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On Experimental Assessment of Wireless Network Technologies

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Abstract

The advancement in wireless communication networks and pervasive computing is perhaps among the most significant developments that have marked few past decades. We are transforming towards a society where efficient transmission of digital contents is paramount in especially due to advent of high speed-services, multimedia and low-power applications. Such development has made the demand for effective deployment of communication networks. Lately, research works in protocol development have enhanced the performance significantly. However, efficient transmission in wireless environment is still a challenging task. Theoretical techniques are applied for wireless networks prototyping, to solve this problem. One of the key challenges of such techniques in wireless environment is also achieve the same efficiency gain in practice.

This work takes the advantage of multi-user multiple-input multiple-output (MU-MIMO) technology which is being conceived as a potential candidate for next-generation wireless communication systems to meet such demand. Assuming that, we designed an adaptive transmission system that adapts transmit power and modulation to maximize the system capacity by exploiting the beamforming in time-varying imperfect channels. This system devises the closed-form expression in MU-MIMO to define the switching thresholds for various modulations. Then, based on the derived expression, it optimally allocates the transmit power, by taking the doppler frequency into account, and designs the linear pre-coding scheme for each mobile terminal (MT).

Being aware of the theoretical and simulative shortcomings, which lack the realism in results, in technology evaluation phase, in this thesis, we try to bridge the gap between simulation experiments and real-world testing. We use the network emulation technique to develop the wireless emulation framework to emulate next-generation protocols and algorithms of wireless networks. Finally, we show the feasibility of emulation framework by evaluating the adaptive system in realistic environment. Hence, several experimental results both in simulation and emulation, show the adaptive transmission system improves the overall system throughput which is close to analytical throughput, and demonstrate its validity and potential uses.

This work contributes in both ways, theoretically and practically, to the researches of next-generation wireless networks. As for theoretical implications, this work presets an adaptive transmission system for improving communication performance of each UT and overall system throughput. As for practical implications, we develop a framework to evaluate the protocols and algorithms of next-generation wireless networks in realistic environment. This framework also exhibits a different way to carry out large-scale experiments with next-generation wireless networks which can not be easily accomplished with real wireless testbeds.

Keywords: Adaptive transmission system, time-varying channel, MU-MIMO, realistic environment, NS-3, QOMET

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Chapter 1

Introduction

In this chapter, we briefly explain the motivation of the research in adaptive transmission system and its evaluation in realistic platform in order to position our contribution in this emerging research context. We also give a short overview of the research context to pose the problem. Following that, our contributions will be described before presenting the outline of the dissertation.

1.1 Motivation

The emergence of wireless technologies and inter-operation, unprecedented in the development of recent era. Due to them, the role of data-enabled mobile devices in everyday life is becoming almost vital: to provide business opportunities and connecting us. By enabling the access to information and contents, building backbone networks and providing ubiquitous connectivity, the benefits of broadband mobile services can be immense. In the next-generation mobile technologies such as 3GPP, WCDMA, Long Term Evolution (LTE) and Mobile WiMAX MU-MIMO have become their integral part, and is progressively being rolled out. We are witnessing the commencement of new standards emerging in the mobile scene that promises to satisfy the ever-increasing thirst for data services [1]. As a result of fast and economical deployment solutions, rapid expandability, and ease of integration with other communication system, MU-MIMO has attained widespread popularity. Recently, it has been gaining momentum in research, industry and academic community.

Despite, the success of these communication systems, the demand in scarce radio resources also has increased. To meet such demands, we need to optimize the radio resources in wireless access systems. Typically, the base station (BS) in access system requires channel state information (CSI) for channel quality assessment and to design the downlink pre-coding scheme as well. While significant efforts have been done on enhancing system capacity in conventional communication systems, but these methods can not be applied directly in next-generation wireless networks. The most important reason is conductivities between sender and receiver, those influenced by propagation environment and user mobility. Hence, accuracy of CSI can severely be deteriorated in time-varying channel and inaccurate CSI can degrade the MU-MIMO network performance several magnitude [2]. On the other hand, prior to the commercial deployment of such advanced wireless technologies and their services has to be evaluated in realistic environment to show the practicality limits based on used hardware and underlying protocols and algorithms.

The rapid prototyping as well as evaluation of protocols of such technologies in real-world is often challenging, costly even sometime exhausting. So as to address the above issues, an adaptive transmission system should consider the impact of losses caused by propagation environment on wireless channel. A lot of studies have been done recently to deal with the above factors in link adaptation to improve communication performance. However, most of them carried out the studies without taking into account the impact of channel losses and premature evaluation in realistic environment.

The rest of this dissertation is about an adaptive transmission system which can efficiently adapt the transmit power of each MT along with designing the pre-coding scheme using acquired channel information. The adaptive transmission system aims for next-generation wireless network built with MU-MIMO technology. Furthermore, we also introduce a framework to evaluate a designed adaptive transmission system as well as protocols and algorithms of advanced wireless technologies in an emulated environment.

1.2 Research Context

1.2.1 Multi-user MIMO Technology

Multiple-input-multiple-output (MIMO) is a technology which has been extensively explored in recent decades and has paved a way to many wireless standards because it can increase the spectral efficiency and fidelity of wireless communication systems. While with the exponential increase in devices, this technology has been upgraded from current MIMO to MU-MIMO, where practically a BS equipped with multiple antennas serves a set of single-antenna users [3]. There are two kinds of MIMO: single-user (SU) MIMO and multi-user (MU) MIMO. The SU-MIMO communication system simultaneously serves single user with multiple information and the throughput improved proportional to the number of transmitting antennas. Yet, in MU-MIMO system BS transmits multiple information to a set of single-antenna users, and by doing so multiplexing gain can be extended to the whole set [4].

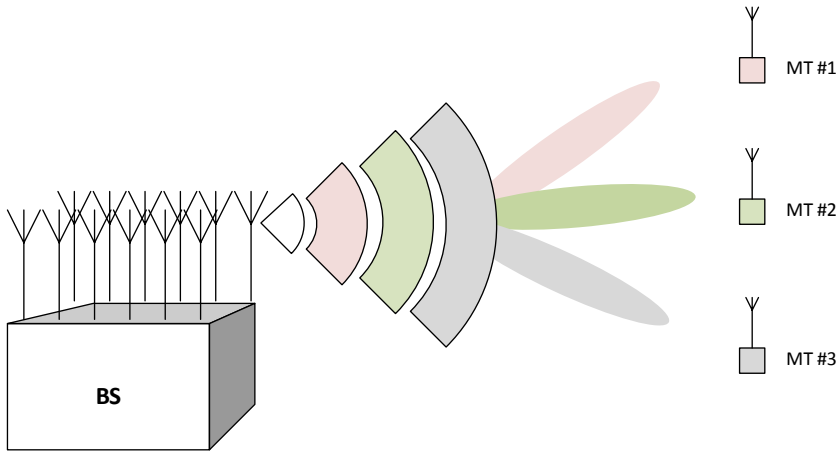

Figure 1.1: Illustration of multi-user MIMO communication network.

Owing to their spectrum efficiency, multi-user MIMO have been accepted as an evolv-

ing technology for future wireless networks. The main objective of this technology is to reap all benefits of conventional MIMO but on a larger scale. In contrast to the conventional, the performance of MU-MIMO systems is less affected by propagation channels. Consequently, this system has become a vital part of several wireless communications standards such as IEEE 802.11x [5], IEEE 802.16 (WiMAX) [6, 7], long-term evaluation (LTE) and LTE-Advanced (LTE-A) [8, 9]. Figure 1.1 shows, an example of a typical MU-MIMO communication system that operates under TDD duplexing scheme in which uplink and downlink transmissions occur in the same frequency resource but are divided in time. In these systems, spatial multiplexing which in turn depends on BS having enough channel-state information, on both the uplink and downlink, plays a key role. The massive MIMO systems, exploit the reciprocity by having the terminals send pilots. On the basis of pilots, BS estimates the channel responses of each terminals and then use the acquired CSI for uplink data transmission and downlink pre-coding of data transmission [10],[11].

1.2.2 Realistic Experimental Assessment

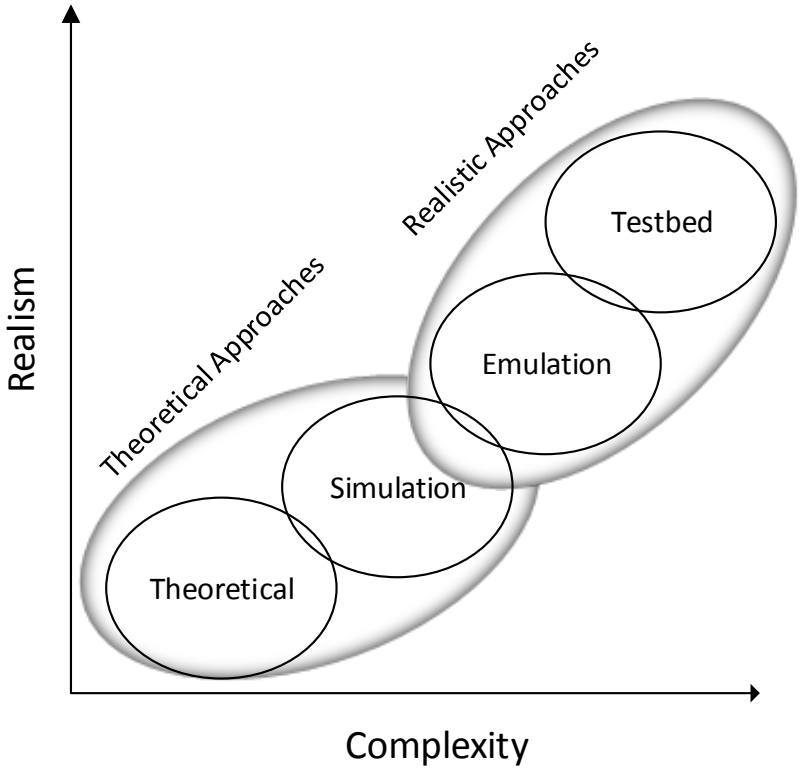

Figure 1.2: Overview of various technology evaluation platform.

The rapid prototyping prior to deployment as well as evaluation of wireless communication technologies is often challenging even sometime exhausting. Usually, as figure 1.2 illustrates, the usage of various approaches/platforms, network researchers have to chose the *analytical* and *simulation models* to study the impact of a proposed modification on

a protocols, but their accuracy depend on the used models. By taking simplified assumptions of the real world into account, simulation models simply neglect the framework of networking protocols and run-time environments, such as that of an underlying operating system, regarding timing synchronization, concurrent processes, resources limitation. Thus, these issues are critical in understanding the system behavior seen in real-world situation. As simulation lacks the fundamental concept of realism, also its abstraction limits its applicability in measuring network performance. *Testbeds* are ideal solutions to evaluate the wireless system under real conditions and has become the source of both reproducible and realistic results. But, constructing such testbeds is expensive in term of hardware, maintenance and labor cost. Moreover, the interaction between higher layers of protocol stack and Medium Access Control (MAC) wireless layer made us realize how difficult it is to extract meaningful information from protocols implemented in hardware or within operating system kernel. In addition, insufficient scalability hinders the study of legacy wireless networks. *Emulation*, is a technique to scale up the experiment size cheaply, maintain a high degree of realism, increase controllability and reproducibility. A network emulator may be considered a hybrid investigation environment where a testbed and simulation are used together and synchronized to a real-world clock. For this purpose, real-world machine passes traffic through simulated network that reproduces the behavior of a communicating network. This way, by imitating packet propagation characteristic within the simulator, it enables simulated protocol modules to interact with the standard implementations.

1.2.3 Why we need Experimental Assessment

The growing demand of wireless applications and the portion of radio resources they consume is driving researchers to investigate new technologies, protocols and algorithms to address the mounting demand. The next-generation wireless technologies must address not only data capacity constraints but also existing challenges, such as energy efficiency, network coverage, reliability, and latency in existing communication systems. Therefore, the prototyping of advanced technologies in realistic environment has become vital. To take the next steps in the prototyping, development and verifications of wireless technologies, it is significant to have proof-of-concept platform where standards and technologies can be tested under realistic environment. This leads to the need of experimentation tool which quickly evaluates such systems, applications and protocols in realistic environment on one hand, and deals with lack of reproducibility, as well as the poor analysis and deployment facilities found in testbeds and field experiments on the other hand, so that can be marketed as soon as possible.

1.2.4 Design constraints

The wireless networking technologies, especially those based on MIMO system, have a broader design space since they can be categorized based on different standards at different layers such as physical layer, data link layer, etc. Designers of networking technologies have to make choices in many dimensions. In this dissertation, we also take some assumptions about the technologies and evaluation platform which are used for the underlying adaptive transmission system to constraint the design space.

As discussed in the Section 1.2.1, we assume that the time division duplexing (TDD)

access network which has a BS equipped with several antennas and perfectly synchronized to communicate with a set of mobile users, each equipped with single antenna. In addition, we assume that the channels are spatially uncorrelated, time-varying and frequency flat, and channel's power spectrum follows Jake's model [12]. This assumption is fit well with both conventional systems and currently in practice, however, it benefits from the multiplexing gain and are supposed to scale the overall network capacity.

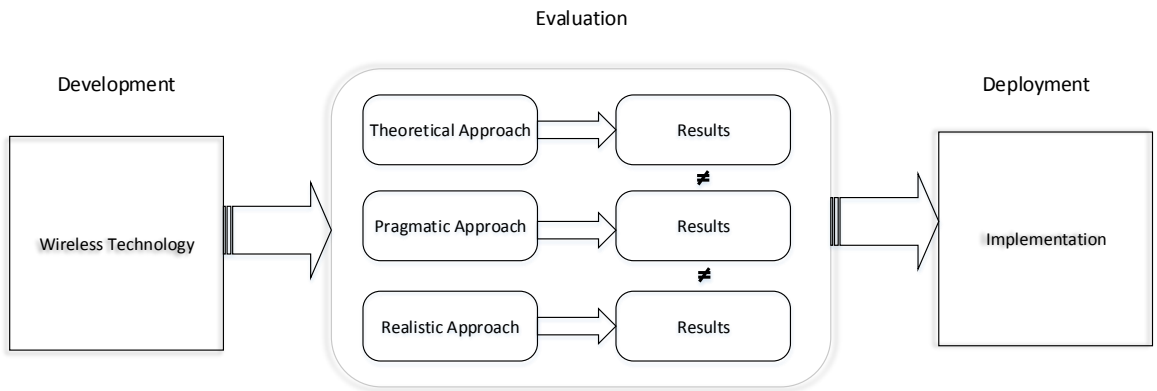

Figure 1.3: Different phases of wireless network evaluation.

Figure 1.3 briefs about the experimental platforms for wireless systems that have very broad design space since each platform has different objectives with respect to evaluation [13], due to different objectives each platform produces different results. Here, we also have to take several assumptions into account concerning the constraint of the design space in a realistic platform that we use for the assessment of the proposed adaptive transmission system. As briefed in Section 1.2.2, we assume the emulation technique to evaluate the underlying MAC and physical layers with real traffic in real network settings, as emulation techniques Bridges the gap between simulation and real-world and meets the researcher's needs.

1.3 Problem Statement

The performance of next-generation wireless communication systems depends on spatial multiplexing of MU-MIMO, but the assessment of channel state information at BS, is also very critical. Since, the uplink pilots symbols are used to estimate the channel of each user, but also introduces difficulties especially in high mobility conditions. Because MU-MIMO system is prone to rapidly changing fast fading. As system performance due to propagation environment/mobility is greatly impaired, link adaptive schemes are employed to improve the system performance. For example, if the scheme is optimal-power based, it means the normalized power is 1 for each user and then the transmit power at BS is allocated so that the probability of error is minimized.

In this regard, for the experimental assessment of the whole wireless system, equipment and applications, simulation techniques are mostly considered as an alternative. Although, these address a scalability, repeatability, and controlability issues, but its accuracy heavily depends on the implemented models. Moreover, these techniques are not

synchronized with real-clock, thus evaluation of underlying network is not conducted with real applications. Since, the problem of such adaptive system assessment in real-time is harder than in widely adopted simulation techniques. As a result of these deficiencies, the network researchers are still in need of an adequate experimental platform. Certainly, the aforementioned deficiencies in the experimental platforms, urge the importance of network emulation technique, since the emulation retains simulation's advantages of flexibility, repeatability and manageability, while potentially mitigating the issue of realism. Unfortunately, most available emulators lack the interaction of real applications with implemented MAC and PHY layers. The deployment of broadband wireless networks such as WiMAX and LTE is paving the way for new applications and service models (e.g. IPTV, video conferencing and video-based online shopping). Hence, performance and reliability assessment of these applications and services with the underlying MAC and PHY layers, are highly desired to be tested in real-time.

Based on the above findings, this research seeks to address the following issues:

- What factors have influence on wireless communication system and what kind of wireless environment increases or decreases its performance?.
- How the operations of wireless technology based MAC and PHY protocols can be verified with real traffic and how new proposals can be tested before its deployment in commercial network?.

1.4 Contributions

This dissertation contributes, both theoretically and practically, in research of wireless networks in general, and to the adaptive transmission system and wireless emulator in particular.

In theoretical part, our main contributions can be summarized as follows:

- First, we evaluate the impact of imperfect CSI in time-varying channels in MU-MIMO system. This helps us to determine the composition of quality loss between BS and user.
- Second, based on the model, we proposed an adaptive transmission system which adapts the transmit power in order to improve the estimation errors and system performance. The adaptive transmission system takes into account the doppler frequency and level crossing-rate to optimize the transmitting power and modulation rate.
- Third, we implement the proposed system in network simulator NS-3 to show its effectiveness over SNR based adaptive scheme [7].

In addition to these three theoretical contributions, this work also contributes four practical contributions:

- First, we have implemented Real Network Communication Interface (RNCI) facility to make NS-3 support transparently and efficiently the automatic conversion of network packets to and from simulated physical layer, hence leading the way to transparent support for real-time simulation.

- Second, we have implemented Real Traffic Communication Interface (RTCI) facility to bridge the MAC layer with a real host. Thus, automatic conversion of real time traffic to and from simulated MAC layer is done.

- Third, we have implemented IEEE 802.16e standard-based Mobile WiMAX PHY model in QOMET to extended the scope of emulation capabilities.

- Fourth, a series of experimental results that validate the correct operation of the network emulation frameworks, and that demonstrate the accuracy of the proposed adaptive system. These experiments provide useful experience for us and also open up a different way to make large-scale experiments with Mobile WiMAX which can not be done easily with real wireless testbeds or simulators.

1.5 Dissertation Outline

The dissertation structure will mirror the research methodology as follows:

The chapter 1 (this chapter) presents the introduction, research motivation, problem statement and contribution of this research. Chapter 2 reviews the necessary background of wireless technologies and current research works regarding the following areas: Real-time emulation, schedulers, QoS and scalability. It also gives overview of adaptive approaches in different transmission techniques. Chapter 3 describes our work on link adaptation and modulation coding metric for WiMAX to scalable the network. It also gives detail of the implementation of PUSC (Partial Usage of SubChannelization) to transfer from OFDM to OFDMA and to help in scalable the experiments. Chapter 4 presents the design and implementation of NS-3 based proposed emulation system for WiMAX and also discusses about StarBED and the implementation of WiMAX model in QOMET which both are currently running on StarBED. Chapter 5 presents the experimental setup and topology, evaluation process of proposed emulation design with real-traffic in real network and results discussion. Chapter 6 presents the conclusion of our work along its significance respective in industry and academia.

Chapter 2

Background

In this chapter, we present the necessary background of multi-user MIMO and its applications in next-generation Wireless standards. The first section gives brief overview of history, emergence and key concepts of MU-MIMO as well as their characteristics and challenges. The second section is about the adaptive transmission systems with respect to MU-MIMO and discussion about their drawbacks. In the final section, we focuses on experimental assessment of wireless networking technologies and their specific applications. This section facilitates us in understanding the design of new experimental framework.

2.1 Next-generation Communication Systems

2.1.1 Brief Introduction of MIMO

In wireless communications, a channel is characterized, between a transmit and a receive antenna, as a propagation environment. So, installing multiple antennas between transmitter and receiver induces multiple-input multiple-output (MIMO) and multiple channels accordingly. Other MIMO family members include: deploying multiple antennas at the transmitter and single antenna at receiver is termed as multiple-input single-output (MISO) and vice versa single-input multiple-output (SIMO), and the traditional where the transmitter and receiver having a single antenna is termed as single-input single-output (SISO) [14].

Multiple-input-multiple-output (MIMO) is a technology which has been extensively explored in recent decades and has paved a way to many wireless standards and technologies because it can increase the spectral efficiency and fidelity of wireless communication systems. With the exponential increase in devices, this technology has been upgraded from current MIMO to MU-MIMO, where practically a BS equipped with multiple antennas serves a set of single-antenna users [3]. Figure 2.1 shows the different categories of MIMO systems, and the most popular one is MU-MIMO because the focus has shifted in recent years to more practical communications systems, and it obtains higher spectral efficiency proportional to the number of antennas. Therefore, it is being actively integrated into almost all advanced wireless communication systems.

Since the MIMO systems have several different requirements at physical layer as per technology where it is employed, the next section will give a short introduction of the multi-user MIMO system.

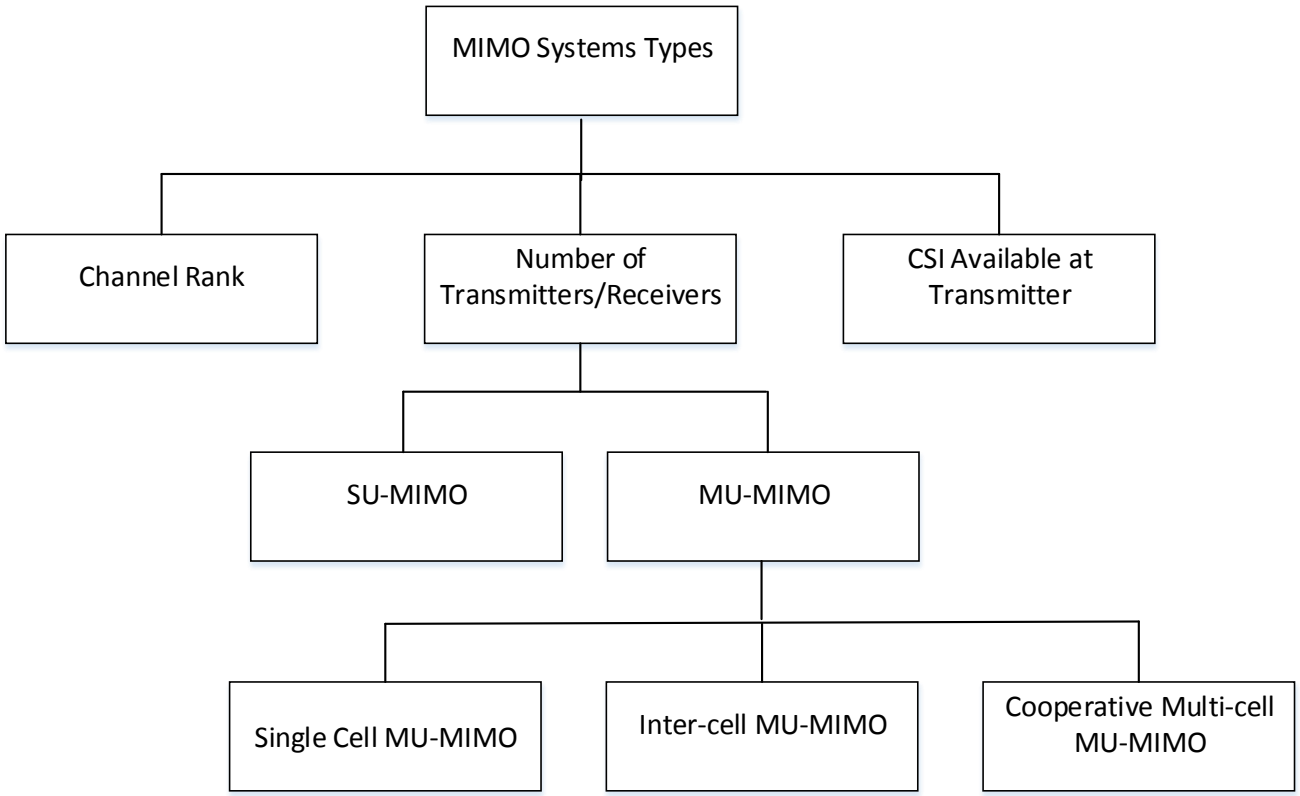

Figure 2.1: A general overview of MIMO systems

2.1.2 Multi-user MIMO

The following is intended to give a short overview about the key concepts of MU-MIMO system that will be later needed to design the adaptive transmission system to show its huge potential in providing wireless capacity gain.

System Model and Preliminaries

A multi-user MIMO system as depicted in Figure 2.2 , is composed of a base station equipped with number of N transmit antennas and K single-antenna MTs.The MU-MIMO system can utilize the promising multiplexing gain while eliminating channel impairments due to unfavorable propagation environments. It also considers the following input-output model which is traditionally described in the MIMO literature [14, 15].

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,n} \\ h_{2,1} & h_{2,2} & \dots & h_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ h_{k,1} & h_{k,2} & \dots & h_{k,n} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_k \end{bmatrix}$$

or equivalently

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{x} + \mathbf{n} \tag{2.1}$$

where:

- $\mathbf{x} = [x_1, x_2....x_N]^T \in \mathbb{C}^{N\times 1}$ denotes the vector of transmitted signals on N antennas, intended for all K MTs;
- $\mathbf{y} = [y_1, y_2....y_K]^T \in \mathbb{C}^{K\times 1}$ is a vector of received signals on K MTs, one output per MT;
- $\mathbf{n} = [n_1, n_2....n_K]^T \in \mathbb{C}^{K\times 1}$ vector represents additive white Gaussian noise (AWGN) and interference at each receiving antenna;
- ρ denotes the transmit signal power;
- $\mathbf{H} = h_{k,n}$ denotes the channel gain matrix. Precisely, $h_{k,n}$ is a channel coefficient of complex flat-fading which is assumed to be independent and to be constant over each coherence interval T_c, from the kth user to the nth antenna of BS.

Channel Estimation

In practice, BS can boost desired signals and mitigate interference by coherent receive combining in uplink and beamforming in downlink. The standard approach of doing this is to estimate the channel and acquiring the CSI at BS by pilot signaling using training sequence. Basically, acquiring perfect CSI in time-varying channel where pilot signals are inevitably affected by MTs' mobility and interference, which is a tough task and this phenomena i.e *pilot contamination* significantly affects the quality of acquired CSI.

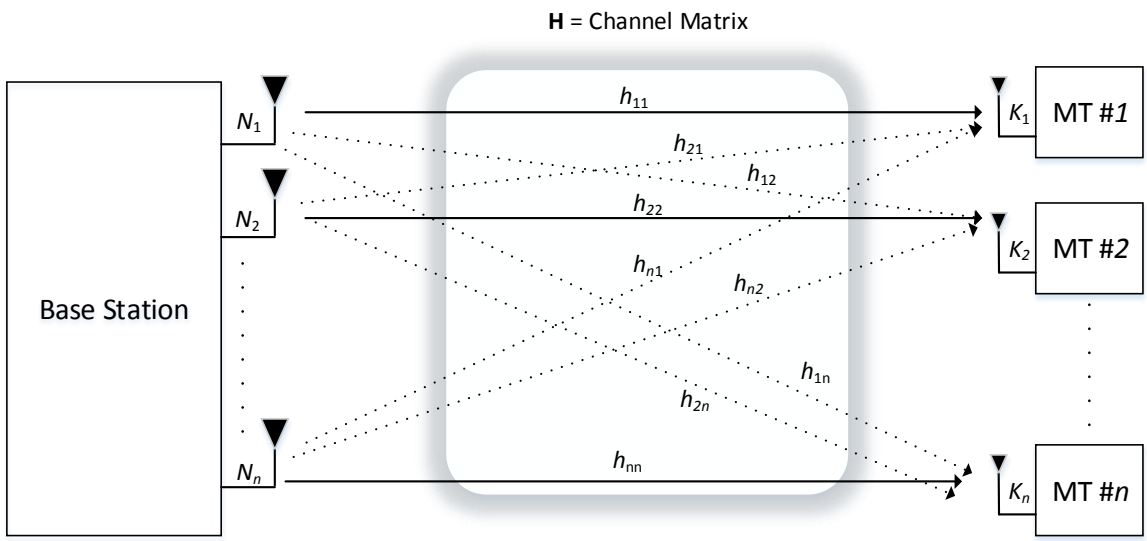

Figure 2.2: A multi-user MIMO systems

As shown in Fig. 2.5, The coherence block consists of time and frequency resources (time-bandwidth product). The dimensions of this block are generally coherence bandwidth B_c Hz and coherence time T_c s, which is equal to $\tau = B_c T_c$ transmission symbols [16]. Since, due to propagation environment the channel responses fluctuate over time and frequency, the channel estimation and data transmission in uplink and downlink directions must fit into a coherence block τ where the channels are probably static. The Canonical MU-MIMO system can operate either in time-division duplex (TDD) or frequency division duplex (FDD). But mostly next-generation wireless system are being engineered for TDD operations, therefore we also choose this scheme for duplexing mode. The reason is that in TDD mode uplink and downlink transmission occurs in the same frequency resource but separated in time. In particular, MU-MIMO systems exploit the uplink and downlink reciprocity to estimate each channel response. According to this frame, all MTs send uplink data signals. Next, MTs send pilot training sequences. BS exploits the sequences and estimates the channel response. Then, BS takes the estimated CSI into account to detect the uplink data and to generate transmit precoding of downlink data.

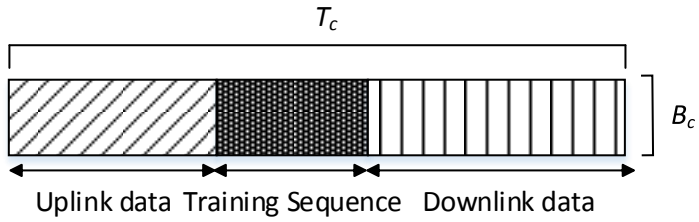

Figure 2.3: An illustration of MU-MIMO transmission protocol

We have introduced several key features of MU-MIMO technology as above. Today, it

is an essential physical layer component of several next-generation wireless technologies, such as WiMAX, IEEE802.11n and LTE. In this dissertation, We select WiMAX as a case study to design the adaptive transmission system with application's data and further to show the feasibility of emulation approach.

2.1.3 IEEE 802.16/WiMAX

Recently, IEEE 802.16 [6] has been under the spotlight due to providing the broadband (high-speed) wireless access (BWA) in a metropolitan area. The term WiMAX (World Interoperability for Microwave Access) [17], is an industrialized complement of IEEE 802.16, was described in 2001 by an industry consortium called the WiMAX forum to ensure interoperability and conformance to IEEE 802.16 based products from different vendors. It defines a Medium Access Control (MAC) and Air Interface to support high data rates, extreme mobility and low deployment, these features make it an appealing alternative to DSL/Cable services. Theoretically, Base Station can offer up to 50 Km in Line of Sight (LoS) operation in the 10-66 GHZ range frequency for fixed users as well as can support 15 Km for Non Line of Sight (NLOS) operation for stationary and mobile systems operating in sub 11 GHz licensed and licensed-exempt bands, with 70 Mbps (1Gbps for stationary subscribers will be provided by the 802.16m extension). In case of IEEE 802.16e, various channel spectrum are supported by scalable OFDMA. For example, a WiMAX network may use 128, 512, 1024 or 2048 bit FFT size corresponding to channel bandwidth 1.25MHz, 5MHz, 10MHZ or 20MHz, respectively.

IEEE 802.16 Salient Features

IEEE 802.16 is a broadband wireless technology that renders a rich set of properties with a lot of flexibility in terms of deployment options and diverse service offerings. Some of the salient features that deserve to be highlighted are as follows:

- *Scalability*: WiMAX PHY layer supports scalable OFDMA that allows for the data rate to scale easily with available channel spectrum. The scalable feature promises to offer basic, portable and full mobility but at the expense of more complex PHY and MAC layer design. In addition, WiMAX can operate on both TDD (Time Division Duplexing) and FDD (Frequency Division Duplexing), as well as a half-duplex FDD, which helps in system implementation to reduce the cost.

- *Quality of Service*: The QoS is a very prominent feature of WiMAX. The MAC layer due to connection-oriented architecture supports a variety of applications according to their service level agreement (SLA) requirement, including voice and multimedia services. The concept of scheduling class is introduced to reflect the flexibility, rate and latency adjustment that an application can tolerate [18] . The QoS requirements of various applications and their corresponding service class in WiMAX as illustrated in table 2.1.

- *Mobility*: One of the major features of IEEE 802.16e/Mobile WiMAX is to support mobility in a coverage area. Basically, mobility supports seamless handovers operation for fully-mobility and delay-tolerant applications when MT falls in the

Table 2.1: Scheduling Service Classes in WiMAX

Class	**Application**	**Bandwidth**	**QoS parameters**
Unsolicited Grant Service (UGS)	E1, Multilayer Interactive Gaming	50-85 Kbps	Low latency and jitter
Real-Time Polling Service (rtPS)	VoIP & Video Conferencing	4-384 Kbps	Low latency and jitter
Enhanced Real-Time Polling Service (ertPS)	VoIP with silence suppression	4-150 Kbps	Low latency and jitter
Non Real-Time Polling Service (nrtPS)	Streaming Media and FTP	5 Kbps - 2 Mbps	Tolerated latency with low jitter
Best Effort (BE)	Web Browsing & Data transfer	10 Kbps to 2 Mbps	Latency and jitter tolerated

overlapping coverage area of two or more adjacent cells, then it switches from serving BS to an another respectively. In mobile WiMAX, handover is divided into two categories as follows:

- *Hard handover*, in this category, the MT tears down its communication link with serving BS before setting up with new BS.
- In *Soft handover*, the MT sets its communication link up with new BS before halting with serving one. The MT may have two or more BSs in its list based on power measurements and chooses one of whom from the list as new BS. Evidently, The soft handover is faster than the hard handover.

- *Physical layer*: Here, we briefly discuss the physical layers of IEEE 802.16, which formed by a number of air interfaces such as WirelessMAN-SC, WirelessMAN-OFDM and WirelessMAN-OFDMA [18].

  - *OFDM*: Orthogonal frequency-division multiplexing (OFDM) is a digital multi-carrier modulation scheme, which employs multi carrier modulation that yields higher throughput and diminishes spectral interference effect with multi-path signal. Principally, OFDM transmits many narrow-band orthogonal frequencies simultaneously. Hence, Modulated subcarrier can have smaller bandwidth than single carrier so that provide a better resistance in multipath propagation.
  - *OFDMA*: To solve the variable and higher data rate demands with low latency in the same geographical area, the IEEE 802.16 standard introduces the combination of OFDM and TDMA (Time Division Multiple Access) which is viewed as orthogonal frequency division multiple access (OFDMA), which is also called multi-user version of of OFDM as show in Figure 2.4. It provides multiple access by assigning subsets of sub-carriers, to individual users/flows.

Also, it permits multiple users to access the channel at the same time. Because, a channel is partitioned into several subchannels.

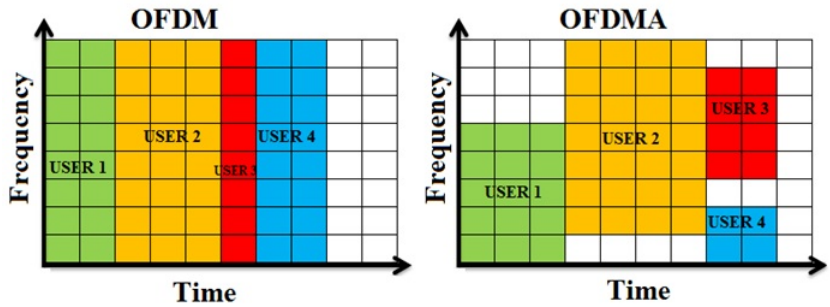

Figure 2.4: Comparison between OFDM and OFDMA

- *MIMO*: The WiMAX supports, a number of hooks built into the physical-layer design, a full-range of smart antenna techniques including multiple-antenna techniques, such as beamforming, space-time coding, and spatial multiplexing. The MIMO technique with multiple antennas increases data rates through multiplexing or to improve performance through diversity. Indeed, the remarkable spectral efficiency can be achieved with MIMO. In addition to spectral efficiency gains, Inter Symbols Interference (ISI) and interference caused by other users, can be controlled using this technique. The cost of leveraging the multiple antenna techniques is the added cost of installing multiple antennas, the space and power requirements of these extra antennas.

Frame Structure

In OFDMA, the frame structure is different due to the subcarriers distribution. A frame is divided into downlink and uplink subframe. Some of the parameters are mandatory and the rest are optional. The first symbol in DL subframe is reserved for preamble for timing and frequency synchronization and channel estimation. The DL subframe contains the DL-MAP and UL-MAP. The DL-MAP describes the downlink channel access and concerning adaptive burst profile. The UL-MAP contains the allocated bandwidth information in the form of time slots in which user transmits the data, along with it describes adaptive burst profile as shown in Figure 2.5.

After DL-MAP and UL-MAP, the resources are allocated for frame control header (FCH). FCH contains the information about DL-MAP and UL-MAP. The uplink subframe contains the information about the following parameters:

- Information of ranging opportunities
- Number of time slots allocated for data transmission
- CQI (Channel Quality Information) as fast feedback that might be used for adaptive modulation or handover purpose
- Other optional signaling data allocation and subchannels.

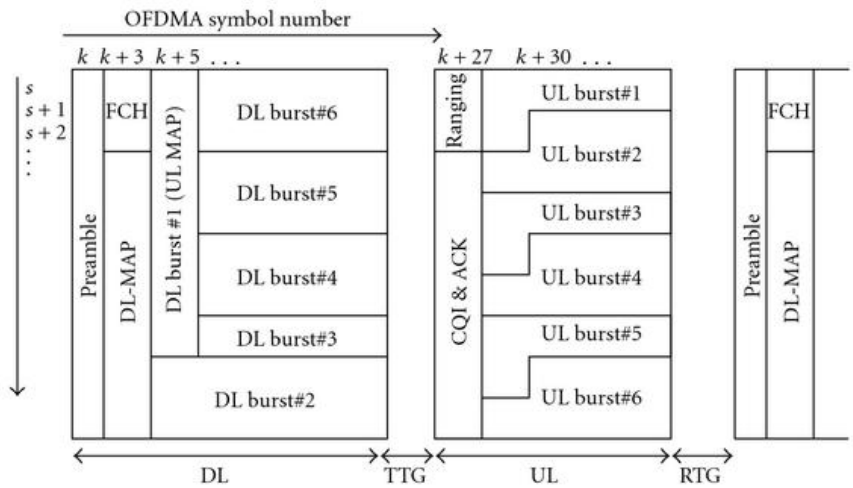

Figure 2.5: OFDMA frame structure in Mobile WiMAX [19].

2.2 Review of Adaptive Approaches in Wireless Networks

Since, the performance of wireless networks heavily relies on channel quality, therefore a mechanism to combat the channel's impairments and enhancing overall system capacity is essential in such networks. Adaptive transmission is the process of finding solutions for these impairments. This section presents overview of adaptive mechanisms in wireless networks.

2.2.1 Limitation of Traditional Approaches

Efficient transmission is a fundamental issue in wireless communication systems. There are a large number of efficient approaches proposed for traditional wireless communication and few of them are widely employed. Basically, adaptive approaches for efficient transmission are prevalent in wireless networks with two kind of antenna transmission techniques; single-input single-output (SISO) and multiple-input multiple-output (MIMO). In SISO, transmission occurs based on point-to-point while in MIMO between multiple transmitters and receivers. Most of efficient transmission approaches used in wireless networks today belong to one of them.

In typical wireless networks such as point-to-point communication systems, resource efficient approach is quite popular. It is sometimes referred as spectral-efficient approach. So, the widely recognized indicator for system efficiency is expressed, the ratio between what the system delivers to what it consumes [20], as a system efficiency function:

$$\eta_E = \frac{f(\varphi)}{g(\varphi)} \tag{2.2}$$

where $\varphi \in [0, \hat{P}]$ represents the resource and constrained by $\hat{P}$, $f(\varphi)$ is unit function and $g(\varphi)$ is the cost of the resource. The optimal approach is required to find the optimal φ^* and maximize the system efficiency. Furthermore, the system efficiency function can

be classified into two types based on $f(\varphi)$ function; if $f(\varphi)$ is an increasing S-shaped function, it is called quasi-concave w.r.t φ and optimal solutions unique and non-trivial $\varphi^* \gtrsim 0$, in contrast, if $f(\varphi)$ is an increasing concave function then it is a convex, has trivial $\varphi^* \to 0$ optimal solution and decreases w.r.t $f(\varphi)$ [20, 21].

Additionally, as wireless medium due to shared nature is very hard to manage. Because, it is not only affected by self-interference but also by the inter-user interference in the whole network. Hence, a system approach for detail level modeling of adaptive transmission is required. For this purpose, various practical and information theoretical approaches/tools are used to find the gap between theoretical limits and practically achievable system performance. Moreover, due to the different natures of wireless medium in both techniques, adaptive approaches for them are also different. Adaptive transmission methods are mainly classified for two techniques (SISO and MIMO).

In single antenna scenario, efficient transmission is seen as capacity per unit cost, and it is mostly analyzed in AWGN channel in case of information theoretic analysis and in realistic propagation environment for pragmatic modeling. Some well-known optimization schemes for resources allocation are applied to find the optimal solution for any user which corresponds to the transmit power while satisfying the power constraint. But, these optimal solutions have different performance depend on the wireless technologies where they are employed. For example, some adaptive transmission techniques designed for cellular network can not be applied into wireless sensor networks. Some known optimization policies in this category are: water-filling (including optimal, discrete and channel inversion), game theory and water-pouring.

MIMO is an advanced communication technique and have been extensively evaluated for various wireless communication systems to provide high system capacity. Several bandwidth and resource efficient transmission policies have been also suggested, based on stated optimization solutions to ensure QOS of each user by exploiting spatial diversity [22]. However, major problem in MIMO networks especially in advanced MIMO techniques, is the quality of received data strongly depends on the pre-coding schemes. Because, transmitter selects a pre-coding scheme according to the health of channel state information.

The advantage of MIMO transmission techniques over single-antenna system is the reliable and efficient communications among users. However, highly reliable communication generally implies high power consumption, particularly in practical manner where electronic circuit energy consumption is a biggest factor in MIMO communication system. In addition, since efficient transmission approaches need to consider the cell size (deployment) of network and capacity of outage, because without taking these factor into account communication system may not be highly reliable for rich content applications.

2.2.2 SISO based Adaptive Approaches

In this section, we elaborate the different approaches that are basic components of any adaptive framework. As we will see, they actually help to design the adaptive transmission schemes of MAC and physical layers.

Spectral efficiency is defined as de-facto performance indicator of any wireless network evaluation. To characterize the system capacity for SISO network in AWGN channels, Shanon's capacity formula has a key role in it [23]. Moreover, the water-filling scheme, very well known for optimizing the resources, is usually employed to maximize the spec-

tral capacity by taking the total transmit power into account. In [24, 25], Goldsmith and Varaiya presented some of the adaptive transmission policies, namely: optimal transmit power with rate adaptation - constant power with optimal rate adaptation - channel inversion with fixed rate. The idea of adapting optimal power combining with modulation and coding rate was to determine the *maximum average spectral efficiency* (MASE) over flat-fading channels having perfect channel state information (CSI) with respect to both the transmitter and receiver. In practical networks, the monotonic relation between optimized transmit power and achievable spectral efficiency is not proportion to each other. A practical approach in determining the spectral efficiency is adapted by [26], for discrete-rate multilevel quadrature amplitude modulation (MQAM) for fading channels. While in [27] using trellis coded modulation have overcome the observed gap between the achievable spectral efficiency and MASE.

Power efficiency and spectral efficiency are convex and monotonically linked and also it's defined as capacity per unit cost. Recently, power-efficient solutions have received much attention in both academia and industrial fields. The work in [28], defines the finite power constraints for communication reliability in terms of the capacity per unit energy. In order to save energy, the transmitter has to send the signal with very low power which implies low throughput. This kind of solution may be optimal in wireless sensor networks but not feasible where minimum communication rates are required [20, 29]. Moreover, in typical multi-cell networks simple assumptions does not hold. Because, interference power not only reduces the spectral efficiency but also effect the overall system performance. Hence, a more detailed evaluation of power-efficient solutions with transmission signals in practical manner can help to find achievable performance of any adaptive framework. Efficient transmission system, from the point of view of efficient resource management can be conceived as allocating the *right* resource to the *right* user at the *right* time.

Quality of Service defines the metrics such as bandwidth management, traffic statistics and service latency, that are MAC layer oriented, instead of physical layer. Accordingly, the adaptive system should deal with both channel and traffic impairments, which make the design of adaptive system more complicated. To make the system bandwidth efficient, spectrum sensing and utilization of unused spectrum using cognitive radio (CR) techniques have been explored [30]. With the evaluation of wireless technologies, the currently deployed systems are more flexible with high spectrum and its dynamic adjustment [23]. Furthermore, due to the diversity of wireless services and processing of terminals enhanced, the content of rich applications and their traffic uncertainties have become center point of these networks. As a result, fully utilization of wireless bandwidth with fixed transmission rate can severely affect the system performance. Hence, the designed protocols/algorithms for wireless resource management deserve for rigorous realistic evaluation prior to be deployed.

2.2.3 MIMO based Adaptive Approaches

In contrast to single-antenna case, MIMO techniques have been proven more better in improving network capacity and spectral efficiency as well as reliability. MIMO networks are classified into several special cases, but we will keep the focus of our discussion only on the general MIMO case. In this section, we will review several well-known adaptive approaches for MIMO networks.

Owing to the antenna gain, MIMO system can provide very high *Spectral efficiency*

with simple linear processing. Therefore, advanced MIMO techniques are considered as promising candidates for next-generation wireless networks. In order to take the advantages of MIMO, the accurate knowledge of channel state information (CSI) is mandatory. Extensive spectral efficiency analysis has been carried for MIMO systems, but with primary focus on perfect channel state information. Particularly, the accuracy of channel-state information is deteriorated by the time-varying channel caused by the user terminals (UTs) or some objects around the UTs. Hence, inaccurate CSI has impact on spectral efficiency and intra-cell and inter-cell interference mitigation, and ultimately degrading the system performance [31]. Closed-loop MIMO schemes such as pre-coding and beamforming, are adapted to enhance the spectral efficiency. However, high spectral efficiency with CSI mechanism usually leads to high power consumption, which is sometime unacceptable for *power efficient* systems especially when hardware level power consumption is also accounted [22]. Recently, it has been proven that radiated energy of massive MIMO system can be reduced significantly [32]. The problem here is more difficult, because the single antenna based transmission efficient solutions can not applied directly. Fortunately, the channel hardening effect in advanced MIMO techniques such as massive and large scale, are trivial over the frequency domain and primarily rely on large-scale fading in the time domain.

Resource allocation usually im MIMO system is also termed as time-frequency resources are assigned among users, to satisfy their specific QoS constraints, to allocate the best subcarriers for each user, and to combat the channel impairments by power control [11]. Since, *temporal diversity* and adaptive transmission has convex relationship, it is necessary to optimize the length of coherence block. As stated earlier, transmitting with wide spectrum makes the transmission efficient. But, different frequency bands experience different fading particularly in MIMO systems [33]. As shown in [34], system becomes efficient by adapting data rate and optimal power in flat-fading channels, as *frequency diversity* gain increases. In an another study [35], instead of water-filling the authors introduced the scheme that optimizes the overall transmit power for globally link adaptation, according to the states of subchannels. It is emphasized that transmission efficiency improves when frequency diversity exists within the channels. Likewise, *spatial diversity* is also very significant to manage user performance as well as to optimize the overall network efficient transmission. Several studies have shown an improvement in energy efficiency and overall system capacity by designing the adaptive transmission system which exploits the spatial diversity gain.

As, we are witness that the system performance achieved of both transmission techniques with theoretical approaches may not be achieved in practical network due to several hardware constraints as well as in realistic network.

2.3 Experimental Platforms

The key concern of these wireless systems is the development as well as realistic performance evaluation of the applications and protocols running over these systems. The realistic evaluation has always been a challenging task. In this regard, there are two key concerns. First, it is fundamental to reiterate the experimental process multiple times in a deterministic manner. Second, a major constraint is the capability/facility of investigating these kinds of systems in a real-world environment [38]. Typically, testing of the respec-

tive systems and the performance evaluation under real conditions are performed over a wireless testbed of prototype implementation. Although real-world wireless testbeds offer great value, on the other hand they are expensive in terms of hardware cost and very hard to maintain, as Figure 2.6 illustrates the substitution of testbed which is inexpensive and meet the evaluation's requirements. Network simulations are synthetic environments for running representations of mathematical models. However, network emulation studies are preferred for system modeling and its evaluation in a real-time environment.

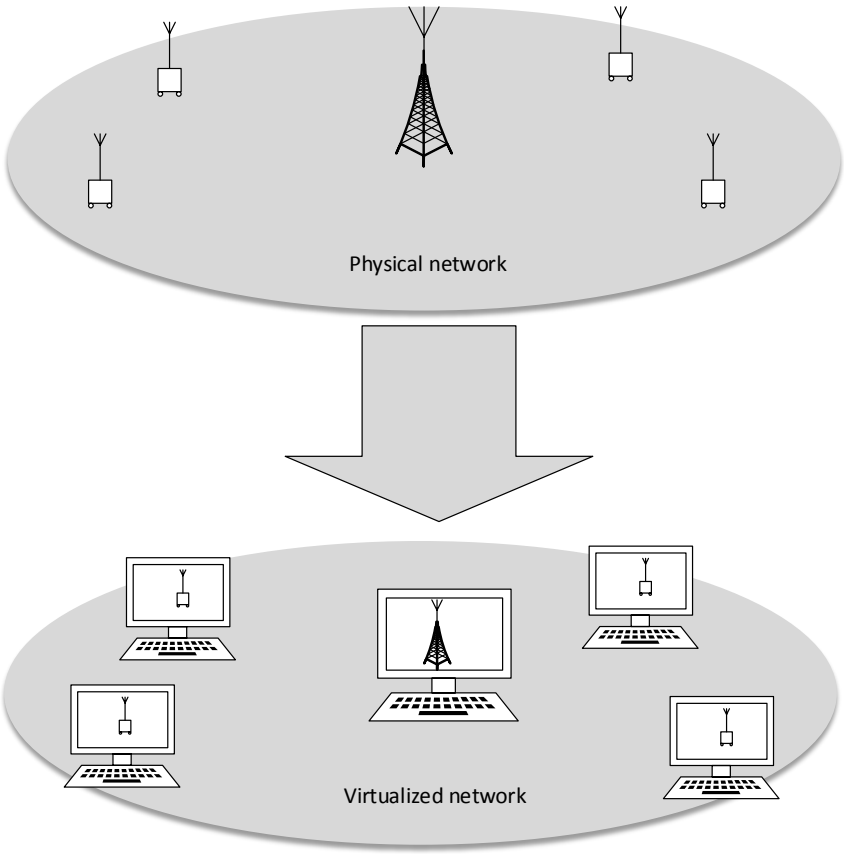

Figure 2.6: Presentation of real network and its vitalization.

2.3.1 Review of Existing Realistic Platforms

Several other projects use emulation in order to evaluate WiMAX network performance. In the case of the NCTUns based hybrid system presented in [39], a real WiMAX network is interfaced with the NCTUns simulator. However, the simulator itself only reproduces the backbone network and wired end nodes, hence the communication conditions in the WiMAX network are not under users control.

The work related to the WEBS WiMAX emulation testbed [40] actually focuses on the multimedia components of the testbed, whereas the WiMAX emulation itself is done by using the already existing emulation capabilities of the QualNet simulator, namely the IPNE module. The authors only emulate a network with one BS and one SS, and no analysis is done about scalability, which we assume to be low given our own experience

with IPNE. Other testbeds use real WiMAX devices, such as the WiMAX Extension to Isolated Research Data networks (WEIRD) [41]. WEIRD is an architecture for outdoor testbeds that was used for several deployments in various locations. The focus of the architecture is however on the applications running over the WiMAX network, and experiment conditions cannot be controlled.

The GENI project provides a WiMAX vitalized experimental testbed [42], in which real WiMAX devices are connected to each other via a programmable attenuator, with a total of 1 BS and 8 SSs. While offering realism and control to users, the testbed is limited by its physical scale. Moreover, aspects such as mobility are not directly addressed.

2.3.2 Limitations in Existing Platforms

In order to model novel and existing networking protocols and algorithms, researchers mostly rely on wireless testbeds or simulation to execute experiments. Although *simulation* is a widely adopted technique of evaluation in academia or research communities, but its accuracy depends on used models. Abstract simulation models frequently make simplified assumptions of the real world. Often, they neglect the system framework of networking protocols and run-time environments, such as:

- Underlying operating system
- Timing synchronization
- Concurrent process
- resource limitation

These issues are critical in understanding the system behavior seen in real-world situation. As simulation is lacking the fundamental concept of realism, also its abstraction limits its applicability in measuring network performance.

Testbeds are ideal solutions to evaluate the wireless system under real conditions and has become the source of both reproducible and realistic results. But, constructing such testbeds faces the following problem:

- Maintaining testbeds are very expensive in term of hardware and labor cost
- Insufficient scalability hinders the study of legacy wireless networks

Moreover, the interaction between higher layers of protocol stack and Medium Access Control (MAC) wireless layer made us realize how difficult it is to extract meaningful information from protocols implemented in hardware or within operating system kernel.

Network emulation [13], is a powerful technique for performance evaluation using real network applications and protocols, and it is particularly useful for scenarios involving wireless networks and mobility, which are difficult to reproduce and control accurately in real environments. Moreover, the use of real applications and protocols provides an increased realism compared to pure network simulation experiments.

2.4 Summary

In this chapter, we briefly presented the background of the research. The first part of the chapter is about an overview of next-generation communication systems including the model of MU-MIMO, its basic features and brief description of WiMAX, which we select as case th study technology to evaluate our proposed adaptive transmission system and implemented realistic platform. Second part of this chapter reviews adaptive approaches and their limitations as well. In the final part, we discuss more about the advantages and the drawbacks of each evaluation platforms, and we claim that it is necessary to design a experimental platform for network evaluation purposes which keeps all the essential characteristics of simulation platform without using logical time while still fulfill the needs of real-time evaluation. In the next chapter, we will focus on the design of adaptive transmission system.

Chapter 3

Adaptive Transmission System for Scalability Enhancement

This chapter also serves as one of our main works. We present adaptive transmission framework that adapts transmit power, modulation and coding rate, as well as exploits the maximum-ratio combining (MRC) diversity for efficient bandwidth transmission in wireless system. For this purpose, we select three different adaptive policies to examine the performance of each one. Through this technique it is possible to find the switching thresholds, by taking diversity gain into account, to switch the modulation and coding rate, so as to match the channel conditions. Finally, we show the feasibility of adaptive transmission framework which improves the overall system throughput which is close to analytical throughput, and demonstrate its validity and potential uses.

3.1 Introduction

Efficient bandwidth transmission is a paramount in wireless communication systems, especially due to the demand of high-speed services, multimedia and low-power applications it plays important role in system efficiency. With the advent of high data transmission, quadruple-play applications and in general, high quality contents rich streams in wireless systems are at the moment in mainstreams. While, these demand expeditiously have been burgeoning, the demand of scarce radio resources also has increased. So, next-generation wireless communication systems are projected to be viable and attractive way to provide high data rates communication.

yet, the capacity is a prime concern in the design of such wireless communication systems. As, the wireless link quality due to the fading is greatly impaired, since the fading mitigation schemes are already being employed in wireless communication systems such as Digital Video Broadcasting-Satellite Version 2 (DVB-S2) [43], WiMAX [7] and LTE [8]. Among several alternatives the IEEE 802.16e standard considers Orthogonal Frequency Division Multiple Access (OFDMA) as physical layer scheme in order to diminish the dire affect of multi-path fading and inter-symbol and inter-carrier interference(ISI and ICI) [44]. Due to adaptive transmission nature (assign each subchannel, symbol, modulation and power independently to the users) enables mobile terminal to achieve higher efficiency in term of bit-error rate (BER) and throughput.

The main motivation behind fully exploit the features of MU-MIMO, diversity combining gain and flexibility offered by OFDM scheme, is to optimize the use of network

resources and improve the system capacity by adapting transmit power, appropriate modulation and coding or a combination of these parameters to each data transmission according to channel conditions. In this chapter, we focus on the link capacity, described as the average received data rate (throughput) for a specified averaged transmit power and given target *BER*.

One of the fading compensation techniques as well as boosting link performance is the diversity combining technique which accumulates signals received from several paths. In [48], the authors use diversity combining techniques to design a system for maximum spectral efficiency. They have evolved closed-form expressions for the general theory of adaptive transmission from [25] into three adaptive transmission and diversity combining techniques for Rayleigh fading channels. Although, diversity provides large capacity gain for each unit bandwidth over all the techniques, however in [50, 48] it has been proved, there must be a trade-off between the conflicting targets; complexity and capacity of the adaptation methods. The evaluation of various power and rate adaptation policies were also considered in [51], where closed-form solutions were derived for maximum-combining ratio (MRC) of the generalized Rician fading channel. It is reported that truncated channel inversion adaptation policy has performance advantage over the different single antenna reception policies. Moreover, channel inversion with fixed rate policy is the preferable MRC policy and equal gain combining (EGC) diversity techniques [52].

Fading mitigation/compensation methods with diversity combining enable the adaptive transmission policies to achieve capacity close to Shanon limits in flat fading channel [50]. Shanon capacity is considered idealistic limit for communication systems, and also a de-facto reference to compare adaptive schemes with respect to spectral efficiency. Unlike prior mentioned work [48]- [52], design adaptive transmission system employing fading compensation methods (e.g power and rate adaptation) that adequately consider the target BER in conjunction with MRC diversity. The design also optimized adaptive power and constellation size for continuous power and rate adaptation while handling truncated channel inversion with fixed rate and continuous power and discrete rate adaptation. Hence, the primary purpose of this adaptive transmission system is to balance the link budget in real-time through adaptive variation of the various important parameters such as symbol rate, transmit power, constellation size, coding rate, or any combination of these parameters [26, 48]. Moreover, a suitable model of the diversity combining adaptive process was also outlined to extend the obtained results to different adaptive transmission policies with respect to those considered.

The proposed mechanism takes the influence of channel in terms of attenuation caused by multipath fading into account, and also examines the diminishing effect of BER in conjunction with MRC diversity on selected adaptive transmission schemes. These considerations formulate adaptive constellation size for transmitting optimal symbols to improve the spectral efficiency when considering a certain fading distribution. The main contributions of this chapter are as follows:

- The target BER and diversity combining gain at Rayleigh fading channel are assumed while deriving closed-form expressions using constrained spectral efficiency maximization of adaptive transmission policies;

- The constellation switching thresholds and its adaptive power for discrete-rate policy are optimized to maintain the target BER in conjunction with diversity combining.

- A series of numerical results that validate the operations of proposed system, show the introduction of power adaptation with respect to diversity combining and target BER in the selected policies have good agreement in terms of spectral efficiency increase and reducing the possibility of no transmission, even when the number constellations size are finite.

3.2 System Model and Problem Formulation

3.2.1 System Model

In this section, a single-link wireless communication model will be considered as shown in Figure 1, similar to the one described in [48, 49]. In a given wireless communication model, the discrete-time channel oscillates slower degree than the data rate. In this analysis, it is assumed to be slow varying and frequency-flat Rayleigh fading channel. By the probity of these assumption the distribution of the received Signal-to-Noise Ratio (SNR) γ is represented by an exponential distribution [55].

$$f_\gamma(\gamma) = \frac{1}{\bar{\gamma}} e^{-\gamma/\bar{\gamma}}, \tag{3.1}$$

Where $\bar{\gamma}$ is the average received SNR and γ represents the instantaneous received SNR.

In this analysis, MRC combining technique is considered where the amplitudes and phases of the received signals are assumed known by the receiver perfectly. By virtue of this assumption we can term it *perfect combining*. It is proven in [55, 50, 48], that MRC yields maximum spectral efficiency improvement relative to all combining techniques as a result of *perfect combining*. It requires the received signals to be weighted by their own SNR (weighting parameter) independent from each diversity branch to compose the output decision variable. For a Rayleigh fading channel, the output of a linearly combined MRC combiner with L-branch is given in [55] as a distribution of the instantaneous received SNR.

$$f_{\gamma_{mrc}}(\gamma) = \frac{1}{(L-1)!} \frac{\gamma^{L-1}}{\bar{\gamma}^L} e^{-\gamma/\bar{\gamma}}, \tag{3.2}$$

We simply consider throughout in our study, as in [26, 25], the channel state is perfectly tracked by the transmitter via error-free feedback channel. Accordingly, the proposed model coordinates with power adaptation scheme $P(\cdot)$ to adapt transmit power. Let N denotes the quantization levels of available constellations M_n that represent the instantaneous received SNR γ. The γ range is partitioned into $N+1$ non-overlapping successive fading regions, with boundary points denoted by the switching thresholds $\{\gamma_T^n\}_{n=0}^{N+1}$. Specifically, constellation n having spectral efficiency SE, is chosen when $\gamma \in \left[\gamma_T^n,\ \gamma_T^{n+1}\right)$ and within this region, the transmission rate does not change; yet the adaptive policy might change the transmit power in order to compensate for the fading. To overcome strong channel fading, data would be buffered for output SNR of fading regions $\gamma_T^0 \ \leq \gamma < \gamma_T^1$. For convenience, we suppose $\gamma_T^0 = 0$ and $\gamma_T^n = \infty$.

3.2.2 Problem Formulation

This section shows capacity of flat fading channel having a perfect channel state information (CSI) with respect to the transmitter side and the receiver as well. Which is widely

represented as $C(\gamma) = B\log_2(1+(P(\gamma)/\bar{P})\gamma)$ data bits/s. This capacity is considered as a yardstick to evaluate adaptive transmission schemes regarding its spectral efficiency [26]. By taking this effective diversity combining based approach, there exists constellation size that can achieve spectral efficiencies that can achieve $C(\gamma)$ bits/s, while maintaining certain target BER. The presence of such constellation/modulation is assured according to the well known Shannon's theorem (channel coding). Our aim here is to optimize a set of capacities with transmission modulation rates and switching threshold to guarantee the desired BER and power adaptation schemes. This should maximize the corresponding spectral efficiency in the given fading distribution.

The outage probability P_{out} of adaptive policy with target BER can only appear when the set of channel states is below the optimal cutoff SNR γ_0, which normally appears within the first interval of fading regions. Only at that time data is buffered for the corresponding period. The associated coding rate of other fading regions accommodate fluctuations. Thus, for adaptive systems the resulting spectral efficiency can be expressed as

$$SE = \sum_{n=1}^{N} M_n P_n \tag{3.3}$$

Where $M_n = \log_2(M_n)$ represents the constellation size or modulation code, and P_n is defined as the probability of selecting code n:

$$P_n = \int_{\gamma_T^n}^{\gamma_T^{n+1}} f_{\gamma_{mrc}}(\gamma)d\gamma \tag{3.4}$$

3.3 Adaptive Transmission Policies

The center of attention in this work is on the performance characterization of an adaptive transmission system with MRC diversity. The former studies emphasize on maximizing spectral efficiency of adaptive transmission under constant power constraints while maintaining target BER [36] and different power levels [37] unlike those studies, this research is interested in evaluating the adaptive system with MRC diversity while sustaining a certain BER, in selected adaptation policies. Accordingly, it is first argued in [61, 62]that the approximate BER of a rectangular MQAM uncoded modulation in AWGN can be expressed by the form

$$P_b \approx a.exp\left(-\frac{b\gamma}{(M-1)}\right) \tag{3.5}$$

Where a and b are positive fixed constants used to approximate the bounds of the expression and M is the size of a constellation. The desired bound within 1 dB it is achieved with $a = 0.2$ and $b = 1.5$ for $M \geq 4$ and received SNR $0 \leq \gamma \leq 30$ dB [24]. Though, evaluations of P_b e.g lose or tighter bounds described in literature clearly argue that using curve fitting techniques we optimize the value of a and b such that the expression yields good accuracy even for low γ. The error probability for MRC diversity combining with L-branches, in independent and identically distributed (i.i.d) Rayleigh-fading channels can be derived by substituting (2) the pdf of γ into (5). That way for the AWGN channel

with uncoded modulation, the error rates would be averaged out. It is possible to obtain closed-form expression by simplifying as in the following

$$P_b^{mrc} = \int_0^\infty P_b.f_{\gamma_{mrc}}(\gamma)d\gamma$$
$$\approx a.exp\left(-\frac{b\bar{\gamma}}{(M-1)}+1\right)^{-L} \tag{3.6}$$

Accordingly, we use this expression when needed, since it is easy to invert. Hence, for a given target P_b, adaptive transmission policy and L-branches or diversity combining levels, the required M constellation level can be determined numerically.

By selecting the adaptive transmission policies, now we are ready to determine the rate and power which fluctuate according to time-variations of the channel. The transmitter compensates/reciprocates to channel fluctuations by adjusting the constellation size $M(\gamma)$ and the transmission power $P(\gamma)$ relative to diversity combining and BER_T. At the receiver, the received SNR becomes $\gamma\frac{P(\gamma)}{\bar{P}}$, thus the approximation of instantaneous P_b can be approximated by (6) for each value of γ as:

$$P_b^{mrc}(\gamma) \approx a.exp\left(-\frac{b}{(M-1)}\frac{\gamma P(\gamma)}{\bar{P}}\right)^{-L} \tag{3.7}$$

By re-arranging the above in terms of M, we obtain an expression for maximum constellation size as a function of target BER BER_T, diversity level L and instantaneous received SNR γ:

$$M(\gamma) = 1 + K_n\frac{\gamma P(\gamma)}{\bar{P}} \tag{3.8}$$

Where $K_n \triangleq b.L\sqrt{a.BER_T}$ represents MRC diversity combining and $a = 5.0$ and $b = 1.5$, to power diminishing parameter inversely proportion to BER_T.

3.3.1 Continuous power and rate adaptation policy

In the following, we maximizing spectral efficiency of the MQAM scheme for a specified average transmission power with the target BER BER_T in the first adaptation policy. The spectral efficiency of a fading channel and received SNR distribution $f_{\gamma_{mrc}}(\gamma)$ with respect to diversity combining, is maximized by maximizing (8) as follows [24]:

$$E[\log_2 M(\gamma)] = \int \log_2\left(1+\frac{K_n\gamma P(\gamma)}{\bar{P}}\right) f_{\gamma_{mrc}}(\gamma)d\gamma \tag{3.9}$$

Introducing a maximum spectral efficiency scheme (9), which subject to average power constraint $\bar{P}(\gamma)$, then constrict the average power (using an equal) rather than just bounding (using inequality) $\frac{\partial J}{\partial P(\gamma)} = 0$ Lagrangian optimization solution. Optimal power adaptation for MQAM mentioned in [24] can be expressed as follows:

$$\frac{P(\gamma)}{\bar{P}} = \begin{cases} \frac{1}{\gamma_0^*} - \frac{1}{\gamma K_n} & \gamma \geq \gamma_0^*/K_n \\ 0 & \gamma < \gamma_0^*/K_n \end{cases} \tag{3.10}$$

Where γ_0^*/K_n is the optimal level SNR at which at the cutoff fade. Beyond that level transmission would be deferred. This optimal cutoff and MRC combining γ_0^* follow:

$$\int_{\gamma_0^*}^{+\infty} \left(\frac{1}{\gamma_0^*} - \frac{1}{\gamma^* K_n} \right) f_{\gamma_{mrc}}(\gamma) d\gamma = 1 \tag{3.11}$$

For the above equation of optimal cutoff SNR while maintaining BER performance, a closed-form expression adopts the numerical root finding techniques and substitutes (2) in (11) to find γ_0^*:

$$\frac{\Gamma(L, \frac{\gamma_0^*}{\bar{\gamma}})}{\frac{\gamma_0^*}{\bar{\gamma}}} - \frac{1}{K_n} \Gamma(L-1, \frac{\gamma_0^*}{\bar{\gamma}}) = (L-1)! \bar{\gamma} \tag{3.12}$$

Where $\Gamma(\alpha, x) = \int_x^\infty t^{\alpha-1} e^{-t} dt$ is a complementary incomplete gamma function [50],[56]. Let $x = \frac{\gamma_0^*}{\bar{\gamma}}$ and define:

$$f_{K_n}^{mrc}(x) = \frac{\Gamma(L, x)}{x} - \frac{1}{K_n} \Gamma(L-1, x) - (L-1)! \bar{\gamma} \tag{3.13}$$

Note that $\frac{\partial f_{K_n}^{mrc}(x)}{\partial \gamma_0^*} < 0 \; \forall \; x > 0$ and $L \geq 2$. By virtue of $\lim_{x \to 0^+} f_{K_n}^{mrc}(x) = +\infty$ and $\lim_{x \to +\infty} f_{K_n}^{mrc}(x) = -(L-1)! \bar{\gamma}$, hence it is assumed that there is a unique positive γ_0^* such that $f_{K_n}^{mrc}(\gamma_0^*) = 0$ and restricted by (12). Gnu Scientific Library (GSL) optimization routines [57] are used to obtain numerical results. The results show γ_0^* with MRC diversity and BER performance always lies in the interval $[0, 1]$.

Based on the result of (13), we can devise the closed-form expression of (9) by substituting (2) in (9), for the channel capacity $\langle C \rangle_{\text{CPRA}}$ as:

$$\langle C \rangle_{\text{CPRA}}^{\text{mrc}} = \mathcal{J}_L \left(\frac{\gamma_{K_n}^*}{\bar{\gamma}} \right) \frac{{\gamma_{K_n}^*}^L}{\bar{\gamma} \log_2(e)(L-1)!} \tag{3.14}$$

Where $\gamma_{K_n}^* = \gamma_0^*/K_n$ is a cutoff SNR threshold. Beyond that threshold deferring of the data transmission occurs. B represents to channel bandwidth (in Hertz). Letting $\alpha = \frac{\gamma_{K_n}^*}{\bar{\gamma}} > 0$, using the evaluation of $\mathcal{J}_L(\alpha)$ which is given in Appendix A [56], and rearranging the (14). For MRC diversity, we obtain the SE [bits/s/Hz] and BER performance by using continuous power and rate adaptation policy as:

$$\frac{\langle C \rangle_{\text{CPRA}}^{\text{mrc}}}{B} = \log_2(e) \left(E1(\alpha) + \sum_{k=1}^{L-1} \frac{\mathcal{P}_k(\alpha)}{k} \right) \tag{3.15}$$

Where $\mathcal{P}_k(\cdot)$ is Poisson distribution defined as $\mathcal{P}_k(\alpha) = e^{-\alpha} \sum_{j=0}^{k-1} \frac{\alpha^j}{j!}$ and $E1(\alpha) = \int_1^\infty \frac{e^{-\beta t}}{t} dt$ is an exponential integral function of first-order [56]. To achieve the capacity (15), instantaneous received SNR γ should not fall below $\gamma_{K_n}^*$. Since, no data transmission occurs when $\gamma < \gamma_{K_n}^*$, the policy is vulnerable to outage. Outage probability under BER_T performance for the MRC diversity case is expressed below:

$$f_{out_{mrc}} = \int_0^{\gamma_{K_n}^*} f_{\gamma mrc}(\gamma) d\gamma = 1 - \int_{\gamma_{K_n}^*}^{\infty} f_{\gamma_{mrc}}(\gamma) d\gamma \tag{3.16}$$

Substituting (2) in (16), for the probability of outage, we obtain the following closed form expression:

$$f_{out_{mrc}} = 1 - \mathcal{P}_L(\alpha) \tag{3.17}$$

3.3.2 Truncated channel inversion policy

Another adaptation policy where the transmitter inverts the channel higher than the fade depth γ_0^* to maintain the SNR received. This power adaptation policy is termed Truncated Channel Inversion with Fixed Rate (TCIFR) that is employed in inner-loop power control mechanism [58], which adapts the transmitting power to achieve a desired SNR at the receiver. Then, adaptive system transmits fixed-rate MQAM constellation that maintains the BER_T with diversity combining. Hence, introducing $P(\gamma)/\bar{P} = \sigma/\gamma$ in (8) and multiplying by the probability that $\gamma > \gamma_0^*$, we obtain a new expression for channel capacity expressed by:

$$\langle C \rangle_{\text{tcifr}}^{\text{mrc}} = B \log_2 \left(1 + K_n \frac{1}{\int_{\gamma_{K_n}^*}^{\infty} \frac{f_{\gamma_{mrc}}(\gamma)}{\gamma} d\gamma} \right) (1 - f_{out_{mrc}}) \tag{3.18}$$

Where $f_{out_{mrc}}$ is calculated as in (16) to maximize (18). In order to find the closed-form expression, we substitute (2) into (16) and rearrange to obtain the SE [bits/s/Hz] under TCIFR policy and BER_T performance for MRC diversity as:

$$\frac{\langle C \rangle_{\text{tcifr}}^{\text{mrc}}}{B} = \log_2 \left(1 + \frac{(M-1)!\bar{\gamma}}{\Gamma(M-1, \gamma_0^*/\bar{\gamma})} \right) \frac{\Gamma(M, \gamma_0^*/\bar{\gamma})}{(M-1)!\bar{\gamma}} \tag{3.19}$$

Using properties of $\Gamma(\cdot,\cdot)$ of complementary incomplete gamma function [50][56], (19) further can be simplified as follows

$$\frac{\langle C \rangle_{\text{tcifr}}^{\text{mrc}}}{B} = \log_2 \left(1 + \frac{(M-1)\bar{\gamma}}{\mathcal{P}_{M-1}(\gamma_0^*/\bar{\gamma})} \right) \mathcal{P}_M(\gamma_0^*/\bar{\gamma}) \tag{3.20}$$

3.3.3 Continuous power and discrete-rate adaptation policy

We now proceed to extend the design of adaptive system for continuous power and discrete-rate adaptation policy, by restricting adaptive MQAM to N fading regions, whose constellations size $M_n = 2^{2(n-1)}$ and whose BER can be approximated by (7) for $n = 2, ..., N-1$ under diversity combining. Recall that instantaneous SNR γ is partitioned into N fading regions [24], [63], the modulation size M_n is used whenever $\gamma \in [\gamma_T^n, \gamma_T^{n+1})$. Thus, the adaptive system is lower bounded by γ_T^n to maintain the BER_T with diversity combining, after transmission power adaptation.

Following (8), this policy also requires the boundaries of switching threshold be determined. Therefore, by substituting (10) into (8) yields the constellation size for a given γ as:

$$M(\gamma) = \frac{\gamma}{\gamma_\beta^*} \tag{3.21}$$

Where γ_β^* is a optimized parameter found by numerical methods to optimize the switching thresholds and maximize spectral efficiency. Former, the fading region n of switching

threshold and associated constellation size M_n are determined, then we obtain the power adaptation policy based on (8) to maintain the fixed BER_T and satisfies the average power constraint $\int P(\gamma) f_{\gamma_{mrc}}(\gamma) \leq \bar{\gamma}$ as follows:

$$\frac{P_n(\gamma)}{\bar{P}} = \begin{cases} \frac{(M_n-1)}{\gamma K_n} & M_n < \frac{\gamma}{\gamma_\beta^*} \leq M_{n+1} \\ 0 & M_n = 0 \end{cases} \tag{3.22}$$

Where $P_n(\gamma)$ represents post adaptation power, and when $\gamma < \frac{\gamma}{\gamma_\beta^*}$ no transmission ocurrs and data is buffered. The maximized spectral efficiency SE of CPDA policy for a given diversity level and BER_T with distribution $f_{\gamma_{mrc}(\gamma)}$, is defined as the sum of spectral efficiencies associated with each of the fading regions:

$$\frac{\langle C \rangle_{\text{CPDA}}^{\text{mrc}}}{B} = \sum_{n=1}^{N-1} \log_2(M_n) f_{\gamma_{mrc}}(M_n \leq \frac{\gamma}{\gamma_\beta^*} < M_{n+1}) \tag{3.23}$$

Since M_n is a function of γ_β^*, by maximizing (23) with respect to γ_β^*, we arrive at the following optimization problem where (23) is maximized subject to power constraint must be satisfied:

$$\sum_{n=1}^{N-1} \int_{\gamma_\beta^* M_n}^{\gamma_\beta^* M_{n+1}} \frac{P_n(\gamma)}{\bar{\gamma}} f_{\gamma_{mrc}}(\gamma) d\gamma = 1 \tag{3.24}$$

If we assume equation (2) Rayleigh fading channel with diversity combining the closed-form expression of (24) can be written as follows:

$$\begin{aligned} f_{mrc}(\gamma_\beta^*) = \sum_{n=1}^{N-1} \frac{M_n - 1}{\bar{\gamma} K_n (L-1)!} \Big(& \Gamma(L-1, \frac{M_{n+1}\gamma_\beta^*}{\bar{\gamma}}) \\ & - \Gamma(L-1, \frac{M_n \gamma_\beta^*}{\bar{\gamma}}) \Big) \end{aligned} \tag{3.25}$$

With the increase of diversity gain, relative to others polices, the discrete-rate adaptive policy will have reasonable agreement in term spectral efficiency but significantly has less probability of outage as we show in results section.

3.4 Numerical Results and Discussion

In this section, we obtain the numerically evaluated results for *continuous power and rate adaptation* (CPRA), *truncated channel inversion with fixed-rate adaptation* (TCIFR) and *continuous power and discrete-rate adaptation* (CPDA) at target BER_T. For the following, a Rayleigh fading distribution and MRC diversity combining technique have been assumed.

Using described techniques in [50] and [48], we have designed an adaptive MQAM system which takes the target BER_T into account and utilizes the diversity combining gain, to maximize the spectral efficiency. As can be seen in Figure 3.1, the gap between the spectral efficiencies is induced by a effective power loss parameter K_n, since it is a function of BER_T and number of L diversity levels. Moreover, we also observe that K_n

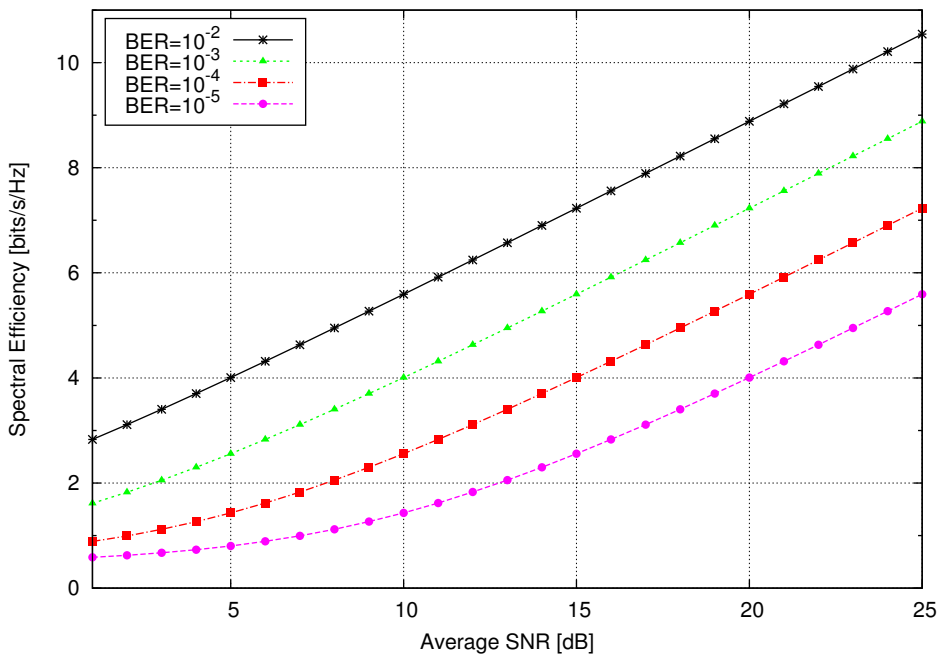

Figure 3.1: Spectral efficiency of continuous power and rate adaptation for various target BER_T with diversity level L=4 , versus average received SNR $\bar{\gamma}$

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diminishes the performance within 4 dB with constant L as BER_T advances. Hence, we fix the target BER_T in the following, and evaluate its effect on spectral efficiency and power adaptation for proposed adaptive system with diversity combining techniques.

Figure 3.2 presents the resulting channel capacity for each bandwidth unit or spectral efficiency acquired using closed-form expression (15), (19) and (23) . The capacity per unit bandwidth increases with the number of diversity levels. We noted that the spectral efficiency curve for CPRA policy has increasing trend at low received SNR (0 dB to 10 dB) in the beginning, afterward gradually comes close to other policies keeping slightly larger spectral efficiency(when SNR is greater than 10 dB). The cause of this effect is the CPRA policy of leveraging the water-filling nature at lower received SNR and it only holds this instinct for diversity level(L = 1 or L = 2).

In Figure 3.2, the discrete-rate policy has similar behavior even in diversity combining [24], by restricting it to the fading regions and it yields low spectral efficiency. That resulting efficiency is 1 dB compared to that produced by CPRA. However, the spectral efficiency curves are very close to each other in almost all diversity levels.

The optimal switching thresholds $\{\gamma_T^n\}_{n=1}^N$ for CPDA policy which is suitable for adaptive system, are shown in Figure 3.3, at Target $BER_T = 10^{-4}$ and for 0 dB $< \bar{\gamma} <$ 25 dB under various diversity levels. Obtain the thresholds using expression (21) with 4 fading regions and optimized power adaptation (22), and γ_β^* found through numerical methods, where the threshold γ_T^n equals the minimum target SNR to obtain the desired BER_T.

As, it is obvious in Figure 3.3 γ_T^n in each diversity level exploits the diversity gain after 3 dB and it monotonically widens with the increment of diversity level. By taking the leverage of diversity gain, the adaptive system switches the modulation code when $M_{n+1} > M_n$ and maximizes the spectral efficiency by the probability $\int_{\gamma_T^n}^{\gamma_T^{n+1}} f_{\gamma_{mrc}}(\gamma)d\gamma$

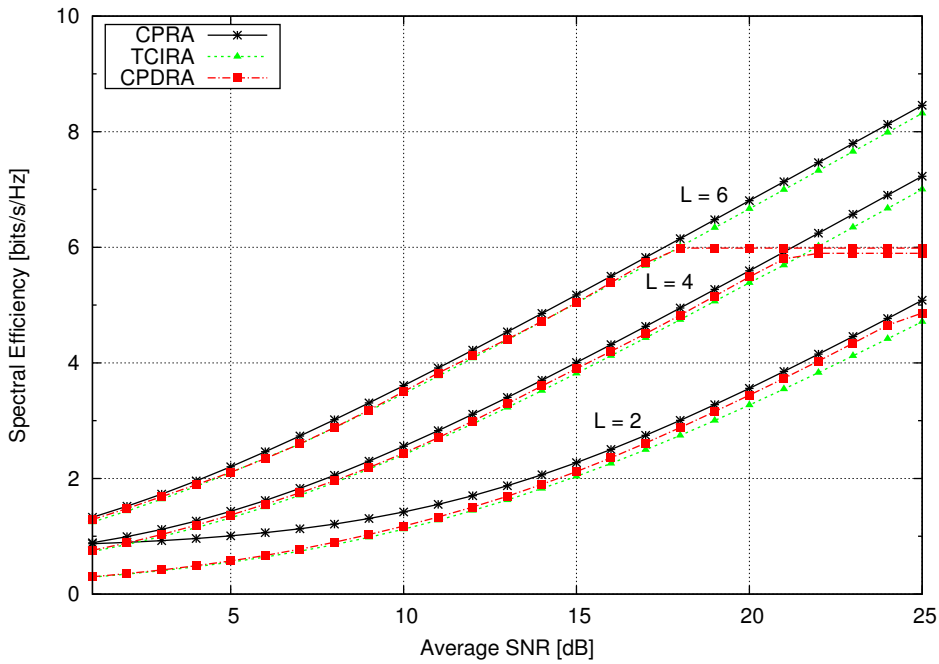

Figure 3.2: Spectral efficiency of various adaptive policies with various diversity levels and $BER_T = 10^{-4}$, versus average received SNR $\bar{\gamma}$.

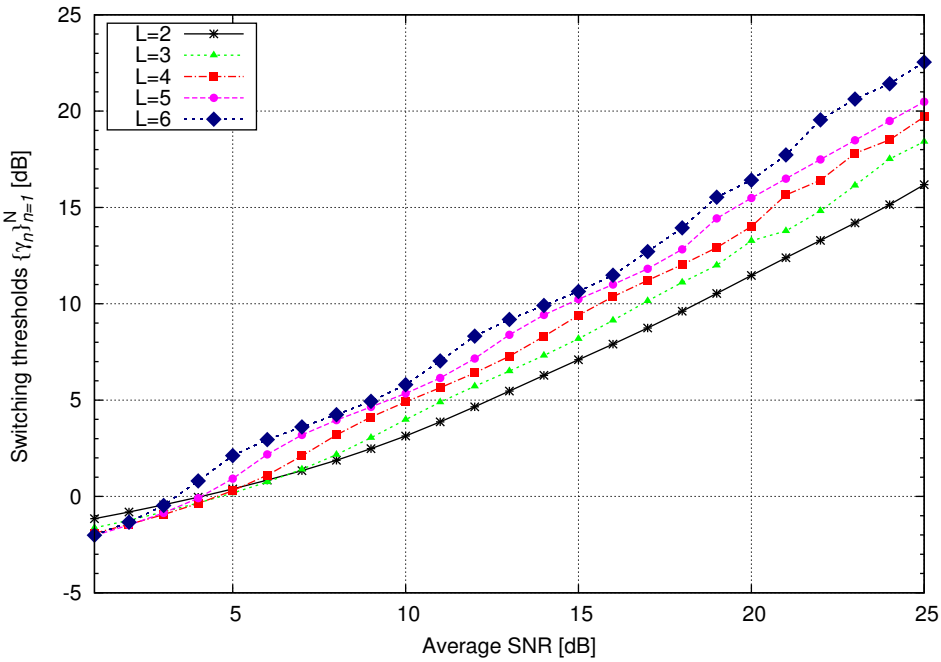

Figure 3.3: Switching thresholds $\{\gamma_T^n\}_{n=1}^N$ under continuous power adaptation policy with target $BER_T = 10^{-4}$ as a function of various diversity levels.

that the instantaneous received SNR falls in region n.

For each $\bar{\gamma}$ of interest, designed the constellation size above for spectral efficiency. The optimized policy for power adaptation is the used and presented in (10). Figure 3.4, highlights the continuous power adaptation policy used in designing the adaptive system,

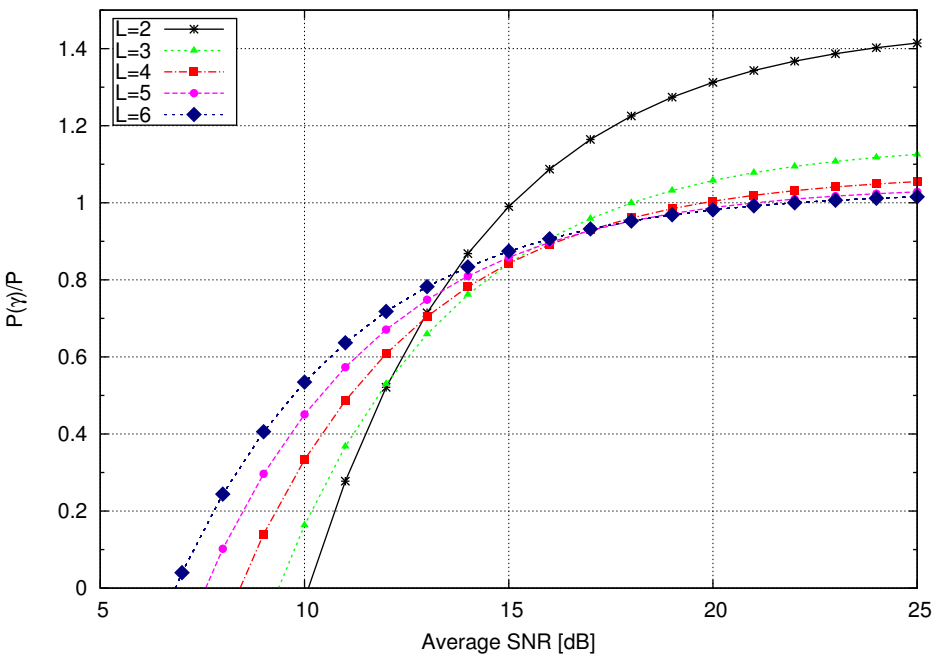

Figure 3.4: Power adaptation scheme $P(\gamma)/\bar{P}$ with various diversity levels with respect to average received SNR, plotted for an average SNR $\bar{\gamma} = 15$ dB.

for $\bar{\gamma} = 15$ dB. We noticed the range of the optimized transmission power $P(\gamma)$ is 0 to $1.4\bar{P}$. Following the water-filling nature, it can be seen that most for the power is allocated to the best SNR channels regardless diversity gain. In addition, it is interesting to point out that with the upsurge of diversity gains the optimized power becomes uniform especially when $\bar{\gamma} \geq 15$ dB. It is pertinent to mention that due to low diversity combing gain, 35% more transmit power is allocated when diversity level is L = 2. In this analysis, it is also noticed that by virtue of various diversity gain, $P(\gamma)$ does not take rigorous peak values.

3.5 summary

In this chapter, power and rate adaptation policies have been devised to maximize the spectral efficiency of MQAM system in Rayleigh fading channel with MRC diversity combining technique. In particular, closed-form expressions of selected adaptive policies are obtained, in order to maintain target BER and maximize spectral efficiencies in conjunction with diversity combining.

The results were compared for a continuous power and rate adaptation policy under the constraint of BER and its effect on spectral efficiency under diversity gain. We concluded that the performance of the proposed adaptive system significantly influenced by K_n value. On the other hand, we observed that the difference in each step of BER alone extends/reduces the system spectral efficiency almost 4 dB. Additionally, we optimized the switching threshold for discrete-rate adaptation policy and power adaptation policies through numerical techniques. It is interesting to note that the continuous power and rate adaptation policy has only a little better spectral efficiency compared to discrete-rate and truncated channel inversion policy, despite the increment in diversity branches and average SNR retaining it.

Chapter 4

Emulation Framework for Realistic Evaluation

This chapter also presents our one of main works. We present an architecture of a emulation platform which is designed and implemented for the evaluation of adaptive transmission system in realistic environment.

In first section, we provide some background on how emulation platform came to be, and we report on its core architecture. Before discussing some of the technical details of its low-level interfaces, we review first the design and its implementation. We describe in section 3.1 the system/platform design with its salient features in conjunction with ns-3 discrete time event-driven simulation engine. In section 3.2, we talk in detail over WiMAX implementation in QOMET. Section 3.3 outlines experimental topologies, setup and settings. This section also provides the experimental results which show the performance of proposed emulation framework. Finally, section 3. concludes the chapter with findings.

4.1 Introduction

The key concern of wireless communication systems is the development as well as realistic performance evaluation of the applications and protocols running over these systems. The realistic evaluation has always been a challenging task. In this regard, there are two key concerns. First, it is fundamental to reiterate the experimental process multiple times in a deterministic manner. Second, a major constraint is the capability/facility of investigating these kinds of systems in a real-world environment [38]. Typically, testing of the respective system and the performance evaluation under real conditions are performed within a wireless testbed of prototype implementation.

In order to model novel and existing networking protocols and algorithms, researchers mostly rely on wireless testbeds or simulation to execute experiments. *Network simulation* is an invaluable approach for researchers; it allows us to model the network, equipment and applications of a whole wireless system. Primarily, renowned simulators, such as ns-2 [70] or ns-3 [71], QualNet [72], OPNET [73] and OMNeT++ [74] are designed to control and reproduce the condition of various wireless networks in a scalable fashion. Particularly, discrete event simulation technique due to its trait of formulating state transition as sequences, allows to model telecommunication networks. Although simulation is a widely adopted technique of evaluation in academia or research communities, but its accuracy

depends on the accuracy of the used models. Abstract simulation models frequently make simplified assumptions of the real world. Often, they neglect the system framework of networking protocols and run-time environments, such as that of an underlying operating system, regarding timing synchronization, concurrence processes, resources limitation [38]. These issues are critical in understanding the system behavior seen in real-world situation. As simulation is lacking the fundamental concept of realism, also its abstraction limits its applicability in measuring network performance.

Testbeds are ideal solutions to evaluate the wireless system under real conditions and has become the source of both reproducible and realistic results. But, constructing such testbeds is expensive in term of hardware and labor cost. Moreover, the interaction between higher layers of protocol stack and Medium Access Control (MAC) wireless layer made us realize how difficult is it to extract meaningful information from protocols implemented in hardware or within operating system kernel. In addition, insufficient scalability hinders the study of legacy wireless networks.

Network emulation [13, 75], is a technique to scale up the experiment size cheaply, maintain a high degree of realism, increase controllability and reproducibility. A network emulator may be considered a hybrid investigation environment where a testbed or simulation are used together and synchronized to a real-world clock. For this purpose, real-world machine passes traffic through simulated network that reproduces the behavior of a communicating network. This way, by imitating packet propagation characteristic within the simulator, it enables simulated protocol modules to interact with the standard implementations.

4.1.1 Intuition

The objectives accomplished in this chapter asked for a real-time network emulation platform that would help the researchers to evaluate the novel/existing protocols in real-time. Basically, the key concern of the wireless network technologies is the development as well as realistic performance evaluation of the applications and protocols running over these technologies. Since, the realistic evaluation has always been a challenging task. In this regard, there are two key concerns as follows:

- It is fundamental to reiterate the experimental process multiple times in a deterministic manner;
- The major constraint is the capability/facility of investigating these kind of wireless technologies in a real-world environment;

Deeply, we realized early that in order to model novel and existing networking protocols and algorithms, researchers mostly rely on wireless testbeds or simulation to execute experiments. Typically, testing of the respective technologies and the performance evaluation under real conditions is performed within a wireless testbed or its prototype implementation. Thus, such needs led us to focus on the platform that should produce a high degree of realism and could fulfill all of these requirements together.

4.2 System Design and Implementation

4.2.1 Overview of System Design

The aim of this section is to briefly describe a high level overview of the system in order to allow the emulation of Wireless network. Our work on wireless network emulation started with the assumption that the components under test will be real network applications and protocols running on top of the emulated wireless networks; examples include robot motion planning algorithms [69], or routing metrics for wireless mesh networks [76]. This task is achieved in the most efficient manner by modeling both lower network layers, PHY and MAC.

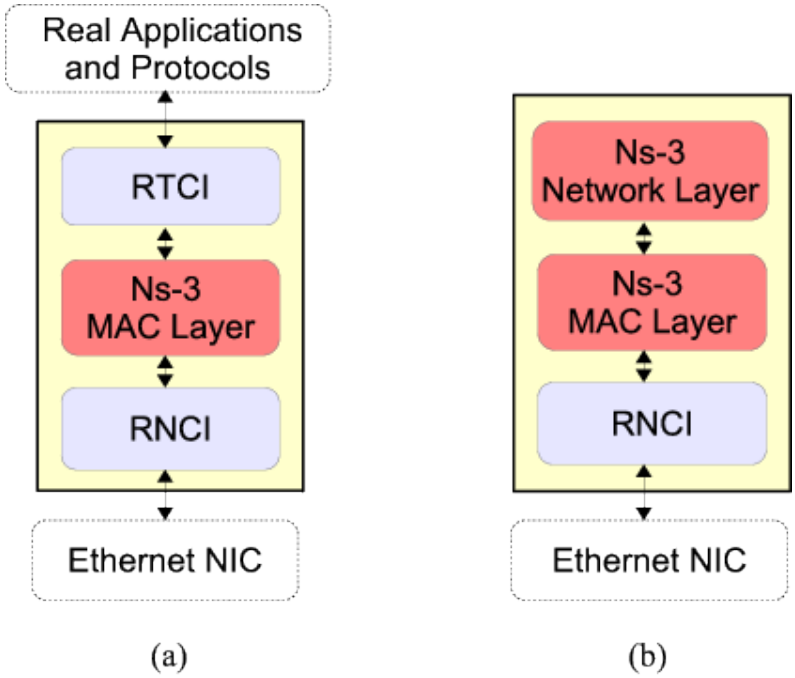

Figure 4.1: Overview of a emulation experiment approach for WiMAX network

For some wireless network technologies, software implementations of the MAC layer are readily available as open source. This is the case for instance for open80211s [77], an open-source implementation of the IEEE 802.11s wireless mesh standard. In other cases (e.g., WiMAX or LTE) such implementations are not yet publicly available. Developing a MAC layer module from scratch is time consuming, and we believe that a promising alternative for fast prototyping is to reuse existing simulation code such as that in ns-3. In [64] we presented in detail our approach for making possible ns-3 based emulation of WiMAX networks, and we summarize here the main points.

In Figure 4.1 we show the conceptual structure of the ns-3 based emulation framework that we developed. In the case of the Subscriber Station (SS), two supplementary modules were required in addition to the ns-3 WiMAX MAC code.

- One was the Real Traffic Communication Interface (RTCI), which allows passing real application and protocol traffic between the OS and the WiMAX module.

- The other one was the Real Network Communication Interface (RNCI), which allows passing traffic between the WiMAX module and the Ethernet NIC so that it can reach other nodes, thus enabling distributed execution.

In the case of the Base Station (BS) only the RNCI module is required, because the BS doesnt need to communicate with actual applications/protocols, hence it can use the default network layer (Layer 3) in ns-3.

Real Traffic Communication Interface (RTCI)

The RTCI component leverages the TapBridge NetDevice class in [71] to provide real traffic communication between the actual host PC and the ns-3 instance, so as to connect the host PC network stack with the ns-3 MAC layer. In particular, we configured the UseBridge mode of the TapBridge device, thus effectively extending a host OS bridge into ns-3.

To accomplish this, one needs to create a virtual device and add it to a predefined bridge. Ns-3 will then create a tap device and connect it to the same bridge, so that the host OS treats the tap device as a real network device connected to that bridge. Ns-3 then uses inter-process communication to connect the tap device to the equivalent bridge present in the simulator instance, which is in our case part of the WiMAX MAC layer implementation.

Real Network Communication Interface (RNCI)

By default, in ns-3 all the scenario nodes will be executed on the same machine. However, for emulation, which requires real-time execution, this can quickly become a bottleneck. The RNCI component is essential for making it possible to execute different WiMAX nodes on different hosts PCs. Such a distributed execution environment dramatically improves experiment scalability, since the available computing resources can be used in a more flexible manner.

For this purpose, RNCI makes it possible to send and receive the traffic of the ns-3 MAC layer over the experiment network of StarBED. The design of RNCI is inspired by the EmuNetDevice class in ns-3, and it has been adapted to the case of WiMAX. The RNCI of the sender connects to a real network interface and encapsulates the WiMAX frames into Ethernet frames, which are then sent over the testbed network, decapsulated by the RNCI of the receiver, and passed on to the corresponding ns-3 instance.

Packet transmission over real-network The application generates packets to be passed down and wrapped in appropriate layers on its way out of the system. When the burst (group of packets at PHY) is about to cross the boundary between ns-3 and underlying OS, the RNCI copies all channel parameters that are necessary for the receiver to perform further actions. Once burst is ready to be sent over the network, burst data structure with necessary parameters is written to the memory buffer reserved by RNCI.

Packet reception from real-network At the receiving end, data is received and queued on the ns-3 side; multi-thread process of ns-3 utilizes its read thread functionality of RNCI to asynchronously receive data. Once data is received, an event is created in the emulator thread. After a specific time interval, RNCI creates a packet from memory, then

free the memory space since the data was received, it also takes care of the pending thread to avoid memory overflow at OS level. Secondly, RNCI removes and records additional header of the newly created packet with protocol number and channel parameters. In the final stage, packet data is copied into the buffer. Finally, a burst is created out of this buffer and supplied to the physical layer with the necessary channel parameters to perform further actions.

4.3 WiMAX Implementation in QOMET

In this section we present our approach for making possible MAC layer protocol evaluation through network emulation. To demonstrate the feasibility of this approach, we implemented the corresponding experiment framework using WiMAX as a case study. Our framework is built on top of the large-scale network testbed StarBED [67], and extends the wireless network emulation tool-set QOMET [66], which are both developed and managed by the Hokuriku StarBED Technology Center of the National Institute of Information and Communications Technology (NICT) in Ishikawa, Japan.

The main contributions of this section are as follows:

- An IEEE 802.16e standard-based mobile WiMAX PHY model that was implemented in QOMET;
- The integration of the above PHY model with an ns-3 based WiMAX MAC module that was previously developed on StarBED [64], thus providing full WiMAX emulation functionality.

4.3.1 StarBED: A Framework Infrastructure

The infrastructure for our framework is represented by the large-scale network experiment environment called StarBED, located at the Hokuriku StarBED Technology Center of NICT in Ishikawa, Japan [67]. StarBED makes available for experiments more than 1400 PCs and the interconnecting network equipment. The large number of experiment hosts, and the versatile network architecture of StarBED make it possible to conduct a wide range of network experiments on this testbed. The StarBED experiment and control networks are separated, so as to isolate experiment traffic from the management one.

SpringOS is the fundamental experiment-support software tool for StarBED [67]. SpringOS makes it possible to perform complex experiments with a large number of hosts by assisting users in the following tasks:

- Experiment preparation: Configure the experiment hosts and network so that they are ready to use;
- Experiment execution: Effectively carry out the experiment by performing the necessary commands on the experiment hosts in the required order.

4.3.2 QOMET: Wireless Network Emulation

The wireless network emulation capabilities discussed in this work are based on the extension of QOMET (Quality Observation and Mobility Experiment Tools) [66]. QOMET

is a set of tools for reproducing the communication conditions between experiment nodes. QOMET relies on the experiment management mechanisms of StarBED for its distributed execution to achieve the emulation of the overall network on the testbed. The main QOMET features are:

- *Wireless network technologies*: Support for standards such as IEEE 802.11a/b/g, IEEE 802.15.4, etc;
- *Topography*: The topography of the emulated environment (streets and buildings), can be defined in 2D/3D;
- *Node mobility*: Several models can be used to describe the trajectory of the emulated nodes: random way, behavioral model, etc.

The core functionality of QOMET is provided through the libraries called `deltaQ` and `wireconf`. The `deltaQ` library is used to compute the communication conditions between wireless nodes given a user-defined scenario. The library includes the implementation of models for wireless network technologies, propagation, and mobility. The user-defined scenario specifies the properties of the wireless nodes (position, network technology parameters, mobility pattern), and of the environment in which they are placed (attenuation, shadowing, street and building structures, and so on). These properties are used to create a "virtual world" that corresponds to the emulated scenario, in which the wireless nodes move and communicate with each other.

The `wireconf` library recreates during live experiments the communication conditions computed by `deltaQ` by applying the corresponding network degradation (packet loss, delay and bandwidth limitation) to the experiment traffic. This is effectively achieved on the testbed by means of the `ipfw3` link emulation module [78].

WiMAX PHY Model

The function of the WiMAX PHY model that we implemented in the QOMET `deltaQ` library is to make it possible to calculate the PHY layer conditions that are to be reproduced through emulation. The parameters that describe these conditions are: (i) bandwidth; (ii) frame error rate; (iii) delay. The models used for the first two parameters will be described next. Delay in WiMAX results implicitly from the operation of the MAC layer, therefore at PHY layer it is not necessary to introduce any additional delay; hence nothing needs to be done for this parameter in the PHY model.

Bandwidth The model that we implemented in order to compute the available bandwidth in WiMAX at PHY layer is based on the IEEE 802.16e standard [7] and the discussion in [19]. The algorithm is the following:

- Initialize the model parameters (sampling factor, FFT size, signaling overhead, number of downlink and uplink symbols, number of subcarriers) depending on the modulation selected and other relevant user settings;
- Compute the basic parameters of the model (sampling frequency, sample time, subcarrier spacing, symbol and guard time, total number of symbols, number of downlink and uplink slots);

- Compute the bandwidth-related parameters (e.g., bytes per slot) and the resulting data rate depending on other PHY settings, such as MIMO configuration, repetition factor, etc.

We emphasize the fact that bandwidth in this context refers to the bandwidth available at PHY layer for the WiMAX nodes, and that will be enforced by wireconf during the live experiment. Aspects such as how this bandwidth is shared by multiple nodes are handled at MAC layer by the ns-3 based MAC module, therefore they do not need to be dealt with in the PHY model.

The above model has a low computation complexity, and it only needs to be reevaluated if the configured WiMAX modulation changes. Thus, for real-time operation it is preferable to the ns-3 model, which does certain calculations on a per packet basis, since it doesnt use the concept of available bandwidth. Moreover, our model can still be used with WiMAX MAC implementations other than the ns-3 one if they are available.

Frame Error Rate (FER) In order to determine the frame error rate corresponding to a certain WiMAX modulation and its associated PHY parameters, the receive sensitivity threshold for that modulation is necessary. The value of this threshold could be obtained from the specifications of particular WiMAX devices, but we opted here for a more generic approach. Thus, we calculate the receive sensitivity threshold, S, based on the corresponding recommended equation in the IEEE 802.16e [7] standard:

$$S = -114 + SNR_{Rx} - 10\log_{10}(R) + 10\log_{10}(F_s \cdot N_{Used}/N_{FFT}) + Imp_{Loss} + NF, \quad (4.1)$$

where SNR_{Rx} is a modulation-dependent Signal-to-Noise Ratio constant, R is the repetition factor, F_S is the sampling frequency, N_{Used} is the number of used downlink subcarriers, and N_{FFT} is the size of the FFT. For the additional constants Imp_Loss, the implementation loss, and NF, the noise factor, we use the default values specified in the 802.16e standard, namely 5 and 8, respectively.

As done previously in QOMET [66], the threshold S computed above is then used to calculate the bit error rate, BER, according to an exponential dependency:

$$BER = BER_s \cdot e^{\gamma(S+\delta-P_r)}, \quad (4.2)$$

where BER_S is the bit error rate at the sensitivity threshold (equal to 10^{-6} according to the 802.16e standard), γ and δ are calibration constants, and P_r is the received power strength in dBm. Through fitting with respect to the corresponding detailed analytical models for error rate, the values for γ and δ were determined to be equal to 1.7 and 0.0 for AWGN fading, and 0.23 and 32.73 for Rayleigh fading, respectively (as average for all modulations). Note that we limit the BER given by the previous equation to the value 1.0, since it represents a probability.

Finally, the frame error rate, FER, which will be enforced during emulation by `wireconf`, is calculated from BER as:

$$FER = 1 - (1 - BER)^{8 \cdot F_{size}}, \quad (4.3)$$

where F_{size} is the frame size expressed in bytes.

4.4 Experiments

The experiments presented here focus mainly on demonstrating that the emulation architecture used in our framework produces similar results when compared to ns-3 simulation (as expected given that the ns-3 MAC implementation is integrated into the framework), while having the advantage of using real network applications/protocols on the end nodes.

The simulation experiments were done using ns-3.18. The emulation experiments were carried out on StarBED, with each emulated node running on a different physical host with dual-core Pentium 4, 3.2 GHz CPU and 8 GB RAM.

4.4.1 System Architecture of Experiment Framework

The overall architecture of the hybrid system that we implemented is shown in Figure 4.2. Each StarBED host can work either as a WiMAX base station or as a subscriber station. SSs will run the real applications and protocols used during the evaluation, the ns-3 based MAC module, as well as the QOMET emulation components: `deltaQ` (that includes the WiMAX PHY implementation) and `wireconf`. The BS will only run the ns-3 based MAC module together with the ns-3 network layer, and the QOMET components. Experiment traffic produced by the nodes is communicated over the StarBED experiment network, whereas the management is done via the control network.

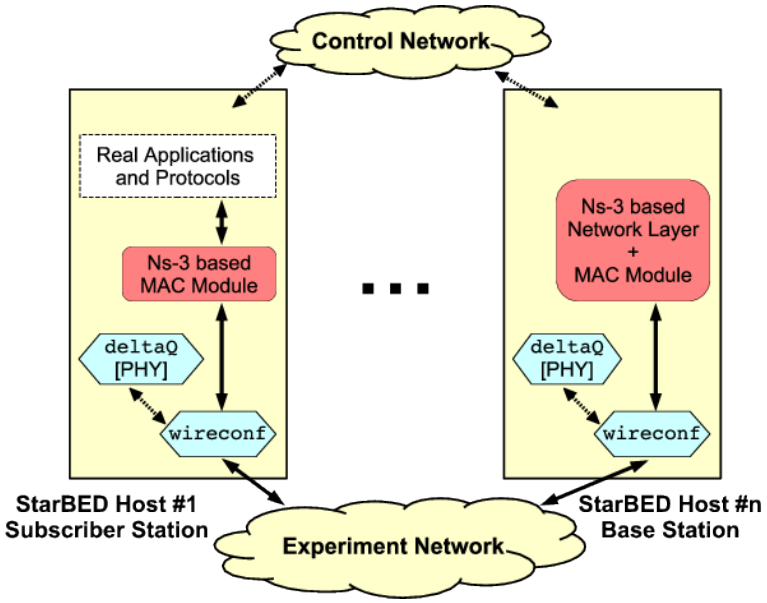

Figure 4.2: Overall system architecture of the experiment framework.

4.4.2 Topology

4.4.3 Results and Discussion

This section is dedicated to evaluate the implementation of emulation framework in WiMAX network. The first set of experiments is devoted to validate the correctness of the designed framework in static environment, and study whether emulation framework introduces performance degradation or not. The second set of experiments illustrates the

mobility impact of the emulation framework on throughput with different modulation and coding rates.

Static We tested first a static scenario in which 1 BS and 2 SSs are in the vicinity of each other, and the WiMAX modulation used for communication was set to the default one, `qam16_12`. In the case of simulation, traffic was generated using the UdpClient and UdpServer ns-3 applications for UDP experiments, and BulkSend and PacketSink for TCP ones. For emulation we used iperf v2.0.5 both for UDP and TCP transfers. The experiment duration was 300 s. In both cases the experiment traffic was classified as real-time traffic by the WiMAX classifier, and we used either the default ns-3 WiMAX scheduler (named "Simple Scheduler") or the Real Time Polling Service (RTPS) scheduler.

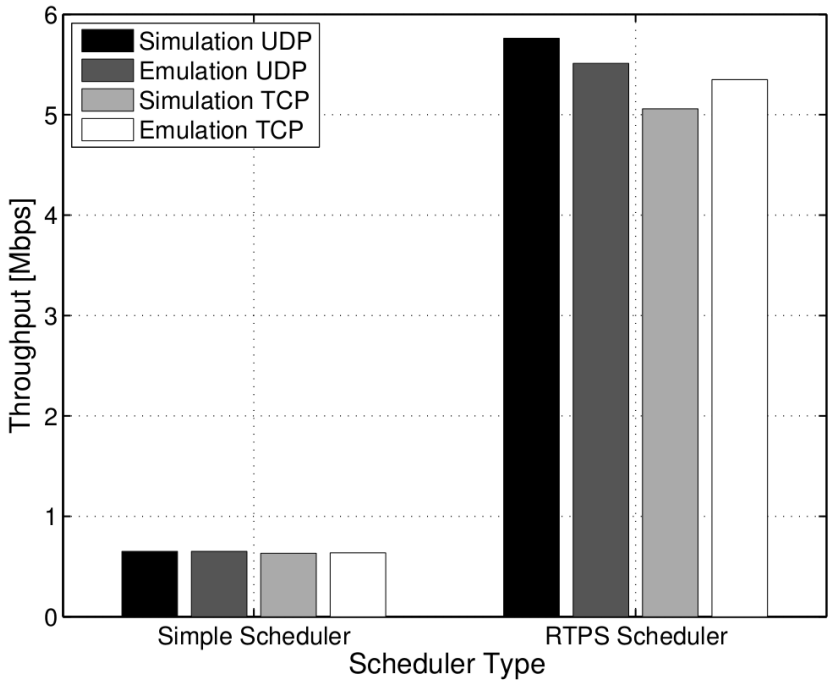

Figure 4.3: Throughput results with two different schedulers.

As it can be seen in Figure 4.3, for the Simple Scheduler there are essentially no differences between simulation and emulation, and for the RTPS scheduler the differences are not larger than about 5%. We attribute these differences partially to the effects of the real network communication in the case of emulation, and more importantly to the differences between the applications used to generate traffic: ns-3 models for simulation, and iperf for emulation. Thus we conclude that there is a good general agreement between simulation and emulation results.

Experiments done in Figure 4.4, with ping in the same circumstances (results not shown here due to space limitations) show that, as expected, there is a fixed increase in the end-to-end delay when using emulation by about 10 ms. This is due to the fact that application traffic has to pass through several virtual and real network interfaces from sender to receiver, as follows: RTCI and RNCI of the sender SS, RNCI of the BS, then RNCI and RTCI of the receiver SS. We will study possible OS optimizations that would allow us to decrease these OS level delays. Note that, although the experiment

traffic is forwarded over the real testbed network, this delay is only of a few hundreds of microseconds, hence it does not significantly affect the end-to-end delay.

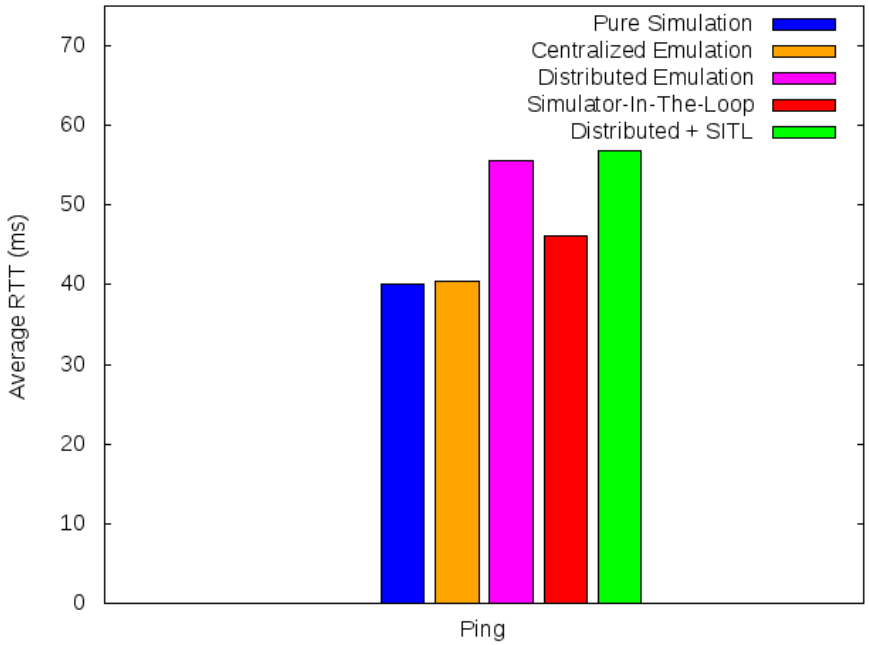

Figure 4.4: Average RTT results with different approaches.

Mobility A second series of experiments investigated a mobility scenario in which one of the SSs moves away from the BS and the other SS with constant speed. Various WiMAX modulations available in ns-3 were used, and throughput was calculated using UDP traffic sent by the mobile SS in the same conditions as those described above. The scheduler used was RTPS Scheduler.

The throughput results are plotted in Figure 4.5 versus the distance between the mobile SS and the BS. Simulation results are shown with continuous line and emulation results with dashed line. For all modulations the maximum throughput values are close to each other, and for several of them (`qam16_12` and `qpsk_14`) the behavior is similar even as the mobile SS moves farther and farther away from the BS.

Given that the capacity-based PHY model implemented in QOMET is different from the one in ns-3, a certain difference in the communication range, as noticed for some modulations (e.g., `qpsk_34` and `qpsk_12`), was expected. Hence, we conclude that for mobility experiments too there is a generally good agreement between simulation and emulation results for all modulations, although differences in communication ranges are observed for some of them.

4.5 Summary

We have presented an emulation framework that uses a hybrid approach in order to allow the evaluation of MAC protocols in realistic conditions. This is achieved by running MAC protocol implementations over a wired network that reproduces PHY level network

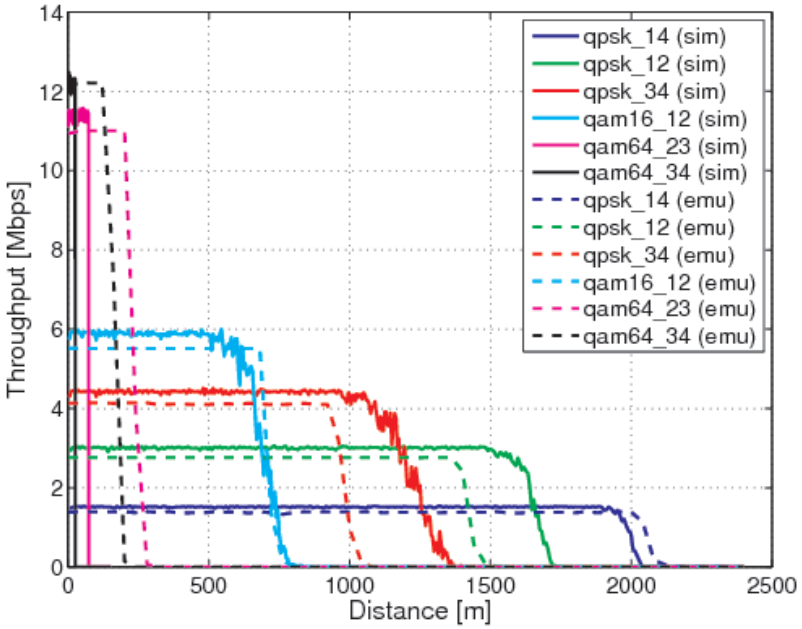

Figure 4.5: Throughput results for mobility experiments with one SS moving away from the BS and the other SS; we used UDP traffic and various modulations.

conditions. The traffic is generated by using real network applications and protocols (Layer 3 and above). To demonstrate the potential of this approach we have used WiMAX as a case study, by modeling the PHY layer of IEEE 802.16e and running on top of it the ns-3 WiMAX MAC layer implementation. Appropriate interface modules were created to make possible sending and receiving real traffic to and from this implementation.

A series of static experiments showed that the emulation framework has good accuracy in terms of throughput compared to simulation, both for UDP and TCP, with differences not exceeding 5% in all the tested cases. In mobile scenarios too comparable results in terms of throughput were obtained for all modulations, although communication range differences were observed for some of them. Our scalability experiments showed that the CPU is a bottleneck for the BS when exceeding a total number of 12 SSs, but the measured throughput had similar trends in simulation and emulation. We believe that this issue can be solved by utilizing more powerful hosts for emulation, and we are currently in the process of evaluating this solution.

The approach that we used when designing our WiMAX emulation framework can be used for ns-3 based LTE emulation with only minor changes, and we plan to add such support in the future in order to enable experiments with this wireless network technology as well.

Chapter 5

Adaptive Transmission System Evaluation over Realistic Platform

In this chapter we present the evaluation of our designed adaptive transmission using emulation platform. We evaluate adaptive system by performing experiments which includes various number of nodes. In this section we also evaluate the performance of OFDM and OFDMA to compare which one is suitable to our system. The QOMET is used for physical layer to produce like real-network conditions. The experimental results show that adaptive mechanism often enhances system capacity than SNR based technique.

5.1 Introduction

To increase the link capacity and maintaining the link budget in faded channel is a topic widely studied and investigated in the recent literature. In [44], a design accounting for the efficient adaptive modulation and coding techniques was presented by showing improvement in terms of overall throughput. This works takes two approaches into account: in first keep the error probability below a specified threshold, in second the modulation and coding selection is based on amount of received packets with errors. While, in [45], the focus is on the impact of jointly AMC and call admission control (CAC) schemes on the QoS in presence of mobility in OFDMA system. Also, the queuing process induced by AMC technique jointly with truncated ARQ protocol is analyzed in [46], based on instantaneous rather than average SNR. The design and analysis of adaptive resource allocation in OFDMA system was also considered in [47], where the collision avoidance mechanism based on a two-dimensional back-off scheme was proposed to emulate the multi-channel and then analyze its saturated throughput.

To overcomes the system efficiency limitation by employing discrete power and adaptive modulation and coding (AMC) techniques, as well as by exploiting the OFDMA transmission system features. First, we implemented an OFDMA transmission system to exploit time, frequency and multi-user diversity, by doing so, communication system improved the efficiency even close to the scheduled access system. Second, we designed an adaptive transmission technique that adapts transmit power, modulation and coding rate in discrete manner, by exploiting the maximum-ratio combining (MRC) diversity in fading environment. Through this technique it is possible to find the switching thresholds, by taking diversity gain into account, to switch the modulation and coding rate, so as to match the channel conditions.

In this chapter, we focus on adaptive transmission and diversity combining techniques that are exploitable in IEEE 802.16e standard [7] due to the use of the slot basis bandwidth and power allocation to each data transmission. Moreover, a suitable model is outlined here to find the optimal switching thresholds and transmit power in order to exploit the diversity combining gain. The novelty of our work consists mainly in the way in which we combined several components, such as OFDMA system, adaptive power and modulation, and evaluation of proposed model using emulation technique in order to make possible realistic experiments with IEEE802.16e networked systems. The main contributions are:

1. The implementation of an OFDMA as digital modulation scheme that utilizes radio resources efficiently, and we analyze the system capacity based on this scheme;

2. The outline of adaptive transmission system that is compliant with the OFDMA standard and improves overall throughput by considering the impact of MRC diversity in conjunction with discrete power and modulation coding rate transmission;

   (a) In this section, we implement a discrete power and rate adaptation policy in adaptive transmission system, which is not very complex concerning link quality calculation in real-time;

3. A comparison of realistic results obtained through emulation, with simulated and theoretical that demonstrate the performance of our designed adaptive system and emulation framework with the power introduction.

5.2 System Model

In this section, we consider a wireless communication link with OFDMA and OFDM systems based on Time Division Duplexing (TDD) between transmitter and receiver. The OFDMA scheme can utilize the channel resources more efficiently than OFDM, where total bandwidth B is divided into N_{subch} narrow-band sub-channels [47]. In a considered communication system, Base Station (BS) allocates channel resources in form of variable number of slots N_{slot}, to different user. Communication occurring among users are independent from each others, because the channel condition of the allotted slots assigned to one user are independent from the channel condition suffered by the slots allocated to another user [44]. Following the channel estimation, the adaptive transmission module at transmitter side updates the transmit power, modulation and coding rate according to received feedback for data user. The processing unit at the MAC layer is a packet that contains N_p bits, while the processing unit at the physical layer is frame consisting of transmitted symbols [46].

Our system model adheres to the following assumptions.

1. In a given wireless communication model, the discrete-time channel oscillates at a much slower degree than the data rate. So, we assume it in our analysis as slowly varying and frequency-flat Rayleigh fading channel, by probity of these assumption, the distribution of received Signal-to-Noise Ratio (SNR) γ is denoted by an exponential distribution [55].

$$f_\gamma(\gamma) = \frac{1}{\overline{\gamma}} e^{-\gamma/\overline{\gamma}}, \tag{5.1}$$

Where $\overline{\gamma}$ is the average received SNR.

2. Rest of the model is similar as defined in theoretically previously.

3. We simply assume throughout in our study, as in [25], the channel state is tracked by transmitter via feedback channel to choose the constellation and power level according to the channel state. The feedback channel is error free and has no latency, could be approximated as fast feedback link with robust error control coding. The discussion on particular techniques to derive channel state is out of topic in this work. However, the interested reader is encouraged to pursue further extensive surveying of the most used approaches in [59].

Accordingly, the proposed model coordinates with power adaptation scheme $P(\cdot)$ to adapt transmit power. Let N denotes the quantization levels of transmission modes available that represent the instantaneous received SNR γ. We divide the range of γ into $N+1$ non-overlapping successive fading regions, with boundaries point denoted by the switching thresholds $\{\gamma_n\}_{n=0}^{N+1}$. Specifically, mode n with spectral efficiency η, is chosen whenever $\gamma \in [\gamma_n,\ \gamma_{n+1}\}$ and within this region, the transmission rate remains constant; yet the adaptive scheme can adapt the transmit power to compensate the fading. To avoid the deep channel fades, data will be buffered when output SNR is in fading regions $\gamma_0\ \leq \gamma < \gamma_1$. For convenience, we suppose $\gamma_0 = 0$ and $\gamma_n = \infty$.

5.3 Adaptive Transmission System Implementation in Emulation Framework

In order to describe the design of OFDMA-based adaptive system, we first discuss the basic implementation of OFDMA air interface and then we describe the policies of adaptive system. Based on that, we present/compare its desirable traits over the OFDM layer.

5.3.1 OFDMA

One of the major advancements of the last decade in the field of wireless communication is the functional endorsement and cost effective implementation of an OFDMA. At the moment, almost all network access technologies including such as Digital Video Broadcasting-Satellite Version 2 (DVB-S2) [43], Mobile WiMAX [7] and LTE [8], use OFDMA. Hence, it is most important to understand the operations of OFDMA for performance modeling of IEEE 802.16e. Therefore, in this chapter we briefly outline the features that lead us formulate the terms which are used in our analytical modeling. The reader is encouraged to pursue further study on [19]-[54].

Basic Performance and Configuration Parameters

The power and modulation with coding rate are adapted on a frame basis. Mobile WiMAX permits not only Frequency Division Duplex (FDD) but also Time Division Duplex (TDD), where a frame is partitioned into downlink (DL) subframe and uplink (UL) subframe and are separated by a Transmit to Transmit Gap (TTG) and Receive to

Transmit Gap (RTG). In our analysis, We assume a frame duration N_f 10 ms and channel bandwidth 10 MHz, which can be vary from 1.25 MHz to 28 MHz according to the Scalable OFDMA concept, is divided into 1024 subcarriers N_{FFT} (grouped into different subchannels) and one or more slots N_{slot} are allocated to user in a frame. A *slot* composes of one subchannel N_{subch} and for a specified number of OFDM symbols N_{sym}. In addition, the exact composition of a slot depends upon the subchannelization methods and on the direction of transmission: DL Partially Used SubChannelization (PUSC) makes a N_{slot} up of 1x2 and UL PUSC forms of 1x3 subchannel-symbols. Hence, the number of slots[1] S_f^x in a subframe are as in [60].

$$S_f^x = N_{subch}^x \cdot \left\lfloor \frac{N_{sym}^x}{N_{sym}} \right\rfloor, \tag{5.2}$$

In OFDMA, the throughput depletion caused by overhead could be significant. Therefore, in this analysis we categorize the overhead T_{oh} in upper and lower layers overheads. *Upper layer overhead* characterizes the application workload including the type of transport layer used. In this analysis, we consider the User Datagram Protocol (UDP) over Internet Protocol (IP) traffic, which produces per packet overhead (8+20) bytes. The second category of overheads is *lower layer overhead* which composed of MAC and PHY layers overhead. The basic unit at MAC layer is a MAC protocol data unit (MPDU) which included at least 6-bytes MAC header and variable length of payload [19]. Each payload section carries application data, number of optional subheaders (2-bytes each) and an optional 4-bytes Cyclic Redundancy Check (CRC).

The PHY overhead is further divided into downlink and uplink overhead. The overhead in DL subframe S_f^x comprises of preamble, Frame Control Header (FCH) S_{FCH}^{DL}, DL-MAP S_{MAP}^{DL} and UL-MAP S_{MAP}^{UL}. Substantially, the MAP entries can contribute significantly in overhead. Since, the fixed part of DL_MAP and UL_MAP is 11 and 6 bytes long, and in variable part one entry per burst is required, so it consists 60 and 52 bits per entry respectively. Similarly, UL subframe also begins with preamble and has fixed and variable parts. Ranging, contention, Channel Quality Indication (CQI) and Acknowledgments (ACKs) are in fix portion allocated and their size depends on system configurations.

To maintain the highly reliability these are transmitted with the greatest robust MCS (QPSK 1/2) and repeated 4 times. Hence, the available data slots in a DL subframe S_f^{DL} are calculated after subtracting them. This is significant and can severely reduce the capacity of any wireless system [7] [19].

$$\begin{aligned} N_{user}^{DL} = & \left\lceil \frac{B_{MAP}^{UL} \times DIE + CRC}{B_{slot}} \right\rceil \times r \\ & + \left\lceil \frac{B_{MAP}^{UL} \times UIE + CRC}{B_{slot}^n} \right\rceil \times r \\ & + \left\lceil \frac{D}{B_{slot}^n} \right\rceil \end{aligned} \tag{5.3}$$

$$N_{user}^{UL} = \left\lceil \frac{D_{bytes}}{B_{slot}} \right\rceil \tag{5.4}$$

[1]This equation S_f^x is valid for both S_f^{DL} in downlink and S_f^{UL} in uplink.

Where, D_{bytes} is a application data with MAC header and subheader overheads and r is a repetition factor for management traffic . The total Number of users supported in downlink N_{user}^{DL} and uplink N_{user}^{UL} are calculated as function of nth modulation and coding scheme.

5.3.2 Modification in Emulation Framework for Adaptive Transmission System

As mentioned above, various modulation and coding rate schemes are achievable in 802.16e systems, each with different spectral efficiency. Unlike many of the former studies with emphasis on maximizing spectral efficiency of adaptive transmission under constant power constraints while maintaining target BER [36] and different power levels [37], our aim here is to design of adaptive transmission system exploiting the PHY layer features under MRC diversity combining and target BER_T, considering that the modulation size and coding rate and transmitting power of a slot could be adapted according to the channel state information (CSI). This mode of resource assignment is possible in 802.16e OFDMA systems by using the diversity combining techniques.

Discrete Power and Rate Adaptation (DPRA)

By selecting the adaptive transmission policies, now we are ready to determine the discrete modulation rate and corresponding power levels which fluctuate according to time-variations of the channel. The transmitter compensates/reciprocates to channel fluctuations by adjusting the constellation size $M(\gamma)$ and the transmission power $P(\gamma)$ relative to diversity combining and BER_T. At the receiver, the received SNR becomes $\gamma\frac{P(\gamma)}{P}$, thus the approximation of instantaneous P_b can be approximated.

5.4 Experimental Results

In this section, we resort to network simulation and emulation to verify the performance of the adaptive system described in section 4. In particular, we use emulation framework to verify the characteristics of adaptive transmission system in realistic environment, and compare its performance with SNR based scheme which uses fixed switching thresholds. To proceed further, first we present brief detail of our approach for making possible MAC and PHY layers protocol evaluation through network emulation. To demonstrate the feasibility of this approach, we implemented the corresponding experiment framework using WiMAX as a case study, for further detail please see [64] [65].

5.4.1 Experimental Framework

Our framework is built on top of the large-scale network testbed StarBED [67], and extends the wireless network emulation tool-set QOMET [66], which are both developed and managed by the Hokuriku StarBED Technology Center of the National Institute of Information and Communications Technology (NICT) in Ishikawa, Japan. For detail, readers are encouraged to study the chapter 4.

5.4.2 Results and Discussion

The results presented here focus mainly on demonstrating the ability of emulation platform, and furthermore the designed adaptive system evaluation in simulation and emulation is also presented. The simulation experiments were done using ns-3.18. The emulation experiments were carried out on StarBED, with each emulated node running on a different physical host with dual-core Pentium 4, 3.2 GHz CPU and 8 GB RAM.

DPRA Evaluation

First, the implementation of described scheme, discrete power and rate of designed adaptive system, is tested and compared to the analytical scheme and to the adaptive SNR scheme (adaptive SNR is derived based on defined thresholds in [7]). Seven different modulation and coding rates ($N = 7$) are used for communication and a maximum $BER_T = 10^{-3}$ is assumed in the whole experimental scenario.

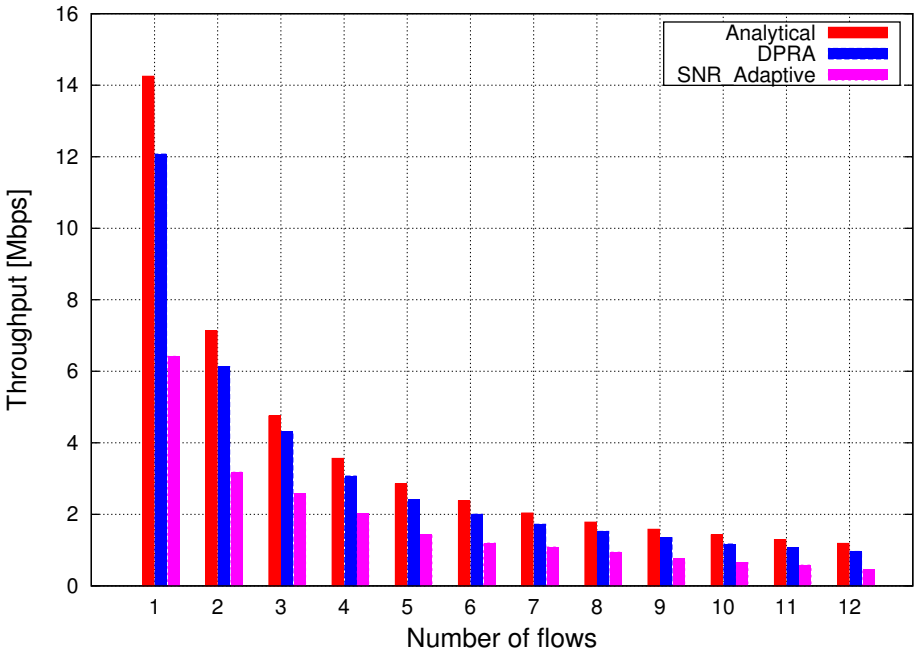

Figure 5.1: Throughput comparison for DPRA.

Figure 5.4.2 shows the performance of analytical, DPRA, and adaptive SNR schemes in terms of aggregate throughput. As it can be seen there are essentially not much difference between analytical and DPRA schemes in all experiments scenario. Specifically, limiting our adaptive scheme to just seven modulations and power levels results in a aggregate throughput that is 15% less than the throughput yielded by analytical scheme, which indicates the remarkable impact of accurately calculated modulation switching thresholds. In order to show the effectiveness of this technique the results are compared with SRN adaptive scheme, and it is straightforward to note that it has worse performance as compared to adaptive one. This is mainly due to the fact that predefined switching thresholds lead to wrong modulation selection. In particular, this allows the high bandwidth efficient modulations selection at the expense of a higher bit error rate at the receiving ends.

Thus we conclude that there is a good general agreement between adaptive scheme and analytical results.

Furthermore, experiments done, in the same circumstances under the light of proposed adaptive system, to show the effectiveness of developed emulation framework. Figure 5.4.2 illustrates the cumulative distribution function (CDF) of throughput, as expected, emulation framework yields realistic throughput in the right magnitude. Regarding the throughput obtained using simulation is slightly better than the measured in emulation framework. We attribute these differences partially to the effects of the real network communication in the case of emulation, and more importantly to the differences between logical and real world clock.

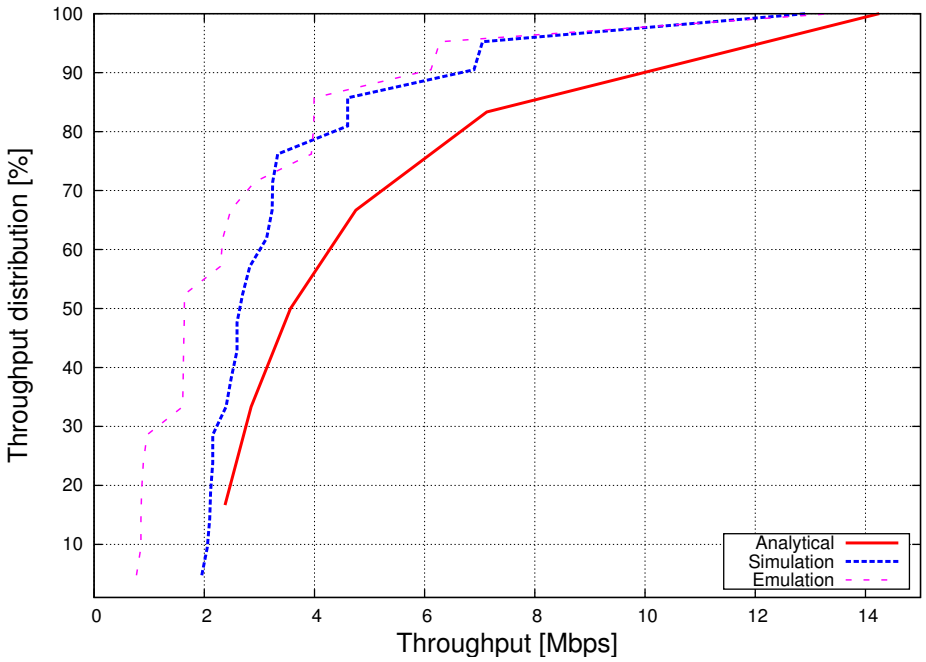

Figure 5.2: CDF of throughput for simulation and emulation.

We now investigate the packet delay behavior in our emulation framework. As depicted in Figure 5.4.2, the observed application end-to-end delay is almost the same in simulation and the emulation systems, since the number of flows are less. One thing to note, as the number of active flows increased in emulation system, end-to-end delay jumps from 50% percent to almost twofold. This is due to the fact that application traffic has to pass through real network interfaces from sender to receiver, as follows: RTCI and RNCI of the sender SS, RNCI of the BS, then RNCI and RTCI of the receiver SS. Hence, in the whole system BS becomes bone of contention due to centralized nature, it significantly affects the end-to-end delay. We will study possible OS (operating system) optimizations that would allow us to decrease these OS level delays.

Performance Evaluation

In the next set of experiments, we evaluate the computational capacity in term of CPU and memory overhead introduced by the implemented emulation and simulation frameworks. We instantiate this set of experiments with same circumstances in simulation

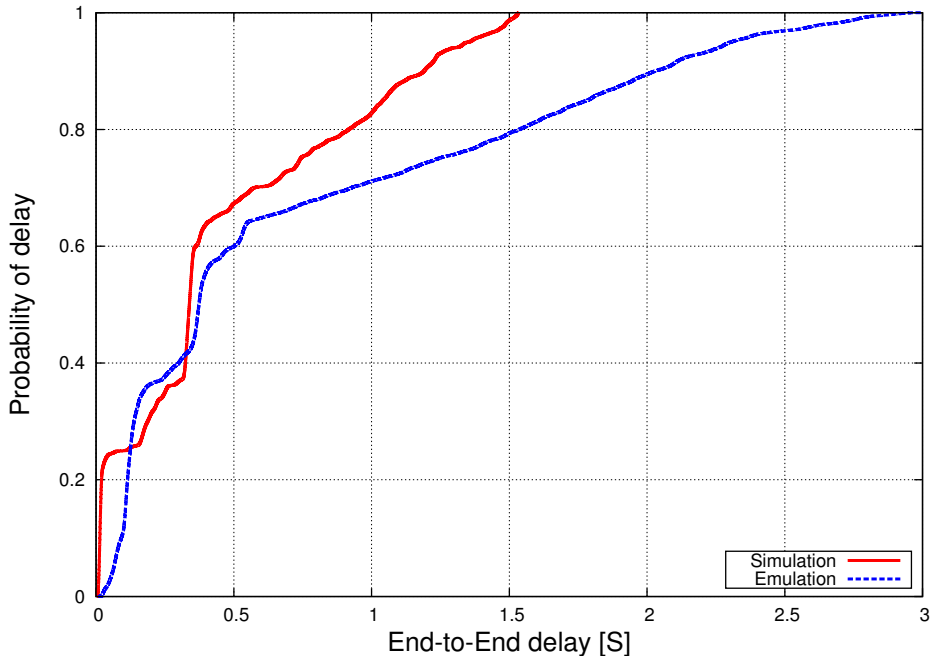

Figure 5.3: Application end-to-end delay for simulation and emulation.

and emulation to illustrate their relative CPU and system time efficiency. Figure 5.4.2 describes, the CPU utilization increases linearly, as the application traffic and number of flows increased. With a larger number of flows, the CPU utilization in simulation, is almost 50% of time. Unsurprisingly, the emulation, over 90% of time, consumes CPU resources between 100% and 120%, and only 5% of time CPU utilization reaches 200% and the system becomes unstable.

Likewise, Figure 5.4.2 compares the system time usage in both simulation and emulation environments: the simulation has approximately same system usage time in different scenarios. Moreover, in emulation framework the time usage increases as the number of flows increased. This is due the fact of real communication interfaces used and CPU has to spent time in executing simulated code and system kernel code respectively. Note that, in emulation experiments both observations, CPU utilization and system time, confirm the above stated claim of the end-to-end delay. Although, the experiment traffic is forwarded over the real-time emulation network, this delay, per packet level, is only of a few hundreds of microseconds, hence it does not significantly affect the end-to-end delay.

5.4.3 Scalability Evaluation

Finally we did, to make sure the claim which is based on OFDMA in [54], considerable scalability experiments to see how our framework performs in scenarios with a larger number of nodes/flows. We used the same application traffic and other configuration parameters in both environments.

After evaluating various scenarios, as shown in Figure 5.4.3 that OFDMA supports extra scalability in terms of throughput as a function of number of flows, as compared to OFDM in both simulation and emulation. We notice that the magnitude of received throughput show similar trends in OFDMA and OFDM, albeit with lower performance in

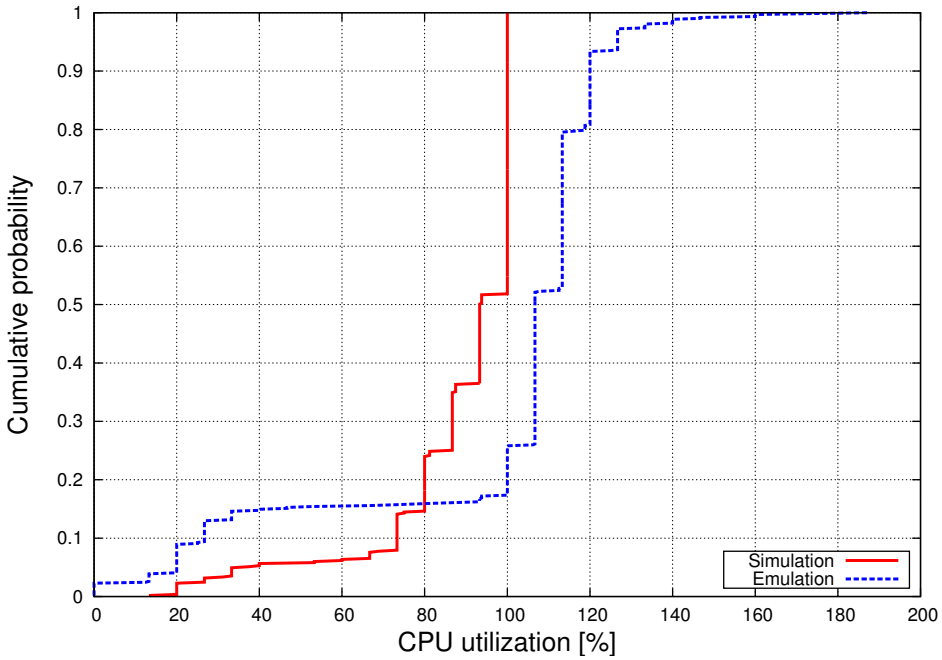

Figure 5.4: CPU utilization of simulation and emulation.

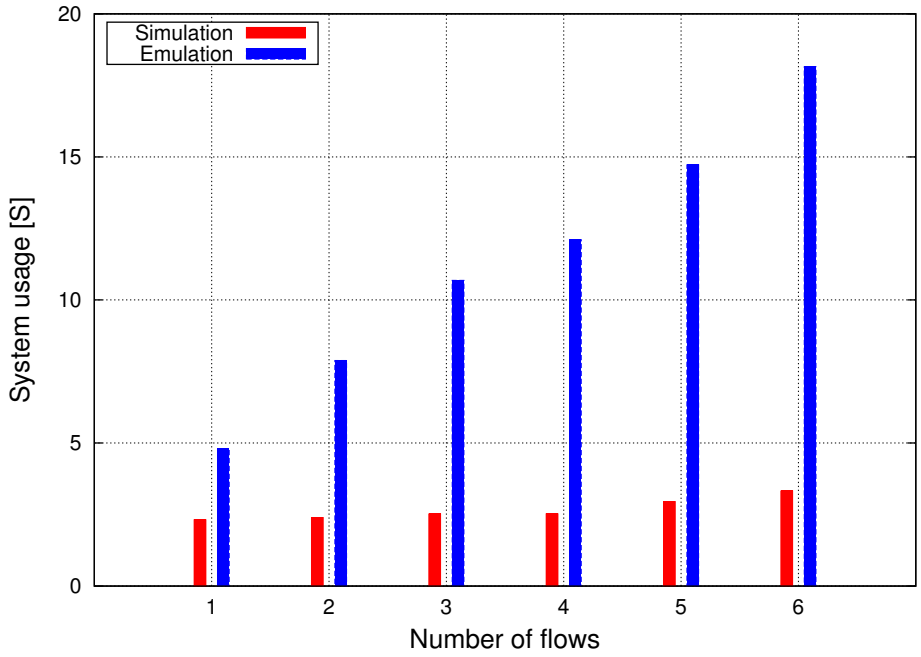

Figure 5.5: System usage time in simulation and emulation.

the case of OFDM. Note that scalability in OFDMA is precisely due to its flexible nature and efficient channel utilization. Hence, we assume this difference, of about 10% at most, to be acceptable for some scenarios.

We also observed that with the used testbed PCs the maximum number of users/SSs we can have in an emulation experiment is 32. With a larger number of users, the CPU

utilization of the BS exceeds 80% and the system becomes unstable. One solution is to move at least the BS, which represents the bottleneck of the system since it handles the traffic of all the SSs, to a more powerful machine. Various optimization techniques could also potentially be applied.

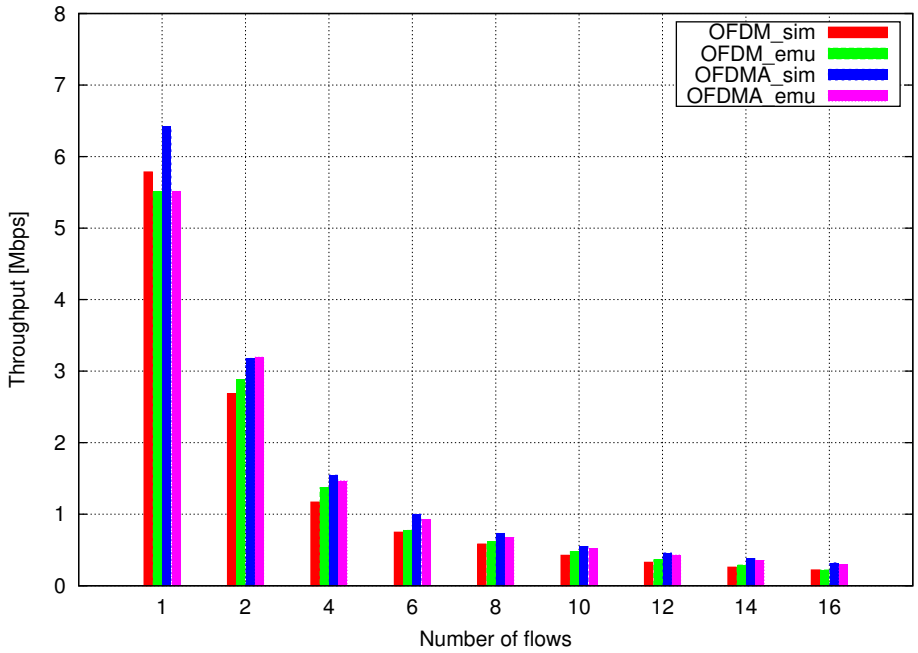

Figure 5.6: Throughput results for scalability experiments with 32 SSs.

5.5 Summary

In this chapter, we have presented the design of an adaptive system that maximizes the user throughput by adapting transmit power and modulation according to channels condition. To demonstrate the potential of hybrid approach we have integrated the adaptive transmission system at MAC layer into emulation framework to optimize its accuracy in realistic conditions, by modeling the PHY layer of IEEE802.16e and running on top of it the ns-3 WiMAX MAC layer implementation. We have also implemented an SNR based modulating adaptive scheme as described in [6, 7], to validate and compared the accurate selection of threshold boundaries for an adaptive system.

A series of experiments showed that the adaptive system has good accuracy in terms of throughput compared to analytical, with differences not exceeding 12% in all tested cases. Later, comparable results in terms of throughput, delay and computational evaluation were obtained for emulation and simulation framework, although disparities in delay were observed for some of them. But overall reasonable agreement exists between the results obtained through emulation and the results obtained through simulation. Our scalability experiments encouraged the use of OFDMA base PHY layer especially in mobile environment, while analyzed that the CPU in emulation platform is a bottleneck for the BS when exceeding a total number of 32 SSs, but the measured throughput had similar trends in simulation and emulation.

Chapter 6

Conclusion & Future Work

This chapter concludes our work by showing the contributions of this dissertation in the first section, as well as opening up the possible future work in the second section.

6.1 Conclusion

The main aim of this work is, to overcome the system efficiency limitation, therefor we proposed the adaptive system which leverages by employing optimal power and adaptive modulation and coding (AMC) techniques, as well as by exploiting the OFDMA system features. First, we implement OFDMA system to exploit time, frequency and multi-user diversity, while communication system improve the efficiency even close to the scheduled access system. Second, we propose new adaptive transmission technique that adapts optimal power, modulation and coding with continuous power and discrete rate by exploiting the maximum-ratio combining (MRC) diversity order in fading environment. Through this technique it is possible to find the switching threshold by taking diversity gain into account and to switch the the modulation and coding rate, so that match the channel conditions. The results we obtained from experiments using proposed adaptive system, once more, confirm our claims about the efficiency of proposed system.

To contribute practically, we developed emulation system that combines some of the advantages of real-world testbeds such as the use of real network applications and protocols, with those of simulation environments, such as good condition control, repeatability and propagation environment. In contrast to other approaches this enables seamlessly integrating emulation realm with physical world. By making use of the open-source ns-3 simulation framework, we emulation framework based on WiMAX entities, protocols and procedures. Our approach provides the means of transferring real application data on real network between ns-3 simulation entities, and allows physical hosts to connect with the simulated WiMAX network. Thus, the proposed system offers realism and accuracy similar to that of hardware with the cost, configurability and scalability of simulation. To show the feasibility of our design, we include several validation experiments, including using real application data in the emulated environment. Through this system we ease the prototyping of technology that will bring us closer to the realization of the present and future mobile Internet.

Based on the above developed framework, we proceeded to develop hybrid design in QOMET, in which PHY layer is represented by a probabilistic model, whereas the MAC layer is executed as a functional module. Actual network applications and protocols are

employed in order to create realistic test conditions. A standard-based model for the WiMAX PHY was developed, and it was integrated with the WiMAX MAC implementation in ns-3 to make WiMAX performance evaluation through emulation possible. Several experimental results, both in static and mobile scenarios, demonstrate the validity of the framework and indicate some of its potential uses.

In the end, we summarize the contributions of this thesis as follows:

- The implementation of an OFDMA as digital modulation scheme that utilizes radio resources efficiently, and we analyze the system capacity based on this scheme;
- The outline of adaptive transmission system that is compliant with the OFDMA standard and improves overall throughput by considering the impact of MRC diversity in conjunction with discrete power and modulation coding rate transmission;
- A framework is designed by making use of the open-source ns-3 simulator, our approach provides the means of transferring real application data on real network using following two designed interfaces;
  - One was the Real Traffic Communication Interface (RTCI), which allows passing real application and protocol traffic between the OS and the WiMAX module.
  - The other one was the Real Network Communication Interface (RNCI), which allows passing traffic between the WiMAX module and the Ethernet NIC so that it can reach other nodes, thus enabling distributed execution.
- An IEEE 802.16e standard-based mobile WiMAX PHY model that was implemented in QOMET;
- The integration of the above PHY model with an ns-3 based WiMAX MAC module that was previously developed on StarBED, thus providing full WiMAX emulation functionality;
- A series of experimental results that validate the correct operation of the network emulation framework and proposed adaptive system, and that demonstrate its practicality.

6.2 Future Work

6.2.1 Improving Adaptive Transmission System

The value of switching thresholds plays an important role in designed adaptive system. The current implementation for switching thresh-holds determines the fading regions through the value of Bit Error rate, which is directly measured based on receptions of channel feed-backs. Several studies have revealed that channels response in broadcast and unicast are different [3, 79]. The authors emphasize that channel measurement through uplink pilots could affect the performance of downlink network. The accuracy of estimating link quality depends on the number of pilot tones allocated to each user. Usually, allocation of large number of pilot tones to user leads to notable latency in the downlink

communication. On the other hand, the network performance depends on the design of pre-coding techniques as well as the number of transmitting antennas. Thus, the performance of adaptive framework is specific to channel quality. Nevertheless, traditional adaptive approaches are not directly applicable in advanced communication systems.

One approach to improve the adaptive transmission system is to quantify the channels measurement (inter and intra-cell cell interference) based on advanced statistics modeling. However, this approach, in advanced communication system such as advanced-LTE, mobile WiMAX or even 5G networks, due to latency sensitive applications does not allow us to measure the channel with very detail. Another approach is to quantify the traffic data and adaptive system should prioritize the wireless and system resources according to application data.

Recently, cross-layer adaptive approaches have been proposed to optimize the system-level performance by passing the information between layers. With spectral efficient communications, the adaptive system should be able to capture the system-level parameters through cross-layer approach that have trade-off nature between system efficiency and power efficiency. Based on this kind of flexibility, it will be interesting to how the adaptive transmission system can adapt to dynamic channel responses and traffic patterns to avoid in reducing the worst-case system performance.

6.2.2 Improving Emulation framework

At the moment, even though the evaluation of wireless network show that designed emulation framework can effectively emulate WiMAX network. While this work has provided solutions that make this platform viable, there are many open research issues to pursue. Hence, further detailed investigations are required to explore the promising directions of emulation platform more thoroughly under different scenarios.

The clearest open research issue is that of extending emulator support for others MIMO based technologies such as advanced-LTE. Particularly, implementation of massive MIMO network which is being considered a primary application of future 5G networks, should provide reformed emulation framework at greater scale; extending the emulation framework for these kind of networks is a high priority.

Moreover, infrastructure densification, increased number of users with diverse traffic demands, will be the prior aspect of future communication networks. In addition, heterogeneous networks, composed of moving networks and ad-hoc social networks, make the propagation channels more dynamic. Yet, dense and dynamic network could pose serious challenges in terms of wireless link quality (interference and mobility). Hence, going with the development of QOMET as link wireless link emulator which emulates the WiMAX propagation environment in realistic manner, should also provide support of others technologies such as propagation or channel modeling of milli-meter wave radio, massive MIMO, dynamic or heterogeneous networks etc..

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