

RESOURCE SHARING IN A WIFI-WIMAX INTEGRATED NETWORK

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RESOURCE SHARING IN A WIFI-WIMAX INTEGRATED NETWORK

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Nirmal Andrews, son of Philip Andrews and Usha Philip, was born on March 6, 1984 in Dubai, United Arab Emirates. He completed his Bachelor of Engineering at K.G.G College of Technology, Anna University, in Chennai, India. He entered the Electrical and Computer Engineering graduate program at Auburn University in August of 2006.

THESIS ABSTRACT

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Resource allocation is a challenging issue in integrated wireless environments due to factors like difference in participating network protocols, design of hierarchical network architecture, user mobility and multiple traffic types. In order to ensure fair access and efficiency of bandwidth usage among the component networks in an integrated network, resource allocation algorithms should be properly designed. The resource considered in this thesis refers to the wireless channel bandwidth. The design of such resource allocation algorithms becomes complex in wireless networks when compared to wired networks because of the error prone nature of the wireless medium. However, when a widespread Wi-Fi network is integrated with a next generation network such as WiMAX, both the subscribers and the service providers benefit significantly.

This thesis describes two different resource allocation algorithms in an integrated network of Wi-Fi and WiMAX. The first algorithm is an improvement over an existing two threshold mechanism suggested by Yahya et. al. for an integrated Wi-Fi and WiMAX network. In the existing model, the channels are classified as reserved and shared. Reserved channels are to be accessed only by specific users to which they are assigned and shared channels can be accessed by users of the component networks i.e. Wi-Fi or WiMAX based on availability. The proposed algorithm assigns priorities to the users and employs hybrid resource sharing.

Complete sharing, complete partitioning and hybrid sharing approaches and their shortcomings in WiMAX-Wi-Fi integrated networks are described. To overcome some of the shortcomings, a second algorithm called *Prioritized Resource Sharing* algorithm is proposed. In this algorithm, the channels are *prioritized* for different traffic classes rather than strict reservation or open access. The prioritized resource sharing algorithm's objective is to improve channel utilization. Channel utilization is improved because prioritized sharing allows the users to access any of the channels if they are not being used, unlike in complete partitioning where users are restricted to use only allocated channels even when channels restricted to other users in the integrated network are not being used. Prioritized sharing method is an improvement over complete sharing as it guarantees a minimum number of channels due to the prioritization, unlike in complete sharing where no reservation is provided which could lead to users of one network capturing all the channels instead of fairly sharing them.

Finally, the proposed algorithms are analyzed using two dimensional continuous time Markov chains. It is observed via simulations that using the forced termination model, in unbalanced loads both Wi-Fi and WiMAX component networks get unbiased service and neither network is starved. The simulation results also indicate that the *Prioritized Sharing* model achieves the best system utilization compared to other algorithms.

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CHAPTER 1
INTRODUCTION

Development of Internet and wireless networks has been the two most significant contributions in the information revolution. An ever increasing user demand for ubiquitous data and voice access at lower cost has instigated the necessity for a next generation network. The aim of these networks would be to provide multimedia services, such as voice, video and continuous data streams at high data-rates to mobile users in large coverage areas at all times. The architecture for the next generation of wireless networks aims to integrate multiple networks and benefit from the resulting synergy. There are various standardization bodies working towards this vision. Examples include the 3GPP (3rd Generation Partnership Project), 3GPP2, IEEE 802.21 Media Independent Handover Working Group and Network Working Group (NWG). However, to achieve a seamless integration there are several technical challenges that have to be addressed such as mobility management, resource allocation, admission control, protocol adaptation, security, and pricing. On the brighter side, the advances in integrated circuit design and software radio make it possible to implement multiple network interfaces in a single mobile terminal. Such terminals can access different types of wireless and mobile networks, which provide more versatile and flexible access options, making the integration feasible.

It is envisioned that beyond 3G networks, systems will integrate to provide overlapping coverage for mobile users, due to the complementary characteristics of various networks especially for wider coverage and higher data rates. Integration involves various challenges as mentioned earlier such as choosing the most efficient architecture for integration based on the standards that are being integrated and how to share resources (such as bandwidth, power, etc.) among the integrated networks. For example, the architecture of the integrated networks could be centralized, decentralized or it could be a combination of both depending

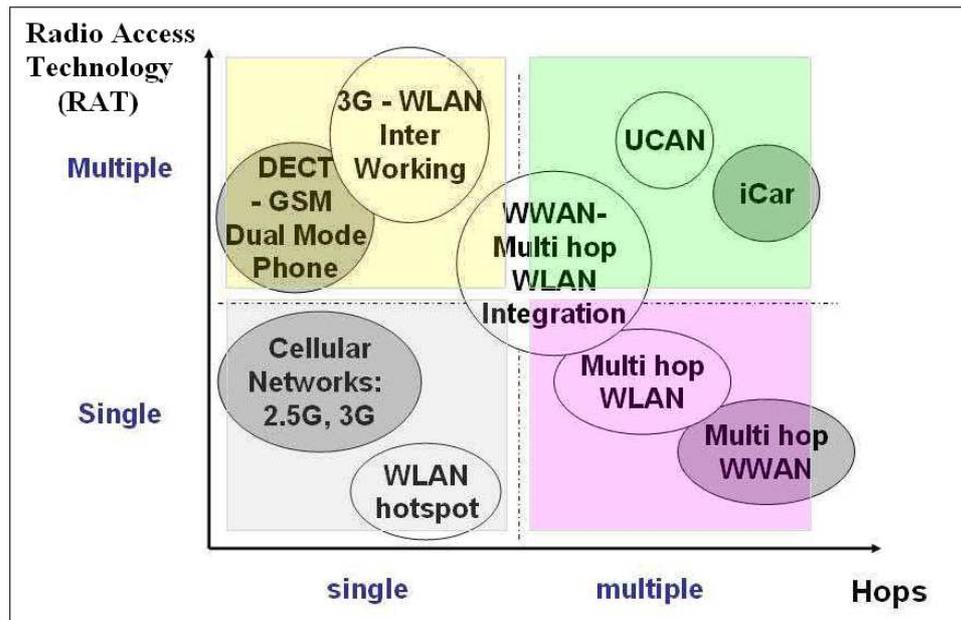


Figure 1.1: Representation of Wireless networks represented based on Radio Access Technologies and number of hops required to communicate [1]

on the different features that are expected from the integration. If it is centralized, a base station handles all computation or it could also be distributed within different base stations. Each of the architectures has its own advantages and disadvantages, which should be weighed and analyzed to make a choice on the best architecture for integration. The decision takes into consideration various features that the subscribers and service providers are expecting from the integrated network as well as the compatibility of the standards.

Figure 1.1 from [1], shows a possible design space for integrated wireless networks and establishes a difference between integrated networks and other architectures such as WLAN hotspots, relay based networks, multi-hop networks, mesh networks etc. The difference is based on two factors which are represented as the two axis in Figure 1.1, the number of hops required to connect to the Internet and the number of radio access technologies (standards) involved. Integrated networks have multiple standards working together and use single hop communication. Wide area networks like 3G can be integrated with a local area network such as WLAN. Users can seamlessly roam between these networks using

single hop communication to their respective base stations. On the contrary mesh networks use multiple hops to access a wide area network.

1.1 Existing Models Of Integrated Networks

Integration of multiple wireless access technologies is not a new concept. Multi-homing is an example of integration of various access technologies in wired networks which allowed users to access Internet through dial up, Ethernet, cable, DSL (Digital Subscriber Link), etc. However, within wireless networks the early adopter of the integration concept was wireless voice networks. The dual mode DECT/GSM (Digital Enhanced Cordless Telecommunication/ Global System for Mobile communications)phones indicate the same. This dual mode phone connects to the home telephone networks when indoors and the GSM network for outdoors when the user is not in the range of the DECT base station. The development of new devices such as the dual mode phone and routers that bridge different technologies have brought us closer to realizing integration as a reality.

Although the advantages of integration of networks are numerous, designing the architecture and efficiently integrating the various wireless standards to obtain the numerous advantages is a challenging task. For example, on analyzing the interworking between WLAN and 3G, it could be observed that WLAN was not targeted for public environments as a result of which it doesnt have universal AAA (authorization, authentication and accounting) mechanism, support of roaming agreements, strong mobility management with QoS etc. Similarly, even though 3G has most of these mechanisms inbuilt, vertical handoffs always pose a challenge in mobility management as 3G is built for horizontal handoff.

1.1.1 The Necessity For Introducing An Integrated Network With WiMAX and Wi-Fi

Most of the existing work in integrating wireless networks for next generation communication standards is focused on combing cellular standards along with WLAN. Cellular networks have better mobility management and larger coverage which WLAN do not have

whereas, WLANs have better data rates which are much higher and provide faster data access compared to cellular standards. If they are integrated, the complementary nature of both the cellular and WLAN networks would benefit both the networks by covering up the drawbacks of the individual standards. However, recently the 4G working group defined the following as objectives of the next generation wireless communication standard in [2], [3] and [4]. They are:

1. A spectrally efficient system (in bits/s/Hz and bits/s/Hz/site),
2. High network capacity: more simultaneous users per cell,[2]
3. A nominal data rate of 100 Mbit/s while the client physically moves at high speeds relative to the station, and 1 Gbit/s while client and station are in relatively fixed positions as defined by the ITU-R,[3]
4. A data rate of at least 100 Mbit/s between any two points in the world,[3]
5. Seamless connectivity and global roaming across multiple networks [4],
6. High quality of service for next generation multimedia support (real time audio, high speed data, HDTV video content, mobile TV, etc)
7. Interoperability with existing wireless standards, and
8. An all IP, packet switched network.

In summary, the next generation systems should dynamically share and utilize network resources to meet the minimal requirements of all the 4G enabled users. With this objective set for the next generation networks, it becomes obvious that a combination involving cellular standards would not suffice. Although 2.5 and 3G cellular data services offer wide area Internet connectivity, these services do not provide the broadband speeds of Wi-Fi. WiMAX on the other hand, can provide high speeds in service along with the quality of service. By combining WiMAX and Wi-Fi technologies, service providers can

offer their subscribers a more complete suite of broadband services over a wider variety of user environments. The service providers can leverage both types of spectrum; for example, license exempt for best effort local area traffic and licensed for wide area and QoS sensitive traffic. Similarly, the subscribers get a full range of services at home and office, as well as on the road and economical coverage over large areas. These advantages make integration of WiMAX and WiFi desirable.

1.2 WiMAX and Wi-Fi Basic Operation

The study of integration and coexistence of 802.11 (used interchangeably as Wi-Fi hereafter. Wi-Fi is based on IEEE 802.11 standard) and 802.16 (used interchangeably as WiMAX hereafter. WiMAX is based on IEEE 802.16 standard) networks is impossible without the knowledge of the differences in operation and access schemes of both of these technologies. Table in Figure 1.2 gives a brief overview of each technology and the differences between them. Based on this table it could easily be seen that interworking between both networks needs a lot of coordination at various levels of the network namely physical, MAC, routing and transportation layers.

The table in Figure 1.2, specifically does not mention 802.11e (Wi-Fi with Quality of Service(QoS)) since it is different from the rest of the 802.11 systems and its features and structure make it highly adaptable to co-existence and interworking. The above mentioned 802.11 systems do not focus on QoS architecture and so they usually have only one type of service flow which is Best Effort. Considering the fact that QoS plays an important role while integrating 802.11 and 802.16, it should be understood that 802.16 have different service flows for guaranteeing Quality of Service. The details of the service flows will be discussed later. The mapping of quality of service classes between 802.11 systems and 802.16 systems is quite challenging. Therefore, 802.11e which was developed for providing better Quality of Service standards for the 802.11 systems have categorized service flow which makes it more adaptable to co-existence and integration than its peers. The table shows

Networks	Wi-Fi (802.11 - based on commonly used technical name)			WiMax (802.16 - based on commonly used technical name)			
Operation Mode	1) Infrastructure 2) Ad-Hoc			1) Point to multipoint (PMP) 2) Mesh			
PHY	1) DHSS 2) FHSS 3) Infrared			1) Wireless MAN SCa : 2-11 GHz (PtP) 2) Wireless MAN OFDM: 2-11 GHz(PtMPt) 3) Wireless OFDMA: 2-11 GHz (PtMPt), more carriers 4) Wireless HUMAN (High-speed unlicensed): 2-11 GHz (PtMPt)			
MAC access methods	CSMA/CA (most common)			TDMA/TDD (most common)			
Systems	802.11 a	802.11 b	802.11 g	802.16	802.16 a	802.16 d	802.16 e
Spectrum	5 GHz	2.4 GHz	2.4 GHz	10-66 GHz	<11 GHz	10-66 GHz and <11 GHz	<6 GHz
Data rate	54 Mbps	11 Mbps	54 Mbps	120 Mbps	75 Mbps	120 Mbps	15 Mbps
Modulation	OFDM	DSSS	OFDM	QPSK, 16-QAM, 64-QAM	OFDM, QPSK, 16-QAM, 64-QAM	OFDM, HUMAN (High Speed Utilization)	OFDM

Figure 1.2: Difference between operation of 802.11 and 802.16 except for 802.11e

the difference between 802.11 and 802.16 networks at different levels. The next subsections will explain the working of WiMAX and WiFi standards.

1.2.1 WiMAX

IEEE 802.16 [5] is a radio standard for WMANs (Wireless Metropolitan Area Networks) operating in the frequencies between 2 and 11 GHz often referred to as WiMAX. It specifies four different physical layers (PHYs), as shown in Figure 1.2. IEEE 802.16 has a centralized architecture provided by a central Base Station (BS) with associated Subscriber Stations (SS). Typically, a BS is connected either directly or via additional BSs to the core network. Therefore, 802.16 offers an optional mesh deployment that introduces multi-hop connections via relaying BSs.

In 802.16, the BS estimates the operational power level for each subscriber and broadcasts a ranging code. The initial ranging process is described in [6]. The 802.16 subscribers are allowed to contend in the ranging channel for the initial ranging process and only those

successful subscribers can establish communication with the BS [6]. In [7], the design of a WiMAX based last mile network solution provides a practical example of the various network deployment structures for WiMAX, which includes the working of 802.16 BS and SS too.

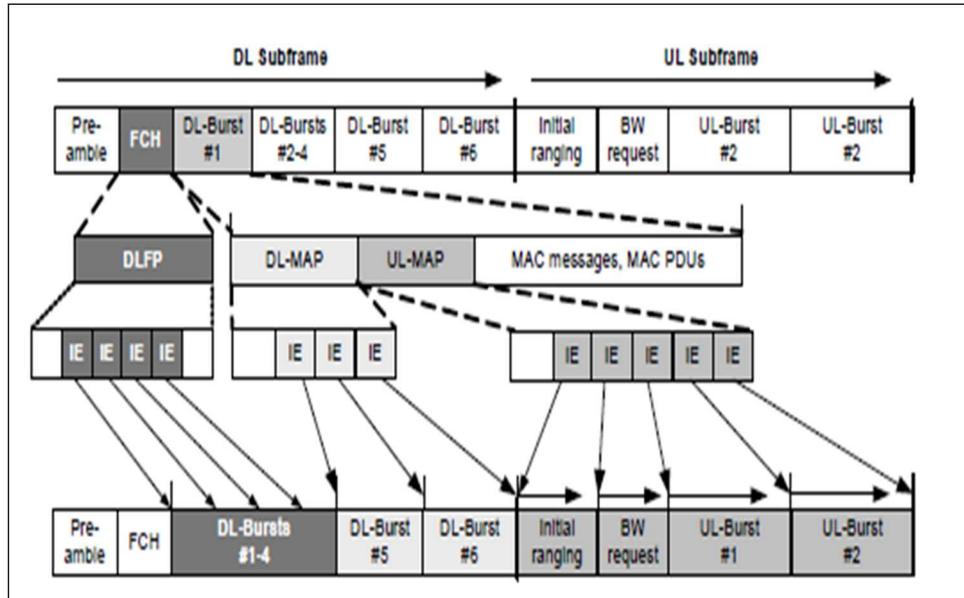


Figure 1.3: Frame format of WiMAX

A detailed analysis over the 802.16 MAC is provided in [8]. With a centrally controlled, frame based MAC approach 802.16 offers guaranteed multimedia quality of service. 802.16 supports non line-of-sight operation and large coverage areas, which enables a rapidly deployable infrastructure. The frame structure of the OFDM (Orthogonal Frequency Division Multiplexing) PHY layer operating in Time Division Duplex (TDD) mode is illustrated in Figure 1.3. Each frame consists of a Downlink (DL) subframe always followed by an Uplink (UL) subframe. The DL subframe starts with a long preamble used for synchronization followed by the Frame Control Header (FCH). The DL subframe consists of one or multiple DL bursts containing MAC Packet Data Units (PDUs) scheduled for DL transmission. The UL subframe starts with contention intervals scheduled for initial ranging and bandwidth request purposes. This is followed by one or multiple UL-bursts follow, each transmitted from a different SS. An UL-burst is initiated with a short preamble and contains one or

several MAC PDUs. DL and UL subframe are separated by the Receive/transmit Transition Gap (RTG) and the Transmit/receive Transition Gap (TTG). An (optional) extension of the DL-MAP with the duration of a burst enables the BS to flexibly arrange concurrent DL bursts. The knowledge of start time and the duration overcomes the restriction of the sequential nature of bursts. This benefits the Space Division Multiple Access operation of IEEE 802.16. The next section gives a similar description of the operation of 802.11 networks.

1.2.2 Wi-Fi

This section provides a brief description of the working of Wi-Fi MAC layer. WiFi technology is based on IEEE 802.11 standard. The IEEE 802.11 standard includes a medium access control (MAC) layer that uses carrier sense multiple access with collision avoidance (CSMA/CA) and an optional handshaking mechanism termed RTS-CTS. The use of these two mechanisms in the distributed coordination function (DCF) mode allows fair sharing of the medium between users in close proximity. The CSMA/CA protocol requires that when the medium is sensed to contain power over a certain threshold, a prospective transmitter must defer to the next available transmission opportunity. If the sensed transmission is decodable (i.e. a transmission from a node using a compatible standard) the deferral uses header information to discover the start of the next available slot. To allow contention between a number of nodes competing for the same transmission slot, a random backoff is selected by each node according to rules defined in the standard. Only the node with the shortest backoff may transmit.

Use of RTS-CTS allows a data transmission to be protected (via CSMA/CA) at both transmitter and receiver ends. The main drawback of the IEEE 802.11 standard is its poor efficiency. There are significant overheads to each data exchange - transmission slot boundaries (termed DIFS periods in DCF mode), backoff intervals, RTS-CTS delays if used, and acknowledgment (ACK) overhead if used (the IEEE 802.11e standard allows for different quality of service (QoS) types which may or may not require ACKs). A typical

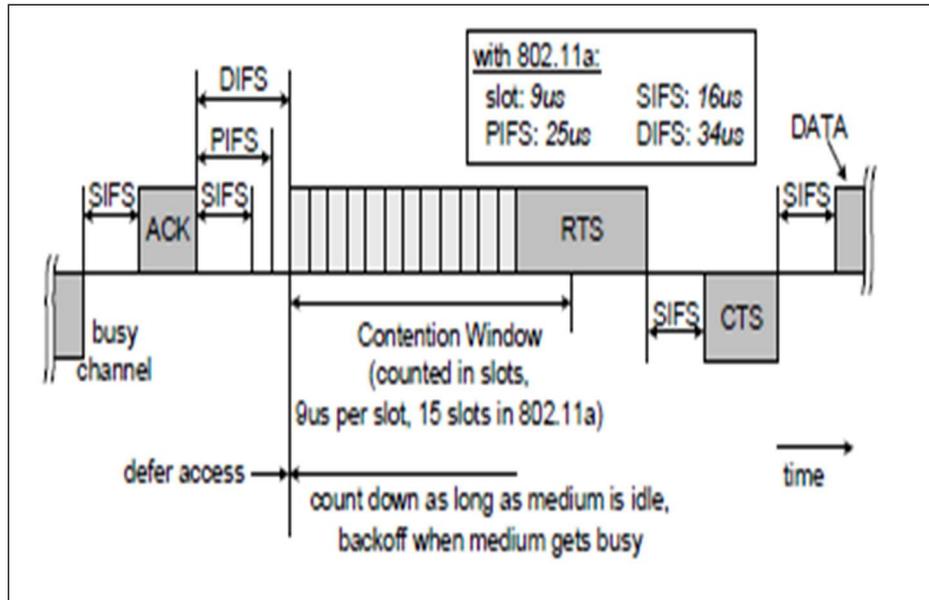


Figure 1.4: Frame format of WiMAX

exchange is shown in Figure 1.4. The actual data transmission occupies less than half of the exchange length. It should also be mentioned that the CSMA/CA mechanism is inefficient since often a node will defer unnecessarily, i.e. when it could have transmitted and not disrupted the transmission that it sensed.

There is also a point coordination function (PCF) mode specified in the standard that allows one node to control the scheduling of packets. This has advantages in improved efficiency (through reduced overheads, backoff time and collisions) and also allowing the controlling node (which typically is an access point to the wired infrastructure and through which most traffic is routed) to offload its queued data with a higher priority. However, the PCF is less compatible with co-existence scenarios.

Integrating 802.11 standard with 802.16 standards would be easier if both the chosen standards had an inbuilt QoS feature rather than implement a new one. In case of 802.11e (802.11 with QoS) and 802.16 the difficulty lies in matching the already existing service flow or QoS class of both the networks to form a common service class. The related work section in the next chapter will describe various methods used to make a common service class for smooth functioning of the integrated networks.

The next subsection explains how a new 802.11 standard was designed to include QoS features which were not included in legacy 802.11 or 802.11a/b and g standard. The 802.11 standard with QoS is named IEEE 802.11e. The description of this standard follows in the next subsection.

1.3 Organization

The rest of this thesis is organized into four chapters. In Chapter 2, a case for the integration of Wi-Fi and WiMAX networks is built by studying the necessity, the advantages and feasibility of such an integration. It also summarizes all the existing work in the area of Wi-Fi and WiMAX integration methods and categorizes the technical challenges involved in the integration of the two networks. Chapter 3 deals with the technical challenges in the integration of WiFi and WiMAX and narrow the focus to resource allocation problem in the network. Resource allocation methods are summarized along with the drawbacks of existing models for integrating WiFi and WiMAX networks. Then two new algorithms to improve over the drawbacks of the existing models, in terms of network utilization and call blocking probability, are proposed. The proposed algorithms for resource sharing are analyzed using MATLAB in Chapter 4. The models are based on 2D Markov chains. The results of the simulations are discussed and the improvement over existing models is shown. Chapter 5 summarizes the results and mentions some future work.

CHAPTER 2

CO-EXISTENCE AND INTEGRATION OF WI-FI AND WiMAX NETWORKS

WiMAX which is WMAN (Wireless Metropolitan Area Network) standard complements Wi-Fi which is a WLAN (Wireless Local Area Network) standard, by providing support for high speed applications requiring data rates of up to 100 Mbps (802.11 a and d) over a wider coverage area with a radius of up to 1 mile as compared to lower coverage radius of 802.11 standards. The complementary nature of both the networks makes the integration of Wi-Fi and WiMAX favorable to offer several advantages such as ubiquitous high data rate provision, high quality of service (QoS) from the inbuilt QoS provision of WiMAX, etc. The service operators get larger network coverage with a small investment and the users get ubiquitous network access with guaranteed service [9]. According to [10], some of the advantages of integrating Wi-Fi and WiMAX are listed below as:

1. High connectivity, where users can connect to either of the networks based on their location, Quality of Service requirements and coverage.
2. Efficient global roaming.
3. Provision of broader range of services both at home as well as on the road.
4. Usage of both licensed and license exempt spectrum based on service requirements.
5. Economical coverage of large areas.

The above mentioned reasons make the integration of Wi-Fi and WiMAX highly desirable. Concisely, the integration results in wide area broadband communication with high QoS. Gakhar et al., in [11] states that efficient interworking of Wi-Fi and WiMAX is required for providing quality of service for delay sensitive and bandwidth intensive applications such

as VoIP, video transmission, large volume FTP etc. According to Thomas et al. in [12], the possibility of integration between Wi-Fi and WiMAX becomes more realistic in the future generations because Wi-Fi is widely established and WiMAX is still evolving providing all the data rate and QoS features that are not available in Wi-Fi.

The standardization of both Wi-Fi and WiMAX technology by Wi-Fi Alliance and WiMAX Forum makes the interoperability within each network and between the two networks feasible. Similarities in both technologies such as the use of IP (Internet protocol) - based technologies to connect to the Internet also favors integration. There are a few requirements for integration Wi-Fi and WiMAX that were suggested by Motorola and Intel in [10]. The most important ones are multi-mode subscriber devices that can communicate with both Wi-Fi and WiMAX networks and maintaining session continuity. Network Working Group (NWG) [10] gives the specifications for allowing transition of users from 802.16 networks to other networks. An ASN (Access Service Network) gateway has been designed by NWG for managing access to services such as AAA (Authentication, Authorization and Accounting), DHCP, session and mobility management [10]. This allows all calls or data transfers to be smoothly handled when Wi-Fi network users or WiMAX network users enter WiMAX or Wi-Fi networks, respectively. These developments will facilitate in making integration of 802.11 and 802.16 feasible.

The next section explains how the WiMAX (802.16) and Wi-Fi (802.11) integrated network will be deployed and what economic benefits will such a deployment have.

2.1 Deployment models of integrated 802.11 and 802.16

Motorola and Intel in [10] recommended four different deployment models for the integrated 802.11 and 802.16 architecture. The different deployment models were:

1. Broadband 'on the go'

Deployment of 802.11 and 802.16 in the user devices, allows service providers to offer transparent service between 802.11 in hotspots and 802.16 beyond the hotspots.

Deployment of 802.16 in areas with high density of Internet users extends broadband services beyond hotspots providing both users and service providers the utility and value of service.

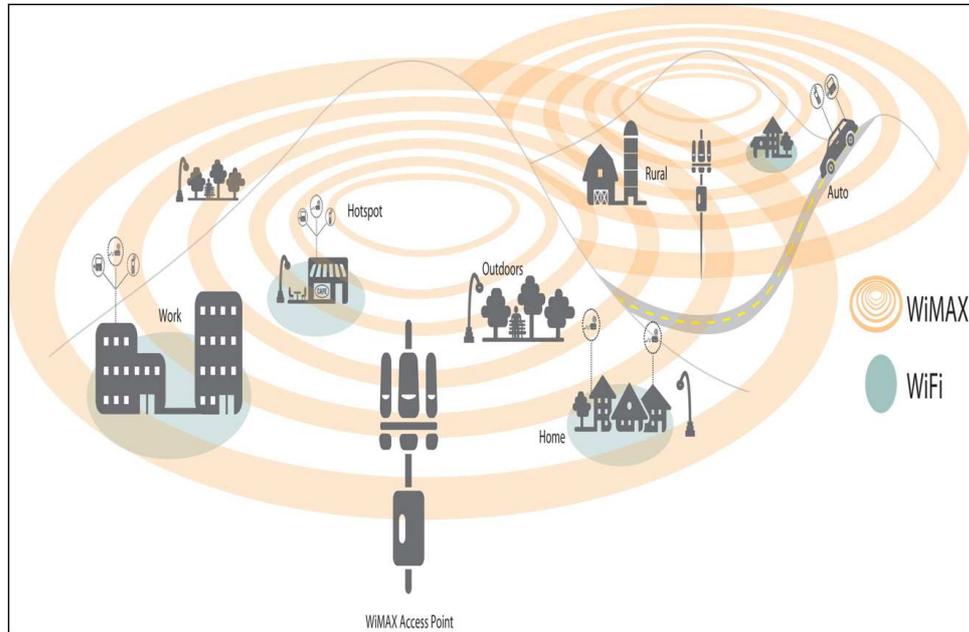


Figure 2.1: A deployment scenario where 802.16 (WiMAX)/ 802.11 (Wi-Fi) is used 'on the go'.

2. Last mile broadband

In rural areas where the population density is scarce the expansion of DSL will be very expensive and in urban areas where it could be difficult to add wired connections to existing multiple dwelling units (MDU) the integrated network can be used to extend broadband connectivity in the last mile. 802.16 will be used as backhaul which will make the extension less costly.

3. Broadband Campus coverage

802.16 can cover larger area. It can provide connectivity beyond the individual buildings to an entire campus as blanket coverage. This allows service providers to offer choice of connectivity to users enabling them to connect to the 802.11 (Wi-Fi) network in the building or the 802.16 network which covers the campus. This usage of 802.16

can reduce the number of 802.11 access points needed to cover the entire campus, thereby reducing maintenance cost.

Gunasekaran V. et al., in [13] suggested a few deployment models that can be used by service providers based on the density of population in the area of deployment. They classified the areas as: dense urban area and low density area. The authors build the integrated network model on top of the underlying 802.11 network which is already deployed widely. They identified the widely deployed 802.11 models as: 1) Location specific models or hotspots covering specific locations where Internet usage could be high such as airports, hotels, cafes', etc. and 2) Extensive or outdoor model which could be an example of areas with low population density where 802.11 is used to provide outdoor coverage. The different deployment scenarios and the integrated Wi-Fi and WiMAX models that suit the scenarios are mentioned briefly as:

1. In the dense urban areas majority of the SOHO (small offices, home offices) and households are in multi dwelling units or apartment complexes as shown in Figure 2.2. The authors suggest that 802.16 be used as backhaul in these dense urban area deployment scenarios instead of the existing wired backhaul for individual 802.11 hotspots. 802.16 backhaul can deliver megabits of data to the multi dwelling units from where 802.11 can be used to distribute services to individual users or rooms.
2. The second case is where the population density is low. This scenario differs in the way that it requires a larger number of 802.11 access points to cover the area. Gunasekaran et al. in [13] suggests a single private owner model for operating the services and selling it directly to the customers. The other possibility is that the local government can make deals with multiple owners to grant license to operate, providing the service providers the city's existing infrastructure like street poles and lamp posts to deploy the network as shown in Figure 2.3. This helps in reducing the capital cost and operating cost, which enables the operators to offer lower cost of service to customers.

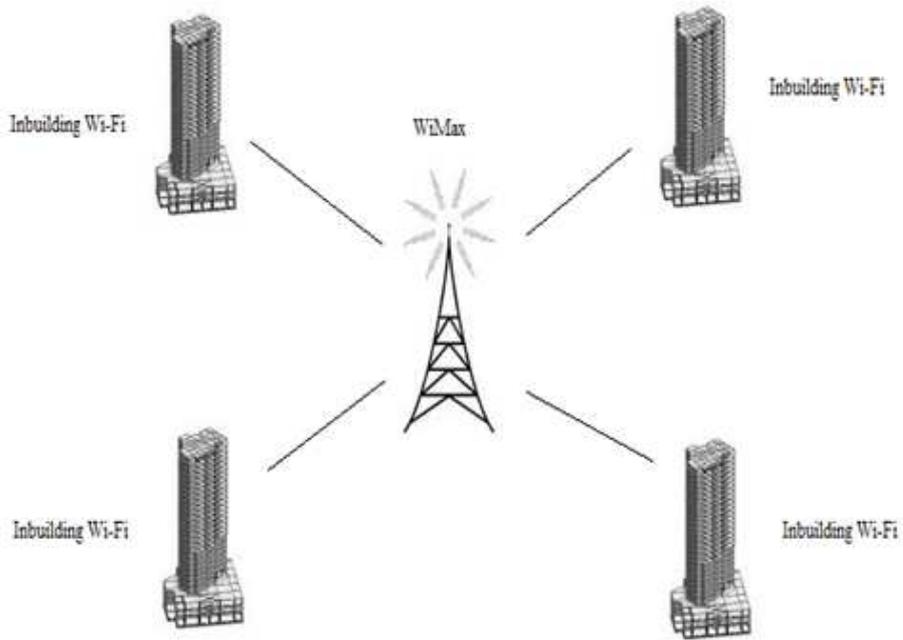


Figure 2.2: Dense Urban area coverage using 802.11 - 802.16.

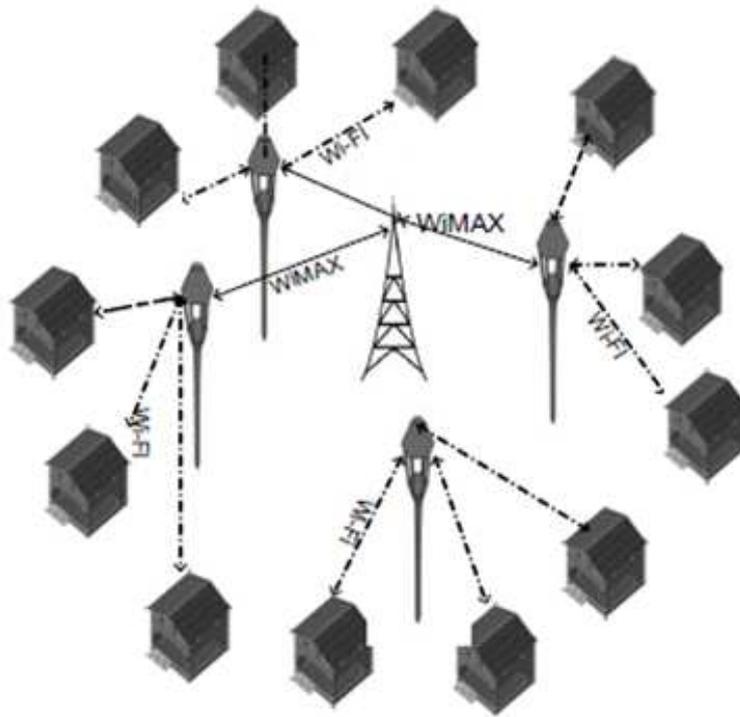


Figure 2.3: 802.11 and 802.16 interworking network serving less populated areas.

- Gunasekaran et al., provide yet another infrastructure for the integrated 802.11/802.16 network shown in Figure 2.4. They use 802.16 mesh as a backhaul. In a thirty six square mile radius assuming that nine 802.16 cells of diameter coverage two miles can be fitted, it would require nine wired connections for each of the BS in the cell, but in case of a 802.16 mesh one wired connection could substitute the nine wired connections instead. Once the 802.16 cells are in place, the next step is to pack these 802.16 coverage cells with 802.11 access points (AP) and using 802.11 as the last mile connection. The authors suggest the usage of 802.11 a/b and g to provide an extensive option for users as well as operators to provide best service.

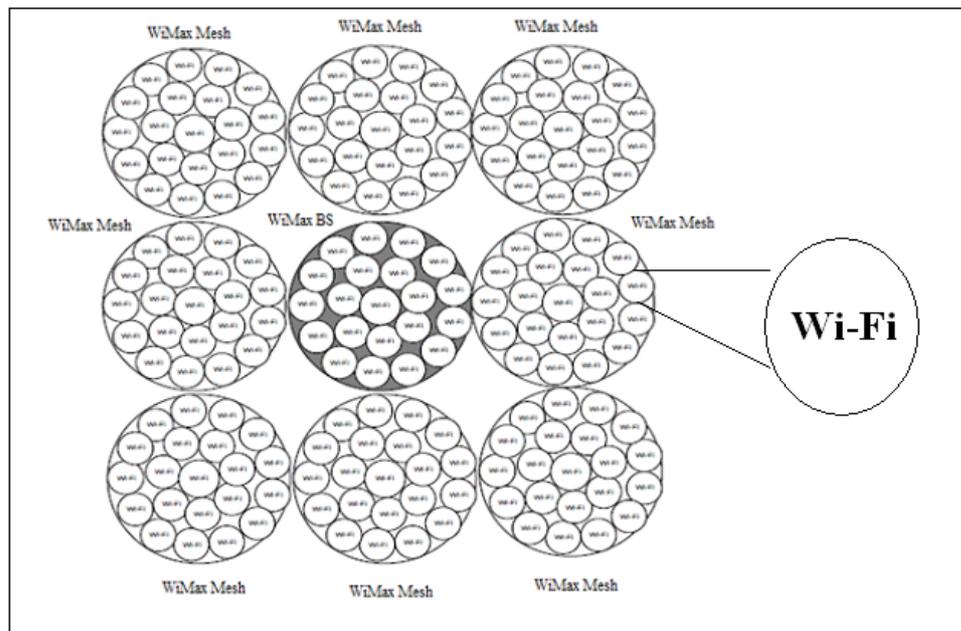


Figure 2.4: City wide model for deployment of integrated 802.11/802.16. Larger cells are WiMax cells and the cells inside them are Wi-Fi cells.

Economic benefits of the integration

Gunasekaran et al., study the most optimal deployment of 802.11/802.16 network based on financial aspects. Using the model shown in Figure 2.4, a cost analysis is performed and an approximate cost of service that the service providers can charge the end users is established. Users are classified as light, heavy and business users. The average bandwidth

for light users is 250kbps and for heavy users is about 500 Kbps. The benefit for the end user is lower cost of service and multiple service provisions. The monthly subscription cost of \$15 for light users and \$30 for heavy users. For business users the service is provided for \$60 per month. On demand users will be charged \$5 per day of usage. \$20 per month will provide voice over WiFi (VoWiFi) which allows users to make unlimited local and long distance calls for an entire month. The model designed based on all the above mentioned assumptions will enable for the operators to recover cost of network deployment within two years of operation.

2.2 Related work in integrated Wi-Fi and WiMAX networks

Figure 2.5, shared the details of integrating WiFi and WiMAX networks and integration have been classified based on the different layers of the protocol stack. It categorizes the most relevant functions performed in physical, data link and network layers of the integrated Wi-Fi and WiMAX network. In this section the previous related work is described in detail and the most prominent issues in an integrated WiFi and WiMAX network are summarized.

Thomas, Nicholas J. et al in [12] studied the effects of coexistence of 802.11 and 802.16 on the performance of both 802.11 and 801.16 and found that the total throughput of the coexisting system drops to about 10% of the combined offered load. This is because of interference between 802.11 and 802.16 networks and the absence of coordination or call admission protocols to eliminate such interferences.

Since it has been proved that the coexistence of 802.11 and 802.16 without any control scheme would lead to severe interference and performance degradation, Jeng Xiangpeng et al in [14] designed three reactive schemes; dynamic frequency selection (DFS), power control (PC) and time agility (TA) to avoid interference. Using time agility throughput of the hotspot could be increased by 30% and using power control scheme the throughput at the 802.16 SS can be increased by 4 times while reducing the throughput of 802.11 hotspots by a very small amount. Jing, Xiangpeng and Raychaudhuri, Dipankar also designed a

proactive scheme in [15] named as common spectrum coordination channel (CSCC) etiquette protocol to consider the hidden station problems which were not accounted for in the reactive schemes. Using CSCC it was observed that in the case of a single BS with single hotspot the DL throughput of 802.16 is improved by 35% with the change in distance between the SS and hotspot. In the multiple BS and hotspot scenario different 802.16 SS geographic distributions were studied. When the SS are distributed uniformly there is an 802.11 throughput increase of 15% and when the SS are clustered around the hotspot the throughput increases by 160% for any larger clusters the throughput degrades.

Berlemann, Lars et al in [16] studied the coexistence of 802.11(a) and 802.16 within the license exempt frequency band and proposed a solution for interference avoidance in such a coexistence scenario. In the proposed solution, full control of the radio resource is provided to 802.16. The solution targets the avoidance of an idle medium for duration of DIFS or longer before and during the 802.16 MAC frame transmission and thereby avoiding interference and protecting the 802.16 MAC frame. This solution proves highly unfair to 802.11a users since they have no control. Unnecessary handoffs in a network also leads to drastic reduction in throughput and call handling efficiency. Nie, Jing et al., in [17] designed a vertical handoff technique for integrated 802.16/ 802.11 networks. In the case of 802.11/ 802.16, both the networks are high bandwidth networks. In the proposed technique, a user in the 802.16 network is handed off to 802.16 network if the bandwidth provided by 802.11 is higher than that offered to 802.16. Now if the user is in 802.11 network, then the handoff decision is made based on average RSS (Received signal strength) and bandwidth. The bandwidth of 802.11 was calculated using NAV packets.

Coexistence just studies the effect that the coexisting networks have on each other. However, interworking goes deeper since it has to consider MAC as well as Quality of Service mapping issues for the combined working of both the interworking networks. For information exchange within an 802.11 and 802.16 integrated network, Berlemann, Lars et al in [18] designed a common frame structure capable of operating in both 802.11e (802.11

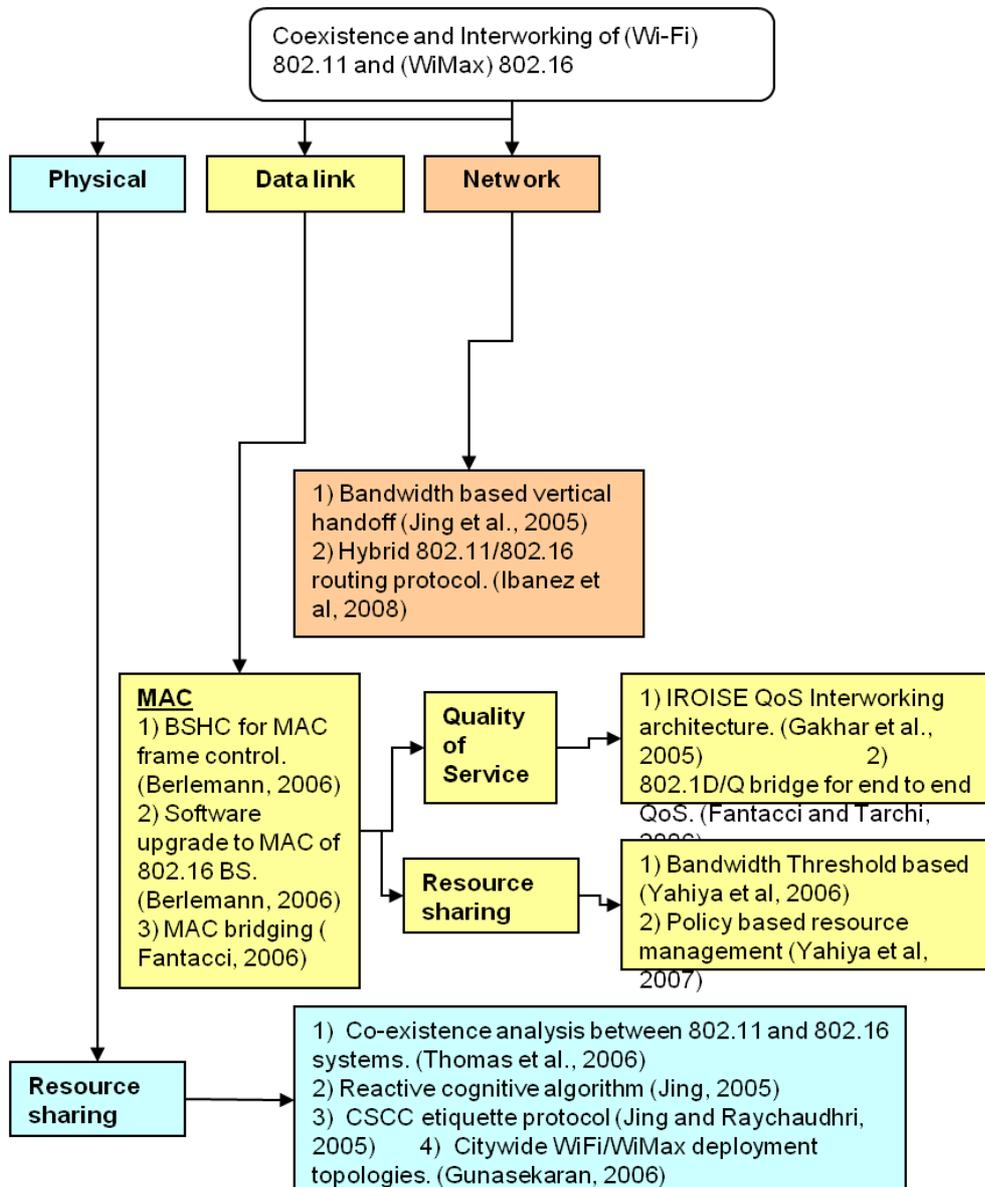


Figure 2.5: The detailed structure of 802.11 and 802.16 interworking network.

with QoS) and 802.16 network according to [18]. The authors propose a single common communication device named as Base Station Hybrid Coordinator (BSHC). The BSHC embeds the 802.11e (802.11 with QoS) transmissions into 802.16 frame structure. Simulation results showed that with increase in the number of 802.11e end users the maximum throughput decreases because of more contention in contention period of 802.16 transmission. Later, Tang-Lin et al suggested the model of an integrated access point named W2- AP which acts as either a bridge in translating frames between 802.11 and an Ethernet interface or as a relay node transferring frames between 802.11 and 802.16 in [19]. The Wi-Fi protocol operation is modified to match WiMAX system. It was observed that the proposed scheme provided significant improvement in end to end delay due to the connection oriented unified approach.

Since the MAC protocols of both 802.11 and 802.16 networks vary, the direct mapping of Quality of Service frameworks of 802.11e and 802.16 are not possible. Gakhar, Kamal et al proposed a Quality of Service framework named Radio Gateway (RG) in [11] for 802.11e/802.16 integration. A common service flow structure was designed which combined the service flows of both 802.16 and 802.11e which made mapping possible. However a drawback of this solution is that initial setup time is required since it involves buffering, mapping and setting up new connection. So, Fantacci and Tarchi in [20] proposed a bridging device capable of transparently interconnecting both 802.11a and 802.16 keeping in mind QoS sensitive applications. Simulation results using the proposed model showed that end to end delay for QoS sensitive applications reduced significantly and thus QoS sensitive applications were served in a timely manner. Ali Yahya et al [21] concentrated on the quality of service maintenance during mobility or vertical handoff between the WiFi and WiMAX integrated networks. A bandwidth reservation policy was used in 802.16 which set aside a dedicated amount of resource for the handoff users in such a manner that the existing 802.16 SS users do not have to suffer loss of quality of service. It was observed that within a set limit of maximum tolerable latency, 802.16 could support 24 voice sessions

and 21 video sessions transferred from 802.11 without any packet drop using the proposed model.

For routing in 802.11 and 802.16 integrated networks, Ibanez et al in [22], modified the existing AODV protocol to accommodate the integration of 802.11 and 802.16. The algorithm sends out a request packet until it can reach a destination node or the 802.11/802.16 gateway. If the destination is outside the coverage of 802.11 network, the AP retransmits the request packet. Once the 802.11/802.16 gateway or the destination node receives the packet it sends a reply packet to the source which helps in route discovery.

2.2.1 Previous works in integrated Wi-Fi and WiMAX resource allocation

From the literature on resource allocation in integrated 802.11/802.16, it can be seen that mathematical modeling of resource allocation problem is achieved using Markov chain models or game theory. Niyato and Hossain [23] in their study aim at providing good Quality of Service to end users by designing efficient bandwidth management and admission control algorithms. The authors use a hierarchical model for the bandwidth allocation. The hierarchical bandwidth allocation is done in two levels; the first level uses a bargaining game to allocate resources to the SS (subscriber stations) and the WLAN APs' and then the second level distribution of the given bandwidth among different WLAN end users. The solutions obtained focus on providing end user Quality of Service based fair bandwidth allocation among the connections in the integrated network. Niyato and Hossoin in [24] extended the idea discussed above to a different scenario of 802.11 in a multihop 802.16 network where 802.16 mesh is used as a backhaul for 802.11 hotspots. The resource allocation in this case was not just between 802.11 APs and 802.16 SS, but it also includes resource sharing with traffic from relay connections. The results in this method indicate that the mesh routers are given fair bandwidth allocation. Niyato and Hossoin [25] also modeled a pricing strategy for the integrated networks. The model uses the Stackelberg equilibrium where the 802.16 BS uses the 802.11 users best response information to provide optimal supply of bandwidth so as to gain highest profit. Numerical results indicate that at equilibrium 802.16 BS charges

the same price for every 802.11 router even though the bandwidth demands differ and when traffic arrival increases the 802.16 BS increases the price on 802.11 APs to compensate for the loss in revenue by degradation of quality of service to SSs.

In [26] and [9] Yahiya Ali et al., study resource allocation in an integrated 802.11/802.16 network. The authors also propose a resource allocation scheme for the efficient performance of the interworking network. The policy based on channel bandwidth threshold is used for managing resources between traffic of both types. Two thresholds are used corresponding to direct and indirect traffic to 802.16 BS. The direct traffic is the traffic from 802.16 users and indirect traffic is 802.11 users traffic. The architecture in this interworking scenario is tight coupling which makes 802.11 traffic dependent on 802.11 BS for reaching the Internet as shown in Figure 3.1. Therefore in this proposed solution for efficient management of resources, priority is given to 802.11 users over 802.16 users. There are several methods of bandwidth allocation which are complete sharing, complete partitioning and a method which integrates both. The authors use the integrated method where the resource is partitioned partially and the rest of the available resource is left for sharing. The resource in this discussion is bandwidth in terms of channel. The users are blocked only when the respective partitioned channels as well as the shared channels are depleted or assigned. The model is analyzed using Markov chains. The results indicate that with variation in partitioning and load the blocking probability also varies.

2.3 Summary of the technical challenges in coexistence and integration of WiFi and WiMAX

Based on the previous work, the different problems in the area of integrated Wi-Fi and WiMAX network are classified as:

1. Handoff

In interworking and coexisting networks there are two kinds of handoff namely vertical and horizontal handoff. When the handoff takes place between similar type of networks

it is called horizontal handoff and when the handoff is in a hybrid network it is called vertical handoff. In an 802.11 and 802.16 integrated network, there are doubly covered areas service by 802.11 as well as 802.16. In such areas, decision is to be made as to how the handoff will be made and on what network criteria it will be made. Unnecessary handoffs can reduce the throughput of the network drastically and also cause unnecessary call droppings which will reduce the Quality of Service provided to the users.

2. Resource sharing

Resource sharing becomes an important issue in interworking networks since users of two different networks are to be served and both of them require Quality of Service with the limited resources available. Network resources should also be fairly shared between the two different networks. Researchers working in this area have adopted various mechanisms for resource sharing such as admission control and channel allocation schemes.

3. Quality of Service

In integrated networks, Quality of service is a major issue since the quality of service provisions for the component networks are different. In fact, it could be said that 802.11 does not inherently have any Quality of Service provisioning where as 802.16 has a very structured quality plan. This mismatch in quality provisions in both these networks will require to be bridged for efficient performance using service mappings or tight coupling where the service provisions of one network are exactly duplicated and used by the other network.

4. Protocol adaptation

The MAC protocol, frame structure and operation mechanism of 802.16 and 802.11 are both different. 802.16 as we have seen earlier uses TDMA access and 802.11 uses CSMA/CA. They use dissimilar frame formats. The incompatibility has to be bridged

in order for communication to be established between the two networks. Solutions that exist for this problems, redesign the protocol and suggest embedding the 802.11 frame in the 802.16 frame. Such solutions lead to throughput loss and hence efficient design becomes a challenge.

5. **Routing**

Routing protocols for interworking networks have to take into consideration factors such as vertical handoff and mobility issues. The traditional routing protocols such as AODV (Ad hoc On-Demand Distance Vector), DSR (Dynamic Source Routing) do not take into account routes between different networks. Interworking brings about new dynamics and more routes to select from and energy efficiency should be considered too.

6. **Price**

Pricing is always an issue in situations where there is interworking where one network uses the other network for data transfer. The most commonly suggested architecture in the 802.11/802.16 interworking network employs 802.16 as a backhaul for the 802.11 hotspots. Depending on how the networks are owned pricing becomes an issue. If both the networks are owned by separate individual owners, then a service level agreement has to be reached to decide on a pricing model. The basis of the pricing could be based on usage, traffic load, bandwidth etc. Another issue related to pricing is the fairness issue.

The existing work in [9], [26], [25] and [24] do not take into consideration cases where one network, which has an aggressive contention based channel access scheme, takes up most of the resources and the other network is starved due to this. Such a scenario could occur under conditions of heavy network traffic. Under such situations the network should be able to fairly support users from both the networks that are integrated without drastically blocking one another. Designing a model for the above mentioned situation of high network

traffic in integrated network has motivated the work in this thesis to focus specifically on resource sharing.

The next chapter will discuss the existing resource sharing models, their drawbacks and also suggest the new models designed to improve over the drawbacks in the existing models.

CHAPTER 3

A PRIORITIZED SHARING AND FORCED SHARING MODEL FOR SHARING RESOURCES IN WI-FI - WiMAX INTEGRATED NETWORKS

3.1 Introduction

Resource allocation in a resource starved environment like wireless networks is important to obtain better network performance. Resource allocation challenges are based on factors like channel conditions, bandwidth requirement and mobility that change with location and time. Designs which do not consider such diversities lead to inefficient use of the resources. There is no single optimization tool that can be used to solve all resource-allocation problems simultaneously. Examples of resource allocation strategies are antenna-array processing, dynamic resource allocation and game theory. Based on earlier work on resource allocation over integrated Wi-Fi and WiMAX networks, it is observed that scheduling and channel assignment are the widely studied resource allocation strategies in the specific area of integrated Wi-Fi-WiMAX networks. This can be observed in Figure 2.5 in chapter two, where most of the functions in the MAC layer are related to channel allocation and resource sharing using scheduling. Designing an efficient resource management scheme in integrated network is challenging due to various network requirements such as avoiding drastic variation in data rate, obtaining high channel utilization and avoiding unnecessary handoffs which reduce the throughput of the system. So choosing the right resource sharing model or modifying the existing ones to fit new networking standards poses a challenge to network designers.

3.2 Resource Sharing Techniques

This thesis, focuses on resource allocation techniques in the MAC layer of the integrated Wi-Fi and WiMAX networks. Some MAC layer resource allocation techniques mentioned earlier are briefly described below.

1. Scheduling: The resource under consideration is bandwidth and scheduling is related to allocation of channels to the users at specific time intervals by either a centralized or decentralized controller. This helps users to occupy the limited available bandwidth for different lengths and periods of time depending on their call requirement, channel condition and fairness. It helps avoiding collision occurring between users trying to occupy same channel at a given time. The controller maintains the information of how to schedule the channels to avoid such collisions.
2. Channel allocation: Limited spectrum availability leads to dividing available bandwidth or spectrum into channels and allocating the channels in such a way that multiple users can use different parts of the spectrum without interference. Co-channel interference is an issue that is to be confronted while allocating channels as it can degrade the quality of service, delay and throughput seen by the applications. Channel allocation can be done based on a central controller or a distributed controller. In centralized scenario, a central controller makes sure that the channels and they are appropriately allocated to all the users served. In a distributed scenario, users communicate among each other to coordinate and achieve proper resource allocation.

The following section will describe the previous resource allocation methods ([9] and [26]) used in integrated Wi-Fi and WiMAX networks specifically. The various issues related to the models used earlier in [9] and [26] are also discussed in detail.

3.3 Channel Allocation in Wi-Fi-WiMAX Network Based On Previous Models

To understand the specific channel allocation methods used in this thesis, it is necessary to have a clear understanding of the system model that is used in Wi-Fi-WiMAX integrated

networks. In [9] and [26], as well as in [23] and [24] the integrated network model that is used is known as tightly coupled model. To understand tightly coupled networks a brief description of two keywords, core network and access network, is required. Core network is the central part of a network which provides various services to customers connected by access network. Core network includes the AAA (Authentication, Authorization and Accounting) server which does the billing, security control etc. Access network is a part of the network which connects a subscriber to their immediate service provider. Now if there are two networks N1 and N2 being tightly coupled, a tightly coupled network is defined as a network in which both N1 and N2 are integrated in such a way that N1 directly connects to the Internet through its wired backbone, whereas N2 connects to the Internet through the core network of N1. For example, if a 3G network and WLAN network are tightly coupled, then WLAN is integrated with 3G network such that WLAN connects to the Internet through the core network of 3G network. It could be coupled in way that 3G connects to the Internet through WLAN core network too. In this case, the billing and authentication services will be provided by WLAN. This indirectly indicates that N1 network should expose its core network functionalities such as authentication, authorization and accounting to the N2 network. Therefore most of the time tightly coupled architecture is adopted by service providers when both the integrated networks are owned by one service provider. The system model used in this thesis is an extension of tightly coupled networks over Wi-Fi and WiMAX networks since the new models proposed in this chapter are an improvement over the existing models (complete partitioning, complete sharing, etc. explained in section 3.3.1 and first come first serve model explained in 3.3.2) which use tightly coupled architecture in [9] and [26].

3.3.1 System model

The system model used in this thesis considers a tightly coupled architecture based on WiMax and Wi-Fi networks as shown in Fig. 3.1. In this architecture there is a WiMax base station encompassing multiple WiFi hotspots. The WiMax BS connects to the Internet and

acts as the backbone to the WiFi network. The WiMax subscribers referred to as subscriber stations, communicate directly to the WiMax Base Station (BS) whereas the WiFi users have to use a special access point (AP) to communicate with the WiMax BS. This special access point is named as *WiFi - WiMax Bridge* (WWB) in this thesis. The WiMax interface is used for communicating with the BS, and WiFi interface for communicating with WLAN stations. Since the range of WiFi users are much smaller than the WiMax counterparts and the access mechanism of WiFi (random) and WiMax (time slotted) are different, the WWB acts as a link for WiFi users to reach the WiMax BS. The WWB aggregates all the WiFi user traffic and requests the WiMax base station for a service. The traffic from WiFi-Wimax bridges are just referred to as WiFi users/traffic since they forward the aggregated WiFi requests and the traffic from WiMax subscriber stations is referred to as WiMax users/traffic. The important issue focused on is the prioritization of these two different traffics and the corresponding changes in channel utilization and blocking of traffic. We assume that each cell has a total of C channels. The admission control residing in the base station manages the resource C between the two types of traffics.

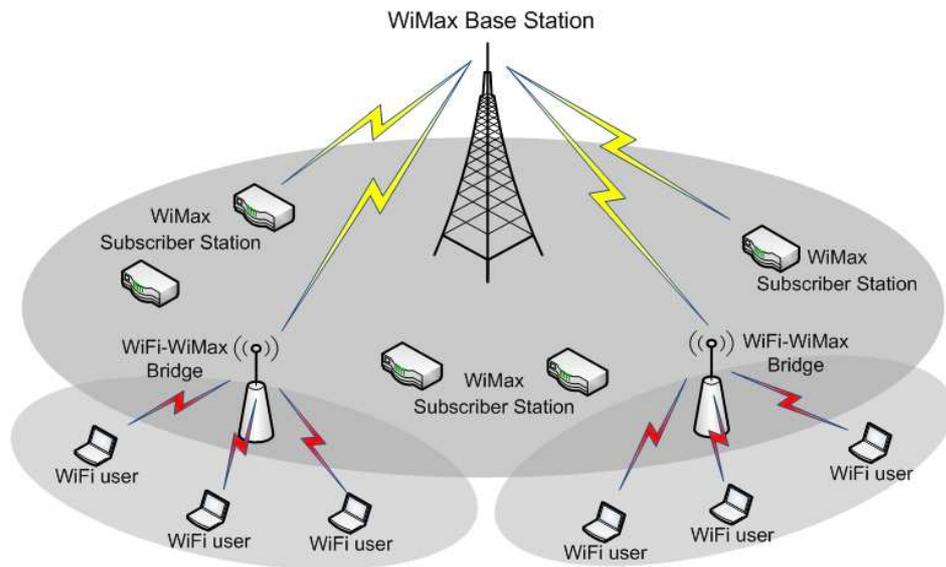


Figure 3.1: System Model of WiMax and WiFi integration.

General Resource Sharing Models

Before describing the resource sharing models in the Wi-Fi and WiMAX architecture described above we briefly explain the already existing allocation algorithms in previous works ([9] and [26]) which are known Complete sharing (CS), Complete Partitioning (CP) and Hybrid Sharing (HS) schemes.

In CS allocation (Fig. 3.2a), WiFi and WiMax have their own queues and both of them share all the available channels. There is no prioritization and the users are served on first come first serve basis. If quality of service is defined as the minimum number of channels assured for a particular class of users, then there is no QoS guarantee in this scheme.

The CP allocation scheme (Fig. 3.2b) is a variant of CS scheme, where different resource utilization thresholds are assigned to WiFi and WiMax users based on each traffic priority. Higher number of channels are reserved for higher priority users, in this case WiMax users. QoS is achieved by reserving channels for each class of users.

HS scheme (Fig. 3.2c) is a combination of CS and CP schemes. There are a set of common channels which can be shared by both the class of users and the rest of the channels are reserved according to the priority of the class of users. In Fig. 3.2c, WiMax and WiFi are allocated three and two channels respectively and the rest three channels are common and are allocated on first come first serve basis. In this type of allocation, there is a trade-off between channel utilization and QoS.

3.3.2 Channel Allocation Problem

Channel allocation has been used as a means of resource sharing in many network solutions. From the second chapter, considering the work of the two main researchers Tara Ali Yahiya et al. and Niyato et al., in [26], [9], [23] and [24] it is observed that there exists a problem in the previous resource sharing model used. The users of one of the networks involved in integration are blocked unfairly in the existing models. Briefly, this problem occurs when resources allocation is random without any pre-defined criteria, where one network captures most of the bandwidth and the other one starves for resource.

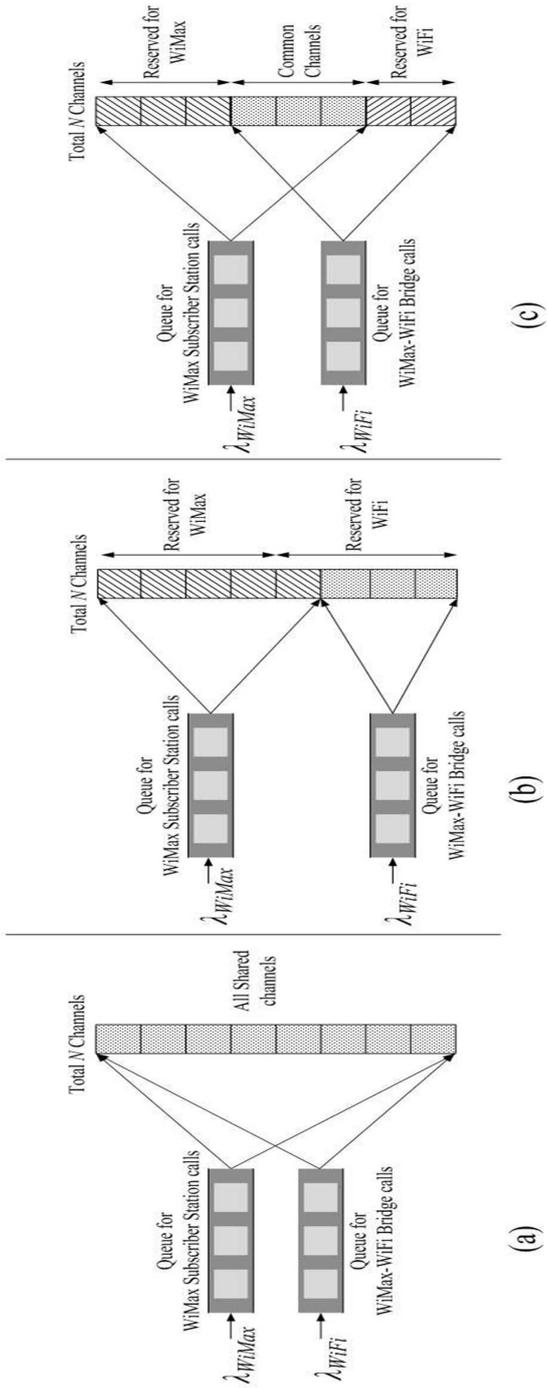


Figure 3.2: a) Complete Sharing, b) Complete Partitioning, c) Hybrid Sharing.

This problem is named as starvation problem in this thesis. The detailed description of the starvation problem will be provided in the subsection below.

First Come First Serve Model

First come first serve model, is based on the hybrid sharing model which is explained in section 3.3.1. As seen in Figure 3.3, in the first come first serve model a set of P channels from a total of N channels are reserved for users from the networks that are integrated. There can be several networks that are being integrated. However, this thesis focuses on the only two networks being integrated which are Wi-Fi and WiMAX. The remaining $N-P$ channels are free to be accessed by users of either Wi-Fi or WiMAX network based on a first come first serve policy. Now, the P reserved channels between users of the two networks can be divided in two ways. In the first way, the P channels can be divided equally between users of Wi-Fi and WiMAX networks, where each network gets $P/2$ reserved channels for their users. In the second way, the P channels are divided unequally among the users of both the networks.

The authors in the previous work [9] use the second way of division so that users of one network can be given more priority. They give users of Wi-Fi network more channels in the division than the channel given to WiMAX. The reason being that Wi-Fi users are not directly connected to the Internet. They have to go through WWB, the integrated bridge, to reach to WiMAX and the WWB supports multiple Wi-Fi users. They assume that at any given time, the traffic on WWB would be high and the bandwidth request for WWB would be higher since it has to serve many 802.11 end users. WWB operates as an intermediate base station in itself in contrast to the WiMAX SS which can be an just an individual end user.

From Figure 3.3, it can be seen that out of a total of seven channels represented by N , three channels are given to 802.11 users as compared to only two for WiMAX users. 802.11 users are given more channels under the assumption that WWB which supports multiple 802.11 users have higher traffic. There are two shared channels that can be used by users of

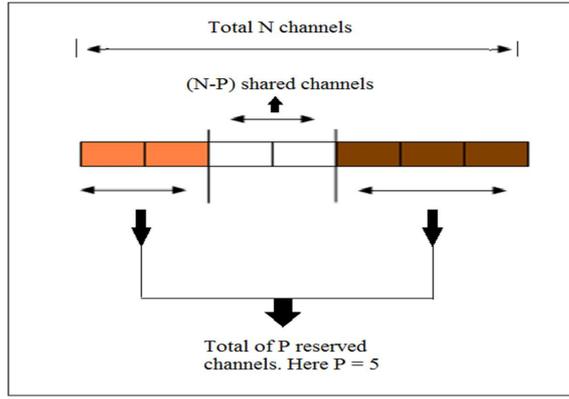


Figure 3.3: Threshold based channel distribution between 802.11 and 802.16 users. N = Total number of channels.

either network on a first come first serve basis. Since the two shared channels can be used by users from either networks, in a worst case scenario, WiMAX users end up getting only two channels always and Wi-Fi users get five channels. This division would prove unfair because with the increase in arrival rate of 802.11 users, 802.16 users are blocked significantly compared to 802.11 users which indirectly shows that 802.16 users are starved of resources. The first come first serve model described above is analyzed using Markov Models. The description of the parameters and the equations used to calculate the parameters in the analysis is mentioned in Chapter 4 of this thesis.

For the analysis of first come first serve model, the arrival rate of 802.11 users is kept fixed and the arrival rate of 802.16 users is varied. The fixed arrival rate of 802.11 users are kept high in order to incorporate the assumption that the authors make where WWB representing 802.11 users traffic (defined in system model) will always be experiencing high load. The graph shown in Figure 3.4 compares the variation of 802.11 with 802.16 blocking probability when the arrival rate of 802.16 users (represented as λ_{WiMAX} in Figure 3.4) increase. (In this thesis, blocking probability is used as the statistical probability that a user does not get a channel for transmission due to insufficient transmission resources)

From the graph in Figure 3.4, it can be observed that blocking probabilities of both 802.16 and 802.11 increases when the arrival rate of 802.16 users is increased. This is

because when the rate of arrival of 802.16 users increase, the probability of more channels being occupied increases which in turn reduces the number of channels available to serve the newly arriving users. This causes the newly arriving 802.16 users to be blocked due to unavailability of free channels for transmission.

Now, when the blocking probability of 802.11 users is compared with 802.16 users, it is observed that the blocking probability of 802.16 is higher than that of 802.11. This is because more number of channels are already reserved for 802.11 and then as the traffic of 802.11 increases they start using all the shared channels too which starves the 802.16 user. The study of performance of first come first serve model is a repetition of the existing work, but it is analyzed in the light of the failure of existing models on the basis of resource starvation of 802.16 users. This result helps in conforming the theory that if the existing models are used under high load conditions the 802.16 users will experience unfair and significant blocking compared to 802.11 users and thus 802.16 users indirectly experience starvation.

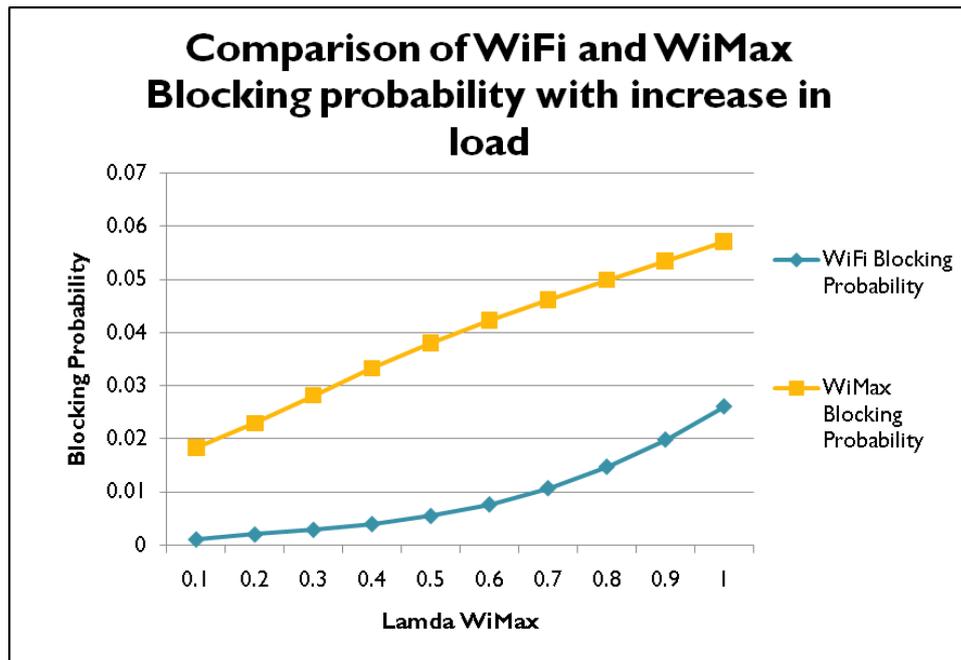


Figure 3.4: Direct comparison of blocking probability of 802.11 and 802.16 users with variation in arrival rate of 802.11 users.

The authors assumed that providing more reserved channels to the Wi-Fi users from the P channels, will offer better connectivity or lesser blocked requests for Wi-Fi networks. The results of the authors simulation of the first come first serve model confirm their assumption. However, the authors do not consider a scenario of congested network with heavy traffic. Under these conditions the resource sharing policy becomes heavily biased to Wi-Fi which increases the number of WiMAX requests being blocked by a significant amount. So, this thesis tries to provide a solution by suggesting additions to the already existing models of resource sharing so that under condition of heavy traffic the resource sharing model provides unbiased service to both the Wi-Fi and WiMAX users.

3.3.3 Forced Sharing Model

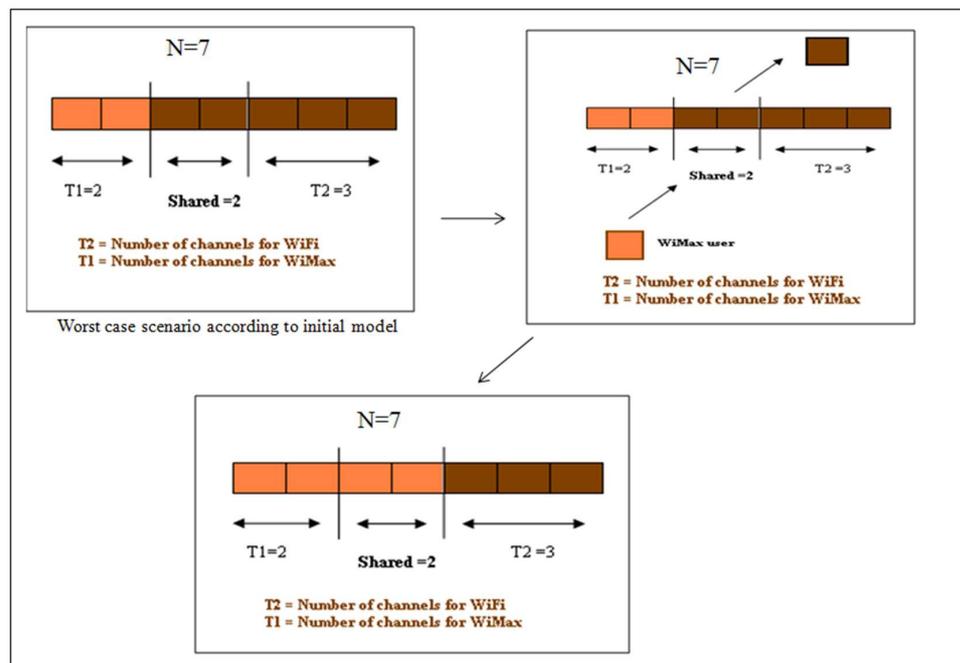


Figure 3.5: Forced sharing mechanism where WiMax user has more priority in the shared channels and is replacing a WiFi user

The previous model appear biased to 802.11 users under heavy traffic conditions because the resource sharing is not well defined. The previous model explained the the last

section also does not take into consideration a sharing policy for high network load condition. Therefore, this model focuses on designing a sharing mechanism within the common channels such that the model shares the available resource in an unbiased manner between the different users. In this model ,if one of the networks gets more priority through more reserved channels the other network will adopt an aggressive sharing mechanism in the common channel region. The aggressive sharing mechanism will force the users with higher priority to be dropped when the traffic of the network experiencing starvation increases . As an example from Figure 3.5 if WiFi network is given three channels out of total seven channels, according to earlier distribution the WiFi users get a minimum of five channels including the common channels in the worst case. This is because all the reserved as well as shared channels were distributed on a FIFO (First In First Serve) basis. According to the FIFO mechanism if the arrival rate of users from WiFi network is more than that of WiMax then WiMax users get only two channels in the worst case. In our model,WiMax which has lower priority, even in the worst case would obtain four channels rather than two in the previous model since they force the WiFi users to be dropped when they experience starvation i.e when the user traffic of WiMAX increases and no channels are available in shared space. So finally WiMax will have four channels and WiFi will have three channels according to the diagram below, which ensures that the users of WiMAX network are not starved when the WiFi users get unfair advantage. Figure 3.5 given above will represent the above discussed forced termination model. This theoretically shows that channels are shared in an unbiased manner between the users even under a situation of highly congested network. This will be proved analytically using simulation results in Chapter 4.

3.3.4 Prioritized Sharing Model

The problem with the complete partitioning (CP), complete sharing (CS) and Hybrid Sharing (HS) schemes that we mentioned earlier are that they solve specifically either channel utilization or blocking probability issues. They do not tackle both the problems simultaneously. In CP scheme the un-utilized channels of one class can not be used by

other class of users and therefore the capacity is wasted. In CS, during unbalanced loads, the class of users with low traffic suffer resource starvation. In HS scheme the QoS for each class is guaranteed but this is achieved at the expense of inefficient total system utilization. Since the forced termination model also is an extension of a hybrid sharing model, the channel utilization problem still exists even though the blocking probability of the involved networks have improved. Our proposed Prioritized Sharing (PS) takes these two problems into account.

It is important to note the difference between the terms *shared*, *reserved* and *prioritized*. *Shared* means that the channels can be accessed by anyone on a first come first serve basis. *reserved* means that the channels are allocated to a particular class of users and no users of any other class can access them. *prioritized* means that the channels can be accessed when they are free but a user can be dropped and queued to accommodate other class of users if certain pre-defined criteria is met.

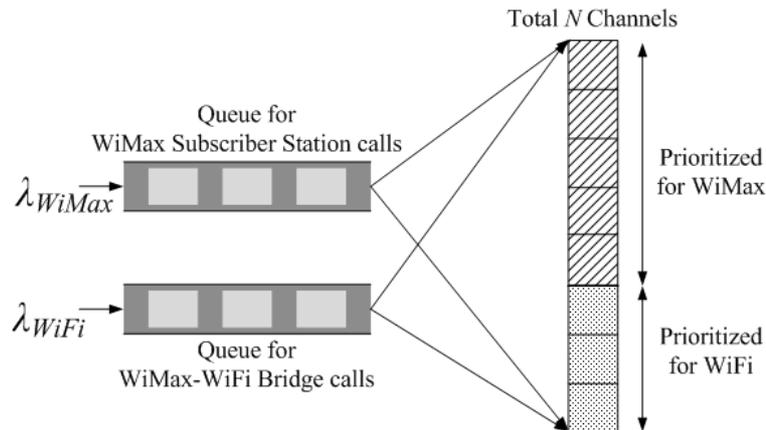


Figure 3.6: Prioritized channel allocation Model.

In PS scheme as shown in Fig. 3.6, both the WiMax and Wi-Fi users are allowed to access all the channels if they are free on first come first serve basis like in CS scheme. This allows the users to use the full capacity of the system. In PS scheme, Quality of Service is achieved by *prioritizing* the channels to WiMax and Wi-Fi users according to their respective QoS requirements rather than strict reservation. In Fig. 3.6, WiMax has

five prioritized channels and WiFi has three, but all the eight channels can be accessed by any user if they are available.

The criteria for call admission and forced termination for WiMax users in Prioritized resource sharing algorithm is stated as follows:

1. A WiMax call is admitted if the at least one channel is free.
2. A WiMax call is admitted if the at least one channel is free.
3. If all the channels are full and if the number of channels occupied by WiMax users is already greater than or equal to the number of prioritized channels the call is blocked.

The same procedure holds for Wi-Fi traffic also. Since, the WiMax and Wi-Fi are allocated a predefined number of prioritized channels, those many channels are assured at the least in any traffic conditions. Hence, QoS of service is achieved as in CP case as will be observed in the simulation results.

In the next chapter we design analytical models for the different resource allocation schemes that we describe above. The results of the simulation of the analytical models will be described and then we discuss how it improves the channel utilization and blocking probabilities.

CHAPTER 4
STUDY OF THE IMPROVEMENT IN CHANNEL UTILIZATION AND NETWORK STARVATION
USING THE NEW SHARING MODELS

As discussed in Chapter 3, most commonly used resource sharing models in homogeneous networks (networks in which all components use same protocol or IEEE standard) are complete sharing, complete partitioning and hybrid sharing shown in Figure ???. From Chapter 3, it is also observed that a direct adoption of the models used in homogeneous networks will not work efficiently in integrated networks. In section 3.3.1, the inefficiency of direct adoption of resource sharing models from homogeneous networks into integrated networks is discussed using the existing first come first serve model suggested by Ali Yahiya et al. in [9] and [26]. The first come first serve model is based on the hybrid sharing concept as mentioned in Chapter 3. It has a total of N channels divided into P reserved channels and $(N-P)$ shared channels. The P channels can be divided equally between users of Wi-Fi and WiMAX network or such that more reserved channels are given to a preferred network.

In [9] and [26], the authors assumed that providing more reserved channels to the Wi-Fi users will offer better connectivity by reducing the number of blocked requests from the Wi-Fi network. To confirm their assumption, the authors' simulated the first come first serve model and showed that the blocking of Wi-Fi traffic is under 2% (which is the accepted rate for voice and calls in cellular networks). However, in a congested network scenario, due to heavy traffic from Wi-Fi stations, the resource sharing policy becomes heavily biased towards Wi-Fi users which significantly increases the number of WiMAX requests being blocked. The unfair blocking of WiMAX under conditions of heavy Wi-Fi traffic is shown in the graph in Figure 3.4. So, the motivation for the work in this thesis is to suggest changes to the already existing first come first serve model to provide an efficient solution

for unbiased resource sharing between Wi-Fi and WiMAX users under conditions of heavy traffic.

In Chapter 3, two different resource sharing models were suggested as an improvement over the first come first serve model. The two new models are Forced termination and Prioritized sharing models. This chapter provides an analytical model for studying the efficiency of the two new resource sharing models. Call blocking probability and channel utilization are the dependencies used to analyze resource sharing efficiency of the proposed models. Measure of call blocking probability indicates if either Wi-Fi or WiMAX user is blocked unfairly and the total channel utilization indicates if the network resource is utilized to its maximum. Typically, a first step in the analysis via computational probability is to model the behavior of the system as a Markov chain.

4.1 Markov Models

A Markov chain is a random process where all information about the future is contained in the present state (i.e. one does not need to examine the past to determine the future). To be more exact, if a process has the Markov property it means that the future states of the process depend only on the present state, and are independent of past states. Since it is a stochastic process all state transitions are probabilistic. Modeling as a Markov chain is possible when system parameters such as service demand (time needed to complete a job) and interarrival time (time between two consecutive arrivals of jobs) are exponential random variables or some combinations of exponential random variables. By analyzing the Markov chain, we can understand the performance of the system with respect to channel utilization and call blocking probability.

To analytically study forced termination and prioritized sharing models, a traffic model for wireless networks has to be developed first. The two main characteristics of a traffic model are:

1. Call arrival process,

2. Call holding time

Prior research indicates that call arrival in wireless networks follows a Poisson process [9], [26], [23]. However, for call holding time, two different approaches can be found. One approach is to model the call holding time (service rate) as general independent identically distributed (iid) process. This approach has been intensively studied by Fang et al. [15], Lin et al. [16], Fang et al. [17], and Bolotin in [18]. The second approach is to model the call holding time as an exponential distribution. This method has been extensively used by Hong and Rappaport [4], Zeng et al. [8], and Nanda [19]. Both approaches have their own advantages. In this thesis call holding time is modeled as an exponential distribution for simplicity of analysis. Also, in the previous works related to resource sharing in integrated networks service rate is modeled as exponential distribution [9], [26].

With the base of the analytical modeling established, the next sections will describe in detail the forced termination model, the prioritized model, the Markov models representing them and results of analysis of each model.

4.2 The Forced Termination Model

In this section, a Markov model representing the forced termination model is designed. The Markov model is simulated using MATLAB. The first come first serve model has been analyzed in [9] and [26] from the perspective of Wi-Fi users. In section 3.3.1, we analyze the first come first serve model and observe that the first come first serve model is biased towards Wi-Fi users traffic when the network is congested. Therefore in this section a forced termination model which improves over the drawbacks of first come first serve model is designed. The proposed model provides a sharing mechanism within the common channels such that the users of Wi-Fi network which are given more reserved channels, gets lesser priority in the common channels. Common channels are another term used for shared channels which can be accessed by both Wi-Fi and WiMAX users. In first come first serve model, Wi-Fi users occupy all the shared channels as well as channels reserved for the them, when the network is congested by high arrival rate of Wi-Fi users. However,

in forced termination model since WiMAX users are given higher priority in the shared channels they can forcefully drop or terminate a Wi-Fi user service in the shared channels. But, this privilege is provided to WiMAX users only when all the channels are full and Wi-Fi users have occupied all the shared channels.

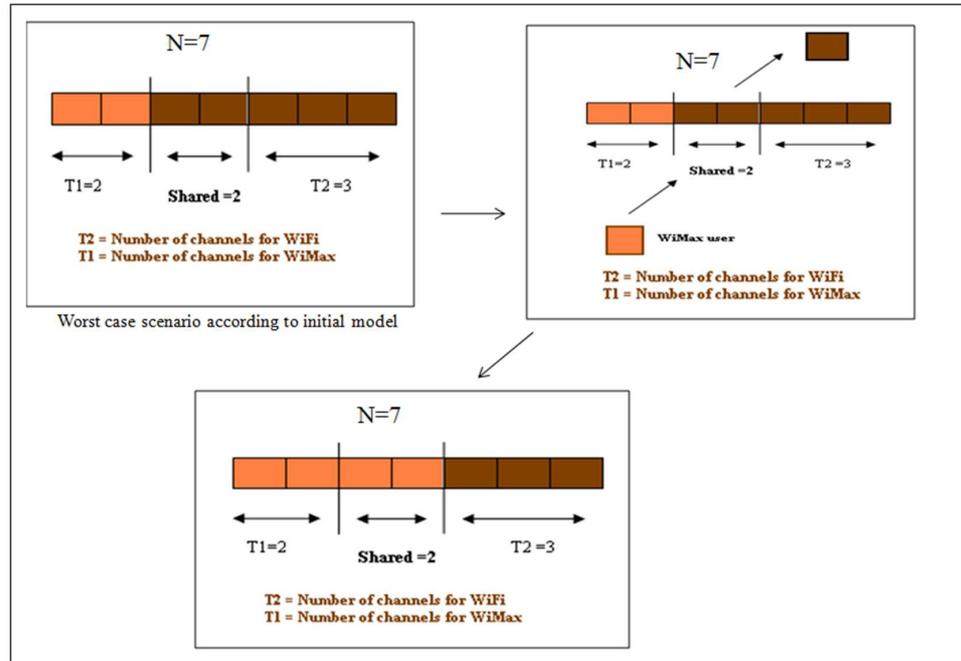


Figure 4.1: Forced sharing mechanism where WiMax user has more priority in the shared channels and is replacing a WiFi user

For example in Figure 4.1, if WiFi network is given three channels out of seven, according to first come first serve model the Wi-Fi users get a minimum of five channels including the common channels. The channels are distributed on a first come first serve basis. According to the first come first serve mechanism if the arrival rate of WiFi users is more than that of WiMax users, then WiMax users get only two channels in the worst case scenario. In our model even in the worst case scenario, WiMAX with higher priority would obtain four channels rather than two as shown in Figure 4.1. So finally WiMax will have four channels and WiFi will have three channels, which indirectly implies an unbiased sharing of resources between Wi-Fi and WiMAX users in terms of channel bandwidth. The forced

termination model is analytically modeled using Markov chains to observe the unbiased sharing of channels between Wi-Fi and WiMAX users.

In order to design the Markov model, it is necessary to understand all the parameters in the forced termination model. Figure 4.1 represents the forced termination model. The lighter shaded channels are reserved for WiMAX users and the darker shaded channels are reserved for Wi-Fi users. The number of channels reserved for WiMAX users is denoted by t_1 and that for Wi-Fi users by t_2 . It can be observed from the Figure 4.1 that more channels are reserved for Wi-Fi users i.e. $t_2 \geq t_1$. From the discussion in Section 3.3.1, the reason for providing more channels for Wi-Fi users is made clear. However, it can also be seen that using forced termination model, when more WiMAX users arrive they can drop Wi-Fi users being served in the shared channels and thereby not be blocked due to unavailability of channels as compared to first come first serve model.

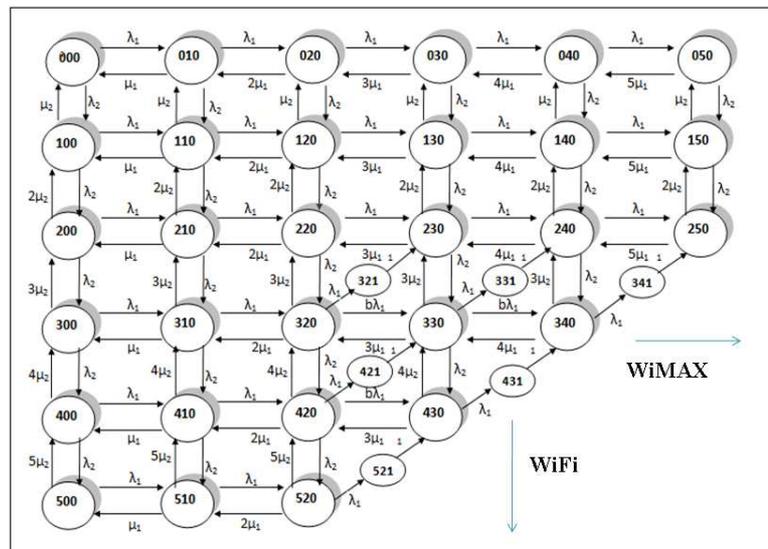


Figure 4.2: Markov Model representing Forced Termination Sharing

In Figure 4.2, each state in the system is represented by a three-tuple of non-negative integers (i, j, k) , where

- i is the number of channels used by WiMAX users or the number of WiMAX users served by the system at any instant.

- j is the number of channels used by Wi-Fi users or the number of Wi-Fi users being served by the system at any instant.
- k represents the states in which users are dropped. k takes two values 0 and 1. If k is 1, then that state represents a dropped Wi-Fi user.

Value ranges of the discrete parameters are $i \in [0, N - t2]$, $j \in [0, N - t1]$ and $k = [0, 1]$. As shown in Figure 4.2, the first come first serve model is represented by a three dimensional Markov chain. The total number of possible states in the Markov chain shown in Figure 4.2 is given by,

$$TE = [((N-t1)+1) \times t1] + \frac{1}{2} [(((N-t1)+2) \times ((N-t2)+1))] - \frac{1}{2} [((t2 \times (t2+1)))] + (N-t1-t2)+1 \quad (4.1)$$

Based on the Markov chain diagram in Figure 4.2 the number of equations and number of states can be found by substituting the values

- λ_1 or λ_{w1} is the arrival rate of WiMAX users,
- λ_2 or λ_{w2} is the arrival rate of Wi-Fi users,
- μ_1 or μ_{w1} is the service rate of WiMAX users, and
- μ_2 or μ_{w2} is the service rate of Wi-Fi users.
- $P(i,j)$ represents state transition probability which is the probability of a user staying in a state (i,j) .

In Figure 4.2, consider a state (2,2). This state indicates that there are two WiMAX users and two Wi-Fi users in this system. When a new WiMAX user arrives with arrival rate λ_{w1} the system moves from state (2,2) to state (3,2) since i represents the number of WiMAX users in the system. Similarly, when a WiFi user arrives with arrival rate λ_{w2} the system moves from state (2,2) to state (2,3). When the WiMAX user is serviced, the system moves back to state (2,2) from state (3,2) with probability μ_{w1} . States in which

Equation 1

For $i = 0, 0 \leq j \leq N - t_1$

$$P_{ij} [\lambda_2 + \delta_1 \lambda_1 + j\mu_1] = \delta \cdot \lambda_1 \cdot P_{i,j-1} + (j+1) \cdot \mu_1 \cdot P_{i,j+1} \cdot \delta_1 + (i+1) \cdot \mu_2 \cdot P_{i+1,j}$$

If $j=0$ then $\delta=0$ else $\delta=1$

If $j=N - t_2$ then $\delta_1=0$ else $\delta_1=1$

Equation 2

For $j=0, 0 \leq i \leq N - t_2$

$$P_{ij} [\lambda_1 + \delta \lambda_2 + i\mu_2] = \lambda_2 \cdot P_{i-1,j} + (i+1) \cdot \mu_2 \cdot P_{i+1,j} \cdot \delta + (j+1) \cdot \mu_1 \cdot P_{i,j+1}$$

If $i=N-t_2$ then $\delta=0$

Equation 3

For $(i+j) < N$ and $0 < j \leq N$ and $0 < i \leq N - t_2$

$$\begin{aligned} P_{ij} [\delta_1 \lambda_1 + \delta_2 \lambda_2 + j\mu_1 + i\mu_2] = \\ = \lambda_1 \cdot P_{i,j-1} + \lambda_2 \cdot P_{i-1,j} + \delta_1 \cdot P_{i,j+1} \cdot (j+1) \cdot \mu_1 + \delta_2 \cdot P_{i+1,j} \cdot (i+1) \cdot \mu_2 \end{aligned}$$

If $j=N - t_1$ then $\delta_1=0$

If $i=N - t_2$ then $\delta_2=0$

Equation 4

For $(i+j)=N$,

$$P_{ij} [i\mu_2 + j\mu_1] = \lambda_1 \cdot P_{i,j-1} + \lambda_2 \cdot P_{i-1,j}$$

Figure 4.3: Balance equations representing first come first serve model

the sum of i and j is equal to N i.e. state $(3,4)$, state $(4,3)$, state $(2,5)$ and state $(5,2)$, both Wi-Fi and WiMAX users are blocked. However, in the last state at each row, for example at state $(5,0)$, only WiMAX users get blocked since they have used all available channels. The available channels include three shared channels and two channels reserved for WiMAX (which provide a maximum of five channels for WiMAX). Any WiMAX user arriving after this stage is blocked. Similarly at state $(0,5)$ all Wi-Fi users are blocked according to Figure 4.2, since Wi-Fi users would have used all their available channels. From this discussion we derive the formula for blocking probability of Wi-Fi and WiMAX given by the equations in Figure 4.4.

<u>Blocking Probability</u>	
BP (WiMAX)	$= \sum_{\substack{0 < i < t_2 \\ j = N - t_2}} P(i, j) + \sum_{\substack{t_2 < i < N - t_1 \\ (i+j) = N}} P(i, j)$
BP (Wi-Fi)	$= \sum_{\substack{0 < j < N - t_1 \\ i = N - t_1}} P(i, j) + \sum_{\substack{t_1 < j < N - t_2 \\ (i+j) = N}} P(i, j)$
<u>Throughput</u> = P(Not blocked or Serviced) * Service rate	

Figure 4.4: Equations to calculate Blocking probability of both WiFi and WiMAX users

4.2.1 Simulation And Results Of Forced Termination Sharing Model

Blocking probability of WiMAX and Wi-Fi users using Forced Termination Model

In the first come first serve model discussed in section 3.3.1, due to biased channel bandwidth distribution between Wi-Fi and WiMAX users, WiMAX users experience unfair blocking. This is because all shared channels get occupied by Wi-Fi users and WiMAX users are starved in terms of channel availability. In the first come first serve model suggested by Yahiya et al. [9], the authors' make two assumptions, which are:

- The traffic on WWB in Figure 3.1, through which Wi-Fi users connect to WiMAX BS, have higher traffic (arrival rate) as compared to the WiMAX BS.
- More reserved channels are allocated for Wi-Fi users than for WiMAX.

The reasons for these assumptions are discussed in section 3.3.1. The forced termination model is designed to overcome the drawbacks of the first come first serve model. Therefore,

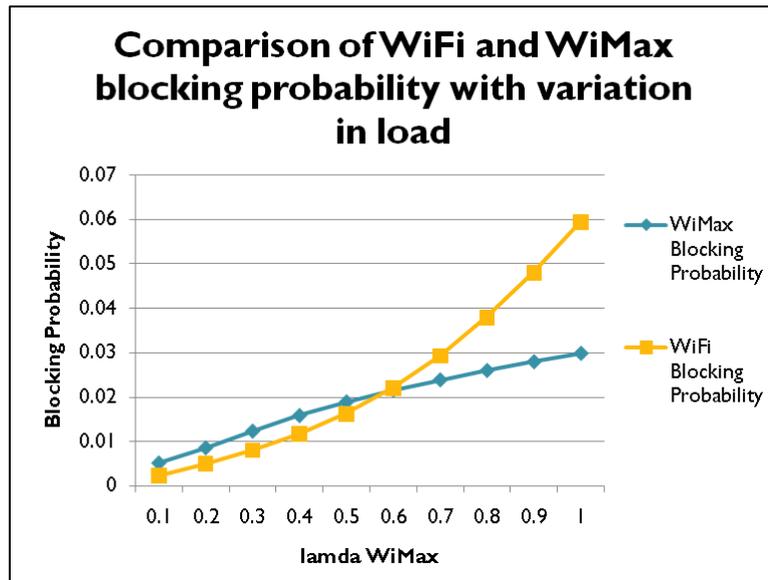


Figure 4.5: 802.11 blocking probability variation with increase in number of reserved channels

the Markov chain representing the forced termination model is simulated using the same assumptions listed above to give a fair comparison with first come first serve mode. The arrival rate of Wi-Fi users, λ_{w2} is kept as 0.8 and the arrival rate of WiMAX users, λ_{w1} is increased from 0.1 to 1. The service rate μ_{w1} and μ_{w2} are kept as 0.05 as per the simulations in first come first serve model suggested by Yahiya et al. [9].

The graph in Figure 4.5 shows variation of Wi-Fi and WiMax user blocking probability with increase in WiMAX user traffic in forced termination model. Comparing the graphs in Figure 4.5, representing forced termination model and Figure 4.6, representing first come first serve model, it is observed that the blocking probability of WiMAX reduces significantly using forced termination model. Using forced termination model it is observed that both the Wi-Fi and WiMAX users experience almost similar blocking probability. This implies that either both Wi-Fi and WiMAX users are being served in an unbiased manner or they are not being served (blocked) in an unbiased manner. This shows that forced termination model is successful in achieving the objective for which it was designed, which is to achieve

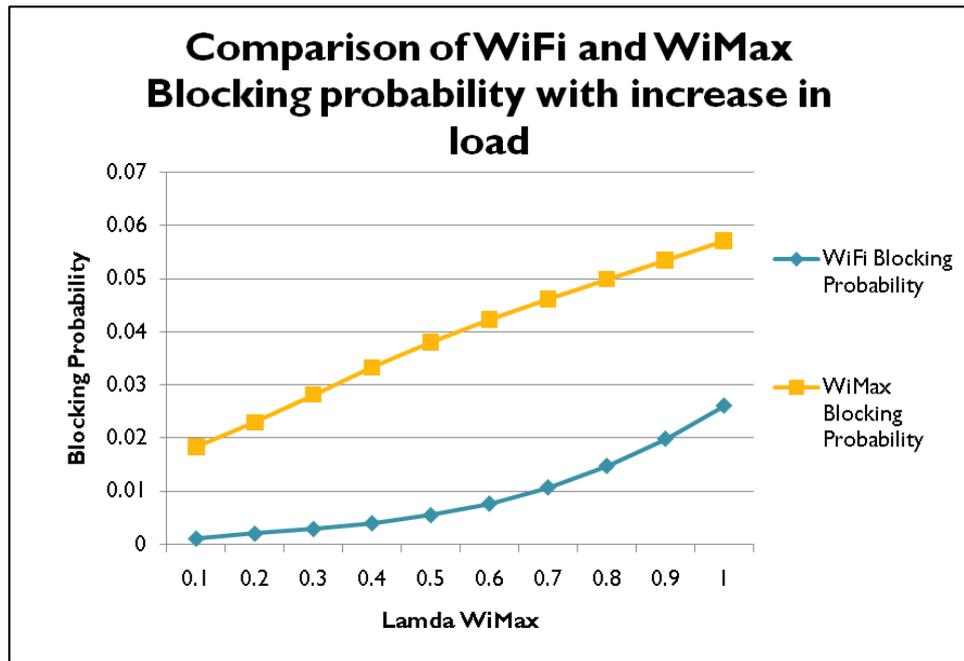


Figure 4.6: Direct comparison of blocking probability of 802.11 and 802.16 users with variation in arrival rate of 802.11 users.

unbiased resource distribution between Wi-Fi and WiMAX users even when Wi-Fi user traffic is high compared to WiMAX.

Effect of increased available channels on WiMAX and Wi-Fi users blocking probability

The effect of variation in the number of channels on the blocking probability of Wi-Fi and WiMAX has not been studied by Yahiya et. al in [9] for the first come first serve model. The knowledge of this effect can help service providers to estimate the minimum QoS they can provide to the subscribers in terms of call blocking probability. This section studies the effect of the variation in the number of available channels on the blocking probability for WiMAX users. From the graph in Figure 4.7 it is clear that with increase in number of available channels, there is a decrease in the blocking probability of WiMAX users.

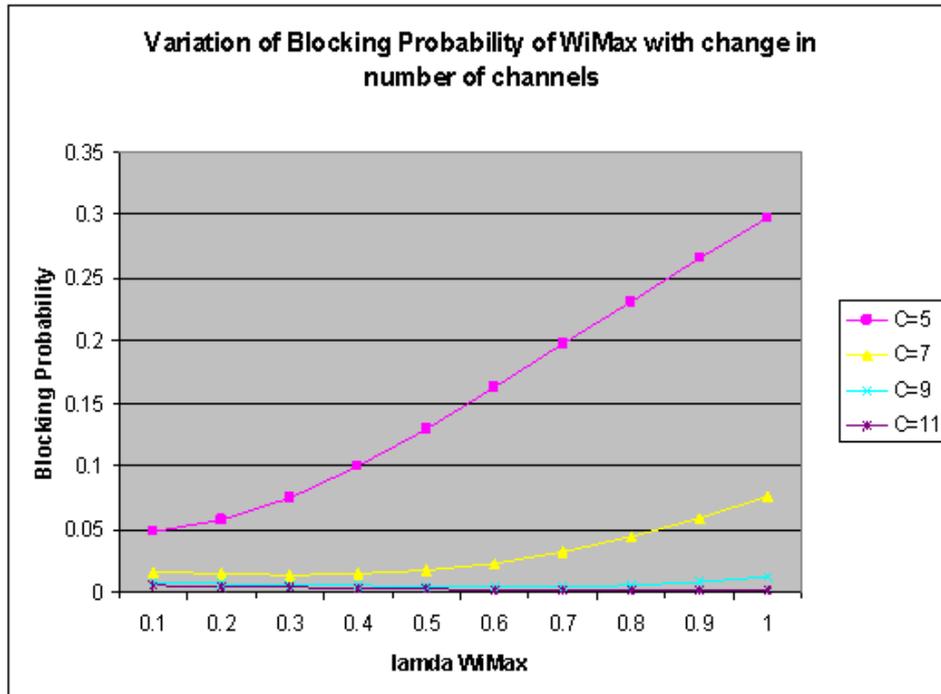


Figure 4.7: 802.16 blocking probability variation with increase in number of channels

Variation of reserved channels on blocking probability of WiMax and WiFi Users

The graphs in Figure 4.8 shows the variation of blocking probability experienced by both WiMAX and Wi-Fi users with the change in number of channels reserved for each of the network. The blocking probability is plotted against the arrival rate of the WiFi and WiMAX users. The first graph in Figure 4.8 studies how the blocking probability of WiMAX user changes with respect to two factors. The first factor is number of reserved channel and the second factor is change in arrival rate of WiMAX users. This study can be done by choosing an arrival rate on the first graph in Figure 4.8. For a 0.8 arrival rate of WiMAX users, we observe the change in WiMAX blocking probability with variation in number of channels reserved for WiMAX. It is seen that when the number of channels reserved for WiMAX increases the blocking probability of WiMAX users decreases because for a fixed number of users in the system more channels are provided. More channel provided to a

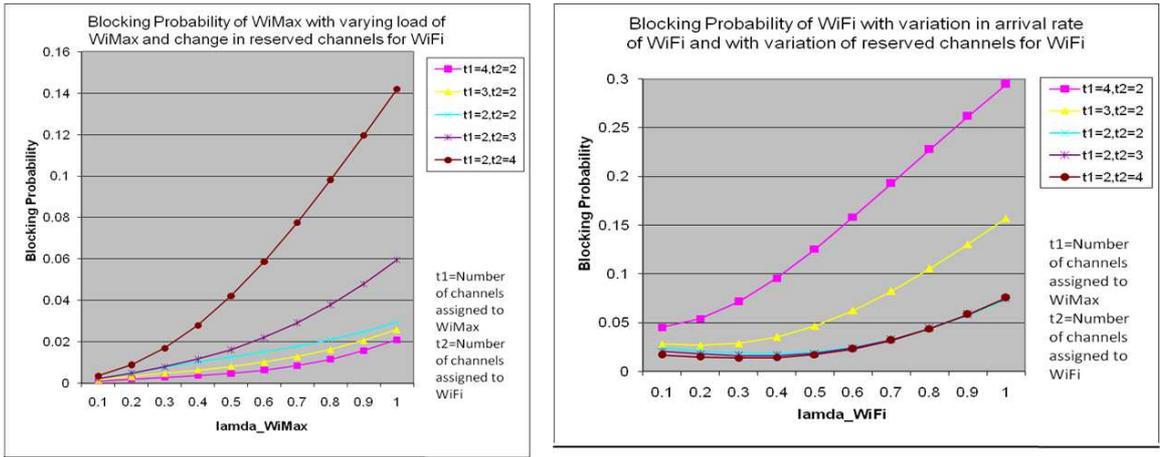


Figure 4.8: (a)Blocking probability of WiMax with change in WiMax load as well as change in channels reserved for WiFi users.(b)Blocking probability of WiFi with change in WiFi load as well as change in channels reserved for WiFi users.

fixed number of users increases the probability that they get served and therefore decreases blocking.

The blocking probability of WiMAX users can also be studied against the change in WiMax user traffic keeping the number of reserved channels a constant. The blocking probability of WiMAX users increase with increase in WiMAX arrival rate because more users are competing for a fixed number of channels. The trend indicated by the analytical study shows similarity in the pattern of variation of blocking probability of 802.16 and 802.11, which is blocking probability increases with the increase in load. In the case of 802.11 blocking probability variation with channel reservation, the difference is that for more channels reserved for 802.16 the blocking probability of 802.11 users increase. This is because 802.11 users end up having lesser channels when more channels are reserved for 802.16 users and moreover 802.16 has more priority in the shared channels. The same trend is observed in Wi-Fi users also.

Throughput improvement of WiMAX users

In the forced termination model, when the WiMAX uses get starved as their traffic increases the WiMAX users forcefully drop WiFi users who already have higher priority in

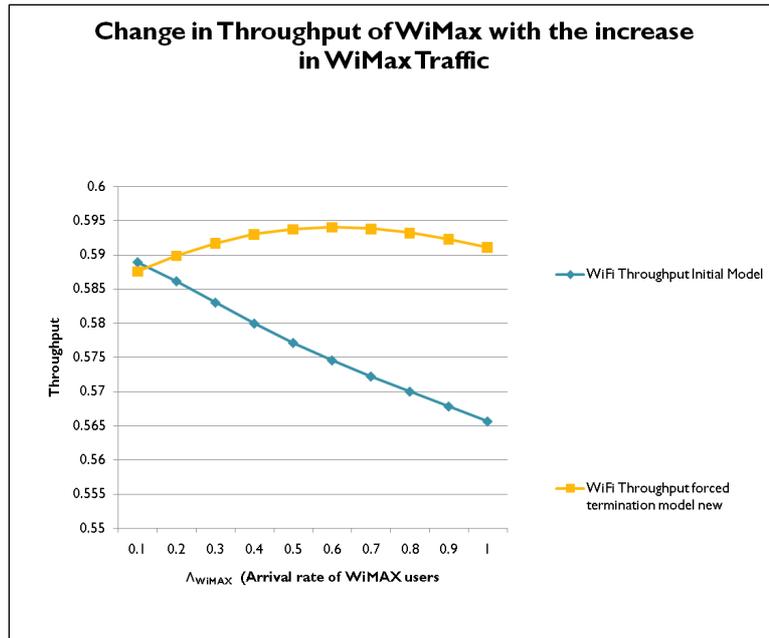


Figure 4.9: Comparison of WiMAX throughput between first come first serve model and forced termination model

terms of number of reserved channels. This results in resource starved WiMAX users getting more channels than in the first come first serve model, and their blocking probability reduces significantly. The throughput of WiMAX users is calculated from the equations in Figure 4.4. Throughput is given obtained by taking the product of service rate and the probability that a user is served. The graph in Figure 4.9, compares the throughput of WiMAX users using forced termination model to the first come first serve model. The throughput of WiMAX users is observed with variation of WiMAX user traffic. The arrival rate of Wi-Fi users is kept high (0.8) as the assumptions made in first come first serve model by Yahiya et al. The WiMAX throughput increased by an average of 30% using forced termination model. This can be attested to the fact that WiMAX users get more channels in forced termination model than they get in first come first serve model. Therefore more WiMAX users get served.

However, the WiFi users that used to get free access of the shared channels apart from channels reserved for them, will experience an increase in blocking probability as shown in

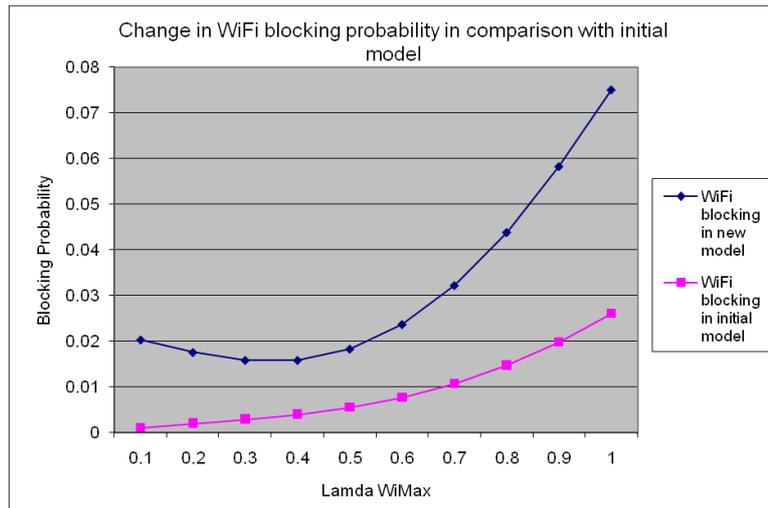


Figure 4.10: Comparison of Wi-Fi blocking probability between first come first serve model and forced termination model

Figure 4.10. The graph in Figure 4.10 shows the comparison of WiFi blocking probability in forced termination with first come first serve model. Even though the Wi-Fi users experience an increase in blocking probability they will receive the minimum guaranteed channels which are reserved for them. The number of reserved channels for Wi-Fi users is more than the channels reserved for WiMAX users in forced termination as well as first come first serve model.

Throughput of WiMAX and Wi-Fi with the change in number of channels reserved

An alternative analysis of the forced termination model would be to keep the arrival rates of both WiMAX and Wi-Fi users constant and observe the variation of throughput of both the networks. The variation in throughput is analyzed with the change in number of channels reserved for both the network. When more channels are reserved for WiMAX the throughput of WiMAX increases but throughput of WiFi decreases since they are given lesser reserved channels. Similarly, when more channels are reserved for Wi-Fi the throughput of Wi-Fi increases but the throughput of WiMAX decreases. The graphs in Figure 4.11 shows that when the reserved channels are equally distributed between WiFi and WiMAX

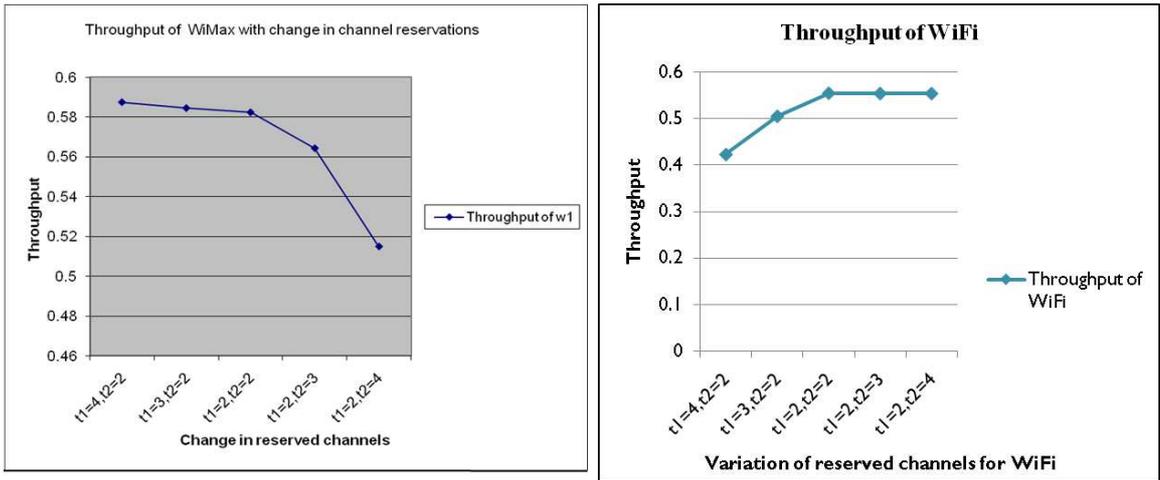


Figure 4.11: (a)Variation of WiMax throughput with change in channel reservation. (b)Variation of WiFi throughput with change in channel reservation.

users, the throughput of both Wi-Fi and WiMAX network is the same. All the other ways of distribution of reserved channels between both the users result in either the throughput reducing or staying almost constant after the maximum value of throughput.

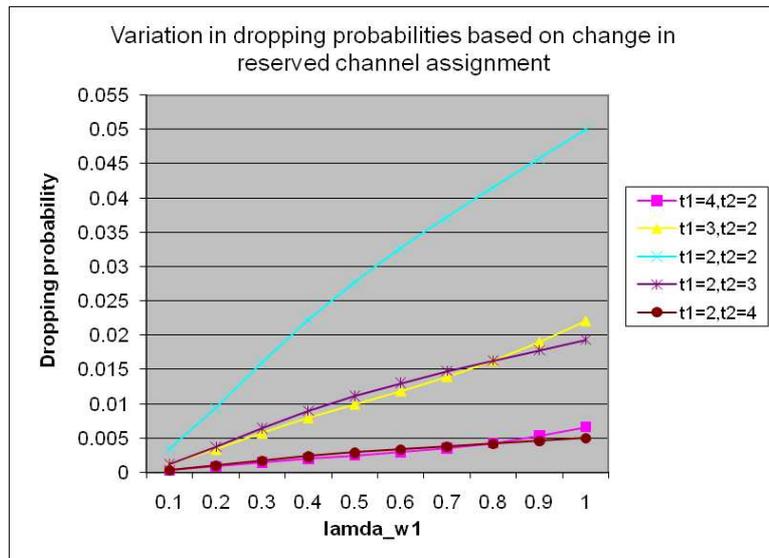


Figure 4.12: 802.11 dropping probability variation with increase in number of reserved channels

However, considering the dropping probability shown in Figure 4.12, it is observed that dropping probability is maximum when the reserved channels are distributed equally

between Wi-Fi and WiMAX users. This can be explained by the fact that when the reserved channels are equally divided between Wi-Fi and WiMAX, the number of shared channels become highest when compared to any other division. When there are more shared channels, the probability that the Wi-Fi user gets dropped increases proportionally. So equal division of reserved channels can be beneficial for throughput of WiMAX users but it increases the dropping probability of WiFi users too. Therefore, the distribution of reserved channels should be made adaptive to the network characteristics such as traffic. It can also be varied based on the network condition and requirement of the subscribers too.

The forced termination model proves beneficial for the WiMAX users in terms of unbiased resource sharing and improved throughput. The forced termination model provides an efficient improvement over the drawbacks of first come first serve model. The first come first serve model is designed based on hybrid sharing policy discussed in chapter 3. From a total of N channels, P channels are reserved for different users in the network and the remaining $(N-P)$ channels are maintained as shared channels which can be accessed by any user when they have exhausted the number of channels reserved for them. In first come first serve model, the users of one network are not allowed to use the channels reserved for users from other network even when they are not being used. This leads to under utilization of the spectrum. The next section discusses another model proposed to improve the channel utilization in integrated wireless networks.

4.3 Prioritized Sharing

In prioritized sharing instead of dividing the N total channels into shared and reserved channels as in first come first serve model shown in Figure 4.13, the N total channel are divided among the users of the networks that are integrated. The channels are divided among the users of both Wi-Fi and WiMAX network based on pre-assigned priorities. But, the prioritized model differs from first come first serve model or hybrid model by avoiding allocation of a specific set of shared channels, instead in prioritized sharing any of the unused channels or free channels act as shared channels. For example, in Figure 4.14 and

Figure 4.15, we see that from total of twelve channels, any of five channels are prioritized for Wi-Fi and the remaining seven channels prioritized for WiMAX users. The prioritized sharing model is explained in detail using three possible scenarios. The scenarios are:

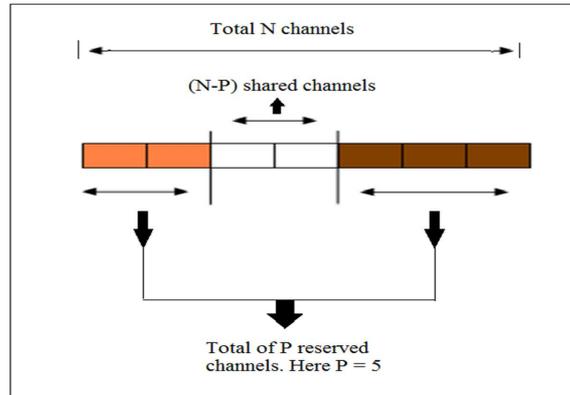


Figure 4.13: Threshold based channel distribution between 802.11 and 802.16 users. N = Total number of channels.

- Scenario 1: Wi-Fi users have occupied the number of channels allotted for them which are seven and WiMAX users have also occupied all the five channels allotted for them. Here all twelve channels are occupied and the both the networks have occupied all the allotted channels for them. In this situation if a new Wi-Fi or WiMAX users arrives then they are blocked due to no available channels for transmission.
- Scenario 2: Wi-Fi users have occupied only four out of the seven channels prioritized for them and WiMAX has occupied all five channels assigned to them. If a WiMAX user arrives then it is allowed to occupy any of the 3 free channels which are not occupied by Wi-Fi.
- Scenario 3: Wi-Fi users have occupied only four of the seven channels prioritized for them and WiMAX users have occupied eight channels which are three more than the number of channels WiMAX is allowed to use. This happens when Wi-Fi traffic is low and WiMAX traffic is high. But, when Wi-Fi traffic is increasing and one more Wi-Fi user arrives then Wi-Fi user can drop any three WiMAX user since WiMAX has exceeded the number of channels allowed for them by three channels.

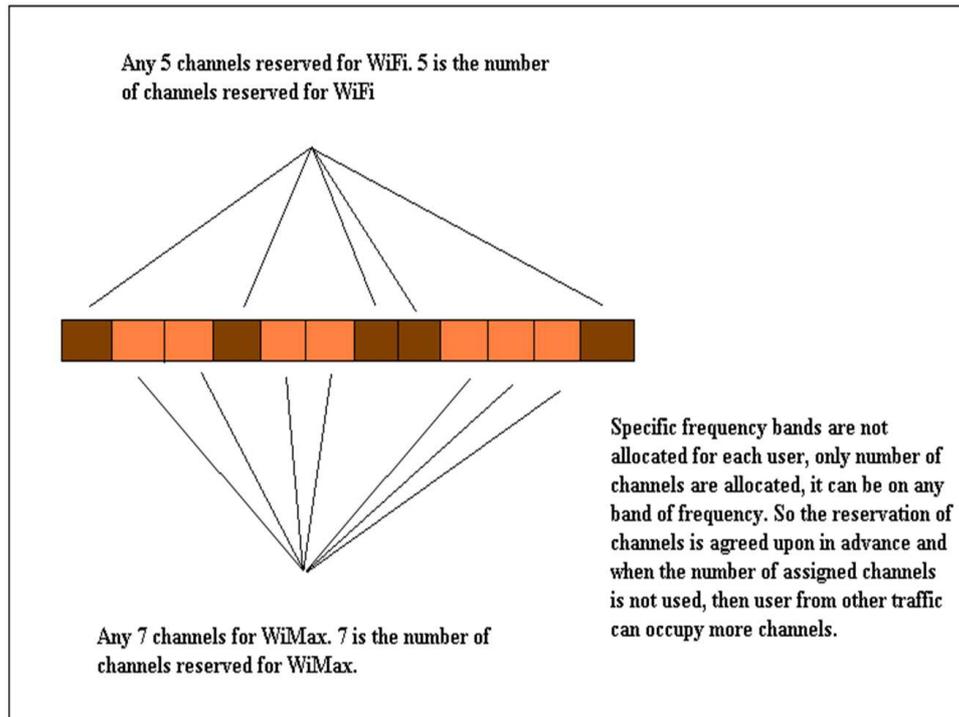


Figure 4.14: Prioritized channel allocation Model.

The criteria for call admission and forced termination for WiMax users in Prioritized resource sharing algorithm is stated as follows:

1. A WiMax call is admitted if the at least one channel is free.
2. If all the channels are full but the number of channels occupied by WiMax users is less than the number of prioritized channels, then the WiFi user who has been most recently admitted is forced to terminate and is queued back until the next channel is free.
3. If all the channels are full and if the number of channels occupied by WiMax users is already greater than or equal to the number of prioritized channels the call is blocked.

Prioritized sharing improves channel utilization compared to previous models like hybrid sharing, complete sharing and complete partitioning. In the case of hybrid sharing and forced termination, we observe from the diagram shown above and the table below that the

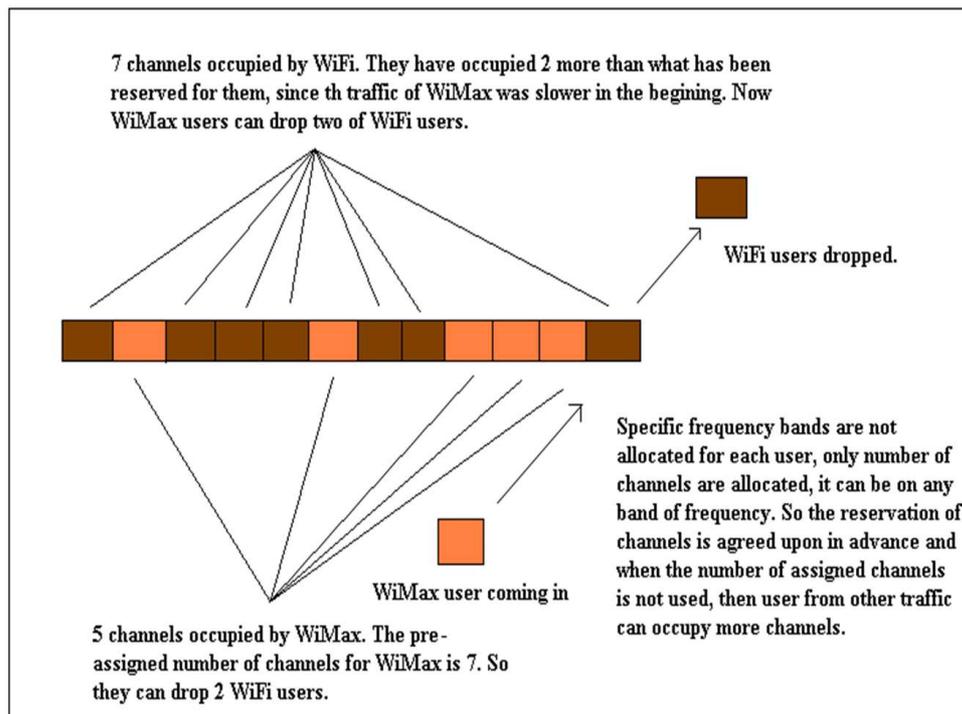


Figure 4.15: Prioritized channel allocation Model.

channel utilization is not good. This is because at any given time the number of channels that the previous models (hybrid sharing or forced termination model) could obtain is only the reserved channels assigned to them even if the channels were unoccupied in the reserved section for the other networks. Another advantage is that this model fits perfectly for tight coupled networks, where the channels are to be assumed to be homogeneous in [9]. The traffic of both the networks can access any of the channels available and will be dropped only in case the channels occupied by one network exceeds the allocated number of channels for that network and the traffic of the other network is blocked due to no available free channel. We represent this model using a 2-D Markov chain and simulate it using MATLAB.

To design the Markov model, it is necessary to understand all the parameters in the prioritized sharing model. WiMax and WiFi network integration architecture is considered as shown in Fig. 3.1. The traffic from WiFi-WiMAX bridges just referred to as WiFi traffic and the traffic from WiMax subscriber stations is referred to as WiMax traffic as mentioned

earlier. Both the traffics are assumed to have Poisson arrivals with average arrival rates of λ_{WiFi} and λ_{WiMax} for WiFi and WiMax traffic respectively. λ_{WiFi} and λ_{WiMax} are varied from 0 to 1. The average service rates are $\mu_{WiFi} = \mu_{WiMax} = 0.005$ all through the simulations. The total number of channels used in this simulation, N is equal to 10. The division of the channels to both Wi-Fi and WiMAX users and how the channels can be accessed by WiMax and WiFi users in different models is summarized in Table. 4.1. ‘Shared channels’ mean that the channels are accessible by any type of users. ‘Reserved channels’ mean that the channels are allocated for a particular class of users and others can’t access them. ‘Prioritized channels’ mean that the channels are accessible by all users but priority is given to the particular type of users to whom the channels are prioritized in Chapter 3.

Table 4.1: Channel Allocation

Allocation Algorithm	WiMax Accessible Channels	WiFi Accessible Channels
Complete sharing	10 shared	10 shared
Complete Partitioning	7 reserved	3 reserved
Hybrid Sharing	4 reserved, 3 shared	3 reserved, 3 shared
Prioritized Sharing	10 shared, 7 prioritized	10 shared, 3 prioritized

Figure 4.16, represents the 2-D model for the prioritized sharing model. In this two dimensional model the rows, which is represented by i indicate the number of WiMAX users in the network and the columns represented by ‘j’ indicate the number of Wi-Fi users. Each circle in the figure represents a state of the Markov model. State (i, j) shows that there are i WiMAX users and j Wi-Fi users in the system at that instant. The probability of the system to stay in a state (i, j) is described as steady state probability and is represented as $P(i, j)$. λ_a represents the arrival rate of a WiMAX user and with the arrival of a WiMAX user the system moves from state (i, j) to state $(i+1, j)$. Similarly with an arrival of Wi-Fi user represented as λ_b the system moves from state (i, j) to $(i, j+1)$. μ_a and μ_b are the

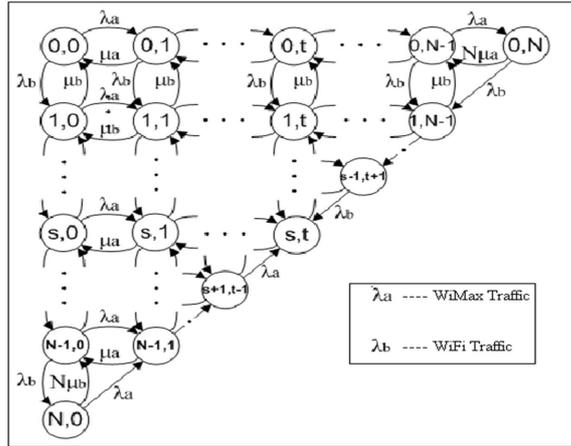


Figure 4.16: Markov Model representing Prioritized Sharing

service time (holding time) or the time taken by the channel to serve the user. In this figure we focus on the end states, which are represented by states where the sum of i and j equals the total number of channels N . The number of prioritized channels prioritized from a total of N channels for Wi-Fi and WiMAX are represented as t and s respectively.

Figure 4.16, shows that when the system reaches state $(0, N)$ which means the all the N channels are occupied by WiMAX users, then when one new Wi-Fi user arrives represented by λ_b , then one WiMAX user gets dropped to free a channel for the Wi-Fi user since it has not received its prioritized number of channels which is t channels. The system moves from state $(0, N)$ to $(1, N-1)$. This process continues till all the prioritized channels of Wi-Fi are occupied which will be at state (s, t) . At state (s, t) both the users would have occupied all the channels prioritized for them and any new user will be blocked. Apart from state (s, t) where users of both the networks have occupied their respective prioritized channels, WiMAX users are blocked when all the channels are full and WiMAX users have occupied more channels that what is prioritized for them i.e. more than s channels. Similarly, Wi-Fi users are blocked when all the channels are full and Wi-Fi users have occupied more channels that what is prioritized for them i.e. more than t channels. We derive the formula for blocking probability of Wi-Fi and WiMAX users from this model, by adding the state probability of all the states where both Wi-Fi and WiMAX will be blocked.

Simulation Results

In this section, the Prioritized Sharing scheme is compared with complete sharing, complete partitioning and hybrid sharing. The blocking probabilities and the channel utilization of these allocation schemes are studied. The definitions of these performance parameters is as follows:

Suppose the set S contains all the possible states, $S = \{(i, j) | (i, j) \leq N\}$ of the two dimensional Markov chain representing prioritized sharing model. s and t are the number of prioritized channels for WiMAX and Wi-Fi traffic respectively. Since s channels are reserved for WiMax traffic, WiMax users will suffer blocking only in those states in which WiMax users have occupied more than s channels. If all the channels reserved for WiMAX users are not used, then Wi-Fi users are allowed to access it. Both Wi-Fi and WiMAX users are blocked at the same time only when users of both the networks have occupied all the channels prioritized for each of them. Suppose, all the states where WiMax users suffer blocking are represented as $H_{WiMax} = \{(i, j) | (i, j) \in S, i \geq s\}$ and the states where WiFi users suffer blocking are, $H_{WiFi} = \{(i, j) | (i, j) \in S, i \leq s\}$. Blocking probability is defined as the states in which Wi-Fi and WiMAX users will be blocked due to unavailability of channels to transmit.

Then the Blocking probability of WiMax users is given by the expression,

$$B_{WiMax} = \lambda_{WiMax} \sum_{(i,j) \in H_{WiMax}} p(i, j) \quad (4.2)$$

and the expression for Blocking probability of WiFi users is,

$$B_{WiFi} = \lambda_{WiFi} \sum_{(i,j) \in H_{WiFi}} p(i, j) \quad (4.3)$$

Channel utilization is defined as the average number of available channels that are occupied for a specified set of arrival and service rates for Wi-Fi and WiMAX users. In

other words, it is the percentage of channels from a total of $N=10$ channel that Wi-Fi and WiMAX occupy together. Channel utilization can be derived as,

$$U_{Total} = N \times 100 \sum_{(i,j) \in S} (i + j)p(i, j) \quad (4.4)$$

The percentage of channels occupied by WiMax users from the total of N channels and the percentage of channels occupied by WiFi users from a total of N channels are referred to as WiMax Channel utilization and WiFi Channel Utilization respectively. Individual channel utilization helps to observe if user of any network is starved for resources. Channel utilization is derived as follows:

Percentage of WiMax Channel Utilization,

$$U_{WiMax} = \frac{N \times 100}{U} \sum_{(i,j) \in S} ip(i, j) \quad (4.5)$$

Percentage of WiFi Channel Utilization,

$$U_{WiFi} = \frac{N \times 100}{U} \sum_{(i,j) \in S} jp(i, j) \quad (4.6)$$

Blocking probability

The graph in Figure 4.17 shows that for complete sharing the blocking probability is highest. This is because the traffic from both Wi-Fi and WiMAX networks can access all the channels that are available. We can see that initially, the blocking for WiMax is negligible when the WiFi traffic is zero. This is because when WiFi traffic is zero; all the channels in the system are available to WiMax users. Once the traffic of WiFi increases, the WiFi users start competing for the channels and start occupying more channels. As a result, the blocking probability of WiMax users increases with increase in WiFi traffic. In the case of complete partitioning, specific number of channels is reserved for both Wi-Fi and WiMAX users. The blocking probability of WiMAX users remain a constant because for any given

traffic of WiFi, the number of reserved channels for WiMax remains a constant and no channels reserved for Wi-Fi users can be accessed by WiMAX even if they are not being used. Therefore the blocking probability of WiMAX users stays constant with variation in Wi-Fi traffic.

In hybrid sharing we observe that the blocking probability lies between the blocking probability of complete sharing and complete partitioning as expected. This is because in comparison with complete sharing model, hybrid sharing is allocated a minimal number of reserved channels. So the users are blocked only when they compete for the shared channels and when the shared channels are full. In complete sharing, there are no reserved channels, so all the channels are competed for right from the beginning. In hybrid sharing, WiMAX can only access the shared channels and channels reserved for them. It cannot access the channels that are reserved for Wi-Fi even if they are free. However in the case of prioritized sharing, we can see that the blocking probability is lowest. It starts off along with complete sharing because like in complete sharing when the traffic of WiFi is zero, all the channels are available for WiMAX, making its blocking negligible. But, when the traffic of WiFi increases the blocking probability of WiMAX also increases since Wi-Fi users start occupying more channels. But the blocking probability of WiMAX users remain lower than complete sharing since there are a minimum number of channels reserved for WiMAX as well as Wi-Fi users.

The graph in Figure 4.18 shows the variation of WiFi blocking probability with the increase in WiFi user traffic for the different models simulated. It is observed that complete partitioning has highest blocking probability. This is because specific number of channels is reserved for Wi-Fi users and it cannot access the channels reserved for WiMAX users even if it is not being used. In complete sharing with the increase in WiFi traffic, WiFi users get more channels since all the channels are open to access. Therefore the blocking probability of WiMAX users is lesser than complete partitioning and hybrid sharing models.

In prioritized sharing, the blocking probability is same as that of complete sharing till a Wi-Fi user arrival rate of 0.2. After that, the blocking probability of WiFi reduces

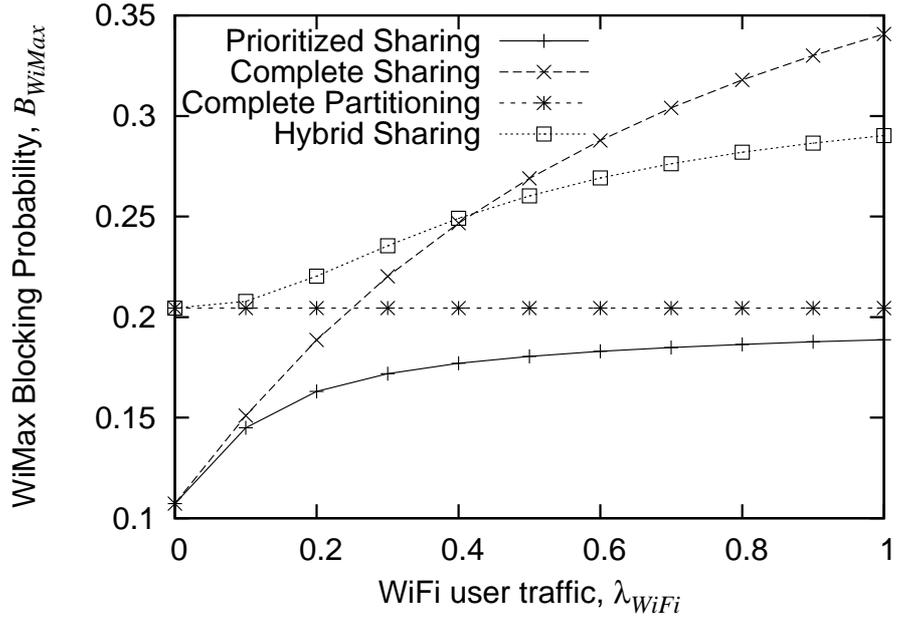


Figure 4.17: Blocking probability of WiMax Users with varying WiFi user traffic.

slightly. This is because even though all the channels are open to access like in complete sharing, prioritized sharing provides a guarantee of minimal number of channels to Wi-Fi users due to reservation. This explains why the blocking probability of Wi-Fi users is lower in prioritized sharing than in complete sharing. Hybrid sharing however has blocking probability between complete sharing and complete partitioning as expected.

Fig. 4.19 shows the blocking probability of WiMAX users as their traffic is varied keeping the WiFi traffic constant. Again, CS should have provided the least blocking because all the ten channels are accessible to the WiMax users from Table. 4.1. But, due to prioritization of channels in PS allocation, PS scheme offers the least blocking than any other allocation method.

Channel Utilization

In this section, the total percentage channel utilization and the WiMAX, Wi-Fi channel utilization as are studied. Fig. 4.20 shows the Total channel utilization of the channels as Wi-Fi user traffic is varied and WiMax traffic constant. Both total utilization as well

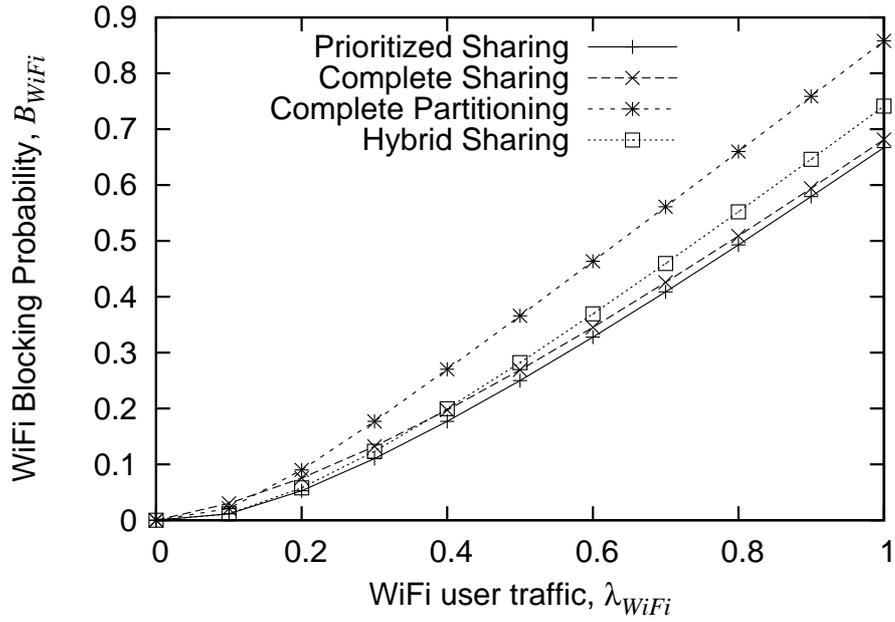


Figure 4.18: Blocking probability of WiFi Users with varying WiFi user traffic.

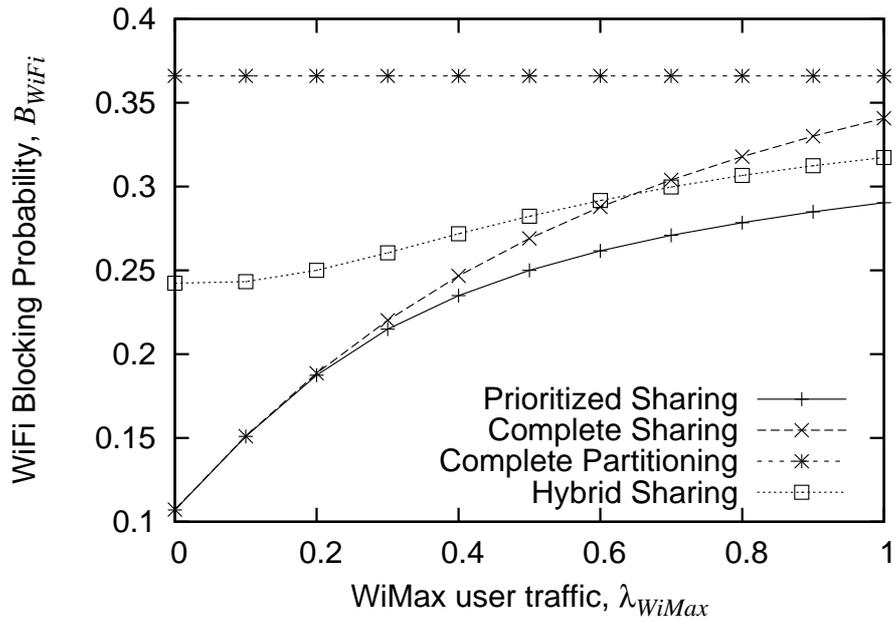


Figure 4.19: Blocking probability of WiFi Users with varying WiMax user traffic.

as individual utilization is high in prioritized sharing as compared to other models. In prioritized sharing since all the channels are available for access when the traffic is low, at

any given time the total channel utilization is highest. This is similar to both complete sharing and hybrid sharing. When the Wi-Fi user traffic increases from 0.2 to 1 in each model the total utilization of the channels becomes full. In the case of complete partitioning what happens is that when the traffic of one network is low and the other is high. The reserved channels are occupied but, the channels reserved for other network user is not allowed to be accessed even when it is free causing the total utilization to be low compared to the other models. In complete partitioning users are blocked even when free channels are available. The total channel utilization of hybrid sharing model is close to complete sharing and prioritized because with increase in traffic all the channels are utilized. This is because apart from reserved channels that are provided to each, there are also shared channels which can be accessed by users of either network. As was discussed, total channel utilization of CS scheme is ideal since all classes of users can access all channels. Since, PS carries the same property that any channel can be accessed by any class of users when they are free, the channel utilization is exactly equal to CS. Complete partitioning has the least channel utilization because free channels of one class of users can not be utilized by other class of users and hence they lay idle.

Fig. 4.21 summarizes the advantages of Prioritized Sharing by showing the total channel utilization and WiMax channel utilization together. Each bar represents the total channel utilization and the shaded region of each bar represents the WiMax share of the utilized channels. It can be seen that the total channel utilization is almost the same for hybrid, complete and prioritized sharing. What is the improvement achieved by Prioritized sharing then? The answer lies in the observation of individual channel utilization. In this study we choose channel utilization of WiMax users. It can be observed that even though the total channel utilization is the same in complete sharing and prioritized sharing, the WiMAX channel utilization in prioritized sharing is highest, which shows that WiMAX users are no longer starved for channels with the increase in Wi-Fi users traffic. In complete sharing the WiMax channel utilization reduces drastically with increase in WiFi user traffic. This

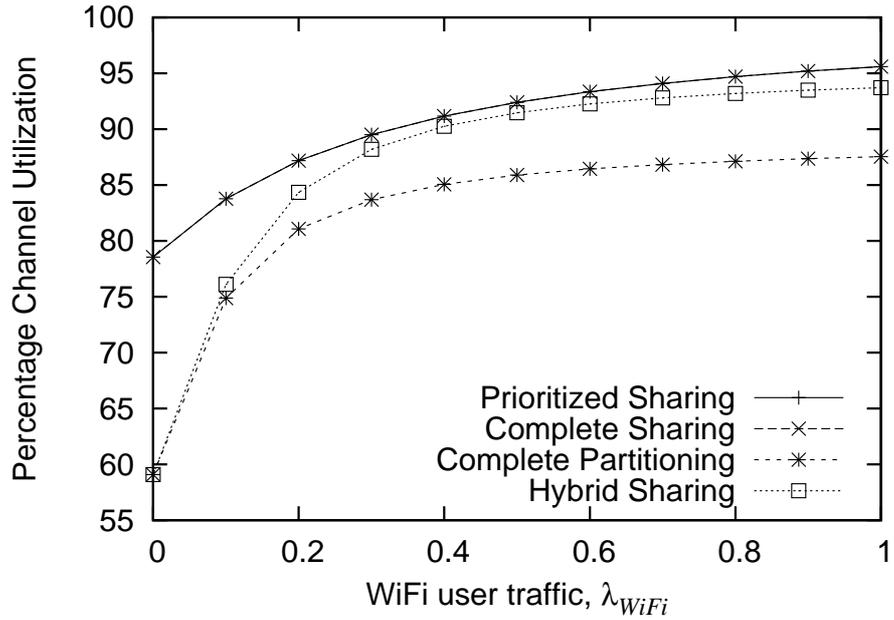


Figure 4.20: Total Percentage Channel Utilization with varying WiMax user traffic.

is because of a first come first serve policy that completes sharing uses. The channel utilization of WiMAX users in hybrid sharing is better than complete sharing because of the reserved channels which guarantee a minimum number of channels for WiMax in hybrid sharing. Complete partitioning the WiMax channel utilization is same as that in prioritized but their total channel utilization is lowest. In prioritized both total channel and individual channel utilization is highest.

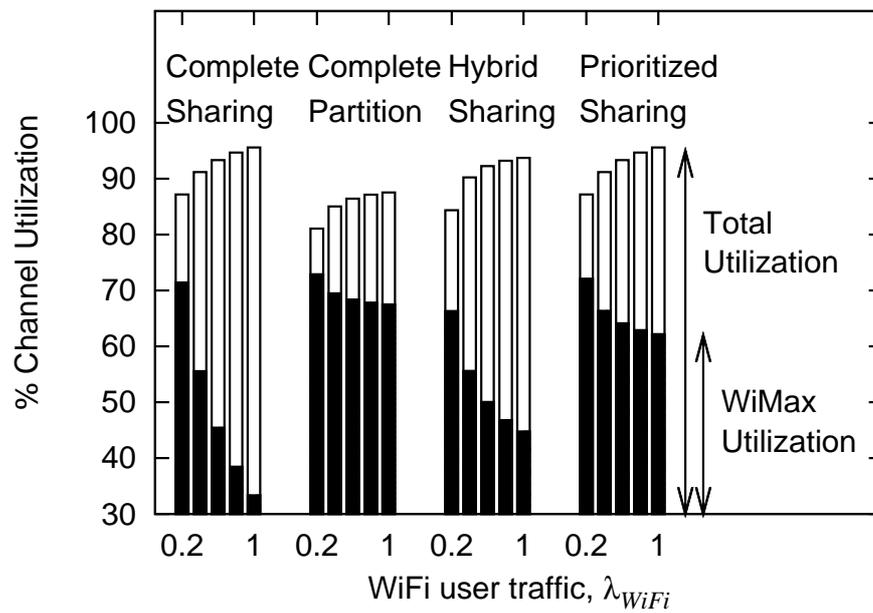


Figure 4.21: Total Percentage Channel Utilization with varying WiMax user traffic.

CHAPTER 5

CONCLUSION

With the advance in wireless technology and the demands of high bandwidth, total channel utilization, global roaming etc. in 4G networks, integration of existing wireless standards is an imminent solution. However, it has been observed that along with such an integration, there would be technical challenges to envision it. Resource allocation which deals with channels utilization, bandwidth usage and various other network efficiency features, is the most important technical issue in layer 2. Two type of resource allocation methods were analyzed and performance analysis and the importance of the allocation schemes were studied.

The first scenario where the two networks, WiFi and WiMax, were tightly coupled and WiFi was given priority in terms of more reserved channels, it is observed that there is a starvation problem. The first algorithm alleviates the starvation problem by terminating the users with undue advantage, and making space for the other network users. Since this algorithm uses a two threshold mechanism the channel utilization is compromised even though it provides a solution to the network starvation problem.

The second scenario however, takes into account the starvation as well as the channel utilization issue. *Prioritized Sharing* (PS) algorithm is proposed for resource sharing in WiMax-WiFi integrated networks and later extended to application in multiple integrated networks. The Complete Sharing (CS) approach which is well studied in literature offers best channel utilization and Complete Partitioning (CP) approach assures minimum quality of service to each class in terms of allocated channels. However, both complete partitioning and complete sharing do not offer good channel utilization. *Prioritized Sharing* algorithm is designed such that the best of the two algorithms is achieved. The algorithm was modeled and analyzed using two dimensional continuous time Markov chains. It is observed through

simulations that PS resource sharing algorithm offers least blocking probabilities and highest channel utilization for WiMax and WiFi users compared to other models.

These solutions clearly indicate the necessity of a resource allocation method specifically for WiFi WiMax integrated network. The existing solutions were designed for homogeneous network and networks with multiple user class. Two important Issues in integrated network related to resource sharing was studied and two algorithms were proposed and analyzed to measure the improvement it provides in the integrated WiFi-WiMax networks.

BIBLIOGRAPHY

- [1] B. B. Chen, “Heterogeneous network resource management,” in <http://www.comp.nus.edu.sg/chenbinb/heterogeneous/index.htm>.
- [2] J. Ibrahim, “4g features,” in *Bechtel Telecommunications Technical Journal*, vol. 1, no. 1, Dec. 2002, pp. 11–14.
- [3] K. Young Kyun and R. Prasad, “4g roadmap and emerging communication technologies.” Norwood, MA, USA: Artech House, 2006, pp. 12–13.
- [4] S. Hussain, Z. Hamid, and N. S. Khattak, “Mobility management challenges and issues in 4g heterogeneous networks,” in *InterSense '06: Proceedings of the first international conference on Integrated internet ad hoc and sensor networks*. New York, NY, USA: ACM, 2006, p. 14.
- [5] I. T. G. d, “Ieee std 802.16-2004,” October 2004.
- [6] H. Mahmoud, H. Arslan, and M. Ozdemir, “Initial ranging for wimax (802.16e) ofdma,” in *Military Communications Conference, 2006. MILCOM 2006. IEEE*, Oct. 2006, pp. 1–7.
- [7] R. Iyengar, P. Iyer, and B. Sikdar, “Analysis of 802.16 based last mile wireless networks,” in *Global Telecommunications Conference, 2005. GLOBECOM '05. IEEE*, vol. 5, Dec. 2005, pp. 5 pp.–3127.
- [8] D.-H. Cho, J.-H. Song, M.-S. Kim, and K.-J. Han, “Performance analysis of the ieee 802.16 wireless metropolitan area network,” in *Distributed Frameworks for Multimedia Applications, 2005. DFMA '05. First International Conference on*, Feb. 2005, pp. 130–136.
- [9] T. Ali-Yahiya, H. Chaouchi, A.-L. Beylot, and G. Pujolle, “Threshold based wimax resource reservation,” in *Mobility '06: Proceedings of the 3rd international conference on Mobile technology, applications & systems*. New York, NY, USA: ACM, 2006, p. 40.
- [10] Motorola and Intel, “Wimax and wifi together: Deployment models and user scenario,” vol. 2, Sept. 2007.
- [11] K. Gakhar, A. Gravey, and A. Leroy, “Iroise: a new qos architecture for ieee 802.16 and ieee 802.11e interworking,” in *Broadband Networks, 2005. BroadNets 2005. 2nd International Conference on*, Oct. 2005, pp. 607–612.

- [12] N. Thomas, M. Willis, and K. Craig, "Analysis of co-existence between ieee 802.11 and ieee 802.16 systems," in *Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on*, vol. 2, Sept. 2006, pp. 615–620.
- [13] V. Gunasekaran and F. Harmantzis, "Financial assessment of citywide wi-fi / wimax deployment," *Communications and Strategy*, vol. 3rd Quarter, no. 63, pp. 131–153, 2006.
- [14] X. Jing, S.-C. Mau, D. Raychaudhuri, and R. Matyas, "Reactive cognitive radio algorithms for co-existence between ieee 802.11b and 802.16a networks," *Proceedings of IEEE Globecom*, vol. 5, 2005.
- [15] X. Jing and D. Raychaudhuri, "Spectrum co-existence of ieee 802.11b and 802.16a networks using reactive and proactive etiquette policies," *Mob. Netw. Appl.*, vol. 11, no. 4, pp. 539–554, 2006.
- [16] L. Berlemann, C. Hoymann, G. Hiertz, and B. Walke, "Unlicensed operation of ieee 802.16: Coexistence with 802.11(a) in shared frequency bands," in *Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on*, Sept. 2006, pp. 1–5.
- [17] J. Nie, X. He, Z. Zhou, and C. Zhao, "Communication with bandwidth optimization in ieee 802.16 and ieee 802.11 hybrid networks," in *Communications and Information Technology, 2005. ISCIT 2005. IEEE International Symposium on*, vol. 1, Oct. 2005, pp. 27–30.
- [18] L. Berlemann, C. Hoymann, G. Hiertz, and S. Mangold, "Coexistence and interworking of ieee 802.16 and ieee 802.11(e)," in *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd*, vol. 1, May 2006, pp. 27–31.
- [19] H.-T. Lin, Y.-Y. Lin, W.-R. Chang, and R.-S. Cheng, "An integrated wimax/wifi architecture with qos consistency over broadband wireless networks," in *Consumer Communications and Networking Conference, 2009. CCNC 2009. 6th IEEE*, Jan. 2009, pp. 1–7.
- [20] R. Fantacci and D. Tarchi, "Bridging solutions for a heterogeneous wimax-wifi scenario," *Journal Of Communications and Networks*, vol. 8, no. 4, pp. 369–377, 2006.
- [21] T. Ali-Yahiya, K. Sethom, and G. Pujolle, "Seamless continuity of service across wlan and wman networks: Challenges and performance evaluation," in *Broadband Convergence Networks, 2007. BcN '07. 2nd IEEE/IFIP International Workshop on*, May 2007, pp. 1–12.
- [22] S. R. Ibáñez, R. A. Santos, V. R. Licea, A. E. Block, and M. A. G. Ruiz, "Hybrid wifi-wimax network routing protocol," in *CERMA '08: Proceedings of the 2008 Electronics, Robotics and Automotive Mechanics Conference*. Washington, DC, USA: IEEE Computer Society, 2008, pp. 87–92.

- [23] D. Niyato and E. Hossain, "A hierarchical model for bandwidth management and admission control in integrated ieee 802.16/802.11 wireless networks," in *Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE*, March 2007, pp. 3763–3767.
- [24] —, "Wireless broadband access: Wimax and beyond - integration of wimax and wifi: Optimal pricing for bandwidth sharing," *Communications Magazine, IEEE*, vol. 45, no. 5, pp. 140–146, May 2007.
- [25] —, "Integration of ieee 802.11 wlans with ieee 802.16-based multihop infrastructure mesh/relay networks: A game-theoretic approach to radio resource management," *Network, IEEE*, vol. 21, no. 3, pp. 6–14, May-June 2007.
- [26] T. Yahiya, A.-L. Beylot, and G. Pujolle, "Policy-based threshold for bandwidth reservation in wimax and wifi wireless networks," in *Wireless and Mobile Communications, 2007. ICWMC '07. Third International Conference on*, March 2007, pp. 76–76.