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DEGREE PROGRAMME IN WIRELESS COMMUNICATION

IMPLEMENTATION OF ADAPTIVE MAC FOR COGNITIVE RADIO TESTBED

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ABSTRACT

The aim of this thesis was to design and implement an adaptive medium access control (MAC) protocol for a cognitive radio network (CRN) testbed. The implementation was realized on Wireless open-Access Research Platform (WARPv2). The proposed MAC protocol was based on time division multiple access (TDMA) that works closely with the underlying orthogonal frequency division multiplexing (OFDM) based physical layer. The MAC protocol first sorts the users based on their bandwidth demand in ascending order from the requests gathered in the request phase of an uplink frame. The MAC protocol has a distributed load balancing algorithm to allocate data transmission slots to the users according to their bandwidth need. The implementation also included preamble based synchronization algorithm to maintain network wide time synchronization. To achieve an up-to-date view of the neighbors on dynamic wireless environment integration with a distributed cognitive engine is also included.

The implementation was tested and verified by multiple performance measurement test cases to ensure the validity and consistency of the implementation. Furthermore, a demonstration describing the cognitive load balancing in CRN by utilizing all available radio resources in a distributed cognitive engine was also developed. The demonstration highlights the benefit of cooperative load balancing in CRN and helps us to explore the different aspects of radio resource sharing in CRN to improve the efficiency of spectrum utilization.

The research work presented in this thesis enhances our understanding about cognitive networks by developing intelligent adaptations and radio resource management techniques in real time testbed environment.

Keywords: cellular, cognitive radio networks, wireless platform, software design.

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PREFACE

The work presented in this thesis was funded by Cognitive Radio Trial Environment (CORE) project at the Centre for Wireless Communication (CWC), University of Oulu. The goal of this thesis was to design and implement an adaptive TDMA based MAC protocol for cognitive radio testbed environment. The implementation was carried out on a wireless research platform which enables us to implement and demonstrate the protocol in a real time wireless environment.

I would like to thank my thesis supervisor Prof. Matti Latva-aho at CWC for all the comments and guidance. Furthermore, I would like to thank my project manager Harri Saarnisaari and team leader Hannu Tuomivaara for giving me an opportunity to work in this challenging topic. I would especially like to thank the WARP team at Rice University for help with the boards and the WARP team at CWC for the entire support and work environment. Lastly, I want to thank my family for all the positive comments and support along the way.

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LIST OF SYMBOLS AND ABBREVATIONS

η_F	frame efficiency
B_h	number of bits in traffic packet header
B_g	number of bits in guard period
B_r	number of bits in control packets
B_t	number of bits in total TDMA frame
N_r	number of control packets
N_t	number of traffic packets
T_f	TDMA frame time, in seconds (s)
R_t	total TDMA throughput, in bits per second (bps)
R_i	available throughput for traffic

ABR	available bit rate
ADC	analog-to-digital converter
AGC	automatic gain control
AGCH	access grant control channel
AMP	advanced mobile phone service
ASA	authorized spectrum access
BEE2	Berkeley emulation engine 2
BPSK	binary phase shift keying
BRAM	block random access memory
BS	base station
CBR	constant bit rate
CCH	common control channel
CDMA	code division multiple access
CF	compact flash
CMC	Centre for Multimedia Communication
CPU	central processing unit
CRCH	channel request control channel
CR	cognitive radio
CRN	cognitive radio network
CSMA	carrier sense multiple access
CWC	Centre for Wireless Communication
DECT	digital enhanced cordless telecommunications
DL	downlink
DSA	dynamic spectrum access
DSP	digital signal processing
EU-FP7	Europe Union Seventh Framework Programme
FCC	federal communication commission
FDD	frequency division duplex
FDMA	frequency division multiple access
FFT	fast Fourier transform
FIFO	first in first out
FPGA	field programmable gate array
GSM	global system for mobile communications
GUI	graphical user interface
HD	high definition
HetNets	heterogeneous networks

HSPA	high speed packet access
IEEE	Institute of Electrical and Electronics Engineers
I/O	input/output
IP	internet protocol
IPV4	internet protocol version 4
I/Q	in-phase/quadrature
ISM	industrial, scientific and medical
JTAG	joint test action group
LTE	long term evolution
LTE-A	long term evolution advance
LE-WARP	Linux enriched wireless open access research platform
MAC	medium access control
Mbit/s	mega bits per second
MIMO	multiple input and multiple output
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OS	operating system
OSI	open system interconnection
OSLR	optimized link state routing
PC	personal computer
PDC	personal digital cellular
PDA	personal digital assistant
PHY	physical
PowerPC	power performance computing
PSTN	public switched telephone network
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RAT	radio access technology
RACH	random access control channel
RF	radio frequency
RSSI	received signal strength indicator
RX	receiver
SDMA	space division multiple access
SDR	software defined radio
SNR	signal to noise ratio
SON	self organizing network
TACS	total access communication system
TCP	transport control protocol
TDD	time division duplex
TDMA	time division multiple access
TX	transmitter
VATech	Virginia Tech
VBR	variable bit rate
UDP	user datagram protocol
UE	user equipment
UHF	ultra high frequency
UL	uplink
UMTS	universal mobile telecommunication system

US	United States
USB	universal serial bus
USRP	universal software radio peripheral
WARP	wireless open access research platform
WiMAX	worldwide interoperability for microwave access
WLAN	wireless local area network

1. INTRODUCTION

In the past few years there have been many developments in the field of mobile telecommunication, resulting in new and innovative wireless radio access technologies such as Worldwide Interoperability for Microwave Access (WiMAX), Universal Mobile Telecommunication System (UMTS) and Long Term Evolution (LTE). In general, LTE has enhanced the 3G wireless technologies by introducing new technologies such as MIMO and OFDM [1]. However, these enhancements are still not enough to match the user requirement for growing demand for delivering modern services, e.g. mobile TV, high speed internet access and other important services [2]. Current crowded spectrum poses an obstacle on obtaining feasible bandwidth for long term evolution advance (LTE-A) [3]. Hence, the deployment of LTE-A to the ultra high frequency (UHF) radio band with the frequency range of 300-3000 MHz or making any kind of heterogeneous network can be an emerging and promising solution for spectrum scarcity [3],[4]. However, the problem is not always due to spectrum scarcity rather in many cases it is due to the inefficient utilization of available spectrum.

A recent study in [5] by the Federal Communication Commission (FCC) shows that most allocated spectrums in the United States (US) are under-utilized. Radio spectrum access has been regulated by government agencies in order to achieve interference avoidance radio spectrum management, but spectrum utilization is not considered that much. In this respect, the proper use of available spectrum, a cognitive radio (CR) is considered the promising and intuitive solution [6]. CR is defined as a radio that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters according to its obtained knowledge in order to achieve spectrum efficiency and to learn from the obtained results [7]. In [8], Mitola describes the cognition cycle as shown in Figure 1 which includes the fundamental activities that a CR should perform to achieve the above mentioned goals: observing the surroundings, self-adjusting, making decision, performing actions and learning from experience. Hence, the main function of CR is to collect statistics which characterize the external environment, such as signal to noise ratio (SNR) measurements, traffic load, packet loss, round trip time etc and take decision based on those parameters, resulting in maximum spectrum efficiency. Cognition cycle is a cyclic sequence of processes that includes the following phases [8]:

- **The Observation** phase consists of statistical data collection from the device, which characterizes the external environment, such as signal to noise ratio (SNR) measurements, traffic load patterns, packet error rate etc.
- **The Orientation** phase includes understanding the impact on the communication performance of the external environment by evaluating parameters like throughput, delay etc.
- **The Plan** consists of evaluating the outcome of the decisions which have been made previously, thereby gathering knowledge to be exploited in future decision phase.
- **The Decision** phase includes a possible configuration which aims to best satisfy user-defined goals, which are expressed in terms of high-level

performance metrics such as throughput, delay and reliability, as well as cost, power consumption.

- **The Action** phase consists of reconfiguring the CR to provide enhanced communication quality with respect to user-defined goals. Such configuration can be, for instance, the choice of the wireless radio interface to be used for communication, or the tuning of the communication system's parameters.

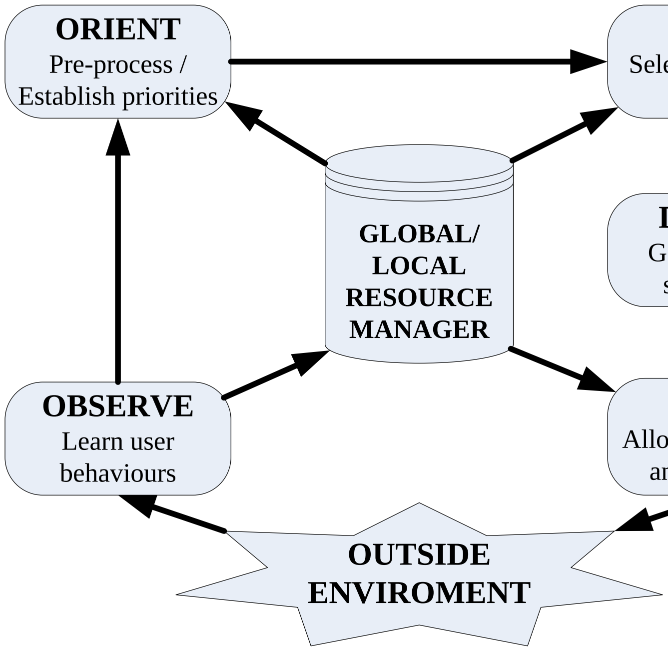


Figure 1. Cognition cycle.

The flexibility of cognitive radios has significant implications for the design of network architectures and protocols at both local network and global levels. In particular, support for algorithms that adapt to changes in physical link quality, radio interference, radio user density, network topology or traffic demand may be expected to require an advanced control and management framework. Furthermore, the allocation of the radio spectrum resource must be carried out in a cooperative manner and balanced between local decisions and global allocation.

The next generation of a mobile cellular network must be able to support a variety of multimedia services with different traffic characteristic and quality of service (QoS) requirements. Some of the traffic is real time such as video conferencing and voice calls while other like web surfing and email are less sensitive to delays and considered as non-real time traffic. Real time applications are sensitive to delays and thus require bounded delay and guaranteed access to medium [9]. A scheduling based medium access control (MAC) protocol with time division multiple access (TDMA) principle is well suited for such applications as it ensures certain performance requirements for the end user's application. [10]

TDMA is a channel access technique for shared medium networks with multiple users. The basic principle of TDMA is to give the transmission medium to a particular user equipment (UE) for a given time period. Each UE is able to access the medium only for a certain time period. TDMA based MAC protocol divides the medium into time slots where UE's can transmit collision free with high probability [10]. In a mobile cellular network, a TDMA based MAC needs to operate in a centralized manner. The successful operation of TDMA system requires a master-slave synchronization algorithm to assure a common notion of time between the user equipment (UE) and the base station (BS). Furthermore, an intelligent scheduling algorithm is required to allocate time slots in each frame to multiple users, based on the traffic demand of each user. This is done to load balance a system effectively or achieve a target quality of service.

This thesis is done as a part of Cognitive Radio Trial Environment (CORE) project [11] which aims to develop a real time testbed environment for testing and prototyping cognitive functionalities on wireless environments. The trial environment focuses on prototype implementation of a cellular scenario, where all the layers can be customized to facilitate the needs of CRN. This thesis focuses on the implementation of an adaptive MAC layer for CRN testbed architecture as illustrated in Figure 2 comprising of two or more networks. Each network has a base station (BS) connected to one or more user equipment (UE) and to a cognitive engine (CE). A base station is responsible for the handling of uplink scheduling based on statistical data collected from UE's and from CE resource manager. An adaptive TDMA based MAC protocol is proposed and its implementation on a Wireless open-Access Research Platform (WARP) is discussed.

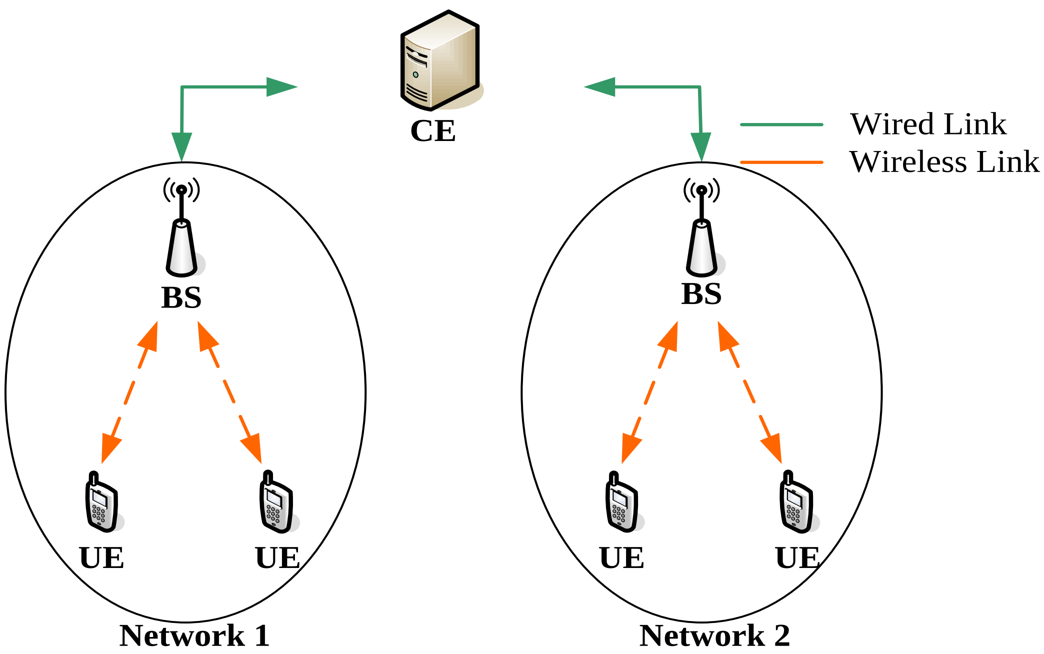


Figure 2. Proposed CRN architecture.

The rest of the thesis is organized into different chapters sequentially as follow. In Chapter 2, cognitive radio network and research challenges in implementing CRN are described. Chapter 3 explains the MAC layer in general and its functionalities like multiple access techniques and radio resource management along with the proposed adaptive TDMA based MAC protocol. The chapter also includes different

MAC layer schemes proposed for CRNs. Chapter 4 provides more details on the implementation. After a brief introduction to the used research platform, the design architecture is presented including details on time synchronization, packet flow and a scheduling process. Chapter 5 gives the analysis of results in terms of performance of the proposed design. Furthermore, verification tests are described along with the demonstration setup. The discussion and future development of the current implementation is then presented in Chapter 6. Finally, the whole work is summarized in Chapter 7.

2. COGNITIVE RADIO NETWORK

CRNs are networks that can sense their operating environment and adapt their implementation to achieve the maximum network performance and spectrum efficiency [12]. Operating environment should include the signal propagation environment, user density, traffic load, mobility, and available spectrum. Wireless networks such as WLAN and LTE already use the rate adaptation and channel selection to increase the network capacity [1]. There is a need for much more aggressive adaptation to dramatically improve spectrum efficiency and wireless network capacity. In the past few years, there has been a significant amount of research in CRNs, looking at adaptation at the physical layer based on modulation and coding, adaptive MAC protocols and collaborative network formation and routing algorithms. [12]

In addition to spectrum sensing to improve spectrum utilization, a cognitive radio in CRN can sense available networks and communication systems around it. A CRN is thus not just another network to interconnect cognitive radio users. The CRNs are composed of various kinds of communication systems and can be viewed as heterogeneous network. The heterogeneity exists in wireless access technologies, networks, user terminals, applications, and service providers [10]. The design of the CRN architecture is to improving the entire network utilization, rather than just spectral efficiency. From the users' perspective, the network utilization means that they can always fulfill their demands through accessing CRNs. From the operators' point of view, they can provide better services to users and allocate radio and network resources to deliver more data rate in an efficient way. [12]

The CRNs can be deployed in centralized, distributed and ad-hoc architectures, and serve the needs of both licensed and unlicensed applications. The basic components of CRNs are user equipments (UE), base station (BSs) and core networks (e.g. internet). In the centralized architecture, a UE can only access a BS in the single hop manner. UEs under the transmission range of the same BS shall communicate with each other through the BS. Communications between different networks are routed through core networks. The BS may be able to execute one or multiple communication standards or protocols to fulfill different demands from UE's. A cognitive radio user can also access different kinds of communication systems through their BS. [13]

- Cognitive Radio Base Station: A cognitive BS is a fixed component in the CRN and has cognitive radio capabilities like spectrum management, mobility management and security management to cognitive UE's. It provides a gateway for cognitive UE's to access the core networks. Cognitive BS can also form a mesh wireless backbone network by enabling wireless communications between them, and some of them act as gateway routers if they are connected with wired backbone networks. [13]
- Cognitive Radio User Equipment: A cognitive UE is a portable device with cognitive radio features. It can reconfigure itself in order to connect to different communication systems. It can sense spectrum availability options and dynamically use them to communicate with cognitive BS. [13]

A CRN can be used to improve resource management, QoS, security, access control, and many other networks goals. These improvements and networks goals will provide a number of benefits that would result in increased access to spectrum and make new and improved communication services available to the users. However, CRN are also limited by the adaptability of the underlying network elements and the flexibility of the cognitive framework. In this respect, designing cognitive process for a particular wireless network may vary from one wireless network to other wireless network. [14]

2.1. Research challenges in cognitive radio networks

Cognitive radio networks impose unique challenges because of the coexistence with different networks as well as diverse QoS requirements. Thus, a CRN has the following critical design challenges: [15]

- Interference Avoidance: a CRN should avoid interference with other networks.
- QoS Awareness: a CRN should support QoS-aware communication and able to decide an appropriate radio spectrum band while considering dynamic and heterogeneous spectrum environment.

A CRN has great potential to improve spectrum utilization by enabling users to access the spectrum dynamically. The main challenge in such network is how to implement an efficient MAC mechanism that can adaptively and efficiently allocate transmission powers and spectrum among cognitive users according to the surrounding environment. Moreover, opportunistic communication with interference avoidance faces a multitude of challenges in the detection of spectrum sharing in multi-user CRN systems. Because of the presence of different user requirement, they pose unique design challenges that are not faced in conventional wireless systems. [16] [17]

The CRN is a novel efficient methodology, extension of software-defined radio, to transmit and receive information over various wireless communication devices. A CRN chooses the best available option based on requirements for each application [18]. The different parameters include frequency, power, transmitter bandwidth, modulation and coding schemes etc that can be varied according to the application. This means that the CRN has to address different radio frequencies and baseband varieties at the same time, thus requiring a robust, efficient and reconfigurable hardware and software architecture. [16]

A CRN will provide the technical means for efficient spectrum management to deliver the services desired by the user. However, to implement such networks have many challenges. These challenges include: the limitation of available wireless radio frequency (RF) channels, inefficient use of RF channels by already existing systems, energy efficient communication to increase network performance and the difficulty of designing QoS aware systems capable of satisfying application requirements.

2.2. Cognitive radio and mobile cellular network

The future of mobile cellular network is anticipated to be an evolution and convergence of mobile communication systems with an IP network, leading to the availability of a wide range of innovative multimedia services over a multitude of radio access technologies (RATs) forming a heterogeneous infrastructure. The concept of the heterogeneous network (HetNets) arises to provide flexible architectures capable of handling multiple wireless radio access technologies along with applications and services comprising different QoS demands. The development of such HetNets requires high degree of inter-communication between the different network entities. In this way, heterogeneous networks may provide large set of available resources than an individual network, allowing a user to seamlessly connect, at any time and any place, to the access technology that is the most suitable for transmission [19]. To achieve this objective, it is necessary to take into account the requirements for heterogeneity in wireless access technologies, comprising different services, mobility patterns and device capabilities. The advancement of authorized shared access (ASA) licenses in LTE-A enable the timely availability and licensed use of harmonized spectrum for mobile networks with predictable quality of service [20]. New techniques must be taken into account for the intelligent management of spectrum among the RATs forming a heterogeneous infrastructure. The term self-configuration and self-optimization applies not only to the selection among a set of available RATs in the service area, but also to the appropriate utilization of radio resource, i.e., careful selection of the operating frequency band. Such issues imply that there is a need for flexible management of radio resources. [21]

2.3. Cognitive radio testbed

For cognitive radio communication techniques to get closer to actual implementation, an important step is to demonstrate some of its main elements using a fully working over-the-air implementation. A testbed can significantly speed up the study and evaluation of CRN techniques.

In [22], a testbed is presented based on Berkeley Emulation Engine 2 (BEE2), which is a multi FPGA emulation platform. Eighteen 2.4 GHz radios are connected to this platform via multi-gigabit interfaces, which can be configured as primary or secondary users. Multiple FPGAs allows the communication and exchange of information through multiple radios simultaneously. The testbed presented enables the evaluation and analysis of various spectrum sensing techniques. Furthermore, in [23], a testbed consisting of Wireless open-Access Research Platform (WARP) based users connected with cloud computing services for extensive computing resources is presented. The testbed highlights two important aspects of CRN, i.e., frequency band shifting and security. The proposed CRN testbed allows us to verify algorithms and protocols for cognitive radio based ad-hoc networks. Furthermore, there are testbeds [24], [25] based on Universal Software Radio Peripheral (USRP) and Software Defined Radios (SDR). In [24], a testbed is presented on USRP to achieve the spectrum sensing and co-existence of primary and secondary users, while implementing the protocols for secondary traffic coordination.

A number of research groups have also proposed and prototyped cognitive radio testbeds, for example, the collaborative CREW project being carried out by eight partners under EU-FP7 project [26]. The main objective of CREW is to establish an open federated test platform comprising of five individual wireless testbeds, which facilitates experimentally driven research on advanced spectrum sensing and cognitive radio networking strategies incorporating diverse radio access technologies enhanced with cognitive sensing platforms. Other groups, like CogNet [27] and VATech [28], have also been working on cognitive network protocol designs and prototypes. More research is needed to compare different cognitive radio implementations.

The CORE project testbed environment is based on the Wireless open-Access Research Platform (WARP). The testbed enables us to experiment and analyze various algorithms in order to develop a set of metrics and test cases. Hence, the testbed will provide a platform for practical evaluation of these proposed designs for setting up a standard for cognitive radio networks. In this thesis, the adaptive TDMA based MAC protocol for CORE project testbed environment is designed and implemented to experiment different load balancing techniques in order to get a better realization of CRN.

3. MEDIUM ACCESS CONTROL

In a mobile cellular network, the mobile users do not have any global knowledge of what other users will send in which time slot and at what bandwidth. Thus a BS has to employ a MAC protocol to provide a reliable communication between multiple users. In CRN MAC, it is more desirable to schedule wireless resources in a way that will guarantee overall global network connectivity and improve spectrum utilization while satisfying different performance requirements such as throughput, network utilization and power dissipation. A novel MAC protocol can greatly improve the network utilization and quality of service (QoS) of the mobile users in the system. QoS is provided by defining multiple access schemes and radio resource scheduling schemes in cellular networks as shown in Figure 3. These two categories are presented later in this section.

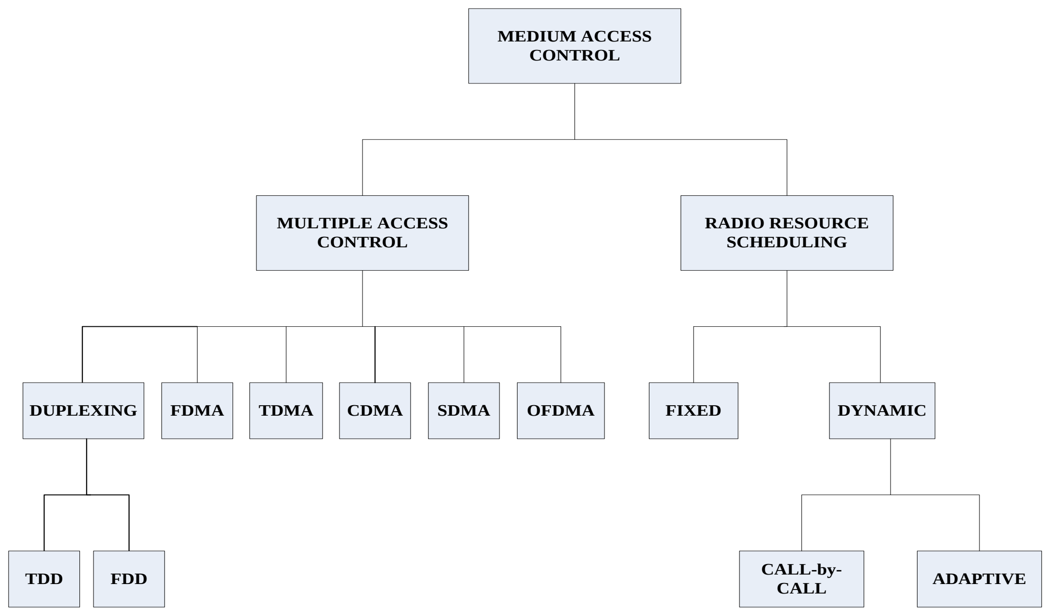


Figure 3. Elements of MAC layer.

3.1. Multiple access schemes

Multiple access control is a technique where multiple users use the same radio spectrum. A sharing of the same spectrum is required in order to facilitate vast amount of users. The following basic methods are designed to accommodate multiple users to share the same physical resources:

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Space division multiple access (SDMA)
- Orthogonal frequency division multiple access (OFDMA)

FDMA is a multiple access technique where the available bandwidth is divided into small chunks of bandwidths depending on the number of users, commonly known as channels. Each channel is independent and non-overlapping in order to avoid interference. Every user is then dedicated one or more channels to access the medium. TDMA is a multiple access technique where the system bandwidth is given to a particular user for a definite period of time, known as a time slot. Each user is able to access the medium only for a certain time period. In CDMA, each user uses the system bandwidth for a complete duration of time. All the users use the same frequency band simultaneously. In order to separate the signals, each user is assigned orthogonal codes [30]. SDMA is a channel access method with multiple antennas enables access to a communication channel by identifying the user location and establishing a one-to-one mapping between the network bandwidth division and the identified spatial location. SDMA can be configured and deployed along with other multiple access techniques. LTE has very small frequency bands known as subcarriers and a small transmission time slots. Thus frequency and time resources are reassigned for diversity or efficiency reasons during ongoing user transmissions. This method is known as Orthogonal Frequency Division Multiple Access (OFDMA) [31]. OFDMA combines FDMA and TDMA behavior in an agile manner. Figure 4 illustrates the multiple access techniques and highlights the major differences between them.

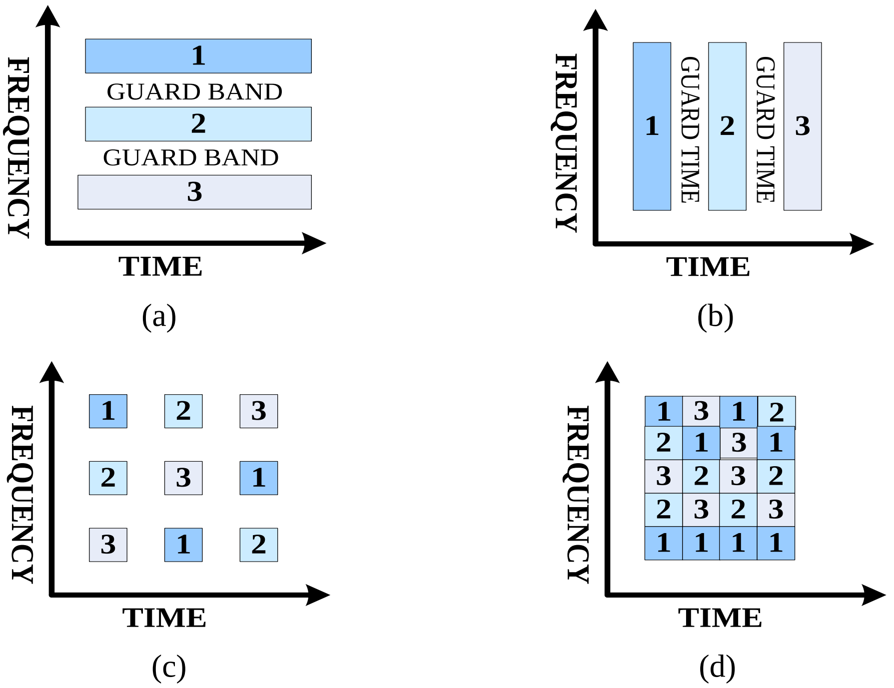


Figure 4. Multiple access techniques: a) FDMA, b) TDMA, c) CDMA, d) OFDMA.

Mostly communication takes place in a bidirectional way which allows simultaneous transmission and reception. Duplexing methods are used for dividing transmission and reception communication channels on the same physical communications medium. In reality, it is not possible to transmit and receive simultaneously but switching between the two phases is done so fast that it is not noticed by the user. Mobile communication systems commonly use two basic duplexing techniques which are as follows:

- Frequency division duplex (FDD)
- Time division duplex (TDD)

In FDD, the frequency band is divided into two partial bands to enable simultaneous transmission and reception. One partial band is given to uplink (from a mobile to a base station) transmission and other to downlink (from a base station to a mobile) transmission. Both the partial bands should be sufficient distance apart from each other known as a guard band. While in TDD, the same frequency band is used for both transmission and reception. Duplex is achieved by switching in time between uplink and downlink. The guard time is also required between uplink and downlink to avoid interference [30]. Figure 5 presents both duplexing techniques and highlights the differences between them.

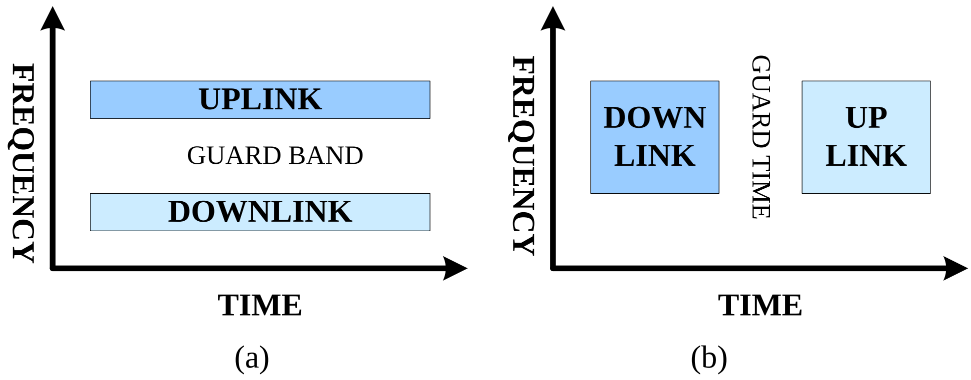


Figure 5. Duplexing techniques: a) FDD, b) TDD.

3.1.1. Performance analysis of TDMA based MAC

The performance of TDMA frame can be evaluated by measuring TDMA frame efficiency and throughput available for data traffic. The efficiency of TDMA frame is an important parameter to measure the percentage of total frame length dedicated to the transmission of traffic data. It is expressed and evaluated as: [32]

$$\eta_F = \frac{\text{Number of bits available for traffic}}{\text{Total number of bits in frame}}, \qquad (1)$$

$$= 1 - \frac{\text{Number of overhead bits in frame}}{\text{Total number of bits in frame}}, \qquad (2)$$

Or in terms of TDMA frame elements

$$\eta_{F}\,(\%) = 1 - \frac{N_r B_r + N_t B_h + (N_r + N_t)\,B_g}{R_t * T_f} \times 100, \qquad (3)$$

Where:

η_F: frame efficiency
B_h : number of bits in traffic packet header
B_g: number of bits in guard period
B_r: number of bits in control packets
B_t: number of bits in total TDMA frame
N_r: number of control packets
N_t: number of traffic packets
T_f : TDMA frame time, in seconds (s)
R_t: total TDMA throughput, in bits per second (bps)

A throughput available for data traffic, e.g., voice, video and internet data is another crucial performance measure. All the following throughputs such as the total TDMA throughput, reference burst throughput, header burst throughput and the guard time throughput are defined in bits per second (bps) [32]:

Total TDMA throughput: $$R_t = \frac{B_t}{T_f}, \qquad (4)$$

Control packet throughput: $$R_r = \frac{B_r}{T_f}, \qquad (5)$$

Traffic header throughput: $$R_h = \frac{B_h}{T_f}, \qquad (6)$$

Guard time throughput: $$R_g = \frac{B_g}{T_f}, \qquad (7)$$

Throughput for data traffic $$R_i = R_t - N_r\,(R_r + R_g) - N_t\,(R_h + R_g), \qquad (8)$$

Where:

R_i: available throughput for traffic

The detailed analysis and verification of proposed MAC frame structure is presented in chapter 4.

3.2. Radio resource scheduling

A base station (BS) in a mobile cellular network is responsible for managing the bandwidth requests and scheduling bandwidth to the UE's according to the service flow requirement of the UE. The resource management procedure includes determining which users to schedule and how to allocate the available radio resources to them. An efficient scheduling algorithm should guarantee system performance by concerning different quality of service (QoS) requirements and various system performance factors as well as available radio resources in scheduling decision. In cellular networks, each BS has its own scheduler and UE follows the scheduling command from the serving BS. In this section, we will present basic scheduling algorithms for mobile cellular network.

3.2.1. Fixed scheduling

A set of a frequency band used in FDMA or time slot in TDMA are permanently allocated to a particular user for data transmission in this scheme. This uniform distribution is efficient if traffic distribution is also uniform. Since in mobile networks traffic can be non uniform, a uniform scheduling of bandwidth may result in inefficient radio resource utilization. It is, therefore, good to adjust the number of bands or slots to match the traffic load by non uniform scheduling [33]. In non uniform scheduling, the allocation depends on a traffic profile. For example, in [34] Delay Sensitive Slot Assignment (EDSSA) channel scheduling scheme is proposed for cellular networks. The proposed technique attempts to allocate the resources in a way so that the end-to-end delay is minimized. Similarly in [35], Non Uniform Compact Pattern scheduling is proposed for scheduling resources according to the traffic distribution. The proposed technique attempts to allocate the resources in a way to minimize the average probability in the entire system that an individual user cannot get access to the service. A fixed channel allocation scheme tends to equally allocate the system bandwidth to the users.

3.2.2. Dynamic scheduling

In dynamic scheduling all available resources, i.e., frequency bands or time slots, are kept in a central pool and are assigned dynamically to user as new request come in the system depending on the bandwidth need. When the users release the assigned bandwidth or time slots, it comes back to the pool and is now available for the other users. The main idea in all dynamic scheduling schemes is to evaluate the cost or price of using a resource and select the one with minimum cost provided that certain interference constraints are satisfied. The selected cost might depend on the probability of not getting access to the service, usage frequency, reuse distance, channel occupancy distribution under current traffic scenario. Based on information used for channel assignment, dynamic scheduling can be categorized as call-by-call and adaptive schemes [36]. For example, in [37], a call-by-call dynamic scheduling scheme based on changes in traffic pattern is presented. Furthermore, in [38], an adaptive scheduling scheme is proposed which tries to assign the same resources assigned before to the existing users to limit the transferring of an ongoing transmission to a new resource without interruption. In the call-by-call scheme, scheduling is based on current channel usage condition whereas adaptive schemes include both current and previous channel usage conditions in the service area.

3.2.3. Comparison of fixed and dynamic scheduling

Table 1 illustrates the comparison of fixed scheduling and dynamic scheduling algorithms [33]. There is a trade-off between quality of service, the implementation complexity of the scheduling algorithms, and spectrum utilization efficiency.

Table 1. Comparison of fixed and dynamic scheduling

Fixed Scheduling	Dynamic Scheduling
Better performance in heavy traffic	Performs well in moderate traffic
Low flexibility in slot assignment	Flexible slot assignment
Centralized control	Centralized or decentralized control
Sensitive to time varying traffic	Insensitive to time varying traffic
Low implementation complexity	High implementation complexity
Low computational effort	High computational effort
Suitable for large environment	Suitable for micro environments

In future, multiple multimedia services will be used in the mobile phones and other portable devices. Cellular communication systems are required to support multiple traffic classes for each user at a time. Also shifting users from one RAT to another is needed to access all the available resources within the surroundings in a way that increases the spectrum efficiency. Moreover, in practical systems, a queue buffer is not infinite, so buffer overflow is possible. Thus, a scheduling algorithm should be aware of buffer status and packet characteristics along with the current radio resource information. [39]

3.3. MAC layer in cognitive radio network

Current wireless networks are characterized by a static spectrum allocation policy under which each licensed spectrum band is statically assigned to the specific licensed users [40]. Recent studies have shown that use of static spectrum assignment has degraded spectral efficiency significantly [5]. Therefore, a new concept of dynamic spectrum allocation (DSA) arises to overcome the critical limitations of the traditional static allocation scheme. DSA plays an important role in several CRN functions like spectrum mobility, resource allocation, and spectrum sharing. Spectrum mobility allows a user to vacate its channel, when a primary user is detected, and to access an idle band where it can reestablish the communication link. Resource allocation is the capability to opportunistically assign available channels to users according to QoS requests. Spectrum sharing deals with contentions between heterogeneous networks in order to avoid interference. [41]

Recently, MAC layer researchers have proposed cognitive MAC protocols based on dynamic scheduling schemes for throughput enhancement in cognitive radio networks. A cognitive MAC with continuous-time Markov chain model is proposed in [42], which enhances performance with the coexistence of multiple parallel WLAN channels based on sensing and prediction. A cognitive MAC (C-MAC) protocol for distributed multi-channel wireless networks is introduced in [43], which is able to deal with the dynamics of channel availability due to user's activity. A stochastic channel selection algorithm based on learning automation is proposed in [44], which dynamically adapts the probability of access one channel in real time. It is shown that the probability of successful transmissions is maximized using the proposed selection algorithm. [45]

A Multi-MAC protocol that can dynamically reconfigure MAC and physical layer properties based on per-node and per-flow statistics is proposed in [46]. In [47], MAC protocol which switches between CSMA and TDMA is evaluated for various traffic patterns using the NS-2 simulator. Similarly in [48], an adaptive MAC protocol is presented and evaluated through simulations assuming that the channel status is known. Different spectrum access schemes using different sensing, back-off, and transmission mechanism are considered, which reveal the impact of several important design criteria, such as sensing, packet length distribution, back-off time, packet overhead, and grouping. [45]

3.4. Adaptive TDMA based MAC

In this section, the concept of an adaptive TDMA based MAC protocol is proposed and designed to be used in cognitive radio testbed. The main idea of an adaptive TDMA based MAC protocol is described in the following order. First, the basic structure and control channels are explained along with their functionalities then flow of designed protocol is explained. Finally scheduling process is elaborated in detail along with the channel shifting procedure. Implementation issues related to adaptive TDMA based MAC protocol will be covered in Chapter 4.

3.4.1. Frame structure

The frame structure of proposed adaptive TDMA based MAC protocol is presented in Figure 6. The TDMA frame is segmented into two equal parts for downlink and uplink, respectively. Each downlink and uplink frame is then further segmented into N sub-slots. An assumption is made that the maximum number of slots is fixed in each TDMA frame. The last sub-slot of both downlink and uplink frame is reserved for the guard time. The guard time is the time interval where no transmission is done by any UE and BS. This prevents possible overlapping of transmission between downlink and uplink when the synchronization between BS and UE is not optimal. The guard time will also accommodate the effect of transmission delay.

In the proposed MAC protocol, the uplink and the downlink frames are divided into sub-slots. The downlink frame is divided into three subframes as shown in Figure 6, namely the common control channel (CCH) slot, the access grant control channel (AGCH) slot, the DATA slot and the GUARD TIME slot. Similarly the uplink slot is divided into four sub-slots as the random access control channel (RACH) slot, the channel request control channel (CRCH) slot, the DATA slot and the GUARD TIME slot. The functionality and operation of each slot are explained in section 3.3.2. The detailed analysis and verification of the proposed MAC frame structure are presented in Chapter 4.

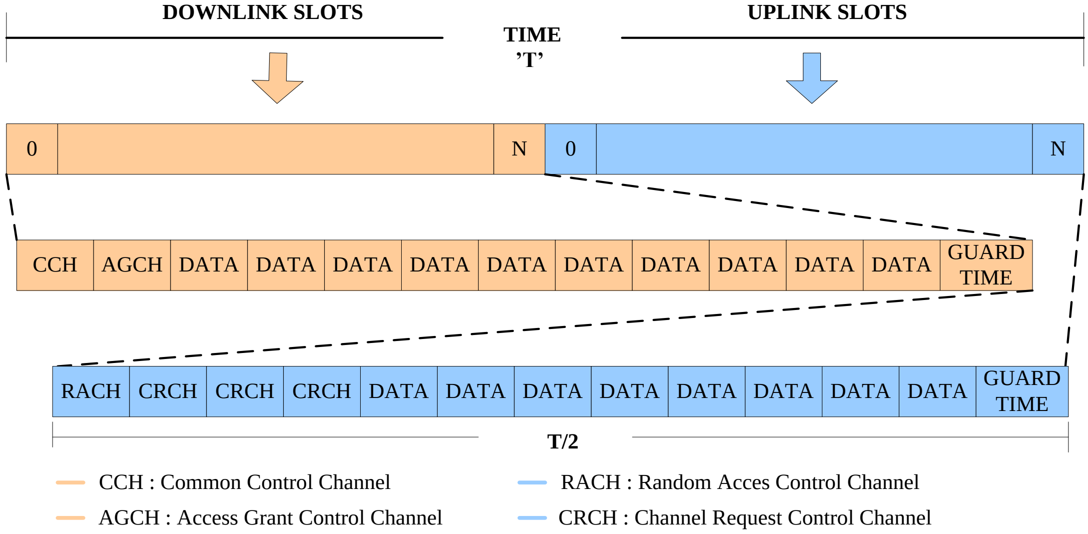


Figure 6. Proposed TDMA frame structure.

3.4.2. Protocol operation

The operation of the proposed MAC protocol is divided into two phases, namely the request phase and transmission phase. In the request phase, UE that have packets to transmit will send a request packet in one of the request slots. If more than one UE sends request packet in the same request slot, a collision occurs and all the request packets are lost. To avoid collision, the proposed MAC is designed with dedicated request slots. After each request slot, scheduling information is transmitted from the BS through the common control channel (CCH) during the downlink frame. The UE will then start transmission according to the given scheduled slot. The implementation can be extended in order to make system more adaptive and dynamic to the changing environment. The implementation is flexible to handle different length of TDMA frames and capable to support different message exchange protocols. Moreover, the protocol is designed in a way to have some free byte in header that can be use in future for various parameters like average load on each channel, UE SNR on different channels, power estimation and other channel parameters. The flow diagram of the complete protocol is illustrated in Figure 7.

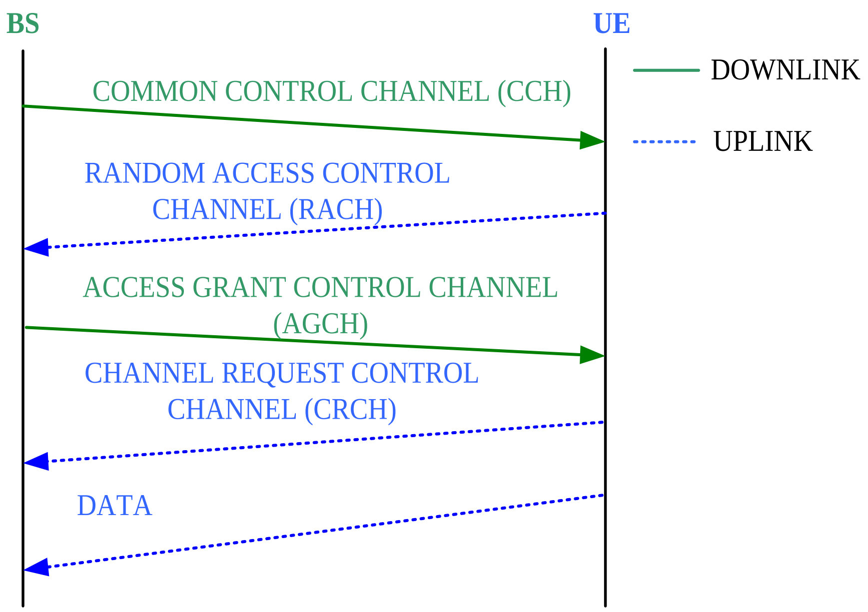


Figure 7. The flow diagram of an adaptive TDMA based MAC.

The message exchange pattern is as follows:

- A BS continuously transmits a common control message at the beginning of every TDMA frame during downlink frame which includes information used for time synchronization, scheduling and channel shifting.
- A UE receives a common control packet and synchronizes its clock accordingly. UE then request for dedicated request channel via RACH channel during uplink.
- The BS then assigns the request slot and sends the required information via the AGCH channel during downlink.
- After getting the request channel, whenever the UE has data to transmit, it first sends a request for acquiring dedicated data slot using that dedicated request slot.
- The BS informs UE about the data slots via CCH.
- The UE then starts its transmission on the assigned data slots.

The low complexity is an important part in the adaptive TDMA based MAC design. The reliable design can let the wireless users achieve the maximum efficiency. The scheduling of radio resources in the design is based on slots requested by UE's. The UE requests the number of slots required for transmission depending on the service type like constant bit rate (CBR), variable bit rate (VBR) and available bit rate (ABR). The BS process the slots requested from all the UE's in descending order. The BS requests the CE to get the resource information about neighboring BSs, if BS does not have enough resources to allocate the slots requested by the UE. After retrieving that information, the BS will decide whether it is possible to fulfill the slot demand of the user by shifting it to neighbor BS for a certain period of time, which is referred as load balancing. Load balancing is a principle to balance the workload over the base stations and divide the load as evenly as possible, aiming to optimize performance measures of the system. The CE is a distributed database to assist the BS in load balancing decisions and provide information about the available resources in neighboring BS's. The implementation shown in Figure 8 includes the bandwidth requested by the UE's in terms of the number of slots.

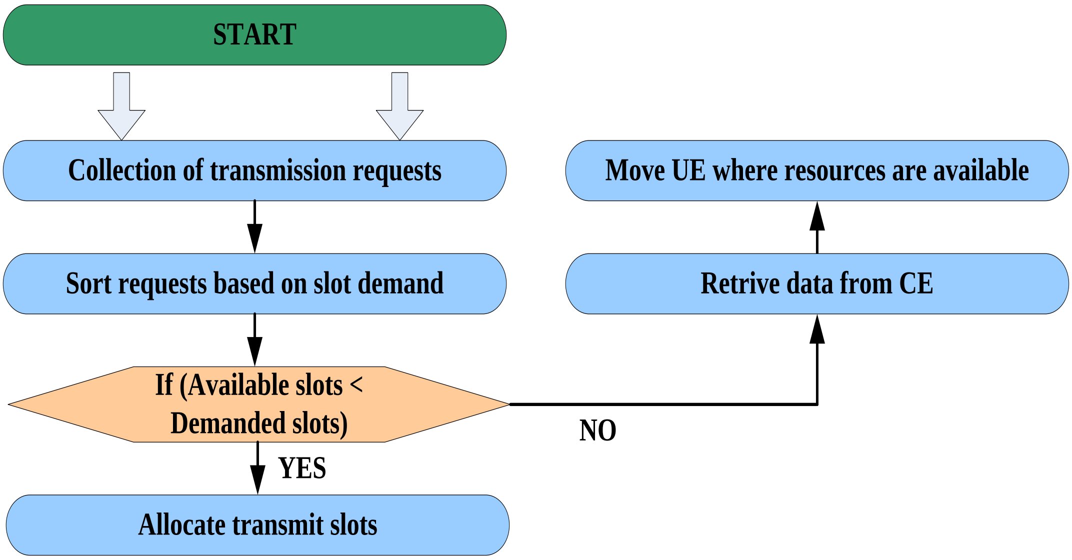


Figure 8. Adaptive TDMA based MAC scheduling process.

4. IMPLEMENTATION

The implementation of an adaptive MAC protocol for a CRN requires access to more than one radio frequency (RF) band and for that it needs a hardware platform which is flexible and allows access to more than one RF band. Wireless Open-Access Research Platform (WARP) is a scalable and extensible programmable wireless platform. WARP enables the prototyping of the protocol stack suited for CRNs. Thus, it allows us to implement and test new spectrum sensing algorithms, SNR estimators, different MAC architectures, routing algorithms and cognitive decision rules. [18, 49]

4.1. Overview of wireless open-access research platform (WARP)

Figure 9 gives an overview of the WARP [50]. The detailed description is given below:

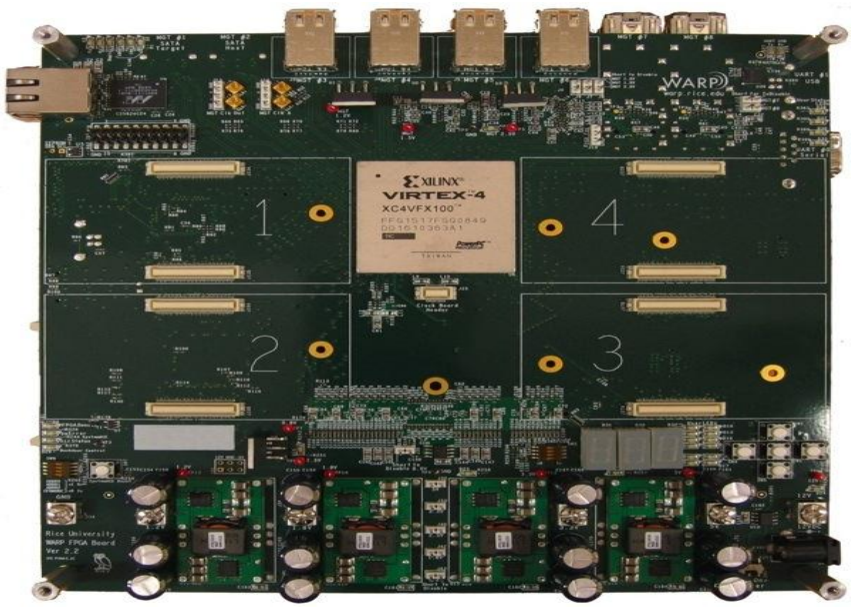


Figure 9. The second generation WARP board.

WARP is a complete system solution with three component layers:

- Custom hardware with scalable processing resources and extensible I/O support.
- A platform with support packages for seamless integration between different hardware components.
- An application design environment matched the needs of multiple wireless research communities.

WARP v2 is a FPGA based platform with Xilinx Virtex 4. This FPGA is well suited for intensive and complex DSP operations that require fast multiplications like FFTs and filtering, detection algorithms and various time critical operations. The chip also has two PowerPC processor cores, providing a resource for implementing higher layer algorithms. Moreover, the WARP hardware also offers 10/100/1000 Mbit Ethernet interface for a wired network connection. [10]

The board has four daughter radio boards for generating an analog RF signal from a digital I/Q signal and vice versa. The radio boards also control RX/TX gains that are used in RF amplifiers on the WARP. The clock board is designed to provide a clock signal to all parts of system design and, by default it is set for clocking the radio board with a stable reference clock, FPGA logic and analog converters. Universal Serial Bus (USB) or Joint Test Action Group (JTAG) connections or a Compact Flash (CF) memory cards can be used for downloading the whole system to FPGA. A serial port connection is also available for reading and giving control information from the WARP board. [10]

4.2. Linux enriched WARP

LE-WARP stands for Linux Enriched Wireless Open Access Research Platform. It is an extension of the WARP platform done in Centre for Wireless Communication (CWC) [51]. It includes additional features like a network layer with IPV4 protocol stack and transport layer functionalities, an application layer to WARP, which results in an improved performance. Linux OS is running on one processor core and MAC operations on the other. This allows MAC development without interfering Linux and vice-versa. Two new Linux kernel drivers were also introduced to interact with the MAC side. Xilinx mailbox and shared BRAM memory are used to send and receive packets from the MAC side and the WARPNET driver is for providing Linux Ethernet interface. Mailbox generates the interrupts of new data in shared memory to the MAC side. One more driver, warptool is also integrated to set the MAC parameters and for this it uses the mailbox for passing information between CPUs [51].The system architecture of LE-WARP is an extended version of the basic WARP OFDM reference design with changes to provide support to the network and transport layers. The main functionalities of LE-WARP are discussed in later sections.

4.2.1. LE-WARP physical layer

The LE-WARP physical layer is using OFDM reference design developed by Centre for Multimedia Communication (CMC) at Rice University based on the IEEE 802.11 a-g standard. After getting the packet from the MAC layer, the physical layer passes the bits in the packet buffer to the base band module for transmission. The physical layer design module and radio board exchange information like TX/RX gains, IQ from analog-to-digital converters (ADCs), RSSI (Received Signal Strength Indicator) from ADC etc. through Radio Bridge. The packet detector detects the RSSI and compares it to the certain threshold value and then sends the arriving packet information to higher layers for further processing. All the modules process IQ, RSSI and other control signals, pass them to PowerPC processor or the radio, depending on whether the data is to be received or transmitted. The LE-WARP physical layer is capable of handling different modulation schemes like BPSK, QPSK and 16-QAM.

The code rate is an important parameter in wireless transmission for error correction. In WARP, the possible code rates are 1/2, 2/3, 3/4, which means that one redundant bit is inserted after every single, second, third bit. The code rate 1 corresponds to no coding meaning no redundant bit is added. [18]

4.2.2. LE-WARP network layer

Network layer is mainly responsible for source to destination packet delivery in order to provide reliable point to point communication. In LE-WARP, Linux OS is providing all the functionalities of a network layer. Linux is running on second PowerPC processor of WARP's FPGA in order to achieve the TCP/IP stack running on every WARP so that any routing protocol can be added. It also allows Linux to function independently and does not interfere with MAC protocols and vice versa. [18]

4.3. System design of adaptive TDMA based MAC

LE-WARP is used as a basis for this implementation but it is necessary to modify that design in order to guarantee successful completion. The MAC protocol explained in section 3.3 is implemented as a software design that is running on embedded PowerPC processor on WARP's FPGA. In this section, different MAC layer modules are introduced and their implementation aspects are elaborated in detail.

4.3.1. Design architecture

The modules are presented as the software design architecture as shown in Figure 10. The architecture consists of a packet flow module which shows all the packet transmission and reception routines from wireless and wired connections. The synchronization module includes all the synchronization related routines. All the software routines for controlling TDMA/TDD related functionalities like TDMA frame duration, slot duration, uplink and downlink frame duration etc, are incorporated in independent TDMA functionality routine. Furthermore, scheduling routine has a module containing all scheduling related functionalities. Finally behavioral control is used to show the dependence of each module to realize the working implementation. The design architecture of the BS and the UE is the same except for the scheduling module which is missing in UE. Only BS is responsible for the scheduling of radio resources and managing those resources among UEs.

The arrows in the figure represent the data and information flow between the modules. All the modules with light gray color are implemented and the dark ones are taken from already existing implementations introduced here [52] and [10].

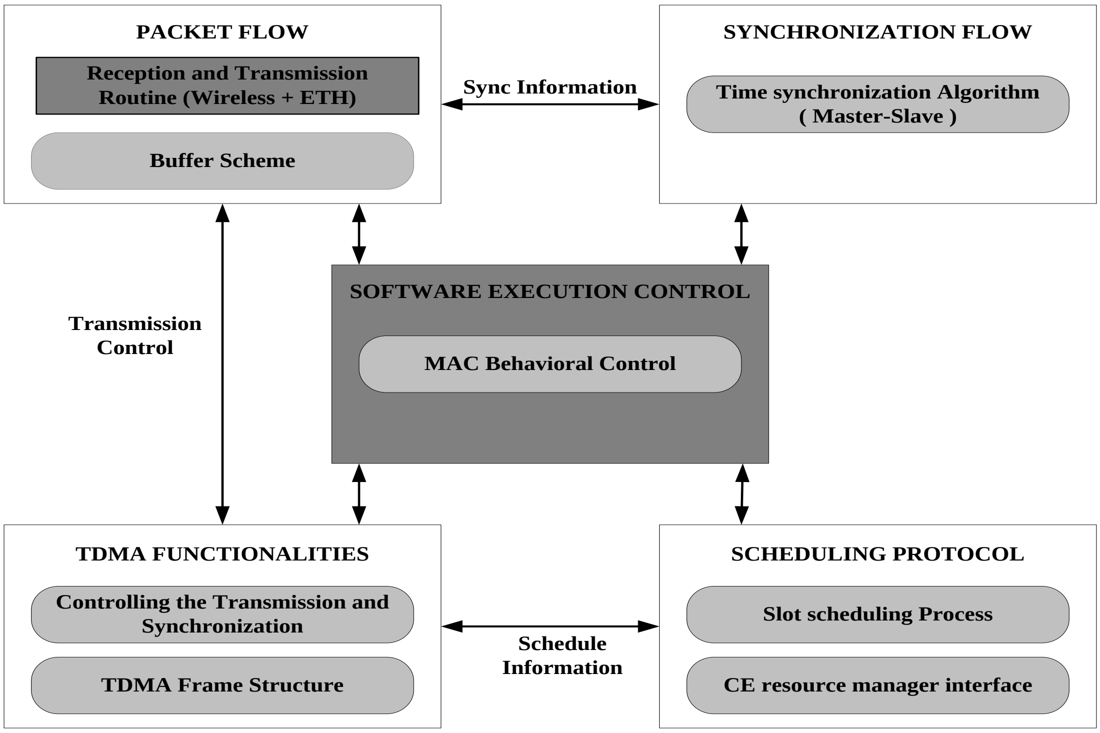


Figure 10. Software architecture of an adaptive TDMA based MAC for BS.

4.3.2. Reception and transmission routine

The reception of a packet is initiated by a change in physical layer register. The change is then identified by PowerPC by polling the memory location of that register. The software routine of receiving a packet is then executed with a callback function [10]. This function is modified, in order to retrieve information from the control packet, which includes synchronization information, scheduling data and mobile shifting decisions from the BS.

In the transmission routine, there are two types of packets, a data packet from the buffer and a control packet. The control packets served for different purposes like the common control (CC) packet, the random access (RA) packet, the access grant (AG) and the channel request (CR) packet. These packets are created from information acquired from other modules e.g., scheduling information, shifting information from the CE and information from the received control packets. A function is designed to pull a data packet from the buffer during a particular data slot over the transmission channel.

The general transmission and reception routine flow chart is presented in Figure 11 of the adaptive TDMA based MAC protocol. The transmission routine is initiated periodically for uplink and downlink in every TDMA frame. The UE starts transmission after verifying that the current slot is its scheduled transmission slot from the BS. On the reception side, the processing of the control packets can be done as individual sub-routines and the data packet is simple forwarded to an upper layer by the code.

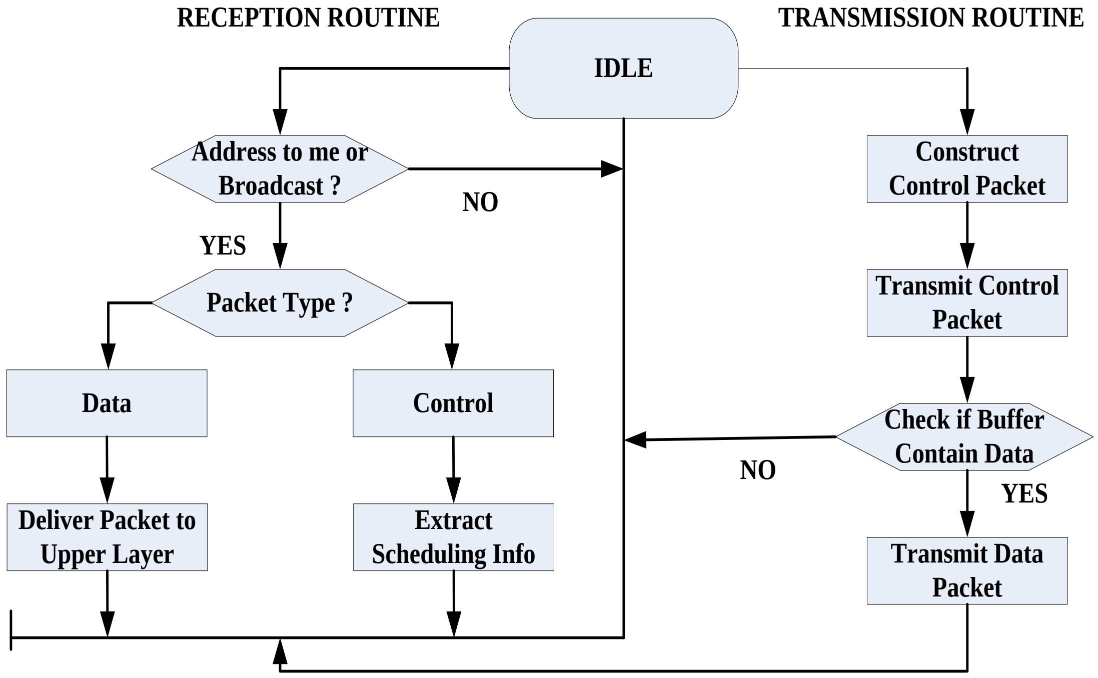


Figure 11. Flow chart of general transmission and reception.

4.3.3. Packet flow

The packet flow in the adaptive TDMA based MAC protocol is illustrated in Figure 12. The LE-WARP boards are connected through the Ethernet interface to PCs. The Linux side and the PC are responsible for taking care of all the network layer protocols and end user applications.

The BS is connected to PC and CE resource manager through Ethernet interface via router and to UE1 and UE2 through the wireless interface. Direct communication between to the UE1 and the UE2 is not possible. Here in, the data packets that are generated by PC are routed from the UE1 to the BS and then to the UE2. The BS is just acting as a relay to pass the information from one UE to another and it also passes internet data from the PC connected to the BS.

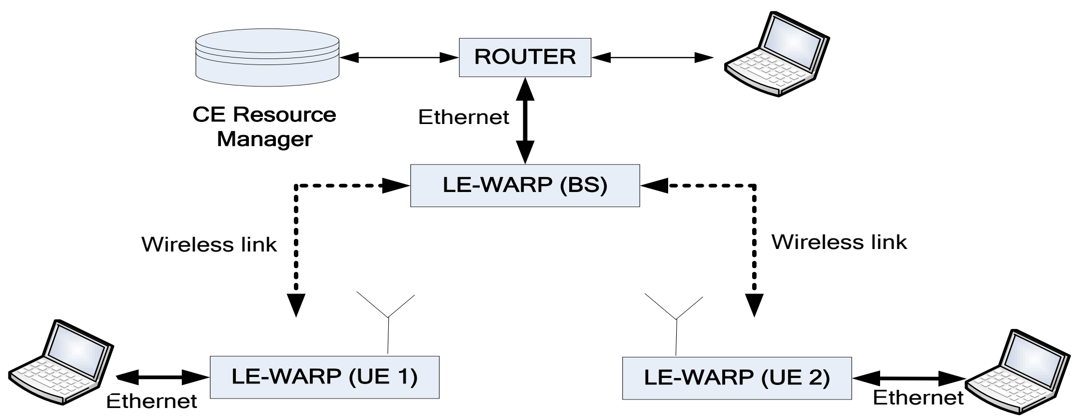


Figure 12. Packet flow of network layer data.

4.3.4. Buffering scheme

Since the implementation is based on TDMA, there is a need to store the packets coming from the network layer to wait for the particular transmission slot to come as it is based on TDMA. For that a circular buffering mechanism in transmission routine is implemented. The circular buffer is a fixed size buffer and it is working according to the First in First out (FIFO) principle. [10]

4.3.5. Time synchronization

The adaptive TDMA based MAC protocol scheme needs synchronization mechanism in the network among the BS and UE to work in a collision free manner. For this purpose an assumption is made that propagation delay is negligible as we are presenting a prototype in an indoor environment with small distances. Even with that assumption we need to implement some sort of synchronization mechanism because of the clock drifting phenomena [53]. As each WARP board has its own local clock running by a local oscillator, it can easily drift seconds per day. As the frame length in many cases is quite small, a common reference time is lost between the clocks as well as between the boards within a small time slot.

As time synchronization is not in the scope of the thesis, therefore synchronization is done where the BS functions as master and sends a common control packet to all UE's at the start of every downlink frame. UE has to adjust a common notion of time with BS on every common control packet received. The weak point in this type of algorithm is that if UE fails to receive the common control packet synchronization is lost. This weakness is covered by having short TDMA frame length so that the synchronization is so rapid that losing one or two consecutive control packets does not have significant impact on synchronization.

4.3.6. TDMA frame structure

The adaptive TDMA based MAC protocol has the fixed frame structure in our design. The frame length, the slot count and the guard time all have fixed duration given in Table 2.

Table 2. TDMA frame structure of an adaptive TDMA based MAC

Attributes	Time (ms)
TDMA frame length	65
Downlink (DL) frame length	32.5
Uplink (UL) frame length	32.5
Slots in each DL & UL frame	13
Slot duration	2.5
Guard time	2.5
Slots for data transmission in DL frame	10
Slots for data transmission in UL frame	8

Packet transmission in a slot is controlled by buffering packets in the circular buffer. During the receiving slot in a TDMA, the UE has to listen to the channel and wait for physical layer to initiate the reception routine.

4.3.7. Scheduling process

During the reception routine, the BS collects the transmission requests from all UEs who want to transmit data during the uplink frame. The BS then buffers that data for a particular interval of time until the transmission routine executes as shown in Figure 13. At the start of each transmission routine the BS calls a scheduling function in which it retrieves the stored information from the CE resource manager and makes decision based on the scheduling algorithm presented in section 3.3.2. After the decision making, a common control message is generated along with scheduling and channel shifting information. The packet is then broadcasted to each UE available in the network.

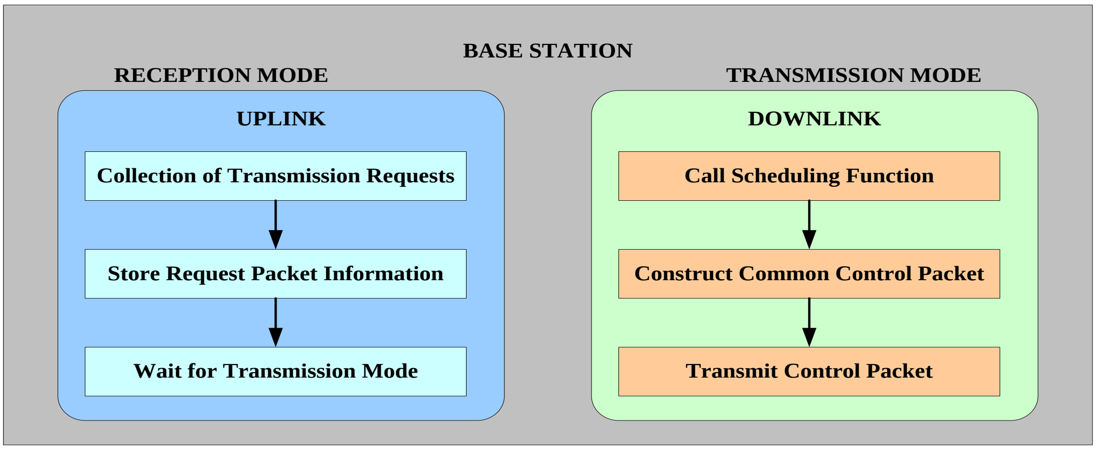


Figure 13. Scheduling process of an adaptive TDMA based MAC.

5. PERFORMANCE VERIFICATION AND DEMONSTRATION

In this chapter, the verification tests are reported for the adaptive TDMA based MAC protocol implementation. The tests are mainly done to verify and prove that the implementation is consistent and efficient according to the expectation. As the implementation is focusing on the scheduling of uplink data slots, therefore all the measurements are carried for an uplink frame of the adaptive TDMA based MAC protocol.

The first verification test is done to validate the time domain behavior of the MAC protocol implementation. The second test includes the effect of different modulation schemes and code rates to the performance characteristics of the implementation based on the utilization of user datagram protocol (UDP). The performance characteristic includes throughput, packet loss and packet size. Subsequently, validation of the performance measure like throughput is presented based on transmission control protocol (TCP). Finally, the focus is on the theoretically evaluated efficiency and data rate. Moreover, a comparison is presented between the theoretical and measured results of the adaptive TDMA based MAC protocol.

5.1. Time domain analysis

To study the time domain behavior of the implementation, the following setup is made. Two PCs are configured as packet generator from the WARP boards running the adaptive TDMA based MAC protocol as illustrated in Figure 14. The analysis helps to adjust the TDMA frame and slot duration according to the packet size and transmission duration to get the maximum performance out of the implementation.

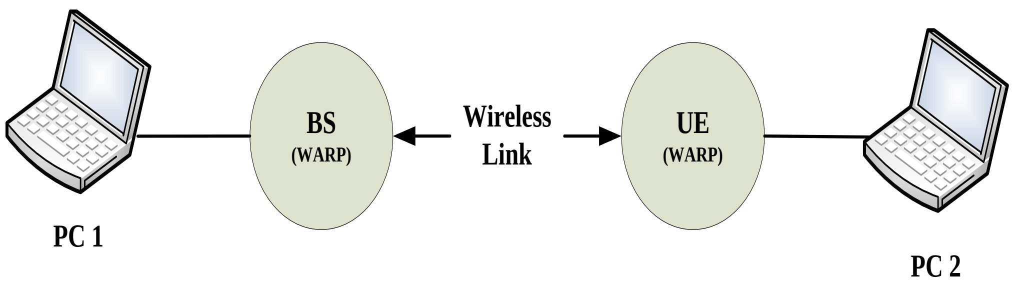


Figure 14. Time domain measurement setup.

The suitable TDMA frame length for the adaptive TDMA based MAC protocol is discovered by measuring the transmission duration of different size packets with different modulation schemes while coding is not used. This is done by utilizing various packet lengths and measuring transmission duration that are spent in the transmission routine. After the measurements, the result includes the comparison between the packet size and the transmission time with different modulation schemes as presented in Figure 15. The results show that the transmission time is almost directly proportional with the packet size. If the packet size is considered as constant, the transmission time varies with the modulation scheme used. BPSK requires more time to transmit the same sized packet than QPSK and 16-QAM. Similarly, QPSK requires more time to transmit the same sized packet than 16-QAM. This is due to the fact that the packet of 1500 bytes will become 700 symbols in QPSK and 350 symbols in 16-QAM after modulation. It is evident from the results that smaller a packet size requires less transmission time. Finally, the results are compared with the average minimum duration for transmitting a new DATA packet given on WARP website [54] and it is observed that the implementation is working accordingly.

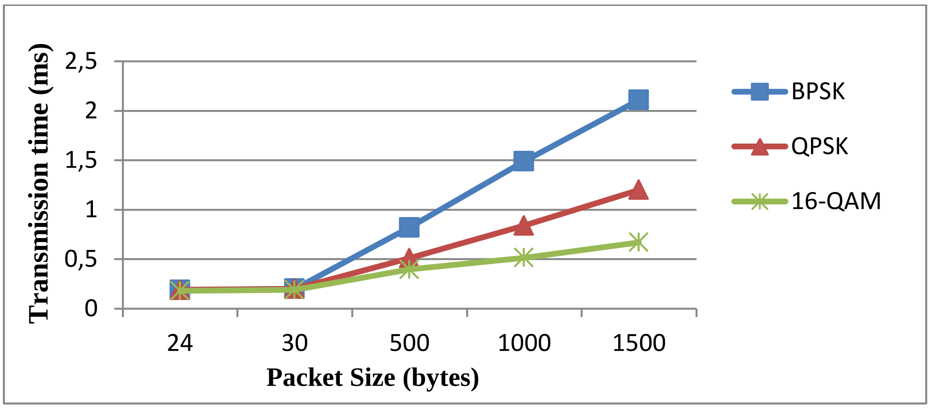


Figure 15. Transmission time with varying packet size.

5.2. Performance measurements

To characterize the performance of the designed adaptive TDMA based MAC implementation, performance measures like the throughput, packet loss and packet size are considered in different test cases with different modulation schemes like BPSK, QPSK and 16-QAM.The throughput measurements are carried out with both the UDP and TCP protocol used for the transport of data across an Internet Protocol (IP) based network. UDP is used with applications that are tolerant to data loss such as video streaming. Other applications which require reliable data stream services uses TCP protocol. Therefore, both the UDP and TCP protocol are considered to investigate the reliability of an adaptive TDMA based MAC protocol for all types of multimedia services.

The measurement test setup consists of four boards as illustrated in Figure 16.Two two boards as BSs and the other two like UEs. Performance was measured using jperf 2.0.2 networking tool [55]. The jperf 2.0.2 is a tool to measure the throughput and the quality of a network link with both the UDP and TCP protocols. The measurements are taken by using UE 1 as sending data to UE 2 via BSs. Also measurements for simultaneous communication from UE1 to UE2 and UE2 to UE1 are taken to verify the TDD nature of the adaptive TDMA based MAC protocol. Computers were connected to UEs (WARP boards) through Ethernet cables.

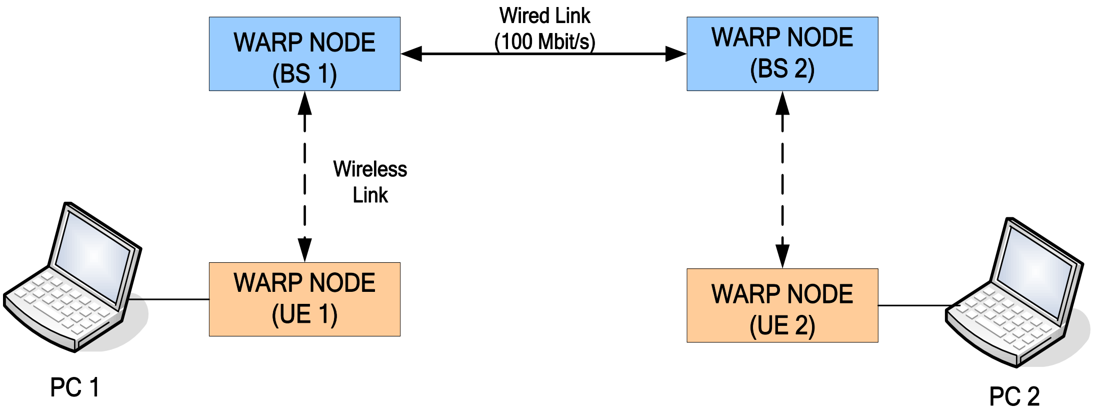


Figure 16. Performance measurement scenario.

5.2.1. Throughput as a function of bandwidth demand

Figure 17 and 18 illustrate how the throughput of the adaptive TDMA based MAC protocol varies with the number of slots allocated to UEs for uplink transmission and the modulation scheme. Figure 17 concentrate on one-way communication, i.e., packets are coming from UE1 to UE 2 and effect of modulation schemes on throughput. Figure 18 describes two-way communication between the UEs. The packet size in jperf is fixed to 1500 bytes, mainly because it is the maximum packet size that the WARP can handle from the PC.

From the results it can be seen that in one-way communication, the throughput increases with the increase in number of slots available for the user. The maximum achievable throughput with all the slots in use is 1.49 Mbit/s in case of BPSK, 2.9 Mbit/s in QPSK and 4.45 Mbit/s in 16-QAM. As the MAC protocol is TDMA based, more data can be transmitted at the same time by using different modulation schemes, giving more throughput. In case of two way communication, the results are the same validating the TDD nature of an adaptive TDMA based MAC protocol.

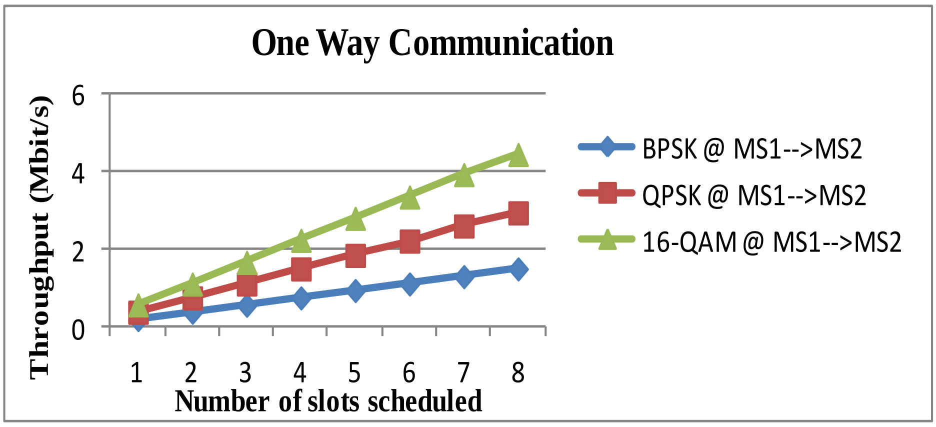


Figure 17. Throughput in one way communication.

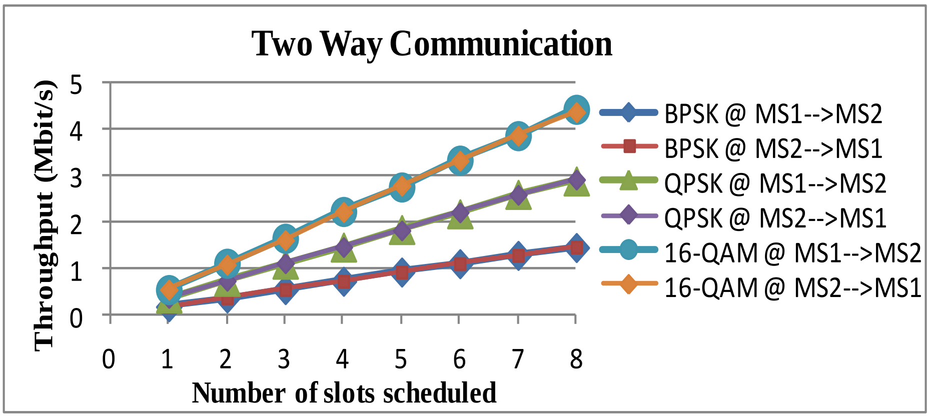
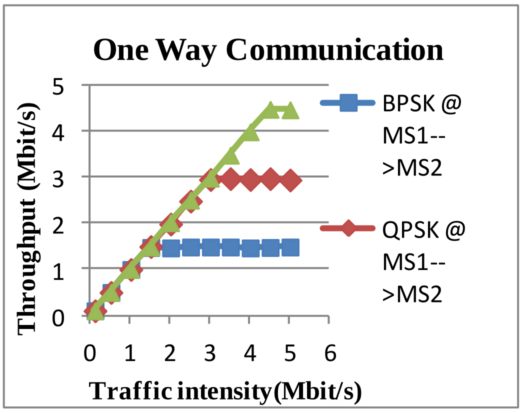


Figure 18. Throughput in two way communication.

5.2.2. Throughput and packet loss as a function of traffic intensity

Figure 19 and 20 explains how the adaptive TDMA based MAC protocol can handle different offered data traffic using different modulation schemes. The figures concentrate on the throughput of the UE as a function of traffic intensity offered by the PC in two different cases. It can be seen from the results that the throughput is directly proportional to traffic intensity until a maximum throughput is achieved as in the previous section. After, a maximum is achieved the throughput becomes constant. The packet loss ratio starts to increase when the load exceeds the capacity of the adaptive TDMA based MAC protocol. When the buffer is full, the WARP starts to drop packets coming from PC. As the packet processing time is more than the incoming packet time a rapid degradation of performance is observed in all test cases. The throughput and packet loss in both one-way communication and two-way communications are almost the same. So it is evident from the results that adding more UE's in the network does not affect the performance of the adaptive TDMA based MAC protocol.



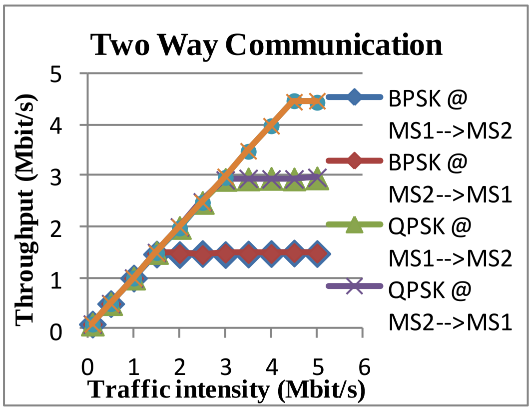


Figure 19. Throughput as a function of traffic intensity.

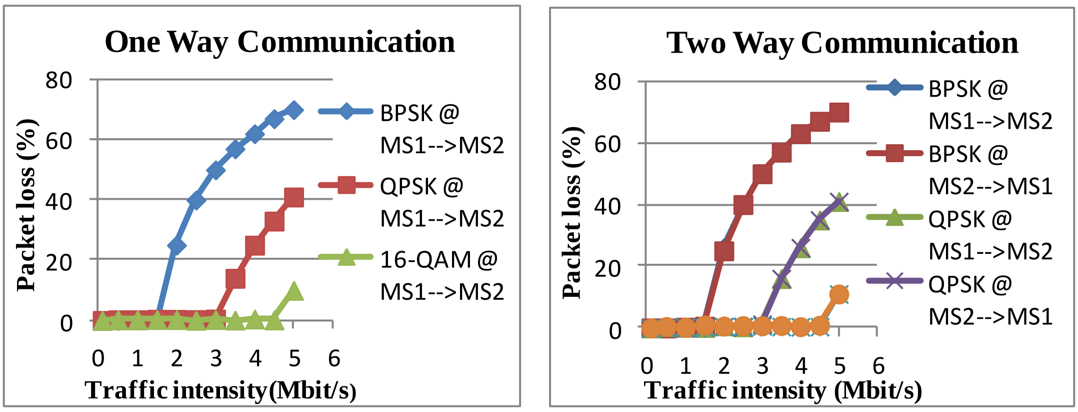


Figure 20. Packet loss as a function of traffic intensity.

5.2.3. Throughput and packet size as a function of code rates

Figure 21 illustrates the effect of different code rates to data throughput. The result shows that the data throughput increases with the increase in code rates while keeping the same modulation scheme. The maximum achievable throughput with all is 2.9 Mbit/s with QPSK and 4.45 Mbit/s with 16-QAM with no coding. As coding is introduced the throughput decrease, because more coding increase the number of redundant bits in data bits for error correction. Wireless links are subjected to transmission error especially when users are mobile as in the case of mobile cellular networks. These errors can degrade the performance for applications with tight quality-of-service requirements. To overcome this problem, channel coding is introduced. However, this solution can compromise the transmission throughput, leading to an undesired end-to-end performance [56].

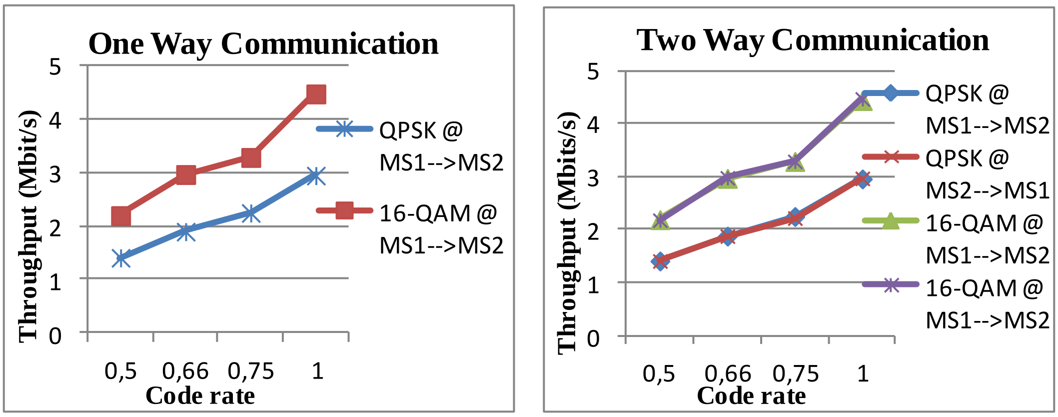


Figure 21. Throughput as a function of code rate.

5.2.4. Transmission control protocol performance

The measurements were taken for all the modulation schemes BPSK, QPSK and 16-QAM with TCP. All measurements were taken for transferred data bytes and the achievable throughput five times and the average shown in Table 3. The results show that the throughput and data transferred bytes increases with the use of different modulation schemes. The maximum achievable throughput in case of TCP with all the slots in use is 1.4 Mbit/s in case of BPSK, 2.61 Mbit/s in QPSK and 2.96 Mbit/s in 16-QAM. The comparison between TCP and UDP results is presented in next section

Table 3. Throughput and transferred data in terms of modulation schemes with TCP

	Transfer Mbytes	Bandwidth (Mbit/s)
BPSK	1.85	1.40
QPSK	3.33	2.61
16-QAM	3.75	2.96

5.2.5. UDP and TCP performance comparison

It is also observed that the throughput achieved with UDP is slightly higher than with the TCP in case of BPSK and QPSK modulation. The TCP performance degrades in case of 16-QAM. This is acceptable considering that TCP is supposed to perform badly over wireless links [57]. As explained in [57], in the wireless environment, the congestion algorithm of TCP will start instantly, considering link error as network congestion. Furthermore, UDP requires less time for the transmission of data than TCP because of the absence of flow control or error correction mechanism.

5.3. Theoretical performance evaluation of adaptive TDMA based MAC

The performance of the TDMA based MAC protocol can be evaluated by measuring TDMA frame efficiency and throughput available for data traffic. Using the equation (3) presented in section 3.1.1. The efficiency of the adaptive TDMA MAC protocol is evaluated and is come out to be 66.66%.

Theoretical throughput available for the data traffic is measured by calculating all throughputs according to (4), (5), (6) and (7) in bit per seconds (bps) for total TDMA frame including both DL and UL. The available data rate is then evaluated by using (8). The results are shown in Table 4. For comparison with the measured throughput in the next section, the throughput mentioned in Table 5 is divided into two equal halves to get the theoretical throughput for an uplink frame of the adaptive TDMA based MAC protocol.

Table 4. Theoretical throughput of an adaptive TDMA based MAC protocol

Control packet throughput (*R*r)	2953,8
Traffic header throughput (*R*h)	2953,8
Guard time throughput (*R*g)	0
Total TDMA frame throughput (*R*t) in Mbit/s	
BPSK	3,27
QPSK	6,53
16-QAM	9,78
Total TDMA frame data traffic throughput (*R*i*)* in Mbit/s	
BPSK	3,21
QPSK	6,40
16-QAM	9,72

5.3.1. Comparison between theoretical and measured throughput

Table 5 shows a comparison between theoretically calculated throughputs of the adaptive TDMA based MAC protocol uplink frame and actually received throughput measured with UDP traffic during the uplink frame. The actually measured throughput is based on measurement result presented in section 5.2.1.

Table 5. Comparison between theoretical and measured throughput of uplink frame

	Theoretical throughput	Measured UDP throughput
BPSK	1,6	1,49
QPSK	3,2	2,94
16-QAM	4.85	4.45

It is observed that the theoretical throughput is slightly higher than throughput measured with UDP traffic in real time scenario. The reason for this performance degradation is because of processing delay, for example, the physical layer requires a minimum time from receiving the last packet over-the-air and starting a new packet reception. The PHY needs to finish processing one packet, deciding whether it was good or bad, before it can begin processing the next. The guard time after the uplink frame and time interval between consecutive packets also result in performance degradation.

5.4. Load balancing demonstration

The implementation presented in this thesis is integrated with the optimized link state routing (OSLR) protocol and distributed CE in the CORE project. The demonstration system is realized by a graphical user interface (GUI) which shows different network parameters such as throughput, radio resource management, packet error rate and modulation. The demonstration describing the benefits of cooperative load balancing in cognitive radio networks is presented at “12th FRUCT Conference” held on 5th November 2012 in Oulu, Finland [58]. The demonstration highlights the CRN running load balancing algorithm to use the system resources efficiently. The complete load balancing scenario is presented in the next section.

5.4.1. Demonstration Setup

The demonstration presents a prototype implementation of smart load balancing algorithms for the cognitive radio network. The demonstrated cognitive radio network is composed of multiple LE-WARP test beds, a distributed cognitive engine and a graphical user interface (GUI). LE-WARP test beds are designed and programmed to function as BS and UEs. The functionalities of the cognitive engine are distributed among LE-WARPs and the PC which is running the database and the GUI. LE-WARPs are gathering information about the network and they are constantly updating the database.

The demonstration showing video stream over a network topology consisting of the CRN which includes three BSs, four UEs and the CE as depicted in Figure 22. UEs are connected to BSs via wireless link. Base stations and CE are connected together via wire. Two of the BSs are considered as rival operators, operator A and operator B, whereas the third BS is considered as an available common resource for both operators. In this demonstration, The VLC application [59] is used for video streaming between two UEs of the different network. In addition, we compare the cooperative and non-cooperative load balancing techniques and show the differences in their network performances. In detail, we highlight the benefits of cooperative load balancing with global load balancing algorithm. More of these scenarios are explained in later sections.

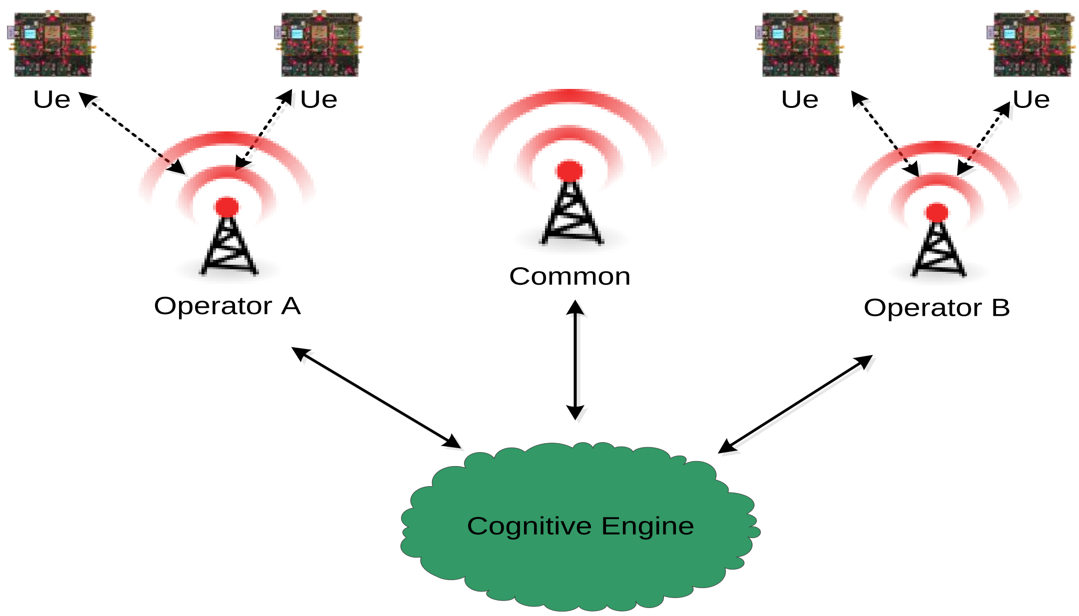


Figure 22. Demo setup for load balancing scenario.

5.4.2. Non-cooperative load balancing

The non-cooperative scenario as shown in Figure 23 consists of local load balancing algorithm within the operators. The local load balancing algorithm is capable to take load balancing decision within the operator's own network as well as of the common resource. In this case, the CE is act as a database and collects all the network information about available resources and passes that information to the operators. As there is no cooperation, if one of the operator is utilizing the common resources other has to wait.

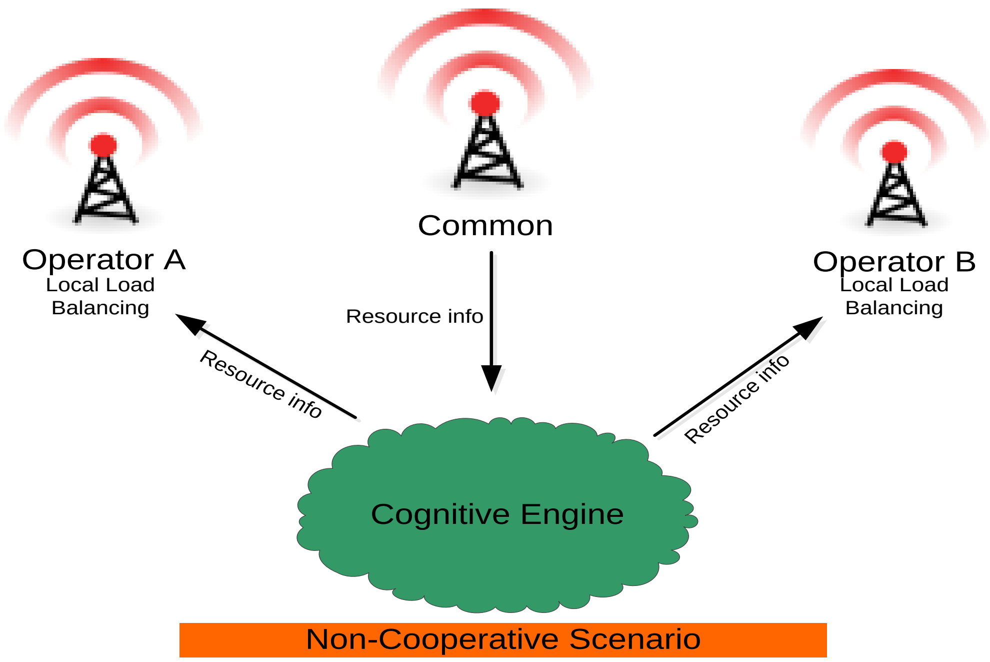


Figure 23. Non-cooperative load balancing scenario.

5.4.3. Cooperative load balancing

In cooperative load balancing as illustrated in Figure 24, the CE has a global load balancing algorithm and capable to take load balancing decisions for the common resource. The operator with local load balancing algorithm is only able to take decision within their own networks. Whenever they have to utilize the common resource they have to request CE for decision making. The CE makes the decision based on global knowledge of the networks and trying to maximize the overall network performance and spectrum efficiency. If the common resource is fully occupied, the CE re-arranges UEs so that resource usage of the system is optimal.

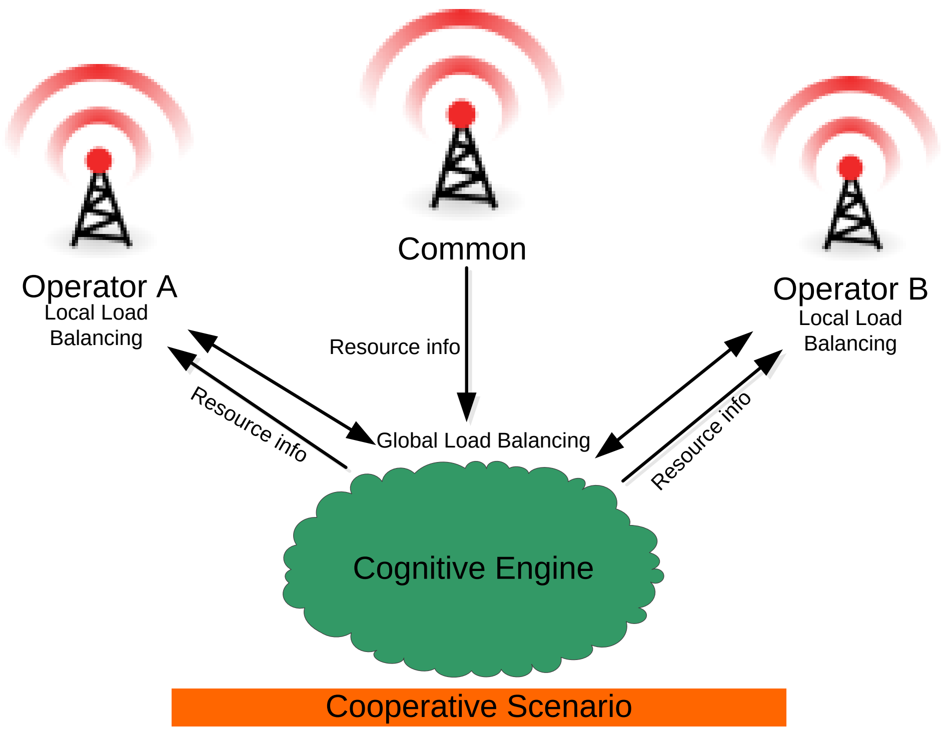


Figure 24. Cooperative load balancing scenario.

The video stream went through as expected during 45 minute demonstration session. However, there was distortion in streaming a couple of time because of the fact that the demonstration arena was filled with several WIFI-users and this might have resulted in interference as we are using 5Ghz band for our transmission. Moreover the results also show that during the non-cooperative scenario, the video quality is not that good while utilizing the common resource if it is already occupied by other operator whereas in the cooperative case, the video stream went through properly by the intelligent balancing of UEs with global load balancing algorithm and we are able to play high definition (HD) video during our demonstration.

6. DISCUSSION

The main contributions of this thesis are the implementation of the adaptive TDMA based MAC protocol for CRNs with the LE-WARP platform and integration with other implementation work done by CWC team members. The integration and implementation included the porting of Linux OS in the WARP platform with adaptive routing protocols and the CE resource manager with a GUI.

During the implementation, several issues have been observed and addressed to improve the throughput and network stability. One of the issues was the design of proper control channel mechanism while maintaining the flexibility and extendibility of the system. To resolve this issue, the protocol is design in a way so that each control channel packet has the header with some free bytes available for future use and also the TDMA frame duration is made to be changeable according to the future extension. Consecutive transmissions of the data packets is another issue resulting in the loss of transmitted data as there is no buffering scheme available in reference design. To resolve this issue, a circular buffer mechanism is implemented based on FIFO principle. Furthermore, the synchronization of UEs with BSs is also addressed. Most of the synchronization methods studied during literature review [60] required two or more messages to exchange between the UEs and BSs resulting in throughput degradation. To resolve this issue, an assumption was made that the CRN is for indoor environment where propagation delay is considered negligible. Based on this assumption, a synchronization algorithm was implemented that requires one BS message to synchronize the symbol timing at UE.

The time domain testbed measurements confirmed the consistency and stability of the proposed MAC protocol. The transmission duration of different packet lengths was measured, so that we can adjust the TDMA frame and slot duration to get the proper performance out of the implementation. The performance analysis confirmed the performance characteristics of the adaptive TDMA based MAC protocol. The throughput and packet loss results gave us the performance limits of our design with different types of modulation schemes and code rates. The results also proved that a collision free transmission can be achieved with this implementation with multiple users and with TDMA/TDD transmission. The adaptive TDMA based MAC also supports both UDP and TCP, with slight differences in overall performance. Finally, the implemented MAC performance characteristics were compared with the theoretical results. The comparison shows slight degradation in implemented MAC performance. The reason for that is the processing delay as it is time consuming for physical and MAC layer of WARP platform to process all the incoming and outgoing packets.

Each executed test scenario highlight different aspect of the MAC design. No major inconsistencies were conceived in the MAC design and it was verified to work properly and consistently with different modulation schemes and code rates. The maximum load that the design can sustain in different cases was verified and confirmed. It is not possible to compare this implementation with the same type of concepts already existing as there is no implementation available that have similarities with our design.

In the future, the implementation can be extended in order to make system more adaptive and dynamic to the changing environment. The implementation is flexible and can be extended to include different channel estimation parameters like SNR, average load on different channels, etc. The implementation is capable of handling different priority metric to experiment different radio resource sharing techniques and can be used to address the future work related to cognitive radio networks like:

- Co-operative CRN: The sensed spectrum and surrounding environment information is distributed across several cognitive engines in cooperative CRNs. The distributed information gives a better topology of the existing network and helps in offloading the users by running distributed load balancing and spectrum sensing algorithms.

- HetNets: With the development of ASA licenses in LTE-A, heterogeneous networks become possible. The implemented prototype can be extended to address the issues like the coexistence of various RATs and the cooperation schemes in making such networks.

The implemented testbed helps to investigate and analyze the constraints in real time environment to deploy such networks and provide better understanding about cognitive radio networks.

7. SUMMARY

In cognitive radio networks, spectrum management and radio resource sharing are crucial for high priority and delay sensitive real-time data transmission. The delay and throughput requirements are often guaranteed by using stable and efficient MAC protocol. Therefore, a cognitive MAC protocol design should have the objective of achieving a working CRN and the features of MAC should focus on the adaptive and dynamic radio resource sharing mechanism to provide reliable communication to users with maximum spectrum efficiency.

In this thesis, the design and real time implementation of an adaptive TDMA based MAC protocol for a CRN testbed was presented. The implementation was carried out on Wireless Open-access Research Platforms. The implementation includes software controlled adaptive TDMA based MAC entity on top of an already existing OFDM based physical layer. Control packets were used to share information among the users and to prevent collision by allocating dedicated request slots. Distributed load balancing algorithms were included in BSs to manage the radio resource sharing among users. The implementation also includes the time synchronization algorithm to have a common notion of time between UEs and BSs. Furthermore, integration with routing algorithms and the cognitive engine is also included to develop a fully function real-time CRN testbed.

The test scenarios verified the current implementation to be valid and consistent. The implementation is capable of acquiring and sustaining a collision free medium access strategy. The end result was a real time implementation of the adaptive TDMA based MAC protocol which could be successfully used for demonstration to highlight the different aspects and operation of cognitive radio networks.

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