ON THE DESIGN OF FAST HANDOVERS IN MOBILE WiMAX NETWORKS

A thesis

submitted in partial fulfilment

of the requirements for the Degree

of

Doctor of Philosophy

in the

University of Canterbury

by

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2012

To My
Parents, Brother and Wife Shaoni

Acknowledgements

I would like to take this opportunity to express my gratitude to all those great people without the help and support of whom this thesis would not have been possible.

I would like to sincerely thank my supervisors, Prof. Dr. Harsha Sirisena, of Electrical and Computer Engineering Department and Prof. Dr. Krzysztof Pawlikowski, of Computer Science and Software Engineering Department, for their constant support, wisdom and enthusiasm throughout my studies. Particularly, I am grateful to Prof. Sirisena, for all those enlightening discussions and invaluable feedbacks on my work.

Thank-you to my associate supervisor, Dr. Allan McInnes, of Electrical and Computer Engineering Department for his helpful advice and encouragements.

I am grateful to my parents, brother Souparno, and other family members, for their unwavering encouragements. They always stood by me and provide their support and guidance.

A special thank you to my lovely wife Shaoni, for being so understanding, and caring throughout the course of my research work. This thesis truly would not have been possible without her constant support.

I have benefitted a lot from all my good lab mates and colleagues in the Departments of Computer Science and Software Engineering and Electrical and Computer Engineering, for their constant help and invaluable suggestions. Thanks to all of them. The enthusiastic and productive environment in the Department of Computer Science and Software Engineering has helped me a lot throughout the whole study period. I am indebted to the University of Canterbury for financially supporting my research work by providing the University of Canterbury Doctoral Scholarship, without which, I could not have pursued the work. I am also grateful to the University of Canterbury and BuildIT New Zealand funds for supporting financially my attendance of a number of conferences worldwide, for presenting my research work. A special thank-you goes to Foundation for Research, Science and Technology (FRST), New Zealand for funding my participation in the prestigious Summer Institute for Entrepreneurship program of Stanford University in the USA.

Finally, I am thankful to all my friends for being so good to me throughout the course of my study.

Abstract of the Thesis

This Thesis is an embodiment of some research work carried out towards achieving faster and more reliable handover techniques in a Mobile WiMAX (Worldwide Interoperability for Microwave Access) network. Handover, also called handoff, is the critical mechanism that allows an ongoing session in a cellular mobile network like WiMAX to be seamlessly maintained without any call drop as the Mobile Station (MS) moves out of the coverage area of one base station (BS) to that of another. Mobile WiMAX supports three different types of handover mechanisms, namely, the hard handover, the Fast Base Station Switching (FBSS) and the Micro-Diversity Handover (MDHO). Out of these, the hard handover is the default handover mechanism whereas the other two are the optional schemes. Also, FBSS and MDHO provide better performance in comparison to hard handover, when it comes to dealing with the high-speed multimedia applications. However, they require a complex architecture and are very expensive to implement. So, hard handover is the commonly used technique accepted by the mobile broadband wireless user community including Mobile WiMAX users.

The existing Mobile WiMAX hard handover mechanism suffers from multiple shortcomings when it comes to providing fast and reliable handovers. These shortcomings include lengthy handover decision process, lengthy and unreliable procedure of selecting the next BS, i.e., the target BS (TBS) for handover, occurrence of frequent and unwanted handovers, long connection disruption times (CDT), wastage of channel resources, etc. Out of these, reducing the handover latency and improving the handover reliability are the two issues that our present work has focused on. While the process of selecting the TBS for handover adds to the overall delay in completing the process of handover, choosing a wrong TBS for handover increases the chance of further unwanted handovers to occur or even a call drop to occur. The latter greatly hampers the reliability of a handover.

In order to contribute to the solution of the above two problems of slow handover and unreliable handover, this Thesis proposes and investigates three handover techniques, which have been called Handover Techniques 1, 2 and 3, respectively. Out of these three techniques, the first two are fully MS-controlled while

the third one is a dominantly serving BS-controlled. In Handover Techniques 1 and 2, which share between them some amount of commonness of ideas, the MS not only itself determines the need for a handover but also self-tracks its own independent movement with respect to the location of the (static) neighboring BSs (NBS). N both these handover techniques, the MS performs distance estimation of the NBSs from the signal strength received from the NBSs. But they (the two handover techniques) employ different kinds of “lookahead” techniques to independently choose, as the TBS, that NBS to which the MS is most likely to come nearest in the future. Being MS-controlled, both Handover Technique 1 and Handover Technique 2 put minimal handover-related workload on their respective SBSs who thus remain free to offer services to many more MSs. This interesting capability of the two handover techniques can increase the scalability of the WiMAX network considerably.

In Handover Technique 3, which is a BS-controlled one with some assistance received from the MS, the SBS employs three different criteria or parameters to select the TBS. The first criterion, a novel one, is the orientation matching between the MS’s direction of motion and the geolocation of each NBS. The other two criteria are the current load of each NBS (the load provides an indication of a BS’s current QoS capabilities) and the signal strength received by the MS from each NBS. The BS assigns scores to each NBS against each of the three independent parameters and selects the TBS, which obtains the highest weighted average score among the NBSs.

All three handover techniques are validated using simulation methods. While Handover Techniques 1 and 2 are simulated using Qualnet network simulator, for Handover Technique 3, we had to design, with barest minimum capability, our own simulation environment, using Python. Results of simulation showed that for Handover Techniques 1 and 2, it is possible to achieve around 45% improvement (approx) in the overall handover time by using the two proposed handover techniques. The emphasis in the simulation of the Handover Technique 3 was on studying its reliability in producing correct handovers rather than how fast handovers are. Five different arbitrary pre-defined movement paths of the MS were studied. Results showed that with orientation matching or orientation matching together with signal strength, reliability was extremely good, provided the pre-defined paths were reasonably linear. But reliability fell considerably when relatively large loads were also considered along with orientation matching and signal strength. Finally, the comparison between the proposed handover techniques in this Thesis and few other similar techniques in Mobile WiMAX proposed by other researchers showed that our techniques are better in terms providing fast, reliable and intelligent handovers in Mobile WiMAX networks, with scalability being an added feature.

Publications Arising from this Thesis

- **Sayan K. Ray, H. Sirisena and D. Deka,** "Fast and Reliable Target Base Station Selection Scheme for Mobile WiMAX Handover", in Proc. of Australasian Telecommunication Networks and Applications Conference (ATNAC 2012), Brisbane, Australia, 7-9 Nov 2012.

- **Sayan K. Ray, S. K. Ray, K. Pawlikowski, A. McInnes and H. Sirisena,** "A Fast and Simple Scheme for Mobile Station-Controlled Handover in Mobile WiMAX", in Proc. of 5th International Conference on Access Networks (Accessnets 2010), Budapest, Hungary, 3-5 November 2010, pp. 32-44.

- **Sayan K. Ray**, K. Pawlikowski and H. Sirisena, "Handover in Mobile WiMAX Networks: The State of Art and Research Issues", in *IEEE Communications Surveys and Tutorials Magazine*, No. 3, August 2010, pp. 376-399.

- **Sayan K. Ray**, S. K. Ray, K. Pawlikowski, A. McInnes and H. Sirisena, "Self-Tracking Mobile Station Controls Its Fast Handover in Mobile WiMAX", in Proc. of IEEE Wireless Communications and Networking Conference (WCNC), Sydney, Australia, 18-21 April 2010, pp. 1-6.

- **Sayan K. Ray**, Krzysztof Pawlikowski and Harsha Sirisena, "A Fast Predictive Handover Mechanism for IEEE 802.16e Systems", Presented in New Zealand Computer Science Research Student Conference (NZCSRSC), 6-9 April, 2009, Auckland, New Zealand.

- **Sayan K. Ray**, K. Pawlikowski and H. Sirisena, "A Fast MAC-layer Handover for an IEEE 802.16e-based WMAN", in Proc. of 3rd International Conference on Access Networks (Accessnets '08), 15-17 October, 2008, Las Vegas, USA. Published as a chapter in Lecture Notes in Computer Science, "*Accessnets*", Vol 6, 2009, pp. 102-117, ISSN: 1867-8211 (Print) 1867-822X (Online).

- **Sayan K. Ray**, A. Mandal, K. Pawlikowski and H. Sirisena et al, "Hybrid Predictive Base Station (HPBS) Selection Procedure in IEEE 802.16e-Based WMAN", in Proc. of Australasian Telecommunication Networks and Applications Conference (ATNAC), Christchurch, New Zealand, 2-5 Dec. 2007, pp. 93-98.

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Chapter 1

Introduction

1.1 Brief History of Modern Communication and Networking

Though human beings had communicated between themselves for millennia, humans entered the modern age of long-distance communication when electrical communication was introduced, first with the telegraph system and then, in the eighteen thirties, with the telephone system invented by A.G. Bell. After the telephone system, employing copper cables, slowly revolutionized the area of modern communication, the age of wireless communication, i.e. electrical communication without the use of any conducting wire, was born.

Wireless communication owes its origin to the painstaking research of many great scientists during the second half of the nineteenth century and the early part of the twentieth century. Among the landmark events that led to the development of wireless communication mention must be made of prediction of electromagnetic waves (J. C. Maxwell), generation of electromagnetic waves in the laboratory using an oscillator circuit (H. Hartz), demonstration of wireless communication within a building (J. C. Bose) and demonstration of transatlantic long-distance wireless communication from Canadian coast to British coast (G. Marconi). Following Marconi's demonstration and, later, invention of amplitude modulation (AM), wireless radio broadcasting was gradually started in many countries. Later, in the nineteen twenties, the concept of frequency modulation (FM) was invented and, thereafter, FM was also gradually introduced in radio broadcasts all over the world.

A major improvement over analogue communication (AM and FM) took place in the nineteen thirties and forties, when digital communication technologies started replacing the existing analogue communication systems gradually. Soon, after electronic digital computers were developed in the late forties, a major growth occurred in data communication and coding technology and high-speed reliable electronic communication of data (i.e. text material) started growing very fast. The growth was spurred by important technological developments like sampling theory, application of Boolean Algebra (G. Boole) in telephone switching (C. E. Shannon), etc. Two important developments took place in communication technology in the decade of the sixties. First was the development of communication satellites heralded by the launch of Telstar. Next, when the prices of computers started coming down, the idea of interconnecting multiple remotely located computers using dedicated cables or telephone networks emerged for sharing resources like databases, program packages, etc., and the era of computer networks began. The best-known computer network of this time was the ARPANET, which is considered as the predecessor of the present day global Internet.

The most notable event in the decade of the seventies was probably the invention of optical fibre, which has now greatly replaced copper cables because of its extremely large data rate, extremely low level of noise and competitive cost. Emergence of the TCP/IP Protocol Suite, which led to the unimaginable growth in internetworking technology, was the most significant development in the decade of eighties. The internetworking technology deals with the interconnection of an arbitrary number of computer networks of arbitrary technologies, and has resulted in the present gigantic size of the Global Internet. Finally, it must be mentioned that the entire human civilization today is revolving around this Global Internet. Of course, it must also be added that this phenomenal growth of the Global Internet really started after its commercial use was allowed in the mid-nineties.

1.2 Spectacular Growth in Wireless Mobile Communication

Since its inception in the early 1940s, with the birth of the mobile telephony system in St. Louis, USA, wireless communications has grown in the most spectacular way and has increasingly pervaded human lives. It has risen to a large height, getting matured in every step of the ladder. The steady global boom in the number of mobile users each year has periodically spurred the development of more and more sophisticated technologies that make provisions for high data rate, quality services and seamless global roaming. According to [4] the number of mobile users in 1940s was over 50,000, in 1950s over 500,000, in 1960s over 1.4 million and so on. In more recent statistics provided by the International Telecommunication Union (ITU) [2], the number of worldwide mobile cellular subscribers increased from 34 million in 1993 to more than a billion in 2003. As an additional piece of information, it was also reported that the number of cellular subscribers surpassed the number of fixed telephone line subscribers during the ten-year period.

The mobility of people worldwide is increasing everyday due to professional, social or personal reasons. People now-a-days want to stay in touch with one another to exchange different types of information with one another, or to communicate on-line, irrespective of their current locations. That can be from home, or from office, or from a cafe, or while travelling by car, bus, train or plane. So, in the current information society, the concept of "anytime anywhere" access and "untethered" access have not only led to the meteoric maturity of mobile communication, which is a vital component of today's life, but has also paved the pathway for development of different types of wireless technologies. These technologies have been ably supporting handy mobile devices like laptops, Personal Digital Assistants (PDAs), iPhones etc., and these modern sophisticated devices, in turn, are allowing the users to avail of the multitude of emerging and sophisticated new services.

The mobile communication and networking era has already passed through four generations, viz., the Zeroth Generation (0G) [3], from 1945 to early 1970s, through the Third Generation (3G), which will be over soon. The era of the Fourth Generation (4G) [4] is currently unfolding. Two important events in mobile wireless communication have occurred during this period. First, the world's first commercial mobile phone network had started operating in Finland in 1971. Second, satellite networks have become commonplace right from 1962 when the world's first true communication satellite, Telstar, was launched. Satellite systems now represent well over $100 billion of investments and efficiently provide an essential ingredient to thousands of businesses worldwide [5]. Satellite communications and networks are heavily used now-a-days in telecommunications, marine communications, global positioning services etc., besides the global TV coverage.

1.3 Wireless Communication Links – An Overview

Wireless communication over which the above spectacular growth in mobile communication has taken place is based on a simple principle. An electronic oscillator (commonly called a transmitter) can generate electromagnetic waves. When an antenna is attached to this transmitter circuit, it radiates the electromagnetic waves in free space to be propagated over long distances and these electromagnetic waves may be received by a receiver, placed some distance away. The electromagnetic waves propagate (in vacuum) at the speed of light (3×10^8 m/sec) and they can be generated at any frequency within an enormously wide range from around 1 Hz to around a few hundred terahertz (i.e. 10^{14} Hz). The different ranges of frequencies that are used for wireless communication and networking and their basic properties are as follows:

(a) *Radio waves (Frequency range: 10 KHz – 100 MHz):* They are omnidirectional at lower frequencies, easy to generate, can travel long distances and can penetrate buildings easily. Because of the last feature, radio waves cause interference between users and hence offer low security. Main uses of radio waves are in AM and FM radio broadcasts and Marine communication.

(b) *Microwaves (Frequency range: 100 MHz – 100 GHz):* They travel in nearly straight lines and can be well focussed using parabolic dish antennas like those used to receive TV signals from satellites. Near-straight line propagation of microwaves and good focussing by parabolic dish antennas make the long distance communication in satellites (earth surface to satellite and back – nearly 72,000 km) possible. Microwave communication is widely used for long distance communication of telephone, mobile phone and TV signals. However, in terrestrial microwave communication, because of the curvature of the earth surface, microwave repeaters, spaced about 100 m apart, are placed between two 100 m high (approx) communicating microwave towers. Microwave communication suffers from a problem called multipath fading. This problem occurs because, in spite of focussing, microwaves suffer from some divergence during their propagation in space. While some waves may reach the receiver in the direct path, some other waves may reach via an indirect and hence delayed path, after reflection from tall buildings. The delayed waves may reach out of phase with the direct waves and may thus cancel the signal. Some more discussion on the multipath problem will be presented in Chapter 4.

(c) *Infrared and Millimetre waves (Frequency range: 100GHz – 100THz):* They travel in almost straight lines and are used for short range communications like remote control on TVs, VCRs, Stereos etc. They do not pass through solid objects like walls and hence do not interfere with other infrared signals in adjacent rooms or buildings. These give good security to infrared signals.

From the above discussion about the electromagnetic waves it may be noted that interference suffered by a certain wireless transmission from other simultaneous transmissions or any electromagnetic waves in the environment is harmful to satisfactory communication. Thus, such interference must be avoided. Also, as another important point, it should be noted that the total spectrum of frequencies available for communication is not adequate to meet the diverse frequency needs of all human beings for all their different kinds of communications. Thus several intelligent techniques for appropriately sharing the scarce frequency spectrum among different users have been devised. The oldest and still widely used frequency sharing or channel sharing techniques (these techniques are commonly called multiplexing techniques) is Frequency Division Multiplexing (FDM). FDM basically partitions the total frequency band into N smaller sub-bands or frequency slots or frequency channels and allocates each frequency slot, which is a fraction of the total frequency band, in a dedicated manner to one user. The second widely used channel sharing technique is Time division Multiplexing (TDM) where a certain repeating time frame is partitioned into N equal time slots and each time slot is allocated to one of the users. This allows each user to communicate at the total frequency band but only during his allocated slot of time. A third multiplexing or channel sharing technique, called Code Division Multiplexing Access (CDMA) does not partition the channel by either frequency or time but by assigning an unique chipping code to each user. These chipping codes being orthogonal, CDMA allows each user to communicate at the total frequency all the time [6], [7].

Finally, an important property of wireless communication links is the pathloss property [8], [9]. In accordance with the pathloss property, electromagnetic radiation attenuates during its propagation and this attenuation depends on various parameters but most significantly on the distance traversed from the transmitter. Even in free space, the signal disperses and this results in a decrease in signal strength in proportion to the distance between the transmitter (sender) and the receiver. Further discussion on the pathloss phenomenon will be presented in Chapter 4.

1.4 Wireless Cellular Networks

1.4.1 Introduction

Wireless communication links described in the previous section are employed to interconnect multiple wireless hosts to form wireless communication networks or, simply, wireless networks. The wireless hosts might be laptops, palmtops, PDAs, mobile phones or even desktops, where the hosts themselves may or may not be mobile. Three well known kinds of wireless networks are most commonly used. They are the Cellular Networks, the Wireless Local Area Networks (WLAN) and the Mobile Adhoc Networks (MANET). The first two kinds are called infrastructure-based networks because they need a network infrastructure to operate. The Base Station (BS) is the key part of this wireless network infrastructure. Somewhat like the router in a wired network, the BS is responsible for communicating with the wireless hosts and forwarding packets between each wireless host that is associated with the BS and the network infrastructure. The BS coordinates the simultaneous transmission and reception of data packets by multiple hosts under its control and from the infrastructure network. In contrast to the cellular LANs and WLANs both of which are infrastructure-based wireless networks, MANETs, the network of the third kind, have no network infrastructure at all. Two or more wireless mobile hosts can, at any time or any place (e.g. in a conference hall, battle field or earthquake-devastated area) themselves set up their own MANET in an ad-hoc manner just to communicate between themselves. Obvious interest in a MANET is fairly limited.

1.4.2 Cellular Architecture: An Overview

In the cellular network, the geographical area of the network is partitioned into a large number of coverage areas called “cells”. Each cell contains a BS, having an omnidirectional antenna, in the middle of the cell to which it is dedicated. However, in many recent systems, the BS, which has directional antennas, is placed at the corners where three cells interact, in order to allow it to provide service to all of them. The coverage area of a cell depends mainly on the transmitting power and the height of the BS and those of the mobiles, besides the presence of buildings and other obstructions, if any, within the cell. All BSs are connected to a telephone network or the global Internet via a number of mobile switching centres (MSC). Each MSC manages the establishment and termination of calls from all the MSs which are serviced by the set of BSs that are connected to the telephone network or the global Internet via the MSC.

Within each cell, many simultaneous calls take place. These calls share a portion of the radio spectrum allocated to the cellular service provider. Two broad approaches for sharing the radio spectrum between the BSs and MSs are employed. The first approach is a combination (hierarchy) of FDM and TDM where the total frequency band is first partitioned into multiple frequency sub-bands and each frequency sub-band is then partitioned into multiple time slots. The second approach uses the CDMA principle, which allows each user to use the total frequency sub-band all the time using his dedicated chipping code. Only when the sender and the receiver use the same chipping code, they can communicate between themselves as the receiver can then recover the sender's transmission from among the simultaneous transmissions from all the other senders in the cell.

Cellular technology has contributed to the spectacular growth in wireless mobile communication during the last two decades. This is due to the fact that the cellular design increases the system capacity (i.e. user capacity) of wireless networks by at least ten or more times as the cell sizes get smaller. In one large cell, only one call on each frequency was possible. But when the large cell is divided into a number of smaller cells, one call in each smaller cell becomes possible if the neighbouring cells are allotted different frequencies so that signal interference will not occur. This scheme of "frequency reuse" allows that same frequency to be used in multiple non neighbouring cells. However, allocating frequencies in this manner to a large number of smaller cells becomes a difficult design problem. A second big advantage of the cellular design is that smaller cells mean very low power transmitters in each cell (i.e. in the BS). This, in turn, means smaller and cheaper transmitters as well as handsets. As a final advantage of the cellular technology, it should be mentioned that when the number of users in a cell becomes too large, the overloaded cell is just split up into a number of smaller cells with more number of smaller and cheaper transmitters deployed in these smaller cells.

1.4.3 Mobility Management in Cellular Networks

In a cellular network, a large number of MSs may move around freely, both within their own cells or from one cell to another. At the same time, they may also carry on their communications. Managing the total mobility of all users poses two big challenges in a cellular network. These challenging problems are called Roaming and Handoff (also called handover), respectively [10]. Roaming refers to the need for the network to reach, at any time, any mobile user who can be present in any cell, for the purpose of either delivering a packet or for initiating a session for voice/data/multimedia communication. The job of finding or locating a roaming user, who can be present in any cell, is accomplished by using a centralised database which maintains the recent information about the current location of each user. For keeping the database up-to-date, subscriber stations (or mobile stations) send location update message whenever they move from one cell to another. For reaching a subscriber station for a session set up, the network pages it over all the BSs around the probable location of the MS available in the database.

The second big challenge in a cellular network relates to the handoff of an MS that is currently having an ongoing communication session from its present cell to the next cell (neighbouring cell) en route. What is important is that the handoff should be performed seamlessly so that ongoing call is neither dropped nor is followed by a ping-pong effect [4]. Performing handoffs fast, efficiently and reliably is still an important area of current research and the present thesis embodies our work on this problem in connection with handover in the Worldwide Interoperability for Microwave Access (WiMAX) network [10]. A brief overview of the WiMAX network will be provided in Section 1.6.

1.5 Evolution of Cellular Wireless Networks

Cellular wireless network technology has been evolving through the last three decades through a broad concept of generations. Each new generation adds new capabilities to make the network more attractive to the users. Loosely speaking, four generations of cellular wireless networks have been seen so far, namely generations 1, 2, 2.5 and 3, which are popularly referred as 1G, 2G, 2.5G and 3G, respectively [4]. The different important networks belonging to each of these generations will be described in this section. Two interesting points in this generation numbering scheme needs special mention. First, the numbering of 2.5G is totally unofficial (off course, the concept of "generation" itself is unofficial!) but it emerged because of the unusually long period of evolution (not yet complete!) from 2G to 3G. Second, the concept of 4G appears to be highly ambitious as well as nebulous. For this reason, we discuss 4G in a separate section (Section 1.6).

1.5.1 First generation (1G)

These networks were solely for analogue voice communication and employed Frequency Division Multiple Access (FDMA). The best known 1G system was the Advanced Mobile Phone System (AMPS) that was invented at Bell labs in the USA and was first installed in 1982 [11]. Although it was voice-only wireless network, it had incorporated much of the cellular network concept. However, it is now almost extinct and was replaced by its Second Generation (2G) version called Digital AMPS (D-AMPS) [11].

1.5.2 Second Generation (2G)

2G networks were also designed for voice communication but it employed digital technology rather than analogue technology. A 2G cell phone converts the input analogue voice signal into a digital format and then modulates the carrier frequency by this digitized voice signal before its transmission into the free space. Digital technology in 2G offers many advantages over the analogue 1G technology. Most of today's cellular providers use 2G technology. Among the widely used 2G systems are the following ones.

(i) *Interim standard 136 (IS – 136),* the successor standard of IS – 54, which is basically the D-AMPS referred to earlier. It uses the FDM/TDM combination [11].

(ii) *Global System for Mobile communication (GSM):* The GSM technology was first deployed in Europe in the early nineties and is now the most widely used cellular communication technology in the world [4]. It also uses FDM/TDM combination like IS – 136.

(iii) *IS – 95 CDMA [11]:* It uses CDMA as the air interface instead of the combined FDM/TDM. It was introduced in the late 1980s and has become fairly popular.

1.5.3 2.5 Generation (2.5G)

The widely used 2G systems, namely, IS–95, GSM & IS–136, were primarily designed for digital voice communication. They were unable to provide satisfactory data communication services and hence Internet services. On the other hand, the proposed 3G standard (this would be discussed shortly) would take a long time to be fully developed and deployable. In this situation, many companies designed interim protocols and standards to provide data communication services over the existing 2G infrastructure. Such systems are collectively known as the 2.5G cellular system and some of them are briefly overviewed below.

(i) *General Packet Radio Service (GPRS) [4]:* GPRS evolved from GSM and provided its services over the GSM services. However, while GSM supports a date rate of only 9.6 Kbps, GPRS provides packet based data services at 40-60 Kbps range. Additionally, GPRS sets aside a number of slots only for data communication and allocates them dynamically on instantaneous demands.

(ii) *Enhanced Data Rate for Global Evolution (EDGE) [4]:* EDGE basically improves the GSM's modulation scheme significantly to provide data communication at a rate of nearly 384 Kbps.

(iii) *CDMA 2000, Phase 1 [8]:* This system evolved from the IS–95 CDMA system. It can provide packet data services up to 144.4 Kbps.

1.5.4 Third generation (3G)

Goal of 3G cellular system is to provide both telephone and data services at significantly higher speeds than their 2G counterparts. The target data speeds are: 144 Kbps at driving speeds, 384 Kbps at walking speeds and 2 Mbps for indoors. Following are the three major standards in 3G:

(i) *Universal Mobile Telecommunication Services (UMTS) [12]:* In terms of network architecture, UMTS is an evolution of GSM. But so far as the radio access interface is concerned, UMTS uses a CDMA technique called Direct Sequence Wideband CDMA (DS-WCDMA), instead of using the FDMA/TDMA scheme of GSM. UMTS is being broadly deployed in the Europe where GSM was rooted.

(ii) *CDMA 2000 [13]:* It is an evolution of and backward compatible with the IS–95 CDMA 2G system. CDMA 2000 is being deployed in North America and several Asian countries.

1.5.5 Fourth Generation (4G) [14]

Even though 3G networks are yet to be fully deployed, work on the design of 4G wireless networks has been going on for several years. Some of the proposed features of 4G systems include mobile Internet with rich multimedia content, anytime anywhere Internet connectivity, highest possible data rate, seamless integration with wired IP networks, automatic and transparent switching from one access technology to another, support of real time voice and video over IP, automatic discovery of user location by the network, etc. It seems to be wish list, although research is progressing. The technologies on which the attention of researchers are particularly being focussed on achieving the goals set forward in 4G are the WiMAX [10] and the Long Term Evolution (LTE) [13].

1.6 4G, WiMAX and LTE

1.6.1 4G Background and Realization

The growing demand for Mobile Internet and wireless multimedia applications has motivated the development of broadband wireless-access technologies. 4G mobile communication systems are required to support advanced services over a wide-variety of operating environments. A much higher peak transmission rate and spectral efficiency than legacy 3G systems are required in 4G systems. Toward implementing the proposed 4G wireless systems at an early date, two of the existing technologies, namely, WiMAX, a standard of the IEEE, and the LTE, a standard of the Third Generation Partnership Project (3GPP) were identified for necessary upgradation [15]. With the objective to satisfy all the International Mobile Telecommunications-Advanced (IMT-Advanced) requirements of the International Telecommunication Union's (ITU) recommendation (ITU-R), both WiMAX and LTE have performed necessary upgradations in their standards to become well-recognized 4G systems [16]. WiMAX (IEEE 802.16), the IEEE standard for Wireless Metropolitan Area Networking (WMAN) was amended to become 802.16m, which is also known as WiMAX 2.0 [16]. Similarly, the 3GPP LTE was augmented to LTE-Advanced (LTE-

A) to become 4G-compliant [16]. Both WiMAX 2.0 and LTE-A has been designed with different QoS parameters and means to enable delivery of the evolving Internet applications.

1.6.2 WiMAX: A Brief Overview

WiMAX is the broadband network technology for WMAN. The WiMAX family of standards were developed by the IEEE 802.16 Working Group [17] and adopted by both the IEEE and the European Telecommunication Standards Institute's (ETSI) High Performance Radio Metropolitan Area Network (HiperMAN) group. The salient features of the technology include a carrier frequency less than 11 GHz (currently it's the 2.5 GHz, 3.5 GHz and the 5.7 GHz), Orthogonal Frequency Division Multiplexing (OFDM) [18], Orthogonal Frequency Division Multiple Access (OFDMA) and Scalable OFDMA-based transmission techniques [18], very high data rates of about 75 Mbps or even more and an outdoor coverage range (distance) up to 20 kms. Since the inception of IEEE 802.16-2001 in 2001 till the recent Mobile WiMAX versions of IEEE 802.16e and 802.16m, the WiMAX family of standards have traversed through different stages. Table 1.1 provides a comparison of the different IEEE 802.16 versions [10], [19]. Mobile WiMAX supports three different types of handover techniques, out of which Hard Handover (HHO) is the default one and Fast Base Station Switching (FBSS) and Macro-Diversity Handover (MDHO) are the optional techniques [10].

1.6.3 LTE: A Brief Overview

The main drivers of the 3GPP LTE technology are better coverage, higher throughput, increased capacity, increased spectral efficiency, lower cost and weaker latency requirements. LTE is an improvement of the UMTS and has an all-IP-flat architecture. LTE aims to achieve a peak downlink data rate of 100 Mbps and an uplink data rate of 50 Mbps as well as round-trip times of the Radio Access Network (RAN) less than 10 ms [20]. Techniques like OFDM and SC-FDMA (Single Carrier-Frequency Division Multiple Access) are, respectively, selected for downlink and uplink scenarios. Also, the use of Multiple Input / Multiple Output (MIMO) antenna technology led to the increase in the overall spectral efficiency of LTE systems. LTE supports hard handover and aims to provide full mobility of an user equipment in the range of 300 Km/hr-500 Km/hr along with seamless global roaming. Apart from providing very high-speed mobile wireless broadband connectivity, the different applications of LTE range from fixed to mobile migration of various Internet applications like VoIP, video TV, video streaming, etc [21].

Table 1.1 Salient Features of Different IEEE 802.16 Versions

Standards	**802.16-2001**	**802.16a**	**802.16-2004, 16d**	**802.16e**	**802.16m**
Frequency Band	10 ~ 66 GHz, LOS	2 ~ 11 GHZ, NLOS and 10 ~ 66 GHz, LOS	2 ~ 11 GHZ, NLOS (mainly in 3.5 and 5.8 GHz) and 10 ~ 66 GHz, LOS	2 ~ 11 GHz (mainly in 2.3 and 2.5 GHz), NLOS	2 ~ 11 GHz, NLOS
PHY Layer	SC	SCa, OFDM, OFDMA	SC, SCa, OFDM, OFDMA	SCa, OFDM, OFDMA	SCa, OFDM, OFDMA
Duplex	TDD, FDD	TDD, FDD	TDD, FDD	TDD, FDD	TDD, FDD
Mobility	Fixed	Fixed	Fixed	Mobile (Vehicular – 120 Km/hr)	Mobile (Indoor – 10 Km/hr; Urban – 120 Km/hr; High Speed – 350 Km/hr)
Standardi-zation Date	Apr. 2002	Apr. 2003	Oct. 2004	Feb. 2006	In near future
Peak Data Rate	-	-	Up to 75 Mb/s	63 Mb/s	100 Mb/s for mobile stations and 1 GB/s for fixed stations
Coverage	-	-	~ 30 miles / 50 Km	Up to 10 Km (optimal: 2 to 4 Km)	1-30 Km (optimal: 5 Km)
Handover Latency	NA	NA	NA	~ 50 ms	< 30 ms

1.7 Wireless LAN: WiFi (IEEE 802.11)

Wireless LAN or WLAN systems are based on IEEE 802.11 family of standards [7]. Wi-Fi is a trademark owned by a trade group called Wi-Fi alliance, that certifies product compliance with 802.11. It is a Local Area Network (LAN) technology providing broadband wireless access over limited area of at the most 1000 feet. WLANs are one of the first hugely deployed and commercialized broadband technologies and as a result they now have a sprawling customer base all over the world. Wi-Fi has truly become the ‘last feet’ wireless broadband access technology in different indoor and outdoor locations like homes, offices, campuses, city centres, metro zones and public hotspot locations [10]. Some of the important WLAN standards are IEEE 802.11 a, b, g and n [18]. Below we briefly discuss the WLAN architecture.

The fundamental building block of the 802.11 architecture is the Basis Service Set (BSS), which contains at least one wireless station or node (e.g. a laptop, notebook etc.) and an access point (AP), which is like a central Base Station (BS). While all wireless stations are allowed to roam, the APs are fixed. They are connected to one another by a distribution system and via this distribution system to the global Internet. The distribution system may be any fixed network like the ethernet LAN, token ring LAN etc. Each AP services the wireless nodes in its own zone, i.e. its SBS. Each node associates with the AP in its current SBS. When any source node sends a WLAN frame to any destination node in any SBS, the AP in the source node’s SBS first receives the frame and delivers it to the AP in the destination node’s SBS via the distribution system. Finally, the AP in the destination node’s SBS delivers the frame to the destination node. It should be noted that the IEEE 802.11 WLAN is considered an Infrastructure WLAN because (i) the AP in each SBS is a fixed infrastructure and (ii) the distribution system is another infrastructure shared by all APs.

1.8 Motivation for the Thesis

Spectacular growth in wireless mobile communication and networking was visible all around us during the first decade of this millennium. This had increased, fascinated and motivated me to choose wireless mobile networking as the broad area of my doctoral research. To me it appears that, in the area of wireless mobile networking, the concept of cellular networking had made the most profound impact on the magnificent growth of wireless mobile networks. In accordance with cellular networking concept, use of a large number of small cells instead of a small number of large cells (cells are assumed to be broadly circular) yields the important benefit of greatly reduced power, and hence physical size, of both the transmitter (BS) and the receiver (MS). Unfortunately, this important benefit comes only at the cost of successful design of two kinds of challenging algorithms. The first kind of algorithm is for arranging frequency reuse among the large number of non-neighbouring cells and the second kind of algorithms is for efficiently handing off (handing over) each MS from its Serving BS (SBS) in the present cell to the Target BS (BS) in the next cell, i.e. in the selected adjacent cell, all along the entire cell-to-cell path of the MS's journey. Between the two problems, the handover problem created greater interest in me because of the multifarious challenges it poses, as will be explained soon. Regarding the handover problem, it was also observed that, in future, the problem of handover may become even more difficult to solve because of factors like increasing user (MS) population, increasing number of different kinds of mobile services requiring increasing QoS (e.g. various streaming multimedia services like video conference and video-on-demand), increasing mobility of the users etc.

The various desirable performance criteria of a handover algorithm may be listed as follows:

1. The primary requirement to be met for a desirable handover is that, out of the multiple Neighbouring BSs (NBS) available, the best possible NBS must be chosen for the MS to be handed over. The "best possible NBS" is the NBS, which if selected as the target BS (TBS) would meet all the required and desired criteria like those described below in the best possible manner.
2. The handover must be very fast because of the combined effects of small radius of each cell, high mobility of the MSs and the requirement of uninterrupted connectivity needed for high speed services like streaming multimedia services.
3. The handover must be highly reliable so that (i) it does not cause a call drop in the ongoing connection, (ii) no second handover is needed quickly after the (first) handover and (iii) the MS does not receive a poor quality of service after it is handed over to the TBS. Additionally, it should be noted that an unreliable handover may cause further unnecessary handovers that may hamper the performance of the network.

4. A handover should be performed only when it is necessary. Avoiding unnecessary handovers can save a lot of network resources to ultimately benefit all MSs.
5. In a hard handover (we investigate only hard handover in this Thesis though we briefly discussed soft handovers and compare their respective advantages and disadvantages with respect to hard handover), a critical part of the total handover delay is the "connection disruption gap" during which an ongoing connection remains broken. This gap must be small so that the hard handover can appear to be nearly seamless even for a streaming video service.
6. An ongoing connection is expected to continue enjoying the same degree of QoS from the TBS after the handover. So, minimization of packet losses during the connection disruption gap in the handover delay is important.

All the above requirements undoubtedly indicate that the concept of handover is not only complex but fulfilling the requirements for a satisfactory handover also involves a proper coordination of the different algorithms and protocols occurring at the multiple layers (particularly MAC and Network) of the Open Systems Interconnection (OSI) model [7]. Thus, providing fast and reliable handovers in different wireless and cellular networks like Wi-Fi, WiMAX, UMTS and LTE networks has become a challenge. Individually, these technologies have different kinds of personalised requirements for the handover activities to take place successfully. Out of all these networks, the focus of this Thesis is on devising new improved handover techniques for WiMAX networks.

As will be discussed in Chapter 3, the existing WiMAX handover mechanism, suggested in the WiMAX standard and used widely, suffers from multiple shortcomings when it comes to providing fast and reliable handovers [22]. Some of these shortcomings are lengthy handover decision process, lengthy and unreliable TBS selection procedure, frequent and unwanted handovers, lengthy connection disruption time (CDT), wastage of channel resources etc. Out of these, the work done in this Thesis focuses on improving the handover latency and improving the handover reliability. Latency is a significant issue when selecting the TBS for the next handover activity and adds up to the overall handover latency or delay in WiMAX. Improvement in the handover reliability reduces the instances of unstable or frequent handovers which otherwise waste the resources of the network. Apart from the above two improvements, our work has made an important contribution on another issue. Standardized WiMAX hard handover technique is largely an SBS-controlled one, although SBSs are always heavily loaded [22]. With the SBS controlling, besides all other activities of all MSs, even the handover activities of all MSs under it, it obviously creates the important problem of scalability of the WiMAX network owing to excessive load on the SBSs. Work done in this Thesis proposes solution for this important problem of scalability of the WiMAX network by having investigated two MS-controlled handover techniques where the role of the SBS is just minimal. Thus, overall, our work in this Thesis aims to not only achieve fast and reliable handover but also to improve the scalability of the WiMAX network.

1.9 Organization of the Thesis

The material presented in this Thesis has been organized into seven different chapters beginning with the current chapter, i.e. Introduction and ending with a chapter on Conclusion. A brief summary of the contents of the remaining six chapters is as follows:

- ***Chapter 2:*** This chapter provides a generic discussion about the WiMAX technology. It includes a discussion of its physical and MAC layers, some important features and its network architecture. A discussion is provided on the different types of handover techniques supported by it and an overview of the comparative advantages of these different handover techniques.

- ***Chapter 3:*** This chapter identifies and provides a detailed study of some of the different shortcomings for the MAC-layer handover scenarios in the hard handover technique in Mobile WiMAX. A brief discussion on some of the soft handover issues is also provided. For each of the hard handover shortcomings discussed, the chapter also discusses some of the different handover schemes researched and proposed by the WiMAX handover research community over the last few years towards the removal or mitigation of these shortcomings. Moreover, a brief survey of some of the different network layer and cross-layer (MAC and network) handover issues in WiMAX is provided in this chapter.

- ***Chapter 4:*** This chapter discusses two novel fast and intelligent hard handover schemes in Mobile WiMAX networks based on "RSS-based distance estimation and lookahead" concepts. The proposed schemes are fully MS-controlled MAC-layer handover schemes providing solution for the base station scalability problem as well. In the first scheme, the MS estimates its current distance and velocity, relative to its NBSs, by periodically monitoring the strength of the signals received from the NBSs through scanning. This enables the MS to perform a lookahead in order to estimate, in advance, which NBS would come nearest to it and hence should be chosen as its next TBS. In the next scheme too, the MS uses the RSS-based distance estimation but employs a different method for performing the lookahead. Here the lookahead is based on the estimation of the angle of divergence (AOD) of the NBSs from the MS to identify the NBS showing the least AOD and then select it as the TBS. Both the schemes greatly reduce the scanning and ranging activities and thus the overall handover delay. The schemes are properly validated through detailed simulation studies discussed in Chapter 6. Improving the scalability of the WiMAX network is probably the major contribution of these twin novel techniques.

- ***Chapter 5:*** The fast and reliable handover technique described in this chapter is predominantly controlled by the SBS, although the MS also plays an important role in the handover process. In order to select the TBS, the SBS employs three different criteria or parameters. These are: (i) Orientation matching between the geographical position (geolocation) of each NBS and the MS's broad direction of motion, both with respect to the SBS, (ii) the current load of each NBS and (iii) the RSS received by the MS from each NBS. The BS assigns score to each NBS against each of the three parameters and selects the TBS based on the highest and (appropriately) weighted average of the three scores. A new idea for load estimation of a BS is also proposed.

- ***Chapter 6:*** This chapter provides an in-depth discussion of the simulation scenarios performed to validate the proposed handover schemes. Discussions are provided about how the simulations are done and how the results are obtained. The different results, clearly showing the benefit of using our proposed schemes in terms of providing fast and reliable handover in WiMAX networks, are properly justified citing reasons.

- ***Chapter 7:*** Finally, this Conclusion chapter summarises the work done in the entire Thesis, makes some relevant and important comments and suggests some future research that may be performed based on these.

Besides the above seven chapters, the Thesis contains a list of references, a list of diagrams, a list of Tables and a list of abbreviations and acronyms. The last-named list, a glossary, is provided in Appendix 1.

Chapter 2

WiMAX Technology: A Working Overview

2.1 Introduction

This chapter provides a working overview of Mobile WiMAX technology including some of its important physical and MAC-layer features, network architecture and the different types of handover techniques supported by it. Mobile WiMAX technology was designed to accommodate both fixed and mobile broadband applications. The original 802.16 standard for WiMAX [23] was based on single-carrier physical layer having a burst time division multiplexed (TDM) media access control (MAC) layer. Many of the MAC-layer related features in WiMAX were adopted from the old DOCSIS or the data over cable service interface specification standard [24]. Broadly speaking, currently, WiMAX operates in three different versions: fixed WiMAX [23], Mobile WiMAX [22], [25] and the multi hop or mesh version [26]. However, in this Thesis, we limit our discussions to the first two versions and because the emphasis in this Thesis is on Mobile WiMAX, henceforth, use of 'WiMAX' will imply Mobile WiMAX, unless otherwise evident from the context. While fixed WiMAX operates in a 2 GHz – 11 GHz frequency band, the mobile version operates within a 2 GHz – 6 GHz band. Both the versions support a gross data rate of 1 Mbps – 75 Mbps and modulation schemes of QPSK, 16 QAM and 64 QAM. Multiplexing and duplexing scheme in both the versions are burst TDM/TDMA/OFDMA and TDD-FDD, respectively. Although, in terms of air-interface designation, both of these are OFDM and OFDMA-based, in terms of implementation, fixed WiMAX uses OFDM in its physical layer and the mobile version is based on the scalable OFDMA (SC-OFDMA) [10]. More discussion of the PHY layer is provided in Section 2.2. The MAC layer of Mobile WiMAX provides an interface between the PHY layer and the higher layers and channelizes data between the upper and lower layers during uplink and downlink communications. The design of the MAC layer in both fixed and mobile versions of

WiMAX, includes a convergence sub-layer that interfaces with different higher layer protocols like IP and Ethernet. Providing support for QoS and security are also important features of the Mobile WiMAX MAC layer. Apart from these, the MAC layer in Mobile WiMAX also provides mobility support for WiMAX mobile stations. More discussion of the MAC-layer is provided in Section 2.3.

Mobile WiMAX has an interoperable network architecture for efficiently handling different end-to-end services for users like provision of IP connectivity, QoS, seamless mobility and handover management, session management and security. These end-to-end networking aspects were developed and standardized by the Network Working Group (NWG) of the WiMAX Forum [27]. Section 2.4 provides an overview of the WiMAX system architecture, discussing the MAC-layer mobility management and network-layer mobility management frameworks. This is followed by Section 2.5 that discusses the different types of handover techniques supported by WiMAX. Section 2.6 provides a discussion on the relative advantages and disadvantage of the different handover techniques supported by WiMAX before the chapter concludes in Section 2.7.

2.2 WiMAX Physical Layer

IEEE 802.16 supports variety of physical layers each having its own characteristics and features. These are the WirelessMAN-SC (Single-Carrier) PHY, the OFDM PHY, the OFDMA PHY and the Scalable OFDMA (SOFDMA). The SC PHY layer was designed for 10-60 GHz spectrum but is not used in WiMAX products mainly because of its LOS requirements. Also rain attenuation and multipath effects are more prominent in the frequency spectrum it was operating [28]. The OFDM, OFDMA PHY and SOFDMA offer efficient schemes for high data rate transmission in multipath radio or NLOS environment. Another distinctive feature of WiMAX technology, to mention here, is its adaptation of the multiple antenna technology. This section provides very brief discussions on each of these features. For detailed discussion on the characteristics of WiMAX physical layer refer to [10], [29].

2.2.1 OFDM

OFDM belongs to a family of transmission schemes called multicarrier modulation [10]. In OFDM, a signal consists of number of closely spaced modulated carriers i.e.

they are all orthogonal to one another over the symbol duration. In an OFDM design, the size of the FFT (Fast Fourier Transform) should be carefully chosen as a balance between protection against multipath, Doppler shift and design cost and complexity [10], [29]. Fixed WiMAX uses a 256 FFT-based OFDM physical layer, out of which 192 subcarriers are used for carrying data, 8 are used for channel estimation and synchronization, while the remaining are used as guard band subcarriers [10].

2.2.2 OFDMA

The OFDMA multiple access was generated by associating OFDM, which was originally designed for single user transmission, with multiple access schemes like TDMA or FDMA in order to facilitate multiple user transmission. In OFDMA, the different available subcarriers are divided into several groups of subcarriers called sub-channels, which form the minimum frequency resource-unit allocated by the BS. Different sub-channels may be allocated to different users as a multiple-access mechanism. Unlike in fixed WiMAX, which does not allow any sub-channelization in the downlink, OFDMA PHY-based Mobile WiMAX allows sub-channelization both in uplink and downlink i.e. a downlink or an uplink user will have a time slot and a sub-channel for each of its communication [29]. The sub-channels can be allocated to different mobile stations depending on their channel conditions and data requirements. Thus, in the downlink, a sub-channel may be intended for different receivers or groups of receivers and in the uplink, a transmitter may be assigned one or more sub-channels. The sub-carriers forming one sub-channel may or may not be adjacent to each other. Using sub-channelization, within the same time slot, a WiMAX base station can allocate more transmit power to mobile stations with lower SNR (Signal-to-Noise Ratio), and less power to mobile stations with higher SNR. Figure 2.1 shows an OFDMA symbol structure in WiMAX.

2.2.3 SOFDMA

Scalable OFDMA (SOFDMA) adds scalability to OFDMA physical layer in Mobile WiMAX. The scalability is the change of the FFT size and then the number of subcarriers. Smaller FFT size is given to lower bandwidth channels, while larger FFT size to wider channels. Although the number of sub-carriers scales with bandwidth, the sub-carrier spacing is independent of bandwidth. Thus, by making the sub-carrier

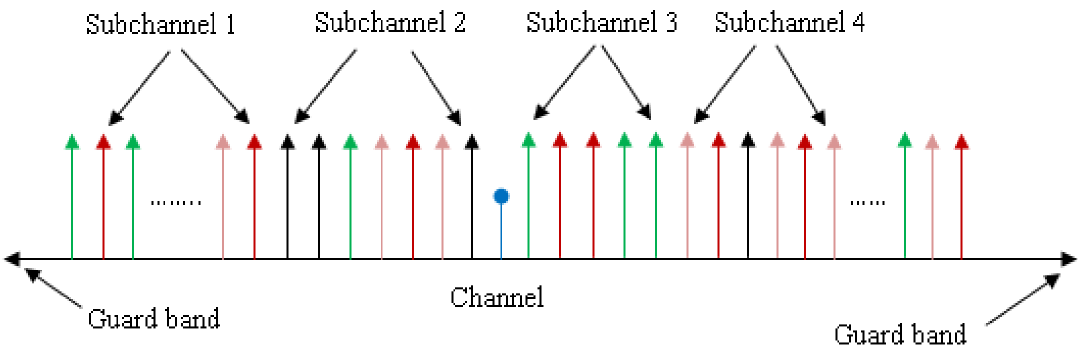


Fig. 2.1 OFDMA symbol structure in WiMAX (Sub-Carriers of the same colour represent a sub-channel)

frequency spacing constant, SOFDMA reduces system complexity of smaller channels and improves performance of wider channels. In order to keep optimal sub-carrier spacing, in SOFDMA, FFT size scales with bandwidth. FFT sizes of 1024 and 512 are mandatory for Mobile WiMAX profiles. With bandwidth scalability, Mobile WiMAX technology can comply with various frequency regulations worldwide.

2.2.4 Multiple Antenna Technology

Adapting multiple antenna technology is one of the most distinctive features of Mobile WiMAX. A Mobile WiMAX system adopts multi-input multi-output (MIMO) technology, having 2 x 2 transmit-receive antennas, to (i) increase the base station coverage area, (ii) decrease the required transmit power, (iii) increase the achievable data rate and system capacity and (iv) decrease the bit error rate and increase the system reliability improve system throughput and spectral efficiency [18], [10].

2.3 WiMAX MAC Layer

MAC layer in WiMAX has been designed and optimised to enable point to multi-point wireless applications. It provides an interface between the higher transport layers and the physical layer. In the downlink, MAC layer accepts MAC service data units (MSDUs), which are packets from higher layers, and organizes them into MAC protocol data units (MPDUs) for transmission over the air. It is the reverse in case of uplink transmission. WiMAX MAC uses a variable-length MPDU and can efficiently aggregate multiple same or different length MPDUs in to a single burst to save physical layer overhead. In the same way, multiple MSDUs from the same higher-layer service may be concatenated in to a single MPDU to save MAC header overload [10]. The MAC layer design in WiMAX includes a convergence sublayer that can interface with a variety of higher-layer protocols, such as ATM TDM Voice, Ethernet, IP, and any unknown future protocol. Besides providing a mapping to and from the higher layers, the convergence sublayer supports MSDU header suppression to reduce the higher layer overheads on each packet.

The WiMAX MAC is designed for point-to-multipoint (PMP) applications and is based on collision sense multiple access with collision avoidance (CSMA/CA). The MAC incorporates several features suitable for a broad range of applications. These are the following:

- Multicast and broadcast services
- Five quality of service classes: unsolicited grant service (UGS), real-time polling service (rtPS), non-real-time polling service (nrtPS), best effort (BE) and extended real-time variable rate (ERT-VR) service
- Power saving features, sleep and idle modes
- Mobility and handover management
- Different channel-access mechanisms
- Security features

Here we provide brief discussions on each of these features.

2.3.1 Broadcast and Multicast Services (MBS)

Some of the MBS related functions and features in WiMAX are:

- MS signaling mechanism to request and establish MBS
- MBS associated QoS and encryption using a globally defined traffic encryption key
- Subscriber station access to MBS over a single or multiple BS, depending on its capability and desire
- Methods for delivering MBS traffic to idle-mode subscriber stations
- Support for macro diversity to enhance the delivery performance of MBS traffic

2.3.2 Quality of Service

An important and fundamental part of the connection-oriented WiMAX MAC-layer design is the support for QoS. In WiMAX all downlink and uplink connections are controlled by the serving BS. WiMAX defines five types of scheduling services [27].

- *Unsolicited Grant Services (UGS):* This is used to support fixed-size data packets at a constant bit rate for real-time services such as Voice over IP (VoIP) in WiMAX. Some of the mandatory service flow parameters defining this service are maximum sustained traffic rate, maximum latency, tolerated jitter and transmission policy.
- *Real-time Polling Services (rtPS):* This service is used to support real-time service flows, such as streaming audio or video. Some of the mandatory service flow parameters defining this service are minimum reserved rate, maximum sustained rate, maximum latency tolerance and traffic priority.
- *Non-real-time Polling Service (nrtPS):* This service is designed to support delay-tolerant data streams, such as File Transfer Protocol (FTP), that require variable-size data grants at a minimum guaranteed rate. Some of the mandatory service flow parameters defining this service are minimum reserved rate, maximum sustained rate and traffic priority.
- *Best Effort Service (BES):* This service is designed to support data streams, such as web browsing, that do not require a minimum service-level guarantee. Some of the mandatory service flow parameters defining this service are maximum sustained rate and traffic priority.
- *Extended Real-time Variable Rate (ERT-VR) Service:* This service is designed to support real-time applications, such as VoIP with silence suppression, that have variable data rates but require guaranteed data rate and delay. Some of the mandatory service flow parameters defining this service are minimum reserved rate, maximum sustained rate, maximum latency tolerance, jitter tolerance and traffic priority.

2.3.3 Power-Saving Features

To support battery-operated portable devices, WiMAX or rather Mobile WiMAX has power saving features allowing portable user devices to operate for longer durations without having to recharge. Sleep Mode and Idle Mode are the two modes for power efficient operation supported by Mobile WiMAX. Sleep Mode is a state in which the MS effectively turns itself off and becomes unavailable for predetermined periods from serving BS's air interface. Sleep Mode is intended to minimize MS power usage and minimize the usage of the Serving Base Station air interface resources. On the other hand, during the idle mode, although the MS is completely switched off and do not get registered with any of the BSs but still it can receive downlink broadcast traffic. Compared to sleep mode, more power is saved with an MS operating in an idle mode as it does not even have to register or do handover activities.

2.3.4 Mobility and Handover Management

WiMAX supports four mobility-related usage scenarios. They are [10]:

- *Nomadic:* The user is allowed to take a fixed subscriber station and reconnect from a different point of attachment.
- *Portable:* Nomadic access is provided to a portable device with expectation of a best-effort handover.
- *Simple mobility:* Movement speed of up to 60 Kmph with brief interruptions of less than 1 sec during handoff is allowed for WiMAX subscribers.
- *Full mobility:* Movement speed of up to 120 Kmph and seamless handover and less than 1% packet loss is supported for WiMAX subscribers.

WiMAX supports three different types of MAC-layer handover activities, namely, hard handover (HHO), fast base station switching (FBSS) and macro diversity handover (MDHO). Of these, the HHO is the default handover mechanism and the two soft handover procedures, the FBSS and the MDHO are the optional types. Detailed discussion on these handover activities are provided in Section 2.5.

2.3.5 Channel-access Mechanisms

In WiMAX, downlink and uplink bandwidth allocation to all users is done by the MAC-layer at the BS. During downlink, BS allocates bandwidth to each of the MS based on the requirements of the incoming traffic. On the other hand, during uplink allocations are done based on requests from individual MSs. The only time an MS in WiMAX has some control over bandwidth allocation is when the MS has multiple sessions or connections with the BS. In that case, BS allocates bandwidth in aggregate to the MS and leaves it to the MS to apportion the allocated bandwidth among the multiple connections. For an MS to request and obtain uplink bandwidth in WiMAX, periodically, the BS allocates dedicated or shared resources to each MS under it. Each MS can use this allocated resource to request bandwidth. This is known as polling and depending on the bandwidth availability it can be done either individually or in groups.

2.3.6 Security Functions

WiMAX systems were designed with a robust security in mind. Support exists for mutual device/user authentication, flexible key management protocol, strong traffic encryption, control and management plane message protection and security protocol optimizations for fast handovers [27].

The usage aspects of the security features are:

- *Key management protocol:* Privacy and Key Management Protocol Version 2 (PKMv2) is the basis of WiMAX security. This protocol manages MAC security, traffic encryption control, handover key exchange, authentication and broadcast/multicast security messages.
- *Device/user authentication:* WiMAX supports device and user authentication using Internet Engineering Task Force's (IETF) Extensible Authentication Protocol (EAP). A variety of credentials, such as username/password, digital certificates and smart cards, are supported.
- *Traffic encryption:* Advanced Encryption Standard in Counter with Cipher Block Chaining (CBC)-MAC (AES-CCM) is the cipher used for protecting all the user data over the WiMAX MAC interface. The keys used for driving the cipher are generated from the EAP authentication.
- *Control message protection:* Control data is protected using AES based cipher-based message authentication code (CMAC), or message-digest 5 algorithm (MD5)-based hash-based message authentication code (HMAC) schemes [10].
- *Fast handover support:* To support fast handovers, WiMAX allows the MS to use pre-authentication with a particular target BS to facilitate accelerated reentry. A 3-way Handshake scheme is supported by WiMAX to optimize the re-authentication mechanisms for supporting fast handovers.

2.4 Network Architecture of WiMAX Systems

Mobility aspects in WiMAX are specified as an individual Mobility Agent (MA) layer, above the MAC-layer, with some network layer signalling to develop a complete solution [10]. This section provides a brief discussion on the system architecture of the mobile WiMAX network to give a clear idea about the link-layer (MAC-layer) mobility management and network-layer mobility management frameworks. In mobile WiMAX, mobility management schemes are jointly developed by the IEEE 802.16e and the WiMAX Forum's NWG. Mobile WiMAX aimed to support a variety of deployment models e.g. centralized, flat and hybrid [30] and usage scenarios e.g. nomadic, portable, low and high speed mobility. So, the objective of the architecture is to support unified range of functionalities for all these models and scenarios. The WiMAX Network Reference Model (NRM) is the common terminology used for the logical representation of the network architecture. The NRM explains the different protocols and functionalities for the different network entities in the architecture along with the different reference points between them [10], [31]. Specifically speaking, the NRM is developed and defined by the NWG based on the IEEE 802.16 specifications. Figure 2.2 shows such an NRM for the Mobile WiMAX network. While the different logical components (i.e. the network entities) in the NRM are conceptually interfaced with the help of multiple implicit reference points, the components itself are bundled together on a physical network node. The architecture consists of three major logical parts: Mobile Stations (MS) used by different subscribers/users to access the underlying network; Access Service Network (ASN) and the Connectivity Service Network (CSN). ASN-Gateways (ASN-GW) are important components of an ASN. Sub-section 2.4.1 provides a detailed description of ASNs and CSNs. So, for each functional entity, the aim of the NRM is to allow multiple different implementation options [27].

Apart from ASNs and CSNs, reference points also play important roles in the Mobile WiMAX network architecture as discussed before. So, before moving on to discussions about ASNs and CSNs, brief idea about the reference points is provided here. The different functional entities of the ASN, CSN and the MS are conceptually connected with the help of multiple different reference points [10], [31]. As shown in Figure 2.2, R1 – R8 are the reference points each playing a different role. While R1 and R2 conceptually interface the MS with ASNs and home CSN respectively, R3

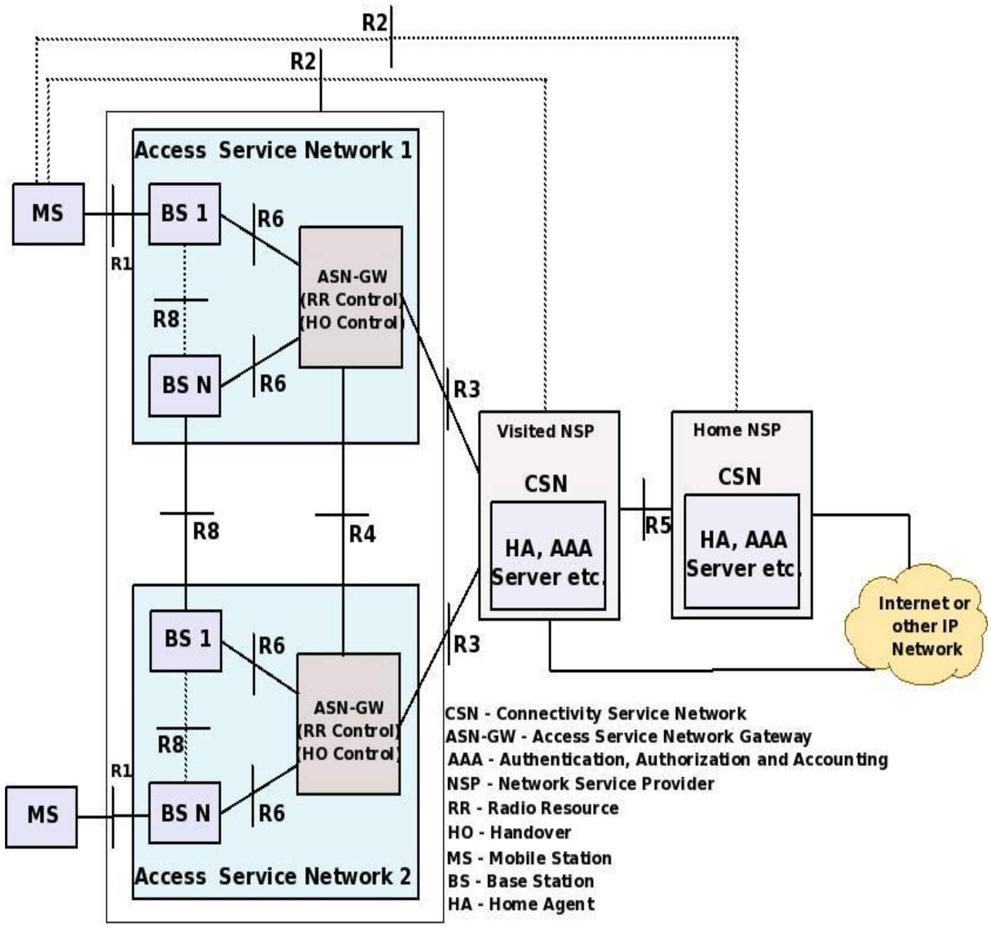


Fig. 2.2 WiMAX Network Reference Model

acting as an interface between the ASN and visited CSN helps in network-layer mobility management by tunnelling data packets and defining different control plane protocols like authentication, authorization, accounting (AAA) and policy enforcement. R4 acts as an interface between two ASN-GWs in an ASN and helps in mobility and handover management by transferring control plane messages and data packets between the ASN-GWs. R5 interfaces between visited and home CSNs of the corresponding NSPs and defines control and data plane protocols to interconnect them. R6 playing a role in both link and network-layer handover management interfaces between multiple BSs and the backbone ASN-GW by defining the different data and control plane protocols. R7 relates to an optional set of ASN-GW control plane protocols. Lastly, R8 acting as interface between the different BSs in an ASN facilitates fast and seamless link-layer and network-layer handovers by transforming mostly control plane packets and optionally data packets. A full list of reference points along with descriptions of their functionalities can be found in [10]. While almost all the reference points play important roles in an overall handover activity in the Mobile WiMAX networks, our focus will be specifically on those related to the link-layer handover mechanisms.

The next sub-sections discuss the functionalities of ASN and CSN along with handover classifications based on these two logical components.

2.4.1 ASN and CSN

Access Service Network and Connectivity Service Network are the two most important logical components in the NRM of a mobile WiMAX system.

A. ASN

Owned by network access providers (NAP), an ASN is an access network infrastructure consisting of multiple BSs controlled by one or more ASN-GWs [31]. The ASN-GWs are logical entities representing a combination of different control plane functions [18]. The foreign agent (FA) remains in the ASN-GW. NAPs basically own and operate multiple different geographically separated access networks. Moreover, how the different functions within an ASN and CSN need to be grouped and distributed into physical devices, depends on the individual owner NAP i.e. NAP decides upon the implementation choices. The basic functionalities of ASN include, providing MAC-layer connectivity with MSs, helping the subscribers to search for and select the preferred NSPs to connect with, acting as a AAA proxy, ASNs help the transfer of AAA messages to the home NSP, helping MSs to establish IP connectivity with CSNs and radio-resource management (RRM) based on QoS policy [10]. Apart from these, ASN also plays important roles in both ASN and CSN-anchored handover and mobility management techniques, paging and location management within the ASN and supporting the tunnelling of packets between ASN and CSN. In our work, we will focus on the MAC-layer handover-related management functionalities of ASNs.

B. CSN

CSN provide IP connectivity and handles the different IP core network functions in WiMAX systems. These are owned by network service providers (NSP). Service contracts of WiMAX subscribers are owned by NSPs. When a subscriber with an MS first signs up to a NSP (which functions as its home NSP), the CSN belonging to the home NSP serves the subscriber. In case of roaming, thereon the subscriber is served by individual CSN of the visited NSPs. For all MSs associated to a CSN, the ASN-GW transfers the different packets between an ASN and the CSN. Specifically speaking, the different CSN-related functions include, allocation of IP addresses for various user sessions, settlement and handling of subscriber billing, inter-ASN and inter-CSN tunnelling support during roaming, admission control etc. CSN contains user databases, AAA and other servers, routers/switches and gateways to handle these varieties of functions [18].

2.4.2 ASN- and CSN-Anchored Mobility

Two types of mobility schemes are supported by Mobile WiMAX networks: (i) ASN-anchored mobility or intra-ASN mobility or micro-mobility and (ii) CSN-anchored mobility or inter-ASN mobility or macro-mobility. Brief descriptions of these are provided here along with a pictorial representation in Figure 2.3.

A. ASN-Anchored Mobility

In this case, an MS moves from under the control of one BS to under the control of another BS without changing the anchor FA in the serving ASN i.e. without a need to update or change its care of address. Handovers resulting due to ASN-anchored mobility are also termed as ASN-anchored handover [31]. Considering the Figure 2.3 handovers across the R8 and/or R6 reference points are the ASN-anchored handovers. Similarly, in Figure 2.3, when an MS moves from under the control of BS1 to BS2 that indicates a ASN-anchored mobility. Generally, in such kind of handovers, Layer-3 remains unaffected.

B. CSN-Anchored Mobility

In case of CSN-anchored mobility, the traffic anchor point, in the ASN, is changed for an MS. So, the anchor FA is changed each time the MS performs a handover (known as CSN-anchored handover). The MS also needs to update its care of address for each handover. However, the CSN remains the same and in order to establish the data-forwarding path with each handover, the new FA and the CSN exchange signalling messages [10]. In Figure 2.3, whenever a terminal performs a CSN-anchored mobility

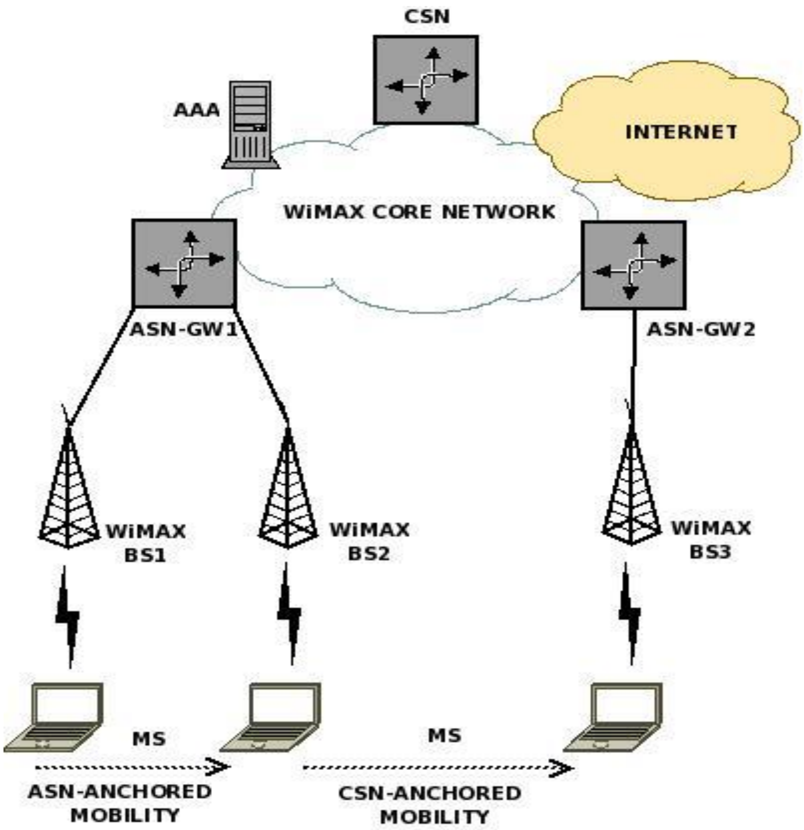


Fig. 2.3 ASN and CSN Anchored Mobility

i.e., an inter-subnet handover (e.g. from BS1/BS2 under ASN-GW1 to BS3 under ASN-GW2), it results to an IP-layer (L3) handover.

In the thesis we will focus on the ASN-anchored handover aspects of Mobile WiMAX networks as the schemes we proposed deal with the betterment of the Layer-2 handover features.

2.5 WiMAX Handover Techniques

The IEEE 802.16 standardization group has defined three types of link-layer approaches towards handover for the Mobile WiMAX technology in a homogeneous environment [10]. Of these, the HHO is the default handover mechanism and the two soft handover procedures, FBSS and MDHO are the optional types. As discussed previously, the IEEE 802.16e standardization group has specified a highly flexible and scalable Layer-2 handover policy, allowing handovers to be initiated by the MS, the SBS or the backbone network.

In Mobile WiMAX, a handover initiation decision by a mobile station (MS) is dependent on the Received Signal Strengths (RSS) from the current serving BS (SBS) and the neighbouring BSs (NBS). The MS and the SBS jointly decide on when to initiate a handover activity. Whenever the RSS from the SBS drops below a certain threshold, which might hamper an ongoing communication session, the MS goes for a handover with one of the chosen NBSs, called the TBS. The HHO is a Break-Before-Make (BBM) procedure, in which the MS breaks its communication with the SBS before getting connected with the TBS. So, the MS experiences a small communication gap between its termination from the previously connected BS and the reconnection to the new targeted BS. On the other hand, both FBSS and MDHO are considered to be of the Make-Before-Break (MBB) type (soft handover), where the MS starts communicating with the new BS even before terminating its service with the previous BS. So, these latter two types of handover procedures do not experience any gaps in the ongoing communication and the MS remains connected to multiple BSs simultaneously. However, although theoretically attractive, design of soft handover techniques is extremely complex and costly. In all the different handover procedures various different MAC-management messages are used for serving different purposes. The next sub-sections briefly describe the three handover procedures, whereas the details can be found in [10].

2.5.1 Hard Handover Procedure

The entire process of HHO procedure in Mobile WiMAX is broadly divided into two phases, namely, Network Topology Acquisition Phase (NTAP) and the Actual Handover Phase (AHOP). Each phase is carried out in few steps as described below.

A. Network Topology Acquisition Phase

This is kind of a cell reselection stage [10], during which a suitable NBS is chosen for handover in the following way. The MS and the SBS, together with the help of the backhaul network, gather information about the underlying network topology before the actual handover decision is made. This is done to identify lists of potential NBSs available for the handover activity, out of which one particular NBS may be chosen as the Target BS (TBS). Figure 2.4 shows the message sequence chart for this procedure.

The major tasks involved in this phase are briefly discussed stepwise as follows. These steps are also shown in the figure.

Step 1: BS advertising the Network Topology: Using the MAC-management message, MOB_NBR-ADV (Mobile Neighbour Advertisement), the SBS periodically

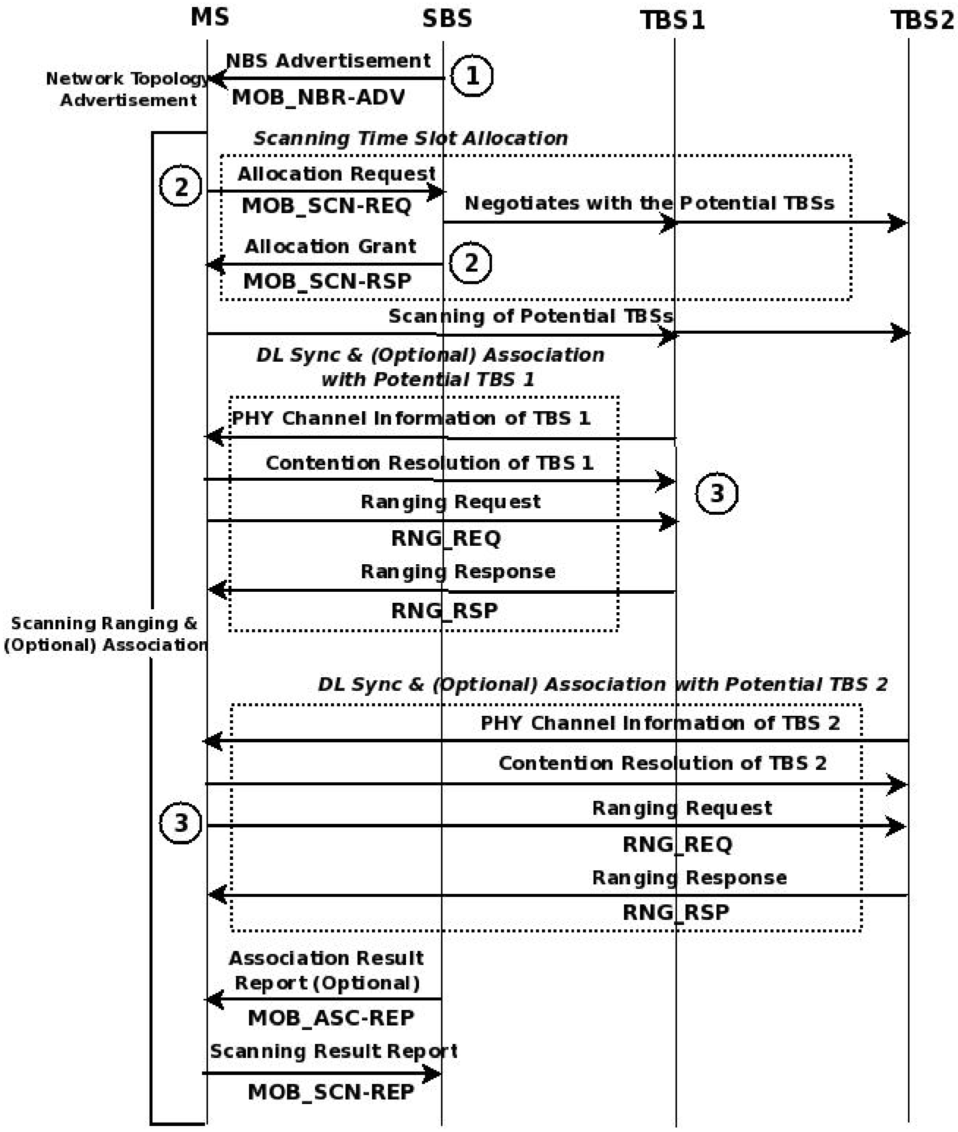


Fig. 2.4 Network Topology Acquisition Phase Message Sequence Chart

broadcasts information about different NBSs for handovers, e.g. the state of the NBSs, description of the uplink channel descriptors (UCD) and downlink channel descriptors (DCD), their respective IDs etc., thus preparing for a potential handover activity. The SBS keeps on gathering these channel information about the NBSs with the help of the backbone network.

Step 2: Scanning and synchronization of advertised neighbouring BSs by MS: Scan procedures of the advertised NBSs by an MS can be activated either by the MS or the SBS in order to measure the signal qualities e.g. carrier-to-interference plus noise ratio (CINR), received signal strength indicator (RSSI), round-trip delay (RTD), of the different advertised NBSs and using the results to select one particular NBS from them as the TBS. In addition to these, MS also performs ranging activity with the different NBSs during the scanning interval. Details of ranging are discussed in the next step.

To start the scanning procedure, the MS sends a scanning interval allocation request (MOB_SCN-REQ) to the SBS containing a list of potential NBSs, selected from the MOB_NBR-ADV broadcasts. In response, the SBS sends back a scanning response (MOB_SCN-RSP) message to the MS allocating scanning intervals (in the form of frames) for the scanning procedure. The response message also contains information about the specified starting frame of the scan procedure, the length of interleaving intervals as well as the number of scan iterations. The MS thus scans the selected NBSs (MS first acquires synchronization with individual NBSs) within specific time frames (as allotted by the SBS), to select suitable candidate BSs for the handover. During scanning, all communication between the MS and the SBS is temporarily stalled and the incoming packets are thus buffered accordingly. Hence, to result in unaffected communication as much as possible between the MS and the SBS, a scanning interval is followed by an interleaving interval (as allocated by the SBS) in which the MS-SBS communication resumes. So, depending on the requirements of scanning, there can be multiple such scanning and interleaving intervals, which are scheduled in a round-robin basis, in the whole scanning process [31]. Scanning results in selection of a list of potential candidate BSs for handover. Results of scanning activity are reported to the SBS by the MS either periodically or at the end of the scanning process with the help of a scanning result report (MOB_SCN-REP) message.

Step 3: Ranging and Optional Association Activities: As part of the cell reselection stage, within the scanning interval contention/non-contention ranging activities take place between the MS and the different NBSs, through which the MS gathers further information about PHY channel related with the selected TBSs. Through the ranging process, an MS can acquire the following different information with respect to the networks of the different NBSs: (i) correct timing offset (ii) power adjustments (iii) any change in burst profile. MAC management messages like Ranging Request (RNG-REQ) and Ranging Response (RNG-RSP) are exchanged, respectively, between MS → NBS and NBS → MS for this purpose. Until the fine tuning between the MS and the respective BSs are completed, repeated ranging request and response steps take place. Sometimes, collision occurs during ranging. This is particularly due to the fact that a BS, at any time, has to serve multiple different MSs, i.e. has to serve ranging requests from multiple different MSs. Such collisions hamper the overall ranging performance. Hence, in order to avoid this, contention resolution techniques have been proposed in Mobile WiMAX standard in which ranging occurs in slots. So, to summarise, ranging can be contention-based or non-contention-based. Detailed description of the different ranging-related parameters can be found in [22]. Ranging information are actually obtained through the association process and plays vital role to select an appropriate TBS for a potential and successful handover activity. According to Mobile WiMAX standard, MSs may get optionally associated to some or all of the NBSs in the list. Three different levels of association are mentioned for that. They are:

- *Association Level 0:* This is basically scan/association without coordination i.e. any kind of ranging performed by the MS is not network coordinated. So, a NBS does not have any knowledge of this and thus the MS performs contention-base ranging with the NBSs.
- *Association Level 1:* This is scan/association with coordination, i.e. in this case the SBS and respective NBSs coordinates among themselves regarding the probable ranging procedure and NBSs allocate dedicated ranging slots to the MS to perform ranging. Hence, collisions among various MSs for ranging slots are thus avoided.
- *Association Level 2:* This is network assisted association reporting. In the previous two cases, on performing successful ranging operation, each of the NBSs sends a RNG-RSP message to the MS indicating the success. However, in association level 2, instead of sending individual RNG-RSP messages containing ranging-success information, each NBS communicates that information to the SBS over the backbone network. Hence, the MS does not need to wait for getting the ranging-success information from each NBS

separately, but expects a Association Result Report (MOB_ASC-REP) from the SBS, which contains all ranging-related information.

A successful ranging-association activity marks the end of scanning interval and thus the end of cell reselection process for a handover activity. Through this, an MS chooses few candidate NBSs as potential candidates for a handover activity. However, association is purely optional and it may so happen that the MS does not perform any kind of association during scanning intervals but may do later. The next phase is the AHOP in which the MS breaks its existing connection with the SBS and reconnects to the TBS.

B. Actual Handover Phase (AHOP)

In this phase, once the handover decision has been taken and initiated, a particular TBS from the list of candidate NBSs (selected during the NTAP) is chosen for the handover activity by the SBS with the help of the MS or even the underlying network. Once the TBS is selected, MS performs network entry activities with it before resuming IP connectivity. The different sub-phases to the AHOP are described (in steps) below. Figure 2.5 portrays a message sequence chart of the process. The steps are marked along with the messages or message sequences.

Step 4: Selection of TBS: The final selection of the TBS can be done either by the SBS or jointly by the SBS and the MS. In case of an MS-initiated handover, the MS communicates a handover request (MOB_MSHO-REQ) message to the SBS indicating the identity of one or more of the candidate NBSs as the potential TBS along with a measurement report of these NBSs. On receiving the message, the SBS negotiates with the potential TBSs to find out whether they can provide the QoS and other important resources to support any kind of connection with the MS after the handover activity. Based on their replies, the SBS summarizes the results and communicates a new (short) list of recommended NBSs to the MS through the handover response (MOB_BSHO-RSP) message. Otherwise, if it’s a SBS or network -initiated handover, the SBS sends a MOB_BSHO-REQ message to the MS containing a set of selected NBSs. In both the cases, on receiving either the MOB_BSHO-RSP or the MOB_BSHO-REQ message, the MS quickly decides upon the particular TBS to perform handover with and sends a prompt handover indication (MOB_HO-IND) message to the SBS with the details of the finalized TBS. At this point the connection between the MS and the SBS is also discontinued and the SBS (or ASN-GW) starts buffering packets meant for the MS in order to avoid packet loss.

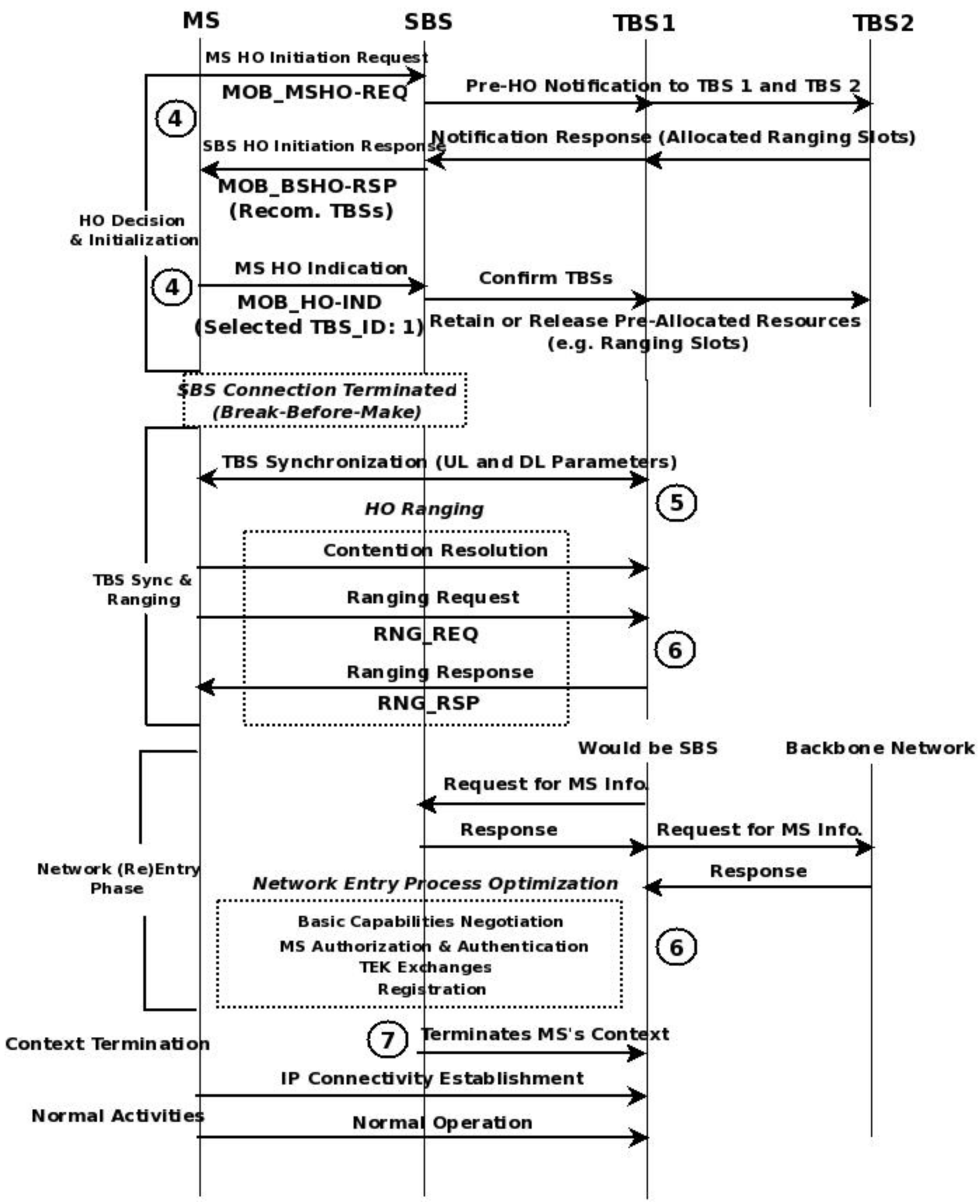


Fig. 2.5 Actual Handover Phase Message Sequence Chart

However, if needed, the SBS could also forward all kinds of MS-related resources to the TBS over the backbone network.

Step 5: MS Synchronization with the Selected TBS: On determining the TBS, the MS synchronizes with its downlink (DL) transmission (i.e. MS performs time and frequency synchronization with the TBS). The MS further decodes the UCD and DCD messages to get the ranging channel-related information of the TBS.

Step 6: Ranging and Network Re-Entry: Depending on whether or not the TBS is aware of the potential handover activity (it can come to know of it from the SBS over the backbone network during negotiation for handover), ranging can be dedicated or contention-oriented. If the TBS is aware of it, then it can arrange for pre-dedicated ranging slots for the MS. Using the ranging channel slots, the MS can synchronize its UL with the BS and thus get further information of the timing and power level. So, the whole process of ranging can be speeded up if it is dedicated ranging. With the UL synchronization process, the MS gets ready to enter the new network. The network re-entry steps include the following:

- *Basic Capabilities Negotiation:* Here after the ranging activity, the MS and the TBS exchange their supported parameters through the communication of SS basic capability request (SBC-REQ) and response (SBC-RSP) messages. The important parameters included in the capability request message by the MS are bandwidth allocation, maximum transmit power, current transmit power, MIMO parameters support, FFT size, focused contention support, security parameters support, power control and save parameters support, handover parameters support, etc.
- *MS Authorization:* Authorization and authentication follows next to get the MS authorized to the new network. Exchange of secure keys occurs in this phase. Privacy Key Management Request (PKM-REQ) and Response (PKM-RSP) messages are exchanged between the MS and the TBS.
- *Registration of the MS:* Through completion of the registration procedure, the MS is 'officially' allowed to enter the new network and becomes 'manageable' by the new SBS.
- *Establishing IP Connectivity:* Once registration is done, the MS tries to obtain an IP address from the Dynamic Host Configuration Protocol (DHCP) server by using the DHCP mechanisms.

Step 7: Termination of MS Contexts: With the completion of the network re-entry activities of the MS, the previous SBS terminates all kinds of MS-related connections and contexts associated with them, e.g. state machines, counters, timers, all kind of queued information, etc.

2.5.2 Macro Diversity Handover and Fast Base Station Switching Procedures

In case of the two optional soft handover approaches, MDHO and FBSS (refer to Figure 2.6), together often called Soft Handover, the MS simultaneously performs communication using the air interfaces of multiple BSs. That is, the MS is connected to multiple BSs at the same time, unlike the HHO procedure in which the MS remains connected to a single BS at any instant (except during the connection break gap time when the MS is not connected to any BS). Both the MDHO and the FBSS use the concepts of Diversity Set (DS) and Anchor BS (ABS). Each MS maintains a DS of its own. Details on both the MDHO and FBSS can be found in [22].

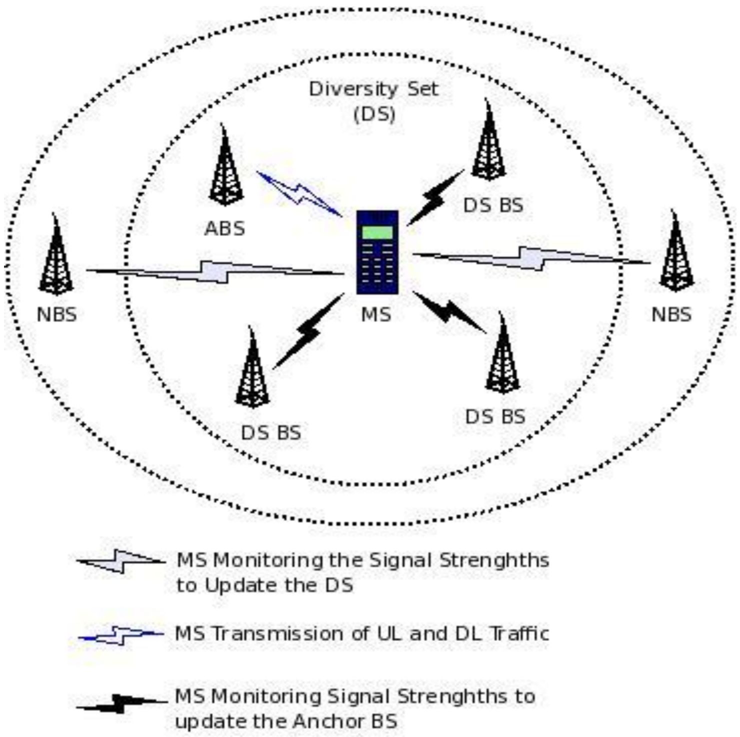


Fig. 2.6 Fast Base Station Switching Technique

At any time, depending on the signal strengths, the DS includes the most active NBSs that could be involved in a handover. In a DS, the ABS is chosen to be the BS with the most powerful signal strength (i.e. the most active BS). In case of FBSS, the MS communicates to, i.e. receives and transmits all packets over the air interface, during the downlink (DL) and uplink (UL) activities, from only the chosen ABS, which serves as the SBS. However, in case of MDHO, although an MS receives the same data packets from all the different NBSs in the DS, yet it only monitors the control information it receives from the ABS (the ABS is also a part of the DS). Regularly updating the DS and thus the ABS is a primary factor in both these soft handover techniques and hence signal strengths of NBSs are continuously monitored by each MS for efficient updating of its DS and ABS. In both the MDHO and FBSS mechanisms, each NBS, in the DS for each MS, always remain ready to become the ABS for the MS because the backbone ASN-GW always multicasts all incoming packets for the MS to all the different NBSs in the DS so that they remain always updated. As mentioned before, updating the entries in the DS and in the ABS regularly is important for an MS. The following sub-sections explain these important concepts in MDHO and FBSS:

- **Diversity Set Updating**

When an MS feels the requirement of updating its DS owing to channel signal variations, it sends a handover request (MOB_MSHO-REQ) message to the ABS of the DS. Update of the DS at any time depends on two different thresholds, the H_Add threshold and the H_Delete threshold, contained in the DCDs that are broadcasted by the BSs. Based on a given MS's scanning of the BSs, those active BSs in its current DS with long-term CINR lower than the H_Delete Threshold value are deleted from the current DS, and new active BSs with long-term CINR larger than the H_Add Threshold value are inserted in the current DS. Once the update is done, the ABS responds with a handover response (MOB_BSHO-RSP) message to let the MS know that the DS has been updated [31].

- **Updating and Selecting the new ABS**

Updating and selection of the new ABS for the modified DS is done by its MS and the BSs based on the signal strength measurements performed. For doing this, 802.16e uses either the traditional MAC management mechanism or the Fast ABS Selection Feedback mechanism [22].

- **Handover Occurrence**

In both the MDHO and the FBSS mechanisms, a handover occurs when a new BS, having a more powerful signal strength than the serving BS, moves into the DS when it is updated. In the case of MDHO, during the handover, the MS simultaneously transmits or receives unicast messages and traffic from multiple BSs included in the DS. On the other hand, in FBSS, the normal handover procedure is not invoked while the MS switches BSs from the current ABS to the newly selected target ABS. This is because in FBSS, an MS is used to have established connection identifiers (CIDs) with all NBSs in its DS. The MS and the current ABS jointly do the selection of the target ABS [27]. During the BS switching, the MS remains connected to the current and the target ABSs.

2.6 Hard Vs. Soft Handover in WiMAX: Relative Advantages and Disadvantages

From the discussion presented in the previous section, it is quite evident that each of the three handover techniques available in WiMAX network, namely, HHO, MDHO and FBSS, has its own advantages and disadvantages, relative to the other two. However, because both MDHO and FBSS are very similar to each other but individually both are quite different from the hard handover (HHO), MDHO and FBSS are often jointly called Soft Handover (SHO) [10]. In this section, we wish to briefly compare between the relative advantages and disadvantages of HHO and SHO and bring into focus why, unlike HHO, both the SHO techniques, namely, MDHO and FBSS, have still been kept only as optional features in Mobile WiMAX standards and not mandatory like the HHO.

The HHO scheme in 802.16e is highly bandwidth-efficient and fairly fast and seamless in nature. This Network Optimized HHO mechanism [32] has the potential to reduce handover overheads, handover delays, resource wastages and cell drops in case of even full-mobility WiMAX (i.e. WiMAX MS moving at a speed of 120 Km/hr). HHO is the simplest Mobile WiMAX technique that ensures efficient support for the provisioning of different high-speed real time applications without significant interruptions and QoS degradation. From the commercial standpoint, the primary advantages of the HHO scheme in Mobile WiMAX are the low deployment complexity and cost, requiring very few BSs spaced appropriately apart. Some of the disadvantages of HHO are the delay in searching and selecting a target BS (adding on to the overall handover delay), non-negligible packet losses and prolonged connection disruption time (HHO is a break-before-make scheme unlike SHO). A detailed list of some of the issues hampering the performance of the HHO technique is provided in Chapter 3 of this Thesis.

So far as the SHO is concerned, theoretically, both MDHO and FBSS have attractive features like very low packet loss (<1%), very fast switching and very low handover latency (<50 ms). Moreover, they have the potential to support high-speed real time voice-centric applications like Voice-over-IP (VoIP) [7]. However, in practice, achieving the above mentioned features is really difficult since the design is extremely complex, costly and wasteful of resources like power. The BSs in the active or diversity sets must be synchronized, must use the same carrier frequency and also must share network entry-related information. In order to maintain a valid connection simultaneously with multiple BSs (SBS and at least one NBS), the MS must be synchronized with the BSs and must spend a lot of its scarce power in communicating simultaneously over multiple interfaces. As a matter of fact, neither MDHO nor FBSS in WiMAX network is fully developed yet [10]. As a consequence, SHO is not yet a part of WiMAX Forum Release 1 network specifications [33]. As a final point, in the current generation cellular systems like LTE and High-Speed Packet Access (HSPA) [13], the use of SHO has been omitted [33] although it was included in Universal Mobile Telephone Systems (UMTS) [12], which was their predecessor. The reason behind this decision is that the two SHO techniques are seen as very costly to build, deploy and maintain, especially in terms of capacity requirements on the air interface and backhaul connection [34], [33]. Because of all the above reasons, we have not pursued any research work on either FBSS or MDHO, i.e. on SHO itself, in this Thesis. Before concluding this chapter, in Table 2.1 we provide a brief comparison between the three Mobile WiMAX handover techniques.

2.7 Conclusion

This chapter has provided an overview of WiMAX technology including some of its important physical and MAC-layer features, network architecture and the different types of handover techniques supported by it. Starting in 2001, the IEEE 802.16 technology has traversed through many stages and versions of WiMAX. The current IEEE 802.16e version has included mobility support for users moving at speeds of up to 120 km/h. The future IEEE 802.16m version will support seamless user movement

Table 2.1 Brief Comparison of the Mobile WIMAX Handover Techniques

Parameters	**Hard Handover**	**FBSS**	**MDHO**
Latency	High	Medium	Low
Implementation Complexity	Low	Medium	High
Reliability	Low	Medium	High
Packet Loss	High	Low	Low
Cost of Implementation	Low	High	High
Support for Delay Sensitive Applications	Low	High	High
Speed	Low	Medium	High
Hardware Complexity	Low	Medium	High
Hardware Cost	Low	Medium	High
Link Quality	Low	Medium	High
Commercial Usability	High	Medium	Low

of up to 350 km/h. IEEE 802.16 supports a variety of physical layers each having its own characteristics and features. These are the WirelessMAN-SC (Single-Carrier) PHY, the OFDM PHY and the OFDMA PHY. The OFDM and OFDMA PHY layers offer efficient schemes for high data rate transmission in multipath radio or NLOS environment. The physical layer of the Mobile WiMAX version also supports the use of scalable OFDMA technology thus enhancing the performance of wider channels. Brief discussions on each of these technologies have been provided in Sections 2.2 and 2.3, which respectively covered the Physical Layer and MAC Layer of WiMAX.

In any cellular technology, from the perspective of different deployment models, the mobility and handover-related actions can be logically classified based on the functions performed in the Physical, MAC and Network layers. Section 2.4 provided an overview of the WiMAX network architecture and discusses the concepts of ASN and CSN-anchored mobility from the perspective of Mobile WiMAX. As explained in that section, mostly Layer-2 handovers occur in case of ASN-anchored mobility or micro-mobility and Layer-3 handovers take place when the mobility is CSN-anchored. However, in either case, the overall handover time (or the total handover latency) depends on the handover times in the individual layers, i.e. for a Layer 3 handover, the overall time will depend on the time taken to perform Layer-2 handover as well as that taken to perform the Layer-3 handover.

Section 2.5 discussed the different types of handover techniques, namely, HHO, FBSS and MDHO, supported by WiMAX systems. Of these, HHO is the default handover mechanism and the two soft handover procedures, FBSS and MDHO are the optional types. WiMAX allows a handover to be initiated by either of the MS, the SBS or the backbone network. Similar to most of the current day cellular technologies (e.g. LTE), WiMAX primarily supports HHO (over the two soft handover techniques), mainly because of its simplicity and low infrastructural costs. The work in our Thesis solely focused on the HHO technique owing to its widespread acceptability in the commercial world. As a matter of fact, though the FBSS and the MDHO (usually jointly called SHO) theoretically offer superior performance compared to HHO, yet both these techniques are not really practical because of their great complexity and high cost of building, deployment and maintenance. As a result, commercial interest in SHO is clearly on the wane. A comparative discussion on the different handover techniques supported by WiMAX is provided in Section 2.6. In WiMAX, the HHO activity of an MS can be broadly divided into two phases, namely, the network topology acquisition phase and the actual handover phase. In the first phase, the MS and the SBS jointly shortlist few of the NBSs, which are termed as candidate BSs, for the potential handover activity. In the second phase, the SBS decides upon the TBS from the shortlisted candidates and MS performs the actual handover with the TBS with the active help of the backbone network. The MS terminates its connection with the SBS and performs different network entry activities with the TBS, before resuming its IP connectivity with the TBS to mark the successful completion of the handover activity.

Chapter 3

Some Research Issues in Mobile WiMAX Handover Techniques

3.1 Background

Chapter 2 described the three different handover techniques: (i) the default Hard Handover (HHO), (ii) the optional Fast Base Station Switching (FBSS), and (iii) Macro-Diversity Handover (MDHO) technique for Mobile WiMAX networks. Although, the IEEE 802.16e NWG has defined only the Layer-2 handover frameworks for the above-mentioned techniques, facilities are provided to support different types of probable handover activities like intra- and inter cell, as well as intra- and inter-system. The handover techniques in Mobile WiMAX suffer from certain handover performance-related shortcomings and research is going on worldwide to resolve them, so that WiMAX can fulfil its potential for more widespread adoption. This chapter provides a study of some of the different research issues of the WiMAX handover along with a survey of the related research solutions as proposed by the relevant research community. As the work done in this Thesis is focused on MAC-layer (Layer-2) hard handover issues in Mobile WiMAX system, mostly, issues related to MAC-layer (Layer-2) hard handover are discussed in detail in this chapter, along with brief overviews of Soft Handover, Layer-3 and Cross-Layer (Layer-2 + Layer-3) issues. A detailed discussion of all these handover issues in Mobile WiMAX along with survey of proposed and potential research works related to those issues, are published in our survey paper [35]. A number of the issues and research solutions discussed in above the survey are valid for other cellular technologies, e.g. LTE, as well. This survey helped us to clearly identify the handover-related issues for our research.

3.2 Mobile WiMAX Deployment Architectures

The NWG in the Mobile WiMAX forum has been working on the implementation of a full-fledged Mobile WiMAX mobility architecture supporting both Layer-2 and Layer-3 mobility. Three different types of probable Mobile WiMAX deployment architectures, namely centralized, flat and hybrid, with individual characteristics, are considered [30]. In the Mobile WiMAX centralized architecture, a subnet consists of one ASN-GW and multiple BSs under its control. In this architecture, handovers are mostly carried out using the MAC-layer (i.e. Layer-2) handover functionalities. In case of Layer-2 handovers, no change in the MS IP (network) layer configuration takes place. On the other hand, in a flat architecture, a subnet consists of one BS and one ASN-GW. The IP-layer functionalities are located in the individual BSs. The architecture mostly supports CSN-anchored mobility (Ref: Chapter 2) or inter-ASN mobility and therefore, the IP-layer (Layer-3) configuration of an MS changes as a result of such a handover. A third option may be the hybrid architecture, in which different BSs control the handover and radio resource activities. From the deployment architecture point of view, in this Thesis, we concentrate on architectures supporting Layer-2 handover.

3.3 Some Research Issues in Mobile WiMAX Handover Techniques

In contrast to the 3G cellular technologies those that have been providing mobility support to users for many years, WiMAX is still a new technology and is no exception when it comes to facing many technological and non-technological hurdles at the early stages. An efficient Mobile WiMAX handover framework is yet to be developed despite considerable research activities worldwide. Both the hard and soft handover techniques in Mobile WiMAX suffer from a variety of Layer-2, Layer-3 and Cross-Layer issues when it comes to providing satisfactory handover performance. Figure 3.1 gives a concise view of some of the handover-related research issues in Layer-2, Layer-3 and Cross-Layer environments, identified, surveyed and published by us in [35]. The current thesis work proposes solutions to a few of the Layer-2 hard handover issues related to handover latency and reliability. Reliability in handover implies that a call should be successfully transferred from the SBS in the present cell

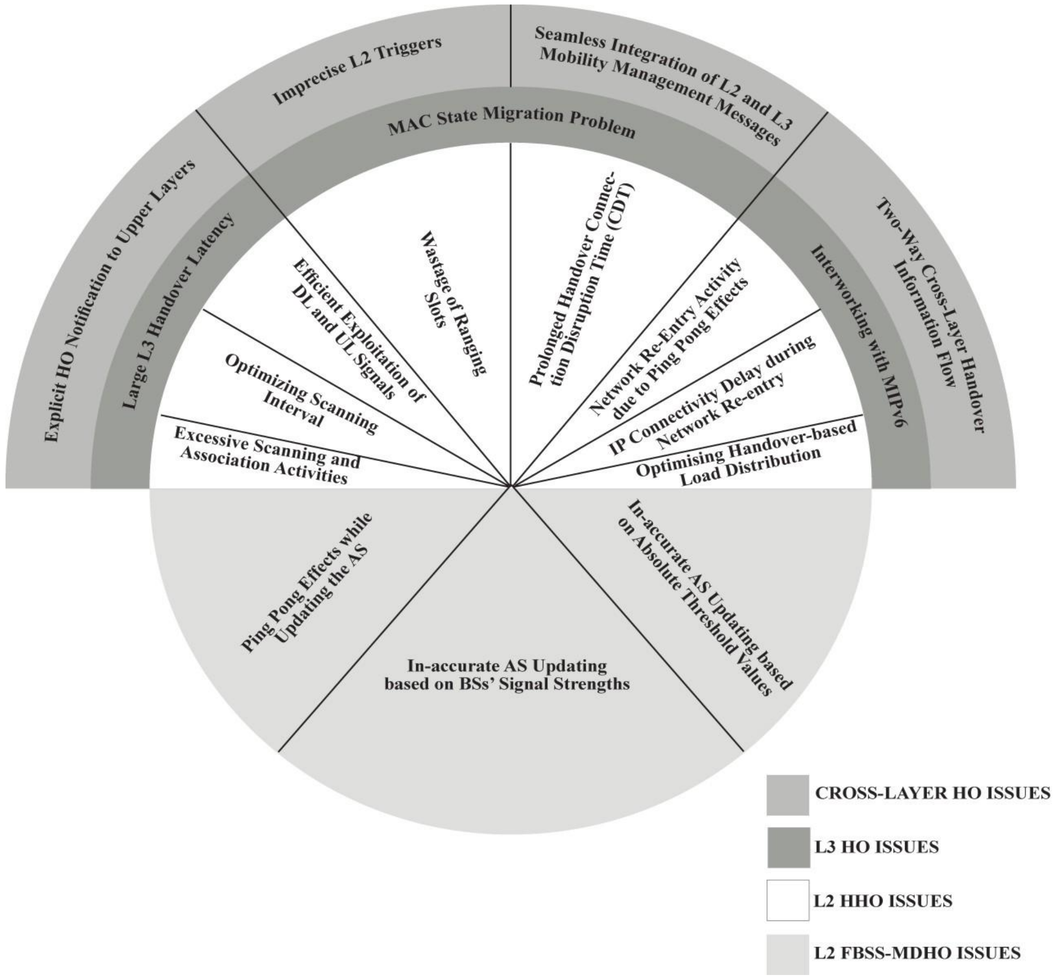


Fig. 3.1 Some of the Mobile WiMAX Handover Research Issues

to the next SBS in the adjacent cell without any call drop and in a seamless manner. Although much work has been done on the latency issue in Mobile WiMAX handover, practically no work has been done on the reliability aspect of Mobile WiMAX handover. So, we do not discuss the reliability issue in this chapter. However, since our Thesis deals with reliability in Mobile WiMAX handover and the concerned work has been reported in Chapter 5, we shall discuss about this topic of reliability in Mobile WiMAX in Chapter 5.

We have also not pursued any research work on Mobile WiMAX soft handover because of reasons stated in Chapter 2. Also, the reason behind choosing Layer-2 handover over upper-layer handover in Mobile WiMAX is as follows. In a handover activity, the overall handover time depends on the individual handover times of the layers i.e. time to perform Layer-2 handover and Layer-3 handover. This implies that even if Layer-3 handover is made faster, the gain in the overall handover time won't be achieved unless time for Layer-2 handover is also reduced. Moreover, how fast the Layer-3 handovers can be achieved, mostly depends on the triggers and notifications of Layer-2 handover. More time is taken to complete the Layer-2 handover part than the Layer-3 handover part. So, while surveying the different issues, our understanding is that overall fast handovers cannot be successfully achieved if Layer-2 handover time is not reduced significantly. This argument is true for handovers not only in Mobile WiMAX technology but for other cellular technologies as well.

3.4 Some of the Mobile WiMAX Layer-2 Handover Issues

Although as per the Mobile WiMAX standard, an MS's Layer-2 handover can be initiated either by the MS or the SBS or even by the underlying network, within a subnet, handovers are mostly controlled jointly by the SBS with some help from the backbone ASN. As discussed in Chapter 2, Mobile WiMAX handover procedure has two main phases, the NTAP, in which the handover is initiated and TBS is decided upon and the AHOP, in which the MS discontinues its service with the previous SBS and reconnects with the TBS as its new SBS. The hard handover technique in Mobile WiMAX has some serious shortcomings in both of these phases that are discussed here.

3.4.1 Some Issues in the Hard Handover Technique

Although hard handover is the mandated and most bandwidth-efficient handover technique in Mobile WiMAX, yet such handover activities are crippled by serious problems like excessive scanning activity in a non-optimized scanning interval before finalizing a TBS, prolonged inter-handover connection gaps, unwanted network re-entry activities during the handover owing to ping-pong effects, IP connectivity delay during the network re-entry phase, and optimization of handover-based load distribution. Apart from discussing these problems, the subsections below also discuss less important hard handover issues like efficiently exploiting both the uplink (UL) and downlink (DL) signals of the SBS and MS before initiating a handover activity and means of avoiding the wastage of unused ranging slots during pre-handover situation. A summary of these issues is provided in Table 3.1 to give an overview of the different aspects discussed before going into the details.

Our current thesis work focuses on issues related to handover delay or latency, e.g., duration of scanning activity along with the issue of enhancing the handover reliability. Surveying the different Layer-2 issues, we felt that time taken for the scanning and ranging-related activities performed during the NTAP to shortlist and choose the TBS for a handover activity accounts most to the overall handover time. The overall handover performance also degrades owing to lengthy NTAP activities. Moreover, this issue is also related to the reliability of a handover activity. Correctly and reliably choosing a TBS can save occurrence of further unnecessary handovers. To do that, if candidate NBSs (Refer to Chapter 2) can be chosen / shortlisted intelligently, prior to scanning, time consumed in pursuing scanning activities can be reduced, which will further improve the overall handover latency.

Table 3.1 Summary of the Probable MAC-Layer Hard Handover-Related Issues in Mobile WiMAX

Issues	**Effects**	**Proposed Solutions**
Excessive Scanning and Association Activities	Redundant NBS scanning, ranging and association activities may lead to unnecessary Layer-2 handover delay and resource wastages.	Based on parameters like MS's trajectory of motion and previous handover intervals along with link quality information [36-37] of the NBSs, an MS can select the potential TBS before the scanning operations.
Optimizing Scanning Interval	Temporary suspension of data exchange between the MS and the SBS during scanning interval degrades the overall handover performance.	In a multi-MS Mobile WiMAX environment, NBSs can exchange configuration parameters to figure out the ideal scanning interval required [38].
Efficient Exploitation of DL and UL Signals	QoS may be hampered if both downlink and uplink parameters are not considered during handover initiation and execution.	Combination of effective measurements of MS's uplink signal strengths and SBS's downlink signal strengths at the handover region enhances the handover performance [39].

Wastage of Ranging Slots	The non-retained ranging slots of the other candidate BSs, allocated during the scanning phase, add up to the handover resource wastage after the MS selects the particular TBS [37].	Selection of the TBS prior to the handover preregistration phase [37] can debar other candidate BSs from allocating ranging slots.
Prolonged Handover Connection Disruption Time (CDT)	Connection gap while performing handover degrades QoS owing to service disruptions.	New MAC management message [40] can enable the MS to receive traffic immediately after the handover. Also, MS can perform the new network entry process during its idle period to receive traffic continuously [41].
Network Re-Entry Activity due to Ping Pong Effects	Unnecessary network re-entry procedures owing to ping-pong effects cause delays and call disruptions.	The SBS notifies the MS about the time duration that the traffic for MS will remain buffered in the SBS [42]. This avoids network re-entry procedures.
IP Connectivity Delay during Network Re-entry	MS needs to know more clearly during or before the network re-entry activity whether a switch in the IP connectivity is required after the handover. Otherwise unnecessary connectivity activities only enhance the overall delay.	If the TBS can know of the MS's previous AR and the IP address, it can help in reacquiring the MS's IP connectivity context [43]
Optimising Handover-based Load Distribution	Evenly balancing the traffic loads and distributing available resources over different BSs in an area is important in Mobile WiMAX. Solving this issue would not only enable better QoS but would also reduce call disruptions and call blockings.	Both BS-initiated directed handovers and MS-initiated rescue handovers are conducted in parallel to offer better load balancing scheme enabling satisfactory QoS and much fewer ping-pong effects [44]

- **Excessive Scanning, Ranging and Association Activities**

One of the primary advantages of Mobile WiMAX handover techniques is the provision of both Layer-2 broadcast and scanning concepts during the NTAP, by which the MS can receive channel signal strength information of its neighbouring BSs (NBS). The MS can scan some of the NBSs as potential TBS candidates. However, the handover technique recommended by the WiMAX standard does not clearly say anything regarding the number of NBSs that a MS may need to scan before ultimately deciding on a TBS. Moreover, nothing has been specified regarding the number of scanning iterations that should take place before an MS can finally decide upon the candidate NBSs suitable for handover. This may result in redundant scanning of NBSs [37] leading to unnecessary wastage of channel resources and degrading the overall performance. Moreover, for the NBSs scanned, activities like synchronization, ranging and association are also performed along with one after another (i.e. not simultaneously), for each of the NBSs, during the NTAP. Hence, redundant scanning, along with prolonged synchronisation, ranging, and association activities proportional to the number of NBSs scanned, increases the overall handover delay. Also, while excessive scanning of the NBSs may affect the scheduler performance of the SBS particularly for the delay sensitive downlink traffic, unnecessary contention-based ranging results in unwanted consumption of the contention slots thereby affecting the overall throughput [45].

Potential Research Solutions: Few measures have been proposed to simplify scanning related procedures during the topology acquisition phase, to minimize the overall delay and enhance the system performance. Unique network topology acquisition schemes to identify the potential TBS before performing any type of scanning-related activities have been proposed in [36-37]. In [37], the authors argued that, from the MOB_NBR-ADV messages, the MS can acquire the preamble-based mean CINR along with the arrival time difference of the downlink signal (relative to the SBS) of the individual NBSs. It should be noted that the smallest arrival time difference signifies the shortest distance. From that, it can select the TBS to be the one having the largest mean CINR and smallest arrival time difference. Then, the MS performs ranging, synchronization and association activities only with that TBS. Though this scheme reduces the handover delay by skipping unnecessary scanning, it considers neither the MS's direction of motion nor the current load of the selected BS. This might lead to unwanted ping-pong activity as well as call drops. The work done in [36] proposed to perform reduced scanning activities with only one selected TBS. The work assumed that the MS performs scanning and association activities only with the nearest NBS, which it identifies, by calculating the distance of that NBS from itself, with the help of a GPS. The authors showed that the scanning is shortened and around 33% improvement in the overall handover time is achieved. However, the scheme did not specify any justifiable mechanism of how the TBS is selected using the GPS. Straightaway selecting the nearest NBS as the TBS may not be the right one selected resulting to further unnecessary handover activities.

Few of the other proposed schemes to reduce scanning activity either by predicting the MS's movement direction or based on the MS's location information are discussed in [46, 47-48]. Of these, [46] proposed an SBS-predicted MS's movement direction-based fast handover scheme, in which it is assumed that, (i) SBS's hexagonal coverage area is divided in to six sectors and (ii) the SBS knows the location coordinates of different NBSs. Through few different scanning iterations, in each sector, the SBS can track the MS's relative movement with respect to the NBSs in that sector and, finally, based on these information, the SBS chooses that NBS as the TBS, which shows the maximum progressive movement with respect to the MS. However, no explanations have been given regarding how the SBS's coverage area is sectorized and how the different NBSs are allocated per sector. In [48], based on both the location information of the MS and the received signal strengths from the NBSs after three rounds of scanning, the TBS is chosen by the SBS. A 60% improvement in the overall handover latency is achieved for an MS moving at 36 Km/hr. The work assumed that all the BSs are sectorized in zones and that the BSs are time-synchronized, which, would however, lead to an overall increase in the infrastructural cost during implementation. Apart from these discussed proposals, elimination of NBSs as TBS candidates, prior to scanning, depending on (i) prediction of MS's movement direction, (ii) QoS, (iii) active service flows and service types and (iv) bandwidth requirements of the MS, are also probable solutions for avoiding unwanted scanning activities and achieving shorter handover delay [47], [49-50]. However, scope is still there to come up with new and intelligent ideas on dealing with unwanted delays and wastage of channel resources owing to excessive scanning, ranging and association related activities during Mobile WiMAX handover operations. Standard methods for performing the CINR measurements are also desirable.

- **Optimizing Scanning Interval**

In the Mobile WiMAX hard handover scenario, scanning of multiple channels is an essential activity for discovering the NBS that is most suitable to be the potential TBS. Hence, though it is difficult to avoid scanning process completely, one can try to keep it within limits, as discussed previously. During scanning, Mobile WiMAX handover mechanisms temporarily pause the uplink and downlink of data transfer between the MS and the SBS. These scanning intervals are allocated by the SBS dynamically on getting scanning interval allocation requests from the MS. However, frequent temporary suspension of data exchange lowers the system throughput, and adds more delay to the overall handover process. Also, QoS requirements may get disrupted owing to this. Moreover, during scanning intervals, all data meant for the MS are buffered at the SBS, what leads to wastage of channel resources. Hence, it is desirable to devise techniques of effective estimation and minimization of both the frequency and the time interval needed for scanning. Required also are the methodologies for carrying out scanning and data exchange concurrently.

Potential Research Solutions: It should be noted that, as the QoS might get hampered in case of both long and short scanning intervals, optimization of scanning intervals is an important issue. An efficient Adaptive Channel Scanning algorithm in a multi-MS oriented Mobile WiMAX environment, relying on the exchange of configuration parameters between the NBSs in order to find out the required scanning time for a MS, is proposed in [38]. Along with optimization of the allocated scanning intervals for all MSs, the scheme also maintains the QoS of the application traffic in the system. However, utilization of unlimited channel buffers, in order to make the packet loss almost negligible, complicates the problem of channel resource wastage. Another proposal, for minimizing the influence of scanning intervals by concurrent scanning and data transmission by the MS is discussed in [37]. This fast synchronization and association model uses the unique IDs of the SBS and the NBSs (unique BSIDs), to distinguish between the UL/DL messages of the SBS and the NBSs. Based on these Ids, the MS can communicate with both the SBS and the NBSs at the same time, with the ranging slots appropriately adjusted by the SBS to minimize the chances of collisions. This scheme, however, neither considers a multi-MS environment nor considers an environment where the different NBSs and the SBS might not be controlled by the same service provider network [38]. An MS's sleep mode option [30] also provides an interesting mechanism for the MS to perform scanning without hampering the communication with the SBS.

- **Efficient Exploitation of Downlink and Uplink Signals**

Mobile WiMAX promises to deliver streaming multimedia applications in the form of voice and data. However, the QoS of data and voice services might not be the same and their requirements may vary for UL and DL transmissions. This would degrade the system performance. Hence, to provide effective and stable QoS for all types of applications, it is advantageous to consider both UL and DL signal parameters while initiating and executing handover. This is particularly important for delay-sensitive voice and data-oriented applications in Mobile WiMAX.

Potential Research Solutions: In a mobility scenario, the UL and DL signals of an MS and the SBS respectively are not strictly correlated with respect to distance between them. From an user's perspective, though, it seems that, as the distance between an MS and its SBS changes, the MS's UL signal strength measured at the SBS and the SBS's DL signal strength measured at the MS also changes in a correlated fashion, this is not true always. DL and UL signals are considered jointly in [39], to propose a hard handover scheme based on the MS's UL signal strengths and the SBS's DL signal strengths measured at the SBS and the MS, respectively. A handover process is triggered once the two signal strengths fall below some pre-determined thresholds. Unwanted delays as well as ping-pong and outage probabilities are thereby reduced significantly. Though much work has not been done yet on utilizing both downlink and uplink signals to direct and initiate a Mobile WiMAX handover, in comparison to the downlink signal-based schemes, this choice may have the potential to provide better QoS, reduced scanning requirements and improved overall system throughput. Clearly, it demands further research.

- **Wastage of Ranging Slots**

Mobile WiMAX supports handovers initiated by either the MS, or the SBS, or even the underlying network. In the case of MS-initiated handovers, when the suitability of the potential candidate NBSs selected by the MS during the NTAP is accepted, the individual BSs allocate ranging slots for the MS, which then selects the new TBS and retains only the ranging slots provided by that BS. The other unused ranging slots add up to the list of resources being wasted during the entire handover process.

Potential Research Solutions: Such wastage of unwanted resources can be avoided if the SBS can select the new TBS before the allocation of ranging slots, as proposed in [37]. So, once selected, only that TBS may allocate ranging slots, debarring the other NBSs from unnecessarily allocating such slots as well.

- **Prolonged Handover Connection Disruption Time (CDT)**

Being a break before make technique, the HHO concept in Mobile WiMAX suffers from a lengthy CDT that could lead to unwanted hazards like packet losses, call disruptions or even call drops, while on the move. This occurs in the actual handover phase, when an MS terminates the connection with the SBS and tries to set-up connections with the selected TBS. While a CDT in the range of 200 ms is acceptable for real-time streaming media traffic [51], anything more than that is disruptive [52]. In Mobile WiMAX, data, voice and multimedia contents are intermixed and each requires different mechanisms for its transmission, particularly during handover. So, such a lengthy CDT may cause serious service disruptions in the case of real-time high-speed delay-sensitive voice and streaming multimedia applications in Mobile WiMAX networks.

Potential Research Solutions: To counter the above drawbacks, considerable research has been conducted over the last few years to minimize the inter-handover service interval time. The IEEE Mobile WiMAX group has optionally incorporated the MDHO and FBSS techniques, which are good for delay sensitive applications like Voice over IP (VoIP). However, as these two techniques are very complicated and can increase deployment costs (refer to Section 2.6 in Chapter 2), research activities have been carried out to further reduce the QoS related hazards to real-time services caused by the CDT in HHO.

Sik Choi et. al. [40] has proposed a link-layer fast handover scheme for Mobile WiMAX HHO scenario that significantly reduces the probabilities of packet loss and transmission delay during handover. This scheme introduces Fast DL-MAP_IE MAC management message, which enables an MS to receive downlink traffic just after the downlink synchronization with the TBS, even before the completion of the uplink synchronization phase. A similar idea, called Passport Handover, is discussed in [52] where an MS could resume the DL re-transmissions with the TBS before the completion of the authorization procedures, by using the CIDs of the previous SBS. Though both these mechanisms managed to achieve an improvement of the overall handover performance, they did not consider potential possibilities of unsuccessful authorization activities while switching domains. Scope of research on these aspects are there, specifically, to see how smoothly the lengthy authorization approach could be done prior to the actual handover phase with or without the help of the backhaul network. This is because transferring the stored authorization messages from the SBS to the TBS may increase the overall load in the backhaul network.

Another interesting idea proposed in [53] deals with an MS maintaining simultaneous network connectivity with the SBS and the TBS. In this case, it is assumed that the coverage areas of the two BSs overlap so that the MS gets sufficient time to complete the network re-entry process at the target network, before it loses connectivity with the SBS. This may be a possible scenario in the case of Mobile WiMAX networks due to the large coverage areas of the BSs. However, this scheme requires further study to investigate such feasibility factors as duration of overlap, effects of blind spots at the overlapped regions and the cost. MS's idle periods could also play an important factor in this issue as suggested in [41]. As stated there, if the MS performs the network re-entry signalling with the TBS during the idle mode of the MS, it would allow the MS to continue data exchange simultaneously with the SBS leading to a very low latency HO procedure. However, this idea requires the BSs to be synchronized, and this might be a problem in the case of HHO. Therefore, it still remains a research challenge to devise suitable frameworks for dealing with the CDT issue in Mobile WiMAX HHO.

- **Network Re-Entry Activity due to Ping-Pong Effects**

In Mobile WiMAX HHO, when an MS wants to get connected to a new BS, it has to complete the entire network re-entry procedure comprising of the series of security and connection re-establishment processes. This takes a long time. Now, there could be situations, where in the middle of an ongoing communication, an MS, that is performing network re-entry procedures with a TBS, wants to come back to the previous SBS due to change in signal strengths, or just after the handover with the TBS, the MS finding the lack of adequate availability of resources, want to come back again to the previous SBS. Such situations lead to further delays if the entire re-entry procedure needed to be performed again for the old SBS. Handover overheads caused by unnecessary re-entry procedures resulting from such ping-pong effects may degrade the overall system performance.

Potential Research Solutions: In order to avoid such situations, performing a handover with a reliable TBS is very important. For reliable handovers, firstly, it is necessary to choose the correct TBS so that ping-pongs or further unnecessary handovers do not occur owing to one non-reliable handover. Secondly, to avoid length network re-entry activities, in case such situation occurs, it is important that the previous SBS can differentiate ping-pong re-entries from new re-entries. Few of the research activities carried out on these issues are mentioned here. It was discussed that while selecting the best TBS for handover, along with the signal strength, parameters like "effective capacity" (the actual available resources in a TBS) [54] and sliding window mechanisms to compensate slow fading interruptions on the received signal strengths [55], should also be taken in to account in order to avoid any kind of ping-pong activity resulting from poor resource availability or wrong reception of TBS's signal strengths. More on these can be found in [54-55].

However, as per our knowledge, it is still an wide open research issue to efficiently make the Mobile WiMAX SBS readily differentiate between a new network re-entry and a ping-pong. Researches in this area has resulted in a mechanism in which the TBS, upon learning about the ping-pong effect, informs the previous SBS about the MS's reverting back to it [56]. This helped the previous SBS to identify the return of the MS as an effect of ping-pong and not as an altogether new network entry. So, provided the SBS has retained the MS's previous connection information, communication resumed quickly as the MS could get access to non-contentious ranging slots. However, this scheme will not work if the SBS has not retained the state information of the MS. In that case, however, the allocated ranging slots for the returning BS will be wasted. So, a more effective method is proposed in [42] in which, prior to a handover, the SBS intimates the MS about how long the MS's connection information would be retained. The MS could thus know the time left for it for re-resume communication with the previous SBS, if needed. However, there is no suitable explanation for such a scenario when an MS, due to the ping-pong effect, has to come back to the SBS in spite of knowing that the SBS is not retaining the previous connection information any longer. Further research is needed to deal with such situations arising from the ping-pong effect. Minimization of handover overheads, reduction of resource wastages and early recovery of any call drops are the important factors which should be kept in mind while formulating such solutions.

- **IP Connectivity Delay during Network Re-Entry**

During a Mobile WiMAX handover process, if an MS moves to a TBS under the same access router within the same subnet, then it does not incur any change in the MS's IP connectivity scenario. MS's IP connectivity context with reference to the new SBS remains the same as with the old SBS. However, this is not the case if the TBS falls under a different subnet altogether. In that case, the MS has to go for the lengthy procedure of IP connectivity acquisition during the re-entry phase to complete the handover process. In the current scenario, it is clearly a challenging issue, regarding how an MS actually determines whether a change in the IP connectivity context is at all required as part of an ongoing handover activity. If a change is not required then it would save a significant amount of handover-related latency as the MS would not go for that at all. In the current Mobile WiMAX standard, a handover optimization flag in the MOB_NBR-ADV message [22] indicates whether an IP subnet switch is required during a handover activity. However, this is not a very fruitful detection mechanism as it could incur administrative overheads.

Potential Research Solutions: In order to get rid of such delays, MSs need to figure out, beforehand, if the TBS falls under a different subnet altogether. If yes, then only it has to initiate the lengthy IP context acquisition procedure during the network re-entry phase, else not. A solution to this problem is proposed in [43]. Depending on the information provided by an MS, a TBS could reacquire the MS's IP connectivity context, thereby minimizing the overall delay. During a handover activity, the MS needs to provide the TBS information regarding its last IP address and Fully Qualified Domain Name (FQDN) of its last Access Router (AR) [43]. Based on this information, the TBS instructs the MS whether or not it can retain the previous IP connectivity contexts. Devoid of any administrative overheads, the solution claims to be independent of any Mobile WiMAX Radio Access Network (RAN) architecture.

- **Optimizing Handover-based Load Distribution**

In a mobile communication environment, the QoS experienced by MSs can degrade significantly owing to increased traffic load in a cell. Problem like unbalanced traffic load distribution [57] between different adjacent cells can force the traffic load in a particular cell to exceed the ultimate capacity of that cell. With the overlapping nature of the cells, unevenly distributed resource utilizations among the different adjacent BSs incur additional cost and hamper the service quality. Therefore, evenly balancing the loads and evenly distributing the different available resources within a cluster of BSs is a relevant and interesting research issue. This is a problem in the Mobile WiMAX environment as well. Though the Mobile WiMAX Forum has supported a RRM framework for efficient load balancing and resource utilization [58] with the help of BS-initiated directed handovers [44], the specification provides only a framework and lacks any detailed implementation concepts and algorithms [59]. Thus, it is an open research issue.

Potential Research Solutions: Mobile WiMAX research has been mostly focussed on designing and implementing an efficient algorithm, for evenly distributing MSs, which reside on the overlapping areas of the adjacent cells, among adjacent BSs. Another idea, which has not been advanced much yet, is to gather the resources to areas where majority of the traffic is located [59]. The Mobile WiMAX Forum has looked at the former idea. In the BS-initiated handover scheme, the congested SBS forces the MS to handover to a non-congested TBS. This scheme offers good QoS in comparison to traditional MS-initiated rescue handover schemes, in which the load balancing logic resides in the MSs and the MS handovers to a less congested TBS whenever the signal strength drops below a threshold.

An efficient load balancing scheme is proposed in [44] in which directed and rescue handover mechanisms are conducted in parallel. The scheme uses Spare Capacity Reports (SCR) [58] broadcasted by the different BSs in an area to let their peers know of their loads. Depending on such reports, the BSs classify their loading status as under loaded, balanced or overloaded. Directed handover to a TBS occurs in the case of under loaded conditions, whereas rescue handover takes place if the TBS is in balanced or overloaded states. This scheme offers satisfactory QoS and much reduced ping-pong activities. Additionally, one could consider different prioritization means by which the MSs can be handed over to the TBS. They could take into account e.g. traffic priority and channel conditions [44]. An MS-initiated rescue handover mechanism is also proposed in [60]. Despite such research attempts, scope of further research is there to understand why the choice of BS-initiated directed handover scheme is better than the traditional MS-initiated rescue scheme.

3.4.2 Some of the issues in the Soft Handover Techniques

The two soft handover techniques in Mobile WiMAX, namely, FBSS and MDHO, also suffer from quite a number of drawbacks (Refer to Table 3.2). While the drawbacks of the NTAP also apply to these handover techniques, both MDHO and FBSS suffer from performance hindrance challenges, specifically with the accuracy of updates of the active sets during the actual handover phase. Although, these issues are still open for future research contributions, they failed to attract considerable attention from the research community owing to reasons discussed in Chapter 2.

- **Ping-Pong Effects while Updating the Active Set (AS)**

In MDHO and FBSS, depending on the signal strengths of the BSs, an MS always maintains an AS, in which, apart from the serving or anchor BS, there are also the NBSs with the most powerful signal strength at that particular instance of time. The MS always monitors these BSs to update the AS, depending on a threshold value. However, specific discussions are required to determine the acceptable threshold value at any particular instance, to avoid unnecessary updating of the AS.

Table 3.2 Summary of the Probable Layer-2 FBSS and MDHO-Related Issues in Mobile WiMAX

Issues	Effects	Proposed Solutions
Ping Pong Effects while Updating the AS	Non-significant differences between new and existing threshold values may cause unnecessary update of the AS enhancing ping pong effects.	Accurately analysing threshold values [61] reduces unnecessary updating of ASs.
In-accurate AS Updating based on BSs' Signal Strengths	Channel resources may be wasted owing to inclusion of unnecessary BSs in the AS depending only on BS's signal strengths.	AS upgrading process may also consider the MS's direction of motion [62] along with the BS's signal strengths.
In-accurate AS Updating based on Absolute Threshold Values	Absolute threshold values may not be the best parameters to upgrade the AS in real-life situations where load of cells changes dynamically.	Relative threshold values can upgrade the ASs more accurately [63].

Potential Research Solutions: The difference between the new threshold value and the existing value should be large enough to trigger the requirements for AS updating as there are always possibilities that due to a very low threshold value difference, NBSs from the candidate set may move in and out of the AS unnecessarily. Such enhanced ping-pong activities would not only make the AS updates meaningless, but also hike the resource consumption in regard to the required signalling [61], degrading the overall performance. So efficient methods of determining the right threshold values to update the AS are required to reduce such performance-hampering activities.

- **Inaccurate AS Updating based on BS's Signal Strengths**

The FBSS and MDHO rely on the signal strength of the NBSs as the sole basis for updating the AS. They take into account neither the path followed by the MS, nor the mobility of the MS. Relying only on signal strengths may lead to channel and resource wastages. This is because, it may happen that the AS get populated by such NBSs with which the MS will not perform a handover activity at the near future. These NBSs even might not fall into the MS's movement trajectory and would automatically drop out of the AS after some time, when the MS moves further away from them, resulting in frequent and unnecessary updating of the AS. Thus, in terms of channel usage, inclusion of such NBSs is a complete waste.

Potential Research Solutions: Inclusion of unnecessary NBSs in the AS can be avoided if, along with the signal strengths, the MS also considers its direction of motion for choosing the AS constituents. The Predictive Base Station Switching scheme in [62] does that. The technique considers not only the signal strengths of BSs but also the current direction and speed of the MS, to make a decision from among the NBSs. So, when devising a potential NBS selection technique, considering criteria like MS's direction of motion and QoS requirements along with the NBSs' signal strengths, could reduce unnecessary resource wastages resulting in better system performance. However, the means of accurately estimating the speed of the MS and its direction of motion need to be formulated, especially during full vehicular mobility.

- **Inaccurate AS Updating based on Absolute Threshold Values**

In the MDHO and the FBSS, the MS updates the AS based on the absolute H_ADD and H_DELETE threshold values contained in the DCDs broadcasted by the BSs. At any instant, all the NBSs in the AS having CINR value less than H_DELETE threshold are removed from set and those, from the candidate set (CS), with CINR values more than H_ADD threshold are added to the AS. However, in reality, with the load of a cell changing often, relative threshold values instead of absolute values seem to be more realistic for accurate updating of the AS.

Potential Research Solutions: A similar technique based on the relative threshold values was discussed in [63]. In this scheme, an NBS from the CS is transferred to the AS provided Neighbour_BS_CINR - ABS_CINR < H_ADD threshold and a BS from the AS is transferred to the CS provided Active_BS_CINR – ABS_CINR > H_DELETE threshold. Though this method provides a more accurate way of active set updating, it is more complicated to implement. Therefore, in the current day scenario, with a substantial increase in the number of mobile users each day, it is an uphill task to formulate suitable means of correctly choosing the threshold values at any particular instant of time in order to correctly update the AS.

3.5 Brief Overview of Some of the Mobile WiMAX Layer-3 Handover Issues

This section provides a concise overview of some of the different Layer-3 handover issues in Mobile WiMAX. A summary of these issues is provided in Table 3.3. A Layer-3 handover mostly occurs in case of CSN-anchored mobility (inter-ASN

Table 3.3 Summary of the Probable Layer-3 Handover Issues in Mobile WiMAX

Issues	Effects	Proposed Solutions
Large L3 Handover Latency	Delay incurred in performing the different L3 handover steps is large. This affects the overall handover performance.	Timely indication of organised L2 triggers [64-65] can lead to early initiation of L3 handover activities.
MAC State Migration Problem	Non-transmitted MAC state frames during HHO may be lost and the delay incurred in retransmitting them may degrade the system performance.	Serving network can buffer the IP packets meant for the MS to reset the lost MAC frames from those stored packets [30].
Interworking with Mobile IPv6 (MIPv6)	Using MIP mobility concepts over non-standardized Mobile WiMAX upper-layer framework may lead to challenges related with maintaining fast handovers, long signalling and handover delays and failed data connectivity.	MIPv6-based fast and advanced handover schemes over Mobile WiMAX are proposed in the forms of Fast Handover for MIPv6 (FMIPv6) [99], Hierarchical MIPv6 (HMIPv6) [100] and Proxy MIPv6 (PMIPv6) [101].

mobility) or macro-mobility scenario, in which an MS moves from the current SBS in the current subnet to a different BS in a different subnet controlled by a different

ASN-GW. Therefore, the IP-layer (Layer-3) configuration of an MS changes as a result of such a handover. Few of the notable handover-related issues e.g. large Layer-3 handover latency, problem with the MAC state migration and interworking with mobile IPv6, are mentioned here and could be studied in detail in our publication [35].

3.6 Brief Overview of Some of the Mobile WiMAX Cross-Layer (Layer-2 + Layer-3) Handover Issues

In a Mobile WiMAX flat architecture, handover performance mostly depends on the integrated performance of the individual layers, specifically the link and the network layers. Hence, optimization of Mobile WiMAX seamless handover performance largely depends on how effectively the Layer-2 and the Layer-3 handover methodologies can be integrated without causing significant breaks in the IP-connectivity between the two handovers. This section provides a concise overview of the cross-layer handover issues in Mobile WiMAX. Table 3.4 lists some of the different cross-layer issues like providing explicit handover notifications to upper layers, imprecise Layer-2 triggers, seamless integration of Layer-2 and Layer-3 mobility management messages and two-way cross-layer information flow. Along with these, different proposed solutions in regards to these issues are also provided here. A detailed discussion on these issues and survey of proposed solutions are published in our paper [35].

3.7 Conclusion

The current chapter has identified and discussed the some of the handover-related research problems, which need to be addressed and resolved in the Mobile WiMAX technology. Although, technological issues are prevalent in the MAC and IP-layers of all the three handover techniques, namely, the hard handover, the FBSS and the MDHO that Mobile WiMAX supports, this chapter mostly provided discussions on some of the MAC-layer hard handover issues. Along with that an overview of the soft handover (FBSS and MDHO) issues were also provided, followed by brief overviews on Layer-3 and cross-layer (Layer+Layer-3) handover issues.

Hard handover being the most commonly used handover technique for various reasons, our research work in this Thesis is focused on that. However, in Mobile

Table 3.4 Summary of the Probable Cross-Layer Handover Issues in Mobile WiMAX

Issues	Effects	Proposed Solutions
Explicit handover Notifications to Upper Layers	Lack of handover generic suitable dynamic event triggers from Mobile WiMAX PHY/MAC layers to the IP-layer degrades handover performance as in that case the Layer-3 handover gets initiated after the completion of the Layer-2 handover.	Explicit Layer-2 to Layer-3 event triggers during the various stages of the overall Mobile WiMAX handover activity are proposed in [69] for enhancing the performance.
Imprecise Layer-2 Triggers	Untimely generation of Layer-2 triggers hampers the maximum boost in the handover performance. In addition, false Layer-2 triggers degrade performance.	MSs can send the Layer-2 handover trigger early enough to the upper layers in the form of predicted RSSI values [70].
Seamless Integration of Layer-2 and Layer-3 Mobility Management Messages	Merely overlaying the Mobile WiMAX Layer-2 and Layer-3 handover procedures without any effective correlation between them increases the overall latency.	Removal of related handover management messages from both the Mobile WiMAX Layer-2 and Layer-3 handover procedures and coincidental processing of both the procedures enhances the overall performance [71].
Two-Way Cross-Layer Handover Information Flow	Dynamic collaboration of the handover procedures of different layers with diverse functionalities is a difficult task.	Multiple event and command services to improve the FMIPv6 handover support over the Mobile WIMAX MAC [72].

WiMAX, large handover latency, mostly owing to excessive scanning and ranging activities performed by a MS with the NBSs while selecting a TBS, non-reliable TBS selection, high connection disruption time etc are some of the important issues that cripple the Mobile WiMAX hard handover technique in spite of low implementation cost. Section 3.4 discussed some of these issues in Mobile WiMAX hard handover technique. Different research proposals have been made by the research community to solve these issues. A survey of the relevant work done in respect to the discussed issues was also provided. Discussions on further potential research directions were also made. In this Thesis, we were mostly interested in providing solutions (i) for the handover latency-related problem, which is mostly caused by the unwanted scanning of NBSs by a MS, and (ii) handover reliability issue, which is mostly caused owing to choosing a wrong TBS for handover and, which may result in further unwanted handover activities. In Section 3.4, we have pointed out that unwanted scanning activities take place when an MS wants to select few of the candidate NBSs, from a list of advertised NBSs, for an impending handover activity. Scanning is an important part of the handover process through which an MS measures the signal strengths of the different NBSs. The problem, however, lies in the fact that scanning, being a time consuming process, as shown in our paper [73], sometimes even up to 50% of the overall handover time can be consumed in scanning. In the conventional Mobile WiMAX handover scenario, an MS may even scan the different NBSs irrespective of its movement direction even if it's moving in the opposite direction to an NBS. Apart from that, sometimes, although, an NBS may provide acceptable signal strength to the MS but it might not provide adequate resources, owing to its present excessive load, to maintain an acceptable QoS after the handover. The MS, unfortunately, cannot identify such an NBS before performing scanning, synchronization and ranging activity with that NBS because, omission of such NBSs, based on availability of resources, only takes place in the AHOP when the MS has already shortlisted candidate NBSs based on scanning. Therefore, it might happen that even a shortlisted NBS may turn out to be not an efficient one as far as resources are concerned.

Work done in the Thesis, takes into account these issues and primarily focuses on proposing techniques for making handovers fast and reliable. In Chapters 4 and 5, different Mobile WiMAX handover techniques are discussed in which fast and intelligent short listing of candidate NBSs and selection of the TBS are done by either the MS or the SBS. The scheme proposed in Chapter 5, provides a solution to the handover reliability problem along with fast selection of TBS. These schemes are simulated and results are presented and discussed in Chapter 6. A comparison of the approaches and mechanisms of these schemes with few of the other relevant Mobile WiMAX hard handover schemes, some of which are discussed in this chapter, are provided as part of Chapter 7, the concluding chapter of this Thesis.

Chapter 4

Fast Handover Based on Distance Estimation and Lookahead

4.1 Introduction

In a Mobile WiMAX network, the total process of handover during transit of an MS from its present cell to a neighbouring cell (the TBS) primarily depends, in accordance with the IEEE 802.16e standard, on the sole parameter called Received Signal Strength (RSS), which is the signal strength received by the MS from its SBS (used for handover process initiation) and from the NBSs (used for making the choice of the TBS). Moreover, the most important operation of TBS selection is mainly controlled by the SBS with the help of the backbone network. Again, as discussed in Chapters 2 and 3, an MS, in accordance with the WiMAX standard, performs prolonged scanning and ranging activities with all its NBSs. Through this scanning and ranging activity, the MS gathers the RSS and other signal-related information about the NBSs and passes this information on to the SBS. Based on this information, the SBS then selects the TBS to which the MS should be handed over. The long procedure of scanning and ranging activities, performed during the NTAP, increases the overall hard handover delay in Mobile WiMAX networks. As a consequence of this larger handover delay, the packet loss and call drop performance may be degraded. Moreover, choosing an NBS as the TBS, solely on the basis of the largest value of the current RSS is a short-sighted policy and may not yield the best choice in many cases. Much of the research on WiMAX handover in recent years has focussed on this deficiency in the recommendation of the standards and on suggesting improved handover techniques.

In order to improve the performance of the handover operation in Mobile WiMAX, in this chapter we have investigated and reported on two allied MS-controlled, MAC-layer hard handover schemes, both using the new concept of "distance estimation and lookahead". These schemes have been published in [74-75]. In accordance with this concept, an MS approximately estimates its current distance, from the SBS as well as from its NBSs, by monitoring the RSS received from the base stations concerned [76]. For estimating the distance, the MS uses the pathloss property [10] of the communication channel. Pathloss is the distance-dependent power loss impairment of the channel that depends on different variables like the nature of the terrain, the antenna heights, the carrier frequency etc. Two or three such distance estimations for each neighbouring base station (NBS), carried out through a sequence of scannings of the NBSs at appropriately chosen time intervals, enable the MS to also estimate its relative velocity or relative angle of divergence (AOD) with respect to each NBS. These estimates of current relative distance also lead to the estimation of the current relative velocity or the current relative AOD with respect to each NBS. These estimates allow the MS to look ahead to determine such important matters like which NBSs to continue/discontinue monitoring and, most importantly, which NBS the MS is likely to come nearest to after it leaves its current cell. This advance knowledge will, in effect, allow the MS to make the best choice of the TBS (among all the NBSs being scanned) to which it (the MS) should be handed over by the SBS.

Thus, the two MS-controlled handover schemes that are described in this chapter specifically promise improvement of the existing Mobile WiMAX hard handover procedure in three aspects. First, unlike the almost blind or blanket scanning and ranging activities done in the conventional handover procedure, the MSs perform many fewer scannings in our schemes. This is not only due to possible initial elimination from further consideration of certain NBSs owing to their excessive current load but also due to possible elimination, in the middle of the scanning process, of one or more NBSs based on their comparatively poor performance in respect of relative velocity or relative AOD in Handover Techniques 1 and 2 respectively. Thus our handover schemes can address the well known problem of excessive scanning that not only substantially contributes to the relatively large handover delay in Mobile WiMAX networks but also adds to the load of the BSs.

The second improvement relates to the increased scalability of the WiMAX network, which can contribute to the growth of Mobile WiMAX networks in terms of serving a larger population of MSs. Scalability is achieved through sharing of much of the handover-related workload of the single SBS by the large number of MSs being served by it. This sharing of handover-related workload with its MSs allows the lone SBS in each cell to accommodate more MSs in its cell. This, in turn allows a large number of MSs to be present in the entire Mobile WiMAX network.

As for the third advantage of our proposed handover methods, in the conventional handover schemes, the MS initiates its scanning activities only when it senses that the level of the RSS received from the SBS has gone below a defined low threshold. Thereafter, the SBS, in conjunction with the network, tries, sometimes in vain, to complete the entire process of handover before the RSS becomes so low as to lead to call drops or a significant loss of packets. In contrast, in our proposed methods of handover (this particular point of discussion also includes our Handover Technique 3, which will be described in Chapter 5) the MS, while monitoring the RSS received from the SBS, periodically during its journey through the cell, perceives itself as occupying, at any time, one of four possible zones, viz., the Zone of Normalcy (ZN), the Zone of Concern (ZC), the Zone of Emergency (ZE) and the Zone of Doom (ZD). The MS performs all the different steps related to the entire handover process within these four concentric zones, making sure that the process of scanning starts well in advance, i.e. much before the RSS becomes too low, so that significant packet losses or call crops may not occur. The four zones are actually created to correspond to appropriately chosen RSS levels. These levels are so chosen that (i) the TBS selection process is normally completed within the ZC and (ii) the remaining part of the process of handover is completed by the SBS and the network within the ZE itself. The idea is to complete the entire handover process before the ZD is entered where the signal becomes too weak and noisy to complete handover.

4.2 Broad Approach of the Proposed Fast Handover Schemes

The two key ideas ingrained in “distance estimation and lookahead”, as published in our papers [74-75], that have been utilized in designing the two fast and simple handover schemes are:

- An MS can, at any time, approximately estimate its present geographical distance from any BS (SBS and NBSs) by measuring the RSS received from the concerned BS.

- Using a set of at least two, but preferably more, distance estimates for each NBS, an MS can perform an appropriate lookahead scheme for itself selecting its TBS via simple computation of either its relative velocity or relative angle of divergence with respect to each NBS. The idea is to be able to anticipate or foresee, sufficiently in advance, which NBS the MS is most likely to come closest to (and thus receive the maximum RSS from) after it leaves the zone (cell) of its present SBS.

  Thus, instead of just directly passing on to the SBS the RSS values received through scanning of each NBS, as is done in conventional handover schemes, the MS in our schemes first utilizes the RSS values to self estimate its own distances from the different NBSs. Thereafter, it computes its relative velocity or the relative angle of divergence with respect to each NBS before itself selecting its own TBS. The various steps that the MS performs in selecting its own TBS are as follows:

  (i) Self-ascertain its need of a handover by using the RSS received from the SBS and make a scanning request to the SBS.

  (ii) Self-estimate its current distances from each NBS by using the RSSs received from the NBSs.

  (iii) With two (preferably more) distance estimates from each NBS, perform lookahead to determine its extent of progressive or regressive movement with respect to each of its NBSs.

  (iv) Select as the TBS for the handover, the NBS, which shows the highest relative progressive movement and, finally,

  (v) Request the SBS to hand it over to its selected TBS.

From the above discussion, it is clear that the process of TBS selection is initiated and totally controlled by the MS. The only role, a very minor one, that is played by the SBS is granting the scanning intervals. The basic steps involved in both the above MS-controlled handover schemes are shown in Figure 4.1 as a combined block diagram of the fast Handover Techniques 1 and 2.

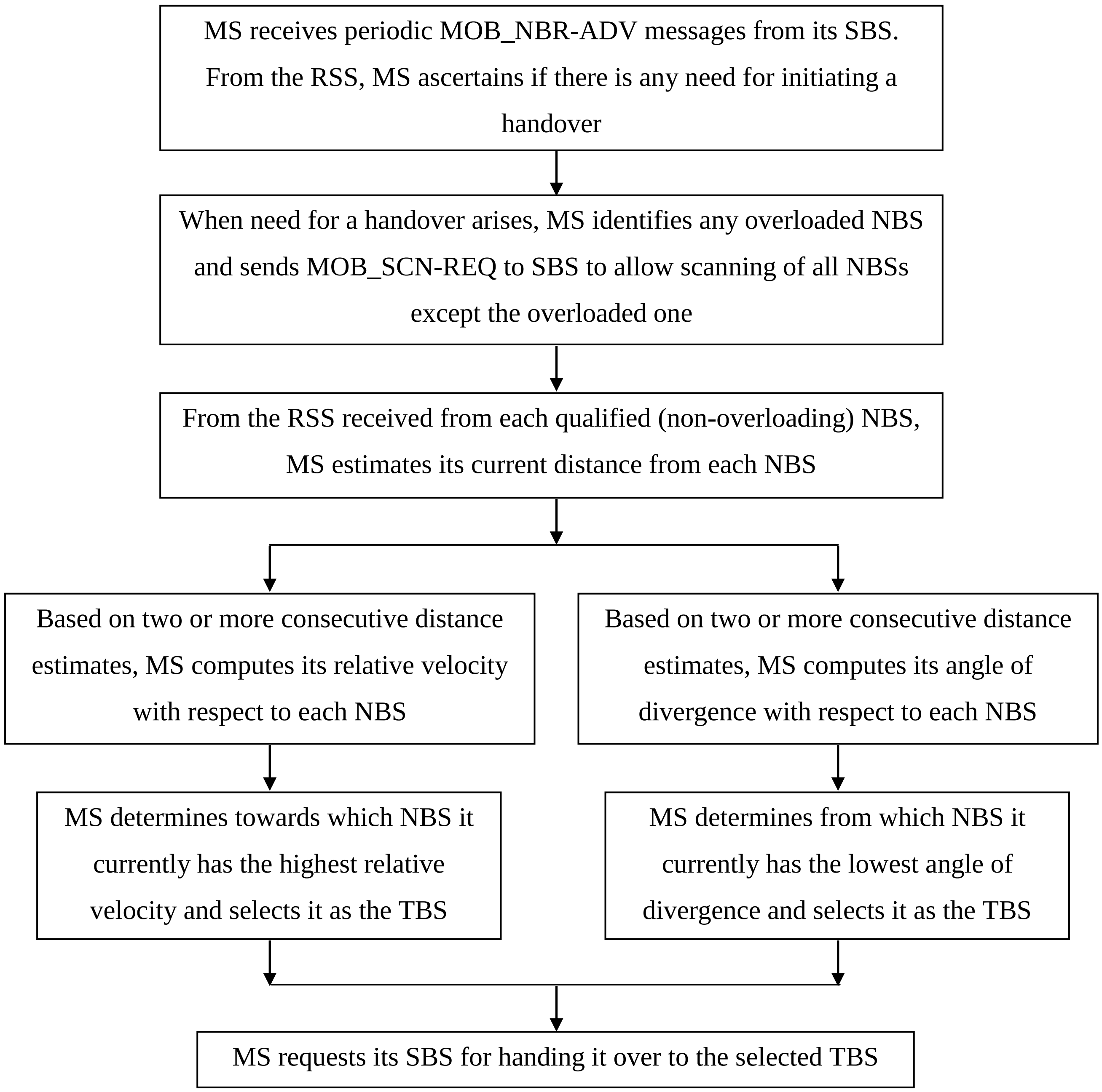


Figure 4.1: Combined Block Diagram of the Two MS-Controlled Fast Handover Techniques 1 and 2

4.3 Principle of Distance Estimation by MS Using the RSS

In this section we discuss the principle of distance estimation using the RSS that an MS receives from an NBS and then employs it to self-estimate its approximate current distance from the NBS. In free space or under the line-of-sight (LOS) condition of wireless signal propagation, the inverse square law for the ”pathloss” which refers to the nature of decay of the transmitted wireless signal with distance, was long known and utilized in the design of early wireless systems for estimating the range of signal broadcasts. This free-space pathloss formula, known as the Friis Formula [10], is precisely given as

$$P_r = P_t G_t G_r (\lambda/4\pi d)^2 \tag{4.1}$$

where P_t and P_r are the transmitted and the received power, respectively with G_t and G_r being the respective antenna gains (if directional antenna is used), $\lambda = cf$ (c is the velocity of light and f is the frequency of transmission) is the wavelength and d is the distance of the receiver from the transmitter.

4.3.1 Pathloss Under Non-LOS (NLOS) Condition

With the introduction of broadband wireless communication over longer distances using cellular architecture, the nature of signal power decay, i.e. pathloss, under the non-LOS (NLOS) condition began to be studied. It was observed that in terrestial communication, reflections from the earth and other objects affect the pathloss significantly if d is large ($d > 1$ Km). Also, a destructive interference is created because the radio waves, reflected from the ground, often experience a 180° phase shift. Developed under these comditions, the common two-ray approximation for pathloss in terrestial communication is given by

$$P_r = P_t G_t G_r h_t^2 h_r^2 / d^4 \tag{4.2}$$

where h_t and h_r are the heights of the send antenna and the receive antenna, respectively. The most important points to note in the above result is that (i) unlike in free space, the signal decays much faster under NLOS condition, approximately as the 4th power of the distance and (ii) besides distance and antenna gains as in Equation 4.1, the received signal now depends on the two antenna heights instead of depending on the frequency of the transmitted signal as in Equation 4.1.

Instead of such theoretically developed pathloss formulas like Equation 4.2, empirical models are often developed using experimental pathloss data. The empirical pathloss formula given by Equation 4.3 is one of the simplest ones that is most commonly used.

$$P_r = P_t P_0 (d_0/d)^{\alpha} \qquad (4.3)$$

This simple empirical formula accounts for all the various effects of antenna heights, antenna gains, transmission frequency etc, into just two paramaters, namely the "pathloss exponent" α and the measured pathloss P_0 at a reference distance d_0. Often, d_0 is 1 meter and P_0, instead of being actually measured at d_0 = 1 meter is approximated simply as $(4\pi/\lambda)^2$. However, more accurate empirical pathloss models like Okamura-Hata model, COST-231 Hata model, Erceg model, Walfisch-Ikegami model etc., are commonly used in practice [10]. These empirical models, unlike the empirical model of Equation 4.3, also consider the carrier frequency.

Out of the above models, the Hata model and its extension, the COST-231 Hata model are valid for a distance of 1 Km – 20 Km whereas the validity of the Erceg model and the Walfisch-Ikegami model ranges between 0.1 Km – 8 Km and 0.2 Km – 5 Km, respectively. Thus the Hata [10] and the COST-231 Hata models [10] are suitable for use in a macrocellular network achitecture where the radius of a cell is more than 1 Km whereas the Erceg and the Walfisch_Ikegami models are suitable for use in a microcellular network architecture where the cell radius is less than 1 Km. Since the radius of a cell is the WiMAX network usually lis in the range 500 m – 2 Km, the WiMAX Forum recommends that the COST-231 Hata model should be used for macrocellular WiMAX architecture and the Walfisch-Ikegami model should be used in microcellular WiMAX architecture. These two models are described in [10] . Between these two models, Walfisch-Ikegami model assumes an urban environment with a series of buildings whose average height, inter-building istance, street width, etc., are used as the parameters in the model. In a metropolitan centre, using the NLOS standard values of the various parameters, a simple equation with only two paramaters, viz., d and f, is obtained as given by Equation 4.4

$$\overline{PL} = -65.9 + 38 \log_{10} d + (24.5 + 1.5f / 925) \log_{10} f \qquad (4.4)$$

However, the COST-231 Hata model is recommended by the WiMAX Forum for Mobile WiMAX in both urban as well as suburban areas. The model is given in Equation 4.5.

$$PL = 46.3+33.9\log_{10}f-13.82\log_{10}h_b+(44.9-6.55\log_{10}h_b)\log_{10}d-a(h_m)+CF \quad (4.5.a)$$

where $a(h_m)$, the MS antenna-correction factor is given by

$$a(h_m) = (1.111\log_{10}f-0.7)h_m-(1.56\log_{10}f-0.8) \quad (4.5.b)$$

4.3.2 Multipath and Shadowing Problems

We showed in Section 4.3.1 that if the values of the relevant paramaters are known reasonably well, the MS can, at any time, roughly estimate its current distance from any NBS, by measuring the average received power RSS and then using this RSS value in the most appropriate pathloss equation. However, it is now well known that the wireless channel for broadband communication under NLOS condition (WiMAX can operate under NLOS condition) suffers from several major impairments besides the greatly increased pathloss, say, from d^{-2} in LOS to d^{-4} (approximately) in NLOS. These other major impairments include the phenomena called shadowing, multipath fading, intersymbol interference (ISI), doppler spread, noise and interference. Besides suffering the dominant distance-dependent pathloss, the received signal also suffers considerable power loss from two of the above impairments, namely, shadowing and multipath fading. Shadowing, also called the ”slow fading”, is caused by the presence of large obstructions in the NLOS path like tall buildings, big trees, foliage, etc. As a matter of fact, the WiMAX Forum recommends adding a 10 dB fade margin to the median pathloss predicted by the COST-231 Hata model to account for shadowing. In addition to the problem of shadowing, various reflecting and scattering objects in the NLOS path causes the transmitted signal to arrive at the receiver via multiple paths. Although this latter problem called ”multipath fading” occurs over small durations, it causes large random variations in the received signal amplitude. Thus, neglecting the remaining phenomena which are not significant, the signal received at the MS from an NBS may be broadly viewed as the sum of three component signals, namely, the pathloss signal, the shadowing or ”slow fading” signal and the multipath random ”fast fading” signal.

Out of the above three signal components the sum of which constitutes the RSS received by the MS, the problem of multipath fading is largely mitigated in WiMAX because of the use of the widely recognized OFDM scheme (as the method of choice for mitigation of the multipath problem in broadband wireless communication) in WiMAX data communication [18, 32, 77]. As an additional point, multipath signal is further reduced by filtering. Thus it may be reasonably assumed that multipath fading affects the RSS in WiMAX only insignificantly. That is, the pathloss and shadowing phenomena together determine the mean received power RSS, while the total received power fluctuates, though only slightly, around this mean value owing to the presence of multipath fading.

Thus, although shadowing can cause a somewhat significant degradation in the RSS value and we propose that the MS estimates its distance from an NBS using the RSS, the following points need to be appreciated to judge the validity of the proposed distance estimation process.

1. Pathloss and shadow fading together determine the RSS. The measured distance error is normally not very significant but increases when the RSS becomes weak. However, in the two distance-estimation and lookahead-based handover techniques described in this chapter, the RSS at the time of scannings is not expected to be weak. This is because the MS makes the scanning request immediately after entering the ZC where the RSS is assumed to be somewhat less than normal but still very much higher than the Minimum Acceptable Signal Level (MASL), as described in Section 4.5.
2. In recent research on localization in WiMAX networks based on signal strength observations [78], the authors proposed using RSS observations for distance estimation towards positioning and tracking in WiMAX networks. They claimed that RSS-based distance estimation provides sufficient accuracy for most of the location-based services. They conducted RSS measurements from a vehicle to 3 BSs in a WiMAX network in the city of Brussels where the environment have relatively dense buildings with heights ranging between four to seven floors. Moreover, some of these buildings were glass buildings. Obviously, shadowing should have had a strong presence in the measured

RSS. However, with the collected RSS Vs distance data, the authors developed the following model for the pathloss curve

$$Y = -22.98 \log_{10}(X) - 23.89 \tag{4.6}$$

where Y is the RSS and X is the distance between the BS and the MS. The matching obtained between the above model and the collected data was claimed to be good. Similar RSS-based localization and distance estimation ideas are also proposed in [79-81].

3. In localization, the RSS-based estimation of the MS's distance from a given BS must be reasonably accurate for reliably delivering location-based services. In contrast, in handover, the RSS-based distance estimation made by the MS for an NBS need not be that accurate. This is because in the former case, the goal of the MS is to measure its absolute distance from a particular BS with reasonably good accuracy. On the other hand, in the latter case, the MS just needs to compare its distance (ultimately by either of the two derived parameters, namely, the velocity or the AOD), from each NBS to select one of the NBSs as the TBS. Since the same pathloss formula is used to estimate the MS's distance from each NBS, an error in the RSS measurement will affect almost all the estimated distances in an identical manner. This will ensure that the error, even if not insignificant, will have no effect on the TBS selection which just requires comparison between the values of either of the two parameters, namely, relative velocity or AOD, both of which are derived from the estimated distances. Similarly, since all NBSs are scanned at the same time, any time-dependent variation of any parameter in the pathloss formula (e.g. two different adjacent wayside plantations crossed by the MS) will introduce the same amount of error in the estimated distances for all NBSs and will thus cause no error in the TBS selection. The only exception to this general observation will occur in case of shadowing by buildings or other tall and wide structures that may, once in a while, obstruct the NLOS path for one or some NBSs but not all. Unfortunately, no solution of the shadowing problem is known yet.

4.4 Load of a Base Station – Concept and Estimation

In a Mobile WIMAX network, as in any other network, the MSs exchange between themselves, via one or more BSs, volumes of data packets generated by them against their respective running applications. These data packets might have been created from text messages (e.g. e-mails), digitized VoIP message (i.e. voice calls) or multimedia messages pertaining to different applications. In order to exchange these messages (each message is broken up into a sequence of packets), an MS opens single or multiple connections to the respective recipient MSs via its SBS. The latter would forward each arriving data packet towards its right destination MS and each packet will thus reach its destination MS via a BS-path, beginning with the SBS and comprising of one or more forwarding BSs. In order to forward all the data packets belonging to all connections that pass through it (these connections have been opened by local and/or remote MSs of the BS), each BS keeps reserved some part of its total computational resource for performing the entire packet forwarding job. Through this important job of packet forwarding, a BS makes its own contribution to the overall MS-to-MS packet transport job performed by the network of which the BSs are some of the vital components.

A parameter for measuring a BS's activity (in terms of its packet forwarding contribution) is the total number of data packets that it forwards per second and this parameter is known as its aggregate packet forwarding throughput or simply "throughput" [82]. The maximum aggregate throughput that a BS is capable of (this is a BS design parameter) depends on its total computational resource and is called its throughput capacity. At any time, a BS has a throughput which is a fraction of its throughput capacity. The current throughput of a BS, when normalised to its throughput capacity, is commonly called the current "load" of the BS. Thus if the throughput capacity of a BS is N packets/sec and if its current throughput is M packets/sec, i.e. if it is presently forwarding M packets/sec on the average, then its current load (CL) is the fraction $CL=M/N, 0\leq L\leq 1$. Knowing the throughput capacity N of a BS, and counting the number of packets currently being forwarded by the BS per second, it is possible to measure the CL of a BS fairly accurately. However, this direct way of measuring the CL, though fairly accurate, is somewhat complex and, additionally, this much accuracy and dynamism of the measurement is not needed in many applications.

An alternative approach of measuring the CL has been employed by us, in all the three handover techniques studied by us. It is somewhat approximate but is simple to measure and offers a fairly static estimate of the CL. It estimates the CL by taking count of the number of connections currently being handled by a BS. As is well-known [82], the amount of resources reserved for a particular connection depends on the type of application and the QoS chosen by the user at the time of opening that connection. However, since a huge amount of packet traffic belonging to thousands of connections pertaining to different applications is aggregated at every BS, we may assume, for simplicity, that each connection requires similar amount of computational resource, on the average, per second. Next, let us assume that each BS has the capacity (in terms of total computational resources available) to open up to N connections at any time. So, if M (M < N) connections have already been opened through a BS, the BS is already consuming M/N part of its computational resource and can approximately allow only N-M more connections to pass through it. In other words, the CL of the BS at this time is M/N, approximately. Two important points should be noted here. First, counting the number of connections passing through any BS at any time is much simpler than counting the number of packets being forwarded by the BS per second. Second, since each connection (e.g. a digitized VoIP call) usually lasts for several minutes, the loss or gain of one or, at most a few connections caused by a single MS's leaving or joining a BS's cell following a handover has negligible effect on the BS's CL. As a matter of fact, the CL of a BS changes noticeably over a time frame of only minutes and not seconds. Thus the connection-based estimation of a BS's CL, though somewhat inaccurate, is fairly static, changing only marginally within time intervals on the order of tens of seconds or even more.

From the above discussion, the choice of CL as a meaningful parameter in the process of TBS selection is reasonably justified because of the following two important reasons.

1. A low value of the CL of an NBS implies that $M << N$ which, in turn, indicates that the NBS is presently running at a low throughput and thus has enough computational resources available for satisfactorily supporting many more connections. Hence the NBS, if later selected as the TBS, will offer good QoS and low call drop probability to the ongoing as well as future connections of any additional MS that maybe handed over to it.
2. Though somewhat inaccurate, connection count-based estimation of the

CL is much simpler and considerably more stable than packet count-based CL estimation and hence is well-suited for use in the WiMAX handover process. In this context, it should be remembered that in Mobile WiMAX the MS velocity varies in the range of 60 - 120 km/hr (this is equivalent to 33.3 - 66.6 m/sec) and the cell radius varies in the range 500 m - 2 Km. Hence the CL value which changes over a time frame of minutes maybe considered to remain fairly static during the process of a handover.

4.5 Distance Estimation-Based Handover and Concept of Zones

In section 4.3, we described the principle of distance estimation by an MS in the WIMAX network using the RSS. From now onwards, we shall assume that an MS can estimate, though somewhat roughly, its current distance from any NBS by first reading the RSS received from the NBS and then using the most appropriate pathloss model. With this distance estimation capability, we now argue that an MS can easily self-track its direction of motion relative to each NBS if we make an assumption that the MS's motion, while it is at the fag end of its journey across a cell, is "broadly linear" over a "certain time frame". Some justification behind this assumption along with some quantitative idea about the "certain time frame" will be presented in Section 4.8 after we have described the two handover techniques, namely Handover Technique 1 and Technique 2 in Section 4.6 and 4.7, respectively. For the present, we shall proceed on the basis of the above stated assumption.

Now, in order to achieve the self-tracking of its motion, the MS scans each NBS (or each selected NBS) and measures the RSS from it at a set of chosen time instants. Then the MS uses these RSS values (samples) to make an estimate of each NBS's distance from it at those time instants. With the help of these estimated distance values (samples), the MS not only works out whether its current movement relative to each scanned NBS is progressive or regressive but also performs an appropriate lookahead to identify the particular NBS towards which it is heading most (or the fastest). With this knowledge, the MS obviously selects this NBS as its TBS, because it reasonably expects to receive the strongest signal after the handover (unless, of course, it moves considerably away from its broadly linear path before the handover is complete). This concept of using RSS-based distance estimation by a mobile node to self-monitor its dynamic neighbourhood and, especially, to look ahead towards identifying its likely-to-join and likely-to-leave neighbours, was used in a Modified Distance Vector Routing (MDVR) algorithm proposed for a MANET [76].

In this Thesis, we have investigated two distance estimation-based lookahead algorithms for handover in Mobile WiMAX. These two handover techniques, called "DiCD-Based TBS Lookahead Technique" and "AOD-Based TBS Lookahead Technique" will be described in Sections 4.6 and 4.7, respectively. It needs to be especially mentioned that, though both these techniques employ RSS-based distance estimation and lookahead, they actually employ two different kinds of lookahead methods. For this reason, they have been studied as two different techniques.

4.5.1 Concept of RSS-Based Zones for Efficient Handover

In order to efficiently manage the entire process of handover in all the three handover techniques that we have studied (Handover Technique 3 will be described in Chapter 5), a novel concept of RSS power based zones has been introduced. By partitioning the dynamic range [0, P_m] of the RSS power P, that an MS can receive from its SBS, into three different levels, P_1, P_2 & P_3, $P_1<P_2<P_3$, the MS creates four conceptual zones as shown in Figure 4.2. These four zones have been named the Zone of Normalcy (ZN), the Zone of Concern (ZC), the Zone of Emergency (ZE) and the Zone of Doom (ZD). They correspond to RSS powers lying in the ranges ($P_m \geq P > P_3$), ($P_3 \geq P > P_2$), ($P_2 \geq P > P_1$) and ($P_1 \geq P$), respectively. The MS periodically monitors the RSS power of its SBS via the MOB_NBR-ADV broadcasts [20] for identifying the zone it is presently in. Very little handover-related activity is needed in the ZN (except for periodic monitoring of the MOB_NBR-ADV broadcasts) and, on the other hand, all handover-related activities (including those carried out by the SBS and the network, after the TBS has been selected) should be completed, as far as possible, before the ZD is entered. This latter requirement is intended to avoid excessive packet losses or call drops which may otherwise occur owing to very poor RSS in the ZD. From the technical implementation point of view of the different zones ZD may be defined as the zone where the RSS threatens to drop below the receiver's (i.e. MS's) sensitivity at the lowest modulation scheme (typically ½ rate QPSK), which defines the upper threshold P_1 of ZD that is also the lower threshold of ZE. Similarly, the lower threshold of ZN, denoted by P_3, may be taken to be the receiver's sensitivity at the highest modulation scheme (typically 5/6 rate 64-

QAM) or one of the near highest modulation schemes to suit the operational requirements of the network operator. The lower thresholds P_2 of ZC and P_1 of ZE may be chosen to divide the interval between P_1 and P_3 into two equal parts based on the operational considerations of the network operator.

It is clear that, being aided by this concept of four zones, the MS can perform its total set of handover-related functions in the right sequence and at the right times. Of special importance is the fact that the MS, unlike as in the conventional Mobile WiMAX handover procedure [20], completes a good part of the handover-related jobs even before the RSS from the SBS reaches the pre-defined handover-threshold level. As a final point, the intelligent utilization of the four zones in the three handover techniques in Mobile WiMAX that have been described in this Thesis will be pointed out during the respective descriptions.

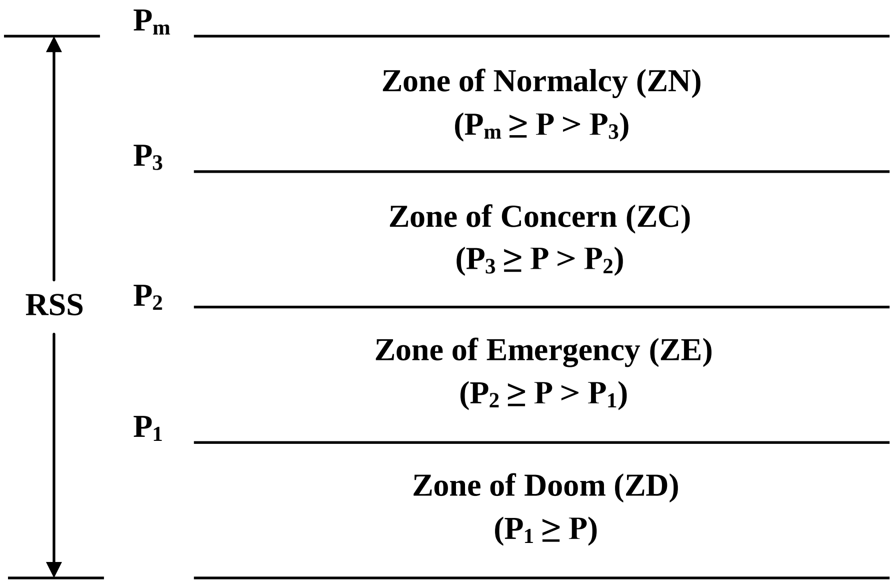


Fig. 4.2 Zones based on RSS Levels

4.6 DiCD-Based TBS Lookahead Scheme

The first distance estimation and lookahead-based HO technique employs the concept of estimating the "Differences in Consecutive Distances" (DiCD) of the MS from each NBS for selecting the TBS on the basis of highest "accumulated forward movement" (AFM). In this "lookahead" algorithm, the MS does multiple distance calculations, periodically, for each of the NBS and from those set of distance samples it can self-ascertain whether its movements relative to a particular NBS is progressive or regressive. The MS can then compare between the progressive movements to identify the NBS with the highest AFM. Basically, the scheme goes like this. From the chosen most appropriate pathloss Equation, the MS can easily get an estimate of its distance from any particular NBS at different points in time. Thus, if its distance d to an NBS is estimated as $d_1 = d(t_1)$ and $d_2 = d(t_2)$ at the time instants t_1 and t_2 $(t_2 > t_1)$, respectively, then, during the duration $T=t_2-t_1$ of the time interval (t_1, t_2), the MS has an average relative velocity of

$$\bar{v}_{1,2}=(d_2-d_1)/T=|\bar{v}_{1,2}|\,\mathrm{sgn}(\bar{v}_{1,2}) \qquad (4.7)$$

with respect to the NBS, where $\bar{v}_{1,2}$ is a simpler representation for $\bar{v}_{t1,t2}$ (i.e. the average relative velocity of the MS with respect to the NBS during the time interval $T=t_2-t_1$).

In Equation 4.7, the magnitude $|\bar{v}_{1,2}|$ of $\bar{v}_{1,2}$ indicates how fast the MS is approaching towards or receding from the NBS, i.e. $|\bar{v}_{1,2}|$ indicates the speed of progression or regression of the MS, relative to the NBS. On the other hand, $\mathrm{sgn}|\bar{v}_{1,2}|$ signifies whether the MS is moving towards [if $\mathrm{sgn}|\bar{v}_{1,2}|<0$] or away from [$\mathrm{sgn}|\bar{v}_{1,2}|> 0$] the NBS, implying thereby whether the motion of the MS, relative to the NBS, is progressive or regressive. It is obvious that if the motion of the MS relative to a particular NBS is regressive, (i.e. $\mathrm{sgn}|\bar{v}_{1,2}|> 0$), then that NBS should not be considered as a potential TBS by the MS. Thus, an MS basically chooses its TBS based on the acquisition of a few periodic samples of the RSS from each NBS and then use of the principle of self-estimation of distance followed by a simple lookahead scheme. We keep all the successive sampling periods (i.e. the inter-scanning intervals) constant at T seconds, i.e. if $T=t_i-t_{i-1}$ for all i, i = 2, 3, …, and assume that $\{d_i\}$ are the distances estimated at the scanning instants $\{t_i\}$, i = 1, 2, …. This makes the values $\{\Delta_{i-1,i}\}=\{d_i-d_{i-1}\}$ (i.e. $\Delta_{1,2}=d_2-d_1, \Delta_{2,3}=d_3-d_2$, and so on) of the successive "differences in consecutive distances" (DiCD) of the MS from an NBS themselves represent the average velocity (after scaling by the factor 1/T) of the MS, relative to the NBS, during the respective equal time intervals (t_1,t_2), (t_2,t_3) and so on. Accordingly, each individual DiCD may, generally speaking, be given by the following vector:

$$\Delta_{i-1,i} = d_i - d_{i-1} = |d_i - d_{i-1}| \operatorname{sgn}(d_i - d_{i-1}) \quad (4.8)$$

Now, in order to explain the DiCD-based TBS lookahead scheme with an illustration, we consider the scenario depicted in Figure 4.3. In the figure, we assume that the MS has six NBSs, B, C, D, E, F and G, clustered around its SBS A and the MS is moving along a straight line (shown in the solid line) in the direction shown in Figure 4.3. Thus, in the above context, referring to Equation 4.8, the DiCD of the MS from an NBS, say NBS B, in Figure 4.3, if scanned during the time interval (t_{i-1}, t_i), will be given by

$$\Delta_{i-1,i}(B) = d_i(B) - d_{i-1}(B) = |d_i(B) - d_{i-1}(B)| \operatorname{sgn}[d_i(B) - d_{i-1}(B)] \quad (4.9)$$

At this point, we make the assumption that the MS is presently enjoying satisfactory

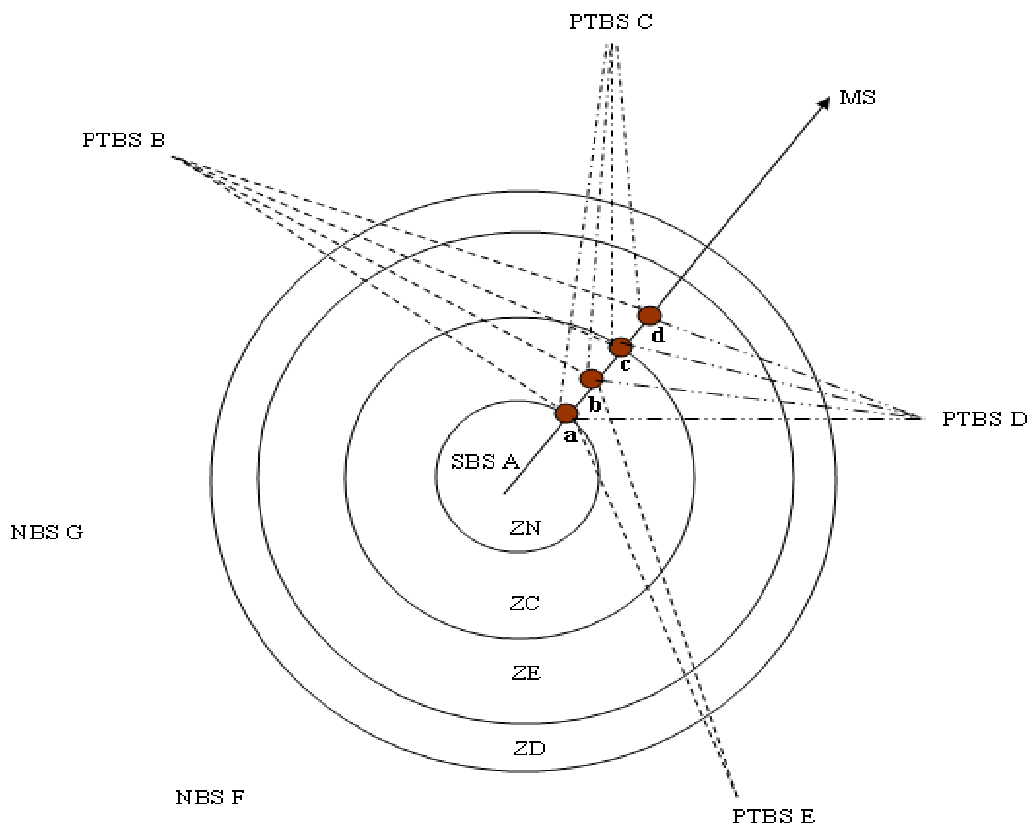


Fig. 4.3 Distance Estimation-cum-DiCD-based Lookahead Scheme

signal strength from its current SBS A so that it ascertains that it is inside the ZN now. This is ascertained by the MS through periodic monitoring of the MOB_NBR-ADV messages broadcast by the SBS that, along with other relevant information, also contain information about the current load (CL) of each of its NBSs. The SBS gathers this information about each NBS through the periodic information exchange between each NBS and the SBS that takes place via the backbone network. How the MS selects its TBS may now be explained as follows:

Step 1: During its stay in the ZN where the MS receives high RSS P ($P_m \geq P > P_3$) from its SBS, it creates a set of Potential TBSs (PTBS) based on some minimum acceptable values for the CL of each NBS. It should be explicitly noted in this context that measuring the RSS P from its SBS comes to the MS automatically and needs no scanning as in the case of measuring the RSS from an NBS. Thus, based on the CL information, only those NBSs that are not highly overloaded are chosen fit for being included in the PTBS set (see Section 4.4 for more details). Thus, in Figure 4.3, we arbitrarily assume that NBSs B, C, D and E are chosen by the MS as the PTBSs and NBSs F and G are excluded. This screening prevents the MS from discovering at a later stage that its selected TBS, because of its excessive CL, is incapable of providing the necessary QoS for the ongoing call. Thus, making the TBS selection from the PTBSs not only reduces the number of NBSs to be scanned but also removes the unfortunate possibility of an MS receiving a poor quality service after handover.

Step 2: When the MS enters the ZC, after leaving the ZN, it starts receiving a power P ($P_3 \geq P > P_2$) from the SBS, which is "somewhat less than normal but still much higher than an appropriately chosen MASL" [31], which should notionally be about P_2 or a little lower than P_2. In anticipation of the possible need for a handover, the MS now starts preparing itself for a possible handover activity. To start with, it requests for scanning each PTBS and when the request is granted, it scans each PTBS at every T second interval. The values of the number of scannings N_s and of T are chosen based on factors such as the current velocity of the MS, the number of PTBSs, etc. Also, the MS continues measuring the RSS of the SBS in order to know which zone presently it is in. We assume, for simplicity, that for the present case (Fig. 4.3), the MS initiates three consecutive scanning cycles at the time instants t_1, t_2 and t_3, where $t_2 - t_1 = t_3 - t_2 = T$. The MS is located at the points a, b and c, respectively, on the line of its motion, at these time instants. At this point, it needs to be noted that unlike T, the inter-scanning interval, which is a constant, the duration of each scanning cycle, during which several NBSs are scanned, is variable in nature, but is much smaller than T. That is, the duration of each scanning cycle is negligible compared to the inter-scanning interval T_1. During each of the scanning cycles, the MS acquires its distance estimates from all the four PTBSs B, C, D and E. Thus it obtains the three sets of approximate distances {aB, aC, aD, aE}, {bB, bC, bD, bE} and {cB, cC, cD, cE} at approximately the three successive T second intervals beginning t_1, t_2 and t_3. All these approximate or roughly estimated distances are shown in Figure 4.3.

Next, utilizing the view of the DiCD $\Delta_{i-1,i}$, as a scaled version of the average relative velocity $\bar{v}_{i-1,i}$ of the MS with respect to an NBS (refer to Equations 4.7 through 4.9), the MS first computes its DiCD with respect to each of the four PTBSs (i.e. B, C, D and E in Figure 4.3) at time t_2, at the end of the first inter-scanning interval (t_1, t_2) as

$$\Delta_{1,2}(B) = bB - aB \tag{4.10}$$

$$\Delta_{1,2}(C) = bC - aC \tag{4.11}$$

$$\Delta_{1,2}(D) = bD - aD \tag{4.12}$$

$$\Delta_{1,2}(E) = bE - aE \tag{4.13}$$

Similar results are obtained for the next inter-scanning interval (t_2, t_3), as well as for any additional inter-scanning intervals, if additional scanning cycles are performed. As explained in Equation 4.7, the sign and magnitude in the value of a DiCD, respectively, indicates the MS's direction of movement and the speed of movement, respectively, with respect to an NBS. Thus, for this 3-scan case ($N_s = 3$), the MS simply accumulates its relative movement samples with respect to each PTBS, i.e. it computes the respective 'Accumulated Forward Movement' (AFM), during the entire scanning session for each PTBS as

$$AFM_B: \quad \Delta_{1,2}(B) + \Delta_{2,3}(B) \tag{4.14}$$

$$AFM_C: \quad \Delta_{1,2}(C) + \Delta_{2,3}(C) \tag{4.15}$$

$$AFM_D: \quad \Delta_{1,2}(D) + \Delta_{2,3}(D) \tag{4.16}$$

$$AFM_E: \quad \Delta_{1,2}(E) + \Delta_{2,3}(E) \tag{4.17}$$

noting that each term as well as the AFM value in each equation may be either positive or negative.

The MS now chooses one or, preferably two PTBSs, which show the highest values of AFM, as the "candidate" TBSs (CTBS). Two CTBSs are chosen only if they both show contending AFM values that are not much different from each other. Otherwise, the PTBS with the highest AFM is directly chosen as the TBS. It should noted at this point that, in our scheme, we proposed three scanning cycles to be carried out before choosing the TBS (or two CTBSs) for more accuracy to be gained by the principle of averaging (division by Ns has been avoided to save MS's battery power), since a decision could certainly be taken after only two scannings. Although performing more number of scanning cycles implies that the TBS can be chosen much more reliably but it also takes more scanning time (or delay) and hence, there is clearly a need for a trade-off. Now, from the chosen CTBSs (i.e. CTBS C and CTBS D in Figure 4.3), the MS will ultimately select one as the TBS after it enters the ZE. In this context, two things may be pointed out that. Firstly, an MS will discontinue further scanning a PTBS if its relative movement with respect to that PTBS at any stage (i.e. during any scanning cycle) becomes regressive. For example, referring to Figure 4.3, it can be seen that relative movement of the MS with respect to the PTBS E after the second scanning cycle is regressive (i.e. sign of the DiCD is positive) and hence MS could discontinue further scanning of PTBS E. Clearly this would reduce the workload of both MS and SBS. Secondly, to be selected as a CTBS, a PTBS should not only show a progressive movement but should also maintain a signal level fairly higher than the MASL at all scannings, including the last one. This progressive movement check and the MASL check should be done only for the two tentatively selected CTBSs (CTBS C and CTBS D in Figure 4.3) and in the last scanning. The second criteria can possibly ensure that the MS will receive at least some minimum signal level from the chosen TBS (the next SBS) for sometime even after the handover.

Step 3: Immediately after reaching the ZE $(P_2 \geq P > P_1)$, the MS finalizes its selection of the TBS from among the two chosen CTBSs (i.e. CTBS C and CTBS D in Figure 4.3) in the manner discussed below and requests the SBS for an urgent handover, by passing the selected TBS's ID to the SBS through the MOB_HO-IND message [22]. The handover should be completed before the MS enters the ZD. However, in this context, it may again be noted that this final selection process between the chosen two CTBSs is needed only if two CTBSs are selected instead of one in the ZC. Moreover, it needs to be stated that in case two CTBSs are selected, deferring the final selection of the TBS from the ZC to ZE is in accordance with the well known "look before you leap" dictum, which requires a last moment check and is necessitated in the present case by the possibility that the MS may change its direction of motion even at the last moment. The MS implements this dictum using the following three algorithmic steps just after having entered the ZE:

(i) The RSS (P) is measured from the SBS. If $P_3 \geq P > P_2$, then the MS has re-entered the ZC by changing its direction of movement after the last monitoring of its RSS and hence no handover is now needed. Otherwise,

(ii) A final scanning cycle for the two chosen CTBSs is performed. Thus, in Figure 4.3, the final scanning cycle is performed for CTBSs C and D at the point d. The CTBS having the highest priority and the CTBS having the second highest priority (if there is one) are denoted as CTBS 1 and CTBS 2, respectively. In Figure 4.3, CTBS C becomes the CTBS 1 as it shows the highest AFM value. If CTBS 1 still shows a progressive movement (with respect to the previous scanning done in the ZC) and also satisfies the MASL criterion, it is selected as the TBS, else CTBS 2 is selected. This step reasonably makes the assumption that at least one of the two CTBSs, selected on the basis of highest AFM together with having shown both progressive movement and above-the-MASL signal level till the last scanning, will hopefully maintain the trend for some more time even after the handover operation has been completed.

Lastly, (iii) the chosen TBS's ID is passed on to the SBS for effecting an urgent handover.

In the zone ZD ($P_1 \geq P$), RSS of the SBS drops below P_1 and chances of the ongoing communication being disrupted, possibly causing a call drop or loss of packets or erroneous communication in general, are very high. In our scheme, the handover activity is expected to be completed, almost all the time, before the MS enters this zone. Figure 4.4 shows the flowchart of the proposed scheme (Handover

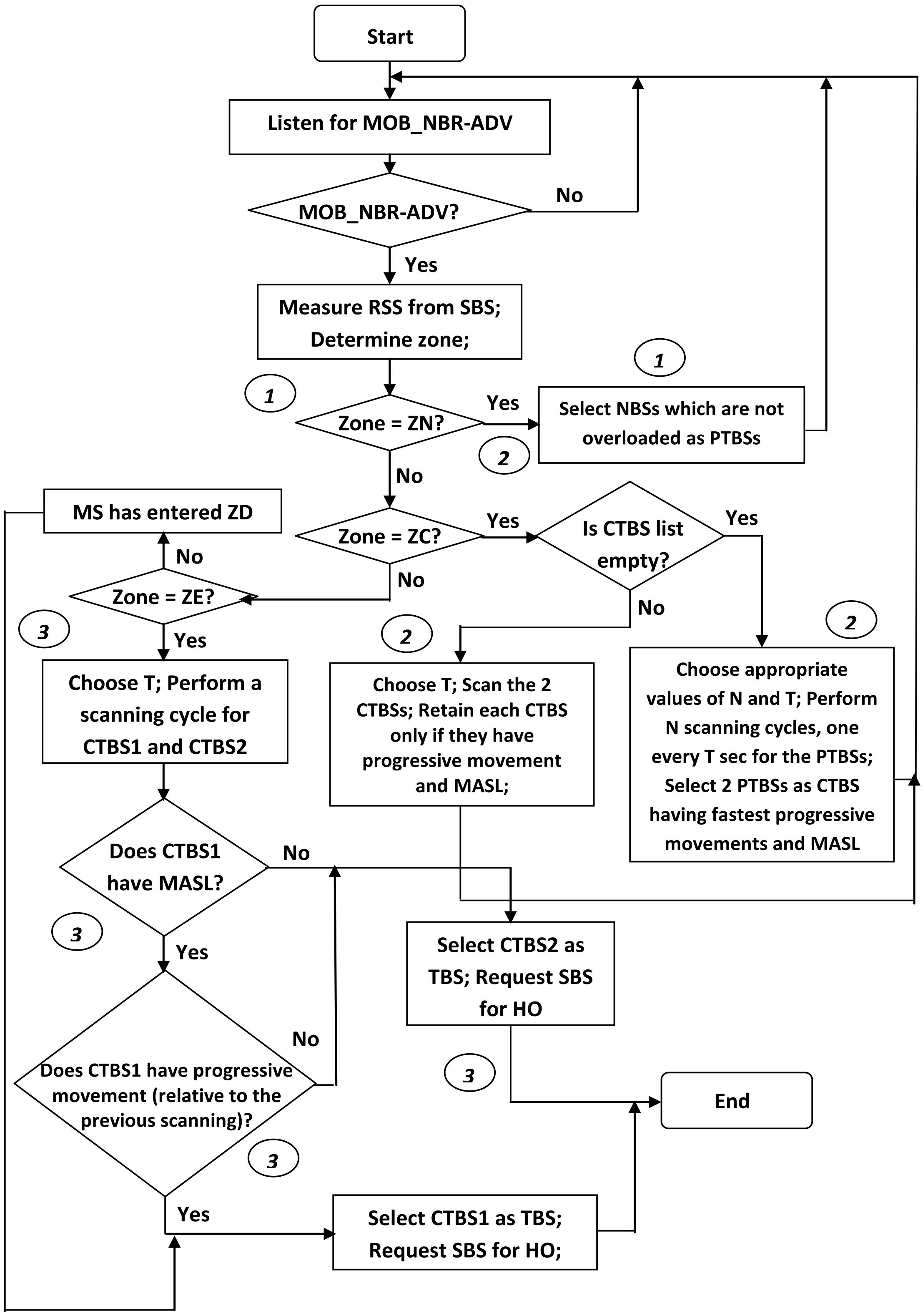


Fig. 4.4 Flowchart of the DiCD-based Fast MAC-Layer Handover Scheme

Technique 1) that has been employed for simulation. The different steps of the DiCD-based lookahead scheme for fast handover that are performed by each MS have been shown in the figure. In order to keep the simulation work simple and manageable, we have made the following two assumptions:

(i) Reverse transition to the adjacent zone (i.e. ZC → ZN, ZE → ZC and ZD → ZE) never occurs. This assumption follows from the assumption of broad linear motion of the MS during the handover process, which is elaborated and justified in Section 4.8.

(ii) TBS selection is always completed in the ZE and the MS performs nothing in the ZD, including monitoring the MOB_NBR-ADV.

4.7 AOD-Based TBS Lookahead Scheme

In this second distance estimation and lookahead-based handover method, Handover Technique 2, an MS performs a lookahead by estimating the angle of divergence (AOD) of each NBS with respect to its own direction of motion. Figure 4.5 illustrates the concept of AOD in the context of an MS and its NBS. Let us assume that an MS moving along the straight line path AbC (MS's motion was assumed to be broadly linear over a certain time frame in Section 4.5) is presently located at b and the NBS is located at B. The AOD of the MS with respect to the NBS is the angle CbB, which is included between the direction of the MS's linear motion and the line connecting the MS with the NBS. It is fairly obvious that smaller the AOD, the faster

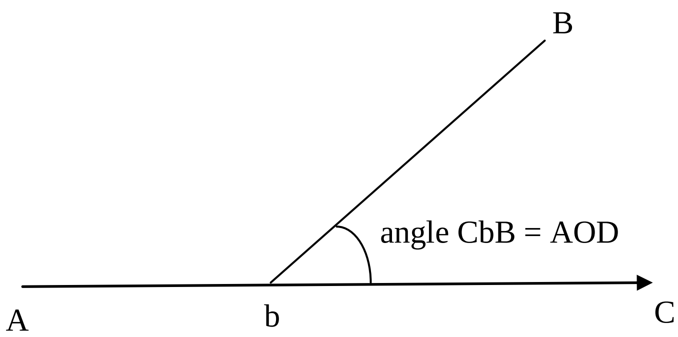


Fig. 4.5 Concept of AOD in the Context of an MS Moving Past the NBS

is the progressive movement of the MS towards the NBS. Clearly, for the MS, the fastest possible movement towards an NBS would occur when the AOD of the MS with respect to the NBS is zero degree. In the present example, the fastest movement would require the line AbC to coincide with the line bB.

For the purpose of explaining the AOD-based TBS lookahead scheme, we consider the scenario depicted in Figure 4.6 where the MS has six NBSs, A, B, C, D, E and F, clustered around its SBS S, and the MS is moving along the straight line XY.

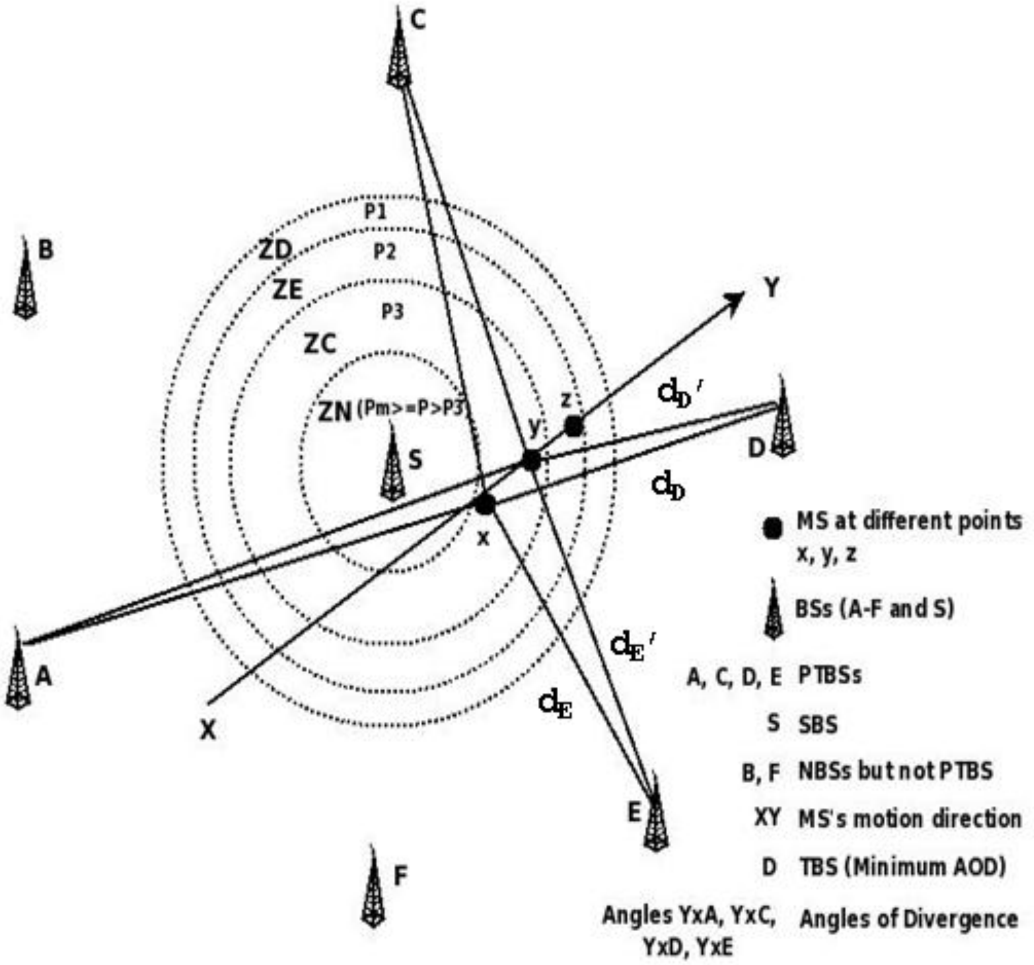


Fig. 4.6 Distance Estimation-cum-AOD-based Lookahead Scheme

How the MS selects its TBS using a 3-step procedure may now be explained as follows:

Step 1: During its stay in the ZN $(P_m \geq P > P_3)$ where the MS receives high RSS P from its SBS, the MS creates, by monitoring the periodic MOB_NBR-ADV broadcasts made by the SBS S, its set {A, C, D, E} of PTBS. That is, the MS has excluded the two NBSs, B and F, which are presently highly overloaded (CL is very high) and thus do not have the capability to become a TBS. As explained in the context of the previous scheme, this screening or short listing prior to the process of scanning not only reduces the number of PTBSs to be scanned but also removes any unfortunate possibility for the MS to receive a poor quality service after handover.

Step 2: When the MS enters the ZC, after leaving the ZN, it starts receiving a power P ($P_3 \geq P > P_2$) from the SBS, which is "less than normal but still much higher than the MASL". So, in anticipation of the possible need for a handover, the MS now starts preparing itself for a handover activity. Accordingly, for initiating the process of scanning of the PTBSs, it sends a MOB_SCN-REQ message to its SBS. Upon receiving the MOB_SCN-RSP message from the SBS, the MS scans each PTBS at every T second interval. The values of N_S (number of scannings), and T, are chosen based on factors such as the current velocity of the MS, the number of PTBSs, etc. Also, the MS continues measuring the RSS of the SBS in order to know which zone presently it is in. The MS initiates two consecutive periodic scanning cycles at the time instants t_1 and t_2 where $t_2 = t_1 + T$ seconds. In Figure 4.6, the MS is located at the points x and y, respectively, on the line of its motion, at these two time instants. So, at the point x, the MS scans the four short-listed PTBSs, A, C, D and E, in order to obtain the RSSs from them for the purpose of estimating their respective current distances d_A, d_C, d_D and d_E, respectively, from it. Next, after the appropriately chosen period of time T seconds, when the MS is at the point y on its line of motion, the MS starts a second scanning cycle for the four PTBSs (or less, if the RSS from any one was below the MASL) to estimate their respective changed distances d_A', d_C', d_D' and d_E' from it.

Now it may be observed from Figure 4.6 that after the two scanning cycles, pair of distance samples for each PTBS have been obtained. These sample pairs are (Ax, Ay) for A, (Cx, Cy) for C, (Dx, Dy) for D and (Ex, Ey) for E and their measures are (d_A, d_A'), (d_C, d_C'), (d_D, d_D') and (d_E, d_E') respectively. Accordingly, a triangle has been formed for each PTBS (e.g. $\triangle xAy$ for A, $\triangle xCy$ for C, $\triangle xDy$ for D and $\triangle xEy$ for E), with all the four triangles standing on the same common side (base) xy which lies on the line of motion of the MS. The assumption of all four triangles standing on the same base xy is justified by the fact, previously pointed out under Step 2 in Section 5.6 that the duration of a scanning cycle is negligible compared to the duration of the inter-scanning interval. More importantly, it should also be observed that the line of motion XY of the MS has created, at the point x, an "angle of divergence" AOD (e.g., angle Cxy) with each PTBS on each triangle. The AOD value θ $(0° \leq \theta \leq 180°)$, which is different for different NBSs, characterizes the direction of motion of the MS relative to the four (static) PTBSs as detailed in Table 4.1. With respect to the table, it should be mentioned that, for the special values of $\theta = 0°$ and $\theta = 180°$, the concept of a triangle itself vanishes.

Table 4.1 Angles and their Characterization of MS's Motion.

Value of θ	**Characterization of the motion of MS w.r.t. the PTBS**
0º	MS is moving exactly towards the PTBS, i.e. will have the highest possible progressive or forward movement towards the PTBS.
$0°<\theta<90°$	The MS is moving towards the PTBS but its progressive movement towards the PTBS will be less than the highest possible value, which occurs at θ=0º.
90º	Movement of the MS is tangential and cannot be characterized as either progressive or regressive w.r.t. the PTBS.
$90°<\theta<180°$	The MS is moving away from the PTBS but its regressive movement away from the PTBS will be less than the highest possible value, which occurs at θ=180º.
180º	The MS is moving exactly away from the PTBS, i.e. it will have the highest possible regressive or backward movement away from the PTBS.

From the above, it is obvious that the PTBS with the lowest value of the AOD θ will promise to offer the strongest RSS to the MS in the near future as the MS will move past nearest to it. As a consequence, this PTBS will offer the strongest signal to the MS and hence should be selected as the TBS. However, to achieve this lookahead, some means of identifying the PTBS having the minimum value of θ must be found out. This problem has been solved with the following two observations:

1. In each triangle, (e.g. $\triangle Cxy$) the lengths of all the three sides are known. While lengths of two of the sides have been estimated through scanning and RSS measurement (sides Cx and Cy), length of the third (common) side xy can be computed from the vehicle's odometer as the actual distance traversed by the vehicle during the time interval T.
2. In accordance with the well known "Law of Cosines" in trigonometry, cosine of any angle of a triangle can be determined, if all three sides of it are known. Using this Law of Cosines in each of the four triangles $\triangle Axy$, $\triangle Cxy$, $\triangle Dxy$ and $\triangle Exy$ in Figure 4.6 (these four triangles all stand on the same base xy), the cosine of their corresponding angles, namely, $Cos\theta_A$, $Cos\theta_C$, $Cos\theta_D$ and $Cos\theta_E$ can be computed as follows:

$$Cos\theta_A = \{(Ax)^2+(xy)^2-(Ay)^2\}/\{2(Ax)(xy)\} \qquad (4.18.a)$$

$$Cos\theta_C = \{(Cx)^2+(xy)^2-(Cy)^2\}/\{2(Cx)(xy)\} \qquad (4.18.b)$$

$$Cos\theta_D = \{(Dx)^2+(xy)^2-(Dy)^2\}/\{2(Dx)(xy)\} \qquad (4.18.c)$$

$$Cos\theta_E = \{(Ex)^2+(xy)^2-(Ey)^2\}/\{2(Ex)(xy)\} \qquad (4.18.d)$$

The PTBS, which corresponds to the minimum among these four angles, θ_A, θ_C, θ_D and θ_E will have the highest value for the cosine of its angle. A look at Figure 4.6 shows that the angle θ_D, i.e. the angle Dxy, is the smallest so that the computation of $Cos\theta_A$, $Cos\theta_C$, $Cos\theta_D$ and $Cos\theta_E$ will reveal that $Cos\theta_D$ is the largest among them and hence D should be chosen as the TBS.

Thus, by computing the cosine of the respective AOD of the PTBSs and comparing them with one another, the MS can select the TBS out of all the PTBSs as the NBS that shows the least AOD. However, if there are two PTBSs that show closely contending AOD values with respect to each other, then the MS does not make the final selection of the TBS at this time in keeping with the well known "look before you leap" dictum, which requires a last minute check. Instead, it selects two

PTBSs, to be called Candidate TBSs (CTBS). The two must have the largest and nearly equal values of $Cos(\theta)$, must show a progressive movement ($0° \le \theta < 90°$) and must have a signal level greater than the MASL.

Step 3: After reaching the ZE $(P_2 \geq P > P_1)$, the MS requests the SBS, through a MOB_HO-IND message [22], for executing an urgent handover by passing the ID of the selected TBS D. As stated earlier, the complete HO process should be completed before the MS enters the ZD to avoid a call drop or excessively erroneous communication owing to poor RSS. However, it is obvious that some additional delay would occur in the ZE if, instead of a single PTBS being directly selected as the TBS, two closely contesting PTBSs are selected as CTBSs in the ZC. In that case, in order to carry out the final selection of the TBS between the two CTBSs, the MS carries out a final pair of scanning iterations for CTBS 1 and CTBS 2 at the point z in Figure 4.6. Then CTBS 1 is selected if it shows both a progressive movement (compared to its previous distance) and a signal level greater than MASL. Otherwise, CTBS 2 is selected. Obviously, it is being implicitly assumed that at least one of the two CTBSs will show both a progressive movement and a signal level greater than MASL. Figure 4.7 shows the flowchart of the AOD-based TBS lookahead scheme where the functions implementing the three major steps in this AOD-based TBS lookahead scheme have been marked.

Before closing this section, an attention is needed to be drawn to an important, though somewhat obvious, point. In order to select the TBS in the DiCD-based TBS lookahead scheme (described in Section 4.6) three scanning cycles were performed to yield two DiCD samples of each NBS, which were averaged in the form of AFM. In contrast, in order to select the TBS in the AOD-based TBS lookahead scheme, described in this section, only two scanning cycles were performed to yield a single AOD sample of each NBS, with no averaging thus being possible to be done. Since, both the two cases were meant for simple illustration, the choice of the different number of scannings in the two cases (three and two respectively) was just incidental. It should be obvious that three scanning cycles will also need to be performed in the AOD-based TBS lookahead scheme to yield two AOD samples of each NBS. These

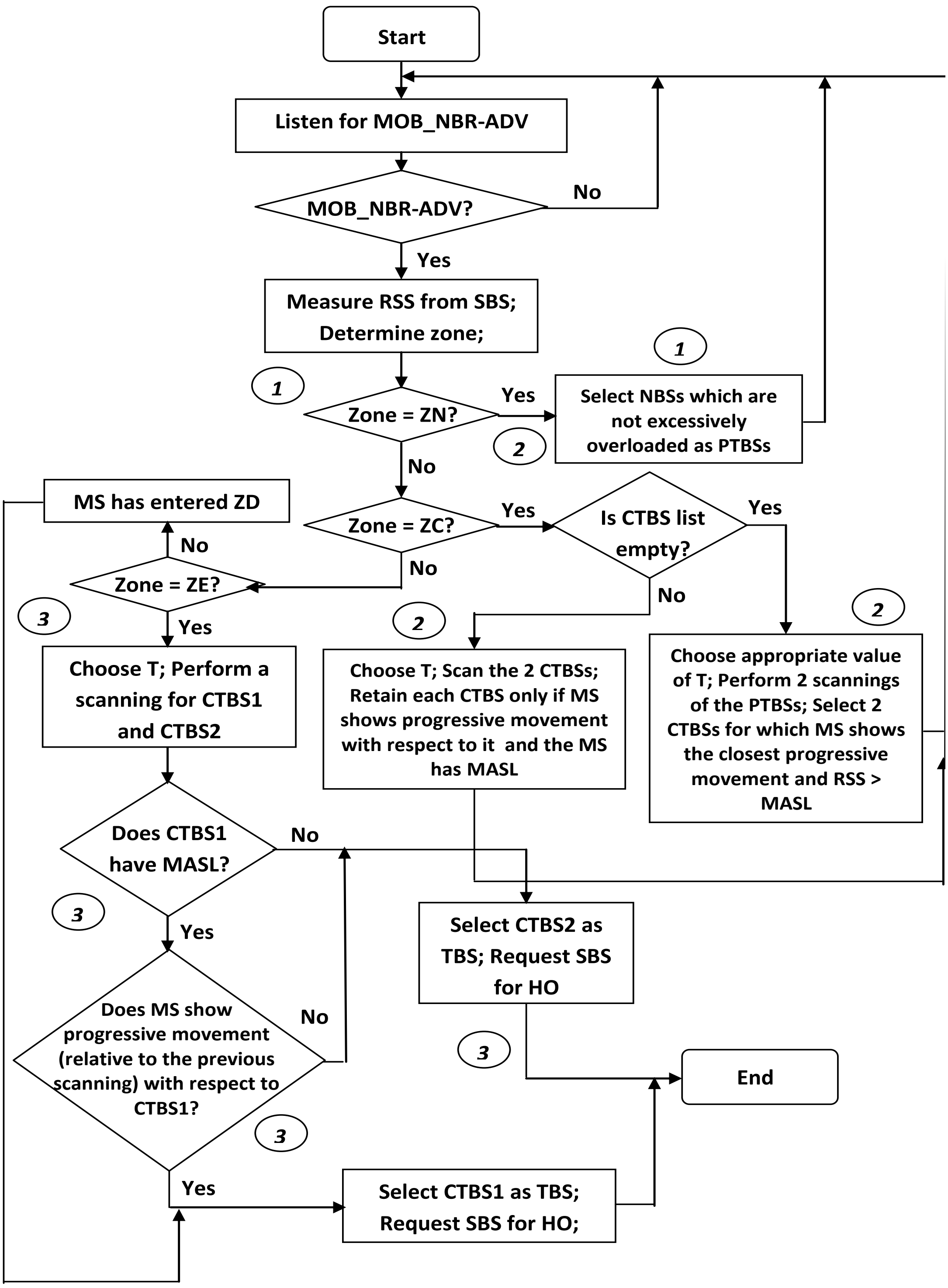


Fig. 4.7 Flowchart of the AOD-based Fast MAC-Layer Handover Scheme

two samples may be averaged to obtain a more reliable selection of the TBS (as in the case of the DiCD-based TBS lookahead).

4.8 On the Assumption of Broad Linearity and Its Time Frame Estimation

The most important assumption that was made in proposing the two distance estimation and lookahead-based handover techniques described in this chapter was made in Section 4.5. The assumption stated that, while the MS is at the fag-end of its journey across a cell, its motion is broadly linear over a certain time frame. In support of the assumption, we make the following four arguments. Similar argument as argument 1, below, has also been made to justify Assumption 5.2 in Section 5.2.2, in the context of Handover Technique 3.

1. In a long journey by vehicle, in practice, generally choice of the shortest path is most common and natural. This is mainly because of the need for ensuring fuel economy to achieve a low-cost travel. Moreover, the shortest path travel is usually, though not always, also accompanied by time economy. Thus, we may assume the path of the vehicle to be "broadly" a near-straight line, with occasional small (i.e. large-radii) curvatures, small zig-zag movements or sharp but non-backward bends all on either side of this near-straight line path. However, predominantly random, zig-zag or curvilinear movement, in general, may be expected to be only rare. Moreover, even if the path becomes so much non-linear, it becomes so only over small stretches.
2. From the description of the two distance estimation and lookahead-based handover techniques presented in this chapter, it should be clear that, out of the total journey time of the MS within a cell, linear movement has been assumed only for a small fraction of the time. This minimum required period of linear motion begins with the 1st scanning cycle and should ideally end approximately at the time when the MS is handed over to the TBS selected by it, i.e., when the MS has nearly reached the cell boundary. The first scanning cycle actually takes place only after the following sequence of events are completed:
   (i) MS recognizes that it has entered the ZC $(P_3 > P \geq P_2)$ during one of the periodic broadcast of the MOB_NBR-ADV message
   (ii) MS makes a request for the grant of the first scanning cycle and
   (iii) SBS grants a scanning cycle after rejecting (i.e. excluding) those NBSs disqualified due to excessive values of the current load.

3. The minimum required period of the MS's linear motion may actually be somewhat less than that estimated above in argument 2. This is because, even if the MS moves or deviates away from its linear path immediately after it has performed the last and final scanning cycle and it has itself selected its TBS thereafter (this time instant occurs much before the time when the MS will reach the cell boundary of its SBS), it will still, most likely, enter the cell of the same BS that it had selected as its TBS. However, this expectation may be belied and the MS then may not actually enter the cell of its TBS (note that the MS had selected its TBS through a lookahead technique) if the MS excessively deviates from its linear path, say, because of a sudden side turn or a somewhat backward turn. In the later case, it would result to a wrong handover and possibly the ongoing call may be disrupted.
4. As another point relevant to argument 3 above, it should be noted that two neighbouring or adjacent BSs usually have some amount of overlap between their respective adjacent cell areas. This means that even if the MS deviates from its broadly linear motion (this begins with the first scanning), before leaving its present cell but only after having entered this adjacent-cell overlap areas, no handover failure will obviously occur. This is because the MS has already entered the cell of its choice i.e. the TBS, which it had earlier selected, through lookahead, after performing the final scanning.

From the arguments 1, 2 and 3 above, it is reasonable to conclude that, for the two lookahead schemes to yield a reliable handover, the MS should have a near-linear motion at least during the entire period of scanning, beginning with the first scanning cycle and ending with the final scanning cycle. Below we have worked out a rough estimate of the Minimum Required Period of Linear Motion (MRPLM) of the MS for the proposed two lookahead techniques to yield a reliable handover.

As were stated earlier, the radius of a cell in a Mobile WiMAX network varies in the range 500 m – 2 Km and the MS velocity generally varies between 60 Km/hr and 120 Km/hr [10]. In order to keep our discussion simple, we shall assume a cell radius of 1 Km and an MS velocity of 90 Km/hr (i.e. 25 m/sec). So far as the cell radius overlap is concerned, we assume a 10% overlap between the neighbouring cells. We further assume that, in the SBS, radii for ZN, ZC, ZE and ZD are 450 m, 750 m, 900 m and 1 Km, respectively, all measured with respect to the SBS centroid. It may be noted that 10% cell area overlap represents the annular zone with internal and external radii of 900 m and 1 Km, respectively. This zone includes all the cell overlap areas between the SBS and each of the NBSs. Incidentally, this annular zone coincides with the ZD, the zone of the weakest signal, and as said earlier, the entire process of handover must be completed before the MS enters this zone.

Now, we note that the MOB_NBR-ADV signal is broadcast every 1 sec and the first scanning cycle takes place sometime after the MS detects (using the MOB_NBR-ADV broadcast) that it has echoed the ZC (argument 2 explains this delay). Accordingly, it is reasonable to assume that the first scanning cycle occurs 2 sec (approx) after the MS enters the ZC. With an average velocity of 25 m/sec, the MS covers a distance of 50 m during this 2 sec interval so that the MS becomes positioned 450 m + 50 m = 500 m from the centroid at the time of the first scanning cycle. The final scanning is performed, in most cases, within the ZC itself. But, in some cases, the final scanning may be performed early in the ZE. Thus, we may assume that the total scanning process is completed, even in the worst case, at around 800 m from the SBS centroid (note that the ZE extends from 750 m to 900 m from the SBS centroid). Since the MRPLM begins at 500 m and ends at 800 m from the centroid, the estimated MRPLM is 300 m. Hence, for the two lookahead schemes to yield reliable handovers, the MS should have a near-linear motion during a period of (300 / 25) = 12 seconds, beginning the first scanning cycle. Apparently, this is not an unreasonable assumption, in general.

In the context of the MRPLM as discussed above, it is worth being aware of practical data relevant to the mean street length in a metropolitan or city area, which is the length of a street between two consecutive intersections. According to a doctoral thesis [83] of the Technical University of Vienna, which is a typical European city, the mean street length is around 100 m in the city centre and around 150 m in the outskirts of the city. Though this mean length is considerably smaller than our MRPLM requirement of 300 m, we make two important points in this context. First, the city roads are strictly linear i.e. ideally meet the MRPLM condition. Second, if a user does not change his/her direction of motion at every intersection (which normally no one does) but usually continues to move in the same general direction through intersections, then the MRPLM condition will generally be satisfied in actual city travel under a Mobile WiMAX network.

4.9 Conclusion

In this chapter, two MS-controlled handover techniques have been investigated. Both employ the principle of distance estimation which utilizes the distance-dependent pathloss property of the RSS received by the MS from its NBSs, followed by their respective lookahead techniques. A discussion of the pathloss phenomenon along with the two major problems, namely, multipath and shadowing, that are associated with pathloss, has been presented. Some arguments have been put forward towards judging the validity of the proposed RSS-based distance estimation process. The MS performs multiple scannings of each NBS, although with a few possible exceptions. An NBS may be totally disqualified from the entire scanning session if its CL is excessive and, additionally, even a qualified NBS may latter be eliminated from any further scanning if its motion relative to the MS is found to be regressive after any scan. A detailed discussion on the concept of CL of a BS (akin to a router) and the method of estimation of the CL, on the basis of the router's throughput capacity and throughput has been explained. An approximate approach towards estimating the CL of a BS has been proposed which is based on taking the count of the number of connections being currently handled by a BS. The most attractive feature of this CL estimation technique is that it is an extremely simple and practical method that is well-suited for WiMAX handover algorithms.

From the RSS samples received from the NBSs, the MS estimates the corresponding distance samples of each NBS and performs an appropriate lookahead scheme to determine, in advance, which NBS it is most likely to get nearest to and hence should be selected as the TBS. The two handover techniques described in this chapter differ in their respective lookahead principles. The first one estimates the Differences in Consecutive Distances (DiCD) and selects as the TBS the NBS, which shows the highest AFM, based on the sum of the successive DiCDs. In contrast, in the second lookahead scheme, the MS selects as the TBS the NBS, which shows the least Angles of Divergence (AOD) with respect to the MS's direction of motion. In this context, it may be pointed out that in our description of the two handover methods, just like accumulation of two forward movement samples has been done in Handover Technique 1, similar accumulation of AOD samples could also be done in Handover Technique 2. Additionally, it may also be pointed out that sample accumulation, instead of sample averaging, has the advantage that it avoids the time-consuming division operation and hence saves MS power.

Two notable novelties have been introduced in the two handover techniques in Mobile WiMAX that have been described in this chapter. Both have yielded significant performance improvement in Mobile WiMAX handover techniques. The first novelty is that the handovers are now totally controlled by the MS. This is unlike the other handover techniques that are either fully BS-controlled or are controlled jointly by the BS and the MS. As a matter of fact, in our MS-controlled techniques, the only job performed by the SBS is just to grant the requested scanning cycles and to carry out the actual handover after the MS has finished the complete TBS selection job by itself. This can drastically improve the scalability of the Mobile WiMAX network in two ways. First, the SBS, with its workload greatly reduced, can now provide service to many additional MSs. Second, much of the communication overhead incurred owing to the use of different standardized MAC-layer MS ↔ BS message like MOB_MSHO-REQ, MOB_MSHO-RSP, MOB_BSHO-REQ, MOB_BSHO-RSP etc. are now avoided thus reducing the congestion in the network, significantly. The second novelty is the concept of four zones based on the RSS power received by the MS from its SBS. Being aided by this concept of four zones, monitored by itself without any overhead, the MS can perform its entire set of handover-related functions in the right sequence and at the right times. This ensures that two important objectives in the handover process are fulfilled, namely, (i) unlike as in other handover techniques, the MS completes a good part of the handover-related jobs even before the RSS reaches the threshold level that has been traditionally used and (ii) the entire handover process is completed before the ZD is entered so that there will be no possibility of excessive loss of packets or call drops.

The two handover techniques described in this chapter have adequately addressed the well known and important problem of large handover delay that often causes call drops, which signifies the failure of the handover in Mobile WiMAX networks. Redundant scanning of NBSs [37] along with prolonged synchronization, ranging and associated activities proportional to the number of NBSs are scanned are known to increase the overall handover delay in Mobile WiMAX. Examples of an MS having up to eight NBSs are performing even up to six different scanning iterations for each of the eight NBSs are found in the literature [47-48]. In our proposed techniques, both the numbers of NBSs scanned and the number of scanning iterations for each NBS, have been reduced considerably to achieve a fast or low-latency handover. Regarding the number of scanned NBSs, the excessively overloaded NBSs are not scanned at all because they would, if selected as the TBS, provide poor QoS and may cause many call drops. Even among those NBSs that are scanned, one or more may be eliminated from becoming the TBS because of regressive movement relative to the MS, after each successive scanning. So far as the number of scanning cycles or iterations is concerned, the minimum number of iterations in both the handover techniques is two for obtaining the first DiCD or AOD sample. Each additional iteration provides an additional DiCD or AOD sample required for successive multi-sample averaging and the resultant increase in the sample accuracy. Between the two handover techniques, the Handover Technique 1 (DiCD-based) is clearly superior because of its much simpler implementation of the lookahead principle. This will save a considerable amount of battery power of the MS, which should obviously be an important criterion in any MS-controlled handover algorithm.

Finally, a brief discussion on the acceptability of such mobile station-controlled handover techniques from a Telecommunication Service Provider's (TSP) perspective is provided here. On top of the advantages mentioned in Section 4.1, such techniques are also better choice over the traditional BS-controlled or network-controlled handovers owing to the following reasons as stated in [84]: (a) Information about each MS's battery status, as well as current position and movement direction of each MS are important to take a handover decision. For BS-controlled handover, such information from many MSs needs to be transferred to the BS frequently, leading to a substantial amount of data interchange, which could be avoided in MS-controlled handover techniques. (b) In terms of handover reliability, in MS-controlled handover techniques, an MS can quickly resume sessions that were interrupted owing to a failed handover activity. The only minor limitation of an MS-controlled handover technique from a TSP-perspective could be the aspect of load balancing, which could be problematic if an MS performs a handover with an already overloaded BS. However, as proposed in Handover Techniques 1 and 2, an SBS, periodically broadcasting updated load information of NBSs to all its MSs, could be a possible way of dealing with this problem [84].

Chapter 5

Fast and Reliable Handover Using MS's Direction of Motion

5.1 Introduction

In the previous chapter we described two fast handover techniques, called Handover Techniques 1 and Handover Techniques 2, both based on the same principle of distance estimation and lookahead employing the RSS received by the MS from the NBSs. Though both techniques were based on the same principle off RSS-based distance estimation and lookahead, yet both were independently and fully studied because they used two different types of lookahead principle. The former employed the concept of estimating and accumulating the successive differences in consecutive distances (DICD) of the MS from each NBS. The later was based on estimating the Angle of Divergence (AOD) of each NBS with respect to the MS's own direction of motion. However, in both the techniques, from among all the NB's of the MS, its TBS was selected after two or three levels of screening. During the first level of screening for short-listing, a few PTBSs were selected that were not overloaded (current load (overload point) were selected. At the second level of short-listing, the PTBS's were scanned a few times for estimating their respective charging distances from the MS and the PTBS which showed the highest relative progressive movement with respect to the MS (this was estimated through either the accumulated DiCD or the AOD) was directly selected as the TBS. In the rather uncommon case of two PTBS's showing the highest but nearly equal progressive movement, both were chosen as CTBSs. A third and final level of the TBS selection process was carried out by performing another scanning cycle to make the final choice of the TBS. In both the TBS selection techniques, the handover was basically controlled by the MS with assistance received from its SBS on three courts: (i) eliminating these NBSs from further consideration which were overloaded (ii) arranging for the scanning cycles as requested by the MS and finally (iii) effecting the actual handover of the MS to the selected TBS via the backbone network.

In the present chapter we describe a third technique for hard handover in WIMAX, called Handover Technique 3, which has been investigated by us. A description of this method at the preliminary stage of the work was presented in a conference [85]. The two handover techniques described in the previous chapter were categorised as MS-controlled because the most important part in the TBS selection process was performed by the MS itself. In contrast, the handover technique described in this chapter is predominantly controlled by the SBS, although the MS also plays an important role in the handover process. In order to select the TBS, the SBS employs three different criteria or parameters. These are: (i) The orientation matching between the geographical position of each NBS and the MS's broad direction of motion, both with respect to the SBS, (ii) the current load of each NBS (see Section 4.4 in Chapter 4) and (iii) the RSS received by the MS from each NBS (no distance estimation or lookahead is used – the RSS is used directly after some scaling). The BS assigns score to each NBS against each of three parameters and selects the TBS based on an appropriately weighted average of the three scores. The scheme of the proposed Handover Technique 3 is described in Section 5.3 after some preliminary discussions and assumptions are made in Section 5.2.

5.2 Preliminary Discussions and Assumptions

Before describing the basic scheme of Handover Technique 3 in the next section, it will be helpful to first discuss in this section about its important similarities and dissimilarities with the Handover Techniques 1 and 2 and, additionally, to state and justify the various assumptions made towards developing the scheme of Handover Technique 3.

5.2.1 Similarities and Dissimilarities

1. Unlike the Handover Techniques 1 and 2, which employ only two criteria, namely, the RSS received by the MS from each NBS (and duly processed) and the current load of each NBS, for the overall process of selecting the TBS from the NBSs, the Handover Technique uses three criteria, as stated in Section 5.1, namely, the orientation matching, the current load and the RSS. The first criterion, i.e., the orientation matching between the MS's direction of

motion and the geographical orientation of each NBS's, both as perceived by the SBS, was proposed in [85] when this work was at its preliminary stage. However, the method proposed in implementing this idea was then somewhat sketchy which has now been made more concrete.

2. The value of the RSS received by the MS from each NBS was used in the Handover Techniques 1 & 2 to first estimate the present distance of the MS from the NBS and then, based on the estimated distances, perform the lookahead towards ultimately selecting the TBS from the PTBSs. In contrast, the RSS has been directly utilized in Handover Technique 3, without any distance estimation.
3. The criterion of the current load of each NBS (see Section 4.4 in Chapter 4) was utilized in the Handover Techniques 1 and 2 only for selecting the PTBSs from all the available NBSs but did not play any role in the ultimate selection of the TBS from the PTBSs (via the CTBSs). However, the handover Technique 3, the criterion of the current load of each NBS has, additionally, been used for the TBS selection also.
4. In the Handover Techniques 1 & 2, the process of selecting the TBS from the PTBSs was based solely on the RSS-based distance estimation followed by either of the two methods of looking ahead for the highest progressive relative movement between the MS and the NBSs. In contrast the TBS selection in Handover Technique 3 is done by first judiciously assigning the score against each criterion to each NBS and then computing an appropriately weighted score of each NBS to identify the highest scoring NBS.
5. The "look-before-you-leap" policy which was used in the Handover Techniques 1 & 2 for selecting one of the two equally promising CTBSs as the TBS has been avoided in Handover Technique 3. This step has been avoided because its need occurs very infrequently but its use increases the scanning time.

5.2.2 Assumptions and Justifications

Having discussed the important similarities and dissimilarities between the Handover Techniques 1 & 2 one hand and the Handover Technique 3 on the other, we next state the various assumptions along with their justifications that have been made in developing the Handover Technique 3.

Assumption 5.1: We consider a Mobile WiMAX network with a large number of cells and assume that the MS starts its journey on a vehicle (highest speed of an MS in Mobile WiMAX is 120 km/hr) from a certain place in the source cells and its destination is another place located in a distant destination cell D. As the justification of this trivial but important assumption it should be remembered that, usually, the location of the destination for any journey is known either precisely or at least approximately (i.e. not precisely but not vaguely either). A totally unknown location of the destination for a journey on a vehicle is extremely rare.

Assumption 5.2: We assume that during its entire long journey, the vehicle carrying the MS broadly takes nearly the shortest possible path to the destination, with no backward, random or zigzag movement, in general. That is, the path may be imagined to be broadly a near straight line, with occasional curvatures and few sharp bends on either side of this broadly near-straight line path (Refer to Section 4.8 in Chapter 4). It must be noted that choice of the shortest path, in general, is most common and natural in practice because of the need for ensuring fuel economy (i.e. low cost) which, usually is also accompanied by time economy. WiMAX being a metropolitan network, there may be a few circular or ring roads but they are unlikely to have large curvatures or many sharp bends. Even if the Manhattan model of roads is imagined, there may be only a limited number of side turns needed to be taken at the four-point crossings.

Assumption 5.3: We assume that each BS has the knowledge about the polar coordinate (r, ϴ) of the centroid of every other BS in the network with respect to its own centroid. How the BS acquires and utilizes this knowledge is explained in sections 5.4 & 5.5 respectively. Each BS maintains its Polar Coordinates Table (PCT) which stores the polar coordinate of every other BS (with respect to its own centroid as the origin of this polar coordinate system) against the latter's BS-Identifier (BS_ID). Table 5.1 shows an example of the PCT maintained by a BS.

Assumption 5.4: During its entire journey, the MS dynamically maintains a small database called the Visited Base Stations List (VBSL). In the preliminary paper [85] this dynamically managed database was called the Temporary Movement Database (TMDB). The VBSL stores the chronological sequence of the BS_IDs of up to K SBSs that the MS had most recently visited. At the time of start of the MS's journey from the cell S, the VBSL is empty and all the K entries are blanks (_), instead of being valid BS_IDs. Thereafter, every time the MS handed over to a new SBS, the MS appends the BS_ID of the new SBS to the list after deleting the BS_ID of its oldest (least recent) SBS from the list. Thus if the MS has just entered the cell M after having chronologically passed through the BS-path S-J-K-L, the VBSL entries are _ _ _ SJKLM (assuming K=8).

5.3 Stepwise Schematic Description

On the basis of the basic assumptions stated in the previous section we now present the following schematic description of the Handover Technique 3. Figure 5.1 shows the block diagram of the complete sequence of steps involved in the implementation of this handover technique.

Step 1: Immediately after being handed over to a new SBS, the MS sends a Mobile Report Message (MOB_MS-REP) to its new SBS and continues its independent motion. MOB_MS-REP is a new message (not included in the present set of messages in IEEE 802.16e standard) that we propose here for the purpose of enabling the MS to pass on some useful information related to any aspect of mobility to its SBS. In the present case, the MS sends an MOB_MS-REP message to inform its SBS about the present direction or orientation of its motion. The direction of motion represented by the VBSL which is dynamically maintained by the MS as was explained earlier under Assumption 5.4 in the previous section.

Step 2: Upon receipt of the MOB_MS-REP message from the MS, its new SBS performs the orientation matching between the MS's direction of motion as represented by the VBSL and the geo-location orientation of the centroid of each NBS using the PCT maintained by it (see Assumption 5.3 in the previous section) and at the same time, assigns an Orientation Matching Score (OMS) of S_{OM} to each NBS. The NBSs, whose geo-locational orientation with respect of the direction of the MS's motion would represent a progressive or forward movement for the MS, are given a positive S_{OM} and those representing a regressive or backward movement are given a negative S_{OM}. Detailed description of the method of orientation matching carried out by the SBS using the VBSL and the PCT will be described in Section 5.5 and the method of assigning S_{OM} will be discussed in Section 5.7.

Step 3: During its journey through the cell, the MS utilizes the periodic MOB_NBR-ADV broadcast by its (new) SBS for two purposes. First, it periodically measures the RSS it receives from its SBS and checks that it is still in the ZN i.e. the RSS power $P > P_3$ (see Figure 4.2 in Chapter 4). Second, the MS learns the BS_IDs of its NBSs.

Step 4: Whenever the MS discovers that P has equalled or dipped below $P_3 (P_3 > P > P_2)$, i.e. it has entered the ZC, the MS sends a MOB_SCN-REQ to its SBS requesting for allocation of a scanning interval to scan all its NBSs for measuring the RSS power (P_j) received from all the NBSs (NBS_j) whatever the number of NBSs maybe.

Step 5: After receiving the MOB_SCN-REQ message from the MS, the SBS performs two functions. In the first function, the SBS collects, through the backbone network, the information about the current load of each NBS (see Section 4.4 in Chapter 4 for a discussion on the concept of load) and assigns a Load-Based Score (LBS) S_{CL} to each NBS. The scoring methodology will be discussed in Section 5.7. Overloaded NBSs which are unlikely to be able to offer satisfactory QoS to additional connections or may even drop calls are assigned a negative S_{CL}. In the second function, the SBS checks the two scores S_{OM} & S_{CL} of each NBS, identifies any NBS with a high negative score (more negative than some chosen negative limit) and sends a MOB_SCN-RSP to the MS allowing scanning of all NBSs except those with either a high negative score for S_{CL} or a negative score for S_{OM}.

Step 6: When the MS receives the MOB_SCN-RSP message from the SBS, it performs the scanning as recommended by the SBS. Thereafter, the MS reports to the SBS the result of scanning, i.e. the RSS receives from each scanned NBS, by sending a MOB_SCN-REP message.

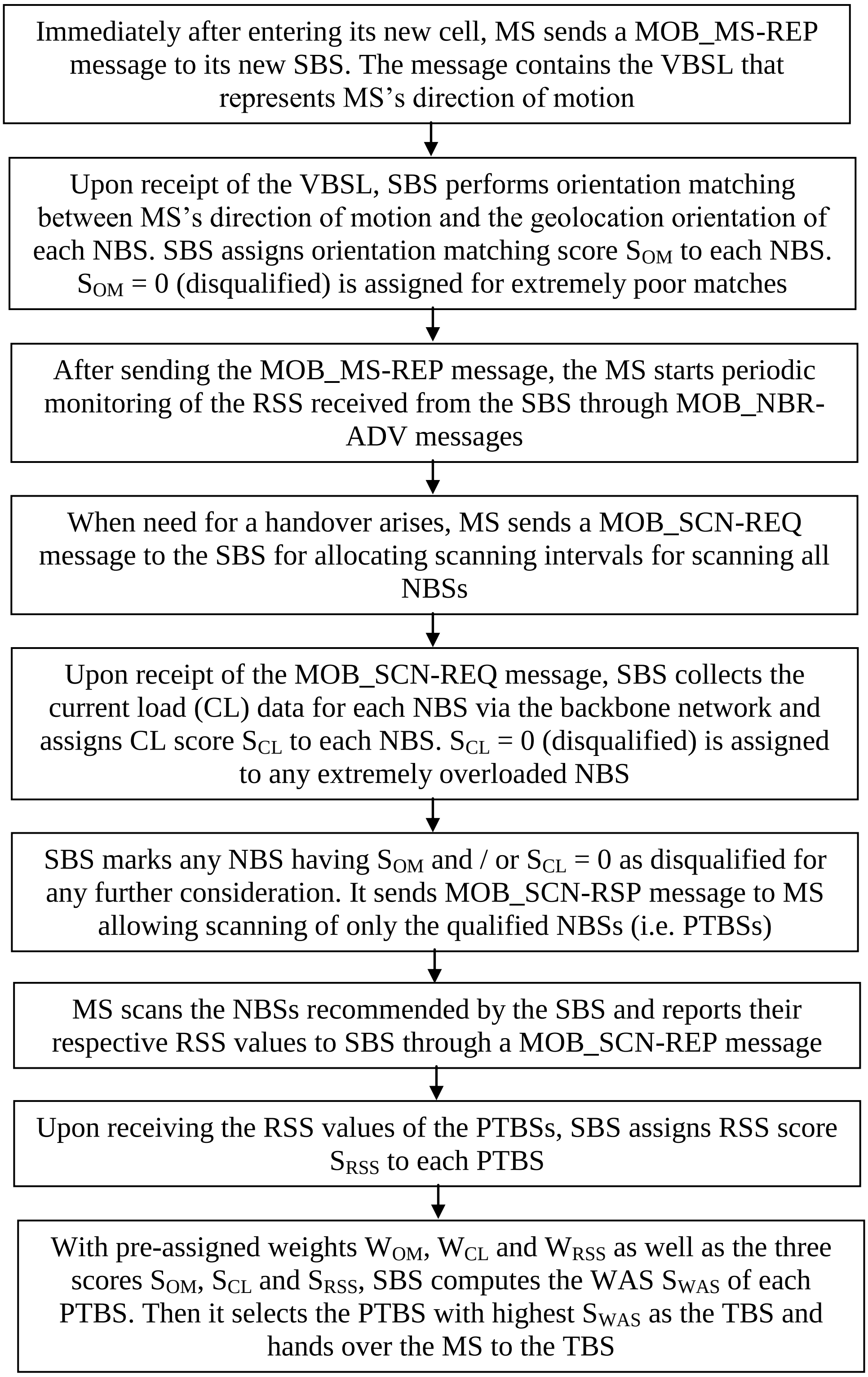


Fig. 5.1 Block Diagram Showing the Complete Sequence of Steps Involved in the Implementation of the Handover Technique 3.

Step 7: After receiving the RSS values of the NBSs that were selected as PTBSs, the SBS first assigns the signal strength score S_{RSS} to each PTBS using the scoring methodology described in Section 5.7.

Step 8: Finally, the SBS computes the weighted average of the three individual scores S_{OM}, S_{CL} & S_{RSS} of each PTBS and chooses as the TBS, the PTBS which has the highest Weighted Average Score (WAS) S_{WAS}. How the three individual scores are assigned to the NBSs and PTBSs and how the S_{WAS} is finally computed will be discussed, in its totality, in Section 5.7.

5.4 GPS-Aided BS and Its PCT

In recent years, there has been noticeable development of the GPS receivers. GPS is basically a global navigation satellite system with 24-30 satellites [86]. GPS provides positioning, navigation and timing services anywhere anytime. An unobstructed view of four or more satellites is required for obtaining these services. Location of the receiver is provided in three dimensions, namely, latitude, longitude and altitude. GPS receivers are now used inside the WiMAX BSs to serve the twin purposes of providing accurate time synchronization between the BSs and determination of their geodetic location (geolocation).

Although many MSs are now GPS enabled, mainly high cost and large power consumption are impeding the growth in their uses. Our interest is not in the use of GPS receivers in the MSs, but only in utilizing the GPS-based geolocation facility that is available in all WiMAX BSs. Now, before we can come to the main point of our discussion, viz., how a BS creates its PCT which relates to our Assumption 5.3 in Section 5.2, we need to have a brief review of the WiMAX network reference model.

In accordance with the basic network reference model (NRM) specified by the WiMAX Forum [58], two different business entities exist in the WiMAX network namely, the network access providers (NAP) and the network service providers (NSP). The NAP provides radio access and infrastructure whereas the NSP provides IP connectivity and deal with subscription and service delivery. We focus our interest on the NSP which is typically deployed as one or more connectivity service networks (CSN) where a CSN is basically a set of network functions that provide IP connectivity to WiMAX subscribers. A CSN may comprise of network elements such as routers, internetworking gateways, various servers-both for meeting the general needs like authentication, authorization, accounting services, etc, and for various important services like those needed for providing location based services (LBS) [79]. The LBS determines and provides users location to applications on the network or the devices. Other elements include home agents and various useful databases. Being aided by GPS receiver, each BS in WiMAX learns the absolute geolocation of itself (its centroid) and sends this information, via the backbone network, to the centralised database in the CSN. The latter maps the BS_ID of each BS in the WIMAX network to its geolocation in the form of (X, Y, Z). Since the table maintains the global geolocation information, we shall call if the Global BS Geolocation Table (GBSGT). The GBSGT can be accessed by any BS at any time. As a matter of fact, because of the availability of this GBSGT, each BS periodically broadcasts its own absolute geolocation as well as the locations of its NBSs in (X, Y, Z) coordinates, using a layer-2 LBS-ADV message defined in IEEE 802.16-2009 [87].

From the above discussions, it may not be unreasonable to assume that the relative positional information of the centroid of every other BS in the network with respect to the centroid of each BS, in polar coordinates, may either be already available in the CSN database or be computed in the CSN database without much difficulty. Thereafter, each BS may be provided with its own specific local relative geolocation table (LRGT) as a subset of the global relative geolocation table (GRGT) which is computed by and resides in the CSN database. Alternatively, given a copy of the GBSGT, each BS can easily compute its (with reference its centroid as the origin) own LRGT as a PCT as shown in Figure 5.2. A and B are two BSs with absolute Cartesian coordinates (x_1, y_1, z_1) and (x_2, y_2, z_2) respectively. Since the area covered by a WiMAX network is a negligible proportion of the earth's surface area and the network area is generally plane (not hilly), the altitude Z in the (X, Y, Z) coordinate may be neglected. Hence the reference BS, say A, can compute the polar coordinate (r, θ) of B with respect to its own centroid as shown in Figure 5.2. This way, we shall assume that each BS has the knowledge of the three-dimensional polar coordinate of the centroid of every other BS with respect to its own centroid. Table 5.1 shows the structure of an example PCT maintained by each BS.

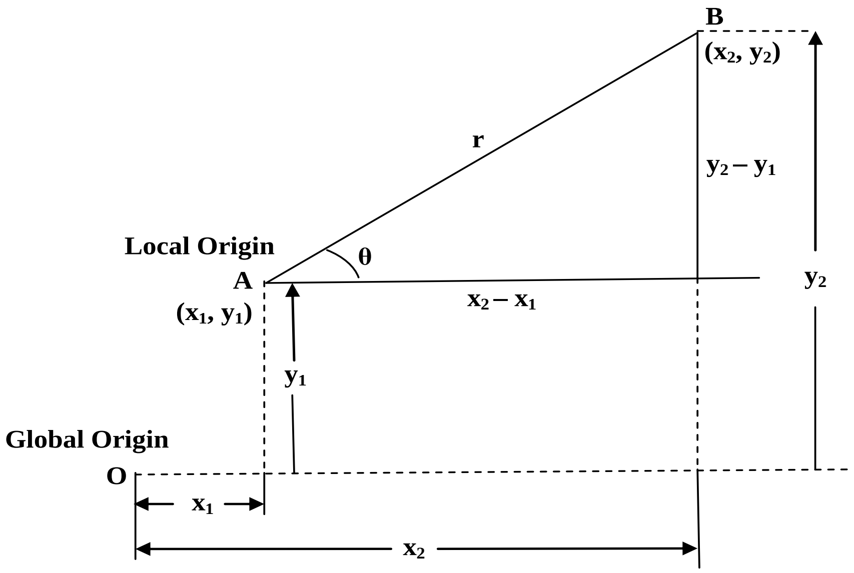


Fig. 5.2 Conversion from Absolute Cartesian Coordinate (origin O) to Relative Polar Coordinate (origin A)

Table 5.1 Polar Coordinates Table (PCT) of BS_i in a Network of N BSs

BS_ID (i)	**Polar Coordinate (j)**
1	r_{i1}, θ_{i1}
2	r_{i2}, θ_{i2}
3	r_{i3}, θ_{i3}
.	.
.	.
.	.
j - 1	$r_{i(j-1)}, \theta_{i(j-1)}$
j	r_{ij}, θ_{ij}
j + 1	$r_{i(j+1)}, \theta_{i(j+1)}$
.	.
.	.
.	.
N	r_{iN}, θ_{iN}

5.5 Orientation Matching Using VBSL and PCT

As stated earlier, the novel criterion towards TBS selection that has been used in Handover Technique 3 is the orientation matching between the independent direction of motion of the MS (see Assumption 5.4 in Section 5.2) and the PCT maintained by the SBS (see Assumption 5.3 in Section 5.2). The detailed procedure adopted by the SBS to perform the orientation matching will be explained in this section. The explanation will be followed by a simple hypothetical illustrative example in Section 5.6.

Upon receipt of the VBSL, contained in the MOB_HO-REP message (see Step 2 in Section 5.3) sent by the MS, BS_i (i.e. the SBS) under consideration, scans the VBSL. For each visited BS BS_k, $k=1,2,...,k$, in the list, it reads out from its PCT the stored value of the polar coordinate (r_{ik},θ_{ik}) of BS_k. These polar coordinates $\{r_{ik},\theta_{ik}\}$ of $\{BS_k\}$ actually represent the {(distance, angle)} pairs of the centroids of $\{BS_k\}$ relative to the centroid of BS_i, which is imagined as the origin of BS_i's own polar coordinate system. From these k angle values or angle samples, $\{\theta_{ik}\}$, the BS_i needs to determine the "average angle of motion of the MS" (AAMM) $\theta_{av}(i)$ with respect to its own polar coordinate system with the origin at its centroid. By matching this AAMM with the geographical orientation (in terms of the polar coordinate stored in the PCT) of its each NBS, the BS_i can predict, fairly well, which NBS the MS is most likely to pass through next, provided the MS's direction of motion satisfies the reasonable assumption made in Assumption 5.2 in Section 5.2. This prediction will significantly influence the TBS selection decision as was discussed in Section 5.3.

For determining the average angle $\theta_{av}(i)$ from the k angle samples $\{\theta_{ik}\}$, two points need to be noted. First, we note that each BS in WiMAX is modelled as a circle having a radius in the range 500 m – 2 Km [10]. Hence, during its journey from BS_1 to BS_i, via the k-1 intermediate BSs, viz., BS_2 through BS_k, the MS's actual position, while it is inside the successive BS_ks, could have been at any random distance d_k $(0 < d_k < 2$ km) away from the respective centroids of $\{BS_k\}$, instead of being, ideally, on the centroids themselves. Clearly, this implies that the sequence of the k angle samples $\{\theta_{ik}\}$, $k = 1, 2, ..., k$, that are supposed to represent the MS's direction of motion relative to the centroid of BS_i are somewhat erroneous and the errors are random and bipolar. They are bipolar simply because, while passing through any BS_k, the MS may be d_k metres away ($0<|d_k|<2$ km) on either the left or the right of the centroid of BS_k. It is easy to conclude that, since $k >> 1$, and the errors are bipolar and random, we can obtain a reasonably good estimate of the MS's angle of motion through simple averaging of the k angle values $\{\theta_{ik}\}$.

However, we have overlooked the more important point that during the MS's journey through the successive k BSs listed in the VBSL, the k distance values $\{r_{ik}\}$ are not constant but reduce progressively as $r_1 > r_2 > .... > r_k$. Clearly, simple averaging will produce an incorrect result for $\theta_{av}(i)$ under this condition. This is because of the well known trigonometrical concept of "measure of an angle in radian", which is given by the relation shown in Equation 5.1 below.

Radian measure of an angle θ at the centre of a circle = (Length x of the arc of the circle that subtends the angle θ at the centre) / (Length of the radius r of the circle)

……………………………….......................... *(5.1)*

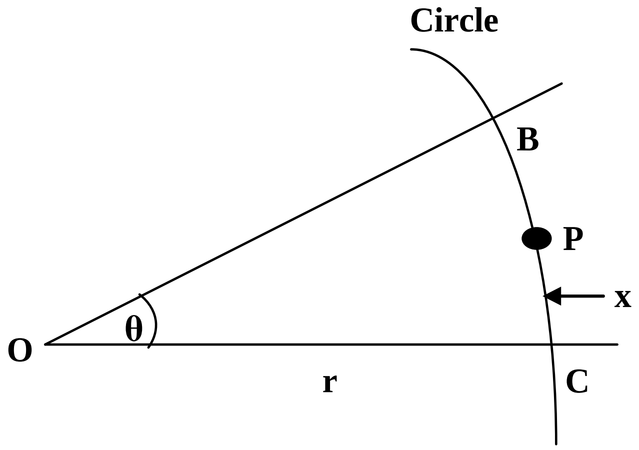
In order to illustrate the above concept we first consider the simple diagram shown in Figure 5.3.(a). In this diagram the arc of length x of the circle, with radius r and centre O, subtends the angle θ at centre O. According to Equation 5.1, the parameters r, θ and x are related by Equation 5.2 below.

$$r\,\theta = x \qquad (5.2)$$

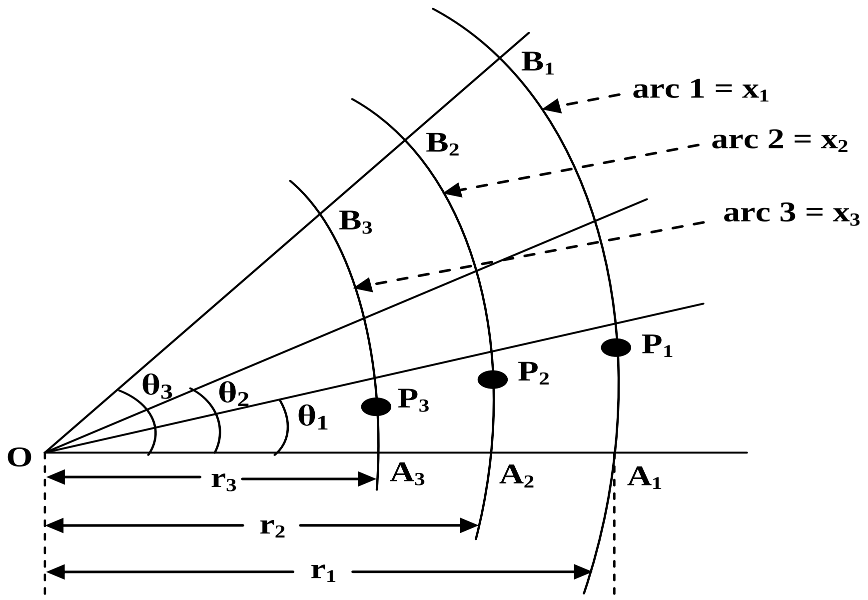
Now, in the diagram shown in Figure 5.3.(b), we consider three circles each having its centre at O. The three circles have different radii, $r_1>r_2>r_3$. Their respective arcs, $arc1=x_1$, $arc2=x_2$ and $arc3=x_3$, subtend angles $\theta_1<\theta_2<\theta_3$ at the centre. We wish to determine the average value θ_{av} of the three angles.

From Equation 5.2, we can obtain the following relation between the averages.

$$\theta_{av} = \frac{arc_{av}}{r_{av}} = \frac{x_{av}}{r_{av}} \qquad (5.3)$$



(a)



(b)

Fig. 5.3: (a) Radian Measure of an Angle AOB subtended by the Arc APB; (b) Radian Measure of three Angles A_1OB_1, A_2OB_2 and A_3OB_3 subtended by three Arcs $A_1P_1B_1$, $A_2P_2B_2$ and $A_3P_3B_3$, respectively, of three Concentric Circles

From Equation 5.2, we also have

$$r_1\theta_1 = x_1 \tag{5.4.a}$$

$$r_2\theta_2 = x_2 \tag{5.4.b}$$

$$r_3\theta_3 = x_3 \tag{5.4.c}$$

Combining Equations 5.3 and 5.4, we have

$$\theta_{av}=\{(x_1+x_2+x_3)/3\}*\{3/(r_1+r_2+r_3)\}=(r_1\theta_1+r_2\theta_2+r_3\theta_3)/(r_1+r_2+r_3) \quad (5.5)$$

Equation 5.5 shows that weighted averaging of the k angles $\{\theta_{ik}\}$ by their respective radii $\{r_{ik}\}$ is required instead of simple averaging. Thus we can express this result more formally as

$$\text{AAMM} = \theta_{av}(i) = \frac{\sum_{k=1}^{k} r_{ik}\theta_{ik}}{\sum_{k=1}^{k} r_{ik}} \quad (5.6)$$

In the next section, we shall illustrate, with a simple hypothetical example, the process of orientation matching that is carried out by the BS_i so as to be able to predict which NBS the MS is most likely to pass through next. However, how the Orientation Matching Score (OMS) is assigned to the NBSs and how the weighted averaging scheme for selecting the TBS is designed will be described in Section 5.7.

5.6 An Illustrative Example of Orientation Matching

The steps, sequentially followed by BS_i to perform the orientation matching are outlined below.

Step 1: BS_i scans the VBSL with the number of visited BSs assumed to be k = 4 and reads out from its PCT the following polar coordinates of the $\{BS_k\}$, $k=1,2,3,4$, against their respective BS-Ids. Here all angles are in degrees.

r_{i1} = 4 Km; r_{i2} = 3 KM; r_{i3} = 2 KM; r_{i4} = 1 Km;

$\theta_{i1} = 105°$; $\theta_{i2} = 100°$; $\theta_{i3} = 90°$; $\theta_{i4} = 100°$;

Step 2: BS_i computes the AAMM using Equation 5.6.

$$\text{AAMM} = \theta_{av}(i) = \frac{\sum_{k=1}^{4} r_{ik}\theta_{ik}}{\sum_{k=1}^{4} r_{ik}}$$

$$= \frac{4*105° + 3*100° + 2*90° + 1*100°}{4+3+2+1}$$

$$= \frac{1000°}{10} = 100°$$

At this point we may refer back to Assumption 5.2 in Section 5.2 and note that the "broad" direction of motion of the MS is a straight line, which makes an angle of 100° with the reference line at the BS_i centroid and the MS's actual path is only a "near-straight line".

Step 3: Having estimated that the MS has entered its cell at an angle of 100° (approximately), BS_i infers that the MS is likely to exit the cell at an angle of $(100^\circ+180^\circ)=280^\circ$ (approximately), if it continues its motion along the average direction of its entire post journey so far for a distance of around the radius of the cell, which varies in the range of 500 m – 2 Km. In Mobile WiMAX, which allows the MS to move at a speed of 60 Km – 120 Km/hr, this distance can be covered in 15 - 60 secs. In case of any change in the direction of the MS's motion, the Expected Angle of Exit of the MS (EAEM) will, of course, change from this computed value of 280°.

Step 4: BS_i next reads its PCT to learn the Geographical Angle of the NBSs (GAON) to determine the Relative Angular Distance (RAD) between the EAEM and the GAON of its each NBS. We arbitrarily assume that BS_i has 6 NBSs, $\{NBS_l\}$, $L=1,2,...,6$ and their respective GAON (in degrees) are:

GAON 1 = 40; GAON 2 = 95; GAON 3 = 160;

GAON 4 = 220; GAON 5 = 285; GAON = 340;

Step 5: BS_i computes the RAD for the 6 NBSs, noting that (i) a negative sign for a RAD is meaningless and, similarly, (ii) an angle greater than 180° for RAD actually means that this apparent RAD angle value should be reduced by 180° (because of clockwise / anticlockwise interpretation) to get the actual RAD value. The actual RAD values are computed as shown in Table 5.2 below.

A pictorial representation of the illustrative example of orientation matching scheme is shown in Figure 5.4. It is evident that NBS 5 shows the closest match to the EAEM.

Table 5.2 Computation of RAD Values of NBSs by BS_i

NBS No.	**AAMM**	**EAEM (AAMM + 180)**	**GAON**	**RAD (Apparent) (EAEM – GAON)**	**RAD (Actual)**
1	100	280	40	240	360 – 240 = 120
2	100	280	95	185	360 – 185 = 175
3	100	280	160	120	120
4	100	280	220	60	60
5	100	280	285	-5	5
6	100	280	340	-60	60

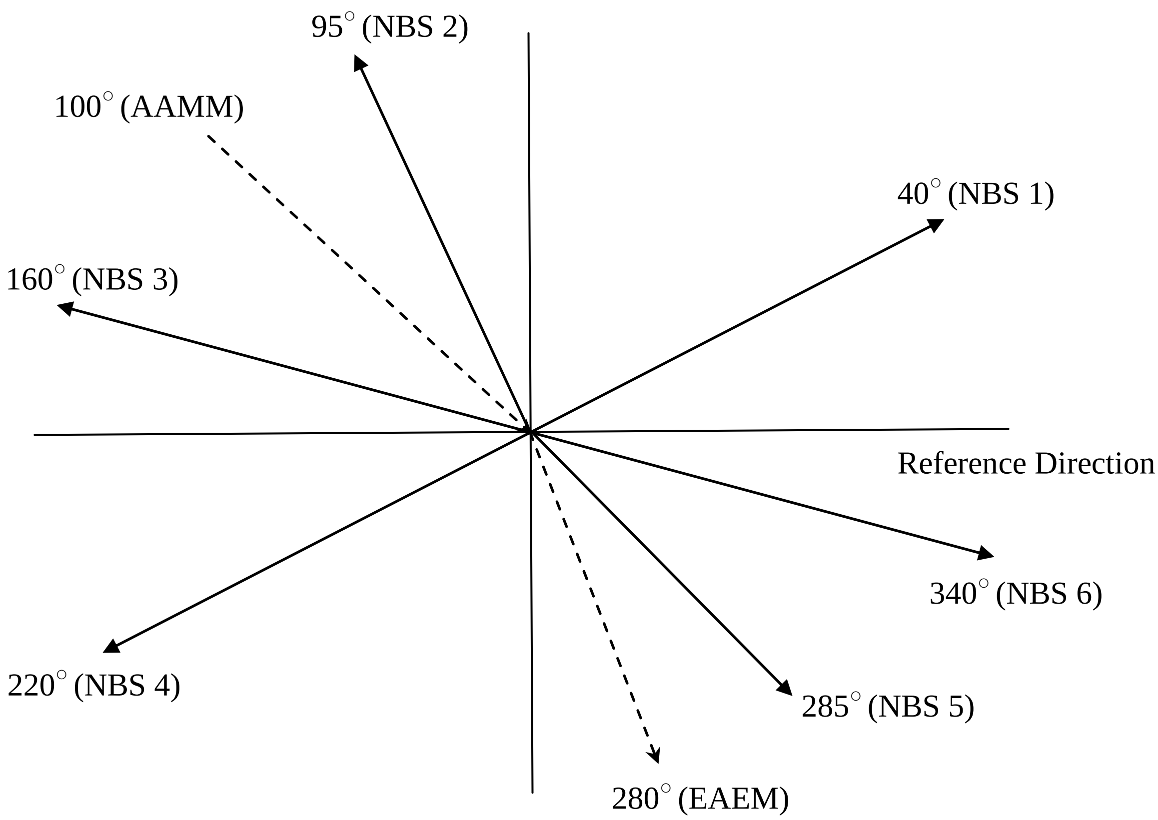


Fig. 5.4 Pictorial Representation of the Illustrative Example of the Orientation Matching Scheme

5.7 TBS Selection through Weighted Averaging of Scores

As was stated earlier in Section 5.1, the TBS is selected by the SBS in Handover Technique 3 by employing 3 different criteria, namely, (i) orientation matching between the MS's direction of motion and the geographical orientation of each NBS, (ii) the current load of each NBS and (iii) the RSS received by the MS from each NBS. In this section, we shall first explain how BS_i assigns score to each NBS against each of the above 3 criteria. We will, then, show how BS_i selects one of the NBSs (actually, these NBSs are PTBSs) as the TBS by computing appropriately weighted score for each PTBS.

5.7.1 Score Assignment against Orientation Matching

To begin with, we choose a simple system of relative scoring, with only positive scores, whereby the sum of the scores of all the NBSs, {NBS(l)}, l=1,2,…,L, is $\sum_{l=1}^{L} S_{OM}(l) = 1$. The score $S_{OM}(l)=0$ is reserved for a "disqualified" NBS_l as will be shortly explained. Because of the constraint $\sum_{l=1}^{L} S_{OM}(l) = 1$, the score $S_{OM}(l)=1$ is not assigned to any NBS as that would require all the remaining NBSs to be disqualified, i.e. have the score $S_{OM}(l)=0$, which is a meaningless idea. Going by the Assumption 5.2 (see Section 5.2), it can be said that, in the illustrative example of the previous section, the MS, after leaving the present cell, is extremely unlikely to enter a cell for which the RAD of the NBS is very large, say greater than chosen limit, which we shall call the RAD_LIMIT. A reasonable choice for the RAD_LIMIT appears to be some value which is somewhat higher than 90°. This is because while backward movement ($90° < RAD < 180°$) or purely random movement of the MS were considered extremely unlikely (see Assumption 5.2 in Section 5.2), side turns to left or right during the MS's journey were considered likely. So, as a reasonable choice, we choose the RAD_LIMIT as 120° and assign positive non-zero scores S_{OM} to the NBSs 1, 3, 4, 5 and 6, which have $RAD \le 120°$ and assign a zero score to NBS 2, which has a $RAD=175°$ (This RAD value indicates almost a complete backward movement for the MS). The choice of zero score is intended to disqualify NBS 2 (or any NBS in general) from any further consideration towards being selected the TBS. This meaning full disqualification is for avoiding some meaningless overhead. Thus BS_i now has to assign the orientation matching score S_{OM} $(0<S_{OM}<1)$ to the 5 NBSs that qualified as tentative PTBSs on the basis of the orientation matching criterion. This assignment of S_{OM} requires an appropriate method of score assignment for which our proposed solution is described below. In this context, it should be pointed out that any of the 5 NBSs may ultimately fail to qualify as a PTBS, if disqualified against the other disqualifying criteria (namely, current load).

It is obvious that the S_{OM} that is assigned to a PTBS should be inversely proportional to its RAD. For instance, NBS 5 with $RAD=5^\circ$ must receive the highest score while NBS 1 and NBS 3, both with $RAD = 120^\circ$ must receive the lowest score. However, neither score 0 nor score 1 can be assigned, as explained earlier. Though many complex (probably non-linear) and more appropriate scoring schemes are possible, we have adopted a fairly simple relative scoring scheme. First, we take the complement value of each RAD and call this complemented RAD value the RAD_COMPL. Then we assign the individual scores as the ratio of the respective RAD_COMPL values to the sum of all RAD_COMPL values excepting those of the disqualified NBSs. One question in this scheme of score assignment is the choice of an appropriate Reference RAD value, to be called the RAD_REF, which will be used for complementing the RAD values. Since, RAD = 0° must receive the highest possible value less than 1 and a $RAD=120^\circ$ must receive the lowest possible value greater than 0, we choose the RAD_REF only a little higher than 120°, say $RAD\_REF = 125^\circ$. With the above choice we can now assign the scores as computed in Table 5.3 below.

5.7.2 Score Assignment against Current Load

As discussed in Section 4.4 in Chapter 4, the CL of each BS can be estimated in a somewhat inaccurate but simple manner and also as a relatively static parameter by taking the count of the number of connections currently passing through each NBS. We assume that all BSs in the network are identical in design and the maximum number of connections that can be maintained or sustained by each BS, i.e. the connection capacity of each BS, is N. Next we assume that during a handover, the SBS has L NBSs $\{NBS_l\}$, $l=1,2,...,L$ and that the number of connections passing through the NBS_l is M_l, so that the NBS_l has a CL of $CL_l = M_l/N$. It is obvious that higher the value of CL_l, more is the current load of NBS_l and lower should be the score $S_{CL}(l)$ assigned to NBS_l. In order to prevent any excessively

Table 5.3 Orientation Score Assignment Scheme Illustrated with the Illustrative Example in Section 5.6

RAD_LIMIT = 120;			**RAD_REF = 125;**		
NBS No.	**RAD**	**Qualified**	**RAD_COMPL (125 – RAD)**	**Sum of RAD_COMPL**	**Score (S_{OM})**
1	120	Y	5	260	5 / 260 = 0.019
2	175	N	-	260	-
3	120	Y	5	260	5/260 = 0.019
4	60	Y	65	260	65 / 260 = 0.250
5	5	Y	120	260	120 / 260 = 0.461
6	60	Y	65	260	65 / 260 = 0.250

overloaded NBS to be selected as the TBS and then offer very poor QOS, we choose to set a higher limit CL_LIMIT of, say, 0.9, to disqualify any NBS with $CL \geq 0.9$ from being further considered for possible selection as a TBS. We assign a score of $S_{CL}(l) = 0$ to such excessively overloaded BSs. To each of the remaining (tentatively) qualified NBSs, we assign scores $\{S_{CL}(l)\}$ to {NBS(l)}, which are inversely proportional to their respective CLs $\{CL_l\}$. In this context, it should be pointed out that any of these remaining tentatively qualified NBSs may ultimately fail to qualify as a PTBS, if disqualified against one or both of the other two criteria toward TBS selection, namely orientation matching and RSS. The method of assignment of scores $\{S_{CL}(l)\}$ to $\{NBS(l)\}$ is described below.

In order to assign scores to the tentatively qualified NBSs, in a very simple manner, we first take the complement value of each CL_l and call this complemented CL value the CL_COMPL(l). Then we assign the individual scores as the ratio of the CL_COMPL(l) values to the sum of the CL_COMPL(l) values of all the L NBSs except the disqualified NBSs. For computing the complemented CL value

CL_COMPL of all the NBSs, we choose a reference CL value $CL\_REF = 0.89$ (since $CL \geq 0.9$ indicates an overloaded NBS) so that the CL_COMPL values $\{CL\_COMPL(l)\}$ of $\{NBS_l\}$ may be computed for each l as

$$CL\_COMPL(l) = CL\_REF - CL_l = 0.89 - CL_l \qquad (5.7)$$

It should be noted that the CL_COMPL values of the qualified NBSs may range between 0 – 0.89. Now, the scores for the $\{NBS_l\}$ will be computed as

$$S_{CL}(l) = CL\_COMPL(l) \ / \ \sum_{l=1}^{L} CL\_COMPL(l) \qquad (5.8)$$

We shall now illustrate the above score assignment process against the CL, using the same hypothetical example of 6 NBSs whose orientation matching scores $\{S_{OM}\}$ were assigned in Section 5.7.1. We assume that the connection capacity of each of the 6 NBSs $\{NBS_l\}$, $l = 1, 2, \ldots, 6$, is 500 and the present number of connections sustained, respectively, by them are $\{300, 250, 452, 200, 350, 150\}$ so that their CLs are $\{CL_l\} = \{0.6, 0.5, 0.904, 0.4, 0.66, 0.3\}$. Clearly, NBS 3 being excessively loaded ($CL_3 \geq 0.9$), is assigned a score of 0 and is thus disqualified from further consideration. Moreover, NBS 2 was earlier disqualified in orientation matching (see Section 5.7.1). So, the remaining 4 NBSs, viz., NBS 1, NBS 4, NBS 5 and NBS 6, which are finally selected as PTBSs, are assigned scores in proportion to their respective CL_COMPL values as shown in Table 5.4. We note that the sum of the 4 CL_COMPL values of NBS 1, NBS 4, NBS 5 and NBS 6 equals $(0.29 + 0.49 + 0.23 + 0.59) = 1.60$.

5.7.3 Score Assignment against RSS

The RSS is the signal power received by the MS from a BS. The RSS that the MS receives from its present SBS is used by it to determine when it needs a handover. The network hands over the MS from its present SBS to one of the NBSs, as chosen by the BS and / or the MS, which is likely to provide it with an adequately higher and satisfactory signal power during its journey through the next cell. As was discussed in Section 4.5, the median pathloss models [10] like the Okumura-Hata model, the COST-231 Hata model, the Erceg model, etc are widely used to roughly estimate the

Table 5.4 Computation of Current Load Score (S_{CL})

CL_LIMIT = 0.9;			**CL_REF = 0.89;**	
NBS No.	**CL**	**Qualified**	**CL_COMPL**	**S_{CL}**
1	0.6	Y	0.29	0.181
2	0.5	N (OM)	-	-
3	0.904	N (CL)	-	-
4	0.4	Y	0.49	0.306
5	0.66	Y	0.23	0.144
6	0.3	Y	0.59	0.368

RSS primarily as a function of the BS-to-MS distance, giving due consideration to various other parameters. Assuming that the transmitted powers of all NBSs are the same and, additionally, that all the other parameters in the median pathloss models, except the distances, are same for all NBSs, the distance-dependent decay is obviously the major cause for the MS receiving different amounts of (reduced) RSS from the different NBSs. Since the signal power tends to decay exponentially with distance, the above median pathloss models are linear on a logarithmic linear scale, although the slope and intercept of the line depends on the other parameters like the overall terrain, the carrier frequency and the antenna heights [10]. Thus, for some given values of these parameters, we can obtain a distance Vs RSS (in dB) linear graph as shown in Figure 5.5.

Now, assuming for example, the radius of each cell in WiMAX to be 1 Km, the distances between the MS and the different NBSs are expected to be bounded by 1 Km for the front NBSs and 3 Km for the rear NBSs (front and rear are with respect to the MS's direction of motion) and the various actual distances will lie within this limited zone. Thus, in Figure 5.5, we assume that the value of the RSS (in dB) received by the MS from any of the 4 NBSs, at the time of scanning, will lie between the two limits RSS_H and RSS_L. The former corresponds to the distance of 1 Km and

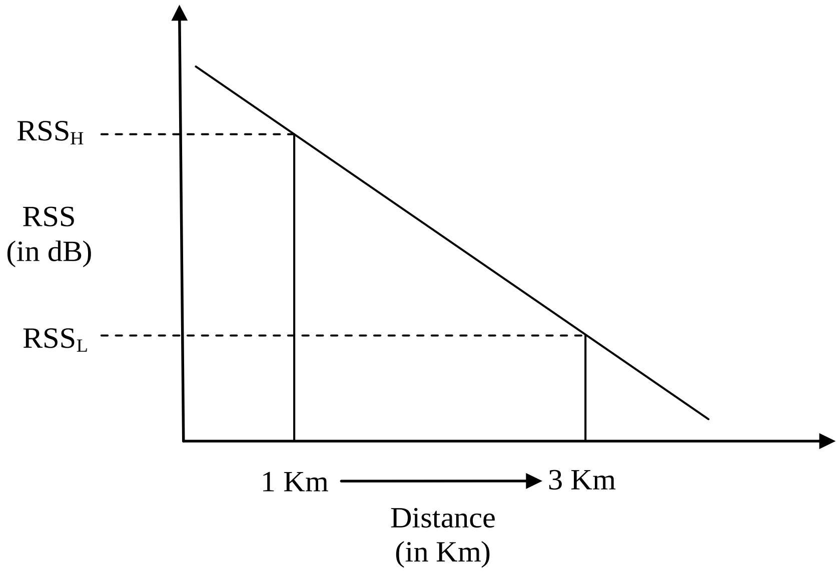


Fig. 5.5 Logarithmic Linear Graph of Distance in Km Vs RSS (in dB)

the latter corresponds to 3 Km, both the distances being only representative.

The above score assignment process against the RSS may now be illustrated with a hypothetical example using a similar approach as was earlier used in the cases of the other two parameters, namely, orientation matching (OM) and current load (CL). We consider that the SBS has the same 6 NBSs $\{NBS_l\}$, $l = 1, 2, \ldots, 6$, which were considered in the earlier two hypothetical examples of score assignment. However, only four of them, NBS 1, NBS 4, NBS 5 and NBS 6 were later scanned. We assume that, depending on the present distance of the MS from each NBS (at the time of the MS's scanning of the four NBSs), the RSS (in dB) received by the MS from the four NBSs are: 60, 80, 40 and 20, respectively. It is obvious that, unlike as in the previous two score assignments, the score against RSS that will be assigned to each NBS will now be directly (not inversely) proportional to the respective RSS values. Accordingly, the scores for the four NBSs may be computed using Equation 5.9 shown below.

$$S_{RSS}(l) = \frac{RSS_l}{\sum_{l=1}^{4} RSS_l} \tag{5.9}$$

The computed values of $\{S_{RSS}(l)\}$ of $\{NBS(l)\}$ are shown in Table 5.5.

Table 5.5 Computed Values of $\{S_{RSS}(l)\}$ for the Scanned NBSs

NBS_l	**RSS_l (in dB)**	**$S_{RSS}(l)$**
NBS 1	60	0.3
NBS 2 (not scanned)	40	-
NBS 3 (not scanned)	50	-
NBS 4	80	0.4
NBS 5	40	0.2
NBS 6	20	0.1

5.7.4 Weighted Averaging of the Scores towards TBS Selection

Having obtained the scores of the four NBSs of the MS against each of the 3 parameters, namely, orientation matching, current load and RSS, the SBS finally computes the weighted average of the 3 scores that are received by each NBS. Then the SBS selects as the TBS that NBS, which receives the highest Weighted Average Score (WAS). The $S_{WAS}(l)$, which is the WAS for the l^{th} NBS i.e. NBS_l, $l = 1, 4, 5, 6$, is computed using the Equation 5.10 as shown below.

$$S_{WAS}(l) = S_{OM}(l)*W_{OM} + S_{CL}(l)*W_{CL} + S_{RSS}(l)*W_{RSS} \tag{5.10}$$

where W_{OM}, W_{CL} and W_{RSS} are the weights, $0 \leq W_{OM}, W_{CL}, W_{RSS} \leq 1$, assigned to the three parameters, respectively, with the condition given by Equation 5.11

$$W_{OM} + W_{CL} + W_{RSS} = 1 \tag{5.11}$$

An important question that arises at this point is how to choose the three weights, satisfying Equation 5.11. Apparently, the choice should depend on two major factors, namely, relative importance and measurement accuracy of the three parameters, viz., RAD, CL and RSS, as well as on the quality (appropriateness) of the three score assignment methods. It is obviously very difficult to deal with these issues. However, we can make some meaningful observations. First, though RAD is the most important parameter among the three, its actual measurement accuracy for each cell depends on how far the expected relationship given in Equation 5.12 below (see Step 3 in Section 5.6) holds true in practice, i.e. whether or not the MS deviates

$$\text{EAEM} = \text{AAMM} + 180° \qquad (5.12)$$

from its broad direction of motion during its transit through the cell. Reference may be made in this regard to our Assumption 5.2 in Section 5.2.2. Second, measurement of the CL is absolutely accurate because each router keeps a count of the number of connections currently maintained by it. However, as discussed in Section 4.4, estimation of the CL on the basis of the number of connections is itself inaccurate and approximate. Finally, the single measurement of RSS (no averaging is done) cannot be relied upon absolutely for TBS selection. However, as an important point, in this context, it should be noted that RSS can offer a useful correction or neutralization of a possible error in the WAS computation, which may, otherwise, lead to a wrong selection of the TBS. This useful role of the RSS, as reflected by its score S_{RSS} in Equation 5.10, can be explained as shown below.

Assume that an MS enters its current cell at an average angle of motion AAMM so that its expected angle of exit from the cell, i.e. the EAEM becomes AAMM + 180°, by Equation 5.11. Accordingly, the NBS, say, NBS_x, whose geographical angle GAON has the minimum relative angular distance RAD from the EAEM, receives the highest orientation matching score S_{OM}. Now, assume that the MS, after having entered the current cell, suddenly and unexpectedly, deviates significantly from its EAEM during the course of its journey within the cell, Clearly, although NBS_x does not now deserve to receive the highest $S_{OM}(x)$, yet, unfortunately, it has already received it. Obviously, this wrong scoring for $S_{OM}(x)$ has occurred because the scoring process for S_{OM} (see Sections 5.6 and 5.7.1) is only anticipatory in nature. Fortunately, this gross error in $S_{OM}(x)$ will be corrected or neutralized to a good extent because the actual weighted average score $WAS_{WAS}(x)$ of NBS will get reduced because it will now receive a much reduced score S_{RSS} against RSS compared to what it would have received if the MS had not deviated considerably from its EAEM. The reason for the $S_{RSS}(x)$ becoming much poorer is that the MS's distance from NBS(x) has now considerably increased because it has now moved much further away from the centroid of NBS_x.

From the above discussions, two points appear relevant to assignment of relative weights W_{OM}, W_{CL} and W_{RSS} to the three criteria. First, W_{OM} should be a little, and not much, higher than either W_{CL} or W_{RSS}, although orientation matching is by far the most important criterion in this handover technique (provided, of course, that the EAEM approximately equals AAMM + 180°). Second, CL and RSS may be assigned nearly equal weights, i.e. $W_{CL} \approx W_{RSS}$. Thus, we finally choose $W_{OM} = 0.4$, $W_{CL} = 0.3$ and $W_{RSS} = 0.3$. Next, using Equation 5.10, the WAS for the qualified and scanned NBSs, viz. NBS_1, NBS_4, NBS_5 and NBS_6, are computed. The WAS computation results are tabulated in Table 5.6. because of its highest WAS, NBS_4 is selected as the TBS and this selection is indicated by the STAR (*) mark in Table 5.6. Fig. 5.6 diagrammatically represents the Handover Technique 3 and Fig. 5.7 shows its flowchart.

Table 5.6: Computation of $\{S_{WAS}(l)\}$ from $\{S_{OM}(l)\}$, $\{S_{CL}(l)\}$ and $\{S_{RSS}(l)\}$

NBS_l	$S_{OM}(l)$	W_{OM}	$S_{CL}(l)$	W_{CL}	$S_{RSS}(l)$	W_{RSS}	$S_{WAS}(l)$
1	0.019	0.4	0.181	0.3	0.3	0.3	0.1519
2	-	0.4	-	0.3	-	0.3	-
3	0.019	0.4	-	0.3	-	0.3	-
4	0.250	0.4	0.306	0.3	0.4	0.3	0.3118(*)
5	0.461	0.4	0.144	0.3	0.2	0.3	0.2876
6	0.250	0.4	0.368	0.3	0.1	0.3	0.2404

5.8 Conclusion

The description of Handover Technique 3 has been presented in this chapter. It offers a fast as well as reliable handover in a WiMAX network as will be explained later in this section. The process of handover in Handover Technique 3 is totally controlled by the SBS, though it is initiated by the MS when it sends its VBSL. Actually, the MS performs only a few simple functions: (i) sends the VBSL to the SBS immediately

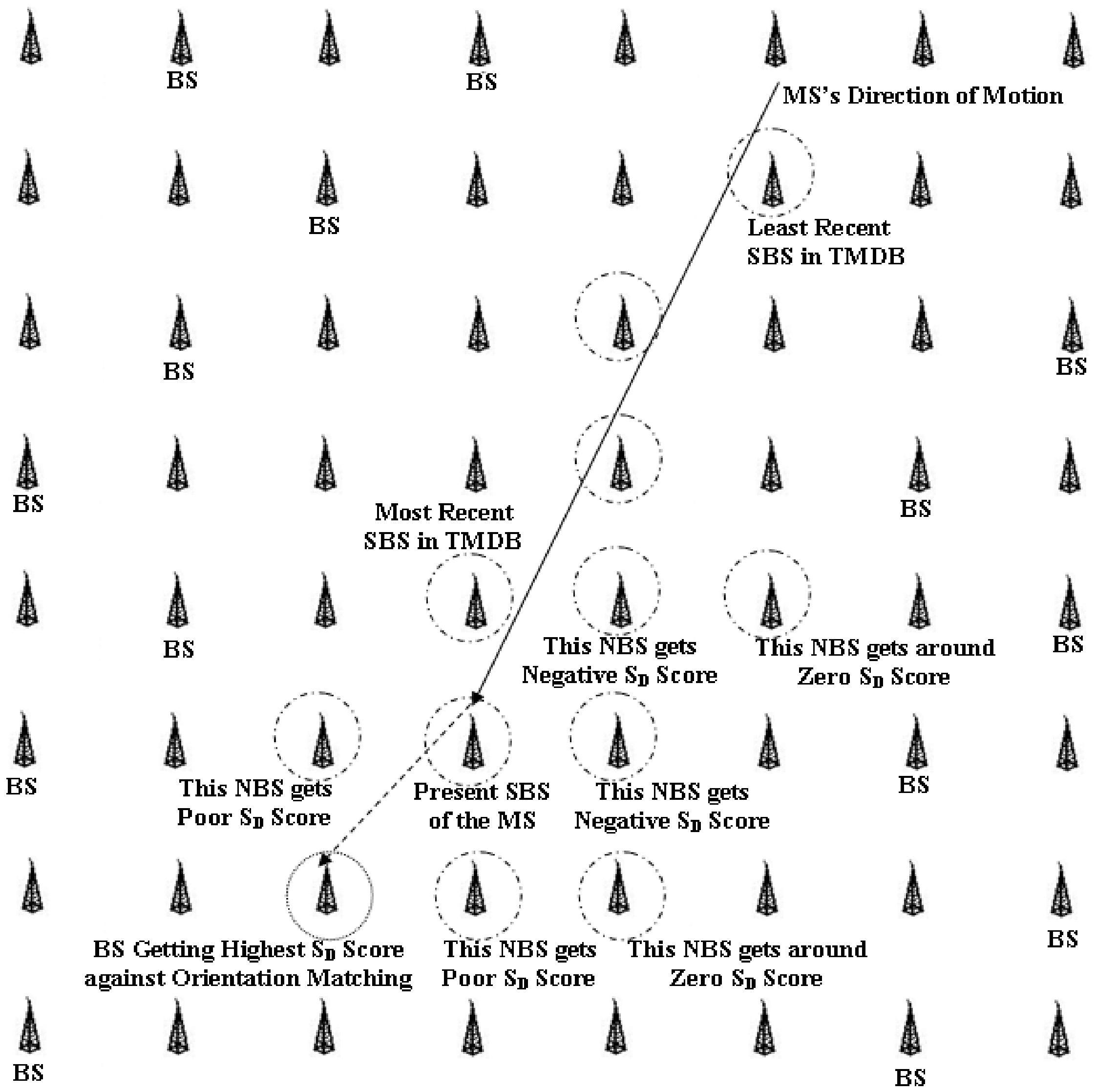


Fig 5.6 WiMAX Network with a Large Number of BSs. Each BS Has Eight NBSs. The NBS Showing the Best Orientation Matching Gets the Highest Score for Direction

upon entering a new cell; (ii) determines when it needs a handover and immediately requests the SBS for a scanning interval; (iii) performs a single scanning cycle and sends to the SBS the RSS values received from the scanned NBSs. On the other hand, the SBS performs all the following major functions:

1. Upon receiving the VBSL, the SBS uses the BS_IDs of the visited SBSs as well as of the NBSs to look up the PCT for their respective polar coordinates and computes the RAD between the MS's EAEM and the GAON of each NBS. It then assigns S_{OM} to each NBS depending on its RAD value.

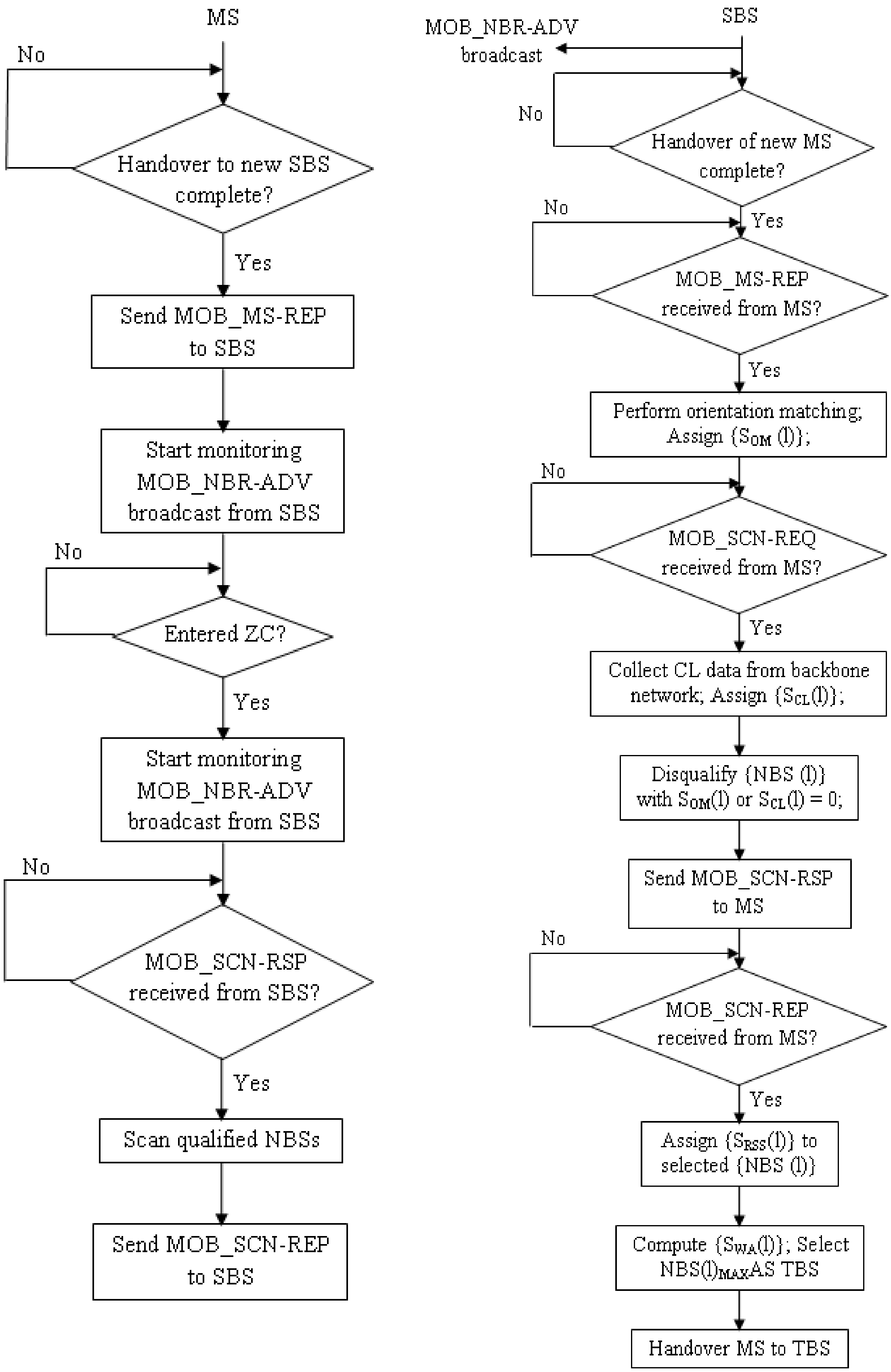


Fig. 5.7 Flowchart of Handover Technique 3

2. Next when the SBS receives the scanning request, it first gathers, via the backbone network, the number of connections passing through each NBS, computes the respective CLs and assigns SCL to each NBS. Then it grants scanning intervals for all NBSs except those that are disqualified because of very poor score in either S_{CL} or S_{OM} or both.
3. Later, upon receipt of the RSS values of the scanned NBSs, the SBS assigns S_{RSS} to them, computes their respective S_{WAS}s, selects the TBS and requests the backbone network for completing the remaining part of the handover process.

It should be noted that OM is a novel concept that has been employed as the most important and dependable among the three criteria (it probably discriminates best between the NBSs) for making the TBS selection in Handover Technique 3. The scheme for implementing OM has been designed by utilizing the GPS-enabled facilities available in the WiMAX BSs. Both the other two criteria that have been employed in making the handover decision in Handover Technique 3, i.e. the CL and the RSS, were also employed earlier in the Handover Techniques 1 and 2. However, they have played fairly different roles in handover Technique 3 than what they had done earlier. CL was earlier used for only eliminating (disqualifying) any extremely overloaded NBS(s) from any further consideration towards being selected as the TBS and had played no other role in the TBS selection. In Handover Technique 3, however, CL has been used both for disqualifying an extremely overloaded NBS from further consideration as well as for (jointly) evaluating the suitability of the remaining qualified NBSs for the TBS selection by assigning them appropriate non-zero scores. On the contrary to the most important role played by the RSS in Handover Techniques 1 and 2, where distances were first estimated from at least two measurements (by scanning) two different RSS that were then used to implement two different lookahead techniques, RSS in Handover Technique 3 has been measured only once and has been directly used as the third parameter to be considered for computing the weighted average score of each NBS.

In support of our assertion that the Handover Technique 3 will be fast well as reliable, we provide the following arguments.

5.8.1 Arguments for a Fast Handover

1. The process of OM is initiated as soon as the MS is handed over to its new SBS. It is completed within a fraction of a second as explained under point 2 below. Thus OM introduces practically no delay at all. In this context, it should be noted that the process of handover generally starts only when the RSS received by the MS from its SBS falls below a certain threshold level. Even at its highest velocity (120 km/hr, i.e. 33.3 m/sec, an MS needs at least 20-30 seconds to travel across a cell, and hence at least 15-20 seconds even to request for scanning).
2. The process of OM including score assignment to the L NBSs is carried out very fast. Please refer to Sections 5.5, 5.6 and 5.7.1, as well as Equations 5.5, Tables 5.2 and 5.3 for the detailed description of the OM process. The reason for the fast execution of the process are elementary operations like memory read, add, subtract, compare, swap etc., with only K multiplications and < (L+1) divisions, which are somewhat time consuming operations. Table 5.7 provides the implementation details of the OM process. It is evident that the total OM process, including score assignment, is unlikely to take more than a fraction of a second even on a slow computer.
3. In all the three WiMAX handover techniques described in this Thesis, we have created four zones, namely, ZN, ZC, ZE and ZD (see Figure 4.2 in Chapter 4), which the MS perceives by measuring the RSS it receives from the SBS. The MS makes the scanning request to the SBS just after entering the ZC, which is somewhat earlier than when the signal falls below the usual threshold level commonly set. In Handover Technique 3, the SBS utilizes this lead time (or a small part of it) for gathering, from the backbone network, the current load (CL) information about all NBSs and assigning S_{CL} to them. The SBS also probably eliminates one or more poorly scoring NBSs from the scanning cycle that it grants to the MS. Since the SBS completes all these jobs extremely quickly (in much less than a second) and well within the lead time, practically no handover delay is incurred.
4. Finally, and most importantly, since the MS performs only one scanning and, probably, of a reduced number of NBSs (one or more NBSs might have been disqualified), the scanning time, which usually contributes significantly to

handover latency, is drastically reduced.

Table 5.7 Implementation Details of the Orientation Matching Process

Step Number	Step Description	Step Function	Operation Type	Operation Numbers
1.	Read out {rik, Ɵik}	Look up PCT at BS_IDs	Read a ROM	K
2.	Read out {GAON}	- D0 -	Do -	L (*)
3.	Compute AAMM	Run program for Equation 5.6	Multiply Add Divide	K 2(K – 1) 1
4.	Estimate EAEM	Compute EAEM = AAMM + 180	Add	1
5.	Estimate {RAD}	Compute {RAD} = {EAEM – GAON} Compare {|RAD|} with 180° {If >, then compute (360° - |RAD|)}	Subtract Compare Subtract	L L < L
6.	Compute {RAD_COMPL}	Compute {RAD_COMPL} = {RAD_REF–RAD}	Subtract	< L
7.	Compute Sum of {RAD_COMPL}	Compute ∑RAD_COMPL	Add	< L – 1
8.	Compute $\{S_{OM}\}$	Compute $\{S_{OM}\}$ = $\{\frac{RAD\_COMPL}{\sum RAD\_COMPL}\}$	Divide	< L
9.	Select the TBS with Min $\{S_{OM}\}$	Run MIN program on $\{S_{OM}\}$	Compare Swap (XCHG)	L – 1 ≤ L - 1

(*) This step need not be performed since GAON value are static and may be, once computed permanently stored in the BS's.

5.8.2 Arguments of a Reliable Handover

Handover being a critical requirement in Mobile WiMAX network or any cellular network in general, few lines of discussion on the reliability of handovers is in order. A reliable handover apparently implies that the MS is successfully transferred from the service of its present SBS to the service of its next SBS without any call break and with the promise of the call being continued seamlessly. Obviously this means that no deterioration in signal strength or QoS should occur. Thus a reliable handover can be usually ensured by choosing as the TBS the NBS, which promises to give the strongest signal and also, which is lightly loaded, i.e., whose current load CL (see Section 4.4 in Chapter 4) is minimum so that it can offer good QoS.

The algorithm in Handover Technique 3 makes the handover fairly reliable because of the following reasons:

1. In most handover algorithms, TBS selection is done solely using a single criterion, which is the RSS. For example, RSS is solely and directly used in handover procedure recommended in the WiMAX standard and has also been used, via distance estimation and appropriate lookahead procedures, in our Handover Techniques 1 and 2. In contrast, the present handover technique (i.e. Handover Technique 3) uses two other independent criteria, namely, the OM and the CL, besides RSS, for TBS selection. It should be noted that OM is capable of, choosing, in advance, the NBS, which will offer the strongest RSS to the MS. Naturally, appropriately weighted averaging of three independent criteria (OM, CL and RSS) would yield a more reliable solution.
2. Elimination of the extremely overloaded NBSs (CL very large) from further consideration towards TBS selection ensures good QoS, avoids possible call drops and hence gives increased reliability of the handover.
3. As explained earlier in Section 5.7.4, during the WAS computation, S_{RSS} offers a useful correction of a possible non-negligible error in S_{OM}. This happens in case the MS, after having entered the current cell, unexpectedly deviates significantly from its EAM (probably by taking a left or a right turn) during the course of its journey within the cell. This advantageous feature of

the WAS scheme for TBS selection considerably increases the reliability of the handover.

4. Reliability of the present handover scheme, i.e. Handover Technique 3, can be further enhanced by taking two or three sets of RSS measurements (instead of a single one) in quick succession and averaging the set of RSS values. However, this will increase the handover latency, though only marginally. Obviously, this will be a desirable trade off.

Chapter 6

Simulation Methodology and Results

6.1 Introduction

This chapter discusses the simulation methodology and results for the three different WiMAX handover schemes proposed by us in Chapters 4 and 5. The two mobile station (MS)-controlled distance estimation and lookahead-based fast handover schemes described in Chapter 4, i.e. the Handover Techniques 1 and 2, have been simulated using the Qualnet 4.5 simulator [88]. For the orientation matching-based handover scheme discussed in Chapter 5, i.e. Handover Technique 3, we have written a Python-based tool to simulate it. For simulating Handover Techniques 1 and 2, our primary requirements were choosing (i) an appropriate discrete-event simulator that would provide us with an implementation of most of the Layer-2 air interface features of the IEEE 802.16e standard and (ii) appropriate mobility models to model different movement patterns of an MS. For the first requirement, we chose Qualnet 4.5 as it provided an implementation of most of the Layer-2 air interface features of the IEEE 802.16e standard that were required for validating the two MS-controlled handover schemes. A concise discussion of the reasons for choosing Qualnet 4.5 is provided in Section 6.2.1. For the second requirement, choosing appropriate mobility models was important. This is because, the schemes discussed in Chapter 4 focuses on implementing fast handover techniques based on the assumption of some pattern of mobility of the MS. Hence, patterns of user movements can play a critical role in the performance of such schemes. As a matter of fact, without selection of appropriate mobility models the mobility-related results obtained may turn out to be poor. A brief discussion on the choice of mobility models is presented in Section 6.2.2. The simulation topologies and parameters in Qualnet were mostly assumed according to the specifications of WiMAX Forum, of which Qualnet is a member [89-90]. Other variable parameters, important in the simulation, like, nature of the terrain, weather conditions and heights of transmitters and receivers, were appropriately chosen to make the overall simulation environment realistic. In each simulation, multiple replications were performed before producing the final results. For simulating the Handover Technique 3, we required a simulation topology providing us primarily with an environment where a huge number of WiMAX BSs (at least in order of 100 BSs) is plotted with the basic backbone architecture of WiMAX network presented. As Qualnet 4.5 did not provide these basic requirements appropriately, we have written a Python-based basic tool to simulate Handover Technique 3. More on this is discussed in Section 6.4.

6.2 Simulation Studies on Handover Techniques 1 and 2

Handover Techniques 1 and 2 described in Chapter 4 promise to offer MS-controlled fast handover in Mobile WiMAX networks. Both the techniques employ distance estimation utilizing the distance-dependent pathloss property of the RSS received by the MS from the NBSs. The MS performs multiple scannings of the appropriate NBSs and, from the received RSS samples of each of these NBSs, the MS estimates the corresponding distance samples of each NBS relative to itself. Based on these changing relative distance samples, the MS performs an appropriate lookahead scheme to determine, in advance, which NBS it is most likely to get nearest to (assuming it continue its present direction of motion) and hence should be selected as the TBS. Though their distance estimation principle is identical, the two handover techniques, described in Chapter 4, differ in their respective lookahead principles. The first one estimates the Differences in Consecutive Distances (DiCDs) and, based on sum of the successive DiCDs, selects that NBS as the TBS, which shows the highest Accumulated Forward Movement (AFM). In contrast, in the second lookahead scheme, the MS selects as the TBS the NBS, which shows the least Angles of Divergence (AOD) with respect to the MS's current direction of motion, assumed to be linear. Making appropriate choices on the simulator, the mobility models and the simulation environment used were very important. The next few sub-sections provide discussions on each of these.

6.2.1 Choice of Simulator

When this research work was started, Qualnet 4.5 [88] was chosen, over other options like NS-2 [91] and OPNET [92], because at that time, it was the only available simulator providing us with a basic implementation of some of the Mobile WiMAX air interface and other features that were required for our work. Also, Qualnet had been extensively used as the simulator of choice to carry on different roaming and handover-related research in WiMAX and other cellular technologies [48, 93, 94-95]. Below we provide a list of requirements that Qualnet fulfilled.

1. *Provision of basic support for Mobile WiMAX air interface*: Qualnet's Advanced Wireless Library provided a basic implementation of the Mobile WiMAX air interface (Layers 1 and 2).
2. *Support for hard handover framework*: A basic implementation model of the Mobile WiMAX hard handover technique, including cell reselection (i.e. handover), scanning-ranging and network re-entry activities were implemented.
3. *Provision of multi-cell WiMAX topologies*: Our requirement of having a simulation topology with multiple appropriately-placed WiMAX BSs, each having its own channel frequency, were met.
4. *Provision of support for mobility models:* The widely used Random Waypoint Mobility Model (RWMM) was implemented in Qualnet and provisions were there to plug-in other mobility models. We thus implemented and used the Random Direction Mobility Model (RDMM) and the City-based Mobility Model (CMM) as well. The last named mobility model is also known as the Manhattan Mobility Model (MMM).
5. *Appropriate random-number generator:* The Developer's Library in Qualnet provided the random-number generator required for the simulation (e.g. simulating packet generation and arrival times).

However, none of the Qualnet Advanced Wireless Library, Wireless Library and the Developer Library that we were using, provided any WIMAX specific pathloss model, like the Erceg Model, the COST-231 Hata Model or the Walfish_Ikegami Model. The only near-relevant model that Qualnet Developer Library had for simulating the pathloss behaviour in Handover Techniques 1 and 2, was the Two-Ray pathloss model, which was used to carry out the simulations. In this regards, the following points should be noted on the probable effects of the type of pathloss model used for simulation on the handover performance. (i) Estimation of distances from the RSS samples in the proposed handover techniques was not dependent on any particular underlying pathloss model and the Two-Ray model was just used because of its free availability with Qualnet. (ii) Use of a non Two-Ray pathloss model, like, COST-213 Hata model or Walfisch_Ikegami model to measure the RSS samples would not have affected how fast the handovers are performed, which is the primary focus of the Thesis work. (iii) Although there is a minor possibility that use of a more appropriate non Two-Ray pathloss model may have resulted in more accurate distance estimation and thus more accurate prediction of MS's movement direction, it would have no way resulted in a failed handover activity. In a worst case scenario, because of a less accurate prediction of MS's movement direction, the MS may have chosen a TBS, which is not the best choice for handover. This could have only resulted in more number of handovers for the MS without compromising the handover speed or latency in any way.

6.2.2 Mobility models used for simulation

For simulating the proposed Handover Techniques 1 and 2, we considered users moving in vehicles with mobile devices. Since, in a Mobile WiMAX-based metropolitan area environment, depending on situations, the users can move in different speeds (i.e. from slow to very fast), we considered the range of movement speeds from as low as 20 Km/h to as fast as 120 Km/h. Moreover, we also considered simulating the movements of MSs in the different situations where

(i) the user is moving along the motorways or the state highways with the roads (i.e. user's movements) being relatively straight and not zigzag or random

(ii) the user is moving in the cities with the roads/movements being straight/curvy/zigzag but not random

(iii) the user is moving along the city centre having roads laid out in the form of grids

To fulfil our requirements, we chose three different mobility models, namely, the RWMM, the RDMM and the CMM. Here we present, briefly, the reasons for choosing these models for our work.

A. *Random Waypoint Mobility Model (RWMM):* This is the commonly used benchmark mobility model for mobile communications research [96]. In addition to being used in MANETS, RWMM is also used to model MS movement patterns in WiMAX [97] and other long-ranged cellular networks [98]. The RWMM is specifically assumed in our simulations because of the following reasons:
   (i) For the simulation, we assumed that MS's movements remain linear over small time frames (refer to Chapter 4) before it changes. RWMM enabled us to simulate such movement patterns.
   (ii) RWMM allowed us to simulate MS's movement in different directions, but over short stretches, in a city.
B. *Random Direction Mobility Model (RDMM):* RDMM is widely used to model user movement patterns in different long-ranged cellular networks [98-99]. It is specifically assumed in our simulations because of the following reasons:
   (i) In RDMM, the MS' random movement is uniformly distributed over the whole simulation area. We thus found it useful to simulate MS's movements over a long stretch of path without changing directions frequently (e.g. movement along a geographical area containing a mix of relatively straight motorways and other not so straight roads).
   (ii) RDMM allowed us to simulate MS's movement covering the different BS's, spread over the whole terrain area (even those that are located in the terrain boundary).

C. *City-based Mobility Model (CMM):* The CMM is used to simulate user movement patterns in the central part of a city, where the streets are mostly laid out in the form of grids. The simulation area is logically divided into a number of horizontal and vertical streets, intersecting each other. So, in our simulations, an MS can choose its movement direction randomly (i.e. left, right or straight) at each crossing (intersection), but it has to move within the grid, in straight lines, over small stretches of path. The model is used by the WiMAX research community to perform handover-related research work [100].

6.2.3 Simulation Topology

The performance evaluation of Handover Techniques 1 and 2 was done using the IEEE 802.16e OFDMA model implemented using the Qualnet 4.5 simulator's Advanced Wireless Library and Developer Library [10, 88].

For our simulation topology, we have chosen a multi-BS environment [46, 48], instead of an environment containing just two or three BSs, as in [95] for the following reasons.

- In a high-speed mobility environment supported by Mobile WiMAX (a MS' speed of up to 120 km/h is supported), simulating handovers among multiple BSs is always a better option. This helps to assess the performance of the handover schemes more critically and realistically using realistic mobility and path loss models, where different type of user movement patterns can be simulated covering the whole of the simulation area.
- Moreover, in case of technologies like Mobile WiMAX spanning over metropolitan areas, it is expected that more than two or three BSs are required to cover the whole city area. As per the Mobile WiMAX standard, an MS may even have six to eight different BSs surrounding it [18, 22].

Thus, in our simulation topology shown in Figure 6.1, we have considered six different cells, each having one BS and three MSs in it. All the six BSs are connected to the backbone network with the help of an Access Network Gateway (ASN-GW). These 25 nodes are spread over a terrain of 1500 m x 1500 m [101]. The six BSs, numbered 4, 5, 10, 13, 17 and 21, are deployed in a multi-cell environment operating with different radio frequencies within the range (2.4 GHz – 2.45 GHz) [101]. We assumed that all the six BSs are under the same administrative domain.

Apart from the six BSs, node 25 is the ASN-GW and the others are the MSs. Within each cell, all the MSs simultaneously communicate with their respective BSs. On the other hand, BSs also communicate amongst themselves through the backbone network via the ASN-GW. The nature of traffic assumed in the simulation is the commonly used Constant Bit Rate (CBR), since using CBR enables the easy tracking of the effects of the handover schemes [22, 93].

As per our simulation model, a single MS (node 1 in Figure 6.1), initially controlled (served) by the BS # 4 (the SBS), is randomly moving between the different NBSs (5, 10, 13, 17 and 21) and perform handovers whenever needed, as per the underlying handover scheme. As explained in Section 6.2.2, we have considered RWMM, RDMM and the CMM to simulate three different movement patterns for the MS. Movement speed of the MS ranges between 20 km/h to 120 km/h [102]. The practical two-ray path loss model, widely used for similar kind of research in Mobile WiMAX environment and available in Qualnet, is used to incorporate the path loss effects during simulation [10, 48, 92, 103-104]. Unfortunately, although tried, we could not manage to successfully incorporate the implemented COST-231 Hata model to the simulator and this has been left for future work. All the graphs depict the final results obtained by the method of Independent Replications. One replication, on average, lasted for approximately 20 minutes of real computing time, which is equal to 5-6 mins of running time of the WiMAX simulation model in Qualnet. This time was sufficient to simulate the MS making multiple numbers of different movements covering most or all, of the six cells and performing multiple numbers of handovers from one cell to another. The results

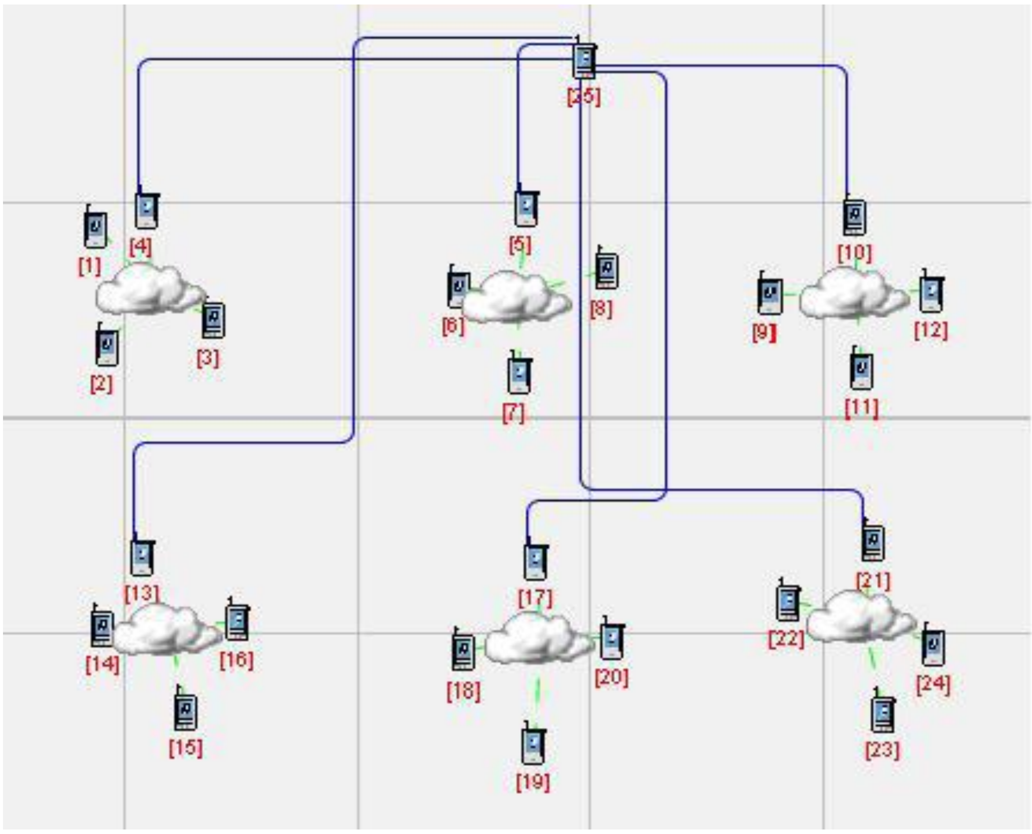


Fig. 6.1 The Multi-Cell Simulation Topology

showed are based on satisfactorily large number of samples of data collected by running 20 independent replications in each case. The maximum relative statistical error observed across the presented results is 8%.

6.2.4 Parameters Considered for Simulation

Table 6.1 lists the important simulation parameters that are used to analyze the correctness of our proposed schemes. These parameters are considered as typical, see [48, 89, 94-95]. Apart from these simulation topology and model-related parameters, we have also considered certain handover-related attributes in order to analyse the performance of our proposed schemes. They include the following handover activity latencies:

- T_{Ini}: Duration of handover initiation time interval before the on-set of the scanning phase.
- T_{Scan}: Time required for an MS to complete scanning, synchronizing and contention-based associated ranging activities with the different NBSs [22]. It depends on the number of NBSs to be scanned.
- T_{Fast_Scan}: Time required for an MS to complete optimized/fast scanning as per our proposed schemes.
- T_{HO_Prep}: Handover preparation time [18]. This constitutes the time related to pre-handover notification message exchanges between the MS and the SBS once the MS identifies few of the potential NBSs for handover through the scanning phase. Messages like MS handover request (MOB_MSHO-REQ) and BS handover response (MOB_BSHO-RSP) are exchanged prior to finalizing the ultimate TBS for the handover activity.
- T_{Normal_Sync}: DL and UL synchronization time of the MS with the different NBSs.
- T_{TBS_Sync}: DL and UL synchronisation time of the MS with the newly selected TBS.
- T_{Cont_Rang}: Contention-oriented ranging time required for an MS to perform a successful ranging with an NBS after contesting with other MSs over available ranging slots [22]. It was assumed that at least two ranging iterations occur before a successful ranging operation is accomplished.

Table 6.1 Simulation Parameters

Parameters	Values
Number of BSs	6
Number of MSs	18
Number of cells	6
Bandwidth	10 MHz
FFT Size	1024
No. of Sub channels	30
MAC Propagation Delay	1 µs
VoIP Application Exists?	Yes
Environment Temperature (K)	290
Noise Factor (K)	10
Default Frame Length	20 ms
Signal Values (in dBm)	-76, -78, -80
BS Antenna Height	15 m
MS Antenna Height	1.5 m
QPSK Encoding Rate	0.5
BS Link Propagation Delay	1 ms
Scan Interleaving Interval	6 frames
MS's movement speed	20 kmph – 120 kmph
Path Loss Model	Two-Ray
Mobility Models	RWMM, RDMM and CMM.
Propagation Limit	-111.0
PHY Transmission Power	20 dBm
PHY 802.16 Cyclic Prefix	8.0
Antenna Model	Omni directional
Antenna Efficiency	0.8
Antenna Mismatch Loss	0.3 dB
Antenna Connection Loss	0.2 dB
MOB_NBR-ADV Message Interval	1 sec
Handover RSS Margin	3.0
PHY 802.16 CDMA Ranging Threshold	11.0
Network Protocol	IPv6

- T_{Cap_Neg}: Time required for performing capabilities negotiation.
- T_{Auth}: Time required for a successful authorization procedure through authorization hand-shaking framework during network entry.
- T_{Reg}: Time required for accomplishing a successful registration policy during network entry.

As per our proposed schemes, fast handovers are achieved primarily by shortening the lengthy NTAP time occurring in the conventional Mobile WiMAX handover technique. Along with that, omission of certain MAC management / communication messages that are exchanged between the SBS and an MS, both during the NTAP and the AHOP, also results in lowering the overall handover time. The next section explains simulation results of the Handover Techniques 1 (DiCD-based) and 2 (AOD-based).

6.3 Simulation Results of Handover Techniques 1 and 2

This section explains the simulation results of the two handover techniques explained in Chapter 4. The proposed schemes focused on improving the handover performance primarily in terms of handover time and in choosing the best TBS for handover. Improvements have been proposed in both the NTAP and the AHOP. The next sub-section discusses the analysis of the two distance estimation and lookahead-based fast handover schemes, Handover Techniques 1 and 2 (described in Chapter 4).

6.3.1 Simulation Results of DiCD- and AOD-based Lookahead Schemes

Some of the results of analysis of these two schemes have been reported in our publications [74-75]. As explained in Chapter 2, the overall Mobile WiMAX handover time comprises of the time for the NTAP and that for the AHOP [22]. Generally, the time spent by the MS in initiating a potential handover process by sensing the MOB_NBR-ADV broadcasts and then carrying out scanning and synchronization activities with the NBSs until the selection of the TBS, marks the total time spent in the NTAP [18]. In contrast with the conventional Mobile WiMAX hard handover scheme [22], where the MS carries out scanning and synchronization activities with all the advertised NBSs (indicated by ΔT_{Scan} in the list of defined parameters in Section 6.2.4) before short listing a few, the overall NTAP latency in our two proposed schemes is reduced due to the fewer scanning activities performed by the MS (indicated by ΔT_{Fast_Scan} in the list of defined parameters) with only the shortlisted NBSs (PTBSs) as discussed in Chapter 4.

The NTAP is followed by the activities performed during the AHOP. In case of the conventional handover phase, the total AHOP time is comprised of such different times as the actual handover preparation time (indicated by ΔT_{HO_Prep} in the list of defined parameters), the MS-TBS synchronization time (indicated by ΔT_{TBS_Sync} in the list of defined parameters), MS-TBS ranging time (indicated by ΔT_{TBS_Rang} in the list of defined parameters), the TBS capabilities negotiation time [22] (indicated by ΔT_{Cap_Neg} in the list of defined parameters) and the MS-TBS authorization and registration time (indicated by ΔT_{Re_Auth} and ΔT_{Reg} in the list of defined parameters). Out of these, the actual handover preparation time indicates the time spent in carrying out activities regarding the finalization of the ultimate TBS before the MS goes for the handover. During this time, the SBS exchanges quite a number of MAC management messages with the MS, as well as with the candidate TBSs (e.g. MS Handover Request message or MOB_MSHO-REQ [22] and BS Handover Response Message or MOB_BSHO-RSP [22]), that are shortlisted by the MS through scanning. These messages are meant mostly to ensure that the MS would receive adequate QoS, BW and other related resources from its next SBS after handover [22]. Exchange of these messages, however, adds up to the overall handover delay. On the other hand, in our two proposed 'lookahead' schemes, potential TBSs (PTBS), that are not overloaded, are shortlisted through inter-BS communication over the backbone network prior to scanning (see Chapter 4). The MS directly goes for the handover (i.e. sends the MOB_HO-IND message to the SBS) as soon as the TBS is finalized through scanning, which implies that use of MOB_MSHO-REQ, MOB_BSHO-RSP or MOB_BSHO-REQ messages are avoided altogether. This omission of the handover preparation time also reduces the overall handover time. The results presented in the next sub-sections, discuss improvements in the NTAP-related time and overall handover time in the conventional Mobile WiMAX hard handover technique, using Handover Techniques 1 and 2. All results are shown together with the relative statistical errors at the 95% confidence level.

A. Simulation Results of Network Topology Acquisition Phase (NTAP) Time

The simulations carried out using the RWMM for six different speeds of the MS (20 km/h – 120 km/h) show that, in comparison to the conventional Mobile WiMAX MAC-layer hard handover technique, our proposed fast Handover Techniques 1 and 2 considerably reduce the NTAP-related time. Figure 6.2 shows the results of the NTAP time analysis for the DiCD-based and the AOD-based lookahead schemes. MS's movement in the terrain is simulated using the RWMM. It can be seen that in comparison to the conventional Mobile WiMAX handover scheme, the proposed DiCD-based and AOD-based schemes can improve the NTAP time by around 35%.

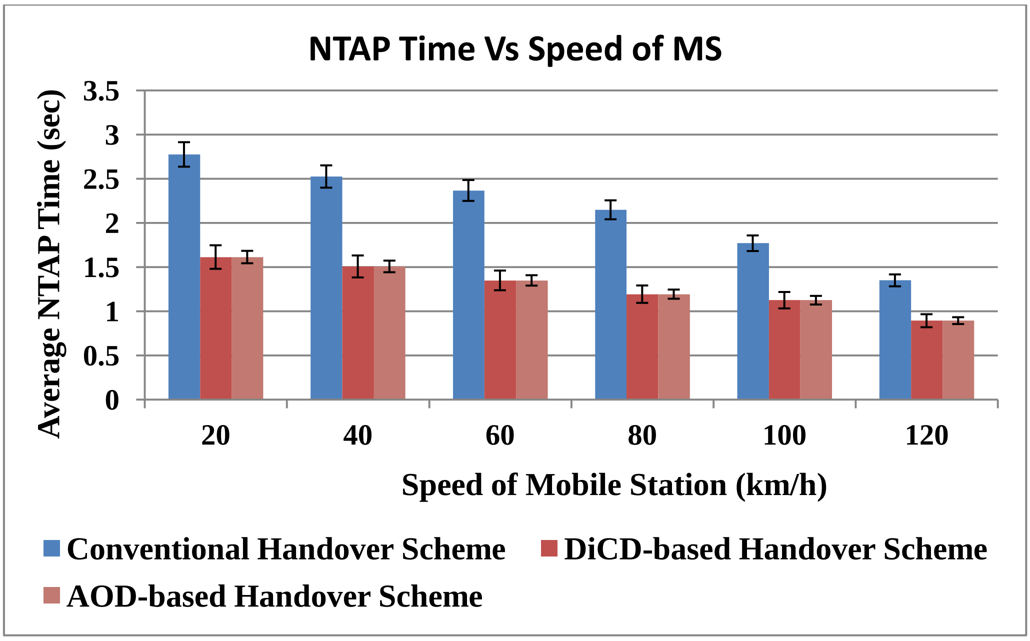


Fig. 6.2 NTAP Time Analysis for DiCD-based and AOD-based Lookahead Schemes Assuming RWMM

The time incurred during NTAP is primarily related to the time taken to complete the scanning and ranging-related activities during this phase. In the conventional hard handover scheme, irrespective of its movement direction, an MS carries out scanning, ranging and synchronization-related activities with all the advertised NBSs, which is often unnecessary. An MS may often need to carry out up to six iterations of such activities with all the different six to eight NBSs around it [10, 22, 48]. The overall time taken to complete these scanning-related activities is thus significantly high. However, in our schemes, an MS scans only those PTBSs that it has selected on the basis of (i) provision of adequate resources after the handover and (ii) progressive movements w.r.t itself (see Chapter 4). Hence, the number of NBSs that an MS needs to scan before selecting the TBS is much less in case of the DiCD and AOD-based fast handover schemes. The MS carries out three to four scanning iterations before finalising the TBS for a handover activity (refer to Chapter 4). As explained, fewer scanning iterations also accounts towards making the overall NTAP completion time faster.

Similarly, to the results presented in Figure 6.2, the results of simulations, depicted in Figure 6.3, using RDMM to model MS's movement shows that in comparison to the conventional Mobile WiMAX handover scheme, the NTAP in Handover Techniques 1 and 2 can be faster by around 45% when RDMM is used to simulate MS's movement, the reasons for such reductions being the same as in RWMM. Lastly, Figure 6.4 shows the results of simulations carried out assuming CMM for the MS's movement. In comparison to the conventional scheme, the NTAP, in this case, can be faster by around 45% for Handover Techniques 1 and 2. The reason for such reductions is the same as explained for Figure 6.2.

In this context, from Figures 6.2-6.4 it can be seen that the NTAP time taken to complete a handover by an MS, decreases with the increase in the speed of the MS, with the maximum time taken when the speed is 20 km/h and minimum at the speed of 120 km/h. The inter-scanning interval being inversely proportional to the speed of the MS is maximum at 20 km/h and minimum at 120 km/h. If the interval remains the same for all speeds of an MS, it may result to a faulty choice of TBS for a handover activity.

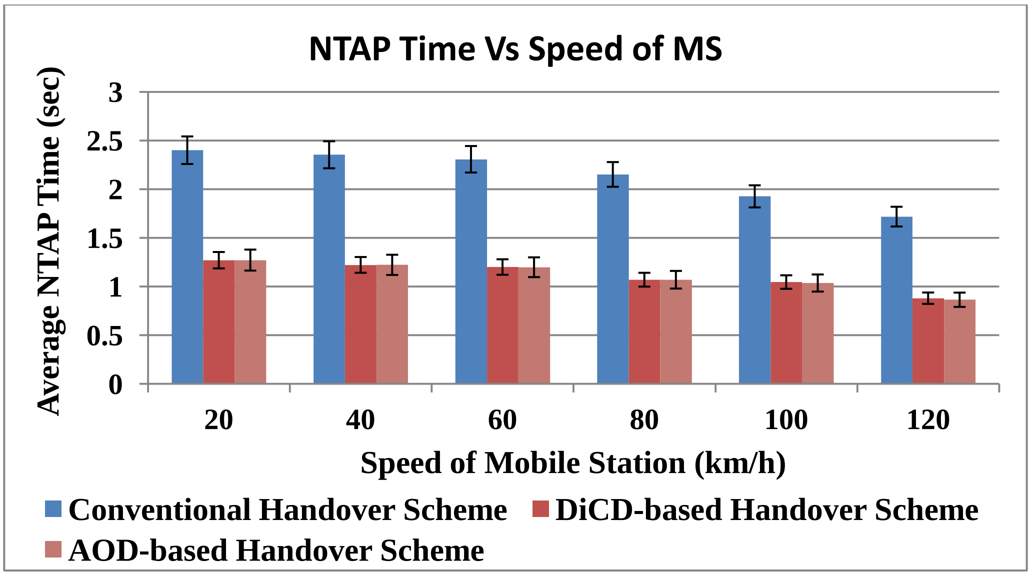


Fig. 6.3 NTAP Time Analysis for DiCD-based and AOD-based Lookahead Schemes Assuming RDMM

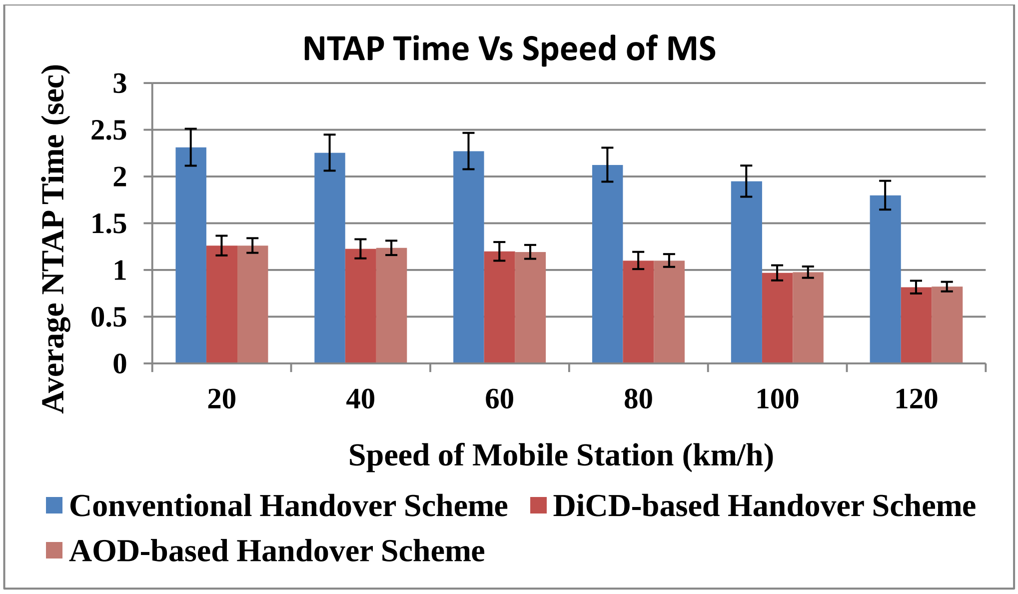


Fig. 6.4 NTAP Time Analysis for DiCD-based and AOD-based Lookahead Schemes Assuming CMM

B. Results of the Overall Handover Time

The overall handover time includes the time taken to complete the NTAP and the time taken to complete the AHOP. Figure 6.5 shows comparisons of the overall handover time of the conventional handover technique and the proposed Handover Techniques 1 and 2, when the MS is moving according to RWMM. Again six different speeds of the MS (20km/h to 120 km/h) are used to study the effects of fast handovers.

The results presented in Figure 6.5 show that in comparison to the conventional handover scheme, both the proposed DiCD-based and the AOD-based lookahead schemes can reduce the overall hard handover time in the Mobile WiMAX technology by at least 32%. This can be accounted from the fact that the overall handover time (i.e. NTAP time + AHOP time), T_{Conv_HO}, in the conventional Mobile WiMAX hard handover scheme is given by

$$T_{Conv\_HO} = T_{Ini} + T_{Scan} + T_{HO\_Prep} + T_{Normal\_Sync} + T_{Cont\_Rang} + T_{Cap\_Neg} + \ + T_{Auth} + T_{Reg} \qquad (6.1)$$

which constitutes of time taken to perform the different individual steps, as explained previously in Section 6.3.1, to complete of the actual handover procedure.

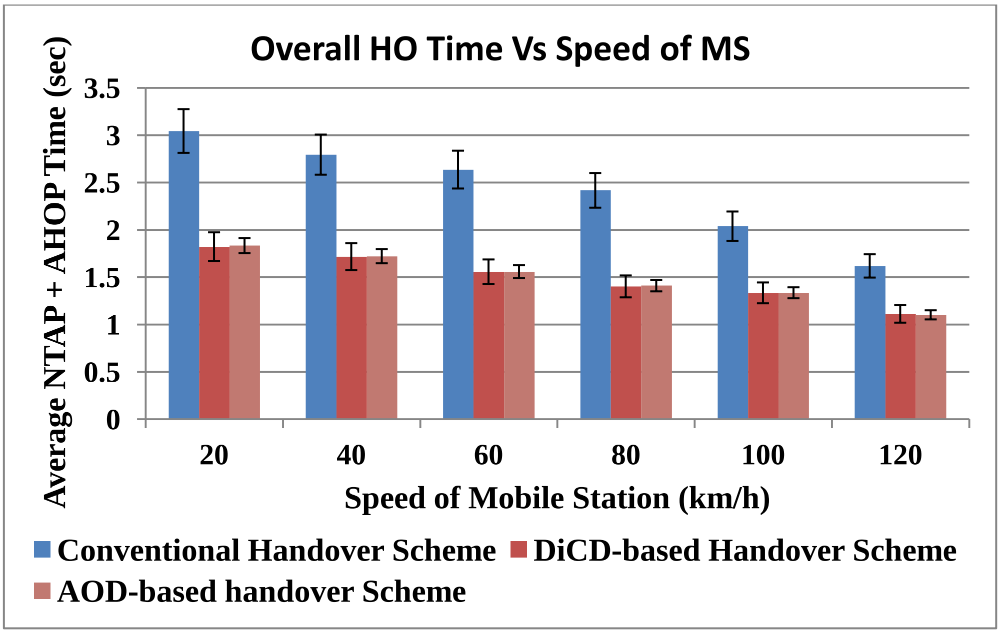


Fig. 6.5 Overall Handover Time Analysis for DiCD-based and AOD-based Lookahead Schemes Assuming RWMM

On the other hand, the overall handover time, T_{Prop_HO} in our proposed scheme equals

$$T_{Prop\_HO} = T_{Ini} + T_{Fast\_Scan} + T_{TBS\_Sync} + T_{Cont\_Rang} + T_{Cap\_Neg} + T_{Auth} + T_{Reg} \quad (6.2)$$

and owing to less number of scanning activities performed and reduced exchanges of MAC-management messages between MS and SBS in the AHOP, $T_{Prop\_HO} << T_{Conv\_HO}$.

In line to the results obtained assuming the RWMM, similar results are also obtained for the RDMM and the CMM. Figure 6.6 shows an improvement of around 42% on the overall handover time when the two proposed handover techniques are simulated assuming the RDMM.

Likewise, in Figure 6.7, the results obtained, assuming the CMM to model the movements of MS in the terrain, show an improvement of around 43% in the overall handover time for the proposed schemes in comparison to that in the conventional handover scheme.

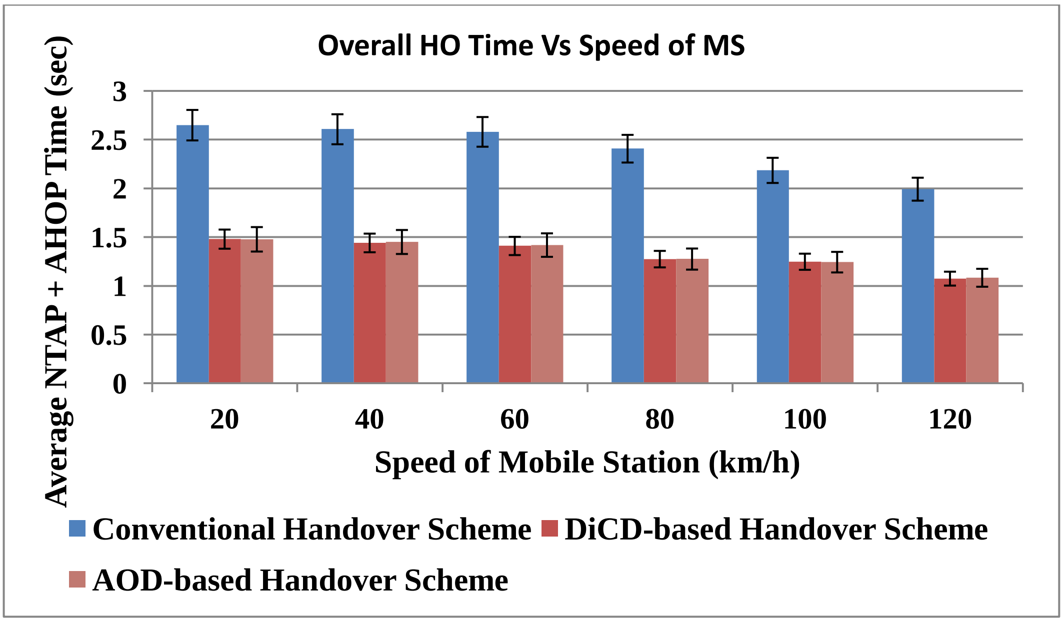


Fig. 6.6 Overall Handover Time Analysis for DiCD-based and AOD-based Lookahead Schemes Assuming RDMM

From Figures 6.5-6.7, it could be seen that the overall time taken to complete a handover is the maximum when the MS moves following the requirements of the RWMM and is the minimum in case of the CMM. This could be due to the fact that

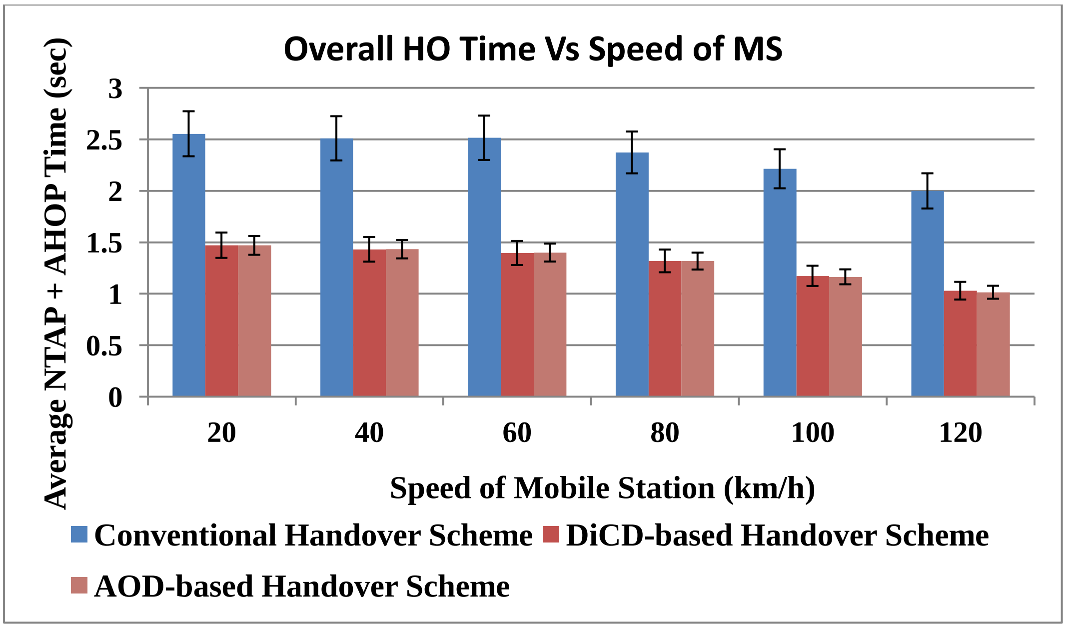


Fig. 6.7 Overall Handover Time Analysis for DiCD-based and AOD-based Lookahead Schemes Assuming CMM

while choosing the next random direction to move, in case of the RWMM, the MS has to randomly choose one direction out of any direction. This is because, in the RWMM, the current movement of the MS is not dependent on the previous movement, i.e., every direction an MS chooses is independent of the previous chosen direction and the MS could choose any direction randomly. So every time the MS pauses to select a different movement direction, it has to choose one from any direction and this takes time. On the other hand, in case of the CMM, where the roads are in the form of grids, the MS just has to choose one random direction out of only four different directions available to choose from. So, the time taken to make each of these choices is shorter than the RWMM one.

C. Results of the Number of Scans Performed per Handover

The number of scans performed per handover in our proposed Handover Techniques 1 and 2 is much smaller in comparison to that performed in case of the conventional handover technique. This is due to the fact that an MS, in the proposed schemes, scans only those NBSs, which would provide the MS with adequate resources after the handover, and which show progressive movements with respect to the MS. In case of the conventional scenario, irrespective of the movement direction, an MS may scan almost all the different advertised NBSs, before selecting the TBS for a handover. So, the number of scanning iterations may go up to even six per handover. On the other hand, in our proposed schemes, the mean number of scans per handover is between three and four, before the MS could finalise a TBS (refer to Section 4.7).

For Handover Techniques 1 and 2, Figure 6.8 shows the results of the number of scans performed per handover when the MS, assuming the RWMM, moves at six different speeds ranging from 20 km/h to 120 km/h. For reasons explained above, the number of scans performed per handover for both the proposed DiCD and AOD-based schemes is much smaller in comparison to the conventional technique and lies between three and four per handover with the inter-scanning interval decreasing with the increase in MS’s movement speed.

Similarly, Figure 6.9 shows the mean of number of scans performed per handover in case of the DiCD-based and AOD-based lookahead schemes when the MS moves following the RDMM. Lastly, Figure 6.10 shows the mean number of scans performed per handover in our DiCD-based and AOD-based lookahead

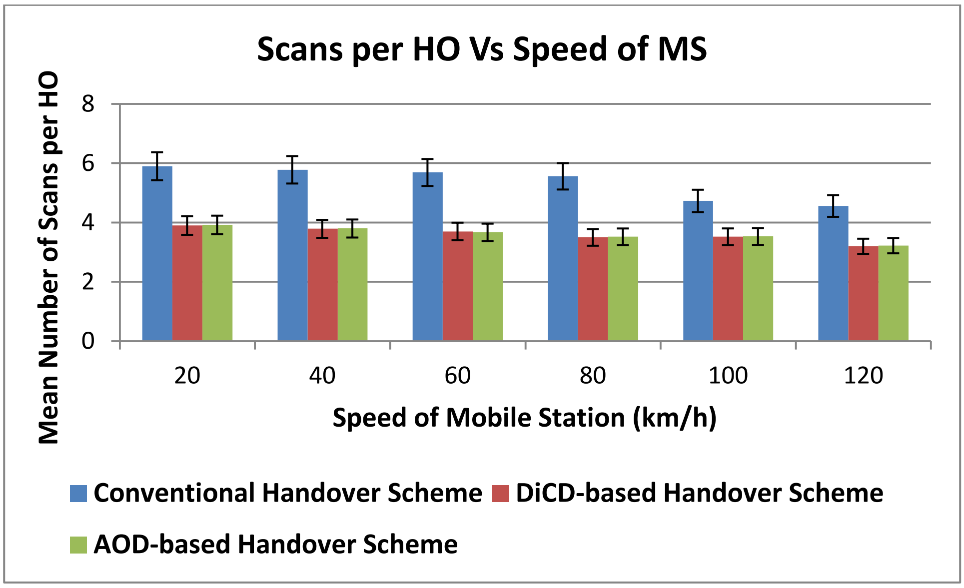


Fig. 6.8 Mean Number of Scans Performed per Handover for DiCD-based and AOD-based Lookahead Schemes Assuming RWMM

schemes when the MS moves following the CMM. Explanations for the obtained results are similar to those related with Figure 6.8.

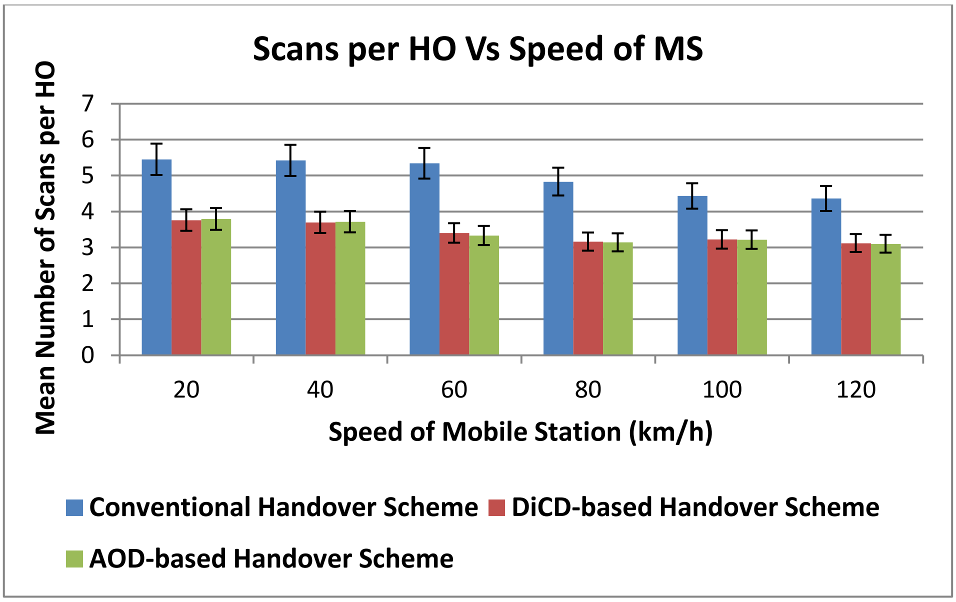


Fig. 6.9 Mean Number of Scans Performed per Handover for DiCD-based and AOD-based Lookahead Schemes Assuming RDMM

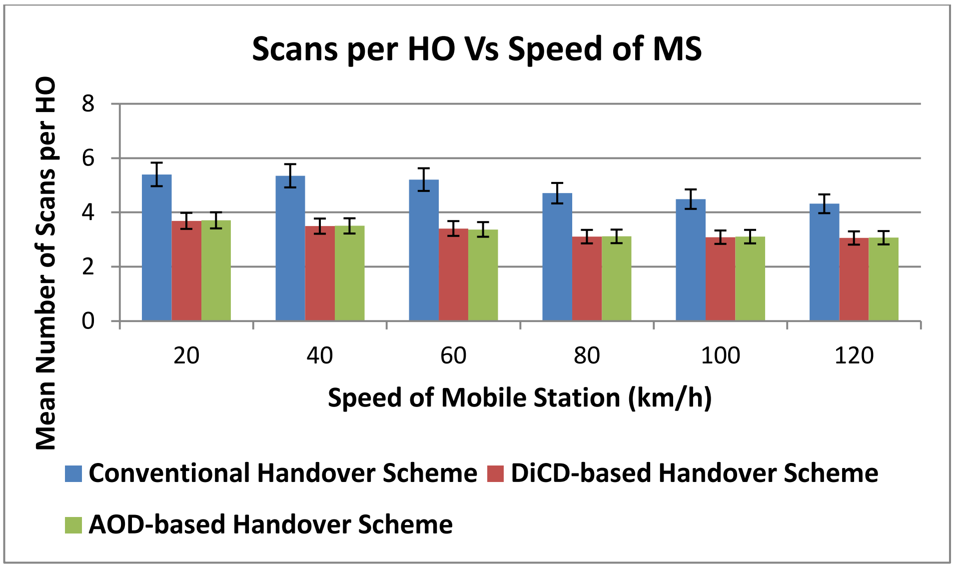


Fig. 6.10 Mean Number of Scans Performed per Handover for DiCD-based and AOD-based Lookahead Schemes Assuming CMM

6.4 Simulation Studies on Handover Technique 3

The Handover Technique 3, which was described in Chapter 5, promises to offer a really fast and, at the same time, a reliable handover in a Mobile WiMAX network. The arguments supporting this claim were explained in Section 5.8. The process of TBS selection in Handover Technique 3 is based on three criteria. These are: (i) orientation matching between the MS's direction of motion and the respective geolocation angle of each NBS, all measured relative to the centroid of the SBS, (ii) the current load of each NBS and (iii) the current value of the RSS received by the MS from each NBS, during the only scanning the MS performs to select the TBS. Each NBS is assigned some score against each of the three criteria and the NBS that obtains the highest weighted average score (WAS) of the three criteria is selected as the TBS. The method of assigning the scores to each NBS against each criterion, the method to appropriately combining these scores by suitably choosing the weight of each score and, finally, obtaining the WAS of each NBS were discussed in Section 5.7. It was pointed out that, out of the three criteria used for the TBS selection, the novel concept of orientation matching provides the most important and dependable criterion that probably discriminates best among the NBSs. An example of the complete process of TBS selection in Handover Technique 3 was also worked out in Chapter 5 to clearly illustrate the orientation matching method, methods of assignment of the three scores (orientation matching, load and signal strength) and the computation process of the WAS of each NBS for making the TBS selection.

Now, it is natural to expect that a suitable simulation experiment should be designed and carried out to validate the proposed principle of TBS selection in Handover Technique 3 and to assess its expected performance. Unfortunately, Qualnet was not found suitable to help in this simulation because this desired simulation experiment would require a simulator capable of reasonably simulating the basic architecture of a Mobile WiMAX network (see Section 5.4 in Chapter 5). Specifically, the simulation should (i) allow at least an order of one hundred BSs to be interconnected in the WiMAX network, (ii) provide the geolocation (in polar coordinates) of each BS with respect to very other BS and, finally, also provide the current load of each BS in the network in terms of either packet throughput or the number of connections (see Sections 4.4 in Chapter 4) being serviced by the BS at present. All these requirements arise because any BS can become a SBS or NBS and may, at any time, be included in the VBSL specified by any of the hundreds of MSs. The Advanced Wireless Library in Qualnet version 4.5, the only WiMAX simulator available to us, was designed primarily for the basic air interface features and provides very little support for the Mobile WiMAX handover environment in terms of appropriate backbone architecture, load measurements of BSs, appropriate pathloss model, etc. Although, it had incidentally provided and supported all the features that were required for simulating the Handover Techniques 1 and 2 (the requirements included scanning and ranging features, mobility models and a pathloss model), it could not provide any of the previously stated requirements of information, that was needed to allow the simulation program for the Handover Technique 3 to handle the two criteria other than the RSS, namely, the orientation matching and the current load.

Thus, as Qualnet could not provide a meaningful simulation environment, we decided to implement our own simulation environment, with the barest minimum facilities, for validating the Handover Technique 3. Below we describe the simulation environment we implemented using Python. Unlike the simulation studies on Handover Techniques 1 and 2, where the main aim was to show how fast the handovers could occur (i.e. how much the overall handover time could be reduced using our proposed schemes), our main aim in this case is to prove the reliability of the proposed Handover Technique 3, i.e., whether the orientation matching scheme is resulting in the right choice of TBSs for handover activities. Handovers performed using this technique would automatically be fast enough as the number of scannings is reduced to only one.

6.4.1 Simulation Environment Created for Handover Technique 3

In the simulation topology, shown in Figure 6.11, we have considered 400 cells, arranged in a 20 x 20 square array, with each cell having one BS in it. The BSs, each one marked by a small "cross" (x), are arranged in a square grid format with all BSs being assumed to be connected to the backbone network. These 400 BSs are placed over a terrain of 40 km x 40 km area. We assume that all BSs are under the same administrative domain. The vertical and horizontal spacing between two adjacent BSs, i.e., NBSs on the same row or column, is considered to be 2 km and the range of coverage of each BS is considered to be 1.5 km. We also introduce the concept of an NBS of any SBS. The NBSs are those BSs that surround the given SBS in the terrain shown in Figure 6.11. In Figure 6.11 each SBS has eight NBSs. We arbitrarily assume that the distance between two grid lines (a large number of closely spaced grid lines lie between two adjacent rows or columns of BSs, although they have not been shown in the figure, for convenience) is 10 m and the MS moves with a 10 m resolution. Thus the terrain may be considered as a 4000 x 4000 grid. There exists coverage overlap between adjacent BSs and no part of the terrain is assumed to be without BS coverage. Each BS has eight NBSs and each individual BS is aware of its location. We assume that each BS has a random an dynamically changing load called current load (CL), lying between 0 and 1. A BS having a CL $\geq$ 90% is considered to be overloaded and is not considered as a potential target BS (TBS). As a reminder, during a handover, the current SBS hands over the MS to the selected TBS, which would then become the next SBS in the MS's movement path.

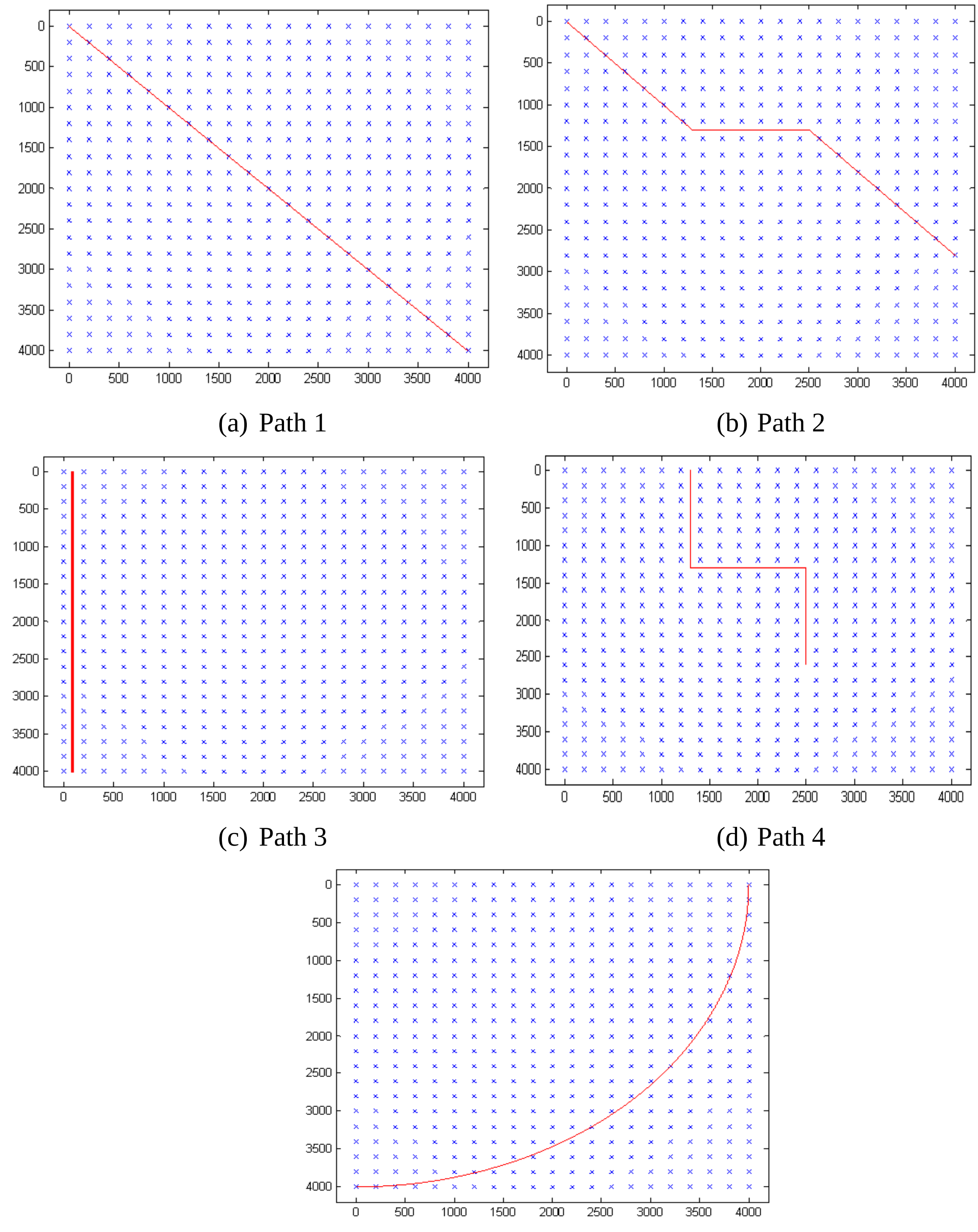
Five different movement paths of the MS, paths 1 through 5, were considered for running the simulation program for Handover Technique 3. Figure 6.11(a) through (e) show the MS's 5 movement paths with each path passing through a large number of BSs, represented by small "x"s. Unlike as in Handover Techniques 1 and 2, in the present simulation we did not need any mobility model to model the movement of the MS in the terrain since we have used pre-fixed or pre-decided movement paths for the MS. None of the paths considered has either a very large curvature (small radius) or a very sharp bend as such paths are somewhat unlikely to be found in practice (see

Assumption 5.2 in Section 5.2.2). We assume that while moving through the terrain, at each step, the MS performs a connectivity check with its SBS in order to be able to request for a handover as soon as it observes that it has entered the ZC from the ZN. We assumed a VBSL of length 3 so that the method of orientation matching (OM) is performed using 3 previously visited SBSs as reported by the MS to its new SBS. We implemented the Walfisch-Ikegami model to realistically simulate the pathloss behaviours.

6.4.2 Simulation Results of Handover Technique 3

The main aim of the present simulation is to validate the reliability of the Handover Technique 3. Proving how fast the handovers are performed is not the main aim because, with only one scanning being performed in each handover, the handovers will clearly be very fast. In this context, one important difference between our Handover Techniques 1 and 2 on one hand and our Handover Technique 3 on the other hand may be pointed out. Like the traditional handover techniques (including that recommended in the Mobile WiMAX standard), our Handover Techniques 1 and 2 also employ multiple scannings for TBS selection, although they do not use the RSS samples directly but employ them for distance estimation and lookahead. In contrast, our Handover Technique 3 depends in a major way on orientation matching for performing TBS selection and only in a minor way on the (single) scanning. Now, for validating the reliability of the handover technique, for every movement path or simulation path of the MS (see Figure 6.11), we have tracked the movement of the MS making multiple successive handovers with different successful NBSs (these NBSs become the successive SBSs for the MS). We have also recorded whether the BSs with which handovers are actually performed, match the BSs as per the prediction or expectation of the Handover Technique 3, (correct) or not (incorrect).

For each movement path considered, we have presented the results in two different tables, although the first table, being of a large size, has actually consumed two tables itself. The first table shows the results based only on the orientation matching and the second table shows the results based on all the three parameters used together, namely, orientation matching, current load (CL) of the NBSs and the Received Signal Strength (RSS) from the NBSs. However, out of the five pairs of tables corresponding to the five chosen movement paths of the MS, we have presented



(a) Path 1

(b) Path 2

(c) Path 3

(d) Path 4

(e) Path 5

Fig. 6.11 Simulation Topology and MS's Movement Paths

in this Thesis, the results of only the first two movement paths for limiting the volume of this chapter as well as the Thesis itself to a reasonable level. Table 6.2, provides a list of the different parameters used in the different columns of the tables as represented by their respective variables.

Figure 6.11(a) shows the first movement path of the MS in red line. At the start of the simulation, the MS starts moving from the top-left corner of the terrain at an angle of 45° with respect to the x-y coordinate. Actually, the point x = y = 0 is the origin of the terrain grid. Simulation stops when the MS reaches the bottom-right

Table 6.2 Variables Used in the Simulation and Their Meaning

Parameter	**Representing Variable**	**Description**
MS's Position Coordinates	MS's Coordinates (x, y)	The (x, y) value pairs indicate the MS's x, y-position coordinates immediately before a handover is performed.
Visited BS List (VBSL)	Id, Ɵ, r	In each simulation run, three previous BSs are considered per handover. The variables signify the respective BS_Ids along with the respective Ɵ (in degrees) and r (in km) (with respect to the current SBS), of each of the three visited BSs.
Average Angle of Motion of the MS	AAMM	AAMM is calculated based on the r and θ values, i.e., the polar coordinates, of the three visited BSs in the VBSL with respect to the current SBS.
Expected Angle of Exit of the MS	EAEM	AAMM + 180°
Current SBS	SBS Id	Id of the current SBS. The SBS Ids shown in the tables correspond to the SBSs chosen immediately after the previous handover. In the simulation set up, the coordinates of the different BSs serve as their respective Ids.
NBSs (Neighbouring BSs)	NBS Id	If two NBSs are shortlisted, then they are represented by "1st NBS Id" and "2nd NBS Id". Out of these, one is selected, by Handover Technique 3, as TBS for handover.
RAD value	RAD	For the shortlisted NBSs, the difference between the EAEM and the NBS's GAON, which is the θ value of respective NBSs with respect to the

		current SBS, gives the RAD (Relative Angle of Divergence) value (in degrees) for a particular NBS.
Selected TBS	Selected TBS Id	Out of the shortlisted NBSs, TBS is the one selected (or predicted) by Handover Technique 3 for the potential handover activity.
Orientation Matching Score	S_{OM}	S_{OM} gives the orientation matching score for the final selected TBS.
NBS Scores	S_{OM}, S_{CL} and S_{RSSI}	Each of the shortlisted NBSs are assigned three different scores against orientation matching (OM), current load (CL) and signal strength (RSSI). Based on these scores, the overall WAS is calculated for each of the NBSs.
Weighted Average Score	S_{WAS}	Based on the overall weighted average score, the final TBS selection (or prediction) is done. The NBS with the highest S_{WAS} gets selected as TBS. The tables only show the S_{WAS} of selected TBS.
Handover Result	Handover Result	Gives the status of a particular handover activity. A 'correct' handover means that the TBS selected according to the Handover Technique 3 matches the actual base station that the MS has performed the handover with while moving along the designated path. For each correct handover performed, the TBS selected, immediately before the handover, becomes the current SBS.

corner of the terrain. Tables 6.3 and 6.4, together, show the handover simulation results corresponding to the MS's movement in Figure 6.11 when only orientation matching is considered. Table 6.4 is actually a "continued version" of Table 6.3. Table 6.5 shows the results when orientation matching along with load and signal strengths are considered. The variables in the different columns of the tables and their corresponding parameters are discussed in Table 6.2. Altogether seventeen handovers occur during the total movement of the MS along the designated trajectory. In the orientation matching tables, the steps followed to select/predict the TBS for each handover activity conforms to the details of handover Technique 3 discussed in Chapter 5.

Table for the orientation matching shows only the highest S_{OM} value (score) and the corresponding NBS that is selected as the TBS on the basis of the orientation

Table 6.3 HO Results for Path 1 - only Orientation Matching

MS's Coordinates		Visited BS List										
		Visited BS1			Visited BS2			Visited BS3			AAMM	EAEM
x	y	Id	θ	r	Id	θ	r	Id	θ	r		
307	307	[0;0]	315.00	5.6	[1;1]	315.00	2.82				315	135
507	507	[0;0]	315.00	8.48	[1;1]	315.00	5.65	[2;2]	315.00	2.82	315	135
707	707	[1;1]	315.00	8.48	[2;2]	315.00	5.65	[3;3]	315.00	2.82	315	135
907	907	[2;2]	315.00	8.48	[3;3]	315.00	5.65	[4;4]	315.00	2.82	315	135
1107	1107	[3;3]	315.00	8.48	[4;4]	315.00	5.65	[5;5]	315.00	2.82	315	135
1307	1307	[4;4]	315.00	8.48	[5;5]	315.00	5.65	[6;6]	315.00	2.82	315	135
1507	1507	[5;5]	315.00	8.48	[6;6]	315.00	5.65	[7;7]	315.00	2.82	315	135
1707	1707	[6;6]	315.00	8.48	[7;7]	315.00	5.65	[8;8]	315.00	2.82	315	135
1907	1907	[7;7]	315.00	8.48	[8;8]	315.00	5.65	[9;9]	315.00	2.82	315	135
2107	2107	[8;8]	315.00	8.48	[9;9]	315.00	5.65	[10;10]	315.00	2.82	315	135
2307	2307	[9;9]	315.00	8.48	[10;10]	315.00	5.65	[11;11]	315.00	2.82	315	135
2507	2507	[10;10]	315.00	8.48	[11;11]	315.00	5.65	[12;12]	315.00	2.82	315	135
2707	2707	[11;11]	315.00	8.48	[12;12]	315.00	5.65	[13;13]	315.00	2.82	315	135
2907	2907	[12;12]	315.00	8.48	[13;13]	315.00	5.65	[14;14]	315.00	2.82	315	135
3107	3107	[13;13]	315.00	8.48	[14;14]	315.00	5.65	[15;15]	315.00	2.82	315	135
3307	3307	[14;14]	315.00	8.48	[15;15]	315.00	5.65	[16;16]	315.00	2.82	315	135
3507	3507	[15;15]	315.00	8.48	[16;16]	315.00	5.65	[17;17]	315.00	2.82	315	135

Table 6.4 HO Results for Path 1 with only Orientation Matching

SBS Id	1^{st} NBS Id	RAD	2^{nd} NBS Id	RAD	Selected TBS Id	S_{OM}	Handover Result
[2;2]	[2;3]	46	[3;3]	1	[3;3]	0.67	CORRECT
[3;3]	[3;4]	46	[4;4]	1	[4;4]	0.67	CORRECT
[4;4]	[4;5]	46	[5;5]	1	[5;5]	0.67	CORRECT
[5;5]	[5;6]	46	[6;6]	1	[6;6]	0.67	CORRECT
[6;6]	[6;7]	46	[7;7]	1	[7;7]	0.67	CORRECT
[7;7]	[7;8]	46	[8;8]	1	[8;8]	0.67	CORRECT
[8;8]	[8;9]	46	[9;9]	1	[9;9]	0.67	CORRECT
[9;9]	[9;10]	46	[10;10]	1	[10;10]	0.67	CORRECT
[10;10]	[10;11]	46	[11;11]	1	[11;11]	0.67	CORRECT
[11;11]	[11;12]	46	[12;12]	1	[12;12]	0.67	CORRECT
[12;12]	[12;13]	46	[13;13]	1	[13;13]	0.67	CORRECT
[13;13]	[13;14]	46	[14;14]	1	[14;14]	0.67	CORRECT
[14;14]	[14;15]	46	[15;15]	1	[15;15]	0.67	CORRECT
[15;15]	[15;16]	46	[16;16]	1	[16;16]	0.67	CORRECT
[16;16]	[16;17]	46	[17;17]	1	[17;17]	0.67	CORRECT
[17;17]	[17;18]	46	[18;18]	1	[18;18]	0.67	CORRECT
[18;18]	[18;19]	46	[19;19]	1	[19;19]	0.67	CORRECT

matching parameter. Table 6.4 shows that for path 1, the overall percentage of correct match found, i.e., match found between the selected/predicted TBS and the actual BS (SBS) to which the MS has performed a handover, is 100. That is, selection of TBS for path 1, according to Handover Technique 3, is 100% correct and thereby proves an all-correct and reliable handover activity. However, it must be noted that this 100% correctness of the TBS selection is because the movement path of the MS is strictly linear.

Table 6.5 shows the results for Path 1 when orientation matching is considered along with load and signal strength parameters. The values presented in Tables 6.3-6.4 and those presented in Table 6.5 are from different sets of simulation runs. For Table 6.5, any of the NBSs with load more than 90% is considered as overloaded and is disqualified, for being considered as a potential TBS.

Cells marked with "NS" in Table 6.5 imply NBSs found "not suitable" to be shortlisted. The three scores S_{OM}, S_{CL} and S_{RSS} for each NBS, can be calculated as per explanations given in Chapter 5. Some of the entries in Table 6.5 have S_{RSS} values as 1, which is owing to the fact that only one NBS is being shortlisted. While calculating

Table 6.5 HO Results for Path 1 - Orientation Matching, Load and Signal Strengths

	1st NBS's Scores				2nd NBS's Scores						
SBS Id	1st NBS Id	S_{OM_1}	S_{CL_1}	S_{RSS_1}	2nd NBS Id	S_{OM_2}	S_{CL_2}	S_{RSS_2}	S_{WAS}	Selected TBS Id	Handover Result
[2;2]	[2;3]	0.17	0.05	0.49	[3;3]	0.33	0.2	0.51	0.34	[3;3]	CORRECT
[3;3]	[3;4]	0.17	0.09	0.49	[4;4]	0.33	0.16	0.51	0.33	[4;4]	CORRECT
[4;4]	[4;5]	0.17	0.09	0.49	[5;5]	0.33	0.16	0.51	0.33	[5;5]	CORRECT
[5;5]	[6;6]	0.33	0.25	1	NS	NS	NS	NS	0.48	[6;6]	CORRECT
[6;6]	[6;7]	0.17	0.07	0.49	[7;7]	0.33	0.18	0.51	0.34	[7;7]	CORRECT
[7;7]	[7;8]	0.17	0.06	0.49	[8;8]	0.33	0.19	0.51	0.34	[8;8]	CORRECT
[8;8]	[8;9]	0.17	0.22	0.49	[9;9]	0.33	0.03	0.51	0.3	[9;9]	CORRECT
[9;9]	[10;10]	0.33	0.25	1	NS	NS	NS	NS	0.48	[10;10]	CORRECT
[10;10]	[10;11]	0.17	0.07	0.49	[11;11]	0.33	0.18	0.51	0.34	[11;11]	CORRECT
[11;11]	[11;12]	0.17	0.11	0.49	[12;12]	0.33	0.14	0.51	0.33	[12;12]	CORRECT
[12;12]	[12;13]	0.17	0.13	0.49	[13;13]	0.33	0.12	0.51	0.32	[13;13]	CORRECT
[13;13]	[14;14]	0.33	0.25	1	NS	NS	NS	NS	0.48	[14;14]	CORRECT
[14;14]	[14;15]	0.17	0.25	1	NS	NS	NS	NS	0.4	[14;15]	CORRECT
[15;15]	[15;16]	0.17	0.16	0.49	[16;16]	0.33	0.09	0.51	0.32	[16;16]	INCORRECT
[16;16]	[16;17]	0.17	0.16	0.49	[17;17]	0.33	0.09	0.51	0.32	[17;17]	CORRECT
[17;17]	[17;18]	0.17	0.1	0.49	[18;18]	0.33	0.15	0.51	0.33	[18;18]	CORRECT
[18;18]	[18;19]	0.17	0.12	0.49	[19;19]	0.33	0.13	0.51	0.33	[19;19]	CORRECT

the WAS S_{WAS}, for each NBS, the following weights are considered: 0.5 for OM and 0.25 each for load and RSS. That is, weights are assigned in the ration 2:1:1. S_{WAS} for each NBS is calculated as per Equation 5.10 in Chapter 5 and the one with the higher value of S_{WAS} is selected as the TBS. As shown in Table 6.5, out of the total of seventeen handovers performed, one is incorrect, which gives a success rate of 94.11%. For the incorrect result, we see that instead of the selected TBS with Id [14;15], the MS wrongly performed a handover with the NBS Id [15;15]. The incorrect result in Table 6.5 occurred apparently due to the (widely) random load values assigned to the NBSs while calculating the results of Table 6.5. The problem of an incorrect handover may occur like this. Assume that, an NBS, which otherwise scores well in terms of OM and RSSI values and should get selected as the TBS, does get a low S_{WAS} to not get selected because of a poor load value (randomly assigned). Te reverse situation may also occur if the NBS gets too high a score for Load and gets selected as the TBS simply because of this high score in Load. However, implementing this technique in a real network with real load numbers is expected to improve the overall reliability of the TBS selection and handovers performed.

Similar to Figure 6.11(a), Figure 6.11(b) shows the second movement path of the MS in red line. Here the MS starts moving from the top-left corner of the terrain and follows a staircase-like path. For this figure, Tables 6.6 and 6.7, together show the handover simulation results corresponding to the MS's movement when only orientation matching is considered. Table 6.8 shows the simulation results when orientation matching along with load and signal strengths is considered.

As in the case of path 1, with all explanations remaining the same for path 2 as well, we can see that for Tables 6.6-6.7, when only orientation matching is concerned, out of the eighteen different handover activities performed by the MS, 77.78% of times, the selected TBS and the corresponding handover activities are correct. The incorrect results have, mostly, occurred at the junctures when there is a sharp change in the movement trajectory. On the other hand, in Table 6.8, when orientation matching is considered along with load and signal strength values, 67% of the results are correct, which is obviously owing to the wide randomness in the load values considered, as explained earlier in case of path 1.

As an interesting point, for all the handovers, as described in Chapter 5, the MS performed scanning and ranging activities only with the selected TBS (predicted by our proposed technique) and not with the other NBSs. This would hugely reduce

Table 6.6 HO Results for Path 2 - only Orientation Matching

MS's Coordinates		Visited BS List									AAMM	EAEM
		Visited BS1			Visited BS2			Visited BS3				
x	y	Id	θ	r	Id	θ	r	Id	θ	r		
310	310	[0;0]	315.00	5.65	[1;1]	315.00	2.82				315	135
510	510	[0;0]	315.00	8.48	[1;1]	315.00	5.65	[2;2]	315.00	2.82	315	135
710	710	[1;1]	315.00	8.48	[2;2]	315.00	5.65	[3;3]	315.00	2.82	315	135
910	910	[2;2]	315.00	8.48	[3;3]	315.00	5.65	[4;4]	315.00	2.82	315	135
1110	1110	[3;3]	315.00	8.48	[4;4]	315.00	5.65	[5;5]	315.00	2.82	315	135
1315	1300	[4;4]	303.69	7.21	[5;5]	296.57	4.47	[6;6]	270.00	2.00	296.44	116.44
1515	1300	[5;5]	288.43	6.32	[6;6]	270.00	4.00	[6;7]	270.00	2.00	279.46	99.46
1715	1300	[6;6]	270.00	6.00	[6;7]	270.00	4.00	[6;8]	270.00	2.00	270	90
1915	1300	[6;7]	270.00	6.00	[6;8]	270.00	4.00	[6;9]	270.00	2.00	270	90
2115	1300	[6;8]	270.00	6.00	[6;9]	270.00	4.00	[6;10]	270.00	2.00	270	90
2315	1300	[6;9]	270.00	6.00	[6;10]	270.00	4.00	[6;11]	270.00	2.00	270	90
2510	1310	[6;10]	288.43	6.32	[6;11]	296.57	4.47	[6;12]	315.00	2.82	296.62	116.62
2710	1510	[6;11]	303.69	7.21	[6;12]	315.00	5.65	[7;13]	315.00	2.82	309.8	129.8
2910	1710	[6;12]	315.00	8.48	[7;13]	315.00	5.65	[8;14]	315.00	2.82	315	135
3110	1910	[7;13]	315.00	8.48	[8;14]	315.00	5.65	[9;15]	315.00	2.82	315	135
3310	2110	[8;14]	315.00	8.48	[9;15]	315.00	5.65	[10;16]	315.00	2.82	315	135
3510	2310	[9;15]	315.00	8.48	[10;16]	315.00	5.65	[11;17]	315.00	2.82	315	135
3710	2510	[10;16]	315.00	8.48	[11;17]	315.00	5.65	[12;18]	315.00	2.82	315	135

Table 6.7 HO Results for Path 2 - only Orientation Matching

SBS Id	1st NBS Id	RAD	2nd NBS Id	RAD	Selected TBS Id	S_{OM}	Handover Result
[2;2]	[2;3]	46	[3;3]	1	[3;3]	0.67	CORRECT
[3;3]	[3;4]	46	[4;4]	1	[4;4]	0.67	CORRECT
[4;4]	[4;5]	46	[5;5]	1	[5;5]	0.67	CORRECT
[5;5]	[5;6]	46	[6;6]	1	[6;6]	0.67	CORRECT
[6;6]	[6;7]	46	[7;7]	1	[7;7]	0.67	CORRECT
[6;7]	[5;8]	72.44	[6;8]	27.44	[6;8]	0.78	INCORRECT
[6;8]	[5;9]	55.46	[6;9]	10.46	[6;9]	0.7	CORRECT
[6;9]	[5;10]	46	[6;10]	1	[6;10]	0.67	CORRECT
[6;10]	[5;11]	46	[6;11]	1	[6;11]	0.67	CORRECT
[6;11]	[5;12]	46	[6;12]	1	[6;12]	0.67	CORRECT
[6;12]	[5;13]	46	[6;13]	1	[6;13]	0.67	CORRECT
[7;13]	[6;14]	72.62	[7;14]	27.62	[7;14]	0.78	INCORRECT
[8;14]	[7;15]	85.8	[8;15]	40.8	[8;15]	0.92	INCORRECT
[9;15]	[9;16]	46	[10;16]	1	[10;16]	0.67	INCORRECT
[10;16]	[10;17]	46	[11;17]	1	[11;17]	0.67	CORRECT
[11;17]	[11;18]	46	[12;18]	1	[12;18]	0.67	CORRECT
[12;18]	[12;19]	46	[13;19]	1	[13;19]	0.67	CORRECT
[13;19]	[13;20]	46	[14;20]	1	[14;20]	0.67	CORRECT

Table 6.8 HO Results for Path 2 - Orientation Matching, Load and Signal Strengths

		1st NBS's Scores				2nd NBS's Scores					
SBS Id	1st NBS Id	SOM_1	SCL_1	SRSS_1	2nd NBS Id	SOM_2	SCL_2	SRSS_2	S_{WAS}	Selected TBS Id	Handover Result
[2;2]	[2;3]	0.17	0.12	0.49	[3;3]	0.33	0.13	0.51	0.33	[3;3]	CORRECT
[3;3]	[3;4]	0.17	0.11	0.49	[4;4]	0.33	0.14	0.51	0.33	[4;4]	CORRECT
[4;4]	[4;5]	0.17	0.06	0.49	[5;5]	0.33	0.19	0.51	0.34	[5;5]	CORRECT
[5;5]	[5;6]	0.17	0.15	0.49	[6;6]	0.33	0.1	0.51	0.32	[6;6]	CORRECT
[6;6]	[7;7]	0.33	0.25	1	NS	NS	NS	NS	0.48	[7;7]	CORRECT
[6;7]	[5;8]	0.11	0.03	0.51	[6;8]	0.39	0.22	0.49	0.37	[6;8]	INCORRECT
[6;8]	[5;9]	0.15	0.25	1	NS	NS	NS	NS	0.39	[5;9]	CORRECT
[6;9]	[5;10]	0.17	0.19	0.51	[6;10]	0.33	0.06	0.49	0.3	[6;10]	INCORRECT
[6;10]	[5;11]	0.17	0.12	0.51	[6;11]	0.33	0.13	0.49	0.32	[6;11]	CORRECT
[6;11]	[5;12]	0.17	0.25	1	NS	NS	NS	NS	0.4	[5;12]	CORRECT
[6;12]	[5;13]	0.17	0.05	0.51	[6;13]	0.33	0.2	0.49	0.34	[6;13]	INCORRECT
[7;13]	[6;14]	0.11	0.15	0.5	[7;14]	0.39	0.1	0.5	0.35	[7;14]	INCORRECT
[8;14]	[7;15]	0.04	0.19	0.5	[8;15]	0.46	0.06	0.5	0.37	[8;15]	INCORRECT
[9;15]	[9;16]	0.17	0.21	0.49	[10;16]	0.33	0.04	0.51	0.3	[10;16]	INCORRECT
[10;16]	[10;17]	0.17	0.19	0.49	[11;17]	0.33	0.06	0.51	0.31	[11;17]	CORRECT
[11;17]	[11;18]	0.17	0.1	0.49	[12;18]	0.33	0.15	0.51	0.33	[12;18]	CORRECT
[12;18]	[12;19]	0.17	0.1	0.49	[13:19]	0.33	0.15	0.51	0.33	[13;19]	CORRECT
[13;19]	[13;20]	0.17	0.09	0.49	[14;20]	0.33	0.16	0.51	0.33	[14;20]	CORRECT

the overall time for scanning and ranging activities in comparison to other WiMAX handover techniques [46-48] where MS performs scanning-ranging activities with either all or multiple NBSs before selecting the final TBS for the handover activity. Also, in this Handover Technique 3, once the TBS is selected, the MS directly goes for a handover with it bypassing the time-consuming message exchanges with the SBS in the AHOP (refer to Chapter 2). This would thus also reduce the AHOP time. So, not only would our technique of intelligent TBS selection produce reliable handovers but also fast handovers. However, in the simulations, we are only showing how much reliable are the selections of the TBSs for each handover activity, i.e., how much reliable are the handovers performed, although improved reliability in TBS selection also improves the speed of the handover as just pointed out.

Figure 6.12 and 6.13 show the handover results for Handover Technique 3 against the MS's five different movement paths shown in Figure 6.11. For each of the five paths considered, Fig. 6.12 gives the percentage of correct handovers that the MS has performed for that path for the two different sets of parameters, namely, orientation matching and orientation matching with RSSI. As we can see, percentage of correct handovers remains the same when only orientation matching is considered as well as when orientation matching with RSSI values is considered. On the other hand, for those different paths, Fig. 6.13 gives the handover results with the variation of NBS load values. From the Figure 6.13, we can see that where load is considered, the percentage of correct handovers noticeably deteriorates because of the (widely) random load values considered. It may also be noticed from Figure 6.13 that the

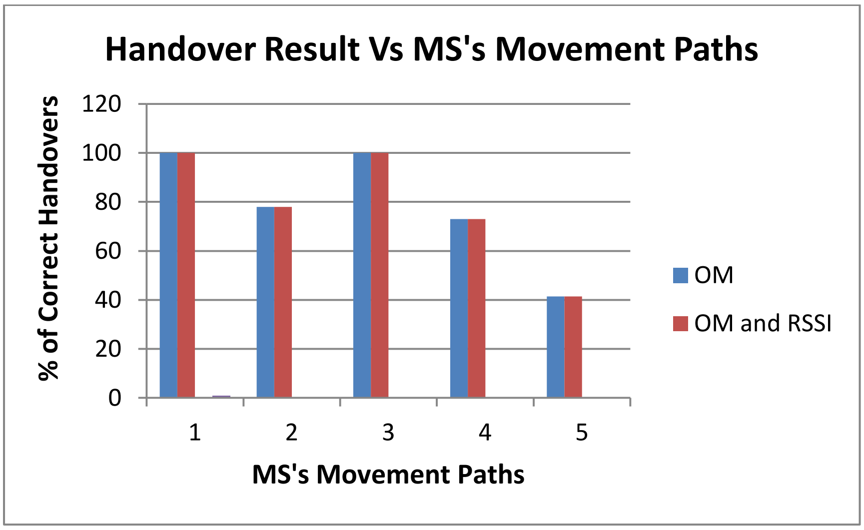


Fig. 6.12 Handover Results for Orientation Matching for Different Movement Paths of MS

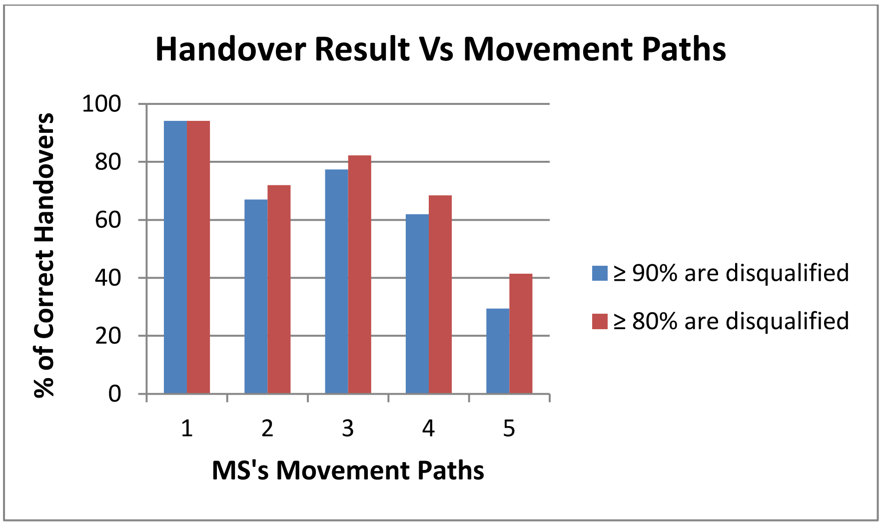


Fig. 6.13 Handover Results for Different NBS Load Considered Vs MS's Movement Paths

percentage of incorrect handovers is more, in general, when the load is limited to (i.e. the upper threshold value) 90% than when the load is limited to 80%. Finally, for the different paths considered, path# 5, gives the worst of the results, in terms of number of correct handovers, for all three sets of parameters (orientation matching, orientation matching with RSSI, and orientation matching with RSSI and load). The reason clearly is the sharp curvatures in that path shown in Figure 6.11(e).

6.5 Conclusion

This chapter discussed the simulation scenarios and presented the results for the two MS-controlled fast Handover Techniques 1 and 2, along with the predominantly BS-controlled Handover Technique 3 proposed by us in the Thesis. For simulating the Handover Techniques 1 and 2, we have used an environment modelled in Qualnet 4.5 Simulator having 6 BSs, 18 MSs and one ASN-GW. The different simulation parameters used are either WiMAX Forum-recommended or are used for similar kind of research by the WiMAX community. Section 6.2.3 provides a discussion on this. Although, a simulation environment consisting of a greater number of MSs (say around hundred), would have been more realistic to better study the effects of load on the different BSs, we could not do that as, quite frequently, the simulator froze while running simulations and, on each occasion, we had to restart all over again after stopping all processes from running and manually cleaning all previous simulation instances. Each time that happened, the whole restart procedure followed was quite time consuming. To model the movement of users in vehicles carrying the mobile devices, more realistically, we have also considered different mobility models. The models we used are: (i) Random Waypoint Mobility Model, (ii) Random Direction Mobility Model and (iii) Manhattan Mobility Model, for reasons discussed in Section 6.2.2. All the simulations are carried out for six different movement speeds of the MS ranging between 20 km/h to 120 km/h.

The results of simulations carried out for the proposed Handover Techniques 1 and 2 showed that, in comparison to the conventional Mobile WiMAX hard handover technique, both the schemes can significantly improve the NTAP-related time and the overall handover time and will thus be useful for high-speed mobility of MSs in Mobile WiMAX networks, which support a mobility of up to 120 km/hr. All the simulation results are shown, together with the relative statistical errors at the 95%

confidence level. However, two observations may be made. First, the DiCD-based lookahead technique is fairly simpler to implement than the AOD-based one. Second, both the handover methods offer scope for obtaining an useful tradeoff between handover delay and handover reliability. This is because increasing the number of scanning cycles increases the number of samples (DiCD or AOD samples) and, then, averaging more number of samples can yield better reliability of lookahead, though at the cost of increased handover delay.

For simulating the Handover Technique 3, we considered a 40 Km x 40 Km terrain having 400 BSs. The MS moved between the BSs in five different trajectories or movement paths, one per simulation, and carried out different number of handovers per trajectory. Owing to the shortage in space, we have shown the results for the first two of the paths only. For each of these two paths, results are provided in three different tables. The first two table together for only orientation matching – the most vital parameter, and the third table for all the three parameters (orientation matching, Load and RSSI) together, for all the NBSs. There are many different fields in these Tables. For both orientation matching alone and orientation matching together with load and signal strength, the result of the TBS prediction (this is given by the number of correct or incorrect handovers predictions) is shown. It shows in how many cases of the different handovers performed per path, the final TBS is predicted correctly. The number of "incorrect" matches is more when there are very sharp turns in the MS's trajectory (as in Path 5 in Figure 6.11), which violates the assumption of a broadly linear motion of the MS.

Chapter 7

Conclusion

7.1 Introduction

We have arrived at the concluding stage of the present Thesis in which we have described three novel techniques for performing handover in the Mobile WiMAX network. The spectacular growth of mobile communication has been ascribed to the concept of cellular technology and handover plays the most critical role in the smooth working of the cellular mobile communication networks. For obtaining an absolutely seamless communication with no call disruption of any form, a "soft" handover is required. Unfortunately, that is difficult and expensive to achieve. Most handovers used today, including the ones we have proposed in this Thesis, are the so called "hard" handovers. These hard handovers suffer very brief call disruptions, on the order of tens or hundreds of milli-seconds, during the actual handover instants.

The existing WiMAX hard handover mechanisms suffer from multiple shortcomings. The notable ones among these shortcomings are lengthy handover decision making process, lengthy and unreliable TBS selection process, frequent and unnecessary handovers, long call disruption times, etc. The three handover techniques that have been investigated in this Thesis, namely, the Handover Techniques 1 and 2, described in Chapter 4, and the Handover Technique 3, described in Chapter 5, address mainly two of these problems. These are, improving the handover latency by choosing the TBS relatively fast, and selecting the TBS more reliably. In addition to these two, improvements, a third but fairly important improvement has also been achieved in our Handover Techniques 1 and 2. This is improving the scalability of the WiMAX network. In the following section, we briefly point out the important research contributions that have been made by us in this Thesis. In Section 7.3, we present a comparison of our work with similar works of other researchers. Section 7.4 presents a brief comparison and discussion of tradeoffs between the three handover techniques proposed in this Thesis. Finally, in Section 7.5 we conclude the section by providing some direction to future research in the area of hard handover in Mobile WiMAX.

7.2 Important Research Contributions

1. *Fully MS-Controlled Handover*: Handover Techniques 1 and 2 in this Thesis, described in Chapter 4 (see Figure 4.1), are fully MS-Controlled where the need for a handover is determined by the MS itself and, additionally, the TBS is also selected by the MS itself. When it needs a handover, the MS simply requests the SBS for granting it the required scanning cycles for scanning the NBSs and after, it has selected the TBS, the MS requests the SBS to simply hand it over to the selected TBS. The SBS thus performs no other role than just honouring these two requests of its each MS. It is clear that, because of this MS-Controlled Handover, the MSs put minimal workload on their respective SBSs who thus remain free to offer services to many more MSs. Additionally, much of the communication overhead that could be incurred, because of the use of the exchange of different standardized MAC layer messages between the SBS and each MS, are now avoided. This would reduce the congestion in the network significantly. As a result of this greatly reduced load on the SBSs in the WiMAX network, the network becomes highly scalable.
2. *Concept of Four Zones*: Based on the RSS power received by the MS from its SBS, the MS creates a virtual concept of four zones, namely, ZN, ZC, ZE and ZD (see Section 4.5 and Figure 4.2). Being aided by this concept of four zones, monitored by itself without any overhead, the MS performs its entire set handover-related functions in the right sequence and at the right times. For example, immediately after entering the ZC from the ZN, the MS determines that it now needs a handover. This virtual concept of zones ensures that two important objectives in the handover process are fulfilled, namely, (i) the MS completes a good part of the handover-related jobs even before the RSS reaches the threshold level that has been traditionally used and (ii) entire handover process is completed before the ZD is ever entered so that there will be no possibility of excessive loss of packets or of call drops.

3. *Self-Tracking One's Own Motion Relative to a Fixed Transmitting Object, Using Lookahead*: With this novel idea of RSS-based distance estimation and lookahead (see Sections 4.5, 4.6 and 4.7), any mobile device, equipped with a receiver (e.g. an MS), can self-track its motion relative to any fixed object equipped with a transmitter (e.g. a BS). Handover Techniques 1 and 2 both are based on this RSS-based distance estimation and variable distance-based lookahead principle; however, the actual method of lookahead, namely, DiCD and AOD, differs in the two cases, which has made them to be studied as two different techniques. Basically, in both the handover methods, the MS has estimated its own motion relative to each (fixed) NBS, via RSS-based distance estimation and lookahead, and has chosen the NBS with respect to which the MS has the largest approaching velocity, as the TBS. The supporting idea is that the MS, during its journey, will come neatest to this NBS and thus will receive from it the strongest signal. At this point, as an aside, it may be pointed out that, if the performance of the RSS-based distance estimation (using pathloss property) between the MS and the NBSs is found unsatisfactory, then signal delay-based distance estimation may be employed. The two lookahead schemes will, of course, remain unaltered as they utilize only the relative distances and relative velocities.
4. *Approximate, Indirect but Simple and Static Estimation of Current Load (CL) of a BS*: CL is an important parameter in routers, BSs etc. It is always considered and checked by a BS before the BS allows every new connection to be opened through it. CL ($0 \leq CL \leq 1$) is given by

$$CL = M/N,$$

where M is BS's current throughput and N is its known throughput capacity, both M and N being measured in packets/sec. Knowing N and actually counting the number of packets currently being forwarded by the BS per second, CL of a BS is measured fairly accurately and dynamically. However, this direct, accurate and dynamic measurement may not be needed in many simple applications like in WiMAX handover where CL is being used only as a static and "somewhat" accurate parameter. A low value of CL in this application will only assure that the BS is currently loaded lightly so that a new connection is likely to receive a good QoS from the BS. So, in this Thesis, we have suggested a simple, static and indirect approach for estimating the CL by taking count of the number of connections presently being handled by the BS. The number of connections presently opened via a BS is usually easily available in any network. Section 4.4 provides a detailed discussion of this particular contribution.

5. *VBSL and Orientation Matching*: As explained in Chapter 5, the concept of VBSL and its utilization (via the use of the PCT) in performing orientation matching between an MS's direction of arrival at a BS and the geographical angles of the NBSs has clearly introduced a novel and interesting criterion for TBS selection in WiMAX handover. By providing the VBSL, the MS effectively provides the broad direction of its journey to the BS. This is because the MS is vehicle-borne and the fuel cost as well as the journey time is known to be the biggest concerns for a vehicular journey. This orientation matching process, described in Section 5.5 and 5.6, intelligently utilizes the availability of GPS in WiMAX BSs but does not require the MSs to be GPS-enabled.

7.3 Comparison with Other Works

In Chapter 6, we have compared the simulation results of Handover Techniques 1 and 2 with only the conventional hard handover technique in Mobile WiMAX networks. We have validated the correctness of the Handover Technique 3 discussed in Chapter 5. In this section we provide a comparison of the handover techniques proposed by us with some of the related works done by different researchers in the area of Mobile WiMAX hard handover. Though Chapter 6 probably would have been a more appropriate place for this material to be included, it would have made Chapter 6 too voluminous. Table 7.1 (for convenience the table is printed in page 180) provides a list of some of the different hard handover-related research works in Mobile WiMAX most of which were surveyed in Chapter 3. As these works have presented results under different assumptions, e.g. (i) none has presented a flowchart to explain, in details, the proposed handover schemes, (ii) very few have provided the name of the simulator used and hardly one or two have used Qualnet and, finally, (iii) hardly few have given the full list of simulation parameters used, these works are not exactly comparable, in a fair setting, with our techniques. Also, very importantly, most of these works have compared the respective validation results with the Mobile WiMAX conventional hard handover technique, as we have done. As a consequence of this situation, we have shortlisted three works (shown with a * in the table) that are somewhat similar to our proposed handover techniques and have compared those techniques with ours.

(i) *Location-Aware Scanning Scheme [48]:* This work reduces the number of rounds of scanning of the NBSs so that the scanning period is shortened and the total time spent in the Mobile WiMAX handover process gets reduced as well. The TBS is identified after three rounds of scanning only. The scheme uses both the location information of the MS and the RSS from the scanned NBSs to select the TBS. The work has made the following assumptions: (a) The scheme has assumed that every SBS has six different NBSs placed in a hexagonal formation with respect to the SBS (b) The overall area of coverage of the SBS is divided into six zones (however, the basis of zone formation is unclear) (c) All the BSs are time-synchronized (d) In the MOB_NBR-ADV, the information about the different NBSs are organized in a sequence following the anti-clockwise direction of the NBSs distribution. During scanning, the MS measures the arrival-time-difference of the DL_MAP from the first, third and fifth NBSs. For the measurement of the arrival-time-difference, the MS records the most recent time point of receiving DL_MAP from the SBS and the time point of receiving DL_MAP from the scanned NBSs during each scanning interval. Based on such measurements the approximate location of the MS is tracked. Next, based on comparison of the signal strengths, the TBS is identified for the handover activity. While validating the scheme, the overall data processing delay for the handover activity is measured as:

(T1 x 3) + T2 + T3 [where T1= time for 1 NBS scanning; T2 = time for initiating the network re-entry; T3 = time for ranging].

The drawbacks of the work are: (a) Time-synchronizing all BSs leads to an increase in the overall infrastructural cost, (b) No explanations are given regarding how the zones are identified and why the NBSs are organized in a sequence following the anti-clockwise direction (c) No explanations are given regarding why the authorization and registration of the MS are not performed with the newly selected TBS before a normal IP connectivity can be resumed. Performing authorization and registration activities would have much increased the overall handover completion timing. (d) Lack of proper explanations or justifications regarding how the different NBSs are chosen or not chosen for scanning activities.

In comparison to this work, our proposed techniques are better for the following reasons: (a) No increase in infrastructural cost when doing practical implementation of the techniques (b) The handover zones in our technique are logical and are implementation dependent. Section 4.8 in Chapter 4 gives an approximate explanation to how the zonal ranges can be selected. (c) Unlike in [48], our proposed techniques clearly specify how the different NBSs are omitted / chosen for scanning. The degree of reliability of choosing the NBSs for scanning in [48] is questionable. (e) In [48], the overall delay per handover is around two sec (MS is moving at a speed of 36 km/h). In comparison to this, moving at a similar speed, in our proposed Handover Techniques 1 and 2, MS can complete a handover in much lesser time. So, handover delay can be better reduced using our techniques.

(ii) *GPS-based TBS Selection Scheme [36]:* The work done in this paper considers that the MS is equipped with GPS function. When the SBS's signal strength goes below a certain threshold, the MS calculates the distance to get the nearest NBS to scan. So, the scheme claims to select the TBS, which is supposedly the nearest NBS with respect to the current position of the MS, with the help of the GPS information and performs scanning and ranging activities with only the TBS to save the scan time efficiently. The scheme claims to have performed simulations using Opnet 14.5 modeler but no simulation parameters have been cited. The results showed that the work has achieved an overall handover delay of just "10 ms", which represents summation of all delays starting right from scanning-ranging activities to completion of network re-entry activities involving even the registration and authentication steps and also claimed that it is more than 33% improvement over the Mobile WiMAX conventional handover delay.

The drawbacks of this work are: (a) The scheme did not specify any justifiable mechanism regarding how the TBS is selected using the GPS.

Straightaway selecting the nearest NBS as the TBS may not be the right thing to do. (b) Using GPS in MSs considerably increases the cost of an MS; (c) The 10 ms overall handover delay claimed by the scheme is an unrealistic one and the work did not specify anything regarding how that delay was measured or computed.

In comparison to this work, our proposed handover techniques are considerably better because of the following reasons. (a) Each of our proposed techniques cites a justifiable method of selecting the TBS out of multiple NBSs. (b) Our Handover Technique 3 uses GPS in the different BSs and not in the MSs. This does not incur any additional infrastructural cost to the users as all BSs are GPS-equipped. (c) Our Handover Techniques 1 and 2 reduce the overall handover delay by almost 40% in comparison to the Mobile WiMAX conventional handover mechanism. This reduction should be much more in case of Handover Technique 3, where only one scanning iteration is performed. So, overall, our proposed techniques are better and provide more realistic solutions in comparison to work done in [36].

(iii) *Movement Direction Prediction Scheme [46]:* In this scheme, it is assumed that an SBS can know the locations and movement trajectory of an MS as well as the location coordinates of its NBSs. An SBS is assumed to have six NBSs and the entire hexagonal area of coverage of the SBS is logically divided into six sectors. In each sector, the SBS calculates the distance between the MS and the NBSs lying in that sector. The SBS calculates the movement of the MS relative to the NBSs twice within an interval of T secs and measures whether the movement is progressive or regressive with respect to the NBSs. The NBS for which the MS shows the highest progressive movement is chosen as the TBS. Simulation results have showed that this scheme has lowered the scanning and ranging-related time by 37% in comparison to the conventional Mobile WiMAX handover technique.

Drawbacks of this work are: (a) No explanations have been given regarding how the SBS's coverage area is sectorized. (b) No explanations have been given regarding how the different NBSs are allocated per sector. (c) No explanations have been given regarding how the SBS comes to know of the MS's trajectory in advance. (d) As value of "T" is not given, it is not known how frequently the SBS calculates the MS's current distance from the chosen NBSs. (e) It is also not known, how the movement trajectory relates to the different NBSs in a given sector.

In comparison to this work, our proposed handover techniques are better because the following reasons. (a) The concept of zones in our work is clearly justified. (b) Unlike in [46], which says nothing about the movement speed of the MS, in our Handover Techniques 1 and 2, choice of the value of "T" is largely dependent on the MS's speed of movement and is inversely proportional to the speed. (c) Each of our handover techniques can reduce the scanning and ranging-related time by almost 50%. So, overall, our proposed techniques are considerably better and provide more realistic solutions in comparison to work done in [46].

7.4 Brief Comparisons and Tradeoffs Between the Three Handover Techniques (HT)

In this section, we intend to briefly discuss the various similarities.dissisimilarities and tradeoffs betwern the three HTs.

1. In all the three HTs, the MS performs scanning of the NBSs, to obtain RSS samples from the NBSs. HT 3 uses these samples directly, whereas HT 1 and HT 2 utilize them to estimate their respective distances from the NBSs using pathloss formulas.
2. Both the HT 1 and HT 2 utilize the distance samples and the principle of lookahead for estimating their respective changing distances from each NBS. Although the lookahead principles are different, the goal of the lookahead in both cases is to determine, in advance, which NBS the MS is most likely to get nearest to and hence should be selected as the TBS. Whereas in the HT 1, the MS estimates the successive DiCDs and selects as the TBS the NBS showing the highest accumulation of the DiCDs, in the HT 2, the MS selects as the TBS the NBS showing the lowest accumulation of AODs with respect to the MS's direction of motion.
3. Though HT 1 and HT 2 can perform accumulation of DiCDs and AODs, respectively, computation of AOD is more complex than computation of a DiCD. Thus HT 2 will consume more battery power than HT 1.

4. In both HT 1 and HT 2, there is a possibility of tradeoff between the handover delay and the reliability of handover via the number of scanning cycles. If the number of scanning cycles (minimum number is two) is increased, then the handover delay increases but the increase number of DiCD or AOD samples obtained can be averaged to yield better reliability of handover. On the other hand, if the number of scanning cycles is reduced, the handover delay decreases but, with less averaging, the reliability of handover decreases.
5. Both the HT 1, HT 2 and HT 3 use current load (CL) of an NBS as a parameter. Whereas HT 1 and HT 2 use the CL only to disqualify some NBSs from being selected as the TBS, HT 3 uses the CL both for disqualification and as a parameter for selection of an NBS.
6. Broad linear motion of the MS is a precondition for satisfactory performance of all the HTs.

7.5 Future Research Work

Despite of the reported contributions towards solving the handover latency, reliability and scalability-related shortcomings in Mobile WiMAX networks, there are still some interesting issues remaining that need to be further studied and addressed. They include the following:

7.5.1 Fast and Reliable Base Station-Controlled Handovers in LTE and LTE-Advanced Systems

Default handover techniques in both LTE and LTE-Advanced systems are mobile assisted network-controlled hard handover, also known as the backward handover [105]. The proposed Handover Technique 3, in the Thesis, has the potential to improve this handover procedure by reducing the latency to provide a better end-user experience. In LTE a BS is known as an eNodeB. Here, in general, the network decides the target eNodeB for an LTE MS (known as an User Element or UE) to handover to. Based on measurements of the different neighbouring eNodeBs performed by an UE (by means of scanning), the serving eNodeB shortlists a few of those as potential candidates for handover and negotiates with one or more of those potential target eNodeBs for handover preparation by sending handover request messages to each of them. The preparation primarily includes reserving adequate resources at the target eNodeB for handover as well as setting up a path between the serving and target eNodeBs to forward data. Based on the handover replies of the target eNodeB(s), the final target eNodeB is selected and the handover decision is made. The serving eNodeB then triggers the handover execution. MS then disconnects from the serving eNodeB and performs the range of network re-entry activities to the target eNodeB. The completion of handover activity is marked by the switching of the network data path from the serving to the target eNodeB.

Similar to the conventional Mobile WiMAX hard handover technique, scanning of the neighbouring eNodeBs by an UE is an important part of the LTE and LTE-Advanced handover techniques. An LTE-compliant UE can simultaneously scan several neighbour eNodeBs (even up to eight) operating in the same frequency within a measurement period [106]. The candidate eNodeB with the best signal quality among the candidates scanned within a measurement period is in general the preferred one to be the target eNodeB. Within a measurement period, if a suitable candidate eNodeB, which has a signal quality better than a certain threshold, is not found, the UE has to continue scanning and monitoring the signal quality of the serving eNodeB. Other important criteria like UE's direction of motion or load of the neighbouring eNodeBs are not taken into consideration when short listing the candidate eNodeBs. The single scanning target eNodeB selection procedure of Handover Technique 3 can be applied to the LTE and LTE-Advanced hard handover techniques to considerably reduce neighbour eNodeB scanning activities and improving the overall handover latency. The technique, being a base station-controlled one, could be readily applied to LTE-related handover activities with minor modifications. The minor modification is mostly required in the way the serving eNodeB dynamically acquires updated load information from the candidate eNodeBs. Such information in LTE and LTE-Advanced systems can be obtained through the backbone network. Pursuing research in this direction is in our plans for future work.

7.5.2 User Equipment-Controlled Handover for LTE and LTE-Advanced Systems

The future hybrid scenario of heterogeneous wireless networks sees a paradigm shift from the current service provider and operator-centric network management to more of a user-centric network management, in which the network should be able to self-govern its behaviour based on key aspects like coverage, mobile device's power conditions, travelling speed and direction and surrounding features. The primary aim of such autonomic network management is to simplify existing network management processes by distributing and automating the decision-making processes associated with optimizing network operations [107]. Such distribution will not only see less involvement and intervention of manual operators in the network management issues, but also more and more intelligence assigned to the user equipments [84]. UE or MS-controlled handover techniques, like Handover Techniques 1 and 2, proposed in this Thesis, will thus gain more importance as the need for providing seamless user-centric services over an integrated heterogeneous environment of wireless networks increases.

In the context of such requirements, our plan for future work is to study the performance of the proposed Handover Techniques 1 and 2 in LTE and LTE-Advanced networks, where the default handover framework is an UE-assisted, network-controlled one. Although, the two proposed handover techniques are expected to considerably improve the overall handover-related latency because of the reduced scanning activities performed, some modifications of the target eNodeB selection procedure is required to enable the techniques to work according to the existing LTE and LTE-Adanced handover framework. Two primary modifications are required. Firstly, an effective mechanism for the serving eNodeB to dynamically share the updated load information of the neighbouring eNodeBs with the UEs is required to disqualify the overloaded eNodeBs from scanning. Secondly, modifications - related to the selection of the target eNodeB from the candidate eNodeBs based on the network measurements is required.

7.5.3 Fast Handover Techniques for Cross-Layer Handovers

It was previously stated in the thesis that the overall handover time depends on the individual handover times to perform the Layer-2 handover and the Layer-3 handover. It would be interesting to see how the different schemes proposed in this thesis could be useful to act as fast Layer-2 handover triggers in Cross-Layer (Layer-2+Layer-3) handover environments with mobility management techniques like HMIPv6 or PMIPv6 existing in Layer-3. For purpose of such experiments, we plan to design and implement a Layer-3 mobility module to the existing Advanced Wireless Library in the Qualnet simulator, which is currently lacking a detailed Mobile WiMAX IP-layer implementation.

7.5.4 Fast Handover Schemes in Heterogeneous Network Environments

It would be interesting to see how the different fast handover schemes proposed by us perform in a heterogeneous network environment particularly constituting of the two important broadband technologies of the current and future generations, viz., WiMAX and LTE. As stated previously, it is expected that our proposed fast handover schemes will perform well irrespective of the underlying heterogeneous environment.

Table 7.1 Some of the Mobile WiMAX Hard Handover-related Research Works Proposed by Other Researchers

Paper Reference Number and Authors	**Main Focus**	**Proposed Technique**	**Flow Chart given?**	**Name of simulator provided?**	**List of parameters provided?**	**What the graphs are showing?**	**Results similar to our proposals?**	**Overall similarity to our proposals?**
1. S. Gu and J. Wang [54]	Enhanced target cell selection for handover	(i) Based on effective capacity estimation of different BSs including SBS (ii) Scans all NBSs (iii) Selects NBS with lowest capacity + highest signal strength	No	NS-2	Some	Throughput Vs Time Packet Loss during HO Vs Time	No	No
2. P. Boone, M. Barbeau and E. Kranakis [100]	Fast TBS selection by reducing the time spent searching for a frequency during handover scanning i.e. reduction in the scanning operation	(i) MS uses a time-of-day mobility profile –i.e. list of most probable freq used and probable BS pairs to HO with at that time depending on previous history (ii) MS equipped with a GPS makes a location-plus-trajectory mobility profile of the terrain its moving	No	No	Very Few	Frequency percentage checked Vs Number of Frequencies Percentage of HO Target probability Vs Number of neighbours scanned	No	Partially
3. D. H. Lee, K. Kyamakya and J. P. Umondi [37]	To reduce wireless channel resource waste and latency during HO by	(i) Target BS estimation using mean CINR and arrival time difference is proposed, which can reduce	No	No	Almost Nil	Ho Operation Time Vs Type of HO (cell loading is taken	Partially (With 0% cell loading,	Partially

	doing reduced scanning and association.	unnecessary neighbouring BS scanning and association process. (ii) A TBS is directly selected based on these and MS performs scanning and sync only with this TBS.				into account)	HO time is reduced by 300-400 ms. With 50% it is reduced by 300-600 ms)	
4. K. Daniel et. al. [55]	Improving the Mobile WiMAX conventional hard handover technique for slow fading affected channels.	(i) A continuous scanning algorithm with a sliding window for the SNR mean value calculation is used. The sliding window mechanism compensates the slow fading-related interruptions. (ii) The MS compares the SNR of the SBS with the SNR of the scanned TBS to decide upon the handover.	No	OmNET++	Almost Nil	SNS Vs Time(sec) Data Rate Vs Time (sec) Handover Delay Vs Scan Duration Sliding Window Length Vs Handover Delay (ms)	No (Although the authors have performance analysed the Mobile WiMAX HHO technique using different scan and frame durations, the paper is not about a new fast and reliable HO scheme)	No
5. P. Boone, M. Barbeau and E. Kranakis [108]	Fast TBS selection by reducing the time spent searching for a frequency during handover scanning	(i) MS maintains a history of the most frequently used and most recently used frequencies of the different BSs and uses this history to reduce the number of	No	No	Very Few	Percentage of frequencies checked per scan Vs no of frequencies	No	Partially

	i.e. reduction in the scanning operation	scanning performed. (ii) MS utilizes a history of handovers performed along a given movement path and based on that it shortlists which of the MOB_NBR-ADV NBSs to scan.				Percentage of HO target finding probability Vs Number of neighbours scanned		
6. Q. Lu and M. Ma [48]	Reduced scanning (only 3 rounds of NBS scanning) and early network re-entry activity	(i) Based on both the location information of the MS and the received signal strengths from the scanned neighbour BSs	No	Qualnet 4.0	Few	No of Handovers Vs HO Latency Simulation Time Vs Total Data Transmission Delay Number of HO Vs Total Data Transmission Delay	HO Latency is improved by 60% in comparison to standard HO for an MS moving at 36% Km/Hr	Yes (*)
7. W. Jiao, P. Jiang and Y. Ma [34]	To reduce the connection disruption gap during the HHO when an MS terminates its connection with the SBS and is yet to reconnect to the TBS	(i) The connection CIDs assigned by the SBS will be accepted by the handover TBS during the process of handing over until new CIDs are assigned (ii) During scanning, MS selects two TBSs and SBS passes on MS HO information to them over the backbone network. When finally one TBS is selected, it	No	No	Few	Downlink and uplink throughput in HO Vs Time	In comparison to 200 ms of connection disruption in conventional scheme, downlink service interrupt interval can be reduced	No

		uses the old CIDs passed on to it by the SBS to resume DL packet passing during network re-entry without waiting for the IP connectivity to completely resume. This shortens the connection disruption gap.					by about 87.5%, and uplink by 60%	
8. S. Choi et. al. [40]	To reduce the connection disruption gap during the HHO when an MS terminates its connection with the SBS and is yet to reconnect to the TBS i.e. an MSS can receive downlink data through specified message from TBS just after synchronization with new downlink of TBS during handover process – it does not need uplink synchronization with TBS	(i) New management messages are introduced to receive downlink data during the handover process and reduce the downlink packet transmission delay (ii) Network re-entry processing time of handover for downlink service can be ignored and the downlink data transmission delay and packet loss probability can be reduced	No	No	Nil	Packet Loss Ratio Vs Average Cell Resident Time Packet Transmission Delay Vs Time Service Disruption Time Vs Required Time for DL synchronisation	No numerical figure(s) on how much improvement (s) is/are achieved is given	No
9. X. Li [36]	Reduced scanning activities with only	(i) Assumes that MS has GPS function. Using that, MS can	No	Opnet 14.5	Nil	HO delay Vs Simulation time	33-50% reduction in	Yes (*)

	one selected TBS. Fast network re-entry process with allocated dedicated ranging slots	calculate the distance to get the nearest BS to scan. It saves scan time significantly. (ii) MS only associates with the TBS selected based on the GPS. (iii) Selected TBS allocates dedicated ranging slots which the MS uses during network re-entry activities to reduce the re-entry steps.				Throughput Vs Simulation time	HO delay	
10. M. A. Ben-Mubarak et. al. [46]	To reduce MS's scanning activities and thus provide fast handover based on MS's movement direction prediction by the SBS	(i) It is assumed that SBS can know the locations and movement trajectory of an MS as well as the location coordinates of its NBSs (ii) SBS's hexagonal coverage area is divided in to six sectors (iii) In each sector, SBS tracks the MS's relative movement with respect to the NBSs in that sector (iv) The NBS with respect to which the MS shows the maximum progressive movement, is chosen as the TBS	No	Qualnet 5.0	Few	Scanning Time Vs Scanning Instances	Around 37% reduction in scanning time in comparison to the conventional scheme	Yes (*)

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Appendix 1

List of Abbreviations

A

AAA	-	Authentication, Authorization, Accounting
AAMM	-	Average Angle of Motion of the MS
ABS	-	Anchor BS
AFM	-	Accumulated Forward Movement
AES-CCM	-	Advanced Encryption Standard in Counter with Cipher Block Chaining (CBC)-MAC
AHOP	-	Actual Handover Phase
AM	-	Amplitude Modulation
AMPS	-	Advanced Mobile Phone System
AOD	-	Angle of Divergence
AP	-	Access Point
AR	-	Access Router
ARPANET	-	Advanced Research Projects Agency Network
ASN	-	Access Service Network
ASN-GW	-	ASN Gateway
ATM	-	Asynchronous Transfer Mode

B

BBM	-	Break-Before-Make
BE	-	Best Effort
BS	-	Base Station
BSS	-	Basis Service Set

C

CBC	-	Cipher Block Chaining
CDMA	-	Code Division Multiplexing Access
CDT	-	Connection Disruption Time
CID	-	Connection Identifiers
CINR	-	Carrier-to-interference plus Noise Ratio
CL	-	Current Load
CMAC	-	Cipher-based Message Authentication Code
CS	-	Candidate Set
CSMA/CA	-	Collision Sense Multiple Access with Collision Avoidance
CSN	-	Connectivity Service Network
CTBS	-	Candidate TBS

D

D-AMPS	-	Digital AMPS
DCD	-	Downlink Channel Descriptor
DHCP	-	Dynamic Host Configuration Protocol
DiCD	-	Differences in Consecutive Distances
DL	-	Downlink
DL-MAP_IE	-	Downlink Map Information Element
DS	-	Diversity Set
DS-WCDMA	-	Direct Sequence Wideband CDMA

E

EAEM	-	Expected Angle of Exit of the MS
EAP	-	Extensible Authentication Protocol
EDGE	-	Enhanced Data Rate for Global Evolution
ERT-VR	-	Extended Real-time Variable Rate
ETSI	-	European Telecommunication Standards Institute

F

FA	-	Foreign Agent
FBSS	-	Fast Base Station Switching
FDD	-	Frequency-Division Duplex
FDM	-	Frequency Division Multiplexing
FDMA	-	Frequency Division Multiple Access
FFT	-	Fast Fourier Transform
FM	-	Frequency Modulation
FMIPv6	-	Fast Handover for MIPv6
FQDN	-	Fully Qualified Domain Name
FTP	-	File Transfer Protocol
4G	-	Fourth Generation

G

GAON	-	Geographical Angle of the NBSs
GBSGT	-	Global BS Geolocation Table
GHz	-	Gigahertz
GPRS	-	General Packet Radio Service
GPS	-	Global Positioning System
GRGT	-	Global Relative Geolocation Table
GSM	-	Global System for Mobile Communication

H

HHO	-	Hard Handover
HiperMAN	-	High Performance Radio Metropolitan Area Network
HMAC	-	Hash-based Message Authentication Code
HMIPv6	-	Hierarchical Mobile IPv6
HSPA	-	High-Speed Packet Access
Hz	-	Hertz

I

IETF	-	Internet Engineering Task Force

IMT-Advanced	-	International Mobile Telecommunications-Advanced
IP	-	Internet Protocol
IS	-	Interim Standard
ISI	-	Intersymbol Interference
ITU	-	International Telecommunication Union
ITU-R	-	International Telecommunication Union’s Recommendation

L

LAN	-	Local Area Network
LBS	-	Load-Based Score
LBS	-	Location-based Services
LOS	-	Line-of-Sight
LTE	-	Long Term Evolution
LTE-A	-	LTE-Advanced
L2	-	Layer-2
L3	-	Layer-3

P

PDA	-	Personal Digital Assistants

M

MA	-	Mobility Agent
MAC	-	Media Access Control
MANET	-	Mobile Adhoc Networks
MASL	-	Minimum Acceptable Signal Level
MBB	-	Make-Before-Break
MBS	-	Broadcast and Multicast Services
MDHO	-	Macro-Diversity Handover
MDVR	-	Modified Distance Vector Routing
MD5	-	Message-Digest 5
MIMO	-	Multiple Input / Multiple Output

MIPv6	-	Mobile Internet Protocol version 6
MOB_ASC-REP	-	Mobile Association Result Report
MOB_BSHO-REQ	-	Base Station Handover Request
MOB_BSHO-RSP	-	Base Station Handover Response
MOB_HO-IND	-	Mobile Handover Indication
MOB_HO-REP	-	Mobile Handover Report
MOB_MS-REP	-	Mobile Report Message
MOB_MSHO-REQ	-	Mobile Station Handover Request
MOB_NBR-ADV	-	Mobile Neighbour Advertisement
MOB_RNG-IND	-	Mobile Ranging Indication
MOB_SCN-REQ	-	Scanning Interval Allocation Request
MOB_SCN-RSP	-	Scanning Interval Allocation Response
MOB_SCN-REP	-	Scanning Result Report
MPDU	-	MAC protocol data units
MRPLM	-	Minimum Required Period of Linear Motion
MSC	-	Mobile Switching Centres
MSDU	-	MAC service data units
MS	-	Mobile Station
MHz	-	Megahertz

N

NAP	-	Network Access Providers
NBS	-	Neighbouring Base Stations
NLOS	-	Non-line-of-sight
NRM	-	Network Reference Model
nrtPS	-	Non-Real-Time Polling Service
NSP	-	Network Service Providers
NTAP	-	Network Topology Acquisition Phase
NWG	-	Network Working Group

O

OFDM	-	Orthogonal Frequency Division Multiplexing

OFDMA	-	Orthogonal Frequency Division Multiple Access
OM	-	Orientation Matching
OMS	-	Orientation Matching Score
OSI	-	Open Systems Interconnection

P

PCT	-	Polar Coordinates Table
PHY	-	Physical Layer
PKM-REQ	-	Privacy Key Management Request
PKM-RSP	-	Privacy Key Management Response
PKMv2	-	Privacy and Key Management Protocol Version 2
PMP	-	Point-to-multipoint
PTBS	-	Potential TBS

Q

QoS	-	Quality of Service

R

RAD	-	Relative Angular Distance
RAN	-	Radio Access Network
RNG-REQ	-	Ranging Request
RNG-RSP	-	Ranging Response
RR	-	Radio Resource
RRM	-	Radio-resource Management
RSS	-	Received Signal Strengths
RSSI	-	Received Signal Strength Indicator
RTD	-	Round-trip Delay
rtPS	-	Real-Time Polling Service

S

SBC-REQ	-	SS Basic Capability Request
SBC-RSP	-	SS Basic Capability Response

SBS	-	Serving Base Station
SC-FDMA	-	Single Carrier-Frequency Division Multiple Access
SCR	-	Spare Capacity Reports
SHO	-	Soft Handover
SNR	-	Signal-to-Noise Ratio
SOFDMA	-	Scalable OFDMA

T

TBS	-	Target Base Station
TCP	-	Transmission Control Protocol
TDD	-	Time-Division Duplex
THz	-	Terahertz
TDM	-	Time Division Multiplexing
TMDB	-	Temporary Movement Database
3G	-	Third Generation
3GPP	-	Third Generation Partnership Project

U

UCD	-	Uplink Channel Descriptor
UGS	-	Unsolicited Grant Service
UL	-	Uplink
UMTS	-	Universal Mobile Telecommunication Services
UMTS	-	Universal Mobile Telephone Systems

V

VBSL	-	Visited Base Stations List
VoIP	-	Voice-over-IP

W

WAS	-	Weighted Average Score
WiFi	-	Wireless Fidelity
WLAN	-	Wireless Local Area Network

WMAN	-	Wireless Metropolitan Area Networking
WiMAX	-	Worldwide Interoperability for Microwave Access

Z

ZC	-	Zone of Concern
ZD	-	Zone of Doom
ZE	-	Zone of Emergency
ZN	-	Zone of Normalcy
0G	-	Zeroth Generation