CHAPTER 1

Introduction

1.1 Introduction

Recently there has been a tremendous growth witnessed in the use of *Internet access* and other broadband services over multiple access networks such as wireless local area networks (WLANs) [1], [2], and cellular networks. With the advances in WLAN technologies, affordability and large bandwidth availability, WLANs are increasingly applied in home and office environments (in fixed wireless mode) over up to a few hundreds of meters for Internet access. On the other hand cellular networks are suitable for mobile users, because of a wider coverage than WLANs and mobility support for Internet access. However, the 2.5G and 3G cellular systems which are primarily designed for low data transmission and voice connectivity are not well suited for extensive Internet access due to high communication cost and narrow bandwidth. To overcome the drawbacks of cellular networks in providing Internet access the IEEE has brought out the standard 802.16x. This standard allows data rates up to 134 Mbps in a fixed mode in the frequency range of 10 - 66 GHz and up to 70 Mbps in mobile environments in the frequency range of 2 - 6 GHz. This access technology is a wireless option to provide a

cost-effective solution to broadband Internet access which can be deployed quickly and with ease.

Capability to provide wireless broadband access to different subscribers ranging from individual to small business groups is one of the important objectives of the present and next generation access networks. There are different types of access networks in use while some of them are stand-alone systems, and others are in hybrid form between different technologies. The hybrid access networks include wireless and wired technologies such as WiFi and ADSL and also a hybrid wired technologies such as Ethernet and ADSL. At present, broadband wireless access (BWA) through WiFi networks connected wirelessly to the wired networks through the IEEE 802.16x wireless metropolitan network (WMAN) is a viable access solution which is likely to gain wide popularity. High speed downlink packet access (HSDPA), high speed uplink packet access (HSUPA), high speed OFDM packet access (HSOPA), and the IEEE 802.20 mobile broadband wireless access (MBWA) are the enhancements of existing technologies aimed at providing BWA to a mobile subscriber and they can be used as alternative solutions. The next generation equivalents of these protocols are also expected to provide high speed BWA wirelessly to a mobile or stationary subscriber. The corresponding subscriber units are aimed at providing wireless access to individual or small or medium scale enterprise subscriber units. The IEEE 802.16m is a 4^{th} generation evolution of the WiMAX 802.16d/e standard, while the Long Term Evolution-Advanced (LTE-A) is the evolution of the 3GPP standard. The subscriber units in such solutions may be providing wireless Internet access to a number of individual systems like WLANs and thus are likely to cater to an aggregated traffic.

The medium access control (MAC) protocol of a network moderates the access to the medium by defining certain rules that allow the users to communicate with each other in an efficient manner and thus plays a vital role in the access performance. With increasing use of multimedia services, MAC protocols of wireless networks are required to satisfy a variety of quality of service (QoS) requirements. MAC protocols play a vital

role also in the efficient and fair sharing of the network bandwidth amongst the different users and services.

In view of the above discussion, several questions arise and it is of interest to explore the following:

a. Performance of the backbone WMAN system in the IEEE 802.11x and 802.16x hybrid wireless access scenario.

b. Enhancements that can be made to the MAC protocols of the IEEE 802.11x WiFi and 802.16x WiMAX protocols to improve the performance.

Therefore, in this thesis, the appropriate investigative studies on IEEE 802.11x and 802.16x protocols have been considered. In this study a hybrid access network involving WiFi in final access and WiMAX or 4G cellular network provides the WLAN with wireless connectivity to a wired network for broadband access will also be considered.

1.2 State-of-the-Art in Wireless Medium Access Control

1.2.1 The IEEE 802.11x WLAN

In recent years there has been a vast development taken place in wireless access networks like WLAN and WMAN. The IEEE brought out the standard 802.11 and its variants [1] - [6] which define the medium access and physical layer characteristics of WLANs. The performance of IEEE 802.11 MAC protocol is based on carrier sense multiple access with collision avoidance (CSMA/CA) random access scheme.

There have been many performance studies on the IEEE 802.11 distributed coordination function (DCF) [7], [8], [9], [10], [16], and [17]. Bianchi [7] introduced a simple and accurate 2-dimensional Markov model to study the IEEE 802.11x DCF under saturated traffic conditions. That is, a station always has a packet for transmission. The analytical model [7] has become a popular means to study the MAC protocol performance of WLANs. Later on, this model has been refined to include further details

of the IEEE 802.11 Protocol operations. Among the refinements, one is due to Ziouva et al., [17] aiming to capture the freezing of backoff counters when the broadcast channel is sensed busy by a station. Existing work on the performance of the IEEE 802.11 MAC has focused primarily on its throughput and capacity under saturated traffic conditions using 2-dimensional Markov chain, mean value and fixed point analysis [10], [16], [20], [22], and [23]. Chhaya and Gupta [10] specifically considered the possibility of capture and the throughput performance of IEEE 802.11x MAC protocol. In most of the studies it is assumed that the channel is lossless. The saturation throughput of IEEE 802.11 for a lossy channel is presented in [13]. The models [14], [15], and [16] have assumed a finite population and a single unit of packet buffer at each station. Tay and Chua [21] presented closed form expressions for the probability of a collision, the saturation throughput and they also provide guidelines on when and how the minimum backoff window size can be adjusted to suite the measured traffic.

The throughput and packet delay performance of IEEE 802.11 network studied in [15] is based on renewal theory. Another approach called a single station superposition technique with discrete time Markov analysis is presented in [24] to investigate normalized throughput and packet delay as a function of number of transmission retries. The effect of changing the arrival rates and the number of users on the performance is also investigated. Cali et al., [8], and J.Weinmiller et al., [12] presented an adaptive backoff mechanism to enhance the performance of IEEE 802.11x WLAN. Cali et al., [9] also proposed a backoff algorithm for p-persistent protocols, where the backoff intervals are sampled from a geometric distribution with parameter p. The IEEE 802.11x exponential backoff wastes channel bandwidth on collision in highly loaded networks.

Two categories of overhead are usually associated with contention resolution process. One is channel overhead, where all contending stations are waiting to transmit. Another is collision overhead, which occurs when multiple contending stations attempt to transmit simultaneously. A pipelined dual-stage contention resolution MAC protocol (DSCR) to reduce the channel idle and collision overhead is proposed in [11]. A fast

resolution (FCR) algorithm [25] is proposed to improve the performance compared to legacy 802.11. This algorithm provides high throughput and low latency while improving the fairness performance. An analytic model for evaluating the queueing delays and channel access times at nodes in wireless networks using the IEEE 802.11 DCF is provided in [23]. The throughput analysis of IEEE 802.11 protocol at the MAC layer in unsaturated conditions taking into account the impact of both transmission channel and capture effects in a Rayleigh fading environments with infinite transmission retries is discussed in [27].

The basic DCF access mechanism of IEEE 802.11x MAC (802.11, 802.11b, 802.11a, and 802.11g) does not provide priorities and service differentiation mechanism to guarantee a faster access to some services at stations. Due to a significant demand for the transmission of delay sensitive streams like voice and video over IEEE 802.11, the IEEE 802.11 task group proposed a standard 802.11e [6], by introducing a QoS aware new mechanisms in the MAC protocol with service differentiation capability. The IEEE 802.11e is considered as an extension of the legacy IEEE 802.11 MAC protocol, with a new hybrid coordination function (HCF). The performance analysis of of IEEE 802.11e MAC is reported in [28] - [39]. There are certain scheduling algorithms presented in the existing literature to support QoS in the IEEE 802.11e [40] -[42].

1.2.2 The IEEE 802.16x WMAN

The wireless hotspots using the IEEE 802.11e wireless LANs have been increasingly providing different data services to Internet users. Because of its less coverage area and due to moderate data rates, a WLAN is mainly used for indoor applications. Traditionally, WLAN hotspots are connected to the Internet through a wired network infrastructure. However, such a wired network may not be available in remote areas. Also it may not be convenient always to provide a wired access to these access points. In order to provide the users with high data rates over a large coverage area, and to cater to broadband wireless access needs, the IEEE has brought out the standard 802.16

and its enhanced versions [43]-[46]. The IEEE 802.16 can also be used to connect the hotspots to the wired Internet.

In [47], the authors have discussed about the technologies and potential market applications, and an architecture for BWA networks. Helmut Boleskei et al., provided an overview of fixed broadband wireless access technology in general in [48]. The BWA service itself, the deployment scenarios and architectural requirements are described in this paper. The MAC alternatives that can find application in local multipoint communication system (LMCS)/ local multipoint distribution system (LMDS) network are capable of supporting multimedia traffic and are focused in [49]. The three protocols; IEEE 802.14, HFC and DOCSIS are examined and compared in terms of mean access delay, the throughput and collision multiplicity statistics. The medium access control and physical layer features of the IEEE 802.16 standard are reviewed in [50]. Many scheduling and admission control schemes have been put forward in the literature to support QoS in the IEEE 802.16x standard. To support all services in the IEEE 802.16, a packet scheduling mechanism which uses a combination of strict priority, early deadline first (EDF), and weighted fair queue (WFQ) is proposed in [52]. In this model, a scheduling scheme based on grant per connection (GPC) mode is used. In GPC mode, the bandwidth is granted to a connection individually. Since the BS need to keep track of all allocations for connections, the complexity involved in scheduling at the BS would increase as the number connections increases. H.Wang et al., [53] proposed a dynamic admission control scheme for scheduling service flows in the IEEE 802.16 to maximize the bandwidth utilization. A reservation based call admission control (CAC) scheme is proposed in [54] which significantly lower the connection block probabilities for higher priority services. An adaptive bandwidth allocation and admission control mechanism based on game theory for the IEEE 802.16 broadband wireless networks is introduced in [55]. Niyato et al., [56] proposed an adaptive queue-aware uplink bandwidth allocation and rate control schemes at an SS for the polling service in the IEEE 802.16 BWA networks.

A pipeline approach which is based on the half-duplex allocation (HDA) algorithm is proposed in [57]. This pipeline approach is used to grant bandwidth at the base station (BS) of an IEEE 802.16 frequency division duplex (FDD) network with half-duplex subscriber stations (SS's). Claudio et al., [58] investigated the effectiveness of real time polling service(rtPS), non-real time polling service (nrtPS), and best-effort (BE) service in managing traffic generated by data and multimedia sources. The performance is assessed with FDD and full-duplex SSs. Dusit et al., [59] introduced a non-cooperative game theoretic approach to optimize the joint bandwidth allocation and connection admission control framework for the IEEE 802.16-based BWA networks. An efficient uplink scheduling algorithm for Voice over Internet protocol (VoIP) services in the IEEE 802.16 BWA systems is presented in [60]. A dynamic bandwidth request mechanism for VBR real time traffic is proposed in [61]. An efficient and simple flexible resource allocation and packet scheduling algorithm for nrtPS traffic is presented in [62]. The cross-layer design for resource allocation procedure is introduced in [63]. An optimization-based formulation for scheduling and resource allocation in the uplink OFDM access network is presented in [64].

There are many studies made on the performance of IEEE 802.16 MAC protocol for BE traffic. There is no QoS constraint applied to this service and it is delay-tolerant. In [69] - [71] the performance of random access in IEEE 802.16 is analyzed. Although an attempt to analyze the bandwidth request scheme was made in [72], the binary exponential backoff process not modeled in their work. An analytical model for the contention based bandwidth request scheme for the IEEE 802.16 network is proposed in [73]. The bandwidth efficiency and channel access delay of the IEEE 802.16 network are obtained as a function of number of active SS's in the network. This model uses a binary exponential backoff algorithm to reduce the probability of request collision. It is assumed that each SS always has a packet for transmission and an SS sent one request per data packet. In [74], a request piggyback (RPB) scheme is proposed and its performance is obtained under unsaturated traffic conditions. Here, the backoff value is taken in terms of frames, and the waiting time spent after sending a bandwidth request

is not considered.

Existing work on the performance of IEEE 802.16d/e random access protocol is presented in [75] - [78]. The performance of IEEE 802.16d random access protocol is investigated using equilibrium point analysis in [75]. The queueing performance of IEEE 802.16d random access protocol for sporadic data transmission with a binary exponential backoff algorithm is analysed in [76]. The queueing performance of an SS for IEEE 802.16e random access protocol with piggyback operation and an automatic request (ARQ) is presented in [78].

There are several scheduling and admission control schemes [79] - [87] have been reported in the existing literature to support QoS in the IEEE 802.16e networks. Some of the recent investigative studies have shown that the model of Internet traffic is different from the conventional Poisson traffic [89] - [91]. It is shown that the actual network traffic characteristics in access networks like Ethernet exhibits the property of self-similarity, which has a deteriorating effect on the network performance. However, there are no proper performance studies reported for hybrid WiFi - WiMAX networks with enhancements in place.

1.3 Motivation for the Thesis Work

In view of the importance of MAC protocols in multiple access networks and since the actual performance of the networks depends sensitively on them, a study of MAC layer protocols of a hybrid access network involving the IEEE 802.11x in the final access network interconnected to the wired infrastructure through the IEEE 802.16x backbone, is taken up as the main objective of the present research work.

Much of the research work on the performance of the IEEE 802.11x and 802.16 MAC protocols was focused on the behaviour of networks under saturated traffic conditions where each station always has a packet to send. But, the networks do not typically operate in saturated traffic conditions and the performance analysis is thus too restrictive

and not applicable in general. The performance of IEEE 802.11x WLAN is highly sensitive to the initial backoff window size, payload size, propagation delay and the number of stations in the network. Studies on these issues are not available in the literature and it encourages us to investigate these issues under varying network load with finite transmission retry limits to enhance the performance. This will also give the vital relationship between the performance and the protocol parameters of the network which is very important for network design and configuration for its operation at the improved performance.

According to the IEEE 802.11x MAC layer protocol, after each collision the channel must remain idle for an interval equal to the distributed interframe space (DIFS). As the number of collisions increases, the DIFS overhead would also increase. To reduce the DIFS overhead, and improve the performance, a goal set to examine and improve the existing backoff algorithm.

This thesis also proposes certain performance enhancement schemes to the standard IEEE 802.16 WMAN. In the downlink direction, scheduling of the traffic is relatively simple because the BS knows the exact status of its queues and their QoS requirements before transmission. However, due to the scarcity of the upstream bandwidth and to contain the scheduling complexity which in turn is due to the distributed need, it has become important to obtain the minislot allocation algorithm in such a way that it uses the bandwidth efficiently. The standard, however, did not specify any algorithm for this purpose. Hence, it has motivated to make an attempt to carry out the study and improve the uplink performance of IEEE 802.16 MAC protocol for VoIP, Video, FTP, and HTTP traffic models.

The aggregated traffic at the SS arriving from individual systems like Ethernet, WLAN, or any other access network exhibits the property of *self-similarity*, which is significantly different from the Poisson traffic model. This motivated to investigate the impact of the aggregated traffic model on the performance of IEEE 802.16 WMAN. The usefulness of actual hybrid access network comprising of the IEEE 802.11x and 802.16x

motivated to take up the case to study the overall performance of hybrid network in terms of uplink utilization of IEEE 802.16 WMAN and the end-to-end delay as a function of network load originating at the IEEE 802.11e WLAN with the enhancements in place.

1.4 Objectives of the Thesis Work

Based on the literature survey and motivated by the factors mentioned in the previous section, we formally state the problems undertaken in the thesis work as follows:

- Study the performance and optimize the parameters of the IEEE 802.11x MAC protocol for improving the steady-state throughput through some of the MAC protocol parameters using simulation studies and compare the results with the analytical performance.
- Study the performance of IEEE 802.11x MAC protocol with a modified backoff procedure, which is aimed at minimizing the DIFS overhead of the IEEE 802.11x DCF basic access method for improving the throughput and reducing the delay.
- Study the performance of IEEE 802.16 MAC protocol, optimize the parameters of the protocol for improving the upstream utilization, reduce the delay and the probability of request collision for BE traffic under a varying network load. The studies are also extended for a composite traffic model.
- Study the analytical performance of IEEE 802.16 for BE traffic using a discrete Markov chain model in ideal and Rayleigh fading channel conditions and compare it with its simulation studies.
- Study the uplink performance of IEEE 802.16 MAC protocol for self-similar traffic which represents the aggregated traffic at the SS's and compare it with that of a Poisson traffic model.
- Study the overall performance in terms of uplink utilization and end-to-end delay of a hierarchical system where the IEEE 802.11e WLAN is used in the final access

and IEEE 802.16 WMAN provides the WLAN with a wireless connectivity to a wired network for broadband access.

1.5 Contributions Made in the Thesis

The overall contributions made in the thesis are summarized below:

I. The investigations are conducted to study the throughput and delay characteristics of DCF basic access mechanism of IEEE 802.11x for varying network load with different minimum backoff window sizes. Further, studies have been made on the sensitivity of the MAC layer performance to the propagation delay. An analytical model is developed to obtain the throughput and delay performance of the IEEE 802.11b network with finite transmission retries. The analytical results are compared with the simulation results and it is shown that the analysis presented is very accurate.

II. The impact of DIFS overhead on the performance of the IEEE 802.11x MAC protocol is investigated. A modified backoff algorithm with reduced DIFS overhead is also developed. The performance is studied with a modified backoff procedure under the assumption of Poisson distributed arrival process and it is shown that the modifications improved the throughput and delay performances significantly.

III. The upstream performance of IEEE 802.16 WMAN MAC protocol with an assumption of Poisson distributed arrival process is investigated to improve the uplink utilization for certain protocol parameters. Specifically, studies are made on utilization, packet delay and probability of request collision when subjected to varying network load for BE traffic with different uplink frame sizes and contention minislots. The impact of request backoff start (RBS) on performance is also investigated. In these studies, it is assumed that the SS sent one request per data packet. Later, the investigation is made on performance by assuming that request is sent for an aggregated traffic at the SS is investigated. An analytical model

is also developed to study the utilization, packet delay and probability of request collision in the IEEE 802.16x network. The analytical results are compared with the simulated ones. An extension of the analysis by accounting for transmission channel effects in a Raleigh fading environments is also provided.

IV. The uplink performance of IEEE 802.16x MAC in terms of utilization, packet delay and probability of request collision is studied for composite traffic. A QoS architecture for a composite service flows and an uplink packet scheduling mechanism are proposed to provide the required QoS in the IEEE 802.16 network. The investigations are also extended to obtain the impact of UGS bandwidth allocation procedure on the performance of other services such as rtPS, nrtPS, and BE.

V. The performance of IEEE 802.16x MAC protocol for an aggregated traffic at the SS is studied. The aggregated traffic at the SS's is modeled as self-similar. The performance of IEEE 802.16 network for self-similar traffic model is compared with the traditional Poisson traffic. Further, the actual hybrid access network involving the IEEE 802.11e and 802.16x WMAN is simulated and the overall performance in terms of uplink utilization of the IEEE 802.16 WMAN and end-to-end delay for varying network load originating at the IEEE 802.11e network is studied with the enhancements in place.

1.6 Outline of the Thesis

A brief description of the work carried out in the proposed thesis work is presented below.

In **Chapter 2**, the background of the thesis including the overview of the topics discussed. It includes an overview of the MAC mechanisms in the IEEE 802.11x and 802.16x standards. Furthermore, the QoS scheduling, request and grant mechanisms in the IEEE 802.16 are presented.

In **Chapter 3**, the dependence of the performance of IEEE 802.11b MAC protocol on the protocol parameters through simulation studies is investigated. The throughput and packet delay performance of DCF basic access mechanism is carried out with finite retry limits for different minimum backoff window sizes and traffic conditions. Further, studies have been carried out on the sensitivity of the MAC protocol performance to the propagation delay. A mathematical model is developed for finite loads with finite retry limits to determine the probability of packet transmission, τ in a slot by a station and the probability of packet collision P_c. These two parameters are used to obtain the throughput and delay performance of IEEE 802.11b network. The analytical performance is compared with the simulation results to demonstrate the effectiveness of the analysis done here. The results presented in this chapter can be used to decide the protocol parameters under a particular network loading condition, so as to achieve the improved performance of the IEEE 802.11x MAC protocol.

The protocol overhead involved in the backoff procedure of the IEEE 802.11x MAC protocol includes that due to the DIFS, short interframe space (SIFS). The impact of DIFS overhead on the performance of the IEEE 802.11x is studied in **Chapter 4**. A modified backoff procedure is proposed to reduce the DIFS overhead which occurs due to idle periods and collisions in a transmission. In the proposed algorithm, the stations which are in the backoff procedure are allowed to decrement the backoff counter without waiting for the duration of DIFS unlike in the existing standard, when a channel condition changes from busy to idle. It is shown through simulation studies that the performance of the proposed access scheme is better and provides a shorter waiting time than the original DCF when accessing the medium.

The upstream performance of the IEEE 802.16 MAC protocol for BE traffic to obtain the effect of protocol parameters such as uplink frame size, the ratio between number of contention and data minislots, payload size, RBS, and the number of SS's for varying network load is presented in **Chapter 5**. In these studies, it is assumed that the SS sent one request per data packet.

A mathematical model is also presented for calculating the probability of request collision and probability of request transmission to obtain the performance for a comparison of the analytical and simulation results. In this model, an aggregated bandwidth request mechanism is assumed. A queue length based round robin (QL-WRR) scheduling algorithm is proposed to provide fairness. An extension of the mathematical analysis for accounting transmission channel effects in Raleigh fading environments is also provided.

The simulation experiments conducted in this chapter are useful for setting the protocol parameters so as to achieve the improved performance in practice in both stand alone and hybrid access network application.

In **Chapter 6**, we provide a QoS architecture for composite service offering, and an uplink packet scheduling algorithm which can be used at the BS in an IEEE 802.16x network. In this architecture a combination of weighted max-min (WMM) and a queue length based weighted round robin (QL-WRR) scheduling method in a hierarchical structure is used to obtain the required QoS. Unlike in the existing scheduling algorithms here, the BE traffic is guaranteed with a minimum bandwidth grant to avoid BE traffic bandwidth starvation or to take the advantage of utilizing excess bandwidth which is not used by the other services such as rtPS and nrtPS.

The investigations are extended to obtain the impact of UGS bandwidth allocation procedure on the performance of other services such as rtPS, nrtPS, and BE. The extensive studies on uplink utilization and packet delay carried out shows the interrelationship among the different service flows.

In a hybrid wireless network involving WLAN in the final access with the access point of WLAN's interconnected to the wired network through WiMAX SS's, traffic at the individual SS's is an aggregate traffic generated at each of the IEEE 802.11e WLANs. Therefore, in the first part of **Chapter 7**, the traffic at the SS's is modeled as self-similar which approximates the aggregate traffic at each WLAN's in order to accurately study

the performance of the hybrid access network. In the second part of the work, the actual hybrid access network involving the IEEE 802.11e and 802.16 WMAN is simulated and the performance is studied with enhancements in place. The overall performance of this system depends on the protocol parameters of the IEEE 802.11e and 802.16 networks. To investigate the overall performance, the services offered in the IEEE 802.11e WLAN are mapped on to the corresponding services in the IEEE 802.16x network and the end-to-end delay as a function of the network load originating at the IEEE 802.11e WLAN is examined.

Finally, **Chapter 8** presents the conclusions derived from the thesis work. It also presents the directions for pursuing future research work in MAC protocols for next generation wireless networks.