from the perspective of the Originator Node there is about a 7% energy saving for the RELAY scenario for all data rates.

Figure 5.15 show the energy consumption with respect to the Originator Node for both the DIRECT and RELAY scenarios over the duration of the 200MByte file transfer. Extrapolating from the two curves, from the perspective of the Originator Node there is about a 7% energy saving for the RELAY scenario for all data rates. This is lower than for the 2-Node scenario.

Figure 5.16 show the total radio energy (WiFi and WUSB) of the Originator Node consumed by the DUT over the duration of the test measurement period of 300s. There is an energy saving for the RELAY scenario for all data rates. Considering just the radio energy consumed, clearly transmitting via the RELAY path via the two intermediate nodes offers a distinct

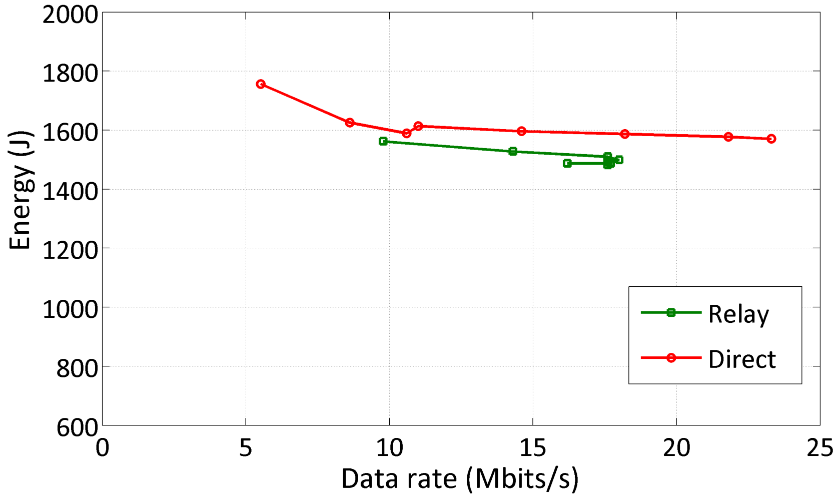

Figure 5.14: Total energy consumption comparison of direct and relay scenario (Fixed duration) with respect to date rate

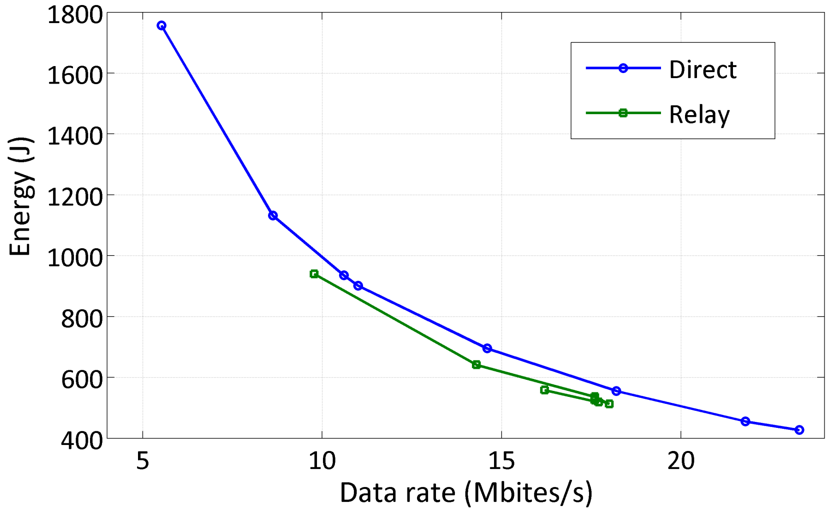

Figure 5.15: Total radio energy consumption comparison of direct and relay scenario (200MB File Transfer).

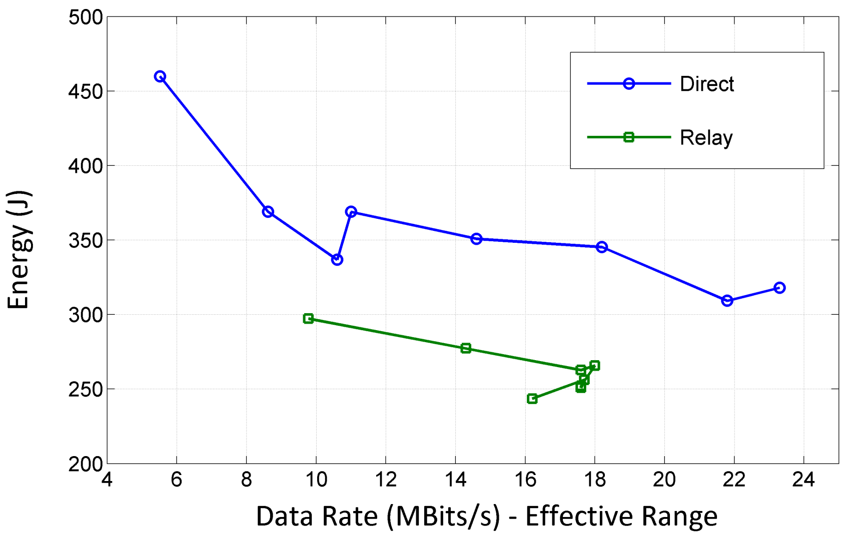

Figure 5.16: Total radio energy consumption comparison of direct and relay scenario (Fixed duration).

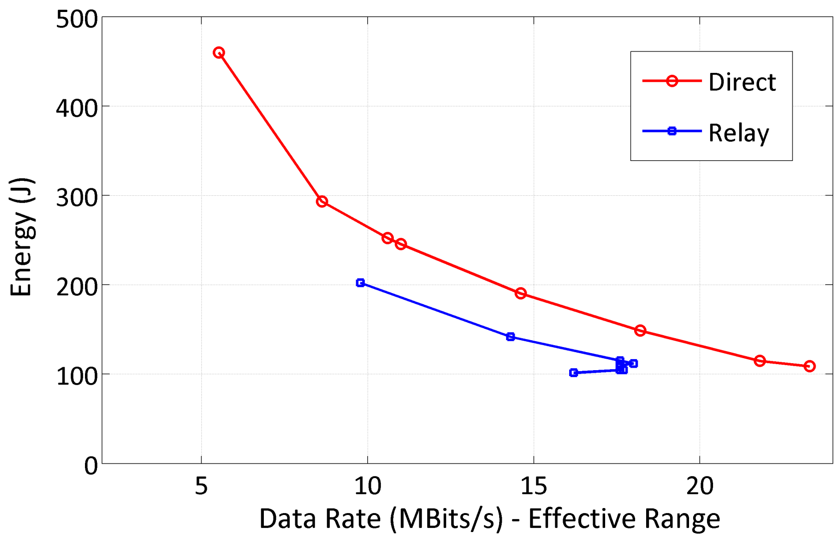

Figure 5.17: Total radio energy consumption comparison of direct and relay scenario (200MB File Transfer).

advantage. There is a substantial energy saving for the RELAY scenario for all data rates due to the lower power consumption of the USB radio on the originator node. Extrapolating from the curves yields an energy saving of between 14% - 23% depending on the data rate. The total radio energy (WiFi and WUSB) of the Originator Node consumed by the DUT for the duration of the 200Mbytes file transfer is shown in figure 5.17. Considering just the radio energy consumed, clearly transmitting via the RELAY path via the two intermediate nodes offers a distinct advantage. There is a substantial energy saving for the RELAY scenario for all data rates due to the lower power consumption of the WUSB radio on the originator node. Extrapolating from the curves yields a saving of between 20 - 25% depending on the data rate.

5.6 Conclusions

In this chapter, we demonstrate a new context based mechanisms and cooperation for energy saving in heterogeneous communication networks using hardware experimental platform. The testbed is composed of several nodes called C2P Nodes and each node is equipped with UWB and WiFi radio interfaces. A new layer called C2P layer is introduced that implements the algorithms running over these multiple interfaces. The testbed is used for an indoor office or coffee shop scenario, and involves a data transfer of 200MByte for 300s in both direct and relay based communication. The WiFi power modes have been tested for the proposed scenario as suitable power modes can have a considerable impact on energy savings of the system. The most energy efficient mode is witnessed in Fast-PSP through testbed results. Fast-PSP resulted in higher throughput, compared to being always awake, and also resulted in 4 times reduction in the radio power in idle mode. In the fixed time duration scenario, the energy saving varied from 3% at a distance of 1m to 14% at 8m. Whereas in the duration of the file transfer scenario, the energy saving varied from 14% at a distance of 1m to 68% at 8m, indicating that applications which disconnect when idle, and handset operating systems that can shut down radios aggressively will benefit the most. Similarly, from scenario 2 results we conclude that the energy usage increased with distance, as the WiFi radio had to increase its transmit power in an attempt to maintain the throughput exploiting rate adaptation, consequently this led to longer transmission time favoring relay based communication.

Chapter 6

Context Aware Radio Resource Allocation for Energy Saving in LTE-A

In this chapter we are utilizing context information in the scheduling process as traditional packet scheduling algorithms are mainly designed for increasing spectral efficiency (SE) but not for energy saving. We used Long Term Evolution Advanced (LTE-A) which is one of the promising technology for achieving higher data rates. We proposed a Context Aware Scheduling (CAS) algorithm which considers the context information of users along with conventional metrics for scheduling. An information model of context awareness along with a context aware framework for resource management is also presented in this chapter. CAS is simulated via a system level simulator and the results obtained show that considerable amount of energy is saved by utilizing the context information compared to conventional scheduling algorithms.

6.1 Introduction

Energy efficiency and low carbon strategies have attracted a lot of concern in the recent years. Driven by the rapidly increasing demand of high data-rate, the Spectral Efficiency (SE) of today's wireless system has dramatically improved over the last few decades. In the recent years, there is a need to improve both the spectral efficiency as well as the Energy Efficiency (EE), since the energy consumption has become an important issue from both economic and environmental aspects; and future devices are expected to become power hungry to support rich content services. The EE can be tackled through the exploitation of techniques and mechanisms from application to physical layer. In this chapter we investigate the energy saving challenge on the network side and in particular tackle the radio resource management aspect.

Radio resource management is pivotal for allocating users to the available radio resources in a dynamic manner and scheduling is a key component in this process. Traditional scheduling policies encompass Round Robin (RR), Maximum Carrier to Interference ratio (Max C/I) and Proportional Fair (PF) scheduling are the three conventional and most popular scheduling methods. RR allocates equal resources to all users, regardless of their current channel condition. On the other hand, Max C/I scheduling aims at maximizing the total cell throughput by considering CQI values fed back to eNB from the UEs. This leads to unfairness, as users that are further away from eNB (or have bad channel conditions) will not be allocated a fair share of the radio resources. The PF algorithm, [128], tries to provide fairness by increasing the priority of a mobile user who has a relatively low value of the C/I ratio. Several variations of the Proportional Fair scheduler, including a channel adaptive version, have been investigated in [129]. However, typical parameters available to scheduling policy are limited to QoS and channel state information. Going beyond this parameter scope in terms of providing context information, can lead to more intelligent scheduling decisions. The word "context" has been applied different definitions and different levels of applicability. In case of wireless networks the context is categorized into two basic categories, UE and network related context [130]. Contrary to the conventional scheduling mechanisms, there are a number of context information available to the UE that can be exploited in resource management based on the motivation and scenarios e.g. transmit power, battery level, mobility, traffic type etc.; this information can be made available from the network. In order to focus on energy saving and QoS provisioning, battery level along with traffic type and channel condition of each UE is considered in our proposed scheduling approach.

The major contributions of this chapter are as follows:

- Context architecture and framework for context based scheduling algorithms.

- Context information based signaling in LTE-A.

- Context based battery priority scheduling algorithm for low battery devices in congested scenarios where UE has limited access to recharging, and utilizing high data rate applications.

- Implementation of context information based module in a system level simulator for LTE-A.

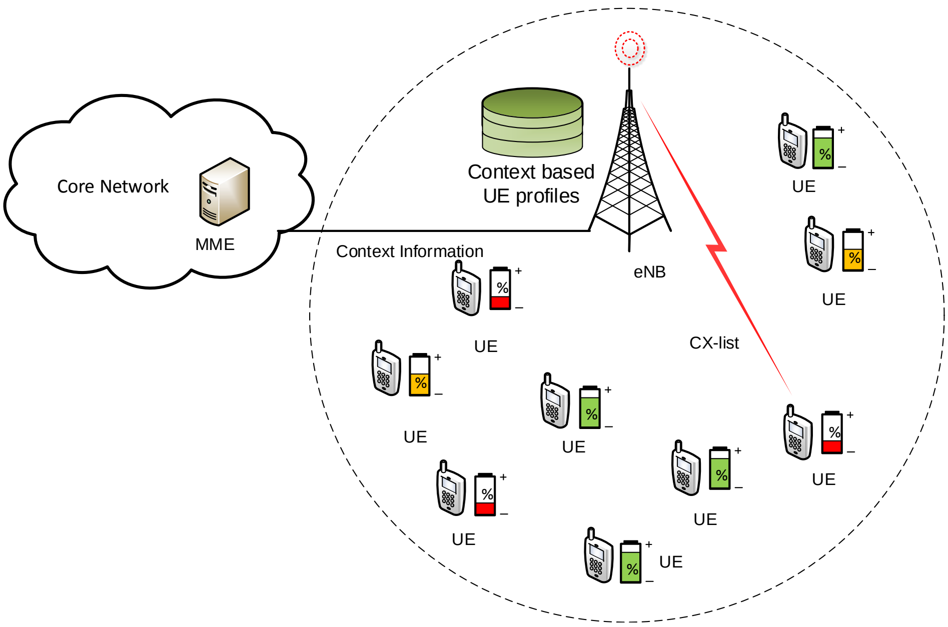

Figure 6.1: Scenario for the proposed context based scheduling.

6.2 Scenario

The proposed scenario for context based scheduling is depicted in figure 6.1. The scenario shows an LTE-A cell having eNB and several UEs randomly deployed inside the cell. Each UE gathers its required context information into a Context list (Cx-list) and sends this to eNB on the LTE-A uplink feedback channel. A context based database is maintained at each eNB which is updated each time it is triggered by the UE, or when there is a change in the UE's dynamic context information e.g. battery level, channel quality etc. The eNB will create a temporary profile for this UE which contains UE's temporary identity as well as key context information associated with the corresponding bearers including priority prioritized bit-rate and etc. The context information will be utilized for eNB downlink and uplink scheduling to guarantee QoS. The created profile for each UE will be removed once the UE moves into another cell, switches into idle mode, or switches off.

6.3 Context Based Scheduling Framework and Architecture

An information model of the context awareness is presented in figure 6.2. This model basically illustrates how Context Information (Cx Info) is extracted and processed by various functional blocks in the context aware architecture. The outcome of this information model is the implementation of energy saving strategies based on the given context settings. What follows is a brief description of the different modules of our context architecture: Context

Provider is the source of Cx Info. This Cx Info is obtained directly from the radio environment (e.g. from terminal measurement or network) without any processing. For instance, the information can be battery levels of MTs or signal strength to determine distance between mobile terminals and BS. If the mapping to the scheduling framework is considered, the context provider resides in both terminal and network side. The policy set is the set of strategies that can be used by radio, in other words it imposes constraints on the radio functionalities. The context manager is responsible for Cx Info processing to provide refined Cx Info for the decision engine. It consists of two blocks: Context Reasoner and Context Filter. The Context Reasoner collects raw Cx Info and generates rules for context filtering based on the constraints from the policy set. The reasoner may need to process the Cx Info to generate rules; however it will not alter the information content. The Context Filter filters the Cx Info based on the rules generated by the context reasoner and output the high level operational Cx Info for the decision engine. The decision engine is the core of the context awareness framework. It makes decisions based on operational Cx Info from the context manager and the constraints from the policy set. The decision will be implemented or used as a knowledge build-up. Configuration profiles represent a knowledge database built based on previous decisions. They can be seen as results of learning process. For example in a learning process, the implementation of a decision will be evaluated. A good (energy efficient) decision will be given a higher score. Good decisions with high scores are likely to be repeated in the future if the context setting permits. The framework is shown in the figure 6.2. The context related to scheduling is gathered at the UE and signaled to the BS. The BS gathers the information from all the connected UEs and its own information in UE context provider module. The collected context information is passed to the scheduling process where the proposed algorithm calculates the priority of each UE, based on the context parameters; which are battery level, channel quality and traffic type. The scheduling is performed in presence of network policies provided by the policy set module. The scheduled decisions are passed to the decision and implementation module.

6.4 The Representation of Context Information

Context information, such as the received SINR, usually is a value/vector in continuous domain, which contains infinite entropy and cannot be processed by today's digital systems. The common method is to predefine a table, which divides the original infinite-number of continuous values/vectors into finite-number of discrete regions. All the values within one region are represented by the index of this region. For example, LTE-A has standardized a QoS table having 9 elements shown in table 6.1. The index of each element in the table is

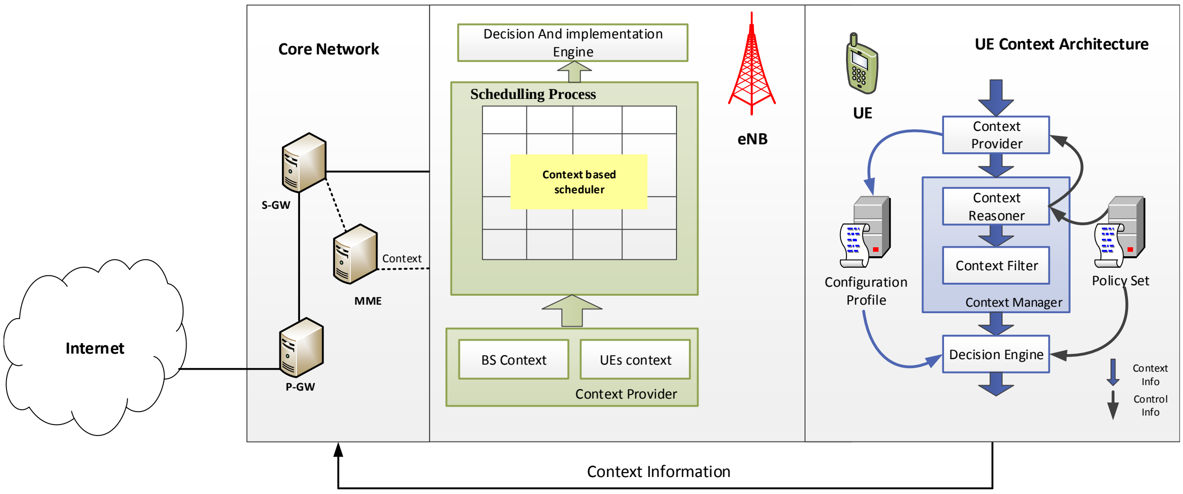

Figure 6.2: Context Architecture and Framework for Proposed scheduling algorithm.

called Quality Classification Indicator, which could be represented using 4 bits. Similarly, the SINR values are mapped into 16 combinations of modulation and coding schemes.

Following the same strategy, we could pre-define a table to represent the battery level.

Table 6.1: LTE QoS classes.

QCI	Upper bound packet error rate	Upper bound delay budget (ms)
1	10^{-2}	100
2	10^{-3}	150
3	10^{-3}	50
4	10^{-6}	300
5	10^{-6}	100
6	10^{-6}	300
7	10^{-3}	100
8	10^{-6}	300
9	10^{-6}	300

Two examples are given below and represented in table 6.2. The first one is set to 30% of the remaining battery as the alarm threshold, which requires 1 bit to represent these two elements. Whilst the second index category constitutes four elements, and requires at least 2 bits for representation. Having a longer table can represent more information, while it also increases the complexity and signaling overhead. Hence, there is a trade-off between the information accuracy and complexity plus overhead.

Table 6.2: Representation of Battery level

Index	Battery level	Index	Battery level
0	$\geq 30\%$	0	$[75\% - 100\%]$
1	$< 30\%$	1	$[50\% - 75\%]$
		2	$[25\% - 50\%]$
		3	$[0\% - 25\%]$

6.5 The Acquisition of Context Information

Two types of context information, BS context and UEs' context, are shown in figure 6.3. The BS's context is measured, updated, and stored at each BS, which is easy to obtain. UEs' context information can be categorized into two types according to its lifetime: quasi-/stable pre-defined context information with less or no changes; and unstable measured context information which frequently changes. For example, the UE's price plan and expected QoS for different applications are pre-defined with low change rate; while the channel quality and battery level need to be measured with high variation. In this section, we will discuss the acquisition of these two types of UE context information.

6.5.1 Quasi-/stable pre-defined UEs' context information obtained from core networks

The quasi-/stable context information is stored in the core network, and transmitted to eNB via backhaul links. Taking the QoS information as an example, the process is illustrated in figure 6.3. As an IP-connected network, all service (voice, data, etc.) in LTE-A are connected to the external Packet Data Network (PDN) through the Packet Data Network Gateway (P-GW). It is natural to configure the quality of service at the P-GW. Since the expected service quality is related to charging, an element called Policy and Charging Enforcement Function (PCEF) is embedded in P-GW. This PCEF is responsible to communicate with other two network elements in the core network. One is called Policy and Charging Function (PCRF), which provides policy and charging control rules. The other one is called Subscription Profile Repository (SPR), which contains users' subscription information such as his/her subscribed price plan.

Having the information of how much a UE is willing to pay, the P-GW configures QoS for difference services through a mechanism named Evolved Packet Service (EPS) bearer. A EPS bearer could be considered as a bi-directional data pipe as a logical connection between the UE and the P-GW. It constitutes three other logical bearers, S5/S8 bearer, S1 bearer and radio bearer as shown in figure 6.3. Once a UE is switched on and connected to the network, a default EPS bearer will be set-up, and remains established until this UE switched off. More

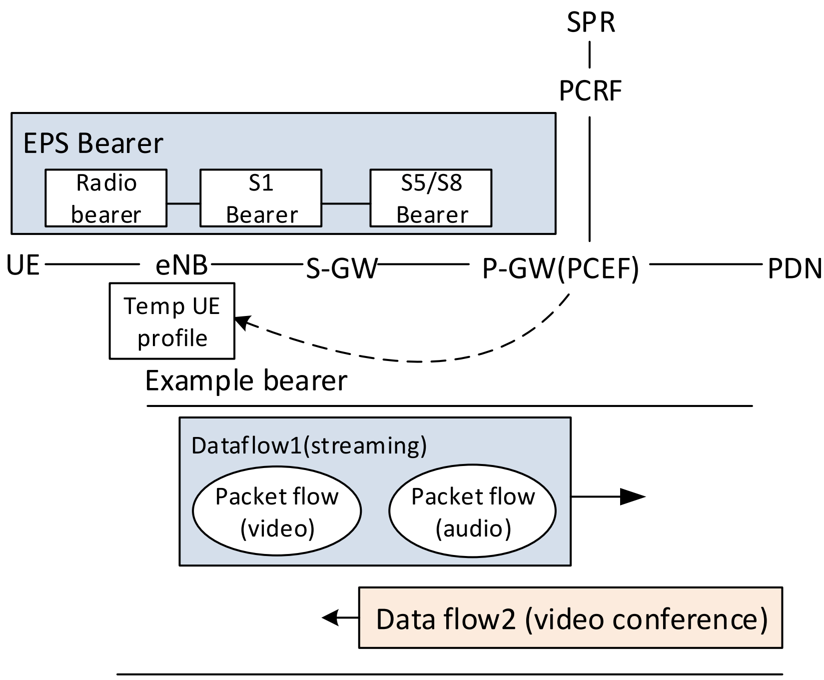

Figure 6.3: QoS information flow.

than one EPS bearer can be set up for difference services. Each EPS bearer is associated with a specific QoS, which defines how the data will be transferred using parameters such as error-rate, delay as shown in table 6.1 (but not limited to these).

One example of ESP bearer is also demonstrated in figure 6.3. This bearer defined a QoS suitable for real-time video transmission, for example QoS having low delay. In this bearer, two service data flows - one for video streaming from the UE to the network, and one for video conference from the network to the UE are supported. Within each data flow, one or more packet flows (e.g. audio and video) are contained for supporting this service. LTE gives the same QoS to all the packet flows within a particular EPS bearer.

The eNBs are not a suitable candidate for storing this quasi-/static pre-defined UE context information because: 1) The operators want to reduce the cost of eNBs; 2) An eNB completely loses connection with a certain mobile once it migrates from the eNB's coverage area. However, once a UE is associated with one eNB, this eNB will create a temporary profile for this UE, which contains the UE's temporary identity as well as key QoS parameters associated with the corresponding bearers including priority prioritized bit-rate and etc. These QoS information elements will be utilized for eNB downlink and uplink scheduling.

6.5.2 Unstable measured UEs' context information obtained from uplink feedback channel

The unstable measured UEs' context information, such as the channel quality and battery level, is obtained from the UE and signaled via uplink feedback channel. There are two feedback modes: periodic and aperiodic. Periodic mode is carried on a regular interval according to the average variable rate of the context information. For example, the channel quality indicator is influenced by the multi-path fading, and has a faster variable rate than the Rank Indicator, which is more influenced by shadowing. Hence CQI feedback is carried out 32 times more frequently than the RI feedback. In contrast, aperiodic node usually carried out on-demand or for abnormal situations. Aperiodic mode is usually has a higher priority than periodic mode.

The uplink feedback channel could be the Physical Uplink Share Channel (PUSCH) or the Physical Uplink Control Channel (PUCCH) depending on the states of the UE. More explicitly

1) If the mobile is in connected mode and has data waiting for transmission via the PUSCH, the context information will be multiplexed with the data at the MAC layer, and transmitted back to the eNB.

2) If the mobile is in connected mode but has no data for transmission, context information will be transmitted via the PUCCH.

3) If the mobile is in idle mode, the mobile needs to invoke a random access request via the Physical Random Access Channel (PRACH), re-establish the connection with the eNodeB, and then feedback its context information via PUSCH or PUCCH as described previously.

In addition, for energy saving purposes, it is more appropriate for an idle-mode mobile to report in aperiodic mode triggered by the change of context information status, for example, the battery level dropped below a certain threshold.

A simplified mapping of several physical channels to radio resources are shown in figure 6.4. The outermost parts of the uplink band are reserved for PUCCH. The rest of the uplink bandwidth is mainly used by the PUSCH. Some resource blocks are reserved for PRACH. For downlink radio resources, a few symbols (varies from frame to frame) at the beginning of each subframe are reserved for control information such as Physical Downlink Control Channel (PDCCH). The rest of the subframe is reserved for downlink data transmission as the Physical Downlink Shared Channel (PDSCH).

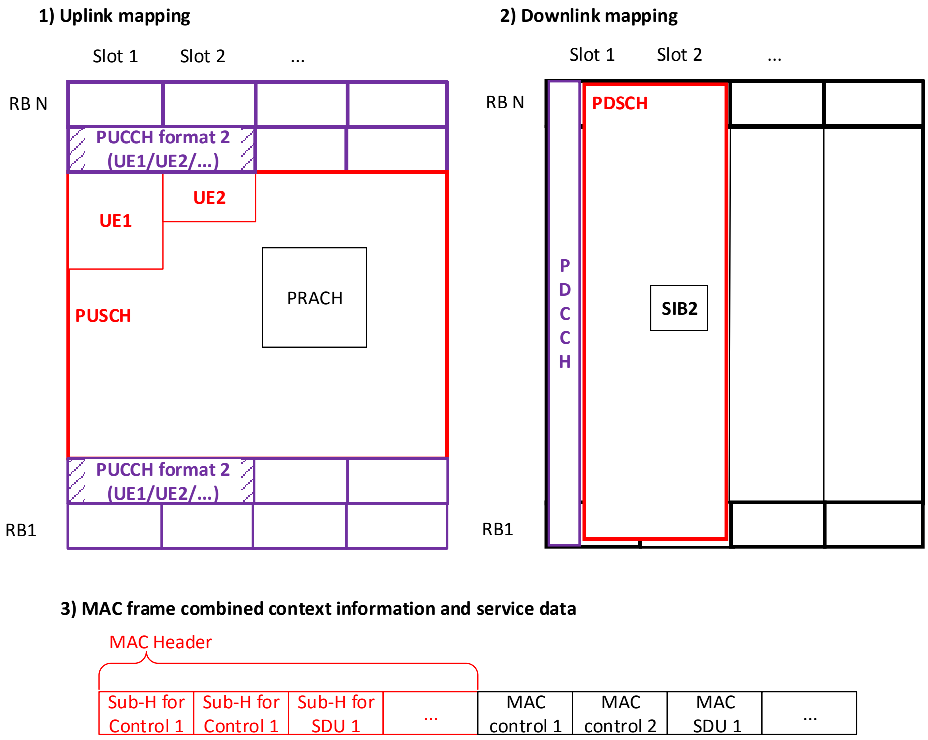

Figure 6.4: Mapping of physical channels and radio resources.

The PUSCH is allocated to individual mobile in units of resource blocks within each sub-frame. An uplink scheduler at the eNB will decide how to allocate which resource blocks to which UE, and sends the UE a scheduling grant on the PDCCH. This grants permission for the mobile to transmit and states all the transmission parameters it should follow, such as transport block size, the resource block allocation and the modulation scheme. If one UE has data to transmit, it will trigger a scheduling request through the PUCCH, and receive such a scheduling grant. If this UE also has context information to feedback, it will concatenate its Service Data Unit (SDU) with context information (denoted as control) as shown in figure 6.4. The type of the context information, their length, and their place in the combined packet are included in the MAC header.

The PUCCH is also shared by all UEs. An individual mobile transmits the PUCCH using two resource blocks, which occupies 1 ms and at opposite sides of the frequency band. To efficiently utilize the limited PUCCH bandwidth, these two resource blocks are further shared by several UEs by using different cyclic shift or orthogonal sequence index, which are assigned to this mobile by the eNB. Moreover, LTE-A standard has a pre-defined list of control formats, which are shown in table 6.3. The resource blocks in the PUCCH are reserved for different control format. The way of reserving which resource blocks are for which type of control format is again decided by the eNB, and advertised in the System Information Block No.2

Table 6.3: LTE-A defined list of control formats.

PUCCH format	Release	Application	Number of UCI bits	Number of PUCCH bits
1	R8	SR	1	1
1a	R8	1 bit HARQ-ACK and optional SR	1 or 2	1 or 2
1b	R8	2 bit HARQ-ACK and optional SR	2 or 3	2 or 3
2	R8	CQI, PMI, RI	≤ 11	20
2a	R8	CQI, PMI, RI and 1 bit HARQ-ACK	≤ 12	21
2b	R8	CQI, PMI, RI and 2 bit HARQ-ACK	≤ 13	22
3	R10	20 bits HARQ-ACK and Optional SR	≤ 21	48

(SIB 2) via PUSCH. As illustrated in the figure 6.4, the two highlighted resource blocks are reserved for transmitting a combination of CQI/PMI/RI. UE1 and UE2 both want to transmit these three types of information. As a result, they will disseminate this control information with their own orthogonal sequence, and occupy these two resource blocks.

6.6 Energy Efficient Context Aware Scheduler

We propose a context aware scheduling (CAS) algorithm which reduces the energy consumption by considering the context information. Most of the conventional schedulers, for example RR , make decisions based on the throughput/QoS and instantaneous channel condition as part of a cross-layer scheduling approach. However, new factors that should be considered to enhance the system performance are the cost of energy per bit and the required energy level (battery level) which until now have been scarcely considered. The transmit energy is insufficient when the radio resources are fully utilized, huge amounts of data are required to be transmitted and most users have poor channel conditions [131]. In this context, if the scheduling metric of a packet schedule were to consider both the ratio of the transmit energy to the number of transmission bits and the remaining battery level energy, greater improvement in system performance can be expected. For this reason, in a system with limited transmit energy, it is more efficient to allocate Physical Resource Block (PRBs) to the users that require the least ratio of the transmit energy to the number of transmission bits and have low remaining energy. Thus, in the proposed packet scheduling scheme, the scheduling metric selects the UEs to be allocated in ascending order of the ratio of the transmit energy,

E_u^m, to the number of transmission bits B_u^m, of the PRB m and BL_u, battery level of the UE u as follows:

$$\Upsilon(u,m) = \arg\min_{u,m} \frac{E_u^m}{B_u^m} = \arg\min_{u,m} \frac{P_u^m T}{B_u^m} * BL_u \tag{6.1}$$

where $\Upsilon(u,m)$ is the scheduling metric which denotes the index of selected UE u and PRB m respectively; energy is the multiple of power and time ($P_u^m.T$) and BL_u, is the battery level. As presented in [132], $P_u^m = \frac{\Psi(B_u^m)}{h_u^m}$, we can redefine the metrics as follows:

$$\arg\min_{u,m} \frac{P_u^m T}{B_u^m} * BL_u = \arg\min_{u,m} \frac{\Psi(B_u^m)T}{h_u^m \cdot B_u^m} * BL_u \tag{6.2}$$

The $\Psi(B_u^m)$ required for the transmission of B_u^m bits with the target BER of Probability of Error (POE) is given by [131]and [132]

$$\Psi(B_u^m) = \frac{(\sigma_u^m)^2}{3}\left[Q^{-1}\left(\frac{POE}{4}\right)\right]^2\left(2^{B_u^m} - 1\right) \tag{6.3}$$

Where $\sigma_{u,m}^2$ is the noise variance for the subcarriers in the PRB m at the UE u, and $Q(x) = 1\big/\sqrt{2\pi} \cdot \int_x^\infty e^{-t/2} dt$.
Let $\hat{P}_u^m$ denote the maximum transmit power at the transmitter that can be assigned for the UE u and the PRB m. Then, the minimum channel gain required for successful transmission of B_u^m bits through the PRB m is given by $h_{\min}(B_u^m) = \Psi(B_u^m)\big/\hat{P}_u^m$. Since we have $h_{\min}(B_u^m) = \Psi(B_u^m)\big/\hat{P}_u^m$, the excess channel gain, $\Omega_u^m(B_u^m)$ is the maximum positive integer that satisfies ($\Omega_u^m \geq 0$) is written as

$$\Omega_u^m = h_u^m - h_{\min}(B_u^m) = \Psi(B_u^m)\left(\frac{1}{P_u^m} - \frac{1}{\hat{P}_u^m}\right) \tag{6.4}$$

From equation 6.4 we get

$$\frac{1}{P_u^m} = \frac{\Omega_u^m}{\Psi(B_u^m)} + \frac{1}{\hat{P}_u^m} \Rightarrow P_u^m = \frac{1}{\frac{\Omega_u^m}{\Psi(B_u^m)} + \frac{1}{\hat{P}_u^m}} \tag{6.5}$$

From equation 6.2 and 6.5 we get

$$\Upsilon(u,m) = \arg\min_{u,m}\left(\frac{T}{\left(\frac{\Omega_u^m}{\Psi(B_u^m)} + \frac{1}{\hat{P}_u^m}\right)B_u^m}\right) * BL_u \tag{6.6}$$

For are too large value of $\hat{P}_u^m$ equation 6.6 can be rewritten as

$$\Upsilon(u,m) = \arg\min_{u,m}\left(\frac{T}{\left(\frac{\Omega_u^m}{\Psi(B_u^m)}+0\right)B_u^m} * BL_u\right) = \arg\min_{u,m}\left(\frac{T}{\frac{\Omega_u^m}{\Psi(B_u^m)}B_u^m} * BL_u\right) \tag{6.7}$$

and

$$\begin{aligned}\Upsilon(u,m) &= \arg\min_{u,m}\left(\frac{T}{\frac{\Omega_u^m}{\Psi(B_u^m)}B_u^m} * BL_u\right) = \arg\min_{u,m}\left(\frac{T}{\frac{\Omega_u^m}{(\Psi(B_u^m)/B_u^m)}} * BL_u\right)\\ \Upsilon(u,m) &= \arg\min_{u,m}\left(\frac{(\Psi(B_u^m)/B_u^m)T}{\Omega_u^m} * BL_u\right) = \arg\min_{u,m}\left(\frac{(\bar{E}(B_u^m)/B_u^m)}{\Omega_u^m} * BL_u\right)\end{aligned} \tag{6.8}$$

where $\bar{E}(B_u^m) = \Psi(B_u^m)T$ equation 6.8 can be rewritten as

$$\arg\min_{u,m}\left(\frac{(\bar{E}(B_u^m)/B_u^m)}{\Omega_u^m} * BL_u\right) = \arg\max_{u,m}\left(\frac{\Omega_u^m}{(\bar{E}(B_u^m)/B_u^m)} * \frac{1}{BL_u}\right) \tag{6.9}$$

and finally, the scheduling metric can be expressed as

$$\Upsilon(u,m) = \arg\max_{u,m}\left(\frac{\Omega_u^m}{(\bar{E}(B_u^m)/B_u^m)} * \frac{1}{BL_u}\right) \tag{6.10}$$

The proposed energy efficient scheduler allocates the PRB m to the UE with larger excess channel gain which is distant to the required received energy per bit and lower battery level as in equation 6.10. The flowchart of the algorithm is shown in figure 6.5.

6.7 Simulation Setup and Results

This section presents the simulation tool, LTE-A frame structure and results.

6.7.1 Overview of simulation tool

Typically, network simulations are divided into two parts: link level and system level simulations (SLS), as shown in figure 6.6. Although a single simulator approach would be preferred, the complexity of such simulator (including everything from transmitted waveforms to multi-cell network) is far too high with the required simulation resolutions and simulation times. Also, the time granularity of both simulation domains are dramatically different: at link level bit transmissions are at the order of milliseconds, while at the system level traffic and mobility models require time intervals of some tens of seconds to minutes. Therefore,

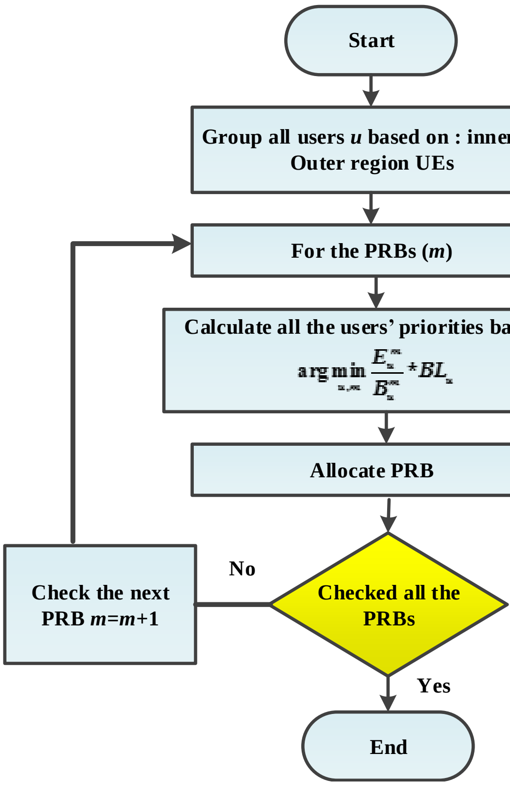

Figure 6.5: Flow chart of the proposed algorithm.

separating link-level and system-level simulations is a necessity.

In SLS, two different types of simulations can be performed: Combined Snapshot-Dynamic mode or a Fully Dynamic mode. In the fully dynamic mode, mobility and handover are enabled and path loss, fast and slow fading are re-computed at every Transmission Time Interval (TTI). In combined Snapshot dynamic mode, mobility and handover are not enabled. Mobiles are randomly deployed in every TTI, path loss and slow fading are computed once at the beginning of each TTI. We consider LTE-A cellular system consisting of single cell and includes three 120-degree sectors, i.e., 57 sectors in total are simulated. All the simulation results are collected from the three central sectors in the central cell, with the other 54 sectors serving as interferers.

The SLS interfaces with the link level simulator through Look up tables (LUTs) as an input to the simulator. Several propagation and traffic models are available, and the simulator computes the entire channel losses (slow and fast fading), thereby ensuring accuracy in the system level parameters computation. The outputs are the parameters that usually characterize packet transmissions: Throughput, BLER, Packet Delay etc. The traffic generation block contains real (i.e., VoIP, WWW) and non-real (i.e., NRTV, FTP) time service traffic models with full queue. The Handover block includes the handover algorithm.

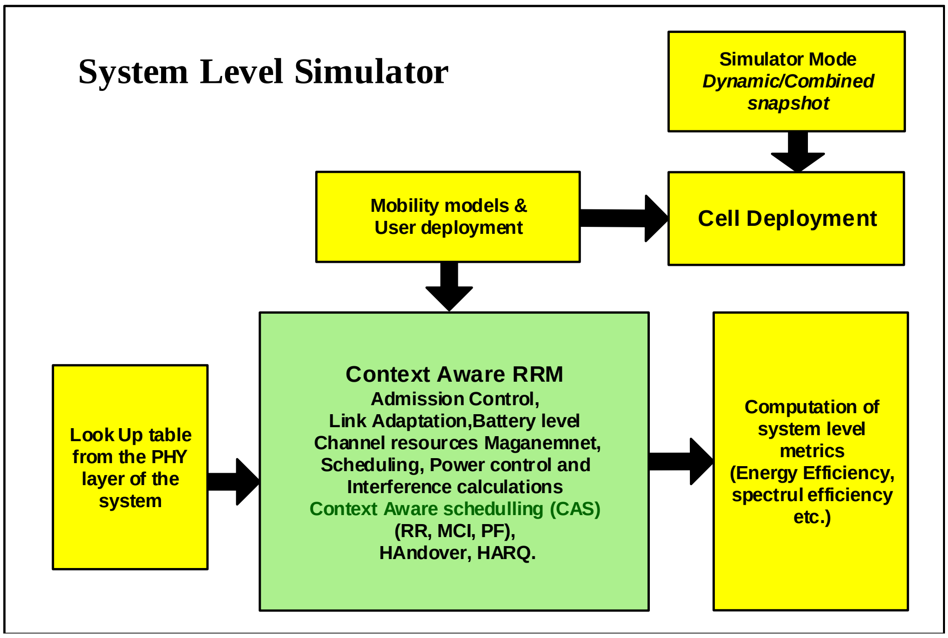

Figure 6.6: Components of system level simulator.

The radio resource management block comprises a call admission control algorithm to regulate the operation of the network; a link adaptation algorithm, to select the appropriate parameters in function of the current radio conditions and a scheduler that decides how to allocate the appropriate resources. In the latter, decisions are based on the context information related to both BS and UE e.g. service type, the amount of data, the current load in the cell, UE application in use, required battery level etc. The Power control block contains mechanisms to provide similar service quality to all communication links despite the variations in the channel conditions. The interference block determines the average interference power received by central base station, i.e., inter-cell interference.

Finally, the computations of system level metrics block returns the network results such as Service Throughput (average spectral efficiency), Block Error Rate and Packet Delay. The mobility block models the mobile movements in the indoor, urban, and rural environments. Parameters associated with mobility include speed, probability to change speed at position update, probability to change direction, and the de-correlation length. The propagation block models path loss, slow fading and fast fading. Channel models for indoor environments, outdoor urban and rural environments are available. The scheduler mechanism will generate the arrival process of the users, according to a Poisson arrival process.

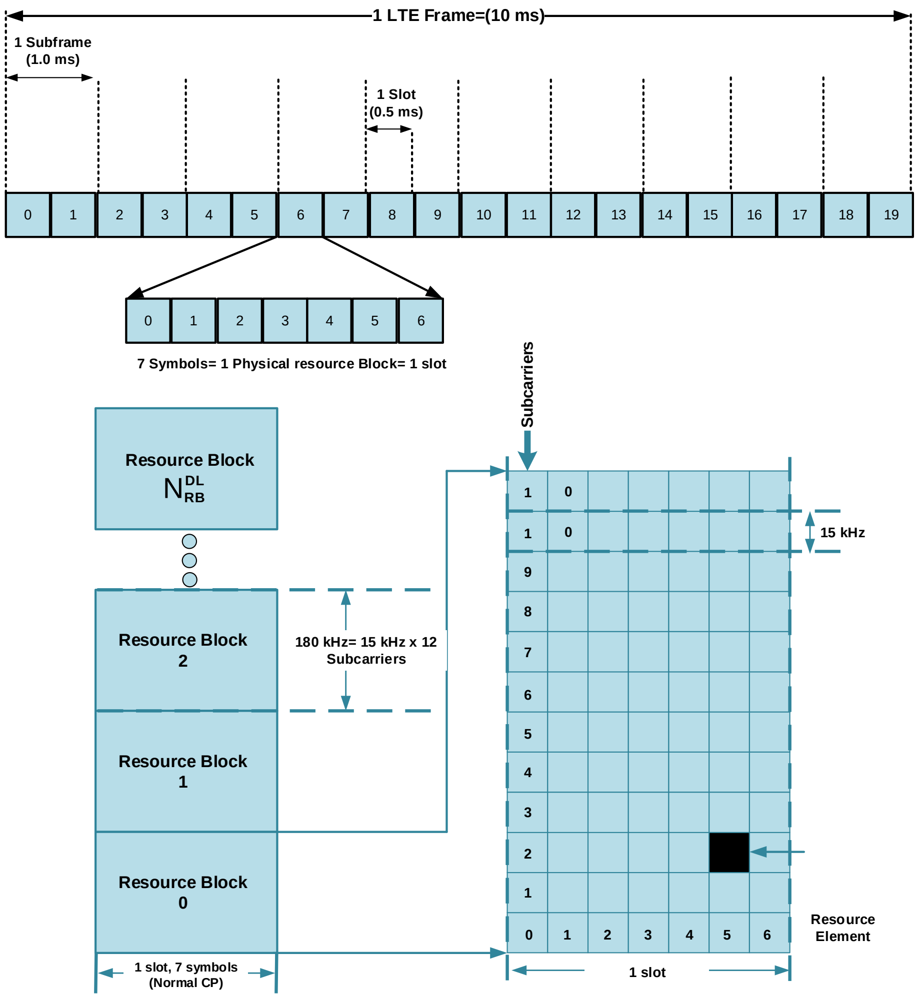

Figure 6.7: FDD frame structure

6.7.2 Frame Structure

The frame structure for LTE-FDD is shown in figure 6.7. The smallest time-frequency unit for downlink transmission is called a resource element (RE), which is one symbol on one sub-carrier. A group of 12 contiguous sub-carriers in frequency and one slot in time form a resource block (RB) as shown in figure 6.7. Data is allocated to each MS in units of RB. RB spans 12 consecutive sub-carriers at a sub-carrier spacing of 15 kHz, and 7 consecutive symbols over a slot duration of 0.5 ms. Thus, a RB has 84 resource elements (12 sub-carriers x 7 symbols) corresponding to one slot in the time domain and 180 kHz (12 sub-carriers x 15 kHz spacing) in the frequency domain. The size of a RB is the same for all bandwidths; therefore, the number of available physical RBs depends on the transmission bandwidth. In the frequency domain, the number of available RBs can range from 6 (when transmission bandwidth is 1.4 MHz) to 100 (when transmission bandwidth is 20 MHz).

Table 6.4: Simulations Parameters

Parameters	Values
Carrier frequency f_c	2GHz
Bandwidth	10MHz
Duplex mode	FDD
Noise density	-174dBm/Hz
Fast fading model	Rayleigh fading using Pedestrian B model (6 taps, SISO) Urban
Log-normal shadowing Variance σ (dB)	LOS σ=4 (dB), NLOS σ=8 (dB)
Number of Cells	Multiple cell
Multiple cell	100 per cell
BS transmit power	43dBm
Time transmission interval	1 ms (sub-frame)
Number of Resource Block	50 RB in each slot, 7 symbol, number of subcarriers per RB=12,total subcarrier=600
Link Adaptation	EESM(Exp Effective SINR Mapping)
Traffic model	Data (File)
Radio Resource Management	CAS, RR
Turbo decoder	Max Log Map (8 iterations)
HARQ	Chase combining, Number of rocess=6,Retransmission interval=6ms,Max Nb of retransmission=3
AMC PER_target	10%
CQI delay	Each TTI, with 2ms delay

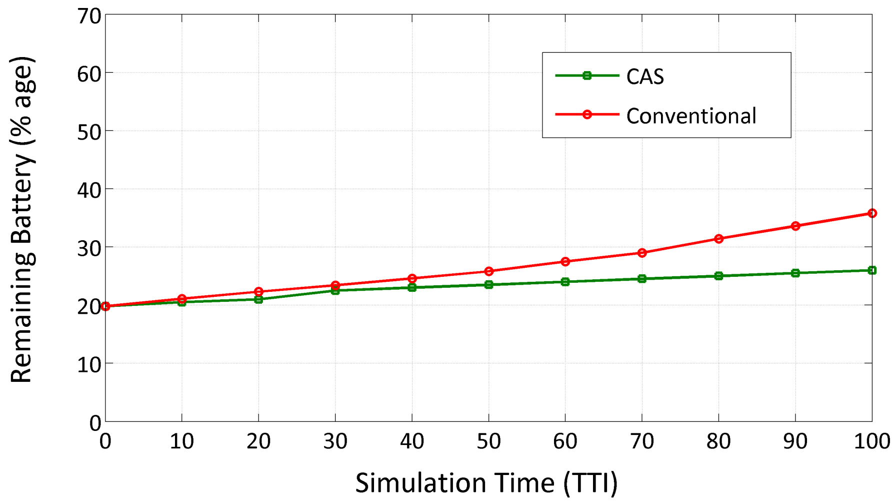

Figure 6.8: Remaining battery (%age) vs simulation time (TTIs)

6.7.3 Simulation parameters and Results

The simulation parameters set for the proposed scenario are shown in table 6.4.
From figure 6.8, it can be observed that the battery consumption of UEs is reduced by around 10% compared to the benchmark algorithm RR. It is also observed that our algorithm effectively saves more energy as simulation time increases, and reaches optimal results within 100 TTIs due to the context aware information in the scheduling. For instance, if we consider battery level as a context entity inside the context aware module, it demonstrates that the lower the battery level the higher the priority of our scheduling, while also considering other parameters. Therefore, in our proposed algorithm, low battery level and minimum energy per bit is assigned higher scheduling priority which eventually leads to reduced battery consumption. For the scheduling process, CAS considers the remaining battery of each UE along with channel quality, traffic demand and adaptive coding which are mostly ignored in the previous algorithms. As result, CAS saves energy and the average remaining battery level of the active users are much higher compared to conventional RR. Figure 6.9, represents the average remaining battery level compared with number of users. The figure depicts that CAS, on average, saves more energy compared to conventional scheduling algorithms. Figure 6.10 shows the Cumulative Density Function (CDF) of the UEs' energy consumption. With the proposed method, almost 50% of the users consume energy which is a value 0.5 mJ. Using the conventional RR, only 20% of UEs' consume the same amount of energy; the gain is 25-30%. This gain is achieved due to the context aware information available at context module for

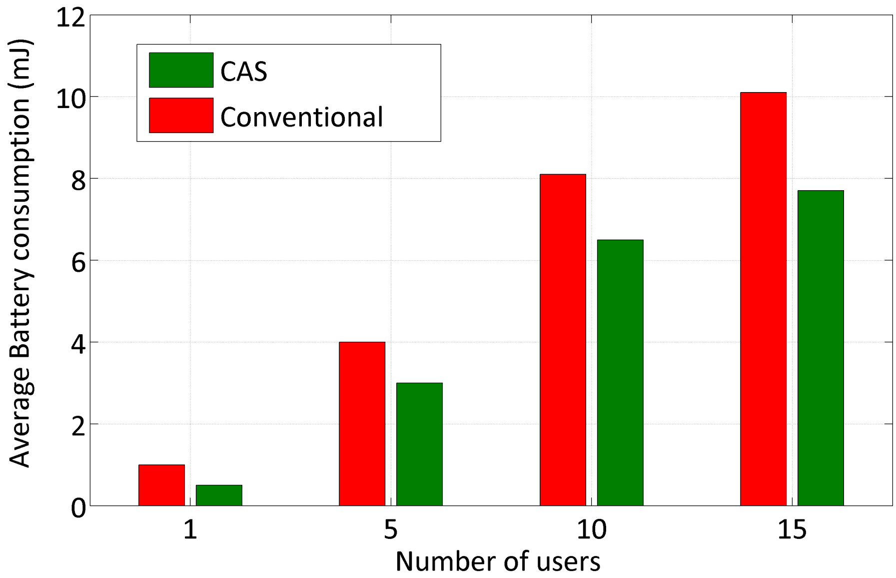

Figure 6.9: Average battery consumption vs number of users.

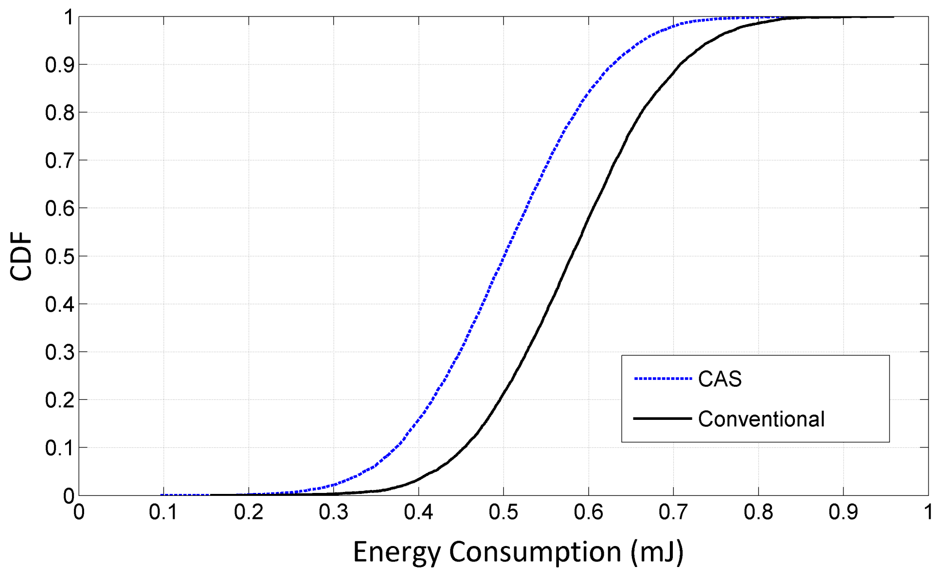

Figure 6.10: CDF vs Energy Consumption

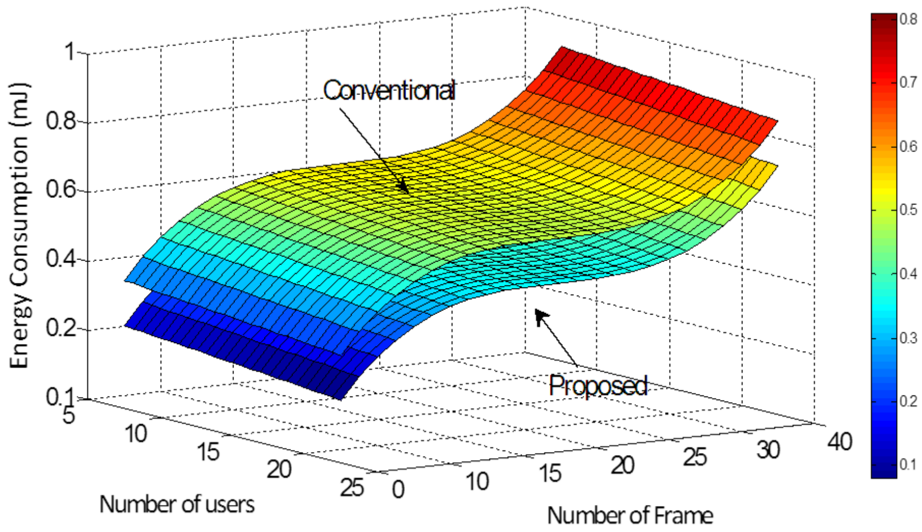

Figure 6.11: Overall comparison of CAS with conventional RR

each mobile user. The context aware module provides the context to the RRM module to consider the battery level of each user in the scheduling process and to adapted its power according to the traffic load in each cell. Thus, the proposed algorithm saves energy and increase the number of UEs to be scheduled.

A 3-D plot is demonstrated in figure 6.11. In this figure, we show an overall comparison between the proposed algorithm and the conventional RR in terms of energy consumption, number of users and simulation frames. Here, we assume all the context entities (battery level, CQI and traffic) that are defined in the proposed algorithm section. It can be observed that the proposed approaches saves almost 0.2 mJ of energy in contrast to the benchmark RR algorithm.

6.8 Conclusions

In this chapter we presented a Context Aware Scheduling (CAS) algorithm for LTE-A. CAS goes beyond state of the art and exploits the context information of UE for energy saving and guarantee the requested QoS. Furthermore, we presented an information model for context awareness which illustrates how context information is extracted and processed by various functional blocks in the context aware architecture of UE. The proposed architecture is not only used for radio resource management, but can further be utilized in various context based mechanisms. The chapter also discuss as the design of context information based signaling in LTE-A. A context aware module is implemented in a system level simulator to test the efficiency of the proposed CAS and to provide a comparison with conventional scheduling. The simulation results showed that CAS has the potential to save energy compared to conventional RR scheduling. In fact, the battery consumption of the UEs are reduced by 10 - 15% by using CAS in contrast to conventional RR scheduling.

Chapter 7

Conclusions and Future Work

This chapter concludes the work presented in the thesis. The chapter summarizes the thesis contributions and highlights the main goals achieved. In the last section we present context based data caching mechanism for future cellular networks as future work for this thesis.

7.1 Conclusion

This thesis tittled inter layer and cooperative design strategies for green networks mainly focuses on the development and demonstration of energy saving for multi-standard wireless mobile devices and networks, exploiting cooperative strategies and context while still enabling the required performance in terms of data rate and QoS to support active applications.
In the following, we briefly review the main results of each chapter.

Chapter 2: Literature survey

The core of this thesis is to present inter layer and cooperative mechanisms for power and energy savings in wireless networks. This thesis targeted three main research challenges: energy efficient node discovery, heterogeneous short range cooperation and radio resource management for long range technology (LTE-A) taking advantage of context information. In this context, the chapter presented the state of the art work on these topics so as to position our proposed solutions. In terms of node discovery, previous works are presented on asymmetric and symmetric protocols. The asymmetric protocols minimizes the chances of channel access collision but limit the network size. Symmetric protocols do not have a centralized entity and expand the size of network but suffers from excessive signaling and collision. Furthermore, the broadcast nature of these protocols lead to excessive battery usage. For heterogeneous cooperative networks we first introduce the fundamentals and related works that maximize the efficiency of wireless network in terms of throughput and energy savings. Most of these works do not consider context information to boost overall system efficiency. Furthermore, scientific works on resource management are also presented and the main drawbacks and deficiencies are highlighted.

RR assign equal resource, but do not consider channel condition. Max C/I maximizes throughput but suffers from unfairness. PF algorithms provide a balance between RR and Max C/I by considering priorities and channel condition. It has been shown that the existing scheduling mechanisms considers parameters but do not exploit specifically context information for energy saving. In the last part of the chapter, a detailed literature survey has been presented on context aware systems. It has been highlighted how these systems exploit context information to achieve the desired goals. However, most of these systems do not exploit context for energy savings and are limited to theoretical work rather than real life experimentation.

Chapter 3: Context Based Architecture for Energy Saving

In this chapter, context information for wireless network is structured and categorized into two basic types; context related to the MT and context related to the network, including specifically raw parameters that could be potentially useful for energy saving. Furthermore, we presented a technology agnostic context based architecture aimed to address energy saving and forms the fundamental building blocks for our proposed context based approaches through out this thesis. The architecture is composed of module and functional elements, that dictate how the context information is to be extracted from the environment, managed and consumed. In particular, the Terminal Context Aware Module (TCAM) module is at the core of the terminal context architecture functionalities responsible for obtaining and providing information from and to the access network and other cooperative MTs. The Context Provider is responsible for collecting the data and raw context. The raw context is extracted from multiple context providers and aggregates the information to compute high level context by Context Inferrer. Similarly, the network functional architecture has two basic modules, namely the Cooperation Mediator and the Radio Resource Management Decision Engine that provide the framework and defines how the context based approaches will interact and work in synergy with the Context Providers to deliver more informed decisions .

Chapter 4: Context-aware Node Discovery for Short Range Cooperation. Node discovery is executed in the initial step to start communication. However, the node discovery mechanism which is pivotal to the bearer establishment process still represents a major burden in terms of the total energy budget. In chapter 4, we propose a technology agnostic approach towards enhancing the MAC energy ratings by proposing a Context Aware Node Discovery (CANDi) which provides a priori knowledge in terms of context information, that supports efficient node discovery by only searching for nodes at the right time and at the right place. Based on UWB, we describe the different beacons required for establishing the cooperation, as well as the context information required, including battery level, modes, location, etc. The presented scenario addresses a hybrid combination of infrastructure architecture and short-range cooperation. Each discovering node can have cluster or nearby nodes to discover; CANDi uses the long range network (WiMAX and Wi-Fi) to distribute the context information about cooperative clusters (UWB-based) in the vicinity. The searching nodes can use this context to locate the cooperative clusters/nodes to facilitate efficient node discovery. CANDi is analyzed both analytically and via simulations. Compared to conventional approaches which do not consider context information and use exhaustive searching, CANDi saves up to 50% energy during the node discovery process thus validating the algorithm, as well as providing viable evidence to support the usage of short range cooperative communications for energy saving.

Chapter 5: Demonstration of Context and Short-range Cooperation for Energy Saving

To investigate and demonstrate the potential of context and cooperative techniques based on advanced short range communications for energy saving, we implemented the proposed mechanisms in the lab using a customized testbed. The testbed is composed of several nodes called C2P Nodes and each node is equipped with UWB and WiFi radio interfaces. A new layer called C2P layer is introduced that implements the algorithms running over these multiple interfaces. The proposed layer is envisioned as part of the context based testbed mobile device and forms part of the device's protocol stack; and makes it easier to analyze and evaluate interoperability in context based network devices. This adaptation layer separates the proposed layer from the underlying radio technologies specifics. Furthermore, each node exchanges specific frames embedded with context information to build cooperative networks. The WiFi power modes have been tested for the proposed scenario as suitable power modes can have a considerable impact on the energy savings of the system. The most energy efficient mode is witnessed in Fast-PSP through the testbed results. Fast-PSP resulted in higher throughput, compared to being always awake, and also resulted in 4 times reduction in the radio power in idle mode. It can be concluded, that operating systems that can shut down radios aggressively will benefit the most. The energy usage increased with distance, as the WiFi radio showed that it had to increase its transmit power in an attempt to maintain the throughput using rate adaptation, leading to lower transmission times thus favoring relay based communication.

Chapter 6: Context Aware Resource Allocation for Energy Saving in LTE-A

Here in, we presented a Context Aware Scheduling (CAS) algorithm for LTE-A for energy saving. Unlike other conventional scheduling algorithms, CAS go beyond state of the art and exploits UE context information for energy saving whilst preserving QoS. Furthermore, an information model is given for context awareness which constitutes of context information and elaborates how the context is extracted and processed by various functional blocks in the context aware architecture of the UE. The proposed architecture is not only used for radio resource management, but can further be utilized in various context based mechanisms. The chapter also discuses the detailed design of the context information based signaling in LTE-A. A context aware module is simulated using a system level simulator to test the efficiency of the proposed CAS and provides a comparison with non context based conventional scheduling. In the defined scenario CAS is tested for energy saving and compared against RR scheduling. The simulation results suggest that the battery consumption of the UEs are reduced by upto 20%.

7.2 Future work

Modern mobile devices are increasingly equipped with a number of rich features resulting in a phenomenal increase in the demand for multimedia contents and services. The current cellular network has a centralized architecture and data is accessed via the core network from the Internet. The centralized approach cannot handle the explosive growth in multi-media mobile traffic due to the limited wireless link capacity and backhaul network. Therefore, the cellular networking paradigm is shifting to adopt decentralized approaches for future emerging networks.

It has been shown in [133] and [134], that the duplicate downloads of content (e.g. multimedia) is one of the major problems leading to the increase traffic. Users frequently download popular videos with large sizes and place extra traffic burden on the network resources. In order to avoid traffic redundancy and to decrease the access latency, researchers are proposing intelligent content cashing and sharing based on context information as shown in figure 7.1.

Moving application processing resources toward the network edge and closer to mobile users will make it possible to simultaneously reduce network traffic and improve quality of experience. Based on this philosophy, we propose an architecture that is based on monitoring and gathering statistics of the most frequent downloads in the networks. To facilitate this, we need intelligent mobile devices that cooperate and play a pivotal role in context-based caching. We assume that mobile devices will be enabled with large amounts of memory. The approach that we propose is to use context parameters prediction to extrapolate the mobile user content usage and requirements and to exploit this knowledge towards off loading redundent traffic from the network. Each mobile device will use context information and user profiling to cache content usage. Considering the mobility parameters, we propose to

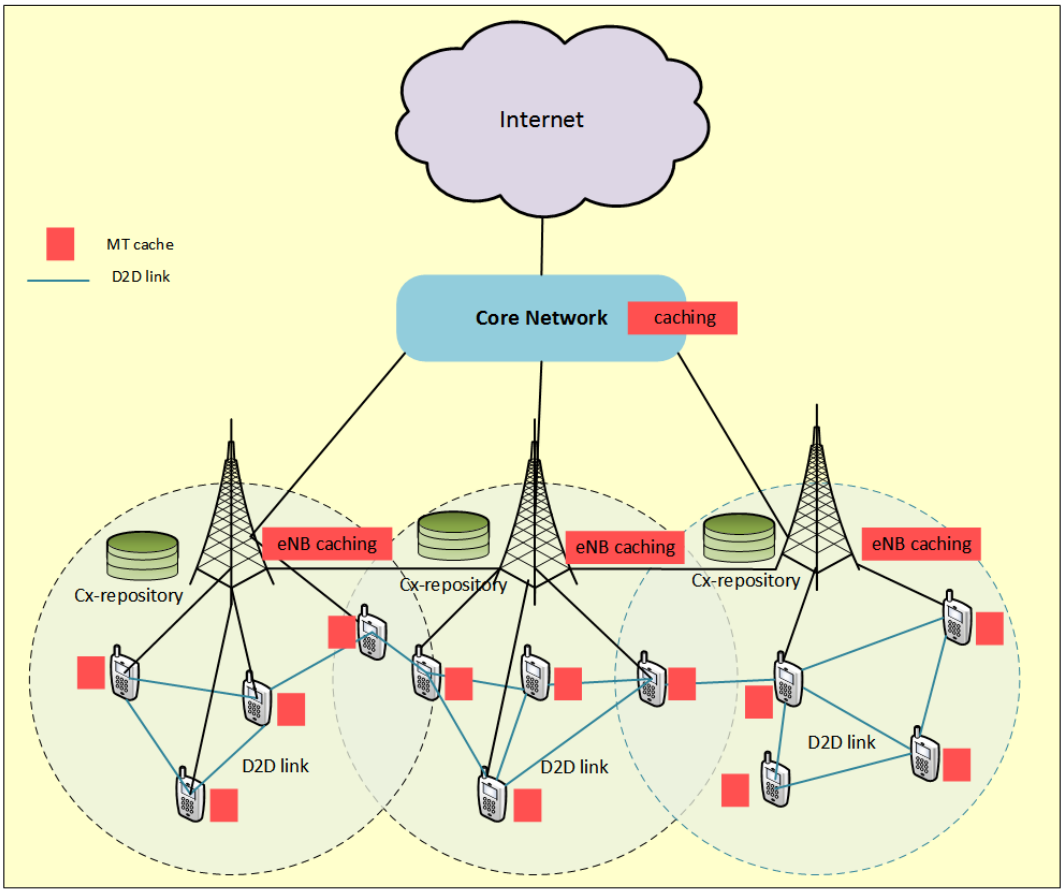

Figure 7.1: Context based caching for future cellular networks.

use context describing the usage and user mobility pattern, to be able to infer where the user is located, what type of content to cache and where the nearby contents are cached. Furthermore, using D2D communication, the content chased by neighbouring devices can be shared locally without accessing the eNB, core network or Internet as shown in figure 7.2.

Furthermore, due to the limitations of device memory to store all available contents, the most frequently used and viral contents will be stored at the eNB. The selection of content will be based on daily regional trends and most viral international contents. Based on the frequency of demands for specific content, each eNB can share and access the content with neighbouring eNB. Also, in case the delay to get access the content from the neighbouring eNB is too high, the data can be cashed at the core network as shown in figure 7.1.
This work proposes context information based caching techniques for mobile cellular networks, a future emerging scenario as we approach 5G era, where D2D communications will play a pivotal role. We believe, the context aware architecture proposed in this thesis can be applied here, but the type and context to cache and how this context can be mined and extracted are

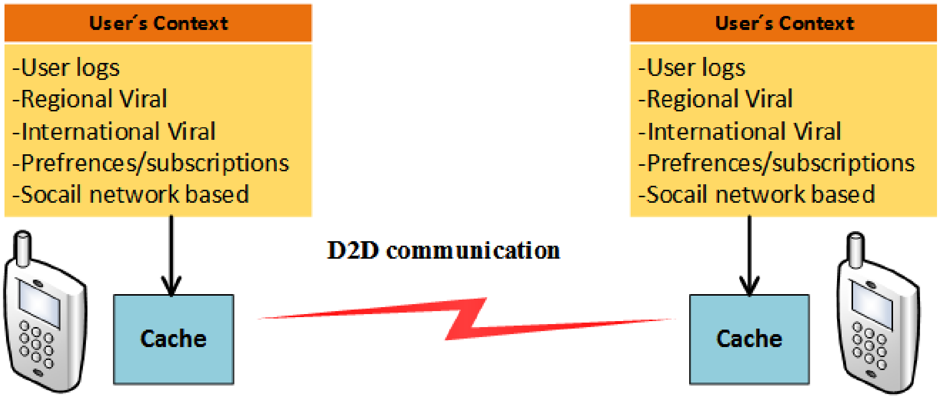

Figure 7.2: MT caching and D2D communication.

all topics for future work.

References

[1] T. Pering, Y. Agarwal, R. Gupta, and R. Want, "Coolspots: reducing the power consumption of wireless mobile devices with multiple radio interfaces," in *Proceedings of the 4th international conference on Mobile systems, applications and services.* ACM, 2006, pp. 220–232. {1,2}

[2] F. H. Fitzek, M. Katz, and Q. Zhang, "Cellular controlled short-range communication for cooperative p2p networking," *Wireless Personal Communications*, vol. 48, no. 1, pp. 141–155, 2009. {1}

[3] E. Walsh, R. Grimes, and P. Walsh, "The performance of active cooling in a mobile phone," in *Thermal and Thermomechanical Phenomena in Electronic Systems, 2008. ITHERM 2008. 11th Intersociety Conference on.* IEEE, 2008, pp. 44–48. {1}

[4] C. Andersson, D. Freeman, I. James, A. Johnston, and S. Ljung, *Mobile media and applications, from concept to cash: successful service creation and launch.* Wiley. com, 2006. {2,12}

[5] F. H. Fitzek and M. D. Katz, *Cognitive wireless networks: concepts, methodologies and visions inspiring the age of enlightenment of wireless communications.* Springer Science+ Business Media BV, 2007. {2}

[6] M. Uusitalo, "Green technology options for future mobile devices," in *1st Workshop on Green Wireless.* WPMC08, 2008. {2}

[7] "Kevin klues, power management in wireless networks,," http://www.cs.wustl.edu. {3}

[8] C. Eklund, R. B. Marks, K. L. Stanwood, and S. Wang, "Ieee standard 802.16: a technical overview of the wirelessmantm air interface for broadband wireless access," *IEEE communications magazine*, vol. 40, no. 6, pp. 98–107, 2002. {3}

[9] I. L. S. Committee *et al.*, "Ieee standard for local and metropolitan area networks part 16: Air interface for fixed broadband wireless access systems," *IEEE Std 802.16TM-2004*, 2004. {3}

[10] "Ieee 802.16etm-2005 std." {3}

[11] "World's first 4g/lte network goes live today in stockholm,," http://www.ericsson.com/thecompany/press/releases/2009/12/1360881 (last visited: 12.5.2013). {5}

[12] C. S. Bontu and E. Illidge, "Drx mechanism for power saving in lte," *Communications Magazine, IEEE*, vol. 47, no. 6, pp. 48–55, 2009. {6}

[13] "Ieee 802.11: Wireless lan medium access control (mac) and physical layer (phy) specifications. (2007 revision). ieee-sa. 12 june 2007." {7}

[14] "Tns online report, two-day battery life tops wish list for future all-in-one phone device,," http://www.tns.lv/?lang=en& fullarticle=true&category=showuid&id=2288/(last visited: 03.04.2013). {12,41,65}

[15] A. L. W. Lu and I. Niemegeers, "On the dynamics and self-organization of personal networks," in *MAGNET Workshop in Shanghai*, November, 2004. {17}

[16] R. Garces and J. Garcia-Luna-Aceves, "Collision avoidance and resolution multiple access for multichannel wireless networks," in *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 2. IEEE, 2000, pp. 595–602. {18}

[17] A. S. Tanenbaum *et al.*, *Computer networks.* Prentice-Hall Englewood Cliffs (NY), 1989, vol. 4. {18}

[18] G. Alonso, E. Kranakis, R. Wattenhofer, and P. Widmayer, "Probabilistic protocols for node discovery in ad-hoc, single broadcast channel networks," in *Parallel and Distributed Processing Symposium, 2003. Proceedings. International.* IEEE, 2003, pp. 8–pp. {18}

[19] M. J. McGlynn and S. A. Borbash, "Birthday protocols for low energy deployment and flexible neighbor discovery in ad hoc wireless networks," in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing.* ACM, 2001, pp. 137–145. {18}

[20] C. Law, A. K. Mehta, and K.-Y. Siu, "Performance of a new bluetooth scatternet formation protocol," in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing.* ACM, 2001, pp. 183–192. {18}

[21] S. Vasudevan, J. Kurose, and D. Towsley, "On neighbor discovery in wireless networks with directional antennas," in *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, vol. 4. IEEE, 2005, pp. 2502–2512. {18,19}

[22] G. Jakllari, W. Luo, and S. V. Krishnamurthy, "An integrated neighbor discovery and mac protocol for ad hoc networks using directional antennas," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 3, pp. 1114–1024, 2007. {19}

[23] E. B. Hamida, G. Chelius, A. Busson, E. Fleury *et al.*, "Neighbor discovery in multi-hop wireless networks: evaluation and dimensioning with interferences considerations," *Discrete Mathematics and Theoretical Computer Science*, 2008. {19}

[24] N. Al-Dhahir, C. Fragouli, A. Stamoulis, W. Younis, and R. Calderbank, "Space-time processing for broadband wireless access," *Communications Magazine, IEEE*, vol. 40, no. 9, pp. 136–142, 2002. {20}

[25] R. Pabst, B. H. Walke, D. Schultz, P. Herhold, H. Yanikomeroglu, S. Mukherjee, H. Viswanathan, M. Lott, W. Zirwas, M. Dohler, H. Aghvami, D. Falconer, and G. Fettweis, "Relay-based deployment concepts for wireless and mobile broadband radio," *Communications Magazine, IEEE*, vol. 42, no. 9, pp. 80–89, 2004. {20}

[26] A. Nosratinia, T. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *Communications Magazine, IEEE*, vol. 42, no. 10, pp. 74–80, 2004. {20}

[27] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. part ii. implementation aspects and performance analysis," *Communications, IEEE Transactions on*, vol. 51, no. 11, pp. 1939–1948, 2003. {20}

[28] J. Laneman, G. W. Wornell, and D. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *Information Theory, 2001. Proceedings. 2001 IEEE International Symposium on*, 2001, pp. 294–. {20}

[29] T. Hunter and A. Nosratinia, "Diversity through coded cooperation," *Wireless Communications, IEEE Transactions on*, vol. 5, no. 2, pp. 283–289, 2006. {20}

[30] J. Laneman and G. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," in *Wireless Communications and Networking Confernce, 2000. WCNC. 2000 IEEE*, vol. 1, 2000, pp. 7–12 vol.1. {20}

[31] J. Laneman, G. W. Wornell, and D. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *Information Theory, 2001. Proceedings. 2001 IEEE International Symposium on*, 2001, pp. 294–. {20}

[32] P. Larsson and H. Rong, "Large-scale cooperative relaying network with optimal coherent combining under aggregate relay power constraints," in *WWRF: New Air Interfaces, Relay based Systems and Smart Antennas*, 2004, qc 20120203. {20}

[33] M. Abouelseoud and A. Nosratinia, "Heterogeneous relay selection," 2013. {20}

[34] Y. Li, B. Vucetic, Z. Chen, and J. Yuan, "An improved relay selection scheme with hybrid relaying protocols," in *Global Telecommunications Conference, 2007. GLOBECOM'07. IEEE.* IEEE, 2007, pp. 3704–3708. {20}

[35] J. Fricke, M. Butt, and P. Hoeher, "Quality-oriented adaptive forwarding for wireless relaying," *Communications Letters, IEEE*, vol. 12, no. 3, pp. 200–202, 2008. {20}

[36] T. Liu, L. Song, Y. Li, Q. Huo, and B. Jiao, "Performance analysis of hybrid relay selection in cooperative wireless systems," *Communications, IEEE Transactions on*, vol. 60, no. 3, pp. 779–788, 2012. {20}

[37] X. Bao and J. Li, "Efficient message relaying for wireless user cooperation: decode-amplify-forward (daf) and hybrid daf and coded-cooperation," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 11, pp. 3975–3984, 2007. {20}

[38] M. Jeong, S. Hwang, D. Kim, and J. Yang, "Performance analysis of cooperative communication with heterogeneous relays," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on.* IEEE, 2011, pp. 1104–1108. {20}

[39] P. Lusina, R. Schober, and L. Lampe, "Diversity-multiplexing trade-off of the hybrid non-orthogonal amplify-decode and forward protocol," in *Information Theory, 2008. ISIT 2008. IEEE International Symposium on.* IEEE, 2008, pp. 2375–2379. {20}

[40] S. Yang and J.-C. Belfiore, "Towards the optimal amplify-and-forward cooperative diversity scheme," *Information Theory, IEEE Transactions on*, vol. 53, no. 9, pp. 3114–3126, 2007. {20}

[41] L. Sun and F. Li, "Adaptive protocol for cooperative communication systems with a single semi-blind amplify-and-forward relay," *Telecommunication Systems*, pp. 1–6, 2013. {20}

[42] O. Falowo and H. Chan, "Effect of mobile terminal heterogeneity on call blocking/dropping probability in cooperative heterogeneous cellular networks," *Telecommunication Systems*, vol. 47, no. 3-4, pp. 337–349, 2011. [Online]. Available: http://dx.doi.org/10.1007/s11235-010-9322-2 {21}

[43] F. Afghah, A. Razi, and A. Abedi, "Stochastic game theoretical model for packet forwarding in relay networks," *Telecommunication Systems*, vol. 52, no. 4, pp. 1877–1893, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11235-011-9471-y {21}

[44] K. Wrona and P. Mähönen, "Analytical model of cooperation in ad hoc networks," *Telecommunication Systems*, vol. 27, no. 2-4, pp. 347–369, 2004. {21}

[45] G. Lim and L. Cimini Jr, "Energy-efficient cooperative relaying in heterogeneous radio access networks," 2012. {21}

[46] Y. Choi, H. Kim, S.-w. Han, and Y. Han, "Joint resource allocation for parallel multi-radio access in heterogeneous wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 9, no. 11, pp. 3324–3329, 2010. {21}

[47] Y. Choi, Y. Lee, and J. M. Cioffi, "Optimization of cooperative inter-operability in heterogeneous networks with cognitive ability," *Communications Letters, IEEE*, vol. 15, no. 11, pp. 1178–1180, 2011. {21}

[48] C. W. Ahn and J.-H. Lee, "Wireless cooperative communication: a survey," in *Proceedings of the 5th International Conference on Ubiquitous Information Management and Communication*. ACM, 2011, p. 78. {21}

[49] J. N. Laneman and G. W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks," in *Wireless Communications and Networking Confernce, 2000. WCNC. 2000 IEEE*, vol. 1. IEEE, 2000, pp. 7–12. {21}

[50] X. J. Li, B.-C. Seet, and P. H. J. Chong, "Multihop cellular networks: Technology and economics," *Computer Networks*, vol. 52, no. 9, pp. 1825–1837, 2008. {21}

[51] Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green cellular networks: A survey, some research issues and challenges," *Communications Surveys & Tutorials, IEEE*, vol. 13, no. 4, pp. 524–540, 2011. {21}

[52] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "Coopmac: A cooperative mac for wireless lans," *Selected Areas in Communications, IEEE Journal on*, vol. 25, no. 2, pp. 340–354, 2007. {21}

[53] Y. Zhang, L. Huang, H. Xu, and Z. Yang, "An incentive energy-efficient routing for data gathering in wireless cooperative networks," *Telecommunication Systems*, vol. 52, no. 4, pp. 1977–1987, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11235-011-9478-4 {21}

[54] J. Feng, R. Zhang, S. X. Ng, and L. Hanzo, "Relay selection for energy-efficient cooperative media access control," in *Wireless Communications and Networking Conference (WCNC), 2011 IEEE.* IEEE, 2011, pp. 287–292. {21}

[55] M. Garcia, S. Sendra, J. Lloret, and A. Canovas, "Saving energy and improving communications using cooperative group-based wireless sensor networks," *Telecommunication Systems*, vol. 52, no. 4, pp. 2489–2502, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11235-011-9568-3 {21}

[56] A. Jalali, R. Padovani, and R. Pankaj, "Data throughput of cdma-hdr a high efficiency-high data rate personal communication wireless system," in *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*, vol. 3, 2000, pp. 1854–1858 vol.3. {22}

[57] G. Aniba and S. Aissa, "Adaptive proportional fairness for packet scheduling in hsdpa," in *Global Telecommunications Conference, 2004. GLOBECOM '04. IEEE*, vol. 6, 2004, pp. 4033–4037 Vol.6. {22}

[58] M. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "Switch-off transients in cellular access networks with sleep modes," in *Communications Workshops (ICC), 2011 IEEE International Conference on*, 2011, pp. 1–6. {23}

[59] M. A. Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, "A simple analytical model for the energy-efficient activation of access points in dense wlans," in *Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking*, ser. e-Energy '10. New York, NY, USA: ACM, 2010, pp. 159–168. [Online]. Available: http://doi.acm.org/10.1145/1791314.1791340 {23}

[60] 3GPP TS 25.214, Physical Layer Procedures (FDD), release 8, v8.9.0, 2010. {23}

[61] "Waqas ahmad khan," "Impact of DRX on VoIP Performance and Battery Life in LTE", master thesis, Jan., 2009. {23}

[62] C. Y. Wu, H. J. Ho, and S. L. Lee, "Minimizing energy consumption with qos constraints over ieee 802.16e networks," *Comput. Commun.*, vol. 35, no. 14, pp. 1672–

1683, Aug. 2012. [Online]. Available: http://dx.doi.org/10.1016/j.comcom.2012.06.012 {23}

[63] A. Asadi and V. Mancuso, "A survey on opportunistic scheduling in wireless communications," pp. 1–18, 2013. {23}

[64] C. Y. Wong, R. Cheng, K. Lataief, and R. Murch, "Multiuser ofdm with adaptive subcarrier, bit, and power allocation," *Selected Areas in Communications, IEEE Journal on*, vol. 17, no. 10, pp. 1747–1758, 1999. {23}

[65] H. Ding, J. Ge, D. Benevides da Costa, and Z. Jiang, "Energy-efficient and low-complexity schemes for uplink cognitive cellular networks," *Communications Letters, IEEE*, vol. 14, no. 12, pp. 1101–1103, 2010. {23}

[66] "F. kelly,," "Charging and rate control for elastic traffic," Euro. Trans. Telecomms., vol. 8, no. 1, 1997. {23}

[67] P. Viswanath, D. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *Information Theory, IEEE Transactions on*, vol. 48, no. 6, pp. 1277–1294, 2002. {23}

[68] H. Kushner and P. Whiting, "Convergence of proportional-fair sharing algorithms under general conditions," *Wireless Communications, IEEE Transactions on*, vol. 3, no. 4, pp. 1250–1259, 2004. {23}

[69] B. Schilit and M. Theimer, "Disseminating active map information to mobile hosts," *Network, IEEE*, vol. 8, no. 5, pp. 22–32, Sept 1994. {23}

[70] R. M. Baecker, *Readings in Human-Computer Interaction: toward the year 2000.* Morgan Kaufmann Pub, 1995. {23}

[71] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," *ACM Transactions on Information Systems (TOIS)*, vol. 10, no. 1, pp. 91–102, 1992. {23}

[72] G. D. Abowd, C. G. Atkeson, J. Hong, S. Long, R. Kooper, and M. Pinkerton, "Cyberguide: A mobile context-aware tour guide," *Wireless networks*, vol. 3, no. 5, pp. 421–433, 1997. {24}

[73] Y. Sumi, T. Etani, S. Fels, N. Simonet, K. Kobayashi, and K. Mase, "C-map: Building a context-aware mobile assistant for exhibition tours," in *Community computing and support systems.* Springer, 1998, pp. 137–154. {24}

[74] K. Cheverst, N. Davies, K. Mitchell, A. Friday, and C. Efstratiou, “Developing a context-aware electronic tourist guide: some issues and experiences,” in *Proceedings of the SIGCHI conference on Human factors in computing systems.* ACM, 2000, pp. 17–24. {24}

[75] P. Prekop and M. Burnett, “Activities, context and ubiquitous computing,” *Computer Communications*, vol. 26, no. 11, pp. 1168–1176, 2003. {24}

[76] R. M. Gustavsen, “Condor–an application framework for mobility-based context-aware applications,” in *Proceedings of the workshop on concepts and models for ubiquitous computing*, vol. 39, 2002. {24}

[77] T. Hofer, W. Schwinger, M. Pichler, G. Leonhartsberger, J. Altmann, and W. Retschitzegger, “Context-awareness on mobile devices-the hydrogen approach,” in *System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on.* IEEE, 2003, pp. 10–pp. {24}

[78] K. Van Laerhoven and O. Cakmakci, “What shall we teach our pants?” in *Wearable Computers, The Fourth International Symposium on.* IEEE, 2000, pp. 77–83. {24}

[79] J. Budzik and K. J. Hammond, “User interactions with everyday applications as context for just-in-time information access,” in *Proceedings of the 5th international conference on intelligent user interfaces.* ACM, 2000, pp. 44–51. {24}

[80] L. Finkelstein, E. Gabrilovich, Y. Matias, E. Rivlin, Z. Solan, G. Wolfman, and E. Ruppin, “Placing search in context: The concept revisited,” in *Proceedings of the 10th international conference on World Wide Web.* ACM, 2001, pp. 406–414. {24}

[81] H. Chen, T. Finin, and A. Joshi, “An intelligent broker for context-aware systems,” in *Adjunct proceedings of Ubicomp*, vol. 3, 2003, pp. 183–184. {24}

[82] T. Winograd, “Architectures for context,” *Human-Computer Interaction*, vol. 16, no. 2, pp. 401–419, 2001. {25}

[83] A. K. Dey, G. D. Abowd, and D. Salber, “A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications,” *Human-computer interaction*, vol. 16, no. 2, pp. 97–166, 2001. {25}

[84] M. Baldauf, S. Dustdar, and F. Rosenberg, “A survey on context-aware systems,” *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 2, no. 4, pp. 263–277, 2007. {25}

[85] Q. Z. Sheng and B. Benatallah, "Contextuml: a uml-based modeling language for model-driven development of context-aware web services," in *Mobile Business, 2005. ICMB 2005. International Conference on.* IEEE, 2005, pp. 206–212. {25}

[86] T. Hofer, W. Schwinger, M. Pichler, G. Leonhartsberger, J. Altmann, and W. Retschitzegger, "Context-awareness on mobile devices-the hydrogen approach," in *System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on.* IEEE, 2003, pp. 10–pp. {25}

[87] D. X. Adamopoulos, G. Pavlou, and C. A. Papandreou, "Advanced service creation using distributed object technology," *Communications Magazine, IEEE*, vol. 40, no. 3, pp. 146–154, 2002. {25}

[88] E. Sirin, B. Parsia, B. C. Grau, A. Kalyanpur, and Y. Katz, "Pellet: A practical owl-dl reasoner," *Web Semantics: science, services and agents on the World Wide Web*, vol. 5, no. 2, pp. 51–53, 2007. {25}

[89] T. Strang and C. Linnhoff-Popien, "A context modeling survey," in *Workshop Proceedings*, 2004. {25}

[90] M. Baldauf, S. Dustdar, and F. Rosenberg, "A survey on context-aware systems," *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 2, no. 4, pp. 263–277, 2007. {25}

[91] H. Ailisto, P. Alahuhta, V. Haataja, V. Kyllönen, and M. Lindholm, "Structuring context aware applications: Five-layer model and example case," in *Proceedings of the Workshop on Concepts and Models for Ubiquitous Computing*, 2002, pp. 1–5. {25}

[92] A. K. Dey, G. D. Abowd, and D. Salber, "A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications," *Human-computer interaction*, vol. 16, no. 2, pp. 97–166, 2001. {25}

[93] T. Gu, H. K. Pung, and D. Q. Zhang, "A middleware for building context-aware mobile services," in *Vehicular Technology Conference, 2004. VTC 2004-Spring. 2004 IEEE 59th*, vol. 5. IEEE, 2004, pp. 2656–2660. {25}

[94] A. K. Dey, G. D. Abowd, and D. Salber, "A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications," *Human-computer interaction*, vol. 16, no. 2, pp. 97–166, 2001. {26}

[95] G. Biegel and V. Cahill, "A framework for developing mobile, context-aware applications," in *Pervasive Computing and Communications, 2004. PerCom 2004. Proceedings of the Second IEEE Annual Conference on.* IEEE, 2004, pp. 361–365. {26}

[96] "C2power,," http://www.ict-c2power.eu/images/Deliverables/C2POWER$_D$2.1.*pdf*(*Lastvisited* : 11.08.2013), . {27}

[97] J. Rodriguez, P. Marques, A. Radwan, K. Moessner, R. Tafazolli, M. Raspopoulos, S. Stavrou, P. Trapps, D. Noquet, K. Sithamparanathan, A. Gomes, R. Piesiewicz, H. Mokrani, A. Foglar, and C. Verikoukis, "Cognitive radio and cooperative strategies for power saving in multi-standard wireless devices," in *Future Network and Mobile Summit, 2010*, 2010, pp. 1–8. {41,42,65,127}

[98] S. Mumtaz, A. Radwan, A. Gomes, and J. Rodriguez, "Green-T (Green Terminals for Next Generation Wireless Systems): Survey and progress," in *Wireless Conference (EW), Proceedings of the 2013 19th European*, 2013, pp. 1–5. {41,42}

[99] M. Di Renzo, L. Alonso, F. H. Fitzek, A. Foglar, F. Granelli, F. Graziosi, C. Grueut, H. Haas, G. Kormentzas, A. I. Perez *et al.*, "GREENET-An Early Stage Training Network in Enabling Technologies for Green Radio," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd.* IEEE, 2011, pp. 1–5. {41,42}

[100] M.Weiser, *The computer for the 21st century. In: In Human-computer interaction: Toward the year 2000.* Morgan Kaufmann Publishers Inc, 1995. {42}

[101] M. Alam, M. Albano, A. Radwan, and J. Rodriguez, "Context parameter prediction to prolong mobile terminal battery life," in *Mobile Multimedia Communications.* Springer, 2012, pp. 476–489. {42}

[102] T. Hofer, W. Schwinger, M. Pichler, G. Leonhartsberger, J. Altmann, and W. Retschitzegger, "Context-awareness on Mobile Devices - the hydrogen approach," in *System Sciences, 2003. Proceedings of the 36th Annual Hawaii International Conference on*, 2003, pp. 10 pp.–. {42}

[103] C. Cordier, F. Carrez, H. Van Kranenburg, C. Licciardi, J. Van der Meer, A. Spedalieri, J.-P. Le Rouzic, and J. Zoric, "Addressing the Challenges of Beyond 3G Service Delivery: the SPICE service platform," in *Workshop on Applications and Services in Wireless Networks (ASWN06)*, 2006. {42}

[104] "Context Casting: FP7 ICT Research Project," *Web Site: http://www. ict-ccast. eu.* {42}

[105] R. Kernchen, D. Bonnefoy, A. Battestini, B. Mrohs, M. Wagner, and M. Klemettinen, "Context-awareness in Mobilife," in *Proceedings of the 15th IST Mobile and Wireless Communication Summit*, 2006. {42}

[106] J. Sienel, A. L. Martín, C. B. Zorita, L.-W. Goix, Á. M. Reol, and B. C. Martínez, "Opuce: A Telco-driven Service Mash-up Approach," *Bell Labs Technical Journal*, vol. 14, no. 1, pp. 203–218, 2009. {42}

[107] P. Liu, Z. Tao, Z. Lin, E. Erkip, and S. Panwar, "Cooperative Wireless Communications: A Cross-layer Approach," *Wireless Commun.*, vol. 13, no. 4, pp. 84–92, Aug. 2006. {42}

[108] S. M. R. I. Moshaddique Al Ameen and K. Kwak, "Energy Saving Mechanisms for MAC Protocols in Wireless Sensor Networks," *International Journal of Distributed Sensor Networks*, vol. 2010, no. 2, pp. 556 –561, October. {43}

[109] L. Bao and J. Garcia-Luna-Aceves, "Transmission Scheduling in Ad hoc Networks with Directional Antennas," in *Proceedings of the 8th annual international conference on Mobile computing and networking*, ser. MobiCom '02. New York, NY, USA: ACM, 2002, pp. 48–58. [Online]. Available: http://doi.acm.org {43}

[110] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, "Using Directional Antennas for Medium Access Control in Ad hoc Networks," in *Proceedings of the 8th annual international conference on Mobile computing and networking*, ser. MobiCom '02. New York, NY, USA: ACM, 2002, pp. 59–70. [Online]. Available: http://doi.acm.org/10.1145/570645.570653 {43}

[111] G. Jakllari, W. Luo, and S. Krishnamurthy, "An Integrated Neighbor Discovery and MAC Protocol for Ad Hoc Networks Using Directional Antennas," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 3, pp. 1114–1024, 2007. {43}

[112] R. Ramanathan, "On the Performance of Ad Hoc Networks with Beamforming Antennas," in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing*, ser. MobiHoc '01. New York, NY, USA: ACM, 2001, pp. 95–105. [Online]. Available: http://doi.acm.org/10.1145/501426.501430 {43}

[113] E. Felemban, R. Murawski, E. Ekici, S. Park, K. Lee, J. Park, and Z. Hameed, "SAND: Sectored-Antenna Neighbor Discovery Protocol for Wireless Networks," in *Sensor Mesh and Ad Hoc Communications and Networks (SECON), 2010 7th Annual IEEE Communications Society Conference on*, 2010, pp. 1–9. {43}

[114] B. Allen, M. Dohler, E. Okon, W. Malik, A. Brown, and D. Edwards, *Ultra Wideband Antennas and Propagation for Communications, Radar and Imaging.* Wiley.com, 2006. {43}

[115] Y. M. Kim, "Ultra Wide Band (UWB) Technology and Applications," *Ohio State University NEST group*, 2003. {43}

[116] M. S. I. M. Zin and M. Hope, "A Review of UWB MAC Protocols," in *Proceedings of the 2010 Sixth Advanced International Conference on Telecommunications*, ser. AICT '10. Washington, DC, USA: IEEE Computer Society, 2010, pp. 526–534. [Online]. Available: http://dx.doi.org/10.1109/AICT.2010.101 {43}

[117] K.-H. Liu, X. Ling, X. Shen, and J. Mark, "Performance Analysis of Prioritized MAC in UWB WPAN with Bursty Multimedia Traffic," *Vehicular Technology, IEEE Transactions on*, vol. 57, no. 4, pp. 2462 –2473, july 2008. {43}

[118] S. Vasudevan, J. Kurose, and D. Towsley, "On neighbor discovery in wireless networks with directional antennas," in *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, vol. 4, 2005, pp. 2502–2512 vol. 4. {54}

[119] A. Varga *et al.*, "The OMNeT++ Discrete Event Simulation System," in *Proceedings of the European Simulation Multiconference (ESM2001)*, vol. 9. sn, 2001, p. 185. {55}

[120] T. Mrugalski and J. Wozniak, "Numbat-extensible Simulation Environment for Mobile, IPv6 Capable IEEE 802.16 Stations," in *Telecommunication Networks and Applications Conference, 2007. ATNAC 2007. Australasian.* IEEE, 2007, pp. 396–401. {55}

[121] L. M. Feeney and D. Willkomm, "Energy Framework: An Extensible Framework for Simulating Battery Consumption in Wireless Networks," in *Proceedings of the 3rd International ICST Conference on Simulation Tools and Techniques.* ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2010, p. 20. {55}

[122] "C2power,," http://http://www.ict-c2power.eu/images/Deliverables/C2POWER$_D7.3.pdf(Lastvisited$ 11.08.2013),. {65}

[123] "Gsa, mobile industry actions towards sustainability," http://www.gsacom.com/news/gsa_292.php4, January 2010. {66}

[124] J.-C. Cano, D. Ferrndez-Bell, and P. Manzoni, “Evaluating bluetooth performance as the support for context-aware applications,” *Telecommunication Systems*, vol. 28, no. 3-4, pp. 333–347, 2005. [Online]. Available: http://dx.doi.org/10.1007/s11235-004-5576-x {66}

[125] D. Daz Snchez, A. Marn Lpez, F. Almenrez Mendoza, C. Campo Vzquez, and C. Garca-Rubio, “Context awareness in network selection for dynamic environments,” *Telecommunication Systems*, vol. 36, no. 1-3, pp. 49–60, 2007. [Online]. Available: http://dx.doi.org/10.1007/s11235-007-9058-9 {66}

[126] R. Matos, S. Sargento, K. Hummel, A. Hess, K. Tutschku, and H. Meer, “Context-based wireless mesh networks: a case for network virtualization,” *Telecommunication Systems*, vol. 51, no. 4, pp. 259–272, 2012. [Online]. Available: http://dx.doi.org/10.1007/s11235-011-9434-3 {66}

[127] D. I. K. ”E. Hossain and . V. K. Bhargava, “”cooperative cellular wireless networks”,” ”2010”,. {67}

[128] A. Jalali, R. Padovani, and R. Pankaj, “Data throughput of cdma-hdr a high efficiency-high data rate personal communication wireless system,” in *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*, vol. 3, 2000, pp. 1854–1858 vol.3. {88}

[129] G. Aniba and S. Aissa, “Adaptive proportional fairness for packet scheduling in hsdpa,” in *Global Telecommunications Conference, 2004. GLOBECOM ’04. IEEE*, vol. 6, 2004, pp. 4033–4037 Vol.6. {88}

[130] M. Alam, M. Albano, A. R. Radwan, and J. Rodriguez, “Context parameter prediction to prolong mobile terminal battery life,” in *Proc International Mobile Multimedia Communications Conf. - Mobimedia, Lisboa, Portugal*, September, 2010, pp. 1–10 pp.–. {88}

[131] J. Song, G.-T. Gil, and D.-H. Kim, “Packet-scheduling algorithm by the ratio of transmit power to the transmission bits in 3gpp lte downlink,” *EURASIP J. Wirel. Commun. Netw.*, vol. 2010, pp. 6:1–6:13, Jan. 2010. [Online]. Available: http://dx.doi.org/10.1155/2010/251281 {96,97}

[132] C. Y. Wong, R. Cheng, K. Lataief, and R. Murch, “Multiuser ofdm with adaptive subcarrier, bit, and power allocation,” *Selected Areas in Communications, IEEE Journal on*, vol. 17, no. 10, pp. 1747–1758, Oct 1999. {97}

[133] J. Erman, A. Gerber, M. Hajiaghayi, D. Pei, S. Sen, and O. Spatscheck, "To cache or not to cache: The 3g case," *Internet Computing, IEEE*, vol. 15, no. 2, pp. 27–34, 2011. {110}

[134] S. Woo, E. Jeong, S. Park, J. Lee, S. Ihm, and K. Park, "Comparison of caching strategies in modern cellular backhaul networks," in *Proceeding of the 11th annual international conference on Mobile systems, applications, and services*. ACM, 2013, pp. 319–332. {110}

Appendix A

Context Based Testbed Platform Architecture

The intension of this chapter is to provide an in-depth overview of the testbed which is used to in chapter 5 to generate results and the database schematic view.

A.1 Testbed Platform Architecture

The results generated in Chapter 4 tittled "Demonstration of Context and Short-range Cooperation for Energy Saving" were generated using this testbed.

The testbed is composed of a number of C2POWER nodes (C2P Node) developed in C2POWER [97] project. The C2P Node is pictured in figure A.1 and consists of three major modules; the Device under test (DUT), a Telemetry Controller (TC) and an Attenuation and Power Measurement Board (APM). Both the DUT and the TC have individual Ethernet connections to the testbed internal network.

A new layer called C2POWER layer (C2P layer) is introduced that implements the cooperative algorithms and is controllable via another UPnP service interface. Control via the UPnP interface makes it possible for the Test Fixture Controller (TFC) or other external controller to enable or disable the C2P layer. Such control makes it possible to carry out automated comparisons between scenarios with and without the benefit of cooperative communications. Traffic passes via the C2P layer and the selected radio, either directly or via relaying and routing to an endpoint connected via the WiFi AP on the TFC. The Traffic Generator, UPnP device and C2P layer all reside in Linux user space.

The TC is a general purpose Commercial Off The Shelf (COTS) development board with a 32 bit CPU, 64MB RAM, and 512MB NAND flash running embedded Linux and has a wide selection of interfaces, including Ethernet, General Purpose Input/Output (GPIO) and Serial

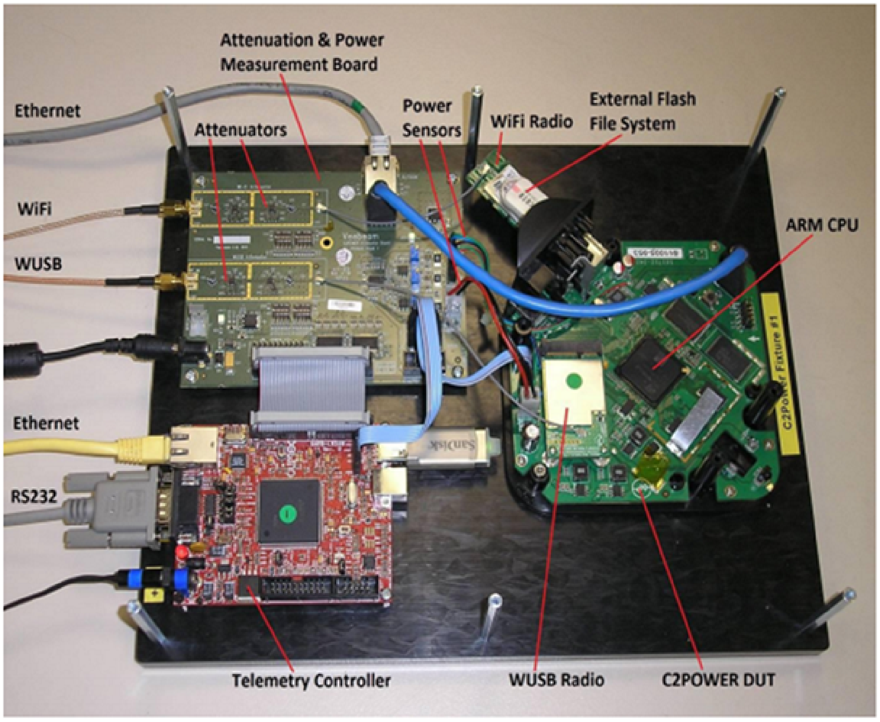

Figure A.1: C2P Node Architecture.

Peripheral Interface Bus (SPI). There are three main software modules in the TC: Universal Plug and Play (UPnP) device, a Programmed input/output (PIO) controller and an Analogue to Digital Converter (ADC) controller. The PIO controller sets the attenuators on the Attenuation and Power Measurement Board (APMB) in response to commands delivered over the Ethernet via a UPnP service interface. The ADC controller receives instructions to gather voltage and current readings from the power sensors on the APMB. The ADC controller can be configured over UPnP to buffer a number of readings for delivery to the TFC in response to later requests. Each measurement is time stamped by a local clock synchronized with the Network Time Protocol (NTP) server on the TFC, which ensures that all readings from all nodes are synchronized across the testbed.

The final module is the Attenuator and Power Measurement Board (APBM). It has two RF attenuators inserted between the antenna connector of each radio. Each one is capable of inserting a wide enough range of attenuation approximately the same as 1-20m of separation in a line of sight over-the-air arrangement. Three voltage/current measurement sensors are connected to the DUT to measure the power consumption of: the main CPU and ancillary hardware, and each of the WiFi and UWB radio modules.

The testbed platform architecture is shown in figure A.2. Each C2P Node is controlled by the Fixture Controller using UPnP protocols. UPnP provides standardized mechanisms for:

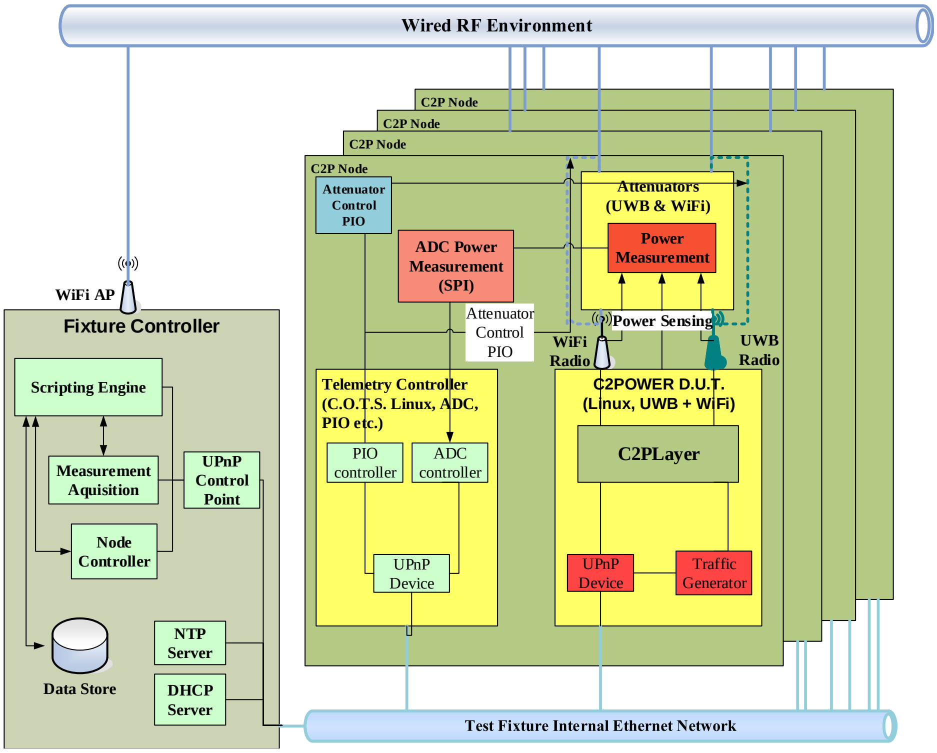

Figure A.2: Testbed platform architecture.

Device discovery, Service discovery, Device control and Event notification. The TFC, shown in figure A.2, is a Linux based system responsible for the control and management of the C2P nodes and the acquisition and storage of performance data and measurements, as well as the control of the programmable attenuators which modify the relative separation of the nodes in the wired radio environment. These functions are automated by a scripting engine and results are preserved in a data store. The scripting engine is Python based, which offers a powerful and well-known means for automating the testbed. Each node includes a Telemetry Controller (TC), which delivers power consumption measurements to the TFC under script control for display and analysis. The TFC provides a time reference propagated to all nodes across the internal network of the testbed to synchronize all nodes for the time-stamping of the current and voltage data and the accurate coordination of node behavior during the execution of cooperative scenarios. The data store holds all the results. The current implementation uses IEEE 802.11g. WiFi in the 2.4 GHz band and UWB operating in WiMedia Band Group 3 (6336-7920 GHz).

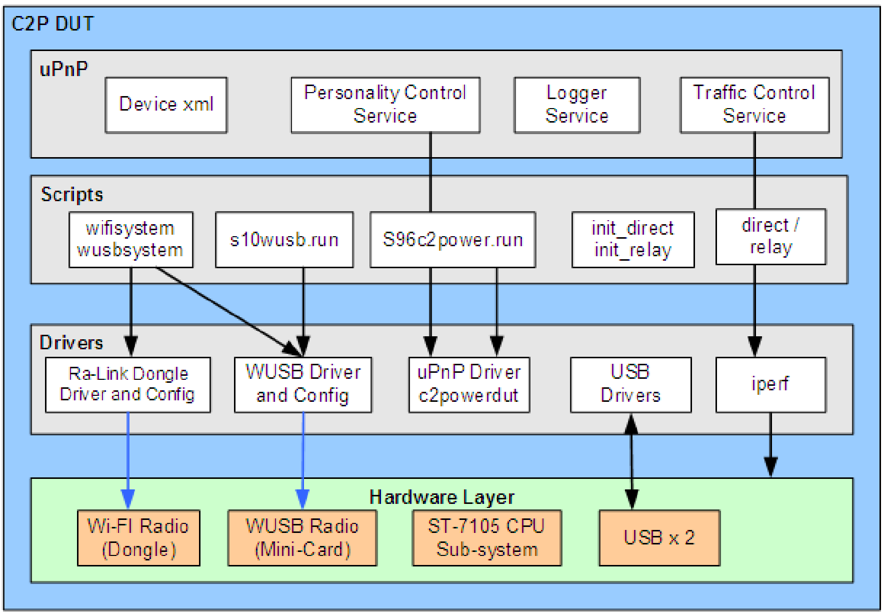

Figure A.3: DUT Software Architecture.

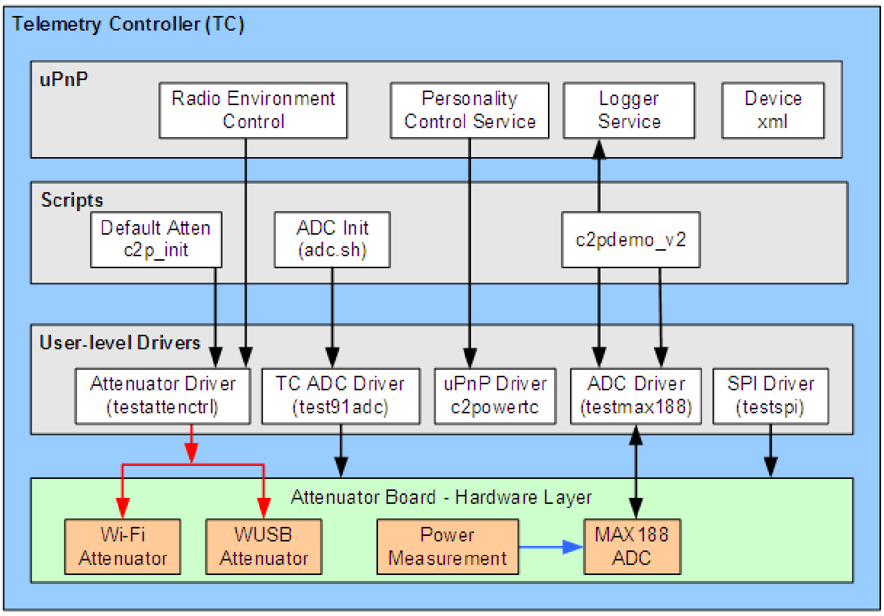

Figure A.4: TC Software Architecture.

A logical representation of the software layers that make up the Telemetry Controller and DUT and how they are interconnected is shown in figure A.3 and A.4. The automation scripts used to control the radio path attenuation, power logging and uPnP services are: TFC runtime scripts, TC runtime scripts and DUT Runtime scripts. TFC runtime scripts configure the IP routing information for either the Direct or Relay scenario and initiate the TCP/IP

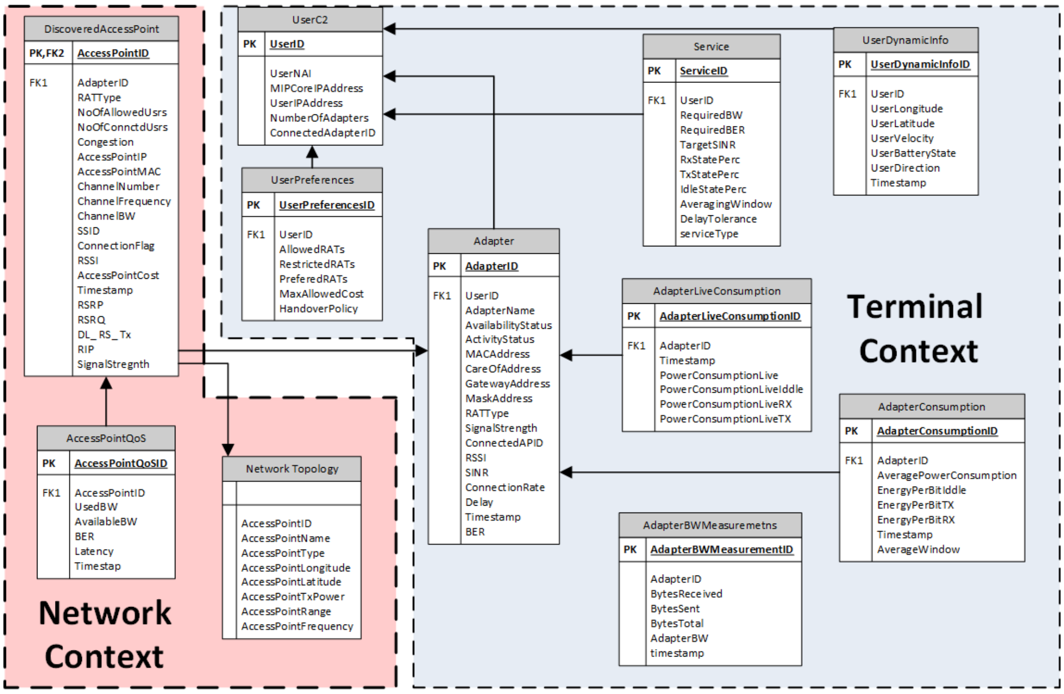

Figure A.5: Schematic view of Database.

the network traffic generator (iperf) server. TC runtime scripts start the measurement run, for the direct and relay scenarios. DUT runtime scripts configure the IP routing tables for either the direct or relay path and start the iperf client to begin the file transfer.

A.2 Schematic View of Database

The database schematic view is shown in figure A.5 is the central point of context exchange within the whole architecture since it receives terminal and network related context from the terminal and network context aware modules and makes this information available to the other modules to process algorithms. This context involves network-based context as seen by the terminal (e.g. available network links, received signal strength, available connection rates), energy context (e.g. power consumption of the adapters of each user and its remaining battery level, user preferences context (e.g. preferred or restricted networks, required cost etc.), user dynamic information (e.g. user position, velocity, etc.). These are provided into the database through the context aware module which is implemented on the terminal. Network related context is also provided like the available bandwidth on each link, the cell load, the network topology etc.