WiMax-WiFi Techniques for Baseband Convergence and Routing Protocols

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Abstract

The focus of this study was to investigate solutions that, when implemented in any heterogeneous wireless network, shall enhance the existing standard and routing protocol connectivity without impacting the standard or changing the wireless transceiver's functions. Thus achieving efficient interoperability at much reduced overheads. The techniques proposed in this research are centred on the lower layers. This because of the facts that WiMax and WiFi standards have not addressed the backward compatibility of the two technologies at the MAC and PHY layers, for both the baseband functions as well as the routing IP addresses. This thesis describes two innovate techniques submitted for a PhD degree.

The first technique is to combine WiMax and WiFi signals so to utilise the same "baseband implementation chain" to handle both of these technologies, thus insuring ubiquitous data communication. WiMax-WiFi Baseband Convergence (W^2BC) implementation is proposed to offer an optimum configurable solution targeted at combining the 802.16d WiMax and the 802.11a WiFi technologies. This approach provides a fertile ground for future work into combining more OFDM based wireless technologies. Based on analysis and simulation, the W^2BC can achieve saving in device cost, size, power consumption and implementation complexity when compared to current side-by-side implementations for these two technologies.

The second technique, called "Prime-IP", can be implemented with, and enhance, any routing protocol. During the route discovery process, Prime-IP enables any node on a wireless mesh network (WMN) to dynamically select the best available route on the network. Prime-IP proposes a novel recursive process, based on prime numbers addressing, to accumulate knowledge for nodes beyond the "neighbouring nodes", and to determine the sequence of all the "intermediate nodes" used to form the route.

Acknowledgments

I would like to thank God Almighty, who created the opportunity for me to have my Dream,

I would like to bow in thanks to Dr. Habib Al-Sherbaz and Mrs Awaz Jiawook (My Parents), who helped me to have my
Dream,

And to my love, my sweet heart, who continues to support me to live my Dream,

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Abbreviations

FFT	Fast Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IEEE 802.11	IEEE WiFi Standards
IEEE 802.16	IEEE WiMax Standards
MAC	Media Access Control Layer
OFDM	Orthogonal Frequency Division Multiplexing
PHY	Physical Layer
RREP	Route Reply Packet
RREQ	Route Request Packet
W^2BC	WiMax-WiFi Baseband Convergence
WiFi	Wireless Fidelity
WiMax	World Interoperability for Microwave Access
WMN	Wireless Mesh Networks

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Declaration

I am hereby declare that all the work in this thesis is my own work ... and, to the best of my knowledge, none of this materials has ever previously been submitted for a degree in this or any other university.

Chapter 1: Introduction

This research work focuses on addressing the shortfalls identified in current Wireless Mesh Networks (WMN). Multi standard interoperability and routing protocols, as deployed in WiMax and WiFi networks, were carefully studied to reduce overheads. This thesis proposes solutions, aimed at the lower layers of the WiMax and WiFi technologies, to reduce not only the baseband implementation overheads, but also enhancement to the most commonly used routing protocols. All this improvements has been achieved without impacting these technologies standards or these WMN protocols.

There have been many attempts to converge wireless transceivers functionality and implementation at various layers (1), (2), (3), (4), (5). The first part of this research was to explore the similarities of the OFDM signals, as used in WiMax and WiFi, to converge their baseband implementation at the physical layer (PHY). This attempt has resulted in a new convergence method by making these baseband functions reconfigurable to serve WiMax or WiFi signals, thus reducing the overheads of having side-by-side implementations of these two technologies. The proposed WiMax-WiFi Baseband Convergence (W^2BC) solution reduces implementation complexity, size, power, and cost, while preserving signal and communication integrity for standalone WiMax and WiFi functionality without impacting the standards. W^2BC is described in Chapter 3.

In their route discovery and selection process, current WMN protocols aims to achieve minimum traffic processing overhead, higher security level, increased data throughput, and reduced error rate (6). Proactive routing protocols achieve better results for very small size networks. The overhead of accumulating knowledge for all nodes in the network reduces the viability of using proactive protocols in favour of the better connectivity but compromised reactive or on demand routing protocols (7). The second part of this research, proposes Prime-IP, an algorithm that enables optimum route path to be selected between the source and destination nodes of a WMN. At the Media Access Control layer (MAC), Prime-IP deploys a novel recursive process, based on prime numbers addressing, to accumulate knowledge for nodes beyond the neighbouring nodes and to determine the sequence of all the intermediate nodes used to form the route. Analysis and simulations of typical dynamic topology of various WMNs proves that Prime-IP functionality can be integrated with existing reactive routing protocols to gain the added benefits of the proactive routing protocols as well, but with minimum overhead. Prime-IP, patent pending, is described in Chapter 6.

1.1. My Research Motivation

The rapid change of wireless technologies development makes research in this field very attractive and challenging. To engage in such research, it is important to clearly understand and investigate the standards of the technologies and the routing protocol, as well as constantly observe new amendments of the same.

Ever since I have completed my MSc degree in communications engineering, I was passionate to work on Wireless stacks especially with the functions staged at the lower layers (PHY and MAC layers). In 2006, I studied the WiMax technology and how it offers the infrastructure solution for the last miles, something that my country and other infrastructureless countries can benefit from. Furthermore, when both WiMax and WiFi are integrated, a sufficient and affordable bandwidth wireless networking can be developed to offer not only Internet services, but also mobile TV and Multimedia applications. i.e. I envisaged that my research work with these two technologies can help impact the future communication services due to being easier to deploy and offering high bandwidth at lower cost when compared with cellular technologies such as GSM and 3G.

I have chosen this research to help me understand the concepts of the WMN infrastructure as deployed by using WiMax or WiFi, as well as how to design, plan, integrate with other networks, configure routing protocols, and choose suitable applications for such networks. I have thoroughly enjoyed this research experience.

1.2. My Research Progress

This research study is spilt into two parts. The various study tasks are shown in the bubble diagram of Figure 1-1 as follows:

- W^2BC part (clear bubbles): representing the research work on combining two wireless technologies into single transceiver.
- Prime-IP part (Shaded bubbles): representing the research work for enhancing current wireless routing protocols based on the use of prime number addressing.

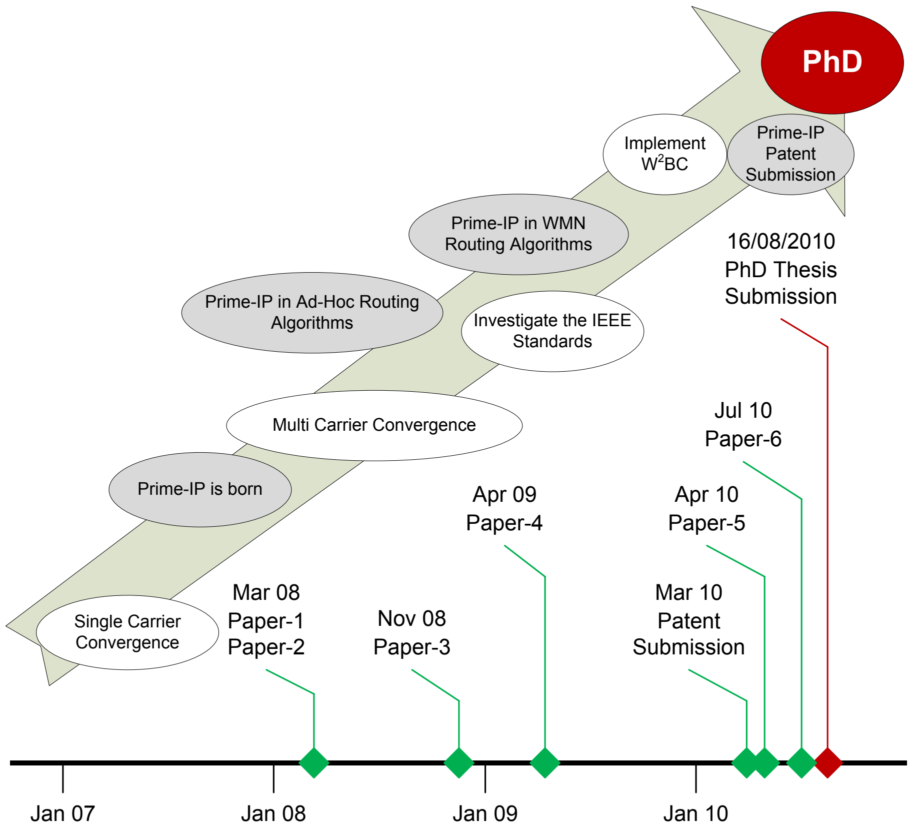

Figure 1-1, The PhD Research Progress and the related publications

This research started by investigating the single carrier WiMax 802.16a and WiFi 802.11b technologies. This thread was concluded by proposing a convergence technique for these two standards (8). This convergence technique is centred on new "device driver functions" to handle the time-synchronisation of the signals. These functions appear as a thin layer between the MAC and the LLC. This approach was swiftly abandoned as both WiMax and WiFi evolved into multi-carrier technologies. The challenges of these new 802.16d and 802.11a were then investigated. WiFi-OFDM-64 and WiMax-OFDM-TDD-256 were identified as common features. This has led to the W^2BC implementation. The W^2BC achieves a compact baseband implementation of these two technologies with no impact on their performance. Thus saving silicon size, cost and power. An estimated 35% size reduction has resulted from sharing a single PHY layer.

For the routing protocol research thread, a thorough study of the current protocols has been concluded by introducing the "prime number addressing" technique. The Prime-IP algorithm was developed to not only offer unique node addressing, but also to offer knowledge of all nodes in the network as well as the sequence of the intermediate nodes in any route. The added value of Prime-IP is that it can be integrated with any of the existing WMN routing protocols to offer these enhancements. Ultimately, the Prime-IP algorithm was filed for patenting (9).

1.3. Research Approach/Methodology and Achievements

In the process of this research, literature investigations of the wireless technologies (standards, protocols, topologies and applications) followed by developing a comparative criteria to identify the most suitable solution. Algorithm decisions are followed by mathematical analysis leading to actual functional and behavioural simulation. Further work to the resultant two proposed techniques can include, but not limited to, cellular based heterogeneous convergence, cross standards mitigation, intelligent routing management, and enhanced security and location wireless networks, Authentication, mobility and scalability of Cloud Computing wireless networks.

Therefore, this 4-year research activity focused on the following:

- To follow the standards: Investigate the possibilities and capabilities to propose solutions without impacting the standards or the protocols. The techniques have been altered to accommodate the latest amendments.
- To keep touch with industry: this is to ensure that the research is commercially viable. This has been achieved by joining industrial working groups, publishing the work in known conferences/journals, and attending relevant events organised by industry (eg. Motorola, Microsoft, Intel, Matlab, Alvarian, Rohd & Schwarts).

During this 4-year research study, the following papers were published with follow researchers within the department of Applied Computing at The University of Buckingham as well as colleagues at the University of Brno, Czech Republic, as part of the COST project (see references (8), (9), (10), (11), (12), (13), (14) for full details):

1. Nov/2010, "WiMax and WiFi Baseband Convergence (W^2BC) Implementation", IET Microwaves, Antennas & Propagation Special Issue on “RF/Microwave Communication Subsystems for Emerging Wireless Technologies”
2. April/2010, “Parameters Adaptation Through A Baseband Processor Using Discrete Particle Swarm Method”, International Journal of Microwave and Wireless Technologies
3. March/2010, “Method and Process for Routing and Node Addressing in Wireless Mesh Networks”. UK Patent Office
4. April/2009, “WiMax-WiFi Convergence with OFDM Bridge”, SPIE Defence and Security Proceeding Conference
5. Nov/2008, “Convergence in wireless transmission technology promises best of both worlds”, SPIE Opt electronics & Optical Communications newsroom

6. March/2008, “Private Synchronization Technique for Heterogeneous Wireless Network (WiFi and WiMax)”, SPIE Defence and Security Proceeding Conference
7. March/2008, “Credibility Based Secure Route Finding in Wireless Ad Hoc Networks”, SPIE Defence and Security Proceeding Conference

1.4. Thesis Organization

Figure 1-2 illustrates the structure of this thesis. Chapters 2, 3 and 4 are devoted to the W^2BC work, while chapters 5 and 6 focus on the Prime-IP work.

For the W^2BC part, **Chapter 2** reviews the latest wireless technologies in general, followed by detailed study of WiMax & WiFi. It describes the concept of the convergence using either protocol or implementational approaches. The motivation of this chapter is to explain the analysis, justification, and challenges of pursuing this approach. **Chapter 3** reviews the W^2BC mathematical implementation of the baseband PHY for both WiFi-OFDM-64 and WiMax-OFDM-256. The analysis focuses on the similarities and dissimilarities for both signals. **Chapter 4** describes the W^2BC simulation model for MATLAB/Simulink. This model uses a close loop system that cover both, the transmits and the receive chains as well as the channel. A discussion on the appropriate static and dynamic test scenarios is laid-out. These test scenarios are designed to prove that the functionality is maintained to the same standard as that of stand-alone WiMax and/or WiFi transceivers.

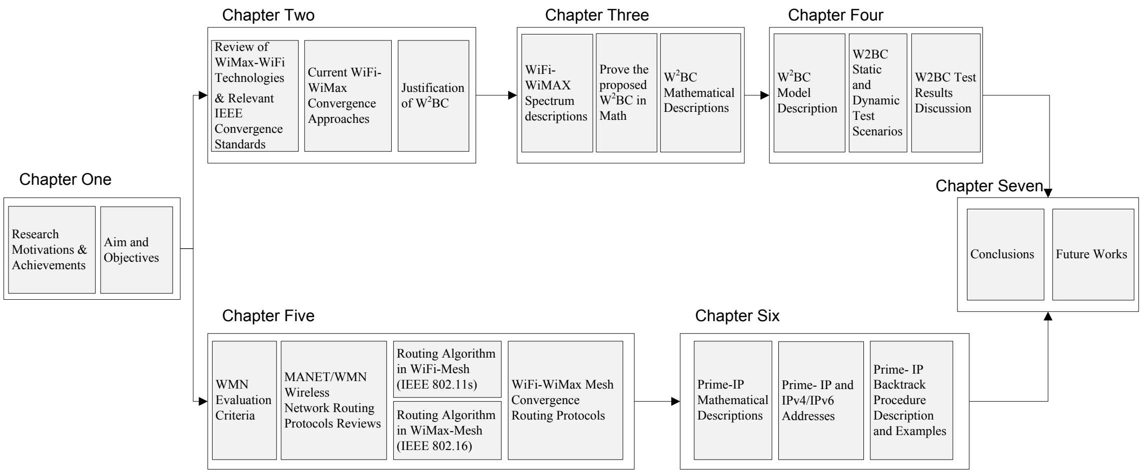

Figure 1-2, Thesis Organisation

For the Prime-IP part, **Chapter 5** reviews the most common WMN routing protocols, and categorise them to appropriate classification. It also describes the evaluation criterions used to classify these protocols. This literature survey has concluded why the Prime-IP algorithm is needed to enhance these routing protocols. i.e. offering existing protocols the capability of acquiring knowledge of neighbouring and other non-neighbouring nodes & route sequence in the network, without the overheads associated with proactive routing protocols. **Chapter 6** describes the mathematical derivation and MATLAB simulation of the Prime-IP to show how the "prime numbers" are embedded in the IPv4 and IPv6 address. The analysis includes the backtrack procedure for reconstructing the route nodes in a particular order.

Finally, this thesis concludes by **Chapter 7** that discusses the main issues, point of views, achievements, and recommendation for future work.

Chapter 2: Review of WiMax and WiFi Convergence Techniques

The objectives of this chapter are to review the current techniques adapted to convergence the WiFi and WiMax technologies, and to justify the convergence approach proposed by this thesis.

The author believes that convergence of available data-centric wireless technologies, the focus of this work, will greatly enhance the experience to users, especially when communicating live and multimedia data. The author aims to discuss these convergence technologies, reviewing their advantages and the impediments in their implementation methods. The review shall focus on the WiFi, WiMax and the "Media-independent handover" (or IEEE 802.21) technologies.

The motivation behind this study was to investigate the best technique to combine WiFi and WiMax signals so to utilise the "baseband implementation chain" to handle both of these technologies. Thus, saving device cost by using the same baseband process instead of the current side-by-side implementations for these two technologies. This convergence idea was initiated from the many similarities between the WiMax and the WiFi technologies. The dissimilarities in these two technologies, although were real obstacles to enable them communicates with each other, but the proposed solution has overcome these issues. In general, the dissimilarities between wireless standards are usually associated with the lower layers, which meant that this work has to focus on these lower layers. i.e. the PHY and MAC layers.

It important to point out that the resultant technique proposed in this thesis does not change the WiFi or the WiMax standards. i.e. the proposed solution, instead, actually implements these two standards in one baseband PHY layer.

Convergence of wireless technologies provides seamless high speed connection while on the go. i.e. A user can have both WiFi and WiMax services available without having to switch between these services. The benefits of these are:

- Offer cheap long distance calls using VoIP over WiFi and/or WiMax connection
- Offer picture perfect video available/watched while on the move as well as when surfing the Internet
- Other benefits include simplified provisioning, easier management, less maintenance, fewer interface, fast provisioning, newer and improved services, and easy user interface

Thus, convergence of WiFi with WiMax will provide users with benefits of both worlds. i.e. high speed connectivity of a LAN as well as mobility of WiMax (15).

For clarification, the following terms are used to mean:

- **Wireless Convergence**: The Oxford dictionary meaning of convergence is "the action or fact of converging, movement directed toward or terminating in the same point (called the point of convergence)", (16) page 939. Thus, for wireless technologies, the same converging concept can apply when two or more protocols are combined in function & implementation, then they can be regarded as converging into one for that function execution.
- **WiMax-WiFi Baseband Convergence-W^2BC**: The W^2BC acronym has been adopted to signify a "single baseband PHY layer implementation chain" that serves both WiFi and WiMax.

2.1. Review of the WiMax and WiFi Technologies

2.1.1. WiMax –WiFi Convergence Review

Converging various wireless and mobile communications technologies has been taking the centre stage of research recently. This is an ever growing and expanding theme. The focal point of this thesis was to investigate the possibilities of combining different wireless standards, focusing on WiMax and WiFi for the implementation and testing.

Today, WiFi is everywhere. WiFi forms the backbone of most wireless high speed WLAN connectivity delivered to millions of offices, homes and public locations such as hotel, cafes and airport. WiFi is enabled in almost every notebook, PDA and consumer electronics devices allowing connectivity on demand (17). WiMax technology complements wireless internet access providing claimed higher data-rates but more importantly offers wider coverage area and mobility (802.16e). As a consequence, in some countries, WiMax has been established as a substitute to wired-DSL, providing competitive broadband service at a competitive cost (18). A Bridging solution for a heterogeneous WiMax-WiFi scenario, interconnecting WiFi and WiMax standards has been proposed in (2). This approach promises much higher date rate compared with cellular networks with much reduced infrastructure cost. Also, this approach is fully compatible with IP networks, which was regarded as the key factor for future broadband convergence networks.

The integration of 802.11 and 802.16 into one WiFi/WiMax module has been also been discussed extensively in the following publications (1), (19), (20), (21), all of which propose approaches for the realization of an internetworking between these two standards. (19), proposes a common framework that allows the operation of 802.11 and 801.16 with optimal bandwidth sharing. Game theory and genetic algorithm have been used to obtain pricing for bandwidth sharing between WiMax BS and WiFi APs/routers, taking into account the bandwidth demand of the WiFi users. (1), has discussed the Impact of wireless (WiFi, WiMax) on 3g and Next

Generations cellular networks. The paper concluded that operators are expected to focus on the roll out of what so called "Pico cells" to support the growing demands for voice and high-speed mobile data services. It further concludes that WiMax & WiFi could also complement third-generation cellular networks by offering a similar experience over a large area. In (20), the proposal was focused on airtime-based link aggregation for WiFi and WiMax. i.e. the airtime cost was used to measure the available resources of heterogeneous wireless links, where it was calculated on a packet basis for single user. (22), concludes that the convergence services are attractive for both consumers and operators. i.e. Convergence aims to not only make the user interaction with these multiple technologies simpler, but also to shift the complexity from the user side into the device and network side.

So, lots of emerging wireless technologies have evolved with their own advantages and disadvantages. Through the convergence of wireless technologies, one technology can eliminate the shortcoming of the other. i.e. WiMax is trying to compete with WiFi in coverage and data rate, while the inexpensive WiFi still be very popular in both personal and business use. However, WiMax–WiFi combination promises expedient and inexpensive broadband connectivity, which creates a new research area and new models for the providers and subscribers, (15). Similarly, this convergence affords the best solution to provide mobile access in areas such as community centres and parks, whereas broadband wireless access networks based on WiMax can provide backhaul support for mobile WiFi hotspots, (19). It is not only convergence of the technologies (WiFi, WiMax and 3G) is increasingly attractive in a client device to competing service providers but also it is convergence and competition on the way to 4G. Likewise, 4G-Evolution promises to also include improvements beyond 3G as well as nomadic and mobile versions of fixed broadband wireless access (BWA), such as WiFi and WiMax, (23).

The author has concluded that exploring the similarities and dissimilarities among the wireless standards is the initial step towered the convergence. In the following sections, this thesis will discuss the developments of these two. Both WiFi and WiMax belongs to the same IEEE standard family, thus a lot of the similarities have been identified. The major similarities are in the adopted OFDM transmission techniques and in the digital modulation types (BPSK, QPSK, 16QAM and 64 QAM). So, this will be the common ground to initiate the proposed convergence between them, and resolving their dissimilarities remains to be the main challenge.

2.1.2. The WiFi IEEE 802.11 Standard Group

Including being cheap, available, applicable, and has multi-vendors, WiFi has many advantages over WiMax, although WiMax fills many gaps that have been found in WiFi, such coverage area and mobility. WiFi is the dominant wireless technology at the present time for wireless LAN. Tri mode WiFi (IEEE 802.11 a/b/g) is already built in most laptop machines, PDAs and iPhones, (24). Early versions of WiFi had less security and poor reliability with low data rate. WiFi standard developers and vendors have tried to overcome these problems with subsequent releases of versions IEEE 802.11i that focus on security and IEEE 802.11e that focus on QoS (Quality of Services). Ultimately, the IEEE 802.11n, (25) has been released as a new WiFi standard claiming to solve all the previous problems identified by using the MIMO-OFDM mechanism, (26). i.e. IEEE 802.11n has the ability, theoretically, to match WiMax data throughput and wireless range. The increased performance promised by 802.11n WLAN could eliminate the last bottleneck enterprise-wide WLAN deployment.

The security improvement (802.11i) and the MIMO-OFDM mechanism (802.11n) have extensively enhanced WiFi usage. These enhancements have enthused the task group (TGs) to define the Extended Service Set (ESS) Mesh Networking Standards. Presently, the WiFi mesh draft standard has been released as IEEE 802.11s. A lot of challenges against the 802.11s have to be harmonized to efficiently provide a large bandwidth over a large coverage area, (27).

2.1.3. The WiMax IEEE 802.16 Standard Group

World Interoperability for Microwave Access (WiMax) is the trade name of the IEEE 802.16 standard. 802.16d is the WiMax FIXED standard, while 802.16e is the WiMax MOBILE version of the standard. The WiMax technology in its current form will complement the WiFi 802.11 standard. The deployment and adoption of the 802.16e standard could decrease the number of WiFi users in favour of increasing WiMax users and WiMax "hot spots." The 802.16d standard will help corporations and Internet service providers by expanding their services to rural markets or the "last mile", (28), (29).

WiMax is designed to meet the requirements of the last-mile applications of wireless technology for broadband access with mobility, high bit rate, security and long distance coverage. The 802.16 is a set of evolving IEEE standards that are applicable to a vast array of the spectrum ranging from 2GHz to 66 GHz, which presently include both licensed and unlicensed (licence exempt) bands, (30). The IEEE 802.16 is the enabling technology standard that is intended to provide Wireless Metropolitan Area Network (WMAN) access to locations, usually buildings, by the use of exterior illumination typically from a centralized base station (BS), (31).

In 2001 the IEEE 802.16 standard was released, whereas the groups continued to modify it to work on NLOS (Non Line-of-Sight) deployments. These modifications have covered the licensed and licensed-exempt bands between 2GHz-11GHz. In 2003 the IEEE 802.16a was released with an extending OFDM techniques added for supporting the multi-path propagation problem. Meanwhile, the IEEE 802.11n standard group has also evolved the OFDM as apart of the physical layer of the WiFi. Besides the OFDM physical layers, the 802.16a established an optional MAC-Layer functions that including supports for Orthogonal Frequency Division Multiple Access (OFDMA), (15).

In 2004, revisions to IEEE 802.16a were made which called IEEE 802.16-2004. It replaces 802.16, 802.16a and 802.16c with a single standard. Moreover, this revised standard was also adopted as the basis for HIPERMAN (High-Performance Metropolitan Area Network) by ETSI (European Telecommunication Standards Institute). In 2005, 802.16e-2005 was completed, a further MAC-PHY layers modification were formulated by using a scalable OFDM to accommodate high-speed mobility, (32).

In addition to Point-to-Point (PTP) and Point-to-Multi Point (PMP) topologies, the 802.16a introduces the WiMax-mesh topology. This topology gains flexibility, reliability and nomadic network architecture based on multi-hop model. Adding the mesh concept to the 802.16 enlarges the geographical area of any network.

2.1.4. Historical Development of the OFDM Technology

Most multi-carriers wireless technologies use the OFDM (Orthogonal Frequency Division Multiplexing) signal multiplexing method including WiFi and WiMax. OFDM advantages over other multiplexing technologies include its elegant handling of multipath propagation, ISI (Inter-Symbol Interference) and channel fading problems efficiently. However, OFDM-transmitter's Front-end is costly to make and is power inefficient. This is especially a problem in the uplink stage when the handset is powered from a battery, (33).

In this context, (34) argues that using a single carrier technique is better than using OFDM in terms of data rate and the packet error rate (PER). I.e. the single carrier technique achieves better data rate when used by portable device for usage in indoors environment. However, the new wireless standards such WiMax and WiFi are being developed under the OFDM techniques because, from cost/performance point of view, OFDM came out as more attractive solution. At the same era, (35) has proposed the use of a mixed OFDM downlink and single carrier uplink for the IEEE 802.16. This will benefit from the features of both technologies to make cost effective Customer Premises Equipment (CPE) with Non-Line Of Sight (NLOS) operation capability. Eventually, the final draft of the IEEE 802.16 has not approved Ran's approach to avoid the dissimilarities between the downlink and the uplink methods. Either case, it was concluded that the advantage of using OFDM and/or single carrier techniques are application dependent. (32), has proposed an architecture of scalable OFDM Physical layer for IEEE 802.16. This concept was then approved by the by IEEE 802.16 task group. This concept enables the PHY layer to deliver optimum performance channel bandwidth from 1.25 MHz to 20 MHz while keeping the product cost low. i.e. This architecture is based on scalable sub-channelisation structure with variable FFT size (channel FFT size is chosen according to channel bandwidth and supporting other features like Advanced Modulation and Coding (AMC), Hybrid Automatic Repeat Request (H-ARQ) and Multiple Input Multiple Output (MIMO)). Furthermore, (36) have implemented a WiFi 802.11a transceiver using a parameterised OFDM IP blocks. These highly reusable IP blocks, which can be instantiated with different parameter for different OFDM based protocols, are then used for a WiMax IEEE 802.16 transceiver. The overall design of the two transceivers was amalgamated together with 85% sharing of the OFDM designs was achieved, resulting in reduced cost of manufacturing such radios on silicon.

2.2. Review of Relevant IEEE Convergence Standards

A lot of terminologies are used to describe the multi standards approaches such as combination, integrations, cross standards, mixed standards, heterogeneous and convergence. Wireless network convergences are considered to combine more than standards in one device. Recently, various multimedia applications such as video streaming and VoIP services have become popular. Therefore; Bandwidth, mobility and converge area are the main demanded parameters that should be improved. The IEEE wireless standard for integration groups are developing to rise above these demands by creating new amendments for internetworking with external networks. The convergence can be done in any layer among the seven OSI layers and the easiest way is to choose upper layers convergence; however more delay and jitter will be experienced. Consequently, the fastest convergence solution is working at lower layer (MAC and PHY), but at the expense of complexity to the system. The developments are going through different approaches, and more details in the following sections:

2.2.1. The IEEE 802.11u- Internetworking with External Networks

It is a proposed amendment to the IEEE 802.11 standards to add feature that improve internetworking with external networks that include other 802 based networks such as 802.16 ,802.3, and non-802 networks as 3GPP based IMS (IP Multimedia subsystem) networks through subscription serves provider network (SSPN). In this case, internetworking refers to MAC layer enhancements that help selection of a network and allow higher layer functionality to provide the overall end to end solution. It is also permit an emergency Call support, authorization from Subscriber Network and Media Independent Handover Support, (4).

2.2.2. The IEEE 802.16.4- WirelessHUMAN

Its associated industry consortium, WiMax, promise to deliver high data rates over large areas to a large number of users in the near future (e.g. IEEE 802.16a, e and Mesh). This standard specifies the MAC/PHY layers of the air interface of interoperable fixed point-to-multipoint broadband wireless access systems which enables transfer DATA and VIOP with high QoS. The PHY layer is specified for both licence and licence-exempt bands and designed for public network access. This standard will be based on modifications of the IEEE 802.16 MAC layer, while the PHY layer will be based on the OFDM mechanism of IEEE 802.11a and similar standards, (5).

2.2.3. The IEEE 802.21- Media Independent Handover

The IEEE 802.21 standard, approved at the IEEE-SA (IEEE Std 802.21 2008), specifies procedures that facilitate handover decision making. It enables handover, mobility and interoperability between heterogeneous network types including IEEE 802, non IEEE 802 and other cellular networks. IT provides the joint at layer 2 (or layer 2.5) to make any two radio technologies work together as one. IEEE 802.21b Task Group approved on Jan-2009 amendment that enables the optimization of handovers between IEEE 802.21 supported technologies and downlink-only (DO) technologies. IEEE 802.21c Task Group proposes a new amendment named “Optimized Single Radio Handovers”. There is a need to develop optimized single radio handover solutions between heterogeneous wireless networks. Dual radio operation requires multiple radios to be transmitting and receiving at the same time. This leads to platform noise and co-existence issues for radios operating in close proximity frequency bands and generally leads to increased cost of mobile device due to need for RF isolation, sharper filtering or active cancellation, apart from increased design complexity. This amendment defines protocols that will mitigate these issues by enabling controls for having only a single radio transmitting at any time during the entire handover process. This will simplify design of mobile devices and reduce service interruption time during handovers, (3).

2.3. Current WiMax –WiFi Convergence Approaches

WiMax-WiFi convergence is a technology that provides the best of both worlds in that WiMax new features can be offered at the low cost of WiFi. In order to create a heterogeneous network between WiMax and WiFi, differences between these two technologies (see section 3.1) have been investigated and resolved.

There are two camp activities in wireless convergence based on OFDM. One camp focuses on consolidating the protocols to adopt both WiMax and WiFi data, (3), (4), (5), while the other camp focus on consolidating the implementation of the transceiver on silicon, (36), (37), (38). As shown in Table 2-1, this thesis has categorised the solutions of the WiMax-WiFi Convergence's Approaches, within each of the two camps, to:

1. Create New Standard (IEEE 802.21)
2. WiMax Standard Amendment (IEEE 802.16.4)
3. WiFi Standard Amendment (IEEE 802.11u)
4. Third Part Bridge: (CPE - Customer Premises Equipment)
5. Transceiver blocks IP sharing
6. W[2]BC: One Baseband PHY Layer serves both technologies. This thesis proposes an implementation based WiMax-WiFi convergence solution, see chapter 3 and 4.

WiMax-WiFi Convergence's approaches						
Criteria	Implementation Approaches			Protocol Approaches		
	W[2]BC	IP Reuse different OFDM	Third Party Bridge	WiFi Std Amendment	WiMax Std Amendment	Create a New Wireless Std
Description	Single baseband PHY layer serves Both WiFi and WiMax	Technique for high-level IP proposed by MIT - Nokia	Dual PHY/RF hardware Single Chip (Intel)	IEEE 802.11u internetworking with external networks	IEEE 802.16.4 Wireless HUMAN	IEEE 802.21 Media Independent Handover Services
Proposed Date	Q1-2008	Q2-2007	Q2-2006	Q4-2004	Q1-2004	Q3-2002
Approval Date	-	-	-	Q3-2010	Q3-2009	Q4-2008
Commercial Deployments			Dual BB	tba	tba	tba
IOT/trails	Passes All Simulation	Verified to RTL stage	Done	On-going	Scheduled	On-Going

Table 2-1,WiMax-WiFi Convergence Comparison

The third party bridge solution of the WiMax-WiFi convergence has been produced as a dual PHY/RF hardware system that is called CPE (Customer Premises Equipment. Basically the CPE task is a bridge, which is forwarding packet to/from WiMax and WiFi wireless network. Despite the facts that, the WiFi wireless nodes are in the WiMax coverage area but even though they could not join the WiMax domain without a third party bridge - CPE.

Alvairan and Motorola have developed a CPE in 2006, but this solution is not competitive due to the high cost per customer comparing to another alternatives. The thesis has focused on the possibilities of get rid of the CPE (thirds party) and split its tasks between the WiFi side and the WiMax side, (Chapter 3 and 4).

Consequently, as shown in (37), Intel is developing a chip that could receive and transmit WiMax and WiFi signals from a single die. Figure 2-1 shows two different wireless networks and individuals, which have been located with these wireless coverage areas. The Individual that has an Intel WiMax/WiFi chip could join only one of these networks simultaneously. This chip operates in the 2.5 GHz band for WiMax and 2.4 GHz and 5 GHz for WiFi, (39). Intel claims, the data rate performance over WiMax is up to 13 Mbps downlink and 3Mbps uplink while it is up to 450 Mbps Tx/Rx over WiFi. Motorola and Intel argued, a system that combines extensions of two radio access technologies, IEEE 802.11 and IEEE 802.16, has been shown to meet the 4G requirements, (15).

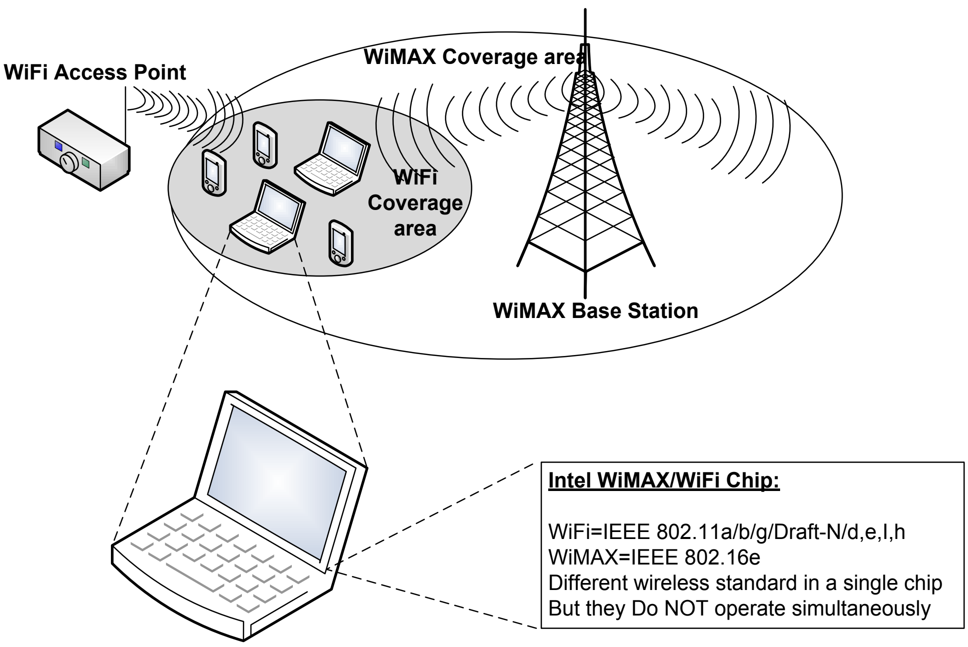

Figure 2-1 , WiMax-WiFi single Chip

The other solutions that proposed by the IEEE Standards Association, shown in (3), **First**: emerging IEEE standard 802.21 for media-independent handover services supports "seamless" mobility between IEEE 802.11 and IEEE 802.16. This mobility integrates the two radio access technologies into one system. It has been suggested that an 802.11VHT + 802.16m + 802.21 system is likely to be proposed for the 4G technology, (40). **Second**: IEEE 802.16.4 standard will be based on modifications of the IEEE 802.16 MAC layer, while the PHY layer will be based on the OFDM mechanism of IEEE 802.11a and similar standards, (5). **Third**: IEEE 802.11u working group that was chartered to allow devices to interworking with external networks, as typically found in hotspots. In this case, interworking refers to MAC layer enhancements that allow higher layer functionality to provide the overall end to end solution, (27).

The Thesis proposal is to find a cost effective approaches to satisfy the convergence in the multi carrier (OFDM) wireless networks, as shown in, (10). In the Multi-Carrier OFDM aspects of WiMax-WiFi Convergence the mismatch in the number of FFT samples cannot be resolved at the MAC layer, and we deal with it as a physical layer issue by creating a ***W****iMax-****W****iFi* ***B****aseband* ***C****onvergence-W*^{2}*BC* (chapter 3).

2.4. Justification of the W^{2}BC Wireless Convergence

This section is concerned with WiMax-WiFi convergence justification. The Convergence as mentioned above is a smart modification in PHY layers that implements a single baseband PHY layer that serves both WiFi and WiMax wireless technologies. Base on the research conducted in this area, this thesis has categorised these contributions into five justifications:

1. **Optimal throughput and pricing for bandwidth:** Broadband wireless access networks based on WiMax can provide backhaul support for mobile WiFi hotspots. It has been considered to integrate WiMax/WiFi network and create a model for optimal pricing for bandwidth where the licensed WiMax spectrum is

shared by the WiFi access points/routers to provide Internet connectivity to mobile WiFi users, (19). Furthermore, the thesis looked at options where the WiFi node may have the choice to by pass the WiFi APs, and connect directly to the WiMax BB. The thesis proposes a controller evaluates the economics of duty such connecting directly to the WiMax may be cheaper, or vice-versa, than connecting via WiFi. The thesis further proposes that kind of controller is integrated within both protocols (i.e. in the upper layers).

2. **Wireless Mesh Network:** Wireless Mesh Networks (WMNs) have been an emerging technology for providing cost effective broadband Internet access. Merging WiFi and WiMax networks offer seamless connectivity for users, (41). It is now commonly accepted in that wireless backbone of a WMN is built using IEEE 802.11s technology. This has been strengthened by the emergence of the IEEE 802.16j standard accommodate for WiMax-MESH mode connectivity. This also enforces the idea of the convergence in the Wireless Mesh Network technologies (WiMax and WiFi), (27), (42). Section 5.6 discusses the WiFi-WiMax convergence in Wireless Mesh Network.

3. **The IEEE 802.21:** The Network Working Group of the WiMax Forum is currently investigating the issues of WiMax-3GPP interworking. Their proposed solutions, and that of the IEEE 802.21 Task Group, are looking into providing seamless handover solutions across heterogeneous networks. This convergence scenario would eventually encompass complimentary and alternative network technologies, such as UMA and fixed-mobile convergence, where advanced mobility and radio resource management would be considered in their global context, (3) , (43).

4. **The 4G standard:** The WiFi-WiMax convergence proposed by this thesis will further be a candidate for the 4G technologies integration. i.e. the collaborations between several technologies allow mobile users to stay connected with the best network while roaming from one base station to another. For example, the video telephony applications can be delivered via 3G networks, while heavy

files uploading or downloading can be accomplished simultaneously via global broadband access networks like WiMax and WiFi. , (44), (45).

5. **Commercial impact:** This study proposes merging the two baseband silicon into a single one. i.e. implementing one Baseband PHY layer to serve both technologies. Thus, reducing the silicon area for the PHY by 85%, (36), (46).

2.5. Summary

As shown in the above literature survey part of this research work, convergence of wireless technologies achieves not only functional benefits but also can save silicon cost when done at the implementation level. The above research focused on combining the function similarities of WiMax and WiFi when they are not working concurrently. i.e. these functions are part of the lower layers of these two protocols (PHY and MAC layers).

The proposed solution does not alter either standard, instead, it propose the implementation of the two standards in a single baseband PHY layer. This solution consolidates the functions of WiFi and WiMax and does not eliminate the importance of each of these technologies in their own rights. i.e.

The motivation behind this study is to utilize the baseband implementation chain so to handle both WiFi and WiMax base band signal. Thus, achieving much design cost saving in silicon implementation where baseband processes are normally implemented side-by-side using similar independent resources.

The arrival of the planned new protocols standards (802.11u, .16.4 and .21) can take advantage of this implementation thus achieving further savings.

Chapter 3: WiMax-WiFi Baseband Convergence (W^2BC)

The focus of the W^2BC work is to share a single implementation of the baseband chain in the PHY layer between WiMax and WiFi signals. The objective of this chapter is to describe the mathematical derivation of the multi-Carrier signal convergence proposed in this thesis. This mathematical model illustrates how the proposed W^2BC works and how it relates to the existing standalone WiMax and WiFi PHY layers. Two specific modulation techniques, the WiMax-Fixed (OFDM-256) and the WiFi-OFDM-64, have been selected as an example to demonstrate this multi-carrier convergence.

The conception of this convergence idea was formed due to the similarities between the WiMax and WiFi functions at this layer. These same functions can be implemented by a single Baseband PHY layer to serve both these technologies.

It has been established that dissimilarities between wireless-standards are typically present at the lower layers. i.e. Protocol stack comparative investigations are typically focused on the PHY and MAC layers of the wireless technologies in question. Previous similar work has established that convergence in WiMax-WiFi multi-carrier OFDM is a physical layer issue, (1). The proposed W^2BC does not suggest changing the standard itself, but instead, to combine the functions of the two WiMax and WiFi implementations into one Baseband PHY implementation using Software Defined Radio (SDR) concept, (36). i.e. by using software controlled by the application layer to switch the PHY functions from one technology signals to the other.

As detailed in the IEEE standard of WiFi (25), and WiMax (47), both technologies use the orthogonal frequency division multiplexing (OFDM) transmission techniques and the same digital modulation types (BPSK, QPSK, 16QAM and 64 QAM). Therefore, convergence at the PHY layer shall reduce the basestation/handset cost significantly. i.e. same silicon block is used for both technologies. Also, controlling the signal selection of the convergence at the PHY layer may increases the complexity of the baseband chip (48), especially when this control can be easily implemented by software at the application layer.

3.1. WiFi-WiMax Spectrum Description

The IEEE 802.11a,n WiFi standards have 2.4GHz or 5GHz carrier centre frequencies respectively, while the IEEE 802.16 WiMax OFDM –TDD standard has a 3.5GHz carrier centre frequency, (49). Figure 3-3 shows these two different OFDM spectrums in their respective frequency bands, plotted around their centre frequency, where, the WiMax-OFDM number of samples (N_{FFT}) is 256 and the WiFi-OFDM N_{FFT} is 64. This mismatch in N_{FFT} is a physical layer issue therefore it can be solved by creating the W^2BC to harmonize the mismatch.

In General, any OFDM signal, S(t), irrespective of its centre frequency, bandwidth, or samples number, can be represented by equation 3-1, (50). This equation underpins the design of the proposed W^2BC.

$$S(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \cdot \sum_{\substack{k=-N_{used}/2 \\ k\neq 0}}^{N_{used}/2} C_k \cdot e^{j2\pi k\Delta f(t-T_g)} \right\} \qquad (3\text{-}1)$$

Where,

N_{used} is the Number of used subcarriers, N_{used} = 200 for WiMax & N_{used} = 52 for WiFi,

C_k is the I-Q complex numbers representing the Data,

Δf is the subcarriers frequency spacing, $\Delta f = 15.625$ KHz for WiMax & $\Delta f = 312.5$ KHz for WiFi,

f_c is the carrier centre frequency,

T_g is the Guard Time, $T_g = 8.0$ μs for WiMax & $T_g = 0.8$ μs for WiFi

Mathematically, equation 3-1 consists of three main parts:

- The Carrier signal $e^{j2\pi f_c t}$ at f_c, where f_c is the factor for deciding which technology is being used.
- The transmitted Data C_k, where k is the "subcarriers frequency offset index" for one sample.
- The Subcarriers signals $e^{j2\pi k\Delta f(t-T_g)}$, where one symbol is equal to the summation of the N_{FFT} samples of the orthogonal subcarriers.

3.1.1. WiFi-OFDM Signal

Figure 3-1 and Figure 3-3 illustrate the WiFi-OFDM-64 in both time and frequency domains, while equation 3-2 shows the mathematical representation:

$$S_1(t) = \mathrm{Re}\left\{ e^{j2\pi f_{c1} t} \cdot \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} C_k \cdot e^{j2\pi k\Delta f_1 (t-T_{g1})} \right\} \qquad (3\text{-}2)$$

Where,

$S_1(t)$ is the time domain equation for the WiFi-OFDM-64,

f_{c1} is the centre frequency that is either 2.4GHz or 5GHz,

k is the frequency index (52 subcarrier indices) that is $-26 \leq k \leq +26$,

N_{used} is 52 subcarriers, 48 data subcarriers + 4 pilot subcarriers. There are also 14 frequency guard subcarriers (7 lower frequency guard subcarriers band + 7 higher frequency guard subcarriers band), which have not appeared in the equation. In total 64 subcarriers (48 data subcarrier + 4 pilot subcarriers+ 14 frequency guard subcarriers) are present in the WiFi-OFDM,

Δf_1 is the subcarrier frequency spacing and depends on the bandwidth and number of FFT samples, ($\Delta f_1 = BW/N_{FFT}$)

$\Delta f_1 = BW/N_{FFT} = 20MHz/64 = 312.5$ KHz,

$= 10MHz/64 = 156.25$ KHz,

$= 5MHz/64 = 78.125$ KHz,

T_{g1} is the guard time ($1/4\Delta f_1$),

$T_{g1} = 0.8$ μs, for 20MHz,

$T_{g1} = 1.6$ μs, for 10MHz,

$T_{g1} = 3.2$ μs, for 5MHz,

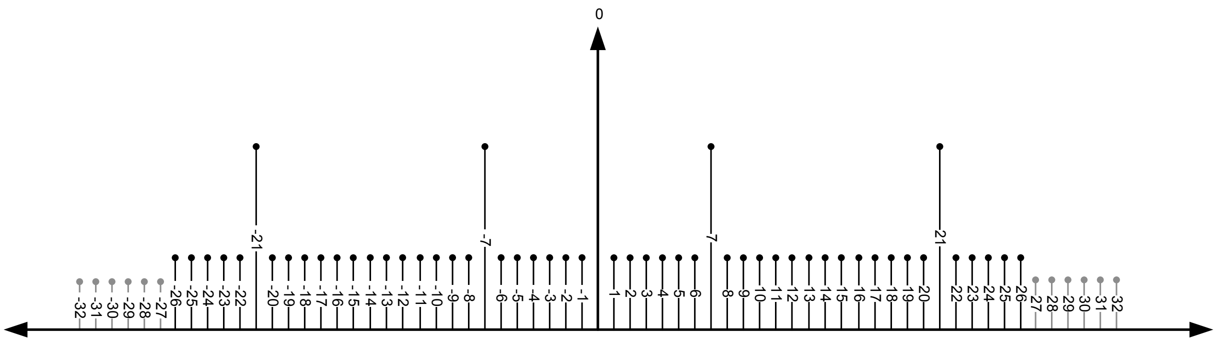

Figure 3-1, WiFi-OFDM-64 Spectrum that shows the Sub-carrier Indices

3.1.2. WiMax-OFDM Signal

Figure 3-2 and Figure 3-3 illustrate the WiMax-OFDM-256 in time and frequency domain, and equation 3-3 represents the mathematical form of it:

$$S_2(t) = \mathrm{Re}\left\{ e^{j2\pi f_{c2} t} \cdot \sum_{\substack{k=-100 \\ k \neq 0}}^{+100} C_k \cdot e^{j2\pi k \Delta f_2 (t - T_{g2})} \right\} \qquad (3\text{-}3)$$

Whereas,

$S_2(t)$ is the time domain equation for the WiMax-OFDM-256,

f_{c2} is the central frequency which is 3.5 GHz,

k is the frequency index (200 subcarrier indices) which is , $-100 \leq k \leq +100$

N_{used} is 200 subcarriers, 192 data subcarriers + 8 pilot subcarriers. There are also 55 frequency guard subcarriers (28 lower frequency guard subcarriers band + 27 higher frequency guard subcarriers band), which have not appeared in the equation 3-3. In total 256 subcarriers (192 data subcarrier + 8 pilot subcarriers+ 55 frequency guard subcarriers +1 DC Subcarrier) are there in the WiMax-OFDM,

Δf_2 is the subcarrier frequency spacing ($\Delta f_2 = 15.625$ KHz),

T_{g2} is the guard time ($T_{g2} = 8$ μs).

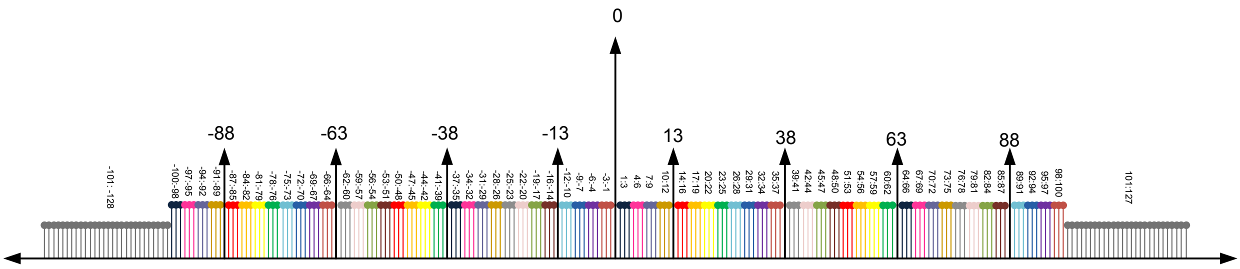

Figure 3-2, WiMax-OFDM-256 Spectrum that shows the sub-carrier indices

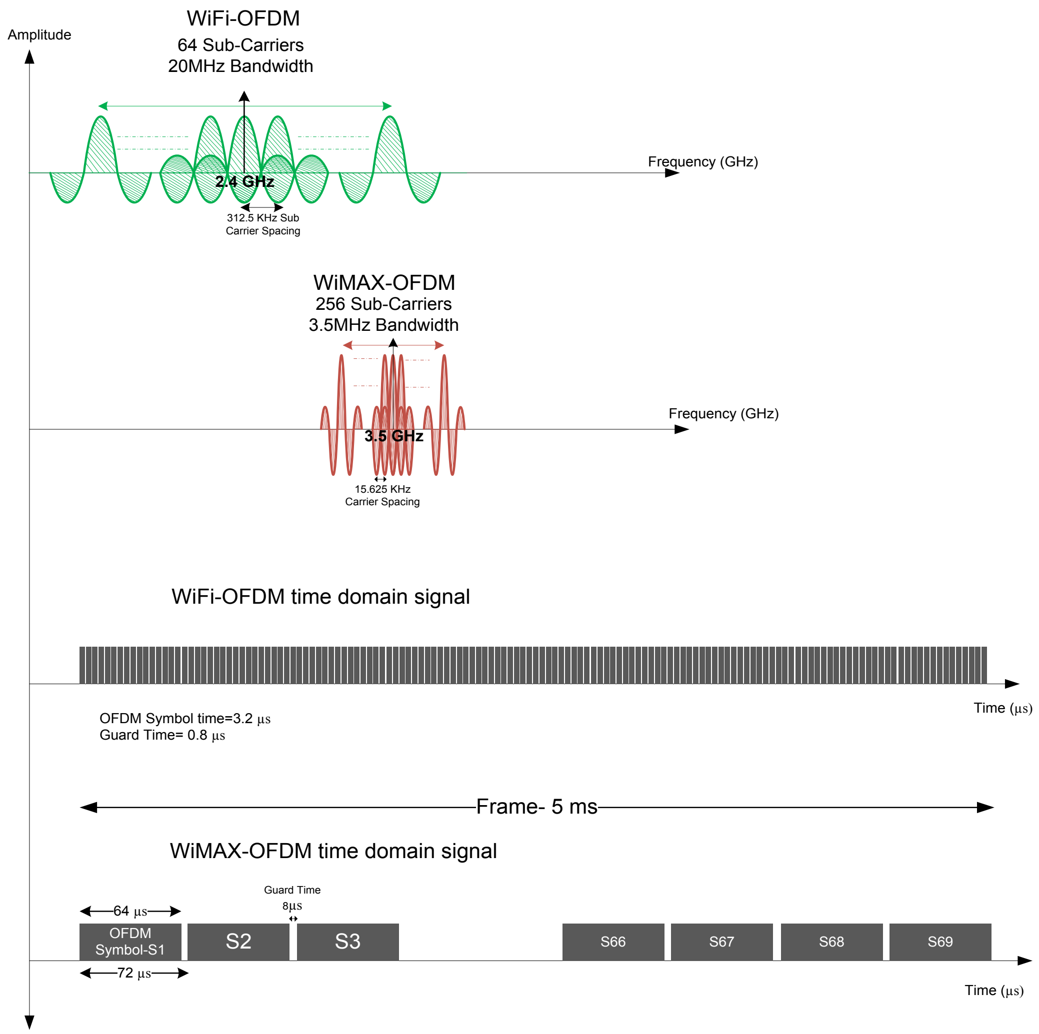

Figure 3-3, WiMax-OFDM, WiFi-OFDM signals (time and frequency domains)

3.2. W²BC - Mathematical Description

Figure 3-4 represents the WiFi/WiMax PHY layer; the top part is the transmitter part of the PHY layer while the bottom part is the receiver. Most of the transmitter/receiver functions are reversible. With this implementation, it is not possible to activate the two modes simultaneously, because they are using the same physical layer blocks in different configuration.

The following steps mathematically explain how a WiFi Signal $S_1(t)$ or a WiMax signal $S_2(t)$ is processed in the proposed W²BC for the receiver part only. The test points (T_1-T_9) in Figure 3-4 will be used to track the signal through the following PHY layer stages:

1. The WiFi-OFDM-64 signal, $S_1(t)$, is being carried on 2.4GHz/5GHz carrier frequency with 64 OFDM samples.
2. The WiMax-OFDM-256 signal, $S_2(t)$, is being carried on 3.5GHz carrier frequency with 256 OFDM samples.
3. The WiFi antenna detects between 2.4GHz and 5GHz carrier frequencies, while the WiMax antenna detects 3.5 GHz.
4. At the first test point T_1, $S_1(t)$ is received by the WiFi antenna then passed on to the WiFi-RF part for processing to a BaseBand signal.

   The equation of the $S_1(t)|_{T1}$ (or $S_1(t)$ at T_1) is:

$$S_1(t) = e^{j2\pi f_{c1}t} . \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} C_k . e^{j2\pi k\Delta f_1(t-T_{g1})}$$

5. At T_2, $S_2(t)$ is received by the WiMax antenna then passed on to the RF part to be formed as a BaseBand signal. The equation of the $S_2(t)|_{T2}$ (or $S_2(t)$ at T_2):

$$S_2(t) = \mathrm{Re}\left\{ e^{j2\pi f_{c2}t} . \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} C_k . e^{j2\pi k\Delta f_2(t-T_{g2})} \right\}$$

6. At T_3, the signal would have been down-converted, amplified, filtered, and quantised in the RF chain. This process starts with an RF-OSC generating a sinusoidal signal, $\mathrm{Cos}(2\pi f_c t) = \frac{1}{2}(e^{-j2\pi f_c t} + e^{j2\pi f_c t})$, that will be multiplied in the time domain by the OFDM symbol.

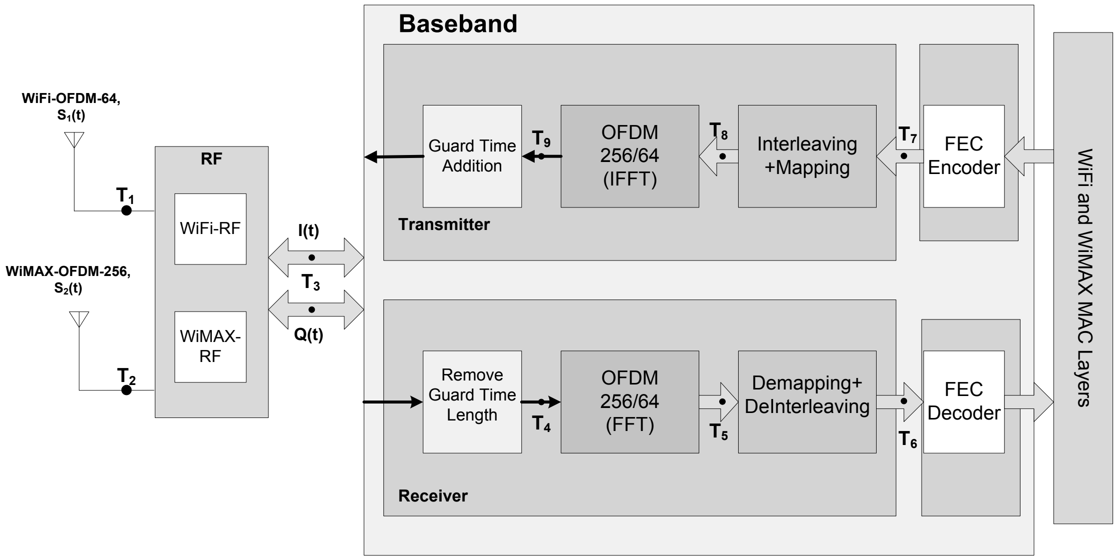

Figure 3-4, WiMax - WiFi PHY Layer Block Diagram

7. At T_3, the WiFi Signal analyses:

a) RF Down conversion,

$$S_1(t)|_{T3} = S_1(t)|_{T2} \times \mathrm{Cos}(2\pi f_{c1} t)$$

$$= \frac{1}{2} \mathrm{Re} \left\{ e^{-j2\pi f_{c1} t} . e^{j2\pi f_{c1} t} . \sum_{\substack{k=-26 \\ k \neq 0}}^{+26} C_k . e^{j2\pi k \Delta f_1 (t - T_{g1})} \right.$$

$$\left. + e^{j2\pi f_{c1} t} . e^{j2\pi f_{c1} t} . \sum_{\substack{k=-26 \\ k \neq 0}}^{+26} C_k . e^{j2\pi k \Delta f_1 (t - T_{g1})} \right\}$$

The second part of $S_1(t)|_{T3}$ is a by-product signal, which represents the second harmonic of the carrier frequency. It has been generated as a result of the multiplication (mixer) of the positive frequency part ($e^{j2\pi f_{c1} t}$) of the OSC signal ($\mathrm{Cos}(2\pi f_{c1} t)$). Any resultant harmonic signal is being eliminated by a suitable Low Pass Filter.

b) Low Noise Amplifier and Filtration stages,

$$S_1(t)|_{T3} = \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} C_k \,.\, e^{j2\pi k\Delta f_1(t-T_{g1})}$$

c) Reconstruct the I(t) and Q(t) signals,

While,

$$\mathbf{C_k}.\, e^{j2\pi k\Delta f_1(t-T_{g1})} = \mathbf{I_k}.\, \mathrm{Cos}(j2\pi k\Delta f_1\left(t - T_{g1}\right) + j.\, \mathbf{Q_k}.\, \mathrm{Sin}(j2\pi k\Delta f_1\left(t - T_{g1}\right)$$

Therefore; $S_1(t)|_{T3}$ could be formed as:

$$S_1(t)|_{T3} = \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} I_k \,.\, \mathrm{Cos}\left(j2\pi k\Delta f_1\left(t - T_{g1}\right)\right) + j. \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} Q_k \,.\, \mathrm{Sin}\left(j2\pi k\Delta f_1\left(t - T_{g1}\right)\right)$$

Or,

$$I_1(t)|_{T3} = \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} I_k \,.\, \mathrm{Cos}\left(j2\pi k\Delta f_1\left(t - T_{g1}\right)\right)$$

$$Q_1(t)|_{T3} = \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} Q_k \,.\, \mathrm{Sin}\left(j2\pi k\Delta f_1\left(t - T_{g1}\right)\right)$$

8. At T_3, for the WiMax Signal analyses :

a) RF Down conversion,

$S_2(t)|_{T3} = S_2(t)|_{T2}$ x $\mathrm{Cos}(2\pi f_{c2} t)$

$$= \frac{1}{2}\mathrm{Re}\left\{ e^{-j2\pi f_{c2}t} . e^{j2\pi f_{c2}t} . \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} C_k . e^{j2\pi k\Delta f_2 (t-T_{g2})} \right.$$

$$\left. + e^{j2\pi f_{c2}t} . e^{j2\pi f_{c2}t} . \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} C_k . e^{j2\pi k\Delta f_2 (t-T_{g2})} \right\}$$

b) Low Noise Amplifier and Filtration stages

$$S_2(t)|_{T2} = \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} C_k . e^{j2\pi k\Delta f_2 (t-T_{g2})}$$

c) Reconstruct the I(t) and Q(t) signals,

$S_2(t)|_{T3}$

$$= \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} I_k . \mathrm{Cos}\left(2\pi k\Delta f_2\left(t - T_{g2}\right)\right)$$

$$+ j. \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} Q_k . \mathrm{Sin}\left(2\pi k\Delta f_2\left(t - T_{g2}\right)\right)$$

$$I_2(t)|_{T3} = \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} I_k . \mathrm{Cos}\left(2\pi k\Delta f_2\left(t - T_{g2}\right)\right)$$

$$Q_2(t)|_{T3} = \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} Q_k . \mathrm{Sin}\left(2\pi k\Delta f_2\left(t - T_{g2}\right)\right)$$

9. At T_4 (receiver part), the guard time length is removed from the signals I(t) and Q(t). Adding guard time (cyclic prefix) to the transmitted signal is to create an "Inter Symbol Interference free channel (ISI-free)". The guard time is one of the modified configuration parameters that have been highlighted in Figure 3-4. For

the WiFi-OFDM-64 signal the guard time is (T_{g1} = 0.8 μs) which represents adding an extra 16 symbols as a cyclic prefix, while the WiMax-OFDM-256 the guard time is (T_{g2} = 8 μs), which represents adding an extra 64 symbols as a cyclic prefix. See (51), page 119, for details of OFDM cyclic prefix. i.e. This stage prepares the IQ signals (an OFDM Symbol) to be transformed from time domain to frequency domain using the Fast Fourier Transform stage. W^2BC is designed to transform 64 or 256 samples in the FFT. The IQ signals equations (an OFDM symbol) will be:

a) For WiFi,

$$I_1(t)|_{T4} = \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} I_k \,.\, \mathrm{Cos}\big(2\pi k \Delta f_1(t)\big)$$

$$Q_1(t)|_{T4} = \sum_{\substack{k=-26 \\ k\neq 0}}^{+26} Q_k \,.\, \mathrm{Sin}\big(2\pi k \Delta f_1(t)\big)$$

b) For WiMax,

$$I_2(t)|_{T4} = \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} I_k \,.\, \mathrm{Cos}\big(2\pi k \Delta f_2(t)\big)$$

$$Q_2(t)|_{T4} = \sum_{\substack{k=-100 \\ k\neq 0}}^{+100} Q_k \,.\, \mathrm{Sin}\big(2\pi k \Delta f_2(t)\big)$$

10. At T_5, the FFT function transforms the I(t) and Q(t) signals from time-domain to the frequency-domain .The FFT block generates two vectors : I-vector and Q-vector with either 64 or 256 length each. The combination of I and Q vectors represent a single OFDM symbol. At this point the IQ-vectors (data) contain complex numbers.

a) For WiFi,

$I = [I_1, I_2, I_3, \ldots., I_{64}]$ and $Q = [Q_1, Q_2, Q_3, \ldots, Q_{64}]$,

b) For WiMax,

$I = [I_1, I_2, I_3, \ldots., I_{256}]$ and $Q = [Q_1, Q_2, Q_3, \ldots, Q_{256}]$,

From the IQ-vectors, this block chooses the data subcarrier indices only, and sends it to the IQ de-mapping (demodulation) block, dropping the other subcarrier indices in the process (DC, Pilot and Guard bands). W^2BC is designed to deal with those different indices and also reconstruct the data from the IQ-vectors weather it is WiFi or WiMax. Table 3-1 shows the subcarrier indices that have been illustrated in Figure 3-1 and Figure 3-2.

Subcarriers	**WiFi-OFDM-64 Indices (k =)**	**WiMax-OFDM-256 Indices (k =)**	
Data Subcarrier	-26:-22 -20:-8 -6:-1 +1:+6 +8:+20 +22:+26	-100:-89 -87:-64 -62:-39 -37:-14 -12:-1	+12:+1 +37:+14 +39:+62 +64:+87 +89:+100
DC Subcarrier	k = 0	k = 0	
Pilot Subcarrier	-21,-7,+7,+21	-88,-63,-38-13 +13,+38,+63,+88	
Guard Band Subcarriers	-32:-27 +27:+32	-128:-101 +101:+127	

Table 3-1, WiFi/WiMax Subcarrier Indices

11. At T_6, each IQ symbol is converted to a binary number. The number of bits per symbol is determined by knowing the modulation type that has been used for the current OFDM symbol. The numbers of bits per symbol are equal to 1, 2, 4 or 6 bits per symbol if the modulation type is BPSK, QPSK, 16QAM, or 64QAM respectively. For instance, if the current OFDM symbol has been sent using 16QAM modulation type, then each C_k (whereas $C_k = I_k + j.Q_k$) is converted to 4 bits binary number. Therefore, a full IQ-vector (one OFDM symbol) generates bits as an input vector to the FEC (Forward Error Correction) block. The WiMax and WiFi technologies use the "Read Solomon block code" and "Vertabi convolution code", (25), (47).

3.3. Summary

The OFDM technique is the common ground among the multi-carriers wireless technologies. Therefore, any OFDM signal can be generated from equation 3-1 irrespective of being a WiMax-OFDM or a WiFi-OFDM. This equation underpins the design of the W^2BC.

The mathematical derivation has clearly shown that Multi-Carrier aspects of WiMax-WiFi Convergence for WiMax-OFDM ($N_{FFT} = 256$) and the WiFi-OFDM ($N_{FFT} = 64$) is possible. This mathematical derivation can be equally used to prove for any other N_{FFT} samples.

The W^2BC does not impact the standard itself, instead, it enables sharing the same PHY baseband functions by multi-carrier signals, while the control of which signal is being handled is done at the upper layers. This saves silicon area and cost at little overheads.

Chapter 4: W^2BC Simulation and Results

The objectives of this chapter are to describe the W^2BC simulation process and to discuss the test results for various scenarios. A closed-loop Simulink* model representing the mathematical derivation of the W^2BC (for both transmit and receive chains) as well as a noise channel (AWGN), as shown in Figure 4-1. MATALB* is then used to simulate various static and dynamic test-benches based on real-world scenarios. W^2BC mathematical derivation is described in chapter 3.

The test scenarios are designed to prove that the functionality and Quality of Service (QoS), including data throughput (Bit Error Rate (BER) at various Signal to Noise Ratio (SNR)) and WiMax-WiFi switching performance, are maintained to the same standard as that of stand-alone WiMax and/or WiFi transceivers.

During roaming, the instructions for association/re-association of the mobile device as it switches from one network to another (e.g. WiFi to WiMax, WiFi to a different WiFi, etc.) are decided in the upper layers. Therefore, all measurements are calculated for the physical layer activities only, and are based on the simulation model of W^2BC. Also, it was important to simulate a "seamless connectivity" scenario (where for example, the mobile device is downloading a live data stream) to prove that W^2BC will not lose any of the data irrespective of the number of network switching during this communication. The results of these test scenarios are discussed in section 4.4.

4.1. W^2BC Simulation Model Description

The W^2BC mathematical derivation was described in the chapter 3. This is then transformed to simulation model using MATALB/Simulink. Figure 4-1 shows a block diagram of this W^2BC Simulink Model. This model represents both the receiver and the transmitter baseband functions, linked by a block of Additive

White Gaussian Noise (AWGN) function to form a channel for this closed- loop system.

The “data source” block contains integer vectors to represent digital data out of an ADC before quantisation. The vector length for the WiMax signal is 192 samples (representing one WiMax OFDM symbol), and for WiFi signal 48 samples (representing one WiFi OFDM symbol).

The “IQ mapper (M-QAM)” and the “IQ Demapper (M-QAM)” blocks transform the sample vectors to IQ data and vise-versa, based on the modulation type selected by the upper layers (M can be set to equal 1 for BPSK, 2 for QPSK, 4 for 16QAM, or 6 for 64QAM modulation types). See Table 4-3 for the actual IQ-Map values based on the IEEE WiMax and WiFi standards, (25), (47).

The “OFDM Modulation” block performs the IFFT, add zero padding and add cyclic prefix functions, while the “OFDM demodulation” block performs the reverse of these functions. i.e. FFT, remove zero padding and remove cyclic prefix.

The AWGN block acts as a channel between the receiver and transmitter chains. It contains a mathematical model of the channel where the only impairment to communication is represented by a linear addition of wideband, or white noise with a constant spectral density, (expressed as watts per hertz of bandwidth) and a Gaussian distribution of amplitude. It allows various SNR values to be selected to enable boundary conditions testing. By the way, for the purpose of testing the W^2BC implementation model, it does not matter which channel model is used. This is because measurement of the switching time during the reception/transmission process is not effected by the channel model. i.e. if there are errors due to the noise channel, then the FEC and the higher layers will deal with it.

The “Data Sink” block gathers the transmitted data in integer vector format similar to that produced by the “data source” block.

The “test point” probes represent signal status at these points. These probes are for DATA_TX, IQ_TX, OFDM_TX, OFDM_RX, IQ_RX and DATA_RX.

The “system Parameters” block is a dummy block to host the values of the configuration parameters. See Table 4-2 for the detailed parameters and their values. Figure 4-1 is showing this block when the configuration is WiMax-OFDM-256 with 16-QAM modulation type.

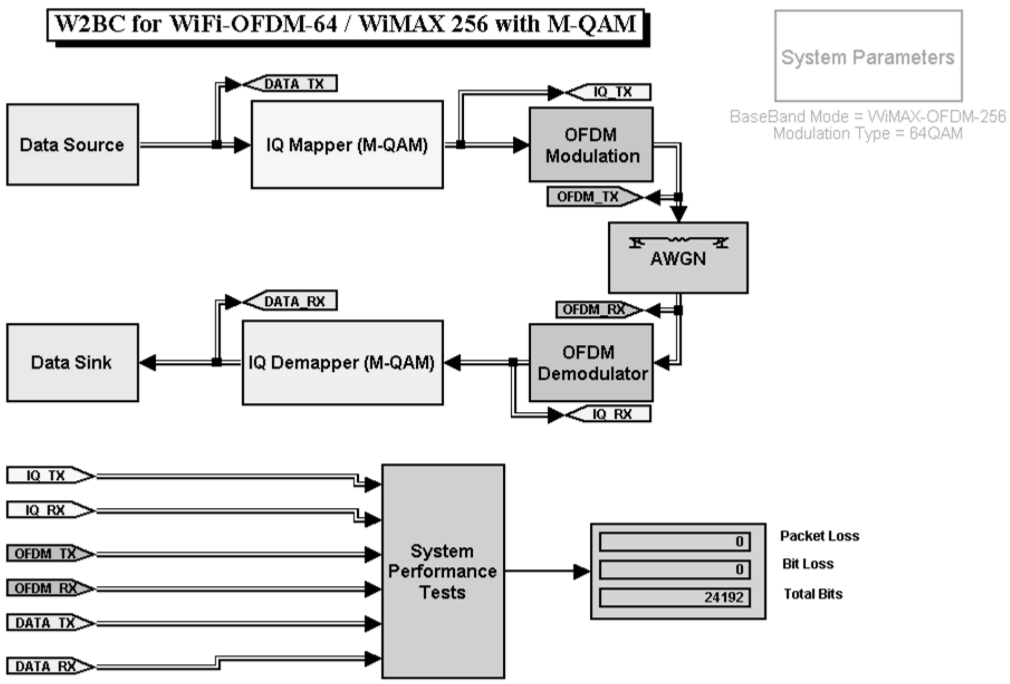

Figure 4-1, Simulink Model for the W^{2}BC

4.2. Static Tests

The static tests verify that the W^{2}BC functions correctly as per the IEEE standards. See sections 4.2.1 and 4.2.2 for details of these tests where, to achieve full compliance with the standards, the BER has to be evaluated across SNR values ranging from 1 up to 25dB. Obviously, for the standalone WiMax or WiFi transceivers, the higher modulation rates at low SNR shall result in the worst transmission BER. Also, as shown in Table 4-1, the W^2BC performance was also compared to WiMax and WiFi products from Atmel, Fujitsu, Freescale and Intel.

Technologies	Chipsets Part –No.	Released Documents
WiMax	Atmel -ATM86RF535A	DataSheet-2006, (52)
	Fujitsu- MB87M3550	Specifications -2006, (53)
WiFi	Freeascle-LP1071	DataSheet-2005, (54)
WiMax-WiFi	Intel-622ANXHMW	Specifications -2009, (37)

Table 4-1, Commercial WiMax and WiFi chipsets

4.2.1. WiMax Static Test

This static test is to establish the behaviour of the W^2BC model (in terms of resulting BER) when it is subjected to various SNR setting using various modulation techniques. The simulator, then, determines the BER value for each test by comparing the transmitted and received data bit by bit at the DATA_TX and DATA_RX probes. For each modulation type, 100 WiMax-OFDM symbols (1920 bits) are transmitted and received for each SNR setting (SNR values range between 0 and 25 dB). In this test, the size of the transmitted/received data, for each modulation type, is 6 MB. As shown in Figure 4-2, the high modulation coding (bit/sample), like 64-QAM with SNR = 5 dB, the resulted BER is very high and approaches 95%. However, this BER is reduced to 5% with the BPSK modulation. Therefore, the BER is inversely proportional with SNR, and the BER is highly dependant on the used modulation type. After comparing the result in Figure 4-2 with the (47) chapter 8 page 692 and (51) chapter 3 page 106, it confirms that the W^2BC model (WiMax part) works correctly in a standalone WiMax physical layer mode. Furthermore, this data is compared to the performance of Atmel and Fujitsu, and shown to be compatible with its performance as well.

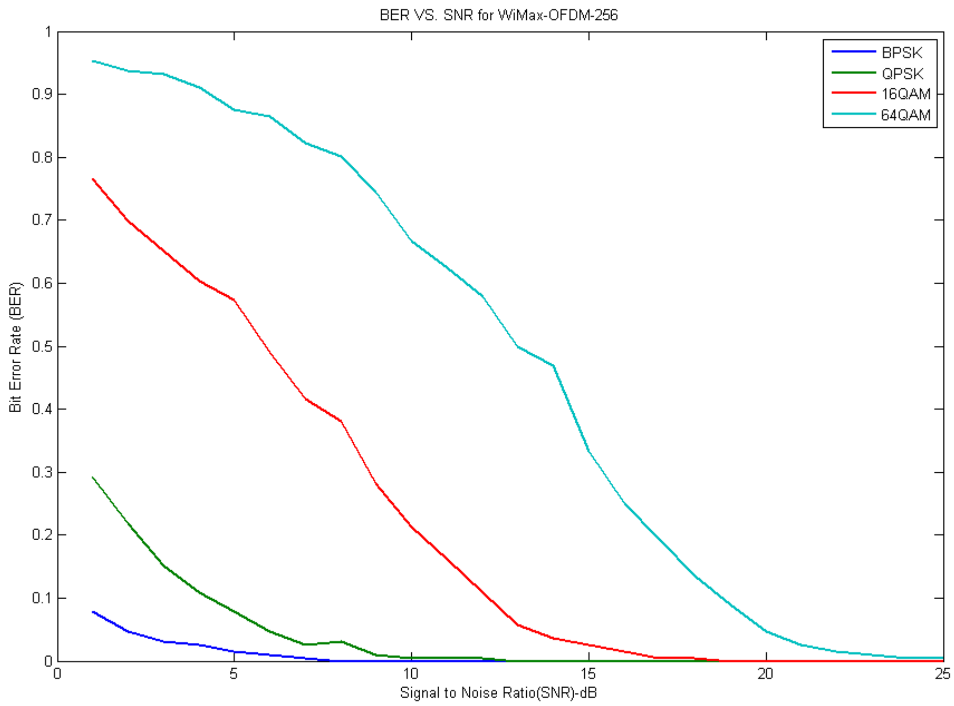

Figure 4-2, Matlab results for W²BC static test showing
BER Vs. SNR forWiMax-OFDM-256 in different modulation types
(B/W = 3.5MHz, fc = 3.5GHz, AWGN Channel)

4.2.2. WiFi Static Test

This static test follows the same procedure as the WiMax test described in 4.2.1. i.e. For the each modulation type, 100 WiFi-OFDM symbols (480 bits) are transmitted and received per one SNR (SNR between 0 and 25 dB), with the size of the transmitted/received data, for each modulation type, is 1.5 MB.

Figure 4-3 shows the performance of W²BC and it conforms to the WiFi standalone standard detailed in chapter 20 page 317 in (25), as well as the Freescale WiFi chip, (54).

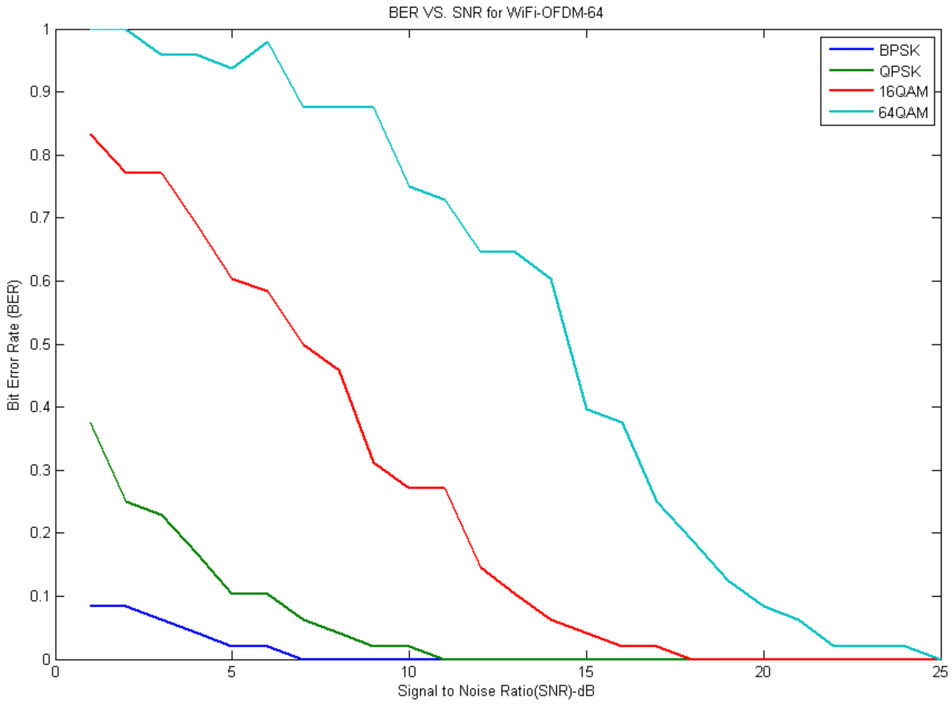

Figure 4-3, Matlab results for W2BC static test showing
BER vs. SNR for WiFi-OFDM-64 in different modulation types
(B/W = 20MHz, fc = 2.4GHz, AWGN Channel)

4.3. Dynamic Tests

The W2BC offers configurability to the baseband-implementation block functions. i.e. real time switching between WiMax and WiFi configurations dependent on usage/requirements of the application. The instructions to switch from/to WiMax and/or WiFi are initiated from the upper layers.

Figure 4-4, illustrates the test setup showing how the W2BC could be configured to switch to different modes as per the configuration Table 4-2. The actual time consumed to load configuration parameters, from the configuration list, plus the time to configure the W2BC from one configuration setup to anther (labelled "Switching Time" T_{wx} from WiMax and T_{wf} from WiFi).

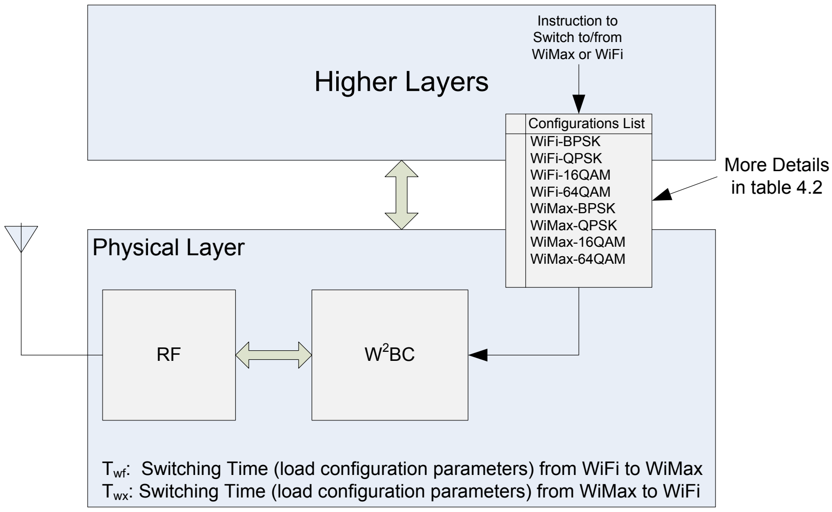

Figure 4-4, a block diagram of the test setup for the W^2BC switching time(T_{wx} and T_{wf})

Table 4-2, shows the list of W^2BC configuration parameters that are used for selecting any of the 8 possible modes. Furthermore Table 4-3 shows the configuration list representing the IQ-MAP values for different modulation types, (25), (47).

The motivation behind the dynamic tests is to measure the switching times (T_{wx} and T_{wf}) in different real-world scenarios. The results of these tests are to prove if any data have been lost due to these switching actions. Note that, the switching time measurement is highly dependent on the simulator model and host processor speed. However, this will be dependent on the silicon technology/process that the PHY is manufactured. Therefore, the switching time is likely to higher in the simulation environment than in real implementation.

Parameters	W^{2}BC Configuration Parameters							
	WiFi-OFDM-64				WiMax-OFDM-256			
	BPSK	QPSK	16QAM	64QAM	BPSK	QPSK	16QAM	64QAM
M-QAM Bits	1	2	4	6	1	2	4	6
IQ-MAP	See Table 4-3							
NFFT	64				256			
Bits/OFDM Symbol	48				192			
Cyclic Prefix indices	49:64, 1:64				193:256, 1:256			
Pilots Subcarriers indices	-7, -21, +21,+ 7				-88,-63,-38-13 +13,+38,+63,+88			
Data Subcarriers indices	-26:-22, -20:-8, -6:-1, +1:+6, +8:+20, +22:+26				-100:-89,-87:-64,-62:-39,-37:-14,-12:-1, +12:+1, +37:+14, +39:+62, +64:+87, +89:+100			
Guard Band Subcarriers indices	-32:-27, +27:+32				-128:-101, +101:+127			

Table 4-2, Configration Paraments for the W^{2}BC to switch to/from WiMax and WiFi

	BPSK	QPSK	16QAM	64QAM
IQ_MAP	[1 -1]	[0.7071 + 0.7071i, 0.7071 - 0.7071i, -0.7071 + 0.7071i, -0.7071 - 0.7071i,]	[0.3162 + 0.3162i, 0.3162 + 0.9487i, 0.3162 - 0.3162i, 0.3162 - 0.9487i, 0.9487 + 0.3162i, 0.9487 + 0.9487i, 0.9487 - 0.3162i, 0.9487 - 0.9487i, -0.3162 + 0.3162i, -0.3162 + 0.9487i, -0.3162 - 0.3162i, -0.3162 - 0.9487i, -0.9487 + 0.3162i, -0.9487 + 0.9487i, -0.9487 - 0.3162i, -0.9487 - 0.9487i,]	[0.4629 + 0.4629i, 0.4629 + 0.1543i, 0.4629 + 0.7715i, 0.4629 + 1.0801i, 0.4629 - 0.4629i, 0.4629 - 0.1543i, 0.4629 - 0.7715i, 0.4629 - 1.0801i, 0.1543 + 0.4629i, 0.1543 + 0.1543i, 0.1543 + 0.7715i, 0.1543 + 1.0801i, 0.1543 - 0.4629i, 0.1543 - 0.1543i, 0.1543 - 0.7715i, 0.1543 - 1.0801i, 0.7715 + 0.4629i, 0.7715 + 0.1543i, 0.7715 + 0.7715i, 0.7715 + 1.0801i, 0.7715 - 0.4629i, 0.7715 - 0.1543i, 0.7715 - 0.7715i, 0.7715 - 1.0801i, 1.0801 + 0.4629i, 1.0801 + 0.1543i, 1.0801 + 0.7715i, 1.0801 + 1.0801i, 1.0801 - 0.4629i, 1.0801 - 0.1543i, 1.0801 - 0.7715i, 1.0801 - 1.0801i, -0.4629 + 0.4629i, -0.4629 + 0.1543i, -0.4629 + 0.7715i, -0.4629 + 1.0801i, -0.4629 - 0.4629i, -0.4629 - 0.1543i, -0.4629 - 0.7715i, -0.4629 - 1.0801i, -0.1543 + 0.4629i, -0.1543 + 0.1543i, -0.1543 + 0.7715i, -0.1543 + 1.0801i, -0.1543 - 0.4629i, -0.1543 - 0.1543i, -0.1543 - 0.7715i, -0.1543 - 1.0801i, -0.7715 + 0.4629i, -0.7715 + 0.1543i, -0.7715 + 0.7715i, -0.7715 + 1.0801i, -0.7715 - 0.4629i, -0.7715 - 0.1543i, -0.7715 - 0.7715i, -0.7715 - 1.0801i, -1.0801 + 0.4629i, -1.0801 + 0.1543i, -1.0801 + 0.7715i, -1.0801 + 1.0801i, -1.0801 - 0.4629i, -1.0801 - 0.1543i, -1.0801 - 0.7715i, -1.0801 - 1.0801i,]

Table 4-3, Actual IQ-MAP values

4.3.1. Roaming between WiMax and WiFi Basestation Tests

These tests (two scenarios) are designed to simulate a real world scenario of a W^{2}BC device roaming/switching between various combination of WiFi and WiMax stations.

To illustrate this in a simple scenario, Figure 4-5 shows the first scenario where a W^{2}BC device is roaming over 3 regions, switching from a WiFi region to a WiMax region and then to a different WiFi region. In this scenario, the W^{2}BC's device is downloading a live data stream. For the WiMax duty, the number of bits per one OFDM symbols is 192 bits and is 48 bits for the WiFi duty. This test takes 96.19 seconds to completely download 65 KB. This test shows that the W^{2}BC's device switches from the WiFi-BPSK to WiMax-16QAM in 1.76 msec, then switches from WiMAx-16QAM to WiFi-64QAM in 1.66 msec.

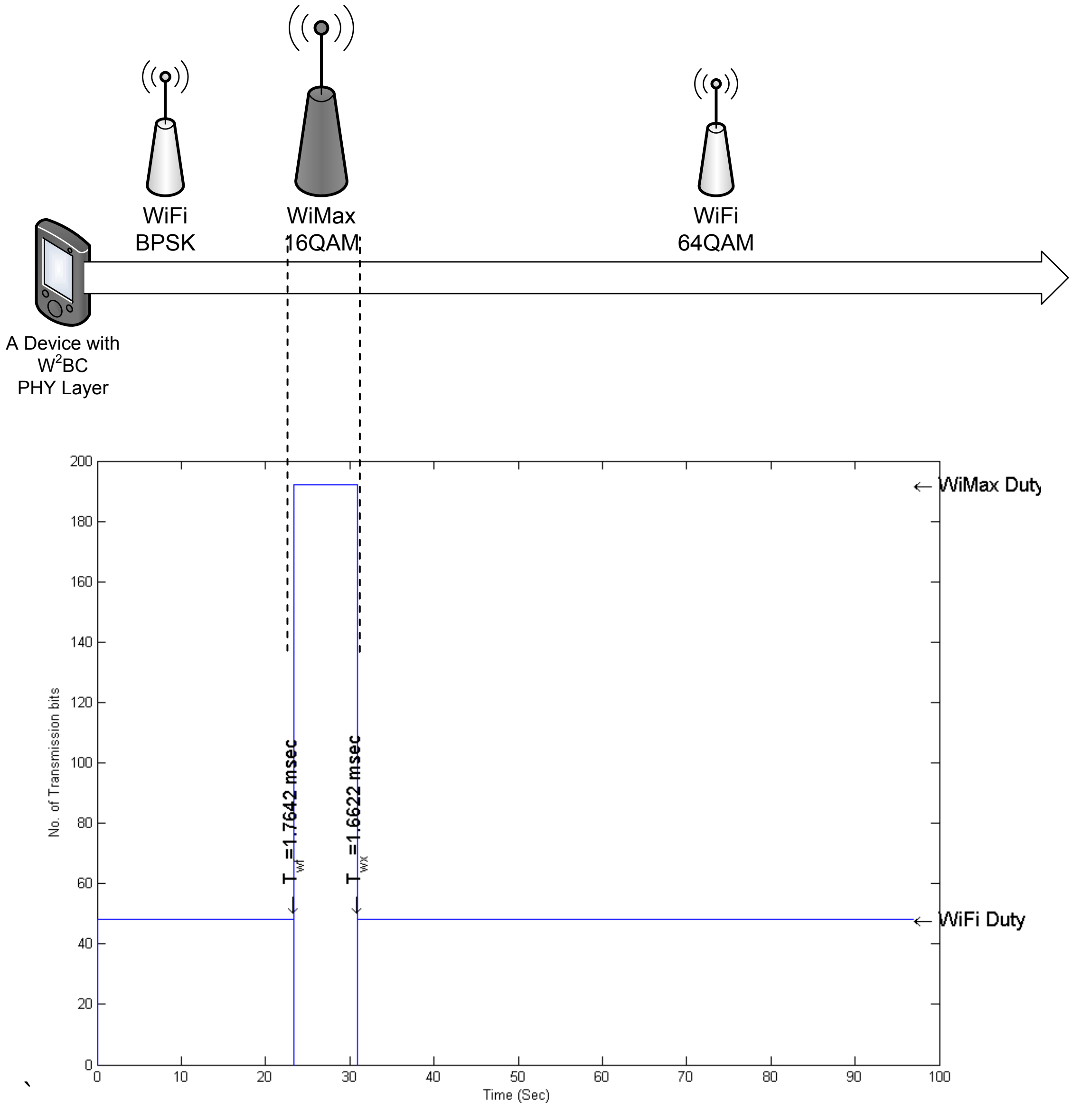

Figure 4-5, Test the W^{2}BC switching time, through WiFi-WiMax-WiFi sequence for downloading a 65Kbytes data stream at 15dB SNR

In the second scenario, shown in Figure 4-6, a W^2BC device is roaming through 8 different WiMax and WiFi basestations, each of which is configured for a different modulation type. The W^2BC device will be downloading a data stream of a 1MByte from a file while roaming. This scenario takes around 802.65 seconds to download and the resultant switching time measured for each region-change ranges between 1.7-2.5 msec.

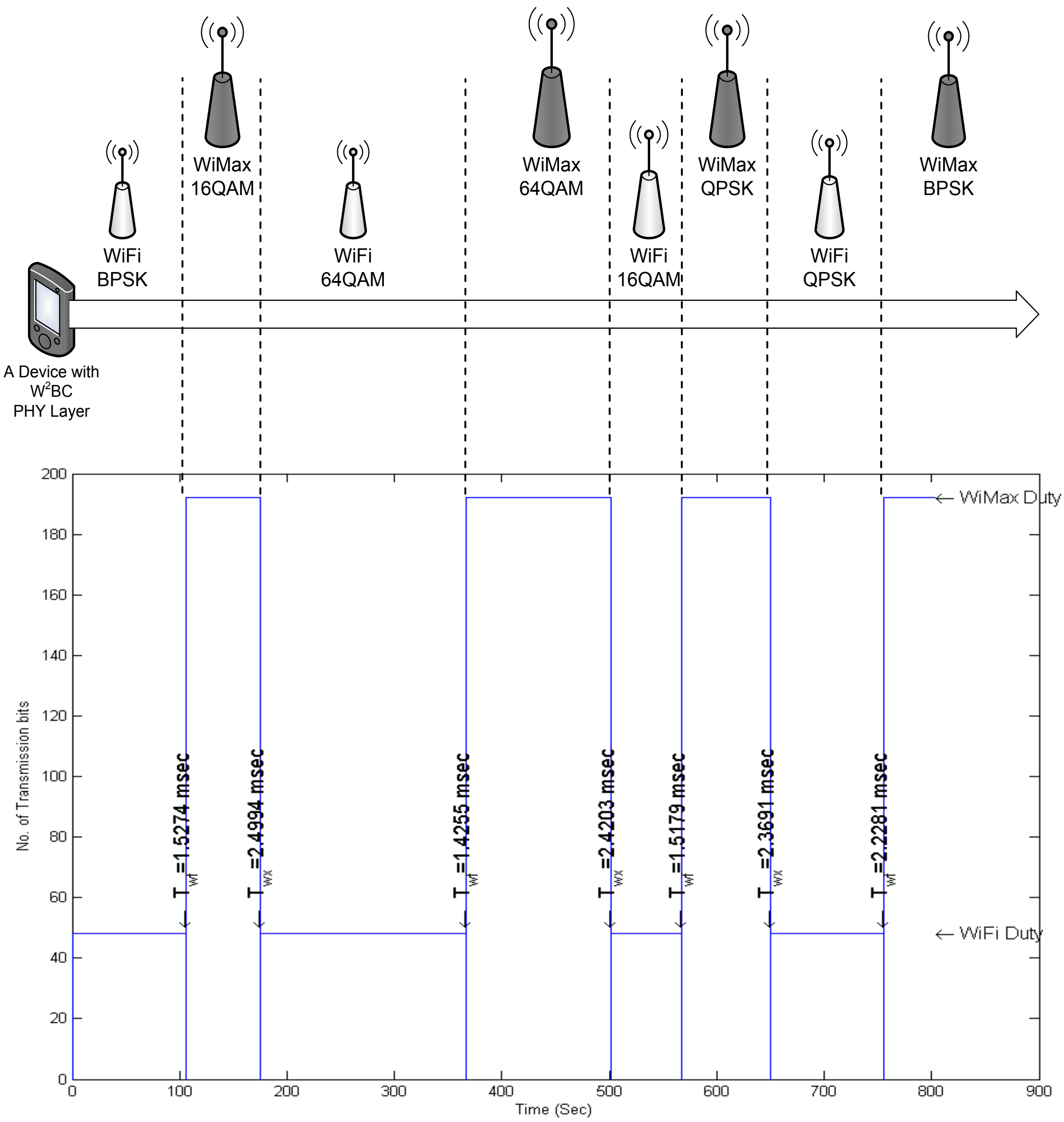

Figure 4-6, Test the W^2BC switching time, through WiMax and WiFi, for 1.05Mbytes data stream at 15dB SNR

The same second scenario is used to simulate the roaming but with different configurations while downloading 3KB data stream. These tests, illustrated in Figure 4-7, Figure 4-8, Figure 4-9, Figure 4-10 and

Figure 4-11, are designed to measure the switching time and BER at various SNR values of 5dB, 10dB, 15dB, 17dB and 20dB. The aim of these tests is to show that the resulted BER, added by the channel noise, does not affect the W^{2}BC behaviour and also the W^{2}BC functions accurately. In these tests, the resultant switching time ranges between 1-2.5 msec, and each tests does take around 2.5 sec.

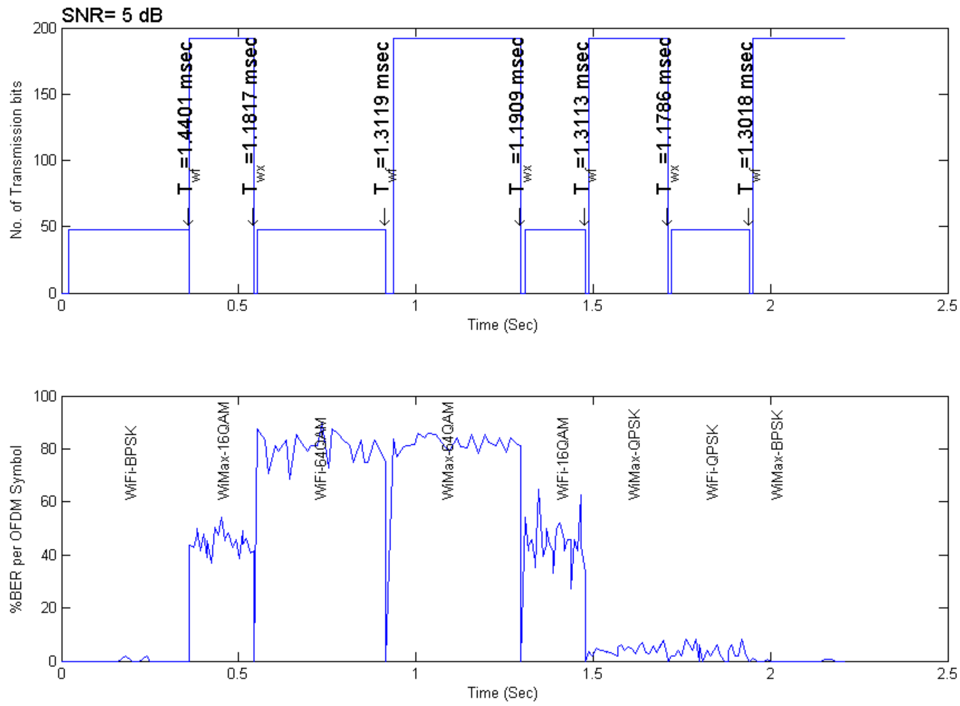

Figure 4-7, showing the W^{2}BC switching time and BER, through WiMax and WiFi, for a 3KB data stream at 5dB SNR

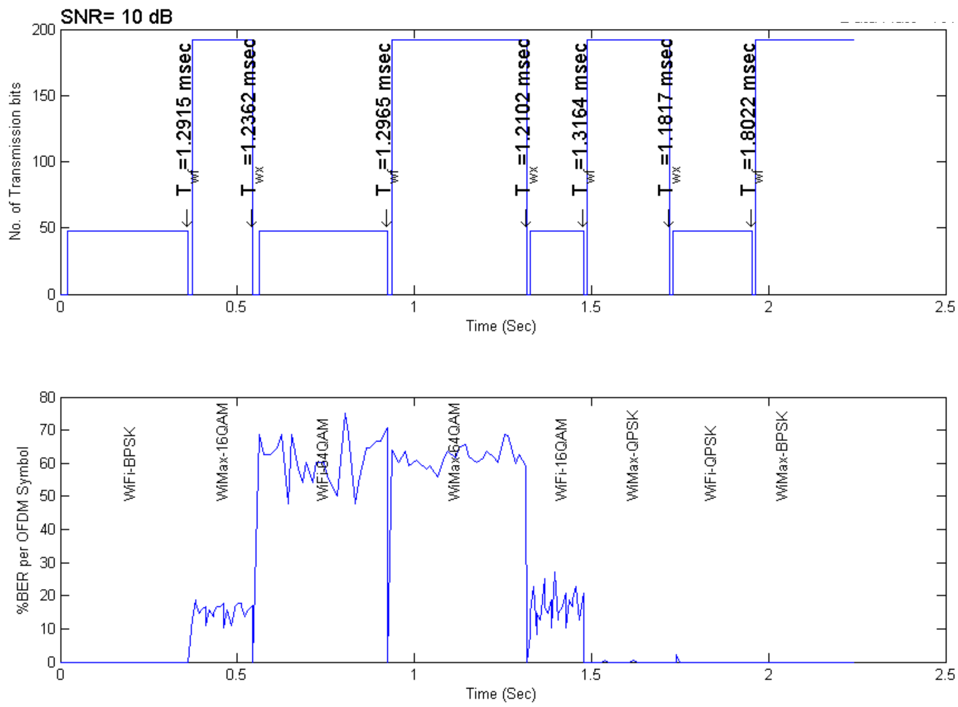

Figure 4-8, showing the W²BC switching time and BER, through WiMax and WiFi, for a 3KB data stream at 10dB SNR

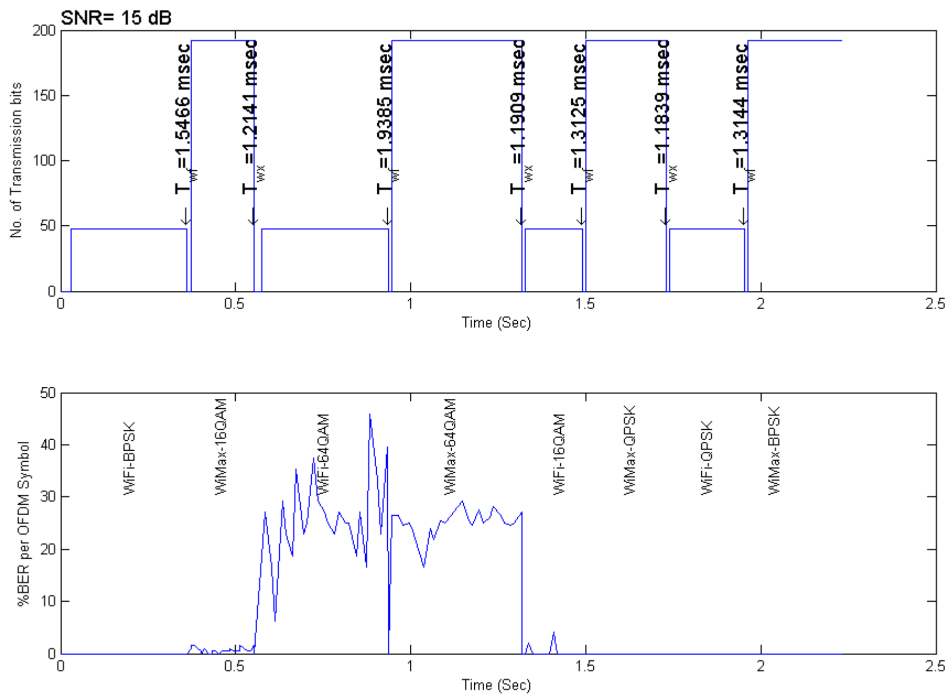

Figure 4-9, showing the W²BC switching time and BER, through WiMax and WiFi, for a 3KB data stream at 15dB SNR

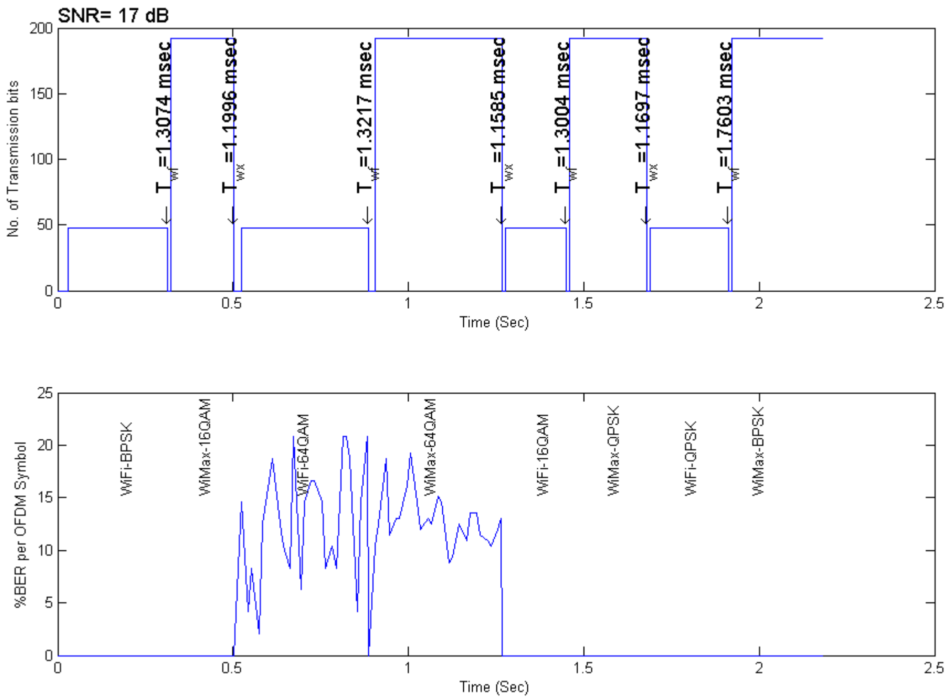

Figure 4-10, showing the W²BC switching time and BER, through WiMax and WiFi, for a 3KB data stream at 17dB SNR

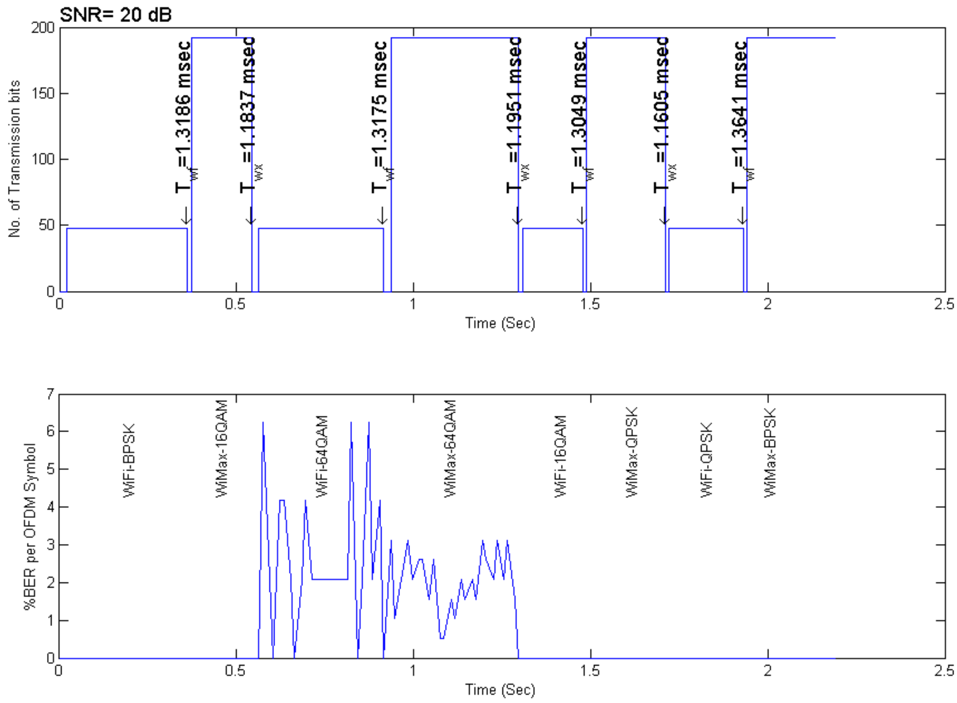

Figure 4-11, showing the W²BC switching time and BER, through WiMax and WiFi, for a 3KB data stream at 20dB SNR

Figure 4-12 shows the BER for the above tests (SNR values). These errors are caused by the noise channle and not by the W²BC implementation. Obviously, the BER results show that errors are highly dependant on the SNR over the particular channel, for the four modulation types. This is expected result when compared to the specification of IEEE standards (25), (47), and also the performance of the commercial chipsets listed in Table 4-1.

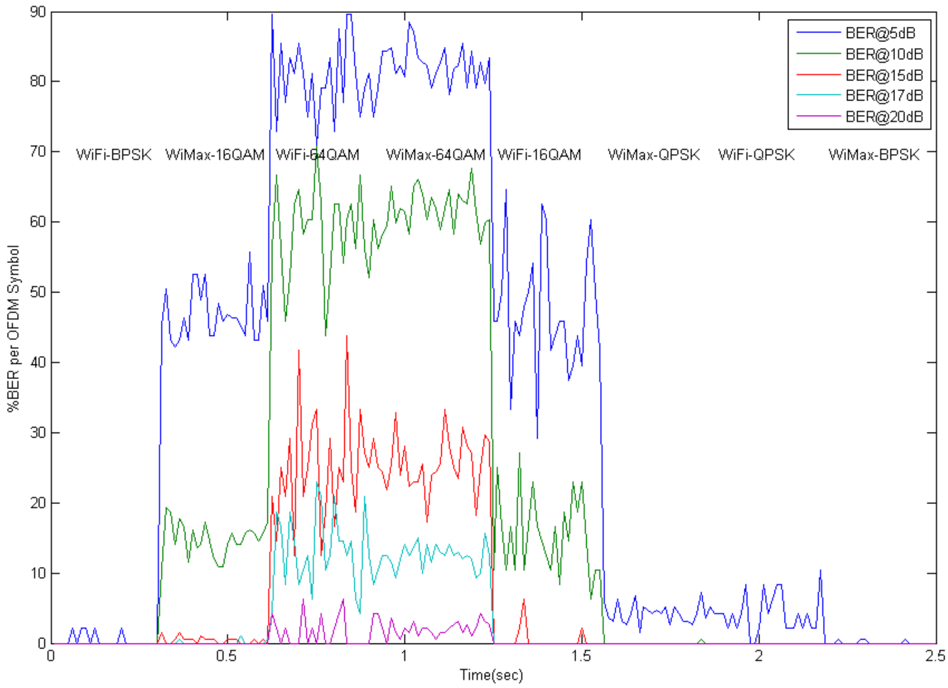

Figure 4-12, BER for SNR values (5, 10, 15, 17 and 20 dB)

4.3.2. Switching/Roaming between various WiMax Test

In these test, the same scenario of section 4.3.1 is repeated to measure the switching time while the W²BC device is roaming between various WiMax basestations, or while the W²BC device is switching between various modulations types while in the same WiMax region/basestation. Figure 4-12 to Figure 4-17 illustrates the measurements obtained for downloading a stream of 4.7Kbytes data. All results demonstrate the same switching times and behaviour of the W²BC.

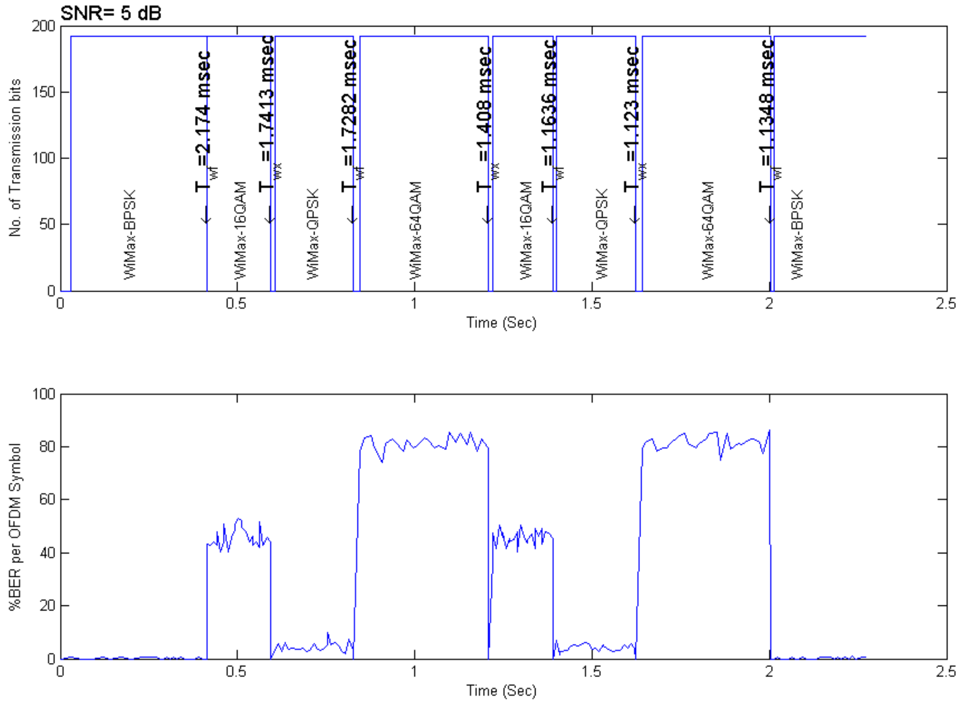

Figure 4-13, showing the W2BC switching time and BER, through WiMax, for a 4.7KB data stream at 5dB SNR

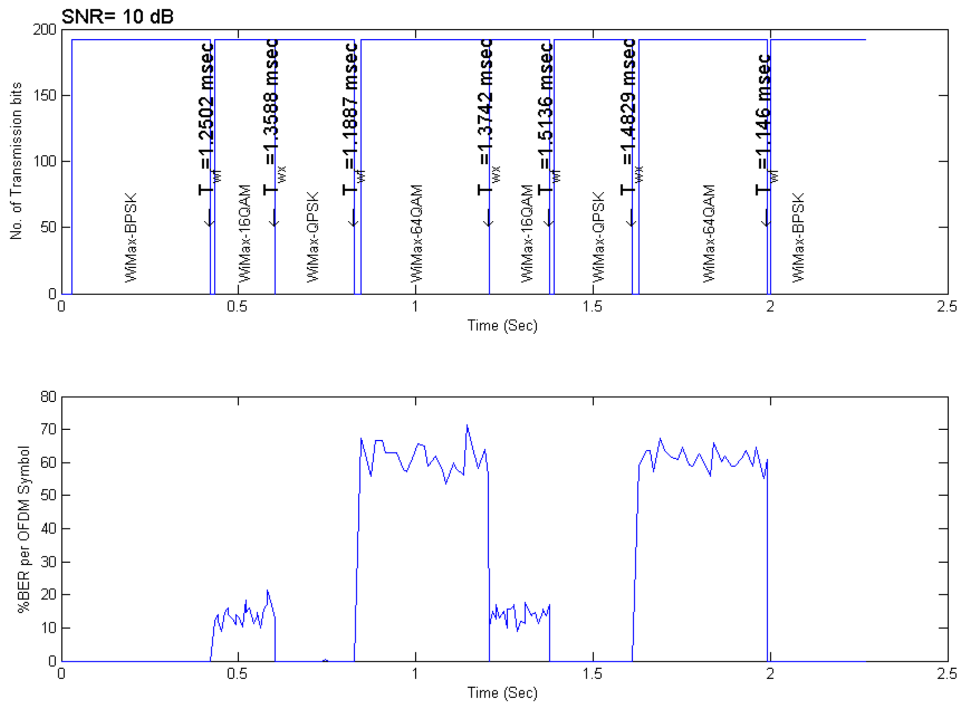

Figure 4-14, showing the W2BC switching time and BER, through WiMax, for a 4.7KB data stream at 10dB SNR

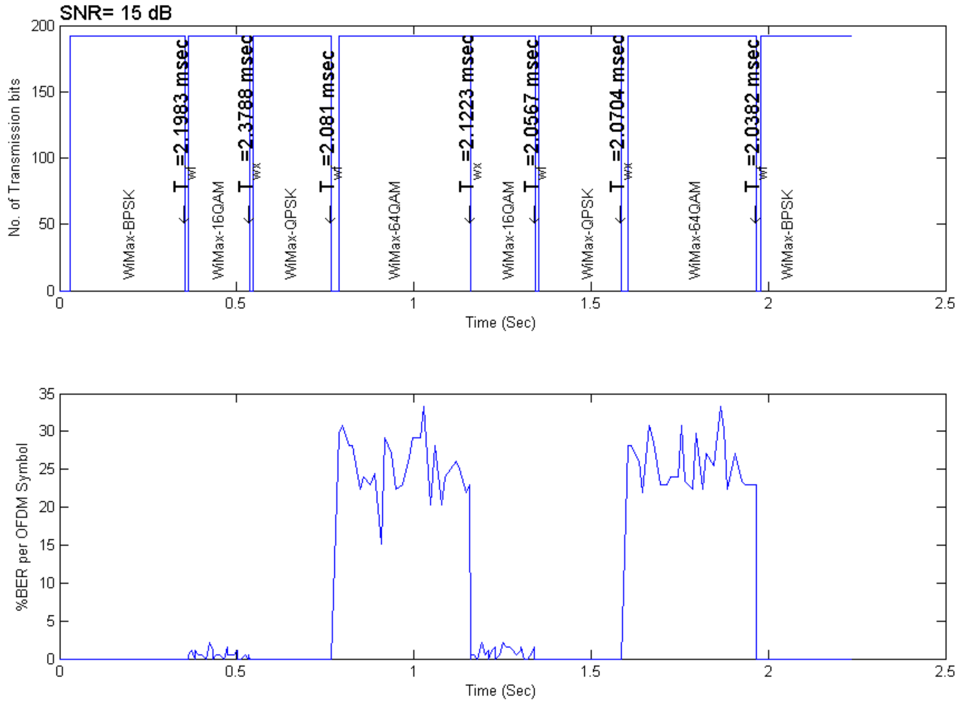

Figure 4-15, showing the W2BC switching time and BER, through WiMax, for a 4.7KB data stream at 15dB SNR

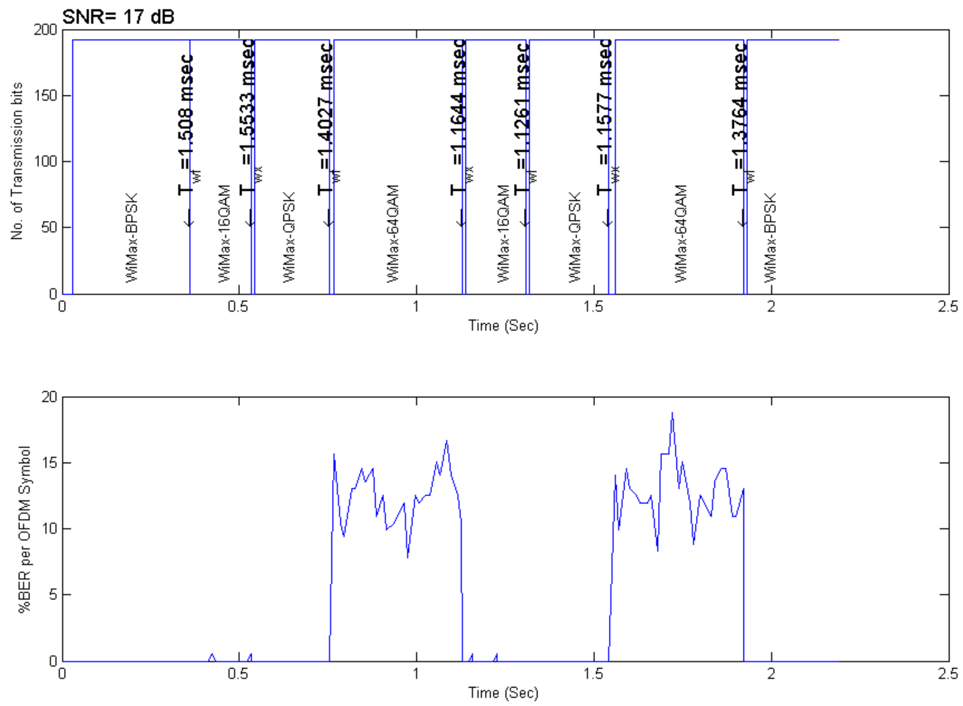

Figure 4-16, showing the W2BC switching time and BER, through WiMax, for a 4.7KB data stream at 17dB SNR

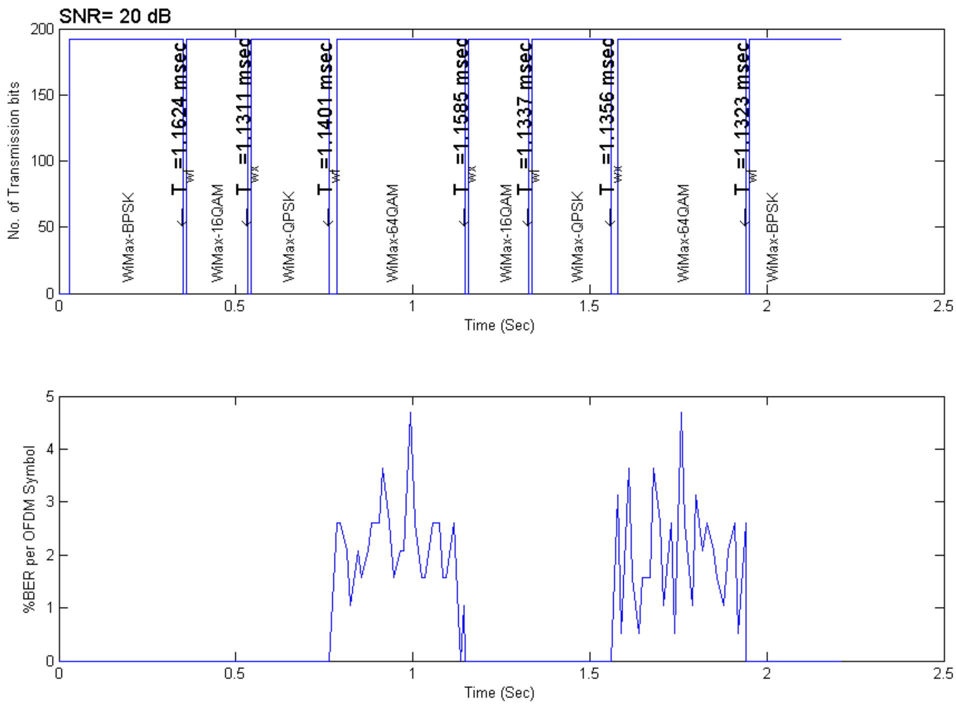

Figure 4-17, showing the W²BC switching time and BER, through WiMax, for a 4.7KB data stream at 20dB SNR

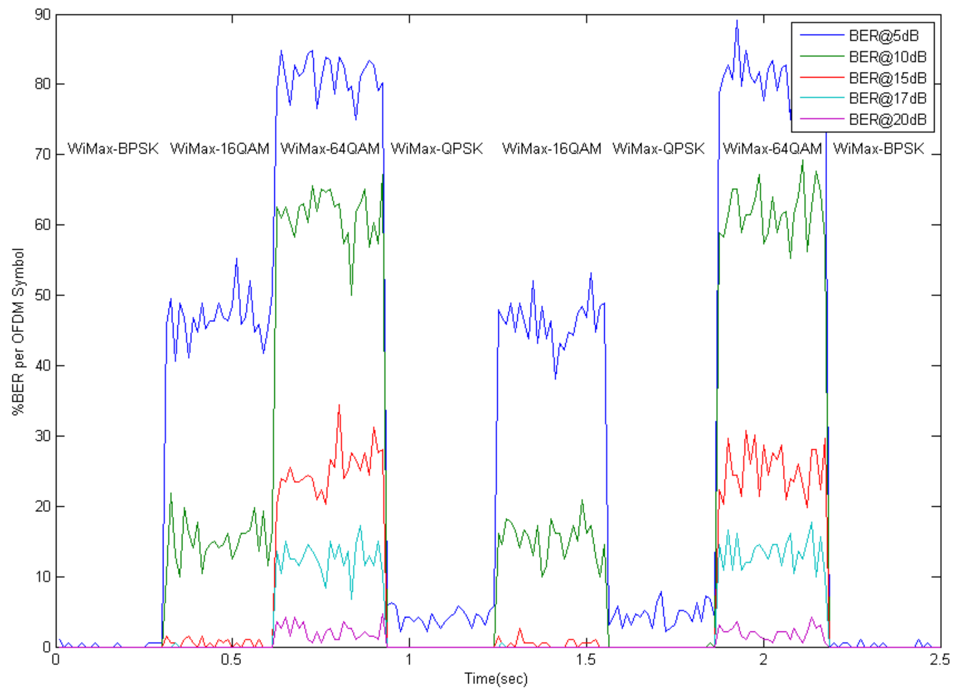

Figure 4-18, BER for SNR range (5,10,15,17 and 20 dB) in WiMax

4.3.3. Switching between various WiFi Basestations Test

In these test, the same scenario of section 4.3.1 is repeated to measure the switching time while the W^2BC device is roaming between various WiMax basestations, or while the W^2BC device is switching between various modulations types while in the same WiMax region/basestation.

Figure 4-4 illustrates the measurements obtained for downloading a stream of 1.2Kbytes data. All results demonstrate the same switching times and behaviour of the W^2BC.

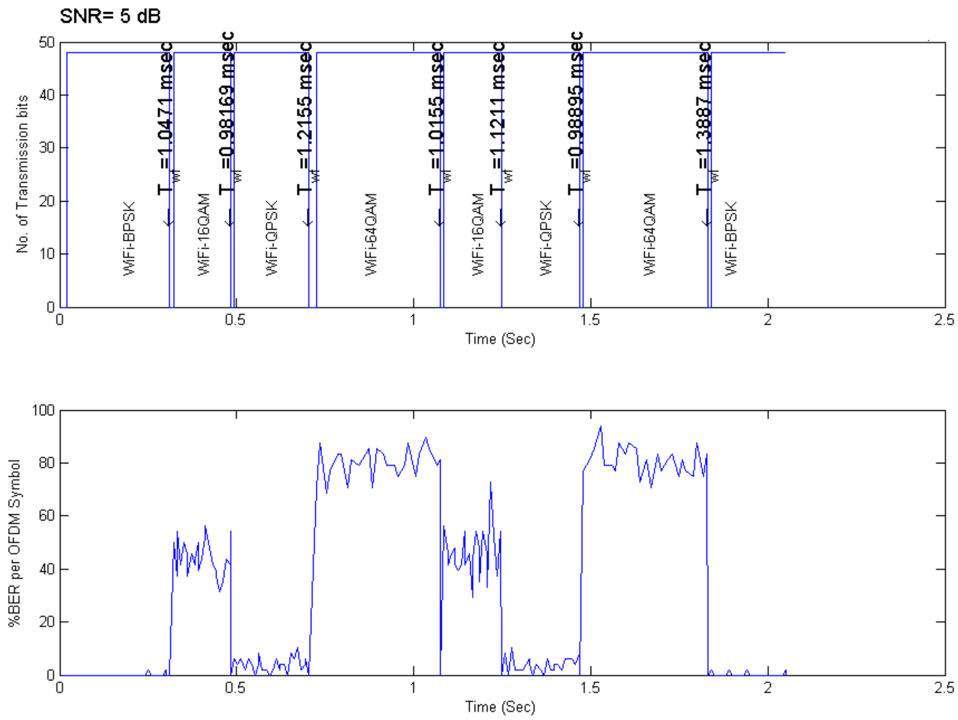

Figure 4-19, showing the W^2BC switching time and BER, through WiFi, for a 1.2KB data stream at 5dB SNR

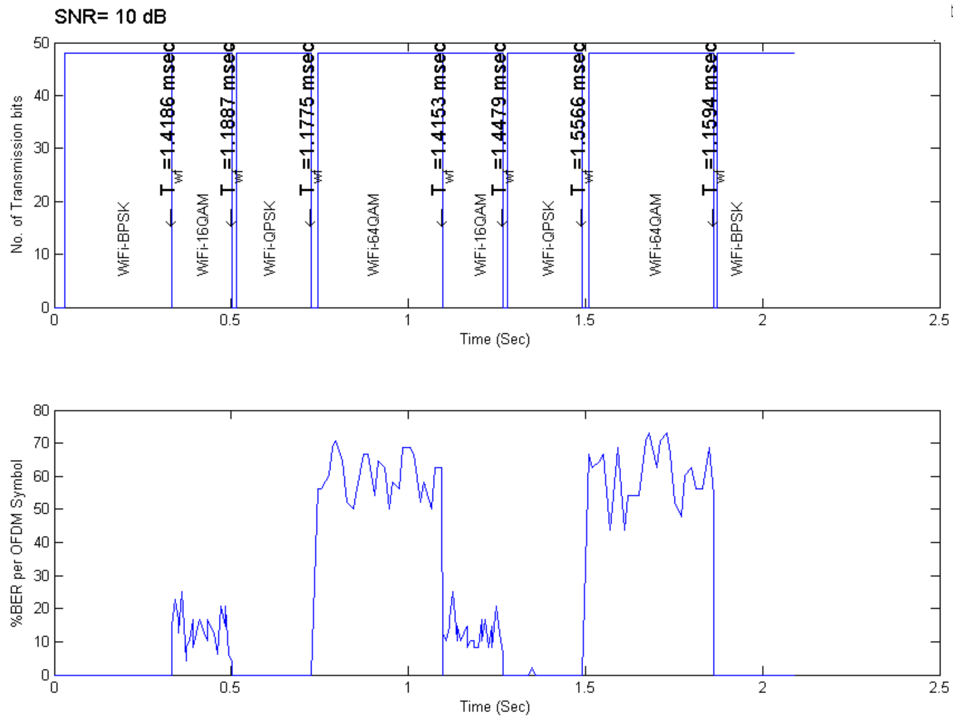

Figure 4-20, showing the W²BC switching time and BER, through WiFi, for a 1.2KB data stream at 10dB SNR

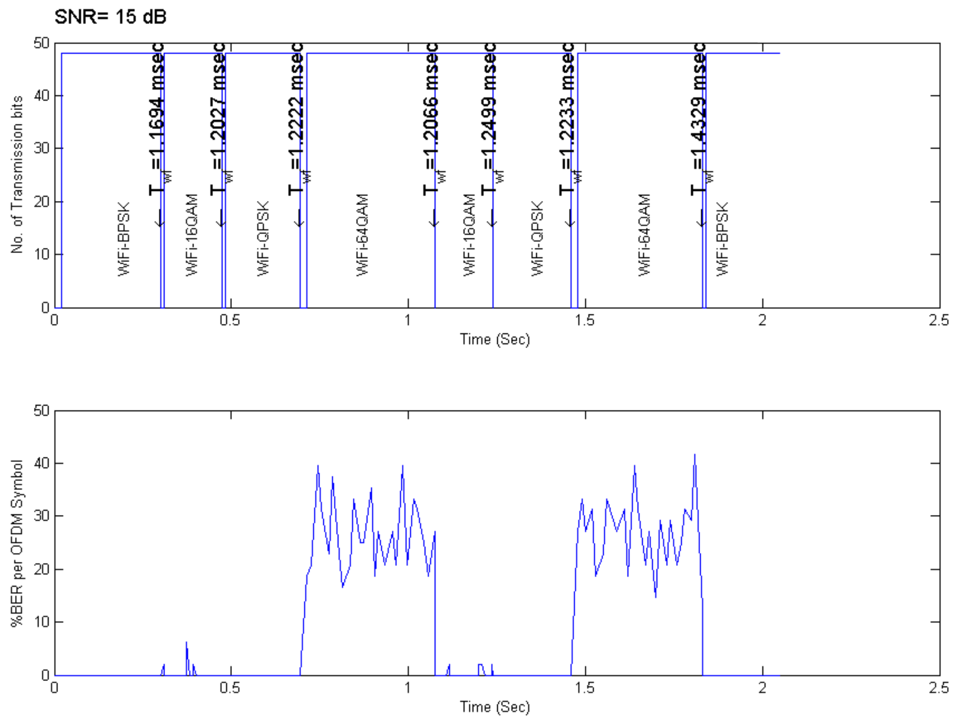

Figure 4-21, showing the W²BC switching time and BER, through WiFi, for a 1.2KB data stream at 15dB SNR

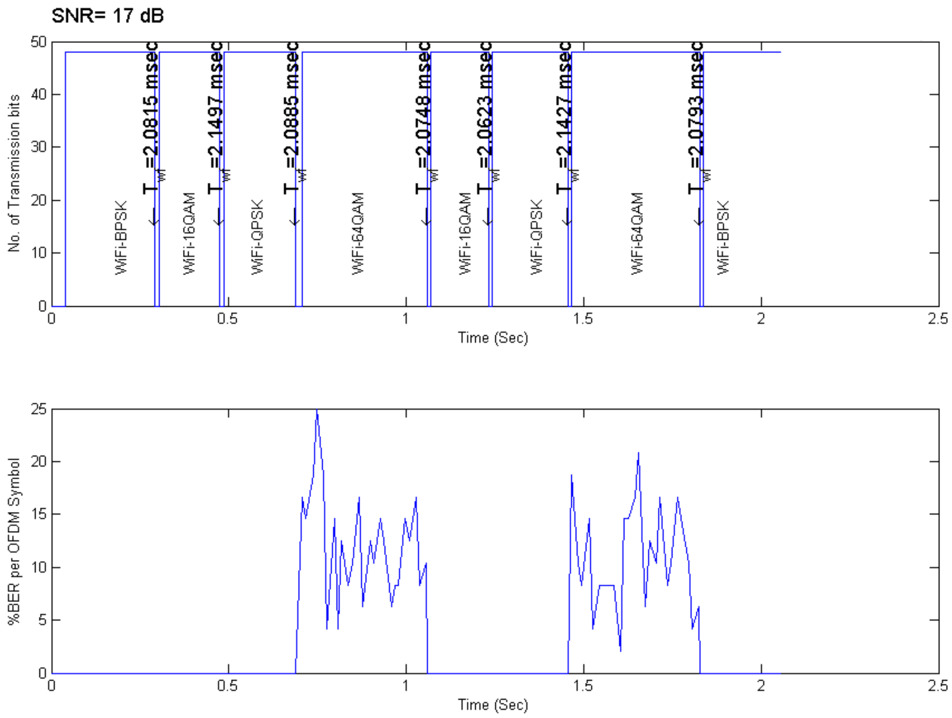

Figure 4-22, showing the W²BC switching time and BER, through WiFi, for a 1.2KB data stream at 17dB SNR

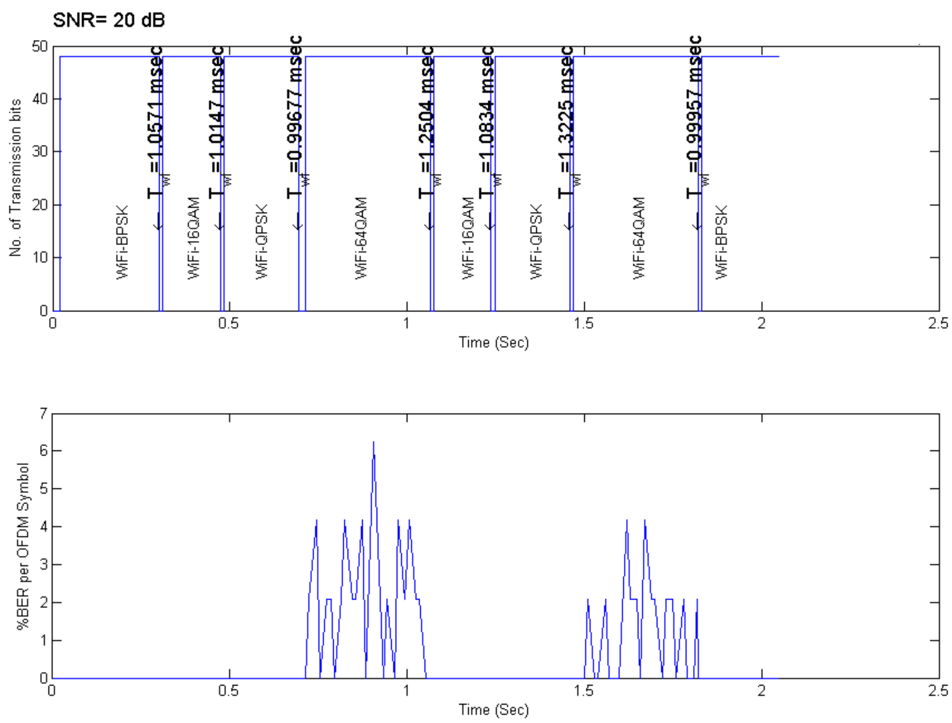

Figure 4-23, showing the W²BC switching time and BER, through WiFi, for a 1.2KB data stream at 20dB SNR

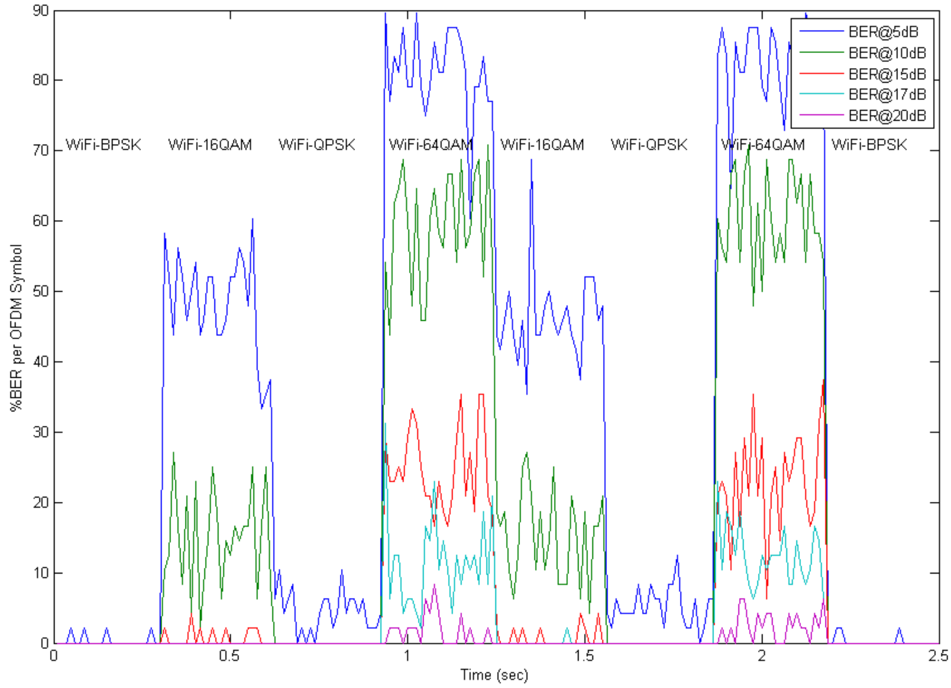

Figure 4-24, BER vs. SNR range (5, 10, 15, 17 and 20 dB) in WiFi

4.4. W²BC Discussion and Conclusion

The proposed W²BC offers a novel implementation concept for convergence of the WiMax and WiFi technologies. The next step would be to implement the W²BC on silicon and a number of potential companies have been approached. Unfortunately, slow deployment of WiMax has resulted in a number of the major companies pulling out of this market. Thus, no decision of sponsoring the silicon implementation has been reached thus far.

The simulation model and test scenarios were the most convenient available environment for this study. It proves that W²BC does offer a viable solution, and performs to the IEEE specification for standalone WiMax or WiFi transceivers as well as commercially deployed products. A summary of the static and dynamic tests are shown in Table 4-4.

The resulted W^{2}BC average switching time range of 1.5-2.5 msec is relevant to the simulator's host processor. This time is less than the time of a standalone WiMax or WiFi frame (the standards specify 5 msec). It is expected that a dedicated silicon implementation will result in much faster switching time (for example, the Freescale WiFi chip has an ARM7TDMI running at 88MHz and supported by own dedicated memory and resources). In such case, an estimated overhead of $< 2\%$ delay will be attributed to the W^{2}BC switching time. Therefore, it is expected that the W^{2}BC switching time in the real-time implementation will be less than 2.5 msec.

The only single chip in the market that supports WiMax and WiFi on a single die is produced by Intel (622ANXHMW). Intel has not released the full datasheet for this product yet. However, from the specifications documents, it can be deduced that a combined WiMax+WiFi baseband implementation, similar to W^{2}BC has been adopted (the marketing data mentions that WiMax and WiFi do not operate simultaneously, and that seamless roaming is achieved by between respective Access Points, (37).

Parameters		W^{2}BC Tests							
		WiFi-OFDM-64				WiMax-OFDM-256			
		BPSK	QPSK	16QAM	64QAM	BPSK	QPSK	16QAM	64QAM
Data Rate (Mbps)		2	4	8	12	4	8	16.1	24.2
BER% Vs. SNR	5dB	4%	10%	66%	94%	1.6%	7.8%	58%	88%
	10dB	0%	4.2%	36%	82%	0%	1%	25%	70%
	15dB	0%	0%	8.3%	50%	0%	0%	3%	37%
	20dB	0%	0%	0%	12.5%	0%	0%	0%	6%
	25dB	0%	0%	0%	0%	0%	0%	0%	0.5%
W^{2}BC Switching Time (msec)		1.5-2.5 msec							

Table 4-4, W^{2}BC Tests Summary

In conclusion, W^{2}BC achieves a compact baseband implementation of these two technologies with no impact on performance. Thus achieving much needed saving in silicon size, power and cost. Sharing a single PHY layer has obviously reduced the size of the total baseband implantation by 35%, (36). The baseband functions that have been made configurable in the W^2BC implementation are clustered within the Cyclic Prefix, the FFT, the OFDM and the IQ-Mapping blocks. The W^2BC concept can be expanded to cover mobile-WiMax (802.16e) OFDM-512, OFDM-1024 and so on. The arrival of the planned new protocols standards (802.11u, 802.16.4 and 802.21) can take advantage of this implementation thus achieving further savings.

Chapter 5: WMN Routing Protocols Review

The objectives of this chapter are to review the most common WMN routing protocols and to justify how the proposed Prime-IP algorithm enhances these protocols. i.e. enables any node in the WMN to have knowledge beyond their nearest neighbors because, in these protocols, information is only available from the nearest neighboring nodes only.

To aid understanding of this review, the protocols have been divided into two groups for those that use a “basestation” or not. Each of these groups has been sub-grouped further as shown in Table 5-1. The literature survey for this review has been on-going since the beginning of this research work in Oct/2006. The review includes the WiFi Mesh routing protocols (IEEE 802.11s) and WiMax Mesh routing protocols (IEEE 80216).

Without changing the reactive routing protocols, Prime-IP focuses on maintaining the knowledge of all nodes in all possible route paths between the source node and the destination node irrespective of the number of intermediate nodes number. This node knowledge is accumulated during the route discovery process. Furthermore, for WMN routing protocols, Prime-IP enhances the current routing protocols as well as security. The Prime-IP algorithm is described in chapter 6.

5.1. WMN Routing Protocols: Evaluation Criteria

The focus of the literature survey was to establish if the most commonly used WMN protocols (a) accommodate knowledge of other non-neighbouring nodes in the network, and (b) if prime numbers are used in the IP address of the nodes. Therefore, these two criteria are used to evaluate all of these protocols without regards to other criteria such as throughput, synchronisation, etc.

The dynamic topology of WMNs has invited many attempts to classify the routing protocols based on various criterions dependent on the approaches adopted in these publications, (7), (55), (56). Reactive routing protocols offer faster dynamic network connectivity and self-configuration as well as scalability for large WMNs than Proactive routing protocols because of the processing-time and hosting overheads required to maintain/update the information about all the nodes in the network in routing tables, (57), (58), (59), (60). However, the proactive protocols offer better network security, Quality of Service (QoS), and network management, (61). Hybrid solutions based on both proactive and reactive routing protocols attempts to compromise on the benefits of both, and also incur the pitfalls of both categories too, (62). For example, route tables are kept up to date for all node changes within zones of limited-nodes thus offering data packet delivery with lower end2end delay locally at a contained amount of overhead, and deploy reactive behaviour for inter-zone connectivity thus achieving higher data packet delivery on the expense of larger end2end delay, (63).

The idea of using the prime numbers to allocate addresses was considered by, (64). This paper/patent proposes a Prime DHCP scheme for address allocation without broadcasting in the whole MANET during the address allocation process. In the proposed prime DHCP, each host serves as a DHCP proxy that can assign addresses to new hosts by running a proposed Prime Numbering Address Allocation (PNAA) algorithm individually to compute unique addresses for address allocation. Prime DHCP uses the prime numbers to generate the addresses and does not embedded the prime numbers in the IP addresses like Prime-IP does. Also, the use of DHCP proxies and the PNAA together eliminate the need for broadcasting in the whole MANET and do not provide solution for the routing protocols.

Table 5-1 summarises the list of WMN routing protocols surveyed in this work. The following sections describe each of these protocols and section 5.8 concludes the findings of this survey.

Wireless Routing Protocols
Ad-Hoc Routing Protocols
<u>Proactive Routing Protocols</u>
1) Wireless Routing Protocol (WRP)
2) Destination-Sequenced Distance Vector (DSDV)
3) Optimized Link State Routing (OLSR) Protocol
4) Fisheye State Routing (FSR)
5) Global State Routing (GSR)
6) Hierarchical State Routing (HSR)
<u>Reactive Routing Protocols</u>
1) Ad Hoc On-Demand Distance Vector (AODV)
2) Adaptive AODV
3) Dynamic Source Routing (DSR) Protocol
4) Temporally Ordered Routing Algorithm (TORA)
5) Cluster-Based Routing Protocol (CBRP)
6) Location-Aided Routing (LAR)
7) Ant Colony-Based Routing Algorithm (ARA)
8) Associatively Based Routing (ABR)
9) Signal Stability-Based Adaptive Routing protocol (SSR)
<u>Hybrid Routing Protocols</u>
1) Zone-Based Hierarchical Link State (ZHLS)
2) Zone Routing Protocol (ZRP)
WMN Routing Protocols
<u>Single Radio Single Channel</u>
1) LQSR (DSR based)
2) Extremely Opportunistic Routing (ExOR)
3) Co-operative diversity based
4) Multi-Channel Opportunistic Routing (MCExOR)
<u>Single Radio Multi Channels</u>
1) Multi-Channel Routing Protocol (MCRP) (AODV based)
<u>Multi Radio Multi Channels</u>
1) Multi-Radio Link Quality Source Routing (MR-LQSR)
2) Multi-Channel Routing MCR (DRS based)
3) Hyacinth (Hop count based)
Routing Algorithms in WiFi-Mesh (IEEE 802.11s)
1) Hybrid Wireless Mesh Protocol (HWMP)
2) On demand routing mode
3) Proactive tree building mode
4) Proactive RREQ mechanism
5) Proactive RANN mechanism
Routing Algorithms in WiMax-Mesh (IEEE 802.16)
1) Interference Aware Routing
2) Routing For Throughput Maximization

Table 5-1, list of WMN routing protocls reviewed in this study

It is worth noting that none of these protocols uses the concept of prime numbers as part of the IP address. Also, few of the "Proactive routing protocols" are capable of having network-wide node information that was inherited from their parent wired protocols.

5.2. MANET Wireless Network Routing Protocols (without infrastructure)

Mobile ad-hoc network (MANET) defines the group of wireless network of mobile nodes formed without any other network infrastructure. Every node in MANET can act as a router. These nodes are free to roam and may switch off without notice. Thus, the topology of MANET changes rapidly as the nodes move or new nodes join the network. This makes MANET highly dynamic and unpredictable in nature which makes routing selection process very challenging. In some types of MANET, such as multi-hop networks, this challenge increases due to the limited bandwidth, the large mix of device types used in the network, high processing power, and restricted battery power. Furthermore, MANET routing exposed more challenges due to the limited resources available as well as the dynamically changing environment. i.e. the routing protocol needs to handle issues such as QoS and scalability required for various applications in varying network size, network partitioning, traffic density, and others, (65), (66). The use of distance-vector and link-state protocols do not work in large MANET as the frequent update of routes take up large part of the available bandwidth as well as increase channel contention, thereby requiring more power which is a scarce resource, in mobile battery powered devices, (67). To overcome these problems, a number of protocols, (68), (69), have been suggested for MANET.

The following sections describe the "Classification of routing protocols for MANET", (57) into 4 categories based on:

a. routing information update mechanism
b. use of temporal information for routing
c. routing topology
d. utilization of specific resources

5.2.1. Classification Based on the Routing Information Update Mechanism

The routing protocol based on the mechanism of updating routing information can be divided into 3 groups, (70) of proactive, reactive and hybrid.

A. <u>Proactive or Table Driven Protocols</u>

In this type of protocols the route to destination is determined at the start-up and stored by each node in the form of a table. Due to this, these protocols are also called "table driven" protocols. This table is then updated periodically to keep information current so that the node, whenever required, can use the information instantly from its table. The change in network topology requires transmitting information to all the nodes about the change. Some of the proactive protocols are, Destination Sequenced Distance Vector routing protocol (DSDV) (71), Wireless Routing Protocol (WRP) (65), Cluster-Head Gateway, Switch Routing protocol and Source Tree Adaptive Routing protocol (STAR), (71).

B. <u>Reactive or on Demand Protocols</u>

In this type of protocol the route is determined only when needed and hence the name "on-demand" routing protocol. The source node initiates procedure for finding out path for a given destination and after the path is found, or in case of non availability of any routes the procedure gets terminated. The reactive protocol for mobile ad-hoc networks have low control overheads and also have better scalability than proactive routing protocols. Since each time a new route is discovered, the source node may have to wait longer for sending data packets. The Dynamic Source Routing (DSR) Protocol (72), Ad Hoc On-Demand Distance Vector (AODV) Routing Protocol (67), Temporally Ordered Routing Protocol (TORA) (73), and Cluster-Based Routing Protocol (CBRP) (74), are few of the reactive routing protocols for MANET, (75).

C. <u>Hybrid Protocols</u>

In this the mix of proactive & reactive strategies are followed to take benefit of merits of each. The hybrid protocol normally use hierarchical network architectures with proactive & reactive strategies used at different hierarchical level. The nodes are segregated in zones depending on their distances form each other or geographical location. The proactive routing is done within the zone and reactive routing is done for nodes located beyond the zone boundary. Protocols such as Zone Routing Protocol (ZRP), Zone-Based Hierarchical Link State (ZHLS) Routing Protocol, and Hybrid Ad Hoc Routing Protocol (HARP) are some of the hybrid protocols, (76).

5.2.2. Classification Based on the use of Temporal Information/Metrics for Routing

The "hop number" is used as metric or temporal information in many MANET. With this methodology MANET can be classified into two types:

A. <u>Using Past Temporal Information</u>

The protocols under this category use latest status of links or metrics for taking routing decisions. However, these types of protocol may face resource crunch in case of sudden link breaks which will change network configuration. DSDV is one of the protocols which use current metric information for routing, (71).

B. <u>Using Future Temporal Information</u>

These protocols use predictions about future status of nodes battery life, link status and others for decision on the route. Flow Oriented Routing Protocol (FORP) which uses prediction about future disconnection to find alternative link before link breaks, comes under this category, (67).

5.2.3. Classification based on Utilization of Specific Resources

In this classification, the protocols groups are divided further based on the roles the nodes are assigned.

A. Uniform Routing Protocols

As the name suggest all the nodes in this group perform similar role, functionality, and are given same importance. The structure of uniform routing protocols is normally flat. Routing Protocols WRP, DSR, AODV, and DSDV are uniform routing protocols, (71).

B. Non-uniform Routing Protocols

Nodes in this category are assigned more and distinct routing functions as compared to other nodes. Non-uniform routing protocols can be divided further into zone-based hierarchical routing, cluster-based hierarchical routing, and core-node based routing, depending on the management and routing functions, (67).

The zone-based routing protocols use different zone-constructing algorithms for organizing nodes into different zones to reduce overheads for routing information maintenance. In zone-based hierarchical routing protocols some nodes function as gateway for inter-zone communication. The ZRP and the ZHLS are two such protocols, (76).

In the cluster-based routing protocols, nodes are grouped into clusters and specific algorithms are used for cluster head selection. Cluster-head Gateway Switch Routing (CGSR) in one such protocol. The multilevel cluster structure, such as the Hierarchical State Routing (HSR), is also used by some protocols, (67).

In the core based protocols some nodes are selected to act a backbone of the mobile ad-hoc network. The backbone nodes take up functions such as routing path construction, control etc. Core-Extraction Distributed Ad Hoc Routing (CEDAR) is a typical core-node-based protocol, (77).

5.2.4. Classification Based on the Routing Topology

The nodes in this category use network topology to make routing decisions. Using this classification, MANET can be divided into two types:

A. Flat Topology Routing

These categories of protocol assume that all nodes are peers, with each node having its own global address. Most of the mobile ad-hoc network protocols are of this type. Protocol DSR and AODV are flat topology protocols, (67).

B. Hierarchical Topology Routing

The protocols in this category group nodes into clusters with one node acting as cluster head to co-ordinate with all other nodes in the cluster. The clustering can have multilevel hierarchy. Cluster-Head Gateway Switch Routing Protocol (CGSR) is one such protocol, (78).

Another category is the “destination-based routing” protocols, where every node only knows the next hop along routing path. AODV and DSDV are destination-based routing protocols. The protocols perform location based routing where the routing is done based on position relationship between the forwarding node and destination node. The location base protocol may use only location information or also use topological information. Location-Aided Routing (LAR) and Distance Routing Effect Algorithm for Mobility (DREAM) are two location-based routing protocols for mobile ad hoc networks, (79) .

5.3. Routing Protocols for Wireless Mesh Networks (with infrastructure)

Wireless Mesh Networks (WMN) technology has emerged to combine localised wireless technologies such as WiFi, WiMax and Bluetooth networks to connect beyond their respective limited area. For example, a number of WiFi networks are connected to each other using other technologies such as WiMax in between so to make a single seamless network covering a much larger area. WMNs are mostly used for Internet connectivity with a wireless router forming the backbone of a typical network. Like ad-hoc networks, WMNs are also dynamically self-configured and self-organized. However, in WMNs, most of the nodes, such as access points or internet gateways, are actually mains-powered and therefore are static and have no limitations of usage power as in the case of battery powered mobile devices that form the MANET. The following are examples of most commonly used WMN protocols.

5.3.1. Link Quality Source Routing (LQSR)

Link Quality Source Routing (LQSR) (80), developed by Microsoft, is a modified version of DSR for use in their Mesh Connectivity Layer (MCL) technology for WMN. In LQSR the routing decisions are based on some additional link quality metrics such as ETX (Expected Transmission Count), Per-hop Round Trip Time (RTT), Packet Pair and hop count. The nodes in WMN are assigned relative weights to the links with other nodes. The information about channel, losses and bandwidth of the every link is determined and sent to all the nodes. The nodes, based on all this data, determine the best route available. LQSR modifies the change in optimum path in case of any link breaks. In LQSR, the knowledge of nodes beyond their next neighbouring node is not maintained. Note that, Prime-IP (see chapter-6) does maintain the knowledge beyond the neighbouring nodes and the principles of Prime-IP can enhance the LQSR protocol if adopted.

5.3.2. Extremely Opportunistic Routing (ExOR)

Extremely Opportunistic Routing (ExOR) work by sending the information over multiples channels concurrently, (81), (82). The packets are broadcasted and the nodes receiving the packets send acknowledgment back to the sender. The sender then selects a node closest to the actual destination for further transmission of packets. This allows transmission of packets using the nodes closest to the destination, which may not be normally available, for data transmission in normal propagation conditions but are available in favourable conditions. ExOR uses loss-rate matrix, indicating probability of successful packet reception between each pair of nodes, for transmission of packets. The information inside both the sent header

& the received acknowledgement header are analyzed to select the forwarding nodes. A timed scheduling algorithm is used to co-ordinate data transfer by using the higher priority nodes and to avoid collisions. In ExOR, the concept of "knowledge of nodes beyond the neighbouring nodes" does not exist. Multi-Channel Opportunistic Routing (MCExOR)

5.3.3. Multi-Channel Opportunistic Routing (MCExOR)

Multi-Channel Opportunistic Routing (MCExOR) (83) extends the ExOR protocol by utilizing multi RF channels instead of the single channel used by the ExOR protocol. Then it chooses the most promising channel set for every transmission. (83), have demonstrated that the increase in number of RF channels increases the overall throughput proportionately. They show that "MCExOR with 2 RF channels surpasses AODV by an average of 140%"

5.3.4. Multi-Channel Routing Protocol (MCRP)

Multi-Channel Routing Protocol (MCRP) (84) uses channel switching technique by assigning the channels to data flows instead of assigning the channels to nodes used in normal practice. A common channel is assigned to data flow across all nodes. This channel is available for duration of the data flow without the need for node to switch channels. The allocation of different channel for different data flow improves the transmission capacity by allowing simultaneous transmissions. In MCRP the information of node beyond the next neighbouring node is not

5.3.5. Multi-Radio Link Quality Source Routing (MR-LQSR)

Multi-Radio Link Quality Source Routing (MR-LQSR) (85) is the LQSR protocol that uses Weighted Cumulative Expected Transmission Time (WCETT) routing metric. The MR-LQSR aims to fulfil following main objectives:

i. The loss rate and the bandwidth of a link should be taken into account for selecting a path;
ii. The path metric should be increasing; and
iii. The path metric should reflect the throughput degradation due to the interference caused by simultaneous transmissions. WCETT has used a metric for this.

The information related to channel assignment on a link; its loss rate and bandwidth are transmitted, as DRS control packets, to all nodes in the network. The use of WCETT as the link gives minimal cost path in terms of link bandwidth and loss rate. (85), reports that the route metric used in MR-LQSR is a multi-radio environment significantly outperforms previously proposed routing metrics by making judicious use of the second radio. MR-LQSR does not keep the information of node beyond the next neighbouring node.

5.3.6. Multi-Channel Routing (MCR)

Multi-Channel Routing (MCR) is an on demand protocol with multi-radio Nodes. MCR uses switching mechanism to change the channels to fully exploit available resources. MCR takes some channels as fixed channels and treats the rest as “dynamically assignable/switchable” channels. The list of fixed channels uses neighbouring node & channel usage is maintained by each node. The HELLO packet transmission by each node periodically allows each node to update its tables & its channel usage. The MCR selects the route based on weighted sum of switching cost (sum of Expected Transmission Time (ETT) values along the path) as well as the channel diversity (maximum ETT cost on all channels) cost. MCR route discovery mechanism is similar to DSR, except that information of channel number and the switching cost is also available. The destination selects the optimum path based on channel number and the switching cost. In MCR nodes do not have the information of node beyond the next neighbouring node, (86), (87).

5.4. Routing Algorithms in WiFi-Mesh (IEEE 802.11s)

The 802.11s standard defines a mesh network as "two or more nodes that are interconnected via IEEE 802.11 links which communicate via mesh services and comprise an IEEE 802.11- based Wireless Distribution System (WDS), (88)." The nodes in such mesh network are called Mesh Station (mesh STA) and the access points in this mesh network are called Mesh Access Point (MAP). The node supporting mesh protocol is called a Mesh Point (MP). The devices use to connect mesh network to non-mesh network are called mesh portal. This protocol only provides information about it neighbours & no information is provided beyond the neighbourhood. The use of Prime-IP algorithm will enhance this protocol by this removing this limitation and providing more information about what lies beyond immediate neighbourhood.

5.4.1. Hybrid Wireless Mesh Protocol

The Hybrid Wireless Mesh Protocol (HWMP) (89) provides proactive tree based routing for fixed part of network as well as the on-demand routing for mobile part of the network. The combination of two parts provides optimal and efficient path selection in many types of mesh networks.

The discovery of on demand routes in HWMP is based on Ad Hoc on Demand (AODV) routing protocol and uses its set of protocol primitives, generation and processing rules. Also, it uses some additional primitives to proactively set up a distance-vector tree rooted at a single root mesh point.

HWMP supports following two non exclusive modes of operation depending on the configuration:

i. **On demand mode:** This mode is used by MPs to communicate using peer-to-peer routes when the root is not configured and in some other special cases.

ii. **Proactive tree building mode:** This uses either the Route Request (RREQ) or Root Announcement (RANN) mechanism.

The above modes may be used concurrently.

5.4.1.1. On Demand Routing Mode

To find out the route, the MP broadcasts a Route Request (RREQ) with destination address and the metric field initialised to 0. Sequence numbers are used to avoid loops. The MP receiving RREQ creates a route to the source if the route is new, or updates the route stored if the RREQ contains a greater sequence number, else offers a better metric than the current route. The new route, or change of existing route, is forwarded along with modified RREQ which also contains the cumulative metric of the route to the RREQ's source. The new route is unicasted by the destination MP back to the source using Route Reply (RREP) whenever the new route is created or modified. The Intermediate MPs, on receiving the RREP, create a route to the destination as well as forward a RREP back to the source. The destination node on receiving RREQs, with a better metric this time, sends the new route information back to source. This way allows the best metric end-to-end route to be established between a source & destination.

5.4.1.2. Proactive Tree Building Mode

HWMP uses two methods to find out the route for reaching the root MP. The first method uses Route Request (RREQ) message to find out routes between all MPs in the network and the root MP. In the second method, a Root Announcement (RANN) message is used to distribute route information for reaching the root. The root MP periodically sends proactive RREQ and RANN messages.

A. **Proactive RREQ Mechanism:** In the tree building process, root MP sends proactive RREQ message to all the nodes along with a sequence number and metric set to zero. The root MP sends these messages periodically, with increasing sequence numbers. The MP record/update their forwarding information to the root MP, the metric and hop count using an RREQ message before forwarding the updated RREQ. This allows MP's to indicate their "availability and distance" to the root MP and to all the nodes in the network. The MP's check the sequence number & updates their route if the sequence number is >= (greater than or equal) to the number of current route, or if a better metric is available. The RREQ is processed as described for the on-demand mode using RREP so to set the shortest path.

B. **Proactive RANN Mechanism:** The root MP periodically broadcasts a Root Announcement (RANN) message to the network. The MP receiving RANN creates, or updates, the route and sends unicast RREQ to the root via the same route as it receives the RANN message. The root then responds to each RREQ by sending RREP. This creates a bi-directional route. The change of route from MP to root is informed to MPs by sending RREP with the addresses of the MPs that have established the route to the root through the current MP.

5.5. Routing Algorithms in WiMax-Mesh (IEEE 802.16)

In IEEE 802.16d, point to point mode of communication takes place between the Mesh base station (MBS) and subscriber stations (SS). This differs from mesh mode communication that can take place between subscriber stations within a mesh directly as well as outside the mesh, using MBS as shown in Figure 5-1 below:

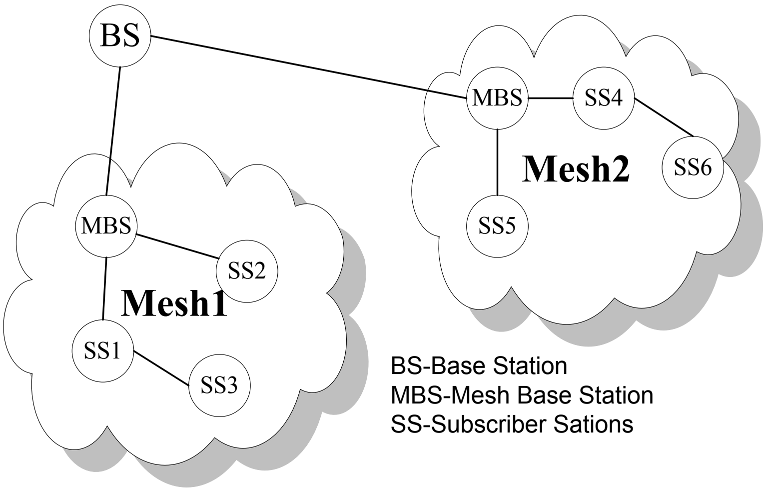

Figure 5-1, A typical mesh network

The Mesh Network Configuration (MSH-NCFG), containing basic networks configuration information, is periodically advertised by active nodes within a mesh. The new node, called Candidate node, wishing to join the mesh selects a sponsoring node by sending a Mesh Network Entry message (MSH-NENT) with Net Entry Request information.

The MAC in WiMax mesh mode supports both centralised as well as distributed scheduling. In s centralised scheme, the radio resource allocation in mesh is coordinated by Mesh BS. Every Subscriber Station sends the resource request to Mesh BS, using Mesh Centralized Scheduling (MSH-CSCH) request message, for resource allocation and transmission. The Mesh BS grants the request using MSH-CSCH Grant message. The Mesh BS then broadcasts the link, node, and scheduling tree configuration information using Mesh Centralized Scheduling Configuration (MSH-CSCF) message to all nodes. This message is further distributed by intermediate nodes.

The wireless mesh network requires a spectrum efficient algorithm for slot allocation so that throughput can be maximized. This protocol provides information about it neighbours & no information is provided beyond the neighbourhood. The use of Prime-IP algorithm will enhance this protocol by this removing this limitation and providing more information about what lies beyond immediate neighbourhood.

Some of the algorithms proposed for WiMax wireless mesh networks are given below:

5.5.1. Interference Aware Routing

Interference Aware Routing (90) is aimed to provide a centralised mesh scheduling scheme which takes into account the demand as well as interference conditions. The modelling of interference level is done by a blocking metric B(k) of a given route from the Mesh BS toward an SS node k. The blocking metric B(k) in a multi-hop environment to show the number of blocked or interfered nodes by the intermediate nodes in route between the root node and the destination node k. The number of blocked nodes are given by a number called blocking value b(η) of a transmitting node η. The blocking metric of the route is the sum of the blocking values of nodes that transmit or forward packets along the route.

The interference aware algorithm consists of two parts:

A. **Inference Aware Route Construction:** Using this scheme the routes with minimum interference is selected by comparing the blocking metric for the different routes to the destination from the source and then selecting the best route.

B. **Interference Aware Scheduling:** The interference-aware scheduling is used to increase the system throughput by exploiting concurrent transmission but keeping interference under control. To do this, the traffic capacity request of each SS is considered. The capacity request of an SS node from k denoted by D(k) can be represented in terms of Y(j) for every link j. The set of active links is calculated by scheduling algorithm for each allocation iteration t. The next allocation to traffic is assigned to the link with highest unallocated traffic demand and by excluding interfering links are located in the neighbourhood of k using Blocked_Neighbor(k) function. This iterative allocation goes on till the allocation demand is fulfilled. Interference-Aware

Routing does not keep the information of node beyond the next neighbouring node as in Prime-IP and hence the use of Prime-IP can enhance its efficiency further.

5.5.2. Routing For Throughput Maximization

The (91) algorithm, in addition to using blocking metric of a route has taken the number of packets into account. The blocking metric B(v) of the node v was taken as the number of blocked nodes multiplied by the number of packets at the node v. The path with minimum B(v) is selected.

The proposed system constructs the routing tree when new node enters the network using broadcast messages MASH-NCFG and MASH-NENT from the new node. The network is then reconfigured by MBS by recalculating the routing node and broadcasting the MASH-CSCH message to the SS's. The MBS periodically recomputed the routing tree with updated data and changes routing tree if required. This algorithm categorised into two types:

A. **Maximum Parallelism Routing:** The aim of this routing algorithm to maximize the parallelism while taking number of packets into account. The algorithm segregates interfering and non interfering pair of edges between two consecutive layers. The edge pair is weighted with the number of packets at the sender node. The set of non-interfering edges with maximum weights on the edge is selected by the algorithm.
B. **Min Max Degree BFS Tree:** Here the breadth first search (BFS) is conducted so that the maximum degree of the tree is minimized and takes advantage of the shortest path (breadth first tree) with least bottlenecks. The periodic re-computation of the routing tree results in extra overhead in these algorithms. These algorithms do not keep the information of node beyond the next neighbouring node as in Prime-IP and the use of Prime-IP can enhance their efficiency further. The considered the Max Weight scheduling algorithm, which extends Fair Queuing, by considering the distance of the node to the BS. The author used Line Scheduling algorithm which further extended the Max Weight by considering fairness of each node

5.5.3. Other Routing Protocols

(92) proposed routing and centralised scheduling depending on different traffic models (i.e. CBR, VBR) to support QoS. In this paper, the Authors took the routing tree as a shortest path routing as it is more effective in deciding the overall performance of the network. The authors provided a finite horizon dynamic programming framework to optimize a cost function over a fixed number of time slots, and using the resultant cost function,, they proposed the algorithm for maximizing the network throughput.

Another algorithm was presented (93), with the aim of maximizing the network's capacity using concurrency among the multi-hop transmissions. The authors proposed algorithm for SS so that the concurrent transmission in both uplink and downlink streams is feasible with no collision to improve the overall end-to-end throughput.

ROMER, (94), was yet another algorithm proposed to provide a resilient opportunistic mesh routing by providing balance between short term opportunistic performance and long-term route stability. In this, the mesh is centred around minimum cost and long term stable path but can expand or shrink to exploit the availability of high quality & high data rate links that may be available for short time. The algorithm selects the high data rate link for forwarding the data. At the same time the data is also sent from other route randomly to provide for redundant path to take care of lossy links, transient node outage, etc. It was demonstrated that ROMER was able to achieve about 68-195% higher throughput gain over single path routing as well as providing better packet delivery ratio than multi-path routing.

5.6. WiMax-WiFi Mesh Convergence Routing Protocols

The properties of WiFi make it more suitable for dense small area network, while WiMax provides large coverage and is more suitable for sparsely populated areas. The integration of these two protocols can bring benefits of both types of these networks.

- The first level integration makes use of WiFi for small areas & WiMax for interconnecting the small areas networks into one big network with point to multipoint capability.
- The second level of integration can be achieved by using WiMax to form a mesh network at broader levels or metro scale areas of WiFi networks. The system once deployed with WiMax in mesh and in the PMP (Point-to-Multi Point topology) can utilize enhanced quality of service (QoS) features of WiMax MAC for enforcement of service level agreements (SLAs).
- The third level of integration is to use a hybrid device with integrated WiFi and WiMax (based on 820.16e) technologies side by side. This will enable seamless connection to both networks, (41), (95). The emerging IEEE standard 802.21 for media-independent handover services will support seamless mobility between IEEE 802.11 and IEEE 802.16, by integrating the two radio access technologies into one system.

Proxim, (96), has come out with MeshMAX product line which integrates three, WiMax, WiFi Mesh and WiFi technologies, in one small unit. MeshMAX is an outdoor tri-radio. It offers WiFi connectivity for access, WiFi mesh gateway for network redundancy and a high capacity WiMax link for backhaul. The integrated device offers end-to-end QoS for triple-play applications leading to substantial reduction in the cost of ownership. The device is also capable of upgrading to future developments in WiMax technology. The user of this device can select WiFi access functions as well as connect to WiMax base station through WiMax subscriber unit with QoS and bandwidth control.

(97), have suggested a hybrid WiFi-WiMax network routing protocol for an integrated network. The system uses gateway for interconnection of two networks. The proposed hybrid protocol aims to "offer users of adhoc network broadband service a device that can select the best route in terms of bandwidth, battery residual energy and distance". The protocol proposed can find best routes within WiMax and provide automatic reconnection in case of route failure. The authors have based their algorithm on Ad-hoc On Demand Distance Vector (AODV) protocol. The modelling was done using OPNET. To find a route, the source node sends a RREQ packet till it reaches destination or the WiFi/WiMax gateway. If the node is outside coverage area, the RREQ packet is resent and the destination node or WiFi/WiMax gateway gives reply using RREP packet to source node. The hybrid algorithm proposed does not keep the information of node beyond the next neighbouring node.

5.7. Wireless Routing Protocol in IPv6

The Wireless Routing Protocol in IPv6 environment can take advantage of various features of IPv6 addressing. The use of 128 bit IP address in IPv6 allows virtually unlimited number of users each having unique address. In IPv6 environment, each of the mobile host can have a valid global IP address and with stateless auto-configuration (RFC 2462) this can be done without user's intervention. The other advantages of using IPv6 will be that the protocols can take advantages of it's built in security features, simpler configuration and mobility features.

The mobility support has been extended to IPv6 in the form of a new protocol call Mobile IPv6. This protocol allows a mobile device to move from one location to another without change of its IP addresses, (98). As the mobile moves, it is assigned a "care of" address which contains the subnet prefix of the mobile's home address. The Mobile IPv6 protocol uses route optimization signalling for advertising about its care-of address to its correspondent node allowing the exchange of packets using shortest path between the two. The WiMax ASN gateway, when encounters

IPv6, lets the MS obtain the care-of address from the ASN, and a home address from the home connectivity service network (CSN).

The Mobile IPv6 also addresses the network-layer mobility management issues and can take care of handover problems in large mobile networks without any additional protocol. Thus, handover protocols can utilise Mobile IPv6 features, thus making them leaner.

The IPv6 supports multicasting whereas WiMax does not. The IEEE 802.16e transmits packets based on a connection identifier (CID) whereas IPv6 uses 48 bit MAC address. This requires new mechanism for sharing multicast CIDs among multicast group members in a WiMax network.

The wireless routing protocols do not have built-in security features. This is another area where the IPv6 built-in security features can be used to provide the required security during registration and discovery phase as well as data transfer. The Mobile IPv6 also provides route optimization which can operate securely even without pre-arranged security associations. This allows secure route optimisation at global scale between mobile nodes & corresponding nodes.

Mobile IPv6 Fast Handover protocol (FMIPv6) defined by RFC5270 performs handover in wireless 80216e networks and features reduction in the handover latency for the real-time traffic, (99). As per RFC 5270 “The proposed scheme tries to achieve seamless handover by exploiting the link-layer handover indicators and thereby synchronizing the IEEE 802.16e handover procedures with the Mobile IPv6 fast handover procedures efficiently."

5.8. Summary

This thesis concludes that the above conventional routing algorithms do not produce knowledge of any individual nodes that are beyond their neighbouring nodes. Some of the WMN routing protocols, for example the "proactive routing protocols", have a link-list table to have knowledge of beyond their neighbours. To do that, they have to exchange entire routing tables repeatedly across the whole network at a great overhead. This routing-table exchange overloads the wireless networks and will reduce the performance of the entire network. To overcome this problem and to allow other protocols gain the ability of node knowledge beyond the route neighbouring node, this thesis proposes the Prime-IP algorithm. Prime-IP can be used by any of the above routing protocols to enables them having knowledge beyond their neighbour without a big overhead. Moreover, Prime-IP is not a standalone routing protocols but it is an add on to the existing routing protocols. The IPv6 can also take benefit of Prime-IP protocol and enhance its functionality by providing additional information about nodes beyond neighbouring nodes.

The Wireless mesh networks are emerging as cost effective means of extending broadband services. The integration of WiMax technology with WiFi allows one to take advantages of best of both and increase coverage area as well as capitalise on better features provided by WiMax technology. The new broadband as well as WiFi standards such as 802.11n, 802.20 and 802.22 have emerged providing higher speed & better mobility. Numbers of routing protocol have been suggested for mesh networks including a hybrid protocol using AOVD as base. However none of these protocols provide to individual nodes to the knowledge about what lays beyond their nearest neighbours. The use of Prime-IP will enhance the current protocol by having a knowledge what are beyond their nearest neighbours.

Chapter 6: Prime-IP Algorithm

This thesis proposes a new method of passing node information along all the nodes in a WMN route. This chapter describes this algorithm named "Prime-IP" algorithm. A patent has been filed with the Intellectual Property Office, UK, (9).

Prime-IP is designed to work in Wireless Mesh Network (WMN) routing. It is a method and process for routing and node addressing in WMN. It enables any node in a WMN to have knowledge of all "intermediate nodes", in all the possible-routes towards the "destination node". i.e. Prime-IP uses a novel recursive algorithm to accumulate knowledge beyond the "neighbouring nodes", as well as the sequence of the "intermediate nodes" used to form these routes. It does this without impacting the routing protocol, and so Prime-IP can be embedded with any existing routing protocol.

In the dynamic topology of the WMN, this new knowledge adds value to the existing node information, and helps identify the optimum route is always chosen, thus achieving ubiquitous route selection. i.e. enables optimum routing in terms of access time and number of hops. This invention can be extended to discover malicious nodes and identify the physical location of the nodes as well.

An extensive literature survey was conducted that led to the proposal of the Prime-IP algorithm (see chapter 5). Based on the various trials and evaluations conducted with many WMN protocols, Prime-IP has always achieved higher Quality of Service (QoS) than the standard WMN implementations because it will always choose the optimum route path between the source node and the destination node. Thus achieving more reliable routes, less traffic processing overhead, higher security level, increased data throughput, and reduced error rate.

6.1. The Overall Process

Prime-IP produces a unique routing path were each individual node are identified, and were the route can be classified by each of these individual nodes. i.e. with Prime-IP, each node will have knowledge of not only the neighbouring nodes, but also nodes that are beyond their neighbours nodes. Consequently, Prime-IP builds, at each node level, a dynamic knowledge database (or map) of all other nodes in the WMN. To achieve this, the following describes the overall process that Prime-IP performs:

1. Assigning a unique prime number in the host-portion of the IP-Address of each individual node.
2. Packs two extra number fields in the Route REply Packet (RREP) named PPN_1 and PPN_2. The value of these two fields will be calculated dynamically during the route reply discovery stage.
3. The values of PPN_1 and PPN_2 are calculated from the prime numbers allocated to the nodes in the WMN, starting with the destination node (the initial value of PPN_1 = "destination node prime number", while PPN_2 = "destination node prime number" - 1). Thereafter, as RREP get forwarded by the destination node to the neighbouring nodes, PPN_1 and PPN_2 values change to ($newPPN_1 = previousPPN_1 \times CurrentNodePrimeNumber$) and ($newPPN_2 = (previousPPN_2 \times CurrentNodePrimeNumber) - 1$). This process continues for the next intermediate nodes until the routes reach the source node.
4. Based on the values of received PPN_1 and PPN_2 from the various possible paths between the destination and the source nodes, the source node then uses a backtrack procedure to construct the intermediate nodes vector in a particular order for each of the received RREPs. This then is used to select the optimum available route out of all the possible path options.

As described in the literature survey in Chapter 5, typical WMN protocols are classified to three categories as: Infrastructure WMNs, Client WMNs and Hybrid WMNs, as shown in Figure 6-1. The intermediate nodes in all these categories, using current conventional routing algorithms, do not accumulate knowledge beyond their nearest neighbouring nodes. Prime-IP can be applied to all of these categories of WMNs and therefore all nodes shall have knowledge beyond their neighbouring nodes.

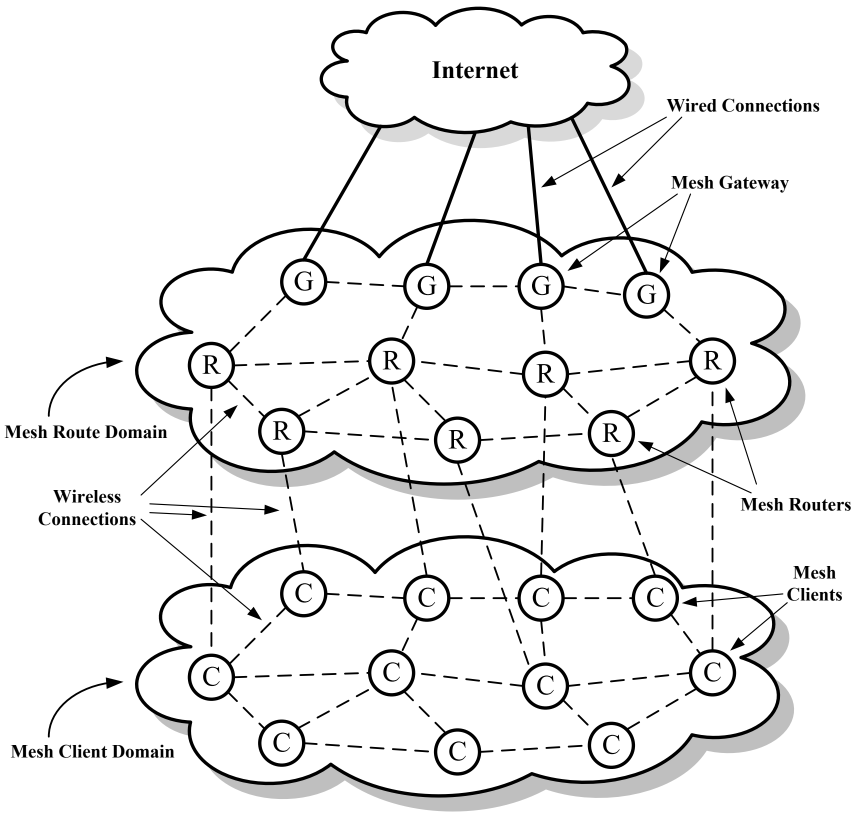

Figure 6-1, diagram of a general WMN topology

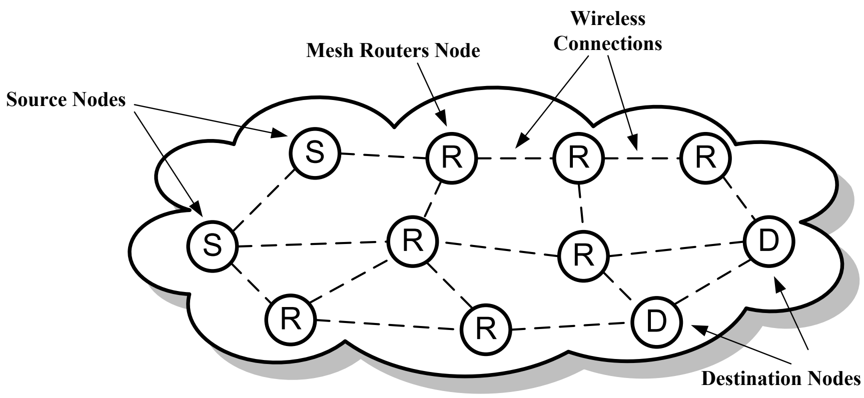

Figure 6-2, general Client Wireless Mesh Network topology or Mobile Ad-Hoc Networks (MANET)

In Figure 6-1, a general WMN has been construct by using three different domains; Internet, Mesh Route Domain (MRD) and Mesh Client Domain (MCD). The MRD, contains "mesh routers" nodes which is equipped with high processing and memory capabilities. Some of the "mesh routers" are also called gateways, which are special wireless routers with high-bandwidth wired connection to the Internet. In the MCD, the "mesh clients" are mobile nodes. The links between the Internet and the MRD through the gateways are wired connections. The links between the MRD and MCD are wireless connections.

In Figure 6-2, a general Client Wireless Mesh Network (also called Mobile Ad-Hoc Network (MANET)) has been illustrated; it is a number of mobile nodes in random topology without base-station or access point. The mobile nodes can be classified to senders, destinations and routers which are dynamically changed upon their instant functionality.

6.2. Mathematical Derivation

Prime-IP is designed for a dynamic network topology such as WMN, where the topology and membership (nodes' association/re-association) may change at any time. It is based on the "*Fundamental theory of Arithmetic*" (100) that states:

"Every natural number n>1 can be represented in one way only apart from rearrangement as a product of powers of distinct prime numbers"

To devise a general formula for calculating PPN_1 and PPN_2 in Prime-IP, it is assumed that any route is represented by a number of nodes starting in sequence from source node being P_1 till the destination node P_d, with any variable number of nodes in between being P_1, P_2, …, P_{d-1}, P_d, as shown in Figure 6-3.

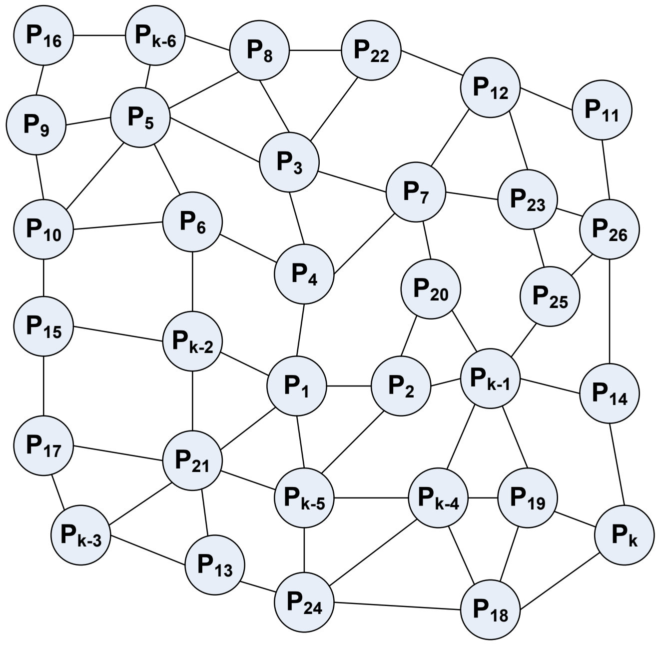

Figure 6-3, random WMN topology with a prime number addresses (P_1, P_2,…,P_i,…, P_k) assigned to every node

Figure 6-3 illustrates a random topology WMN network, where each circle represents an individual wireless node. The lines between these circles are the bi-directional links between two nodes. Finally, all nodes have been assigned a unique prime number as described below.

NB, the use of the term "route" signify a definitive physical intermediate nodes between the source and destination nodes, while term "path" is used to signify any possible route via any combination of physical intermediate nodes.

Also, assume $P_i \in RN$,

Where:

P_i is an arbitrary prime number,

RN is a set of prime numbers

Where:

$RN = \{P_1, P_2, P_3, \ldots, P_i, \ldots, P_{k-2}, P_{k-1}, P_k\}$, in ascending order,

RS is an arbitrary set of prime,

Where

$RS \subseteq RN$,

P_k = largest prime number in RN,

$1 \le i \le k$, i is an integer number,

k = total of prime numbers in RN set,

$RS = \{P_j\}$, where $1 \le j \le d$, $d \le k$, and

d = total of prime numbers in RS set (intermediate nodes)

Then

$PPN_1 = \text{Product}(P_d\, P_{d-1}\, P_{d-2} \ldots P_3\, P_2\, P_1)$, and

$\text{Factors}(PPN_1) \Leftrightarrow \{ P_d P_{d-1} P_{d-2} \ldots P_3 P_2 P_1 \}$

And

$PPN_2 = (((\ldots((P_d - 1)\, P_{d-1} - 1) \ldots)\, P_3 - 1)\, P_2 - 1)\, P_1 - 1$,

$PPN_2 = (P_d P_{d-1} P_{d-2} \ldots P_3 P_2 P_1) - \ldots - (P_3 P_2 P_1) - (P_2 P_1) - (P_1) - 1$

i.e. in general, and substituting for the value of PPN_1 in PPN_2,

$$PPN_2 = PPN_1 - \sum_{i=d-1}^{1} \left[\prod_{j-1}^{i} P_i \right] - 1 \qquad (6-1)$$

This shows that PPN_1 will always be greater than PPN_2

In conclusion, therefore, there is one and only one:

- Factors-set (RS) for each PPN_1.
- PPN_1 is a product of the RS elements set.

However, these operations do not produce the list of prime factors in any particular order. Prime-IP produces the list of prime factors in a particular order, which is the same as the sequence of the factors order produced by the constructing process.

Figure 6-3 shows that all nodes have been assigned a unique prime number as an address Pi {where Pi = $P_1 \ldots P_k$}. Therefore, in order to have a route from a source node to a destination node through intermediate routing nodes, the source node issues "route request packet" (RREQ). A flooding process is then ensued in various paths until the destination node is reached. As soon as the destination node gets this request, a "route reply packet" (RREP) shall be returned to the source node via various path options. Finally, the source node establishes the optimum route from these available route options. i.e. in Figure 6-3, for example, a source node can be P_{16} which issues a RREQ to reach P_1 as a destination node. There are various routes that could be selected to do this, such as:

$RS_1 = \{P_1, P_4, P_6, P_5, P_9\}$,

$RS_2 = \{P_1, P_4, P_3, P_8, P_{k-6}\}$,

$RS_3 = \{P_1, P_{k-2}, P_{15}, P_{10}, P_9\}$,

Etc.

i.e. the P_1 responds by an RREP and puts its prime number address in the reserved fields PPN_1 and PPN_2. So, all the intermediate nodes between P_1 and P_{16} shall replace the value of PPN_1 and PPN_2 by (a) multiplying their prime number address with the existing value of the PPN_1, and (b) multiplying their prime number address with the existing value of the PPN_2 then subtracting 1 from PPN_2. Finally, P_{16} will receive various values of PPN_1 & PPN_2 dependent on the nodes that RREP path passes through. i.e. the value of PPN_1 & PPN_2 in the RREP for RS_1 shall be:

$PPN_1 = P_1 \times P_4 \times P_6 \times P_5 \times P_9$

$PPN_2 = (((((P_1-1)\times P_4-1)\times P_6-1)\times P_5-1)\times P_9-1)$, or

$= (P_1 \times P_4 \times P_6 \times P_5 \times P_9) - (P_4 \times P_6 \times P_5 \times P_9) - (P_6 \times P_5 \times P_9) - (P_5 \times P_9)-(P_9)-1$

As this example demonstrates, the use of prime numbers as an address is unique, and shall provide unique identification of all the nodes, in all the possible paths in any routing discovery process (include both node-IP's and sequence).

NB. The possible prime number assignment is however limited to, for example, 54 prime numbers in any 8-bit addressable field (where all possible numbers are 255). This should not limit Prime-IP because the host portion of IP address filed can be extended to 16, 24 and up to 64 bits in IPv6.

Furthermore, the source node will accumulate information about all possible intermediate nodes to the destination node (generated by Prime-IP backtrack procedure, using only two variables PPN_1 and PPN_2). Therefore, Prime-IP potentially can generate a dynamic map of the entire WMN.

6.3. IPv4/IPv6 Addresses

Figure 6-4 shows both IP address versions (IPv4 and IPv6) with their both host portion and network portions. The length of the IPv4 is 32 bits (The host portion of the IP address is 2-24 bits, while the reminder bits are used for the network portion). The length of the IPv6 address is 128 bits allowing for the host portion to be up to 64 bits.

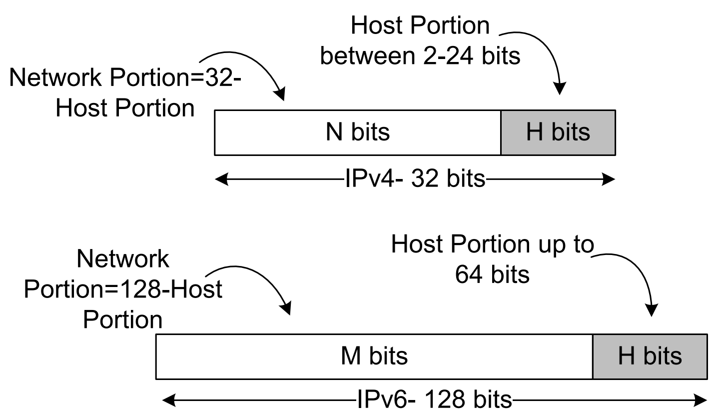

Figure 6-4, IPv4 and IPv6 address format

Table 6-1 illustrates an example of arbitrary prime numbers selection. These are chosen for different host portion lengths for both IPv4 and IPv6.

For 8 bits host portion, there are only 54 prime numbers that are possible (total numbers = 256 or 2^8). For instant, 5 and 239 are prime numbers are converted to 8 bits binary as (00000101) and (11101111) respectively. i.e. to generate the Prime-IP addresses (x.x.x.5 and x.x.x.239) for IPv4 and (xx...5 and xx…EF) for IPv6. Note that "x" in the above IP addresses represents the network portion number.

Bits/ Host	PN-Prime Number	Prime Number (Binary Representation)	Prime-IP IP-Address (IPv4-32 bits)	Prime-IP IP-Address (IPv6-128 bits)
8	5	00000101	x.x.x.5	xx….05
8	239	11101111	x.x.x.239	xx…EF
16	313	00000001 00111001	x.x.1.57	xx… 0139
16	51449	11001000 11111001	x.x.200.249	xx…C8F9
24	2051773	00011111 01001110 10111101	x.31.78.189	xx…1F4EBD
24	12004991	10110111 00101110 01111111	x.183.46.127	xx…B72E7F
48	9990454997	(0002537A3ED5) $_{hex}$	Not Applicable	XX…0002537A3ED5
48	281474076384103	(FFFFCA561B67) $_{hex}$	Not Applicable	XX…FFFFCA561B67
64	9007199254740991	(001FFFFFFFFFFFFF)hex	Not Applicable	XX…001FFFFFFFFFFFFF
64	2305843009213693951	(1FFFFFFFFFFFFFFF)hex	Not Applicable	XX…1FFFFFFFFFFFFFFF

Table 6-1, prime numbers representation in the IP addresses

For 16 bits host portion, there are about 6000 possible prime numbers, out of total numbers of 65,536 (2^16). For instant, 313 and 51,449 are prime numbers are converted to 16 bits binary as (00000001-00111001) and (11001000-11111001) respectively. This is to generate the Prime's IP addresses (x.x.1.57 and x.x.200.249) for IPv4 and (xx...0139 and xx…C8F9) for IPv6.

For host portion using 24 bits, there are around one million prime numbers that can be used (2^24 = 16,777,216). For instant, 2,051,773 and 12,004,991 are prime numbers and are converted to 24 bits binary as (00011111-01001110-10111101) and (10110111-00101110-01111111) respectively. Thus generating the Prime's IP addresses (x.31.78.189 and x.183.46.127) for IPv4 and (xx...1F4EBD and xx…B72E7F) for IPv6.

In the host portion of 48 bits, there are around eight trillion prime numbers out of ($2^{\wedge 48}$) numbers. For instant, 9,990,454,997 and 281,474,076,384,103 are prime numbers which are converted to 48 bits in hexadecimal as $(0002537A3ED5)_{hex}$ and $(FFFFCA561B67)_{hex}$, respectively, to generate the Prime's IP addresses (xx... 0002537A3ED5 and xx… FFFFCA561B67) for IPv6. There is no entry for IPv4 in Table 6-1 because it is 32 bits length, and so it is not applicable in the case.

For 64 bits host portion, there are around $4*10^{17}$ prime numbers out of ($2^{\wedge 64}$). For instant, 9,007,199,254,740,991 and 2,305,843,009,213,693,951 are prime numbers which have being converted to 64 bits in hexadecimal as $(001FFFFFFFFFFFFF)_{hex}$ and $(1FFFFFFFFFFFFFFF)_{hex}$ respectively to generate the Prime- IP addresses (xx...001FFFFFFFFFFFFF and xx…1FFFFFFFFFFFFFFF) for IPv6.

6.4. Backtrack Procedure

For every available route from the source node to the destination node, Prime-IP's backtrack procedure generates the vector containing the intermediate node addresses in a particular order. PPN_1 and PPN_2 numbers are used as input to the backtrack procedure. Figure 6-5, Figure 6-6 and

Figure 6-7 show the diagram from Figure 6-3, but with actual prime number assigned to all node address (P_1…P_k), and highlighting 3 route examples.

The "source node" gets a route replay packets containing the PPN_1 and PPN_2 numbers. As shown in Figure 6-5 and Figure 6-6, two different routes are highlighted between the source node-71 and the destination node-73.

Figure 6-7 shows a highlighted route between source node-7 and the destination node-11. Figure 6-8 shows a tree diagram of how the "backtrack procedure" is applied to determine the track which represents the intermediate nodes vector in that particular order.

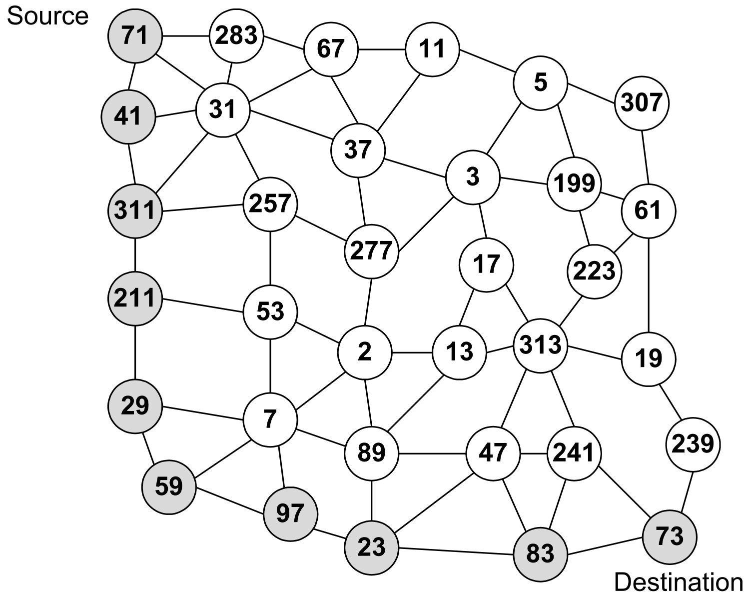

Figure 6-5, Route 1 node addresses

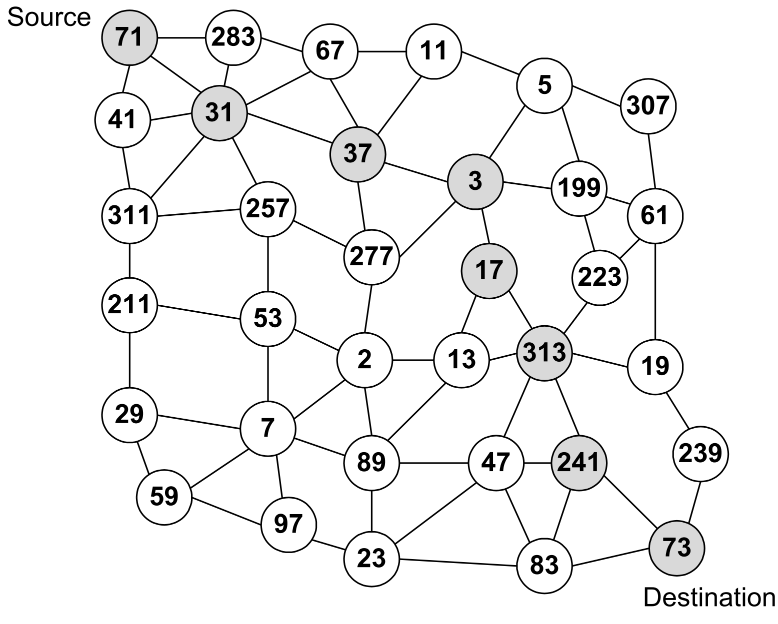

Figure 6-6, Route 2 node addresses

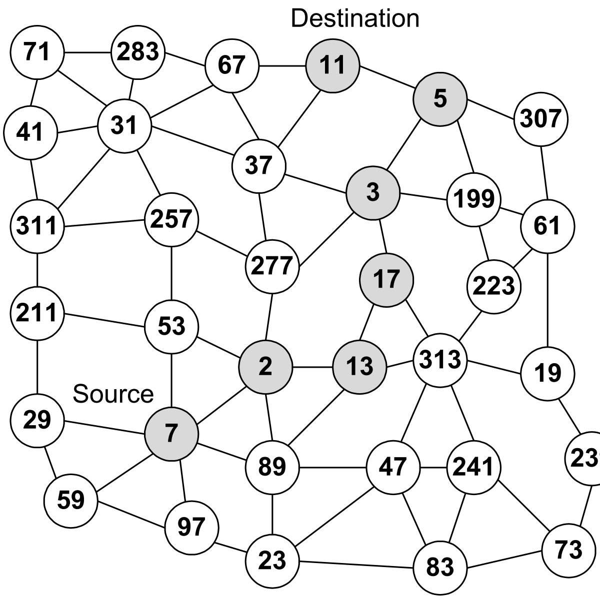

Figure 6-7, Route 3 node addresses

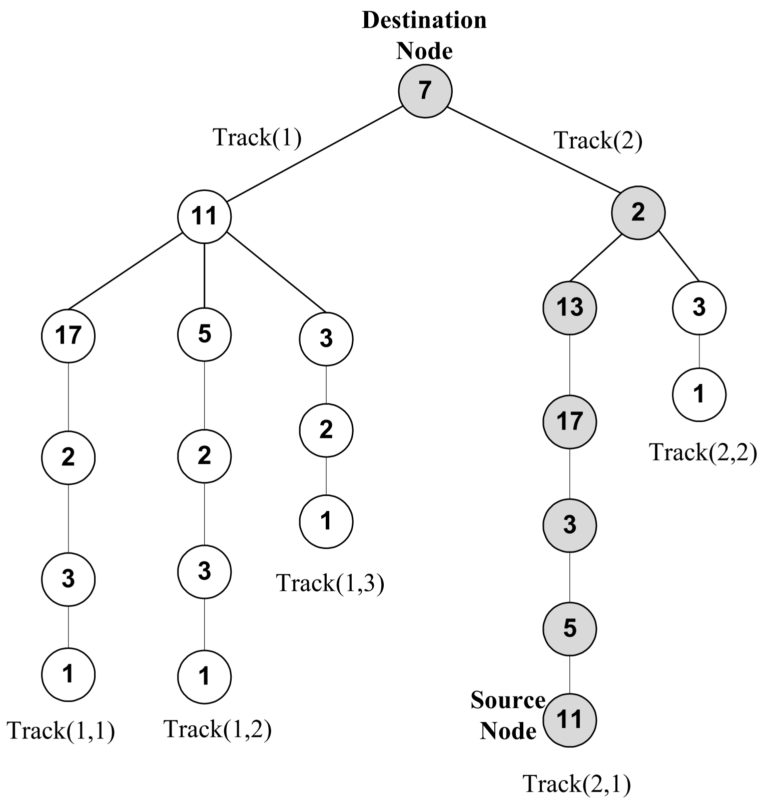

Figure 6-8, "backtrack procedure" for Route 3

Tables Table 6-2,Table 6-3 and Table 6-4 demonstrate the values of PPN_1 and PPN_2 in the highlighted routes that have been illustrated in Figures Figure 6-5Figure 6-6 and

Figure 6-7 respectively. In each of these examples, the source node gets a set of PPN_1 and PPN_2 numbers which is classified as following:

Route 1: shown in Figure 6-5 and Table 6-2:

$PPN_1 = 622,26,766,372,853,959$

$PPN_2 = 61,363,623,565,807,294$

Route 2: shown in Figure 6-6 and Table 6-3 :

$PPN_1 = 322,120,106,673$

$PPN_2 = 317,689,113,736$

Route 3: shown in

Figure 6-7 and Table 6-4:

$PPN_1 = 72,930$

$PPN_2 = 64,503$

After the route reply packet has been received by the source node, the backtrack procedure will start to generate the vector (RS). Figure 6-9 shows a flowchart of this procedure, which includes the iterations performed to consider all possibilities in forming the route vectors.

PPN$_1$ and PPN$_2$ value calculations from Route 1 in Figure 6-5		
PN	PPN$_1$	PPN$_2$
73	73-Destination	72
83	6059	5975
23	139357	137424
97	13517629	13330127
59	797540111	786477492
29	23128663219	22807847267
211	4880147939209	4812455773336
311	1517726009093999	1496673745507495
41	62226766372853959	61363623565807294
71	Source Node	Source Node

Table 6-2, example of constructing and deconstructing of thePPN$_1$ and PPN$_2$ for the Route 1 in Figure 6-5

PPN$_1$ and PPN$_2$ value calculations from Route 2 in Figure 6-6		
PN	PPN$_1$	PPN$_2$
73	73-Destination	72
241	17593	17351
313	5506609	5430862
17	93612353	92324653
3	280837059	276973958
37	10390971183	10248036445
31	322120106673	317689129794
71	Source Node	Source Node

Table 6-3 , example of constructing and deconstructing of the PPN$_1$ and PPN$_2$ for Route 2 in Figure 6-6

PPN$_1$ and PPN$_2$ value calculations from Route 3 in Figure 6-7		
PN	PPN$_1$	PPN$_2$
11	11-Destination	10
5	55	49
3	165	146
17	2805	2481
13	36465	32252
2	72930	64503
7	Source Node	Source Node

Table 6-4, example of constructing and deconstructing of the PPN$_1$ and PPN$_2$ for Route 3 in Figure 6-5

6.5. Backtrack Procedure - Scenario 1

To illustrate the backtrack procedure, as it is simulated by Matlab, the PPN_1 and PPN_2 numbers for Route 1 in Figure 6-5 will be used to explain the flowchart of Figure 6-9 to generate the intermediate nodes vector (RS):

1. In S_1, five variables have been defined:

    Input Variables:

    $PPN_1 = 62,226,766,372,853,959$

    $PPN_2 = 61,363,623,565,807,294$

    Output Variables:

    K: Number of intermediate nodes in a route

    RN: Intermediate Route Nodes vector in no particular order

    RS: Intermediate Route Nodes vector in a particular order

    Local Variables:

    INX: Index

2. In S_2, determine the RN vectors by factorising the PPN_1 number that represents the intermediate nodes in a no-particular order.

    RN = Factors (PPN_1) = [23, 29 ,41 ,59 ,73 ,83 ,97 ,211 ,311]

3. In S_3, add one to the PPN_2:

    $PPN_2 = PPN_2 + 1 = 61,363,623,565,807,295$

4. In S_4, determine the GCD of PPN_1 and PPN_2:

    g = GCD (PPN_1, PPN_2), GCD is Greater Common Division

    = GCD (62226766372853959, 61363623565807295) = [41]

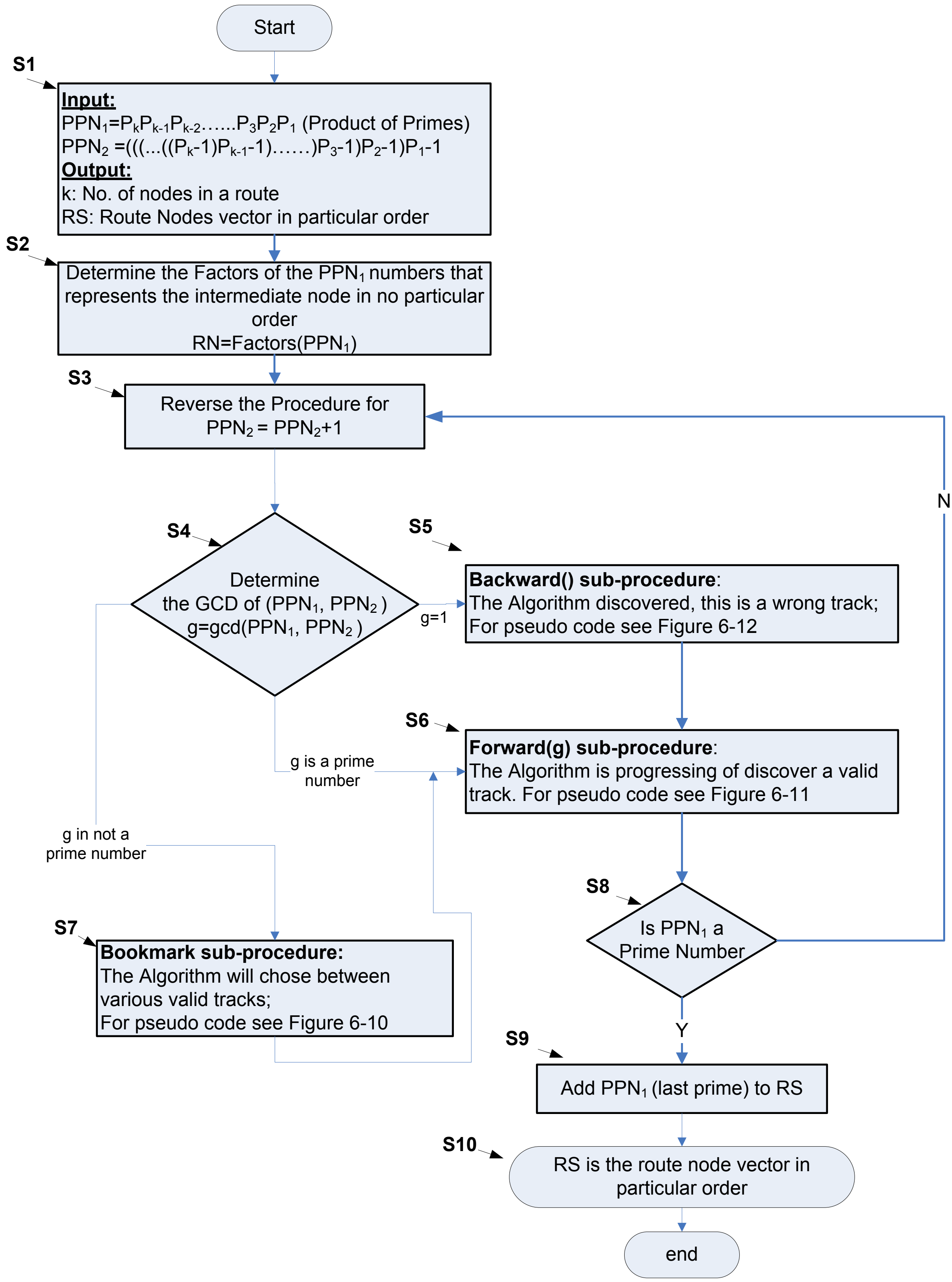

Figure 6-9, flow chart of the overall Backtrack procedure

```
Bookmark sub-procedure:
{
// Whilst g is multiple of Prime Numbers
// gx: is factors of the g
// Bmark: Bookmark array which will be used for the
// backward/forward functions in the Backtrack procedure.
// The Bookmark Structure is:
// Bmark(INX,1) = 0, only one prime
                  > 0,  Multiple of Primes
//Bmark(INX,2) = Number of Factors of the GCD at this point
//Bmark(INX,3) = PPN_1 at this point
//Bmark(INX,4) = PPN_2 at this point
//Bmark(INX,5) = GCD at this point
//Bmark(INX,6) = LB, Previous Benchmark

        gx=sort(factor(g),'descend');
        Bmark(INX,1)=Bmark(INX,1)+1;
        Bmark(INX,2)=length(gx);
        Bmark(INX,3)=PPN_1;
        Bmark(INX,4)=PPN_2;
        Bmark(INX,5)=g;
        Bmark(INX,6)=LB;
        LB=INX;
        Forward(gx(Bmark(INX,1)));
}
```

Figure 6-10, pseudo-code of the Bookmark sub-procedure

```
Forward(g) sub-procedure
{
        PPN_1 = PPN_1/g;
        PPN_2 = PPN_2/g;
        Remove g from RN vector;
        Add g to the end of RS vector;
        INX=INX+1;
}
```

Figure 6-11, pseudo-code of the Forward sub-procedure

```
Backward() sub-procedure
{
//Bsteps : How many backward steps
//LB: Last Bookmark
        Bsteps=INX-LB-1;
        INX=LB;
        Bmark(INX,1)=Bmark(INX,1)+1;
        PPN1=Bmark(INX,3);
        PPN2=Bmark(INX,4);
        GD=Bmark(INX,5);
        bgx=factor(GD);
// Add  the wrong track prime numbers to the RN vector again
          RN=[RN RS(end-Bsteps:end)];
// Remove  the wrong track prime numbers from the end of the RS vector
          RS(end-Bsteps:end)=[];
        if Bmark(INX,1)<=Bmark(INX,2)
            PR=bgx(Bmark(INX,1));
        else
            Bmark(INX,1)=0;
            LB=Bmark(INX,6);
            PR=Backward();
        end
Return PR
}
```

Figure 6-12, pseudo-code the Backward sub-procedure

5. Also in S_4,

- if g = 1: then the procedure is tracking the wrong track; therefore, the backward sub-procedure is invoked (described in Figure 6-12) to backtrack the procedure to the last benchmark in S_5.
- If g = not a prime number (in this example, g = 41): then the procedure will choose between various valid tracks.
- if g = a prime number: then g = 41 and we progress to discover a valid track.

6. In S_6, the forward sub-procedure is invoked as described in Figure 6-11. This moves the process forward by calculating the values to discover node-41:

$PPN_1 = PPN_1/g = 62,226,766,372,853,959/41 = 1,517,726,009,093,999$

$PPN_2 = PPN_2\ /g = 61,363,623,565,807,295/41 = 1,496,673,745,507,495$

Remove the first prime number [41] from RN and add it to RS

RN = [23, 29,59 ,73 ,83 ,97 ,211 ,311]

RS = [41], INX = INX+1 = 1

7. In S_8, if PPN_1 is not a prime number, then go to S_3.

8. Repeat (3-7) above as many times as necessary in order to obtain the final RS that represents all the intermediate route nodes vector in a particular order. The following is to discover node-311:

$PPN_2 = PPN_2 + 1 = 1,496,673,745,507,495+1 = 1,496,673,745,507,496$

$g = GCS\ (PPN_1, PPN_2) = GCD(1517726009093999, 1496673745507496) = [311]$

$PPN_1 = PPN_1/g = 1,517,726,009,093,999/311 = 4,880,147,939,209$

$PPN_2 = PPN_2\ /g = 1,496,673,745,507,496/311 = 4,812,455,773,336$

RN = [23, 29, 59, 73, 83, 97, 211]

Remove the prime number [311] from RN and add it to RS. i.e.

RS = [41,311], INX = INX+1 = 2

Again, for node-211:

$PPN_2 = PPN_2 + 1 = 4,812,455,773,336+1 = 4,812,455,773,337$

$g = GCS\ (PPN_1, PPN_2) = GCD(4880147939209, 4812455773337) = [211]$

$PPN_1 = PPN_1/g = 4,880,147,939,209/211 = 23,128,663,219$

$PPN_2 = PPN_2\ /g = 4,812,455,773,337/211 = 22,807,847,267$

RN = [23, 29, 59, 73, 83, 97],

Remove the prime number [211] from RN and add it to RS

RS = [41,311,211], INX = INX+1 = 3

Again for node-29:

$PPN_2 = PPN_2 + 1 = 22{,}807{,}847{,}267 + 1 = 22{,}807{,}847{,}268$

$g = GCS\ (PPN_1, PPN_2) = GCD\ (23128663219, 22807847268) = [29]$

$PPN_1 = PPN_1/g = 23{,}128{,}663{,}219/29 = 797{,}540{,}111$

$PPN_2 = PPN_2\ /g = 22{,}807{,}847{,}268/29 = 786{,}477{,}492$

RN = [23, 59, 73, 83, 97],

Remove the prime number [29] from RN and add it to RS

RS = [41, 311, 211, 29], INX = INX+1 = 4

Again for node-59:

$PPN_2 = PPN_2 + 1 = 786{,}477{,}492 + 1 = 786{,}477{,}493$

$g = GCS\ (PPN_1, PPN_2) = GCD(797540111, 786477493) = [59]$

$PPN_1 = PPN_1/g = 797{,}540{,}111/59 = 13{,}517{,}629$

$PPN_2 = PPN_2\ /g = 786{,}477{,}493/59 = 13{,}330{,}127$

RN = [23, 73, 83, 97],

Remove the prime number [59] from RN and add it to RS

RS = [41, 311, 211, 29, 59], INX= INX+1= 5

Again node-97:

$PPN_2 = PPN_2 + 1 = 13{,}330{,}127 + 1 = 13{,}330{,}128$

$g = GCS\ (PPN_1, PPN_2) = GCD(13517629, 13330128) = [97]$

$PPN_1 = PPN_1/g = 13{,}517{,}629/97 = 139{,}357$

$PPN_2 = PPN_2\ /g = 13{,}330{,}128/97 = 137{,}424$

RN = [23, 73, 83],

Remove the prime number [97] from RN and add it to RS

RS = [41, 311, 211, 29, 59, 97], INX= INX+1= 6

Again, this time for node-23:

$PPN_2 = PPN_2 + 1 = 137{,}424+1 = 137{,}425$

$g = GCS\ (PPN_1, PPN_2) = GCD(139357, 137425) = [23]$

$PPN_1 = PPN_1/g = 139{,}357/23 = 6{,}059$

$PPN_2 = PPN_2\ /g = 137{,}425/23 = 5{,}975$

RN = [73, 83],

Remove the prime number [23] from RN and add it to RS

RS = [41, 311, 211, 29, 59, 97, 23], INX = INX+1 = 7

Again, finally for node-83:

$PPN_2 = PPN_2 + 1 = 5{,}975+1 = 5{,}976$

$g = GCS\ (PPN_1, PPN_2) = GCD(6059, 5976) = [83]$

$PPN_1 = PPN_1/g = 6{,}059/83 = 73$

$PPN_2 = PPN_2\ /g = 5{,}976/83 = 72$

RN = [73]

Remove the first prime number [83] from RN and add it to RS

RS = [41, 311, 211, 29, 59, 97, 23, 83], INX = INX+1 = 8

9. In S_8, if PPN_1 is a prime number then this is also the destination node, (in this example, $PPN_1 = 73$), and so go to S_9

10. In S9, add (73) to RS = [41, 311, 211, 29, 59, 97, 23, 83, 73]

11. In S_{10}, Finally, RS represents the highlighted route in Figure 6-5 and Table 6-2 in this particular order.

6.6. Backtrack Procedure – Scenario 2

To illustrate the backtrack procedure further, as it is simulated in Matlab, the PPN_1 and PPN_2 numbers for Route 3 in

Figure 6-7 and Table 6-4 will be used to explain the flowchart of Figure 6-9, but when the backward-sub-procedure is also invoked, as follows:

1. S_1, 5 variables have been defined:

   <u>Input Variables:</u>

   $PPN_1 = 72,930$

   $PPN_2 = 64,503$

   <u>Output Variables:</u>

   k: Number of intermediate nodes in a route

   RN: Intermediate Route Nodes vector in no-particular order

   RS: Intermediate Route Nodes vector in particular order

   <u>Local Variables:</u>

   INX: Index

2. S_2, determines the RN vectors by factorising the PPN_1 number that represents the intermediate nodes in no-particular order.

   RN = Factors (PPN_1) = [2, 3, 5, 11, 13, 17]

3. S_3, add one to PPN_2:

$PPN_2 = PPN_2 + 1 = 64{,}504$

4. S_4, determine the GCD of PPN_1 and PPN_2:

$g = GCS\ (PPN_1, PPN_2) = GCD(72930, 64504) = [22]$

- if g = 1: then the procedure is tracking the wrong track; therefore, the backward sub-procedure is invoked (described in Figure 6-12) to backtrack the procedure to the last benchmark in S_5.
- if g is a prime number: No
- If g = not a prime number (in this example, g = 22): then the procedure will choose between various valid tracks, then, S_7.

5. S_7 (more details in Figure 6-10), Bookmark Sub-procedure,

gx: Factors of g in descending order (g is not prime number).

Bmark: Bookmark array used for the forward and backward sub-procedures as described Figure 6-11 and Figure 6-12.

The Bookmark Structure is:

Bmark(INX,1) = Branch :0 only one prime: i^{th} Multiple of (n-1) prime number

Bmark(INX,2) = Number of Factors of the GCD at this point (number of branches)

Bmark(INX,3) = PPN_1 at this point

Bmark(INX,4) = PPN_2 at this point

Bmark(INX,5) = GCD at this point

Bmark(INX,6) = LB is the Previous Bookmark

Figure 6-8 illustrates the behaviour of the backtrack procedure (showing "depth-first search" algorithm when in a tree structure). Prime-IP assigns a bookmark (Bmark array) for every branch, when more than one track is possible. For instant, at this point, gx = factors (22) = [11, 2] in descending order. The procedure shall choose between two tracks, either [11] or [2]. While gx vector has been sorted in descending order, selecting the prime number will also be in descending order. As shown in Figure 6-8, node-11 is selected as the next node is track(1). If the procedure discovers that track(1) is the wrong track selection, then node-2 shall be selected as a next node in track(2).

Bmark(1,1) = 1, track(1)

Bmark(1,2) = 2, represents the number of various valid tracks at this bookmark point

Bmark(1,3) = 72,930, PPN_1 at this point

Bmark(1,4) = 64,504, PPN_2 at this point

Bmark(1,5) = 22, g at this point

Bmark(1,6) = 1, LB represents a Previous Bookmark

Forward(gx(Bmark(1,1))) → Forward[11], move the procedure forward.

6. S_6, the forward sub-procedure is invoked as described in Figure 6-11. This moves the process forward by calculating the values to discover node-11

$PPN_1 = PPN_1/g = 72{,}930/11 = 6{,}630$

$PPN_2 = PPN_2/g = 64{,}504/11 = 5{,}864$

RN = [2, 3,5,13, 17]

Remove the prime number [11] from RN and add it to RS

RS = [11], INX = INX+1 = 2

7. S_8, if PPN_1 is not a prime number: $PPN_1 = 6{,}630$.

8. S_3, add one to the PPN_2: $PPN_2 = PPN_2 + 1 = 5{,}865$

9. S_4, determine the GCD of PPN_1 and PPN_2:

   g = GCS (PPN_1, PPN_2) = GCD(6630, 5865) = [255]

   If g is not = 1 → g= 255

   if g is not a prime number: g= 255, then S_7

10. S_7, this is the start of the "Bookmark Sub-procedure", as shown in Figure 6-10.

At this point, gx = factors (255) = [17, 5, 3]. The process wants to find the right track by performing depth-first search. The procedure will consequently test the following tracks: track(1,1), track(1,2) and track(1,3). Figure 6-8 shows the possible three tracks:

- Selecting [17] as a next node is track (1, 1).
- Selecting [5] as a next node is track (1, 2).
- Selecting [3] as a next node is track (1, 3).

11. Next, the process moves forward following track (1, 1) in order to find all the intermediate nodes in a particular order. Once S4 detects that the process is in a wrong track (g = 1), the backtrack procedure will stop and chooses the next track (e.g. track (1, 2)). Figure 6-10 and Figure 6-8 illustrates the testing of this track as in the following steps:

    Bmark(2,1) = 1, track(1,1)

    Bmark(2,2) = 3, represents the number of various valid tracks at this bookmark point

    Bmark(2,3) = 6,630, PPN_1 at this point

    Bmark(2,4) = 5,865, PPN_2 at this point

    Bmark(2,5) = 255, g at this point

    Bmark(2,6) = 1, LB represents a Previous Bookmark

    Forward(gx(Bmark(2,1))) → Forward[17], move the procedure forward

12. Move forward in the track (1, 2) in order to find the intermediate node in particular order. Once S4 detects that is a wrong track (g = 1 is true), backtrack procedure will stop and undertake the next track (e.g. track (1, 3)). Figure 6-8 and Figure 6-10 illustrates the testing of the track and how the sub-procedures behaviours will be.

    Bmark(2,1) = 2, track(1,2)

    Bmark(2,2) = 3, represents the number of various valid tracks at this bookmark point

    Bmark(2,3) = 6,630, PPN_1 at this point

    Bmark(2,4) = 5,865, PPN_2 at this point

    Bmark(2,5) = 255, g at this point

    Bmark(2,6) = 1, LB represents a Previous Bookmark

    Forward(gx(Bmark(2,1))) → Forward[5], move the procedure forward

13. Move forward in the track (1,3) in order to find the intermediate node in particular order. Once S4 detects that is a wrong track (g = 1 is true), backtrack procedure will stop and undertake a backward track (track(1)), because it is the last track at this bookmark. Figure 6-10 and Figure 6-8 illustrates the testing of the track and how the sub-procedures behaviours will be.

    Bmark(2,1) = 3, track(1,3)

    Bmark(2,2) = 3, represents the number of various valid tracks at this bookmark point

    Bmark(2,3) = 6,630, PPN_1 at this point

    Bmark(2,4) = 5,865, PPN_2 at this point

    Bmark(2,5) = 255, g at this point

    Bmark(2,6) = 1, LB represents a Previous Bookmark

    Forward(gx(Bmark(2,1))) → Forward[3], move the procedure forward

14. In Figure 6-8, Now that the GCD of (PPN_1, PPN_2) is equal to one in all track(1) branches, i.e. the procedure decides it is the wrong track, and so chooses to progress along track(2). i.e. the right track will never give this result (GCD= 1) in S4, because at S8 the PPN_1 will be tested whether it is a prime number or not. If it is a prime number, then the backtrack procedure progress in the right track and it knows that this is the last prime number ("destination node"). However, if the PPN_1, in S8, is not a prime number, then the procedure will move forward. At this point, there is no indication if it is following a wrong or correct track, until S4 will test is reached again

15. The backtrack procedure will now chose the next possible track as follows, in this example, it is track(2):

    Bmark(1,1) = 2, track(2)

    Bmark(1,2) = 2, represents the number of various valid tracks at this bookmark point

    Bmark(1,3) = 72,930, PPN_1 at this point

    Bmark(1,4) = 64,504, PPN_2 at this point

    Bmark(1,5) = 22, g at this point

    Bmark(1,6) = 1, LB represents a Previous Bookmark

    Forward(gx(Bmark(1,1))) → Forward[2], move the procedure forward.

16. S_6, the forward sub-procedure Figure 6-11 moves forward by the following calculations:

    $PPN_1 = PPN_1/g = 72,930/2 = 36,465$

    $PPN_2 = PPN_2\ /g = 64,504/2 = 32,252$

    RN = [2, 3,5,13, 17]

Remove the prime number [2] from RN and add it to RS

RS = [2], INX = INX+1 = 2

17. S_8, if PPN_1 is prime: No, $PPN_1 = 36{,}465$.

18. S_3, add one to the PPN_2: $PPN_2 = PPN_2 + 1 = 32{,}253$

19. S_4, determine the GCD of PPN1 and PPN_2:

    $g = GCS\ (PPN_1, PPN_2) = GCD(36465, 32253) = [39]$

20. In S_4,

    - If $g = 1$ → NO, ($g = 39$).
    - if g is a prime number: No, $g = 39$,
    - if g is not a prime number:, $g = 39$, then S_7

21. S_7 the Bookmark Sub-procedure and as shown in Figure 6-10,

At this point, gx= factors (39) = [13, 3]. The procedure will consequently test the following tracks: track(2,1) and track(2,2) . Figure 6-8 shows the procedure that should have chosen between two tracks.

- Selecting [13] as a next node is track (2, 1).
- Selecting [3] as a next node is track (2, 2).

22. The procedure should have chosen between two tracks, track(2,1) or track(2,2) while gx vector has been sorted in descending order, selecting the prime number will be in descending order also. As shown in Figure 6-8, selecting [13] as a next node is track(2,1) while selecting [3] as a next node is track(2,2) if the first track(2,1) is wrong.

23. S_6, the forward sub-procedure Figure 6-11 moves forward by doing these calculations:

$PPN_1 = PPN_1/g = 36{,}465/13 = 2{,}805$

$PPN_2 = PPN_2 /g = 32{,}253/13 = 2{,}481$

RN = [3, 5, 13, 17]

Remove the prime number [13] from RN and add it to RS

RS = [2, 13], INX = INX+1 = 3

24. In S_8, if PPN_1 is prime: No, $PPN_1 = 2{,}805$.

25. In S_3, add one to the PPN_2: $PPN_2 = PPN_2 + 1 = 2{,}482$

26. In S_4, determine the GCD of PPN_1 and PPN_2:

    $g = GCS(PPN_1, PPN_2) = GCD(2805, 2482) = [17]$

27. In S_4,

    - If $g = 1 \rightarrow$ NO, ($g= 17$).
    - if g is not a prime number, ($g = 17$).
    - if g is a prime number: Yes, $g = 17$,then S_6

28. In S_6, the forward sub-procedure, Figure 6-11, moves forward by doing these calculations:

    $PPN_1 = PPN_1/g = 2{,}805/17 = 165$

    $PPN_2 = PPN_2 /g = 2{,}482/17 = 146$

    RN = [3, 5, 17]

    Remove the prime number [17] from RN and add it to RS

    RS = [2, 13, 17], INX = INX+1 = 4

29. Repeat above steps many times in order to get the final RS that represents Intermediate Route Nodes vector in particular order

$PPN_1 = PPN_1/g = 165/3 = 55$

$PPN_2 = PPN_2\ /g = 147/3 = 49$

RN = [3, 5]

Remove the prime number [3] from RN and add it to RS

RS = [2, 13, 17, 3], INX = INX+1 = 5

30. Repeat it again,

$PPN_1 = PPN_1/g = 55/5 = 11$

$PPN_2 = PPN_2\ /g = 50/5 = 10$

RN = [5]

Remove the prime number [5] from RN and add it to RS

RS = [2, 13, 17, 3, 5], INX = INX+1 = 6

31. In S_8, if PPN_1 prime number, YES $PPN_1 = 11$,

32. In S_9, add [11] to RS = [2, 13, 17, 3, 5, 11],

33. In S_{10}, RS represents the highlighted route in

34. Figure 6-7 and Table 6-4 in particular order.

6.7. Packet Size

Prime-IP inherent overhead associated with the use of PPN_1 and PPN_2. The limits of the PPN values are proportional to the assign host size and number of intermediate nodes. i.e. for a 16-bit host size, actual prime numbers possible are 6542, but the maximum number of possible intermediate nodes is limited to 575 in WiFi (packet upper limit is 2.3Kbytes) and 150 nodes for WiMax-256 (packet size 600 Bytes). This is because the packet upper limit size is fixed for each of the technologies and is dependent on the OFDM symbol size, as well as the bandwidth. Therefore, Table 6-5 and Figure 6-13 are determined to show the max number of intermediate node possible in worst case sceneries.

Bits/host	Total Prime Numbers	Max Number of Intermediate Nodes in:			
		WiFi	WiMax-256	WiMax-512	WiMax-1024
8	54	54	54	54	54
16	6,542	575	150	300	600
24	1,077,871	380	100	200	400
48	$\approx 8 \times 10^{12}$	190	50	100	200
64	$\approx 4 \times 10^{17}$	145	38	75	150

Table 6-5, Max Number of Intermediate nodes for using Prime-IP

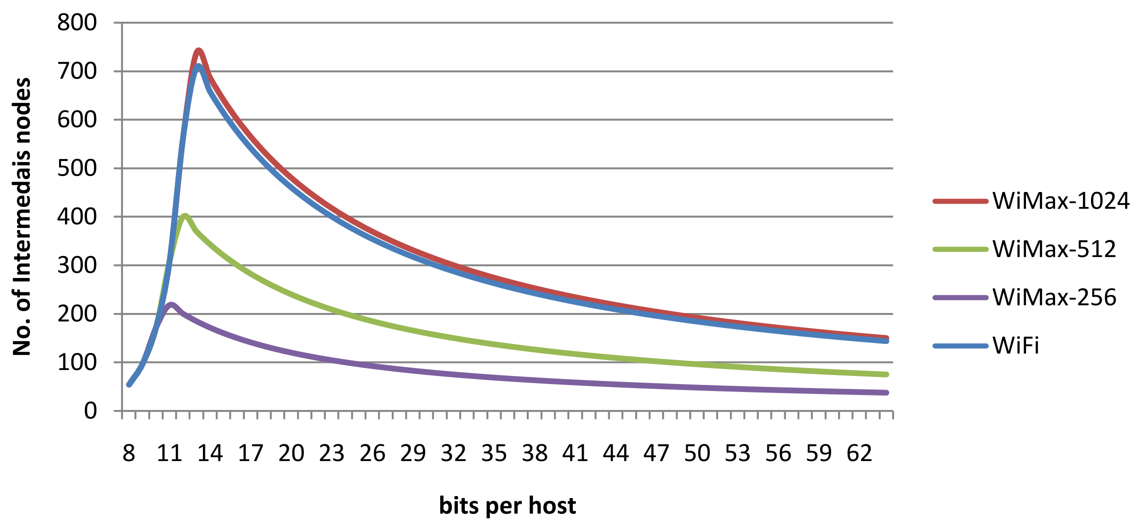

Figure 6-13, Diargam illustrtes the max number of Intermediate nodes in WMN for using Prime-IP Algorthim

6.8. Delay Calculations

Further to the packet size limitation described in section 6.7, the delay associated with calculation of PPN_1 and PPN_2 during the RREP is equal to 10 μsec for the worst case. The 10 μsec is due to these PPN_1 and PPN_2 binary-multiplication operation (i.e. bits shifting + addition). i.e. the number of operations to multiply two binary numbers with N_1 and N_2 bits are N_1 Shifting + N_2 Additions. Therefore, for the worst case scenario:

- Max Bits/host = 64 bits, (see Table 6-5).
- Max Number of intermediate nodes = 750 nodes, (see Figure 6-13).
- Max Packet size = 2600 Bytes, (IEEE Standard).

The length of PPN_1 and the length of PPN_2 are approximately equal, and the maximum size is equal to 1300 Bytes (10400 bits). Therefore, the number of operations at each node to generate the new PPN_1 and the new PPN_2 are:

1. $newPPN_1$ = $previousPPN_1$ x CurrentNodePrimeNumber
   = 10400 shifting +64 additions = 10464 operations
2. $newPPN_2$ = $previousPPN_2$ x CurrentNodePrimeNumber - 1
   = 10400 shifting +65 additions = 10465 operations

This results in a total number of operations = 10464 +10465 = 20929. Based on various trials, the average execution time for this task was 5μsec, with a worst case delay of 10 μsec.

6.9. Summary:

To demonstrate and prove Prime-IP, extensive variations of node scenarios was studied. This chapter highlighted some of these example scenarios. The novelty claims made are focused on using “prime numbers” to be the address of the host portion of node IP and accumulating “node knowledge” of the entire WMN. The resultant “Prime-IP” claims have also been proved mathematically and work for multihop dynamic topology WMNs.

The following is a summary of the claims made for the novelties in Prime-IP:

1. This algorithm, named “Prime-IP”, is designed to uniquely identify a path in a Wireless Mesh Networks-WMN, without impacting the routing protocol.
2. Prime-IP is designed to allow each individual node to uniquely identify a path based on the node’s location within the mesh.
3. The host portion of any Node’s IP address is assigned a unique prime number.
4. Prime-IP is designed to detect, and survive-the-loss-of, any deactivated nodes in the route.
5. Further to point 2, and upon a “source node” issue a request to discover a route to a “destination node”, then, route reply packets received by the “source node” shall contain full path knowledge about their routes.
6. The route reply packet shall have two extra fields appended to the existing packet format.
7. Further to point 6, these two new fields will contain a value related to the “Product of Prime Numbers”, see point 3, and these two fields shall be named PPN_1 and PPN_2.
8. PPN_1 shall have an initial value equal to the “destination route” prime number, and PPN_2 shall have an initial value equal to the “destination node” prime number minus one.
9. Further to points 3, 5 and 8, each intermediate node shall multiply its own prime number by the PPN_1 value present in the route reply packet ($newPPN_1 = previousPPN_1 \times NodePrimeNumber$)
10. Further to points 3, 5 and 8, each intermediate node shall multiply its own prime number by the PPN_2 value in the packet and subtract 1 from the resultant product ($newPPN_2 = previousPPN_2 \times NodePrimeNumber - 1$).
11. The accumulated operations of points 9 and 10 all through the route reply process from the “destination node” to the “source node” shall results in unique PPN_1 and PPN_2 numbers.

12. Further to point 11, Prime-IP shall produce a vector containing full path knowledge (intermediate nodes and their sequence in the route) from PPN_1 and PPN_2.
13. Prime-IP, using backtrack procedure, shall generates a vector of all intermediate nodes, of any route, in a particular order based on the value contained in PPN_1 and PPN_2.
14. Each individual node shall acquire a knowledge of what other nodes exist in the route that are beyond their nearest neighbouring nodes.
15. Prime-IP shall apply for both Ipv4 and Ipv6 address types.
16. Prime-IP applies to all types of wireless mesh networks.
17. Prime-IP applies to all types of multi-hop wireless networks
18. Prime-IP works with both fixed and mobile nodes.

Chapter 7: Conclusions and Future Work

This thesis provides technical solutions to enhance interoperability and routing protocols for the WMN. The author was keen to work within the concept of the backward compatibility of wireless technologies. Therefore, the W^2BC approach was based on backward compatibly between the WiMax and the WiFi. Furthermore, the Prime-IP approach uses backward compatibility to enhance any routing protocols using either IPv4 or IPv6. Recently, the IEEE standard has created new amendments to consider the backward compatibility concept with some of their standards (3), (4), (5). This supports the approach taken by the author.

Mindful of the commercial added value of the research, the focus of the author was on enhancement of existing standards/technology rather than starting from scratch. It is clear that wireless technologies are being superseded well before they fulfil their potential, for example, Nokia has just announced an amendment to existing 2G infrastructures that results in doubling the capacity of these networks. Another example, WiMax has been dropped well before serious deployments despite interest from many third world countries.

7.1. What does W^2BC delivers?

The literature survey of wireless technologies convergence, see chapter 2, has concluded that it achieves not only functional benefits by moving the control from the upper layers to the lower layers, but also saves silicon size, power, cost and complexity when done at the implementation level. W^2BC offers a novel implementation concept for convergence of the WiMax and WiFi technologies. It would have been a great achievement to secure a sponsor to implement the W^2BC on silicon.

Despite repeated attempts to a number of potential companies, but the slow deployment of WiMax has resulted in a number of the major silicon companies pulling out of this market. Thus, no decision of sponsoring the silicon implementation has been reached thus far. However, the simulation model and test scenarios have offered a convenient environment to prove the viability of the W^2BC, and to prove that W^2BC performs to not only the IEEE specification for standalone WiMax or WiFi transceivers, but also that of commercially deployed standalone products. Furthermore, the simulations have confirmed that the average switching time ranges between 1.5 msec and 2.5 msec. This time is less than the time of a standalone WiMax or WiFi frame (the standards recommend within 5 msec). i.e. an estimated overhead of $<2\%$ delay will be attributed to the W^2BC switching time delay.

The recent Intel announcement for a product claims to support WiMax and WiFi standalone functionality on a single die (unfortunately no datasheets has been released yet) is evidence that convergence is commercially attractive. Therefore, W^2BC is relevant to the deployment of near future wireless data/broadband communications.

In conclusion, W^2BC achieves a compact baseband implementation of these two technologies with no impact on performance. Thus achieving much needed saving in silicon size, power and cost. It is estimated that W^2BC implementation on silicon will result in 35% size reduction, in terms of number of gates saved from a dual-PHY implementation.

7.2. What does Prime-IP delivers?

Researching existing wireless routing protocols showed that all reactive protocols and most of the others do not produce knowledge of nodes that are beyond their neighbouring nodes. Proactive and hybrid routing protocols deploy a link-list table to enable them acquire knowledge beyond their neighbours. To do that, they have to exchange the entire routing tables repeatedly across the whole network, degrading the processing capability and battery power of the nodes. This routing-table exchange overloads the wireless networks and will reduce the performance of the entire network. The proposed Prime-IP algorithm shall overcome this problem. Prime-IP can also be embedded with any routing protocol to enables them having knowledge beyond their neighbour without large overhead. Furthermore, IPv6 can benefit from Prime-IP protocol to enhance its functionality by providing additional information about nodes beyond neighbouring nodes.

WMN are emerging as cost effective means of extending broadband services. The integration of WiMax and WiFi technologies offers the advantages of both to increase coverage area as well as capitalise on better features provided by WiMax technology. The new broadband and WiFi standards such as 802.11n, 802.20 and 802.22 are also being developed to provide higher speed & better mobility. Furthermore, the WiMax has also amended to support IPv6. Therefore, Prime-IP can further enhance these new technologies. It is important to mention that there is a practical upper limit to the number of intermediate nodes that for any route. This is due to packet size limitation in the standard.

Analysis of Prime-IP performance in various protocols have shown that it can relieve nodes, in a dynamic WMN, from the burden of relentlessly and continuously updating their knowledge database about other nodes joining and leaving the network. i.e. this algorithm, when embedded with any of the existing reactive routing protocols, shall greatly enhance the network performance, connectivity, security and scalability. Prime-IP algorithm can be further expanded to offer other benefits (eg. localization and better security) efficiently and cost-effectively.

7.3. A vision for the Future

1. A good application that would greatly benefit from the novelties of Prime-IP and W^2BC is the "first responder and disaster management networks". Simulators, such as OPNET, can be used to simulate a variety of WMN technologies

connectivity and establish the gains that can be achieved by the convergence of some of these technologies as well as achieving seamless connectivity from routing based on Prime-IP.

2. WiMax services will be even more attractive with 802.16e (Mobile WiMax). The W^2BC implementation can be extended to include more function configurations for this standard.

3. Prime-IP concept, including prime numbers, can be further adopted to enhance the security of heterogeneous WMN by building profiles to detect malicious nodes.

4. Prime-IP concept can also be used to acquire location knowledge about each and every node in the network. This capability can be further enhanced when combined with GPS and Cellular technologies. A hybrid location based algorithms needs to be investigated, developed and tested. Many applications and services can be developed with such technology, and it will greatly enhance disaster and emergency networks.

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