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By Ardian Ulvan

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WiMAX/IEEE802.16: An Introduction to MAC Layer

Basic functionalities and the enhancement of MAC Layer

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WiMAX /IEEE802.16

Ulvan

This book focuses on the functionality and the enhancement of MAC Layer on WiMAX broadband wireless system. The WiMAX technology is mostly referred to IEEE802.16-2004 and IEEE802.16-2005 with some requirements taken from IEEE802.16j-2006 D2 and initial documents of IEEE802.16m. The first part of this book presents an evaluation of the overhead on the MAC management messages of IEEE 802.16. It is followed by the improvement mechanism of MAC functionality. The final part discusses about the enhancement of handover strategy for advance air interface system.

Ardian Ulvan

Ardian Ulvan received the the Ph.D. degree in Electrical Engineering and Information Technology from CTU Prague, Czech Republic. He is currently working as a Senior Lecturer at Dept. of Electrical Engineering, The University of Lampung, Indonesia, and as a researcher at wireless networks research group of CTU Prague.

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WiMAX/IEEE802.16 NETWORK:

An Introduction to MAC Layer

Ardian Ulvan

Summary

The definition of novel and ultra efficient *Medium Access Control* (MAC) layer of IEEE 802.16 Broadband Wireless Access system is one of the most challenging issues in next generation wireless network. In order to fulfil *the International Mobile Telecommunication-Advanced* (IMT-Advanced) requirements, *the Network for the Future*, the efficiency improvement of current IEEE 802.16-2005 MAC layer is required, as well as the development of IEEE 802.16-2009 *Multihop Mobile Relay* (MMR) and IEEE 802.16m Advance Air Interface, which support the bit rate of 100 Mbps for mobile application and 1 Gbps for fixed application. Obviously, reaching *giga bits per second* (Gbps) peak throughput requires a higher spectral efficiency and much larger bandwidth. Therefore, the optimised MAC layer functionality has a key role for those purposes.

The performance limitations of conventional cellular wireless networks in terms of throughput and coverage have been well recognised. The IEEE 802.11 *Wireless Local Area Network* (WLAN) is the system that reaches the throughput of 54 Mbps, however it has limitation on service coverage. On the other hand, the network cellular provided by 2G/3G systems have a wider coverage but has a limited cell throughput of 2 Mbps.

In this book the broadband wireless system is mostly referred to *802.16-2004* and *802.16-2005* with some requirements taken from *802.16j-2006 D2* and *initial documents of 802.16m.*

In order to enlarge the coverage and support of high speed mobility in mesh mode, the use of relays with number of relay stations (*multi-hop*) and *multi-cell* scenario is considered. This architecture is considered due to geographical distribution of the user terminals and the increase of user mobility in both number and speed. However, the main drawback resides in the bandwidth and spectrum limitations hence the efficient utilisation of time processing and network capacity becomes the objective of the research and technological development activities of this work.

In addition, the handover procedure is exploited in order to examine its performance as the MAC layer functionality. Basically, the handover is a *network-controlled*, in which the decision to implement handover is taken by the *base station* (BS) to which the *mobile station* (MS) is currently attached. Nevertheless, the standards also support the *client-based* handover in which initiated by the MS. This option gives the handover process in 802.16 more efficient, since any changing of necessary parameters or events (such as signal strength, coverage, the quality of service provided by the network, etc.) can be monitored by the MS from its wireless interfaces, then use them to decide to trigger the handover. The client-based handover also give us the opportunity to propose some new metrics, methods or mechanisms that can be utilised to improve the process and the procedure of handover.

Minimizing the MAC overhead regardless of the bandwidth might be an approach for the optimisation of MAC functionality. It becomes the scope of this book. The first objective of the work is to present an evaluation of the overhead on the MAC management messages of IEEE 802.16. The overhead and efficiency are analysed in two different topology scenarios i.e., *Point-to-Multipoint* (PMP) and Mesh modes. The improvement of MAC functionality is considered as the second objective. In the first part, the work is allied to MAC *common part sub-layer* (CPS) by utilised the partition scheme mechanism. The mesh mode is observed since it provides the centralised and distributed scheduling. The second part relates to the *service-specific convergence sub-layer* (SS-CS) by determining the efficient scanning process of handover procedure.

The third objective focuses on the enhancement of handover strategy for advance air interface system. The mobility prediction is proposed as a new metric for handover decision. The Markov chain random modelling is used for the prediction of user's next positions. Upon knowing the user's position in advance, the system is able to estimate to which BS the MS will be connected to. Therefore, all handover procedures can be prepared in advanced as well. Accordingly, the MAC overhead due to handover interruption time can be minimised.

All enhancement schemes, proposals and scenarios taken in this work have been proved to provide the efficient functionality of MAC layer in Broadband Wireless System based on IEEE802.16.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

The next generation wireless networks have been characterized by variable and high data rates, *quality of services* (QoS) and seamless mobility both within a network and between networks of different technologies and service providers. Broadband wireless communications system has seen a fast growth in the last decades. The number of wireless user has already exceeded the number of wired line due to the system's capability to address broad geographic area without the high cost of infrastructure deployment.

The performance limitations of conventional cellular wireless networks in terms of throughput and coverage are by now well recognised. The IEEE 802.11 *Wireless Local Area Network* (WLAN) is the system that reaches the throughput of 54 Mbps [1] however it has limitation on service coverage. On the other hand, the network cellular, provided by 2G/3G systems, has a wider coverage but limited on cell throughput of 2 Mbps.

The implementation of *multi-hop* and *multi-cell* architecture in broadband wireless network topology has been considered due to the geographical distribution of user terminals and the increase of user mobility in both number and speed. However, the main drawback resides in the bandwidth and spectrum limitations hence the efficient utilisation and functionality of broadband wireless system's *Medium Access Control* (MAC) layer become the objective of research and technological development activities of this work.

1.2 Broadband Wireless System

1.2.1 Development of IEEE802.16 Broadband Wireless System

The huge increasing demands of mobile users for internet applications and global internetworking have triggered the fast development of broadband wireless system. The *Third Generation Partnership Project* (3GPP) developed the standardisation of *Universal Mobile Telecommunication System* (UMTS) which is known as the *third generation* (3G) cellular systems. The 3G system are rapidly spreading all over the world with the purpose to extend the service provided by the *second generation* cellular networks (2G) based on *Global System for Mobile* communication (GSM). The system architecture is mainly circuit-oriented hence voice traffic, real-time messaging and streaming are services that can be provided by means of this technology. However, they have a complex network structure and need various protocols to cover the entire system. Accordingly, the next generation wireless network or *fourth generation* wireless (4G) is designed to have a simple structure which based on *all internet protocol* (all-IP).

One of the foremost candidates for 4G technology is based on standard IEEE802.16 and ETSI/HIPERMAN, also known as *Worldwide Interoperability for Microwave Access* (WiMAX). The standard is still under developing for particular purposes. Initially, the IEEE 802.16 was aimed at providing high-speed Internet access in a *Point-to-Multipoint* (PMP) manner only. The support of *Quality of Service* (QoS) was embedded since the first release, which clearly stated the role of IEEE 802.16 as a leading technology for the support to advanced multimedia applications. However, *line-of-sight* (LOS) was required, because the very high frequency of 11 GHz is deployed for the *single carrier* (SC) air interface specification of the IEEE802.16-2001 release [2] . It became a constriction of the initial standard. The specification rigorously affected the implementation of the technology, since it significantly increased the cost of setup of both the *base station* (BS) and *subscriber stations* (SSs).

Thus, during the subsequent years the standard has been amended to include support to mesh non-LOS deployment, the version that support *point-to-multipoint* (PMP) and Mesh topologies being published in 2004 as IEEE 802.16d-2004 [3] The standard is for fixed wireless installations, it promotes bandwidths of 70 Mbps or 2-

10 Mbps/user covering up to 10 Km^2. The standard defines both *Time Division Duplexing* (TDD) and *Frequency Division Duplexing* (FDD) for channel allocation. Both channels are time slotted and composed of frames. The TDD frame composed of downlink and uplink sub frames. The duration of each of these frames can be controlled by BS whenever needed. Downlink channel is broadcast channel. BS broadcasts data to all SS on downlink channel. SSs accept only those packets which are destined to it.

The subsequent mobility amendment, IEEE 802.16e-2005 [4] , adds support for nomadic roaming at vehicular speeds. Data rates are envisioned at 2-3 Mbps/user for portable and 1-2 Mbps/user when mobile covering an area of about 5 Km and the maximum bandwidth is up to 20 MHz. The 802.16e-2005 standard goes a step further with *Orthogonal Frequency Division Multiple Access* (OFDMA), a variant of *Orthogonal Frequency Division Multiplexing* (OFDM), which has the ability to assign a subset of the carriers to specific users.

In 2006, IEEE has started to work on 802.16j *Mobile Multihop Relay* (MMR) under IEEE802.16j's Relay Task Group. The basic idea behind MMR is to allow the BSs which do not have a backhaul connection to communicate with other BSs that do. On the one hand, this scheme will technically reduce the available bandwidth to users in the cells involved in relaying packets. On the other hand, by specifying the *Relay Stations* (RS), it provides the way to save costs and extend network coverage into areas where connecting a BS directly to the network via a fixed line connection is economically or technically not feasible. Eventually, on May 2009 IEEE Std 802.16j was approved by IEEE-SA Standards Board as an amendment to IEEE Std 802.16-2009 [5] . It is the latest 802.16 standard version which is already published

The upcoming version that still under development is 802.16m Advance Air Interface which support the bit rate of 100Mb/s for mobile application and 1Gb/s for fixed application [6] to fulfil the IMT-Advanced requirements (ITU-R M. 1645) [7] It is clear that reaching *giga bits per second* (Gbps) peak throughput requires a higher spectral efficiency and much larger bandwidth. The total spectrum needed by pre-

IMT-2000, IMT-2000 and IMT-advanced systems by year 2020 is estimated to range between 1.2 GHz and 1.7 GHz as described in ITU-R M. 2078 [8]

1.2.2 Multi-hop Wireless Networks

Multi-hop wireless networks have been widely implemented as last-mile access to the users. In multi-hop wireless networks, communication between two end nodes is carried out through a number of intermediate nodes whose function is relay information from one point to another. It is quite common that the relaying nodes, in general mobile and communication needs are primarily between nodes within the same network.

A multi-hop wireless network is designed to extend the conventional point-to-point or point-to-multipoint communication. In addition, it also aimed to provide a broadband wireless access for the telecommunication users. The position of relays, where placed within the BS and at the border of BS's coverage, show different purposes. When relays are within the BS, they increase the capacity. Additionally, the relays extend the coverage when placed on the cell boundary [9] In multi-hop system, beside a dedicated relay such as BS or fixed *relay station* (RS), the relay terminals in the network may perform as mobile relays for some other terminals which require relaying assistance. The technology development to fulfil these characteristics is standardized by IEEE 802.16j [5] . In this work we focused only on the dedicated relay terminals as the hop.

A fundamental issue in multi-hop wireless networks is that performance degrades sharply as the number of hops traverse increases. The performance challenges of multi-hop networks have been recognised and have led to a lot of research, particularly on the medium access control functionality. Other issues are to answer the question of what the optimal capacity of a multi-hop wireless network is, and how to obtain the spectral efficiency.

Since it is a functionality of relaying, most of multi-hop wireless network lays on point-to-point topology. The increasing numbers of multi-hop wireless deployments and proprietary commercial solutions have derived the more complex of network topology called mesh network. Mesh networks serve as access networks that employ multi-hop wireless forwarding by mobile or non-mobile nodes to relay traffic to and from the BS.

Minimizing the MAC overhead regardless of the bandwidth might be an approach for the spectral efficiency. It becomes the scope of this work. In order to enlarge the coverage and support of high speed mobility in mesh mode, the use of relays with number of hops and multi-cell scenario is considered. In this work the broadband wireless system is mostly referred to 802.16d-2004 and 802.16e-2005 with some requirements taken from 802.16j-2006 D2 [10] and initial documents of 802.16m [6] .

1.2.3 Handover

Work on handovers in wireless network has been going extensively. Most of the researches are in the field of cellular networks and done by the mobile operators focused on network-controlled horizontal handover where handover is executed between adjacent cells of the same network. In term of IP-based wireless network, the handover research done typically in wireless local area network based on Wireless Fidelity (WiFi) IEEE802.11.

With the introduction of WiMAX IEEE802.16 networks, 3GPP *Long Term Evolution/Long Term Evolution-Advanced* (LTE/LTE-A) as well as Mobile IPv4/IPv6, the client-based handover began to be investigated. In addition, the inter-system handover or vertical handover is going investigated intensively. The research in both *L1* (physical layer) and *L2* (MAC layer) is undertaken in order to achieve the most efficient handover and reduce the handover overhead.

Since the handover is one of the main functionality that supported by MAC layer in IEEE802.16 technology, it is very interesting to be investigated. In this work, we exploited the handover procedure in order to examine its performance as the MAC layer functionality. The handover option basically is a network-controlled handover in which the decision to implement handover is taken by the BS to which the MS is currently attached. However, the standard also supports the client-based handover in which initiated by the MS. This option gives the handover process in

802.16 more efficient, since any changing of necessary parameters or events (such as signal strength, coverage, the quality of service provided by the network, etc.) can be monitored by the MS from its wireless interfaces, then use them to decide to trigger the handover. In addition, the client-based handover also give us the opportunity to propose some new metrics, methods or mechanisms that can be utilised to improve the process and the procedure of handover.

1.3 Problem Statement

The Wireless Broadband System based on IEEE 802.16 standard has provided the MAC layer functionalities for fixed and mobile environment in both PMP and mesh network topology. Most of current standards provided the MAC capability for communication link between BS and SSs/MSs.

To ensure a strong focus and an appropriate objective, the work proposes to limit the scope of investigations into three questions. These are the most important questions to be coped in this work:

- How to deal with the overhead to obtain the high efficient, most robust MAC layer?
- How to improve the handover procedure as one of MAC functionality?
- How to obtain the optimized handover strategy to fulfil the IMT-advanced requirements?

In addition, the work also considers on the implementation of centralised and distributed relay management in mobile environment, as well as the mobility prediction method for handover purposes. The IEEE 802.16e is used as a basic standard of wireless broadband access in cooperation with the new and on progress standards of IEEE 802.16j and 802.16m respectively. As the standards are new and still under development, other standards and technologies e.g., 3G-UMTS and 3GPP LTE are also considered for selected purposes, since they have proved the capability on mobile and multi-cell environments and services.

1.4 Aims of the Work

The aim of the work is to achieve the enhancement of MAC layer functionality of broadband wireless system based on IEEE 802.16 standard in multi-hop and multi-cell environment. The main objectives of the work are:

- To determine and analyse MAC overhead of IEEE 802.16 broadband wireless system. The overhead evaluation is laid on the MAC management messages of IEEE 802.16. The overhead and efficiency are analysed in two different topology scenarios i.e., *Point-to-Multipoint* (PMP) and Mesh modes.
- To propose the enhancement schemes in order to obtain the efficient functionality of MAC layer. The improvement of MAC functionality is allied on two different sub-layers i.e., *common part sub-layer* (CPS) and *service-specific convergence sub-layer* (SSCS). In MAC-CPS, the improvement is examined by utilising the partition scheme mechanism. The mesh mode is observed since it provides the centralised and distributed scheduling. Additionally, the improvement on MAC-SSCS is achieved by determining the efficient scanning process of handover procedure.
- To introduce and propose the enhancement of handover strategy for advance air interface system. The mobility prediction is proposed as a new metric for handover decision. The Markov chain random modelling is used for the prediction of user's next positions. Upon knowing the user's position in advance, the system is able to estimate to which BS the MS will be connected to. Therefore, all handover procedures can be prepared in advanced as well. Accordingly, the MAC overhead due to handover interruption time can be minimised.

1.5 Organisation of the Book

This book is organised as follows. In **Chapter 2** the overview of current situation of studied problem is presented. The MAC overhead and the efficiency of MAC layer in broadband wireless system are reviewed, extensively on the IEEE802.16 based system. Furthermore, the technical state-of-the-art of MAC overhead methods is reviewed, as well as the algorithms and mechanisms to increase MAC efficiency in IEEE802.16 broadband wireless system.

In **Chapter 3**, a literature study of IEEE802.16 broadband wireless system is presented, to provide a better understanding of the system architecture in both PMP and Mesh topologies. The reference model and general principle of IEEE802.16 MAC layer, including its functionality in multi-hop and multi-cell scenario are presented as well.

The main contributions of this work are presented in Chapter 4, Chapter 5 and Chapter 6. In **Chapter 4**, the analysis of the MAC management messages overhead in PMP and mesh topologies are described in detail. The MAC efficiency performance for PMP is based on the length of MAC *protocol data unit* (PDU), the various modulation schemes and number of burst profiles. In addition for mesh topology, the efficiency performance is determined by the same parameters as PMP, including the various numbers of hop and node level. The distributed and centralised scheduling are also considered for the efficiency performance in mesh. The performance evaluation is proved by means of mathematical analysis and simulation.

Furthermore, the improvement of MAC functionality is then performed in **Chapter 5**. Here, two parts of MAC layer i.e. the MAC *common part sub-layer* (MAC-CPS) and the *service-specific convergence sub-layer* (SS-CS) are taken into account. The increase of utilisation of mesh MAC messages is considered as the improvement proposal of MAC-CPS. Moreover for SS-CS, the improvement is taken in the handover procedure, particularly the network topology acquisition stage of the procedure. Both proposals are proved by means of numerical analysis and simulation.

Chapter 6 describes more detail about the optimisation of handover procedure by applying the mobility prediction method. This method is a novel mechanism for IEEE802.16m's handover decision policy. The Markov chain random modelling is described in order to estimate the user's next positions. The simulation results is carried out and discussed. Additionally, two handover strategies i.e. proactive and reactive handover are also described with regards of the prediction results.

Chapter 7 is the accomplishment of the work by describing the technical and theoretical contribution of the work in the development of the standard and involved project reports.

Finally, in **Chapter 8**, we provide some concluding remarks of the applicability used of the proposed method and algorithm for future works. We also present the potential future direction of research and technological development of broadband wireless system.

Chapter 2

State of the Art

The overhead caused by transporting the MAC messages throughout the network is an important performance indicator, because it significantly influences the system throughput. It is interesting to make an analysis how the MAC efficiency is dependent on the physical and logical configurations of the network. Performance of a networking protocol is commonly evaluated by means of the net throughput, especially on MAC layer and delay. In this chapter, we overviewed the current research works and technological development related to the topic of this work.

2.1 Related Works

The MAC operation of wireless system has been concerned in several research works, most of them are based on the WiFi IEEE 802.11 standard. However, all works concerning MAC overhead reviewed in this section mainly focus on a specific MAC aspect, rather than on presenting an overview of MAC performance.

In [11] , the authors studied the influence of MAC overhead when analyzing the stale cache problem in IEEE 802.11 ad-hoc networks with on-demand routing protocol. They found that the MAC overhead can significantly degrade the wireless performance. Several mechanisms are suggested to address the stale cache problem, including the used of Null MAC layer with negligible MAC overheads, and change in the MAC layer interface to reduce the MAC overhead. The combination of these two mechanisms has improved the overall performance. However, the result of this work has implication beyond performance improvement of a single routing protocol.

Detail performance of MAC functionality is carried out in [12] The authors considered on scheduling algorithm called Real-Time *Hybrid Coordinator Function* (HCF) *Controlled Channel Access* (HCCA) - RTH. This scheduler represents an improved version of the sample HCCA scheduler defined by the IEEE 802.11e standard to support QoS requirements of delay-sensitive traffic. The RTH splits scheduling task into online and offline activities. Online activities take place at the frame transmission timescale and are kept as simple as possible, while offline activities, lasting much longer, are suitable to be scheduled more effectively for the price of more complex computations. The HCF/HCCA-RTH scheduler is quite interesting, however, it needs some further work to verify its performance in IEEE802.16 network.

The flexibility and utilisation of MAC protocols scheduling have an important role for mobility support since the scheduling performance is critical for node association procedure, particularly the network entry and re-entry processes during handover. The standard provides the *Partition Scheme* as the scheduling mechanism which separates the allocation of minislots for scheduling. However, minislot can not be flexibly reserved for centralised and distributed scheduling. Due to this constraint, we adopted the scheduling mechanism proposed in [13] to utilise the allocation of minislot, particularly when the *relay station* (RS) is introduced in the network. In [13] the authors proposed the *Combined Distributed and Centralised* (CDC) scheme in order to provide the flexible used of minislot. Two scheduling algorithms such as Round Robin and Greedy have been used when investigating the performance of CDC scheduler. The work concluded that the CDC scheduler showed better performance compared to Partition Scheme mechanism.

In case of wireless broadband access, the MAC performance has been analyzed in several research works. The authors in [14] studied and analysed MAC performance of the HiperMAN standard based on IEEE 802.16 and the amendment IEEE 802.16a. The work described the MAC layer including its sub-layers and discusses fragmentation, packing, and *automatic repeat request* (ARQ) features of the standard. The PMP topology is considered with a simple scenario. By using one BS and one SS, the net bit rate on the MAC level was calculated. Optimal MAC *Protocol Data Unit* (PDU) length was investigated when introducing ARQ. By assuming a non-zero rest bit error rate, they found that the optimal PDU length is dependent on this rate. When a higher error rate occurs, shorter MAC PDUs are more favourable. The larger the MAC PDU, the more data has to be retransmitted. Furthermore, the influence of padding bits filling the physical burst to be an integer number of OFDM symbols. Using the fragmentation process to fill the end of a burst instead of usage of padding could bring apparent overhead reduction, especially for shorter physical bursts.

The more complex scenario for investigating the MAC overhead was carried in one topic in [15] The MAC overhead determination was dedicated to multi-hop wireless networks based on IEEE 802.16a standard. The net throughput on MAC layer was presented for one chosen multi-hop scenario, as well as when using the Mesh mode with centralized/distributed scheduling and the proposed multi-hop PMP. Moreover, in [16] the MAC layer performance of IEEE 802.16e has been analysed. The author examined some parameters i.e., topological mode, number of SS, type of coding and modulation, etc., that influenced the ratio of the number of OFDM symbols usable for transmission of higher layer data to the total number of OFDM symbols per frame. The MAC performance was analysed based on the specified parameters. Obviously, some analyses that have been carried out in these two references are worth to be embraced.

Another aspect that affects the MAC efficiency in IEEE802.16 technology is the length of MAC messages and number of messages exchanged in the particular process. In this work, we focus much more on the handover procedure as the main functionality of MAC layer. We concerned on the enhancement of network topology acquisition stage in handover procedure to provide a fast handover. The scanning process has been exploited in order to fulfil the IEEE802.16m's handover interruption time requirement.

Several distinguished works in [17] [18] [19] have been performed to acquire the fast handover mechanism. In [17] the fast handover algorithm has been proposed by avoiding the unnecessary neighbouring BS scanning. The single target BS was estimated by using mean *Carrier to Interference-plus-Noise Ratio* (CINR) and arrival time difference. Moreover, the network association process was proposed to be performed before and during handover process. The schemes have reduced the handover operation delay.

Correspondingly, in [18] the handover delay has been analysed and compared in scheme of single neighbour scanning, fast ranging and pre-registration as the mechanism of fast handover. The results showed these schemes can reduce the handover delay and improve the QoS of IEEE802.16e broadband wireless networks. Additionally in [19] it revealed that the MS is not able to send/receive data during handover process due to the hard handover process specified in IEEE802.16e standard. This constraint severely affected the real-time packet data, therefore the enhanced link-layer handover algorithm where a MS can receive downlink data before synchronisation with uplink during handover process was proposed. The authors introduced a new MAC management message called Fast DL_MAP_IE and performed the delay calculation in several handover options. The proposed scheme ignored the network re-entry processing time of handover for downlink service which reduced the downlink data transmission delay and packet loss probability.

2.2 Our Approach

Many technical and theoretical methodologies have been presented for obtaining the technical improvement in the broadband wireless system. Some of the related works overviewed in the previous section can be distinguished as a novel contribution and/or the technical state of the art.

The advanced radio resource management schemes (e.g. in [15] [16]) gave the idea in the measurement of the overhead and efficiency in broadband wireless MAC layer. We follow the idea for analysed the overhead and determined the efficiency of MAC management messages. Nevertheless, we improve the method by distinguishing the analysis separately, i.e. point-to-multipoint topology based on IEEE802.16-2005 and the mesh topology based on IEEE802.16-2004. Thus, our proposed method can be precisely used for each topology and for each standard platform.

We also adopted the distributed and centralised scheduling (e.g. in [13] [20] and improve the entry scheduling algorithm in order to optimising the network entry procedure for multi-hop and multi-cell scenario in mesh topology. The new MAC message signalling for the optimised network entry procedure has been proposed. Meanwhile, the new mechanism in network topology acquisition has been introduced to avoid the redundant scanning process in handover procedure of IEEE802.16m.

We proposed a novel mechanism and a new metric based on mobility prediction for handover decision to ensure the quality of service of the system in high speed mobility environment that supported by the IEEE802.16m standard. The mechanism is combined with the handover strategies (e.g., in [21] [22]) i.e., proactive handover to minimize packet loss and high latency during handover, in addition, the reactive handover strategy is to prevent the very frequent and unnecessary handovers due to high speed mobility of the user.

Chapter 3

Overview of IEEE802.16's MAC Functionality

The primary task of the IEEE802.16 *Medium Access Control* (MAC) functionality is to provide an interface between the higher transport layers and *physical* (PHY) layer. The MAC layer takes packet, called MAC *service data units* (SDUs), from the upper layer. The SDUs are organised into MAC *protocol data units* (PDUs) for transmission over the air [23] . The MAC layer does the reverse when receiving the transmission.

The IEEE 802.16e standard specifies the air interface of a fixed and mobile broadband wireless access system. The specification includes the MAC and multiple PHY layer specifications. It amends the previous version IEEE 802.16-2004, by supporting the *subscriber stations* (SSs) moving at vehicular speed. The amendment give the advantage of inherent mobility of wireless media, and fill the gap between very high data rate wireless local area networks and very high mobility cellular systems [4] .

To enforce compliance to the standard, the organization known as the WiMAX Forum was created. WiMAX Forum promotes the standard and the development of system profiles, which are the specific implementations and the selections of options from the standard [24] . The certification testing is a combination of WiMAX conformance and interoperability testing. The certification process starts with a pre-certification qualification testing by the accomplishment of a subset of the WiMAX conformance and interoperability test cases. The results determine whether the product can start the formal conformance testing. Only after successful conformance testing, the interoperability testing can be started.

The conformance testing is conducted by a certification laboratory or another test laboratory. During this testing, manufacturers of base stations and subscriber stations verify their products if they perform in accordance with the specifications for the WiMAX *Protocol Implementation Conformance Specification* (PICS) document. According to the results, the hardware may be modified and formally resubmitted for conformance testing. The end goal is to show service providers and end-users that they have the option of mixing and matching different BSs and SSs from different vendors in their deployed networks [25] .

By late 2003, the first IEEE 802.16-based equipment began to enter the marketplace. It overcomes many of the IEEE 802.11 limitations when used in a *Metropolitan Area Network* (MAN) environment. The additional spectrum bandwidth and throughput of IEEE 802.16 shall markedly improve wireless data delivery, offering high-speed connectivity to vehicles travelling at over 140 km/h [26]

WiMAX is expected to fulfil the *International Mobile Telecommunication* (IMT) requirements and goal as network for the future. This technology enables a low barrier for service providers to enter the market. It will allow true market-based competition in all of the major telecommunication services: voice (mobile and static), video, and data. The competition does not have to rely on the exorbitant capital investment necessary to deploy a telephone network [27] .

3.1 IEEE 802.16 - Basic Information

The IEEE 802.16e standard specifies several frequency bands to be used for operation of the IEEE 802.16e networks. The applications depend on the chosen spectrum usage. Main frequency bands can be divided as follows: 10 – 66 GHz licensed bands, frequencies below 11 GHz, and license-exempt frequencies below 11 GHz [3] .

The standard also supports two different topologies – Point to Multipoint (PMP) and Mesh. The chosen topology noticeably restricts selection of the physical layer. As it is apparent from *Table 3.1*, five air interfaces are defined by the standard. However, Mesh topology is supported only using WirelessMAN-OFDM or the OFDM version of WirelessHUMAN air interface.

Channel coding in IEEE802.16 is composed in three steps: *randomizing*, *forward error correction* (FEC) and *interleaving*. Randomization is used independently on uplink and downlink. The output of the randomizer is a *pseudo-random bit sequence* (PRBS). The FEC is done by concatenated *Reed-Solomon* (RS) outer code and rate-compatible convolutional inner code. The encoding is performed by passing the data in block format through the encoder and then passing it through a convolutional encoder. Block turbo coding and Convolutional turbo coding are used optionally.

The IEEE802.16 supports various coding rates. Coding rate 1/2 shall always be used as the coding mode when requesting access to the network and in the FCH burst. The mandatory channel coding with different modulations can be found in *Table 3.2*.

Table 3.1 IEEE 802.16 air interfaces.

Designation	*Frequency band*	*Transmission scheme*	*MAC architecture*	*Channel bandwidth*	*Duplexing*
IEEE802.16-2001	10 - 66 GHz	Fixed LOS, SC only	PMP	20, 25, 28 MHz	TDD, FDD
IEEE802.16-2004	2 - 11 GHz	Fixed NLOS, 256 OFDM or 2048 OFDM	PMP and mesh	1.75, 3.5, 1, 14, 1.25, 5, 10, 15, 8.75 MHz	TDD, FDD
IEEE802.16-2005	2-11 GHz (fixed) and 2-6 GHz (mobile)	Fixed and mobile NLOS, SC, 256 OFDM, scalable OFDM	PMP and mesh	1.75, 3.5, 1, 14, 1.25, 5, 10, 15, 8.75 MHz	TDD, FDD
IEEE802.16-2009	below 11 GHz licensed		PMP and mesh	1.75, 3.5, 1, 14, 1.25, 5, 10, 15, 8.75 MHz	TDD, FDD
IEEE802.16m	below 11 GHz unlicensed		Yes (using OFDM only)	No	TDD

Table 3.2 Mandatory channel coding/modulation in IEEE802.16.

Modulation	*Uncoded block size (bytes)*	*Coded block size (bytes)*	*Overal coding rate*
BPSK	12	24	1/2
QPSK	24	48	1/2
QPSK	36	48	3/4
16-QAM	48	96	1/2
16-QAM	72	96	3/4
64-QAM	96	144	2/3
64-QAM	108	144	3/4

3.2 IEEE 802.16 Reference Model

3.2.1 MAC Frame Structure

In IEEE 802.16 uplink (UL - from SS to BS) and downlink (DL - from BS to SS), data transmission occur in separate time frames. In the DL sub-frame the BS transmits a burst of MAC Payload Data Units (PDUs). Since the transmission is broadcast, all SSs listen to the data transmitted by the BS. However, an SS is only required to process PDUs that are addressed to itself or that are explicitly intended for all the SSs. In the UL sub-frame, on the other hand, any SS transmits a burst of MAC PDUs to the BS in a *Time Division Multiple Access* (TDMA) manner.

DL and UL sub-frames are duplexed using one of the following techniques, as shown in *Figure 3.1,* Frequency Division Duplex (FDD), where DL and UL sub-frames occur simultaneously on separate frequencies, and Time Division Duplex (TDD), where DL and UL sub-frames occur at different times and usually share the same frequency. SSs can be either full-duplex (FD-SS), i.e. they can transmit and receive simultaneously[1], or half-duplex (HD-SS), i.e. they can transmit and receive at non-overlapping time intervals.

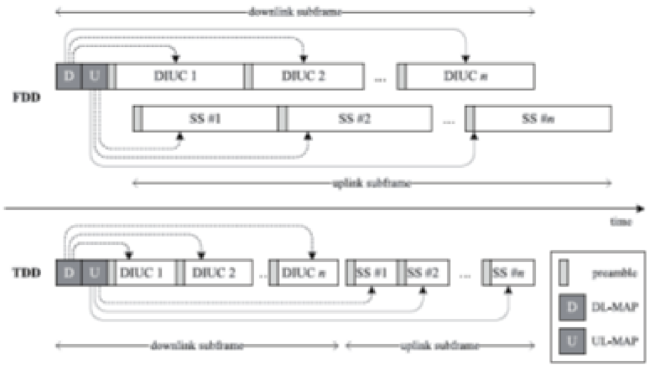

Figure 3.1 *MAC frame structure - FDD (above), TDD (below).*

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[1] FD-SSs must be equipped with at least two radio transceivers to operate simultaneously in two frequency bands

Two different frame structures are defined in IEEE 802.16e for PMP topology and the optional Mesh topology. For PMP, both TDD and FDD duplexing methods are possible, but for license-exempt bands only TDD is used. Mesh supports only TDD.

Point-to-Multipoint (PMP) Topology

The OFDM PHY supports frame-based transmissions. Each frame consists of a downlink (DL) and an uplink (UL) sub-frame. A downlink sub-frame consists of only one downlink PHY PDU. An uplink sub-frame contains intervals for initial ranging and bandwidth request purposes, and one or multiple uplink PHY PDUs, each transmitted from a different SS, as can be seen at *Figure 3.2*.

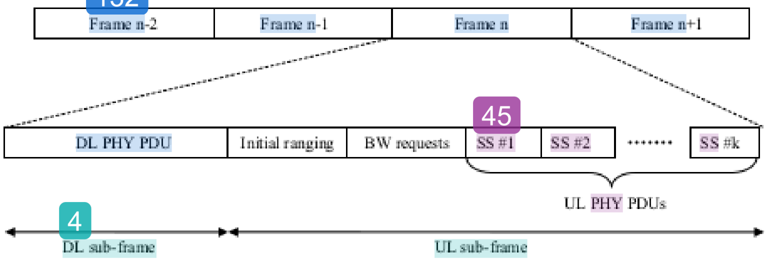

Figure 3.2 *Basic frame structure of PMP-TDD*

Between the DL, an UL sub-frame's TTG (*transmit–receive turnaround gap*) and RTG (*receive–transmit turnaround gap*) are inserted in order to allow subscriber stations to turnaround from transmitting to receiving and form receiving to transmitting.

Downlink sub-frame

A downlink PHY PDU starts with a long preamble, which is used for PHY synchronization. After the preamble, a *frame check* (FCH) burst follows. It is one OFDM symbol long and it is always transmitted using BPSK 1/2 modulation/coding. It contains *Downlink Frame Prefix* (DLFP) information element to specify burst profile and length of up to 4 downlink bursts immediately following the FCH [3]

The burst profile is a basic tool in the 802.16 standard MAC layer. Its allocation, which changes dynamically and possibly very fast, describes the physical transmission [28] . The most important burst profile parameter is Frame Error Check (FEC) code type which specifies the used of modulation and coding scheme (MCS).

The FCH is followed by one or multiple downlink bursts as shown in *Figure 3.3*. DL burst #1 directly follows the FCH and contains broadcast MAC messages. They include ownlink map (DL-MAP), uplink map (UL-MAP), *Downlink Channel Descriptor* (DCD), and *Uplink Channel Descriptor* (UCD), which appear in this order. Even though the broadcast messages play an important role in the frame, it is not mandatory to use the most robust modulation/coding. Some of the messages appear periodically and therefore they don't have to be present in every frame.

Each downlink burst consists of an integer number of OFDM symbols. Location and profile of the first four downlink bursts are specified in the DL-FP. The rest of downlink bursts specifications are included in the DL-MAP message. To form an integer number of OFDM symbols, unused bytes in the burst payload are padded by the 0xFF bytes.

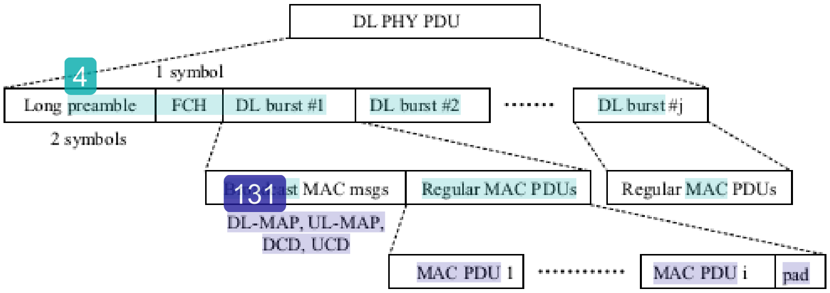

Figure 3.3 *PDU structure of Downlink PHY*

Uplink sub-frame

As stated before, the uplink sub-frame starts with contention slots intended for initial ranging and bandwidth requests. Then UL PHY PDUs from all SSs follow. Each of them starts with the short preamble and then carries regular MAC PDUs from these SSs. The structure is depicted in *Figure 3.4*.

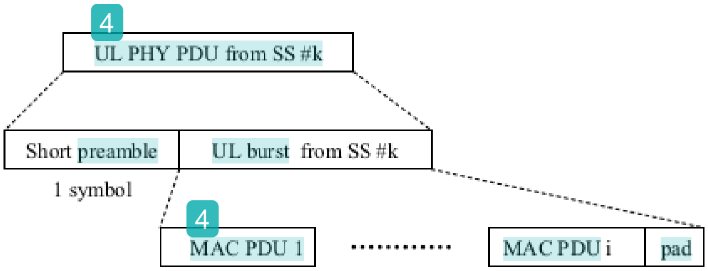

Figure 3.4 *PDU structure of Uplink PHY*

Mesh Topology

For the Mesh topology, an optional frame structure is defined in order to facilitate Mesh networks. A Mesh frame consists of a control and data sub-frames. The length of the control sub-frame is fixed and specified as MSH-CTRL-LEN x 7 OFDM symbols. MSH-CTRL-LEN parameter is included in the Network Descriptor parameter defined in MAC management message MSH-NCFG, which is together with other Mesh MAC management messages. All transmissions in the control sub-frame are transmitted using QPSK 1/2.

The control sub-frame has two different functions. One is called *network control*, which serves for creation and maintenance of cohesion between different systems, and the other is termed *schedule control*, which coordinates data-transfers between systems. The Mesh frame structure is depicted in *Figure 3.5*.

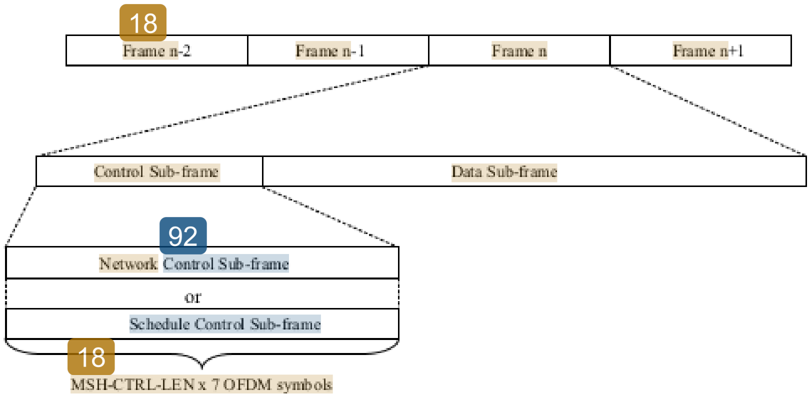

Figure 3.5 *Basic frame structure of Mesh*

Frames with network control occur periodically, as indicated in the Network Descriptor. All other frames contain schedule control information. The data sub-frame is divided into minislots, which are used for assigning available portions of the data sub-frame to individual SSs.

In the context of multi-hop systems, extra relaying phases should be introduced in MAC frames, in order to support relaying transmissions. Each UL or DL subframes are subdivided into sub-subframes so that relay transmission are accommodated. The subframe concept introduces a reserved phase in the UL subframe of the 802.16 MAC frame, which is under the control of the *relay station* (RS). The RS takes over the responsibility to build a complete MAC frame within the reserved phase. This nested subframe contains all necessary information to interpret it as a full 802.16 MAC frame. This concept also allows the allocation of several subframes for multiple RSs of the cell.

3.2.2 MAC Protocol

The IEEE802.16's MAC protocol is connection-oriented, all communications data, for both transport and control, are in the context of a unidirectional connection that is uniquely identified through a 16-bit *connection identifier* (CID). The CID is included in the standard 6-byte MAC header that is appended to each PDU so as to identify the connection to which the encapsulated MAC Service Data Unit (SDU) belongs. In order to reduce the MAC overhead or improve the transmission efficiency, the BS and SSs can fragment a SDU into multiple PDUs, or they can pack multiple SDUs into a single PDU. These operations are illustrated in *Figure 3.6*, which also shows that a DL/UL burst usually consists of the concatenation of many PDUs (or part thereof). A hybrid analytical-simulation study of the impact on the performance of this feature of the MAC layer has been carried out in [29] . Results showed that, if the use of fragmentation is enabled, the frame can be filled almost completely, which can significantly increase the frame utilization, depending on the size of SDUs. These optional features have also been exploited in a cross-layer approach between the MAC and application layers to optimize the performance of multimedia streaming [30] .

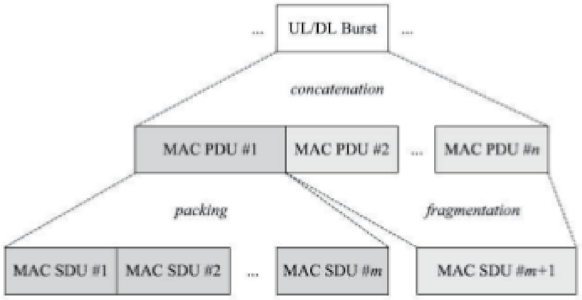

Figure 3.6 *Fragmentation/packing/concatenation of Protocol Data Units (PDUs).*

At the start of each frame, the BS schedules the UL and DL grants in order to meet the negotiated QoS requirements. Each SS learns the boundaries of its allocation within the current UL sub-frame by decoding the UL-MAP message. On the other hand, the DL-MAP message contains the timetable of the DL grants in the forthcoming DL sub-frame. Both maps are transmitted by the BS at the beginning of each DL sub-frame, as shown in *Figure* 3.4. However, the UL sub-frame is delayed with respect to the DL sub-frame by a fixed amount of time, called the *UL allocation start time*, to give SSs enough time to decode the UL-MAP and take appropriate decisions. The IEEE 802.16 specifies that this value must be at least as long as the maximum Round Trip Time delay (RTT), but no longer than the frame duration.

3.3 IEEE 802.16 MAC Layer

The IEEE 802.16 specifies the data and control plane of the MAC and PHY layers, as illustrated in *Figure* 3.7. The MAC layer consists of three sub-layers:

- Service-Specific Convergence Sub-layer (SS-CS),
- MAC Common Part Sub-layer (MAC-CPS)
- Security Sub-layer

.

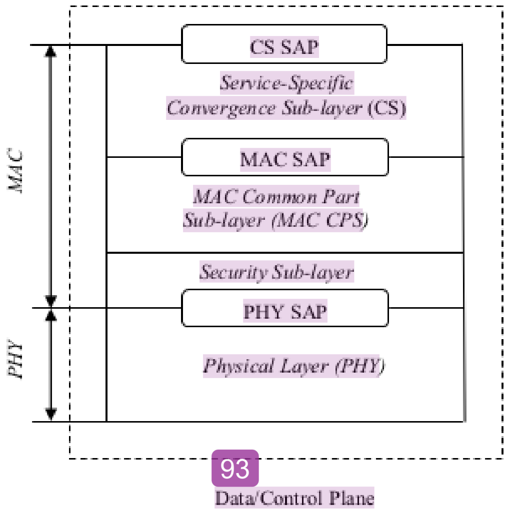

***Figure** 3.7 IEEE 802.16. Data/Control plane.*

The SS-CS receives data from the upper layer entities that lie on top of the MAC layer, e.g. bridges, routers, hosts. It is used for mapping of external network data into MAC SDUs received by the MAC-CPS. This includes classifying external network's SDUs and associating them to the proper MAC *service flow identifier* (SFID) and *connection identifier* (CID). It can also include *payload header suppression* (PHS) function. The MAC-CPS is not required to parse any information from the SS-CS payload. A different SS-CS is specified for each entity type, including support for *Asynchronous Transfer Mode* (ATM), IEEE 802.3 and *Internet Protocol version 4* (IPv4) services.

The MAC CPS is the core logical module of the MAC architecture, and is responsible for system access, bandwidth allocation, connection establishment, and connection maintenance. It receives data from various convergence sub-layers (CSs), classified to particular MAC connections.

Finally, the Security Sub-layer provides SSs with privacy provides (i.e. authentication, secure key exchange) a cross the wireless network, by encrypting data between the BS and SSs.

3.3.1 MAC Common Part Sub-layer (MAC-CPS)

The MAC-CPS is the main part of the MAC layer. As the network utilises a shared medium, it is necessary to provide an efficient sharing mechanism. The MAC layer is responsible for sharing the wireless media between individual subscribers. Both defined topologies, PMP and Mesh, have different requirements on the MAC layer, therefore the MAC-CPS specification is slightly differs.

Addressing

The MAC-CPS provides MAC layer addressing. Each SS has a 48-bit universal MAC address defined in the standard IEEE 802-2001 [2] . It is used during the initial ranging process and also in the authentication process between BS and SS for PMP or between the candidate node and the network for Mesh. In the Mesh mode another identifier is used to address the SS. After a successful authorization in the network the candidate node receives a 16-bit node identifier (Node ID) from the Mesh BS. It is transferred in the Mesh sub-header following the generic MAC header.

Connection

The MAC is connection-oriented and it uses 16-bit connection identifiers (CIDs). At SS initialization, an UL and a DL management connection is established. Both of these connections are bi-directional. Another third pair of management connection may be optionally created. These three pairs of management connections reflect that there are three different levels of QoS for traffic management between an SS and the BS.

The *Basic* management connection is used to exchange short, time-urgent MAC management messages. The *Primary* management connection is used to exchange longer, more delay-tolerant MAC management messages, and the *Secondary* management connection is used to transmit delay-tolerant messages, e.g., DHCP, TFTP, SNMP, etc.

Transport connections are associated with service flows, which are used for bearer services. MAC management messages are never transferred over transport connections and bearer services are never transferred on the Basic, Primary, or Secondary connections. Requests for transmission are based on the CIDs. Many higher-layer session (e.g. TCP/IP) may operate over the same wireless CID.

The Mesh mode uses an 8-bit link identifier (Link ID) for addressing nodes in the local neighbourhood. An ID is assigned by each node for every link it has established to its neighbours. The link ID is used in distributed scheduling to identify resource requests and grants and it is transmitted as part of the CID in the generic MAC header in unicast massage.

MAC PDU formats

MAC PDUs consist of a generic MAC header and optional payload and CRC as depicted in *Figure 3.8*. The generic MAC header has a fixed-length. The payload consists of zero or more sub-headers and zero or more SDUs. Implementation of CRC is mandatory for SCs, OFDM and OFDMA PHY layers.

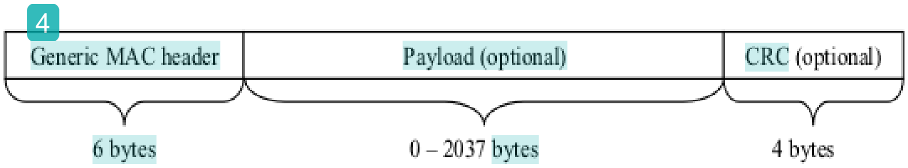

Figure 3.8 *MAC PDU format*

Generic MAC Header and Signalling Header

The generic MAC header is shown in *Figure 3.9*. It is used at the beginning of PDUs containing either MAC management messages or data from convergence sub-layer. ESF stands for extended sub-header field, CI for CRC indicator, EC for encryption control, EKS for encryption key sequence, HCS for header check sequence, and LEN for length. Type field indicates the sub-headers and special payload types present in the message payload. *Figure 3.9* shows the structure of generic MAC header. Lengths in bits of individual fields are given by the number in parentheses.

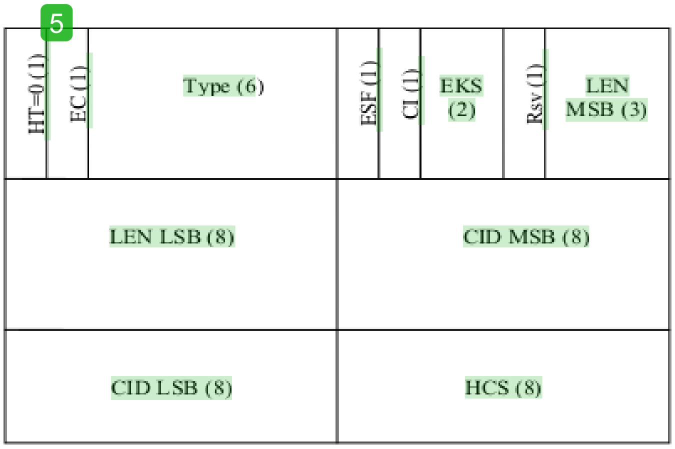

Figure 3.9 *Generic MAC headers*

In addition to the generic MAC header, another header for uplink exists, but it is not followed by any MAC PDU payload, and CRC. It is distinguished by the Header Type (HT) bit, which is set to 1. Two types of this header exist – type I and type II. The length of both of them is 6 bytes.

Header with HT=1 type I is used for many purposes, e.g.: for bandwidth request, PHY channel report, uplink sleep control, etc. Furthermore, header with HT=1 type II is used for feedback and *Multiple Input Multiple Output* (MIMO) channel feedback.

MAC Sub-headers

MAC sub-headers appear in the MAC PDU payload. Six types are defined. They include extended sub-header field, Mesh, fragmentation, FAST-FEEDBACK_Allocation, and grant management sub-headers, which are per-PDU sub-headers, and the packaging sub-header, which is per-SDU sub-header.

Only the Mesh sub-header is further used in evaluating the MAC overhead. Its length is 2 bytes [3] [4]

3.3.2 Service Specific Convergence Sub-layer (SS-CS)

The SS-CS resides on top of the MAC-CPS and performs accepting, classifying and processing of higher-layer protocol data units (PDUs), delivering CS PDUs to the appropriate MAC SAP and receiving CS PDUs from the peer entity.

Two CS types are specified: the *asynchronous transfer mode* (ATM) CS and the packet CS. The ATM CS accepts ATM cells and performs classification and, if provisioned, *payload header suppression* (PHS), and delivers them to MAC CPS. The packet CS has the same functions but it is used to process packet based protocols. Specific parts of packet CS are defined for Ethernet PDUs, VLAN PDUs, and IP PDUs with PHS either disabled or enabled [3] .

3.3.3 MAC Management Messages

In IEEE 802.16e, there are total 64 MAC management messages defined. These messages are carried in the payload of the MAC PDU. They begin with a type field and contain additional fields. Their structure is depicted in *Figure 3.10*. The payload structure of MAC management messages is specified by the standard separately for each message. The payload of the most common messages can be divided into two parts. The first part is a fixed part and the second part is created by type-length-value (TLV) tuples.

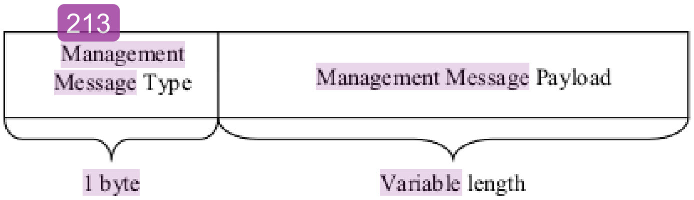

Figure 3.10 *MAC management message structure*

Fixed part

The fixed part of MAC management messages defined by the IEEE 802.16e standard contains fields with certain function that have their set position and size. As an example, the fixed beginning of the DL-MAP message used with OFDM PHY is illustrated in *Figure 3.11*.

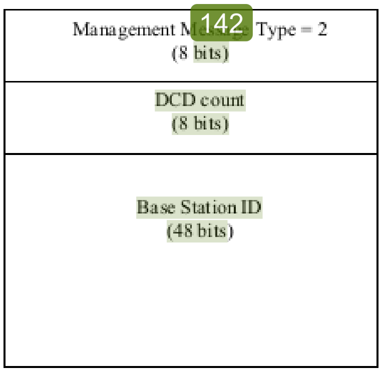

Figure 3.11 *Beginning of the fixed part of the DL-MAP message*

TLV part

The other way of encoding information elements into a MAC management message is by using type-length-value tuples (TLVs). A TLV encoding consists of Type, Length, and Value fields. If the length of the Value field is less or equal to 127 bytes, then the length of the Length field is one byte, the most significant bit (MSB) is set to 0 and the other 7 bits indicate the actual length of the value field in bytes.

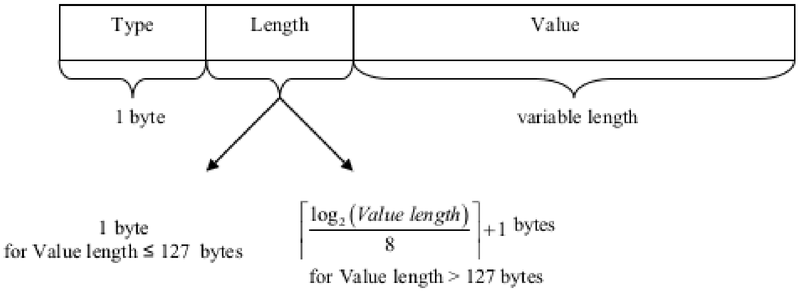

Figure 3.12 *TLV tuple structure*

If the length of the Value field is more than 127 bytes, then the length of the Length field is one byte more than what is actually used to indicate the length of the Value field in bytes, the MSB of the first byte is set to 1, the other 7 bits of the first byte of the Length field indicate the number of additional bytes of the Length field, and the remaining bytes of the Length field indicate the actual length of the Value field in bytes. *Figure 3.12* depicts the structure of TLV part of a MAC management message

Some of the TLV encodings are common to more MAC management messages while other is unique to certain message. The Type value of the common encodings starts at 149 and subsequent values are assigned in descending order. Individual encodings that are not PHY specific start at 1 and subsequent values are assigned in ascending order. Individual encodings that are PHY specific start at 150 and further ascend. Compound TLV encodings are also defined. These are TLV encodings which in their Value field contain another subset of TLVs [3] [4] .

3.4 Bandwidth Allocation

Increasing and decreasing bandwidth requirements are necessary for nearly every connection. The only exception is constant bit rate connections. Bandwidth of all other connections is allocated dynamically.

3.4.1 PMP

IEEE 802.16e defines numerous methods by which the SS can get the bandwidth request message to the BS. They comprise request/grant method, focused bandwidth requests, and CDMA bandwidth requests.

Request/grant Method

By using requests, SSs indicate to the BS that they need uplink bandwidth allocation. The bandwidth requests may be incremental or aggregate. When the BS receives an incremental bandwidth request, it adds the requested bandwidth to the current bandwidth need of the specified connection. If it receives an aggregate request, the BS replaces the current bandwidth need with the new one.

The BS, in accordance with the request, responds with a grant. The bandwidth requests reference individual connections while the bandwidth grants are addressed to the SS, not to individual connection of the SS. The process, by which BS allocates bandwidths to SSs, so that they can make bandwidth requests, is called polling.

Contention-based Bandwidth Requests

WirelessMAN-OFDM supports the mandatory mechanism of sending the bandwidth request header and the contention-based focused bandwidth requests. Furthermore, besides the mandatory mechanism, the wirelessMAN-OFDMA also supports the contention-based CDMA bandwidth requests.

The contention-based bandwidth requests are beyond the scope of this work, since the request/grant method is used for the overhead evaluation.

3.4.2 Mesh

Unlike the PMP mode, using the optional Mesh topology, there are no clearly separate downlink and uplink sub-frames, as can be seen in *Figure 3.5*. Each station is able to create direct communication links to several other stations instead of communicating only with the BS, as in PMP mode. The method of requesting bandwidth is dependent on the scheduling type selected.

Centralised Scheduling

Using centralised scheduling, the Mesh BS performs much of the same basic functions as a BS in PMP mode. The main difference is that there is no requirement for the SSs to have direct connection with the Mesh BS and those SSs can have direct links between each other.

The transmissions are defined by the Mesh BS, which collects request from the SSs. It then uses an algorithm to divide the frame proportionally according to the requests. These assignments are then transmitted to individual subscriber stations. Both the SS resource requests and the BS assignments are transmitted during the control sub-frame.

Centralised scheduling ensures that transmissions are coordinated to ensure collision-free scheduling over the links. This is typically more optimal than the distributed scheduling method for traffic streams, which persist over a duration that is greater than the cycle to relay new resource requests and distribute the new schedule.

The requests are transmitted up the routing tree of the Mesh network to the Mesh BS, which is described in the MSH-CSCF MAC management message. The grants then travel in the opposite direction from the Mesh BS to more distant hops. It means that all nodes transmit the grants, except those that have no children. The same way all nodes except the Mesh BS transmit the requests. An example of requests and grants flow in the routing tree is depicted in *Figure 3.13* and *Figure 3.14*.

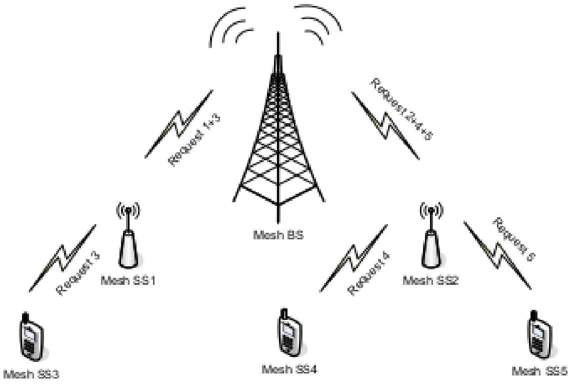

Figure 3.13 *Flow of requests scenario in a Mesh routing tree*

The requests and grants are distributed using MAC management messages MSH-CSCH (Mesh – Centralized Scheduling). The actual assigned bandwidth is calculated from a flow assignment in MSH-CSCH. The validity period of the CSCH schedule is limited by the number of frames during which a new schedule is being made. This schedule is created by means of the above described mechanism.

The received schedule also includes the information when it shall be transmitted further down the tree, designation of the frame when the last node in the tree will receive this schedule, and the original transmission time of the schedule by the Mesh BS.

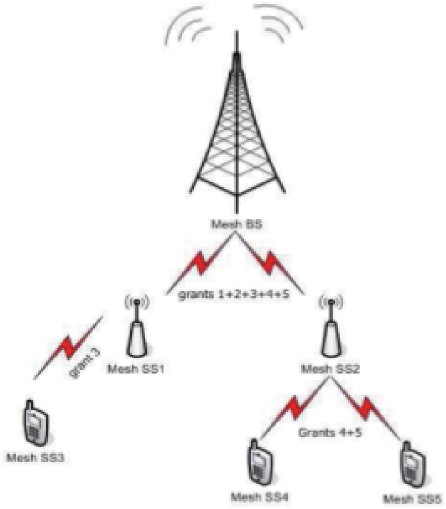

Figure 3.14 *Flow of grants scenarios in a Mesh routing tree*

Distributed Scheduling

Distributed scheduling is different from the centralized since it does not rely on the operation of a Mesh BS. The transmissions are scheduled without using any BS. Distributed scheduling can be divided into *coordinated* and *uncoordinated* distributed scheduling.

In the coordinated distributed scheduling mode, all the stations (Mesh BS and Mesh SSs) coordinate their transmissions in their extended neighbourhood as depicted in *Figure 3.15*. It uses a part of or the entire portion of the control sub-frame to transmit the schedule and proposed schedule changes on a PMP basis to all its neighbours. All neighbours receive the same schedule transmission if they are on a common channel.

The other type of distributed scheduling is the uncoordinated distributed scheduling. It can be used for fast, ad-hoc setup of schedules on a link-by-link basis. Only two nodes which directly exchange requests and grants are involved in the scheduling. Still, they have to ensure that the requests, grants and resulting data transmissions do not cause collisions with data and control traffic scheduled by the coordinated distributed nor the centralized scheduling methods. The MSH-DSCH

MAC management messages that carry uncoordinated distributed scheduling requests and grants is scheduled in the data sub-frame and may collide. On the other hand in the coordinated case, the MSH-DSCH messages are transmitted during the control sub-frame in a collision free manner.

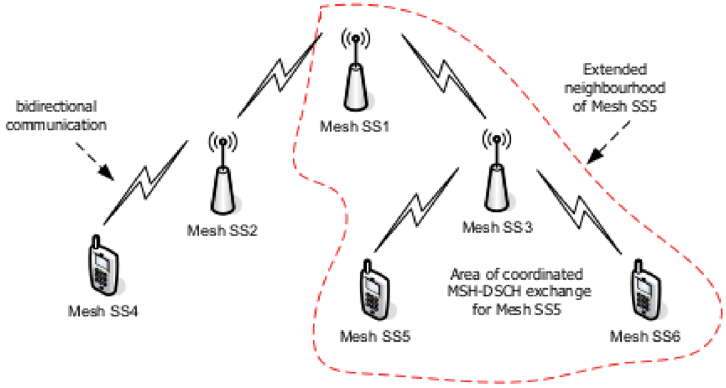

Figure 3.15 *Illustration of coordinated distributed scheduling*

Both distributed scheduling methods employ a three-way handshake mechanism as shown in *Figure 3.16. The MSH-DSCH: Request* is made according to *MSH-DSCH: Availabilities*, which indicate potential slots for replies and actual schedule. . Then *MSH-DSCH: Grant* is sent as a response indicating a subset of the suggested availabilities. The last step of the handshake is a copy of the MSH-DSCH: Grant message sent by the original requester as an acknowledgement [3]

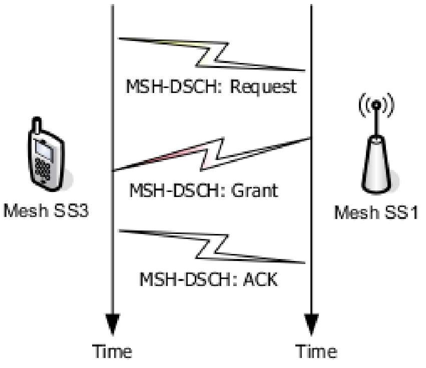

Figure 3.16 *Distributed scheduling three-way handshake*

Chapter 4

MAC Management Messages - Overhead and Efficiency

4.1 Introduction

The *Worldwide Inter-operability for Microwave Access* (WiMAX) is a telecommunication technology based on IEEE802.16 standard. WiMAX network overcome some of the limitations of WiFi (IEEE 802.11) network, e.g. limited range or insufficient Quality of Service support, and also introduce full mobility. Using their conjunction it is possible to create a solution for metropolitan and local area networks.

WiMAX supports two types of network topologies i.e. Point to Multipoint (PMP) and Mesh. In PMP topology, the link connection is only between *Base Station* (BS) and *Subscriber Station* (SS) or *Mobile Station* (MS). Mesh topology, on the other hand, does not limit the link connection between BS – SS/MS only, but also support the connection among SSs/MSs. The SS/MS which have relay capability may be act as *Relay Station* (RS). A connection is required by the MAC layer for the purpose of transporting *Medium Access Control* (MAC) management messages.

The overhead caused by transporting the MAC messages throughout the network is an important performance indicator, because it significantly influences the system throughput. It is interesting to make an analysis how the MAC efficiency is dependent on the physical and logical setups of the network. Performance of a networking protocol is commonly evaluated by means of the net throughput, especially on MAC layer and delay.

The main objective of this chapter is to present an evaluation of the overhead on the MAC management messages of IEEE 802.16. With regards to all previous works mainly in [15] and [16] as our references and previous chapters as theoretical background, the corresponding derivations and computations are carried out. The overhead and efficiency analysis between Point-to-Multipoint (PMP) and Mesh modes is performed independently since each topology used the different version of the standard. The PMP mode is based on 802.16e (WirelessMAN-OFDMA), on the other hand, the OFDM physical layer using TDD specified in 802.16d (WirelessMAN-OFDM) was chosen in order to be able to study the Mesh topology. Several inevitable simplifications need to be done, since our task is quite all-embracing, but still bearing in mind the main task.

4.2 Topology Scenario

4.2.1 Point to Multipoint (PMP)

In PMP topology, a central BS operates with a sectorised antenna which capable of handling multiple independent sectors simultaneously. Within a given frequency channel and antenna sector, all stations receive the same transmission. The SS communicate only with the BS and not with each other. This scenario is shown in *Figure 4.1*.

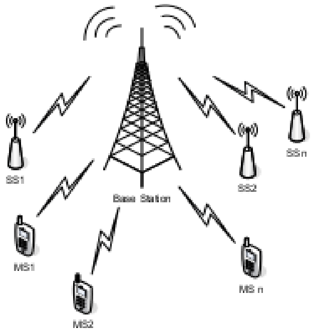

Figure 4.1 *Point to Multipoint topology*

In downlink (DL) direction, the BS is the only transmitter, so that it does not have to coordinate with other stations, except for the overall time division duplexing (TDD) when time is divided into uplink and downlink transmission periods. The broadcast DL-MAP MAC management message determines which part of the downlink transmission is intended for an individual SS/MS. If the DL-MAP does not explicitly indicate the allocation, all SSs/MSs shall listen to the transmission. They check the CIDs in the received PDUs and keep only those addressed to them.

In the uplink direction, SSs/MSs transmit on a demand basis. SS/MS may have continuing rights to transmit, or the rights may be granted by the BS after receipt of a request. Four different types of uplink scheduling mechanisms are defined to handle delay and bandwidth requirements of each user application. They are implemented using unsolicited bandwidth grants, polling, and contention procedures. The system performance can be optimised by combining these bandwidth allocation techniques. The appropriate scheduling method is used according to specific application. In general, data applications are delay tolerant, but real-time applications like voice and video are much stricter in delay requirements, therefore polling instead of contention is used for real-time applications.

The MAC operates in a connection-oriented mode, therefore after the registration of SS/MS, the connections are associated with service flows to provide a reference against which to request bandwidth. Service flows provide a mechanism for uplink and downlink quality of service (QoS) management. In addition, bandwidth is granted by the BS to an SS/MS as an aggregate of grants in response to per connection requests from the SS/MS. Once the connections are established, they may be maintained during their existence, and may be terminated. The maintenance requirements depend on the type of selected service.

4.2.2 Mesh

In case of mesh topology, the traffic can be routed through other SSs/RSs and can occur between SSs/RSs. This can be done on the basis of equality using distributed scheduling, or using a mesh BS as the superior (centralized scheduling), or combination of both. A mesh BS is a system with direct connection to backhaul services outside the mesh network. Uplink is defined as traffic in the direction of the mesh BS and downlink as traffic away from mesh BS. The stations in which a node has direct links are called neighbours and form a (one-hop) neighbourhood.

An extended neighbourhood contains all the neighbours of the neighbourhood. An example constellation of mesh SSs with a mesh BS, where neighbourhood and extended neighbourhood of mesh SS 1 are shown in *Figure 4.2*. Unlike the PMP mode, in mesh topology there are no clearly separate DL and UL sub-frames. Each station is able to create direct communication links to several other stations instead of communicating only with the BS. The method of requesting bandwidth is dependent on the scheduling type selected.

Distributed Scheduling

There are two scheduling mechanisms that would be implemented, i.e. distributed and centralised. In distributed scheduling, all nodes including the Mesh BS shall coordinate their transmissions in their two-hop neighbourhood and shall broadcast their schedules to their neighbours. The schedule may also be established by direct uncoordinated requests and grants between two nodes, which is called uncoordinated distributed scheduling. Nodes have to ensure that their transmissions do not cause collisions in the two-hop neighbourhood. For both uplink and downlink, the mechanism of determining the schedule is the same.

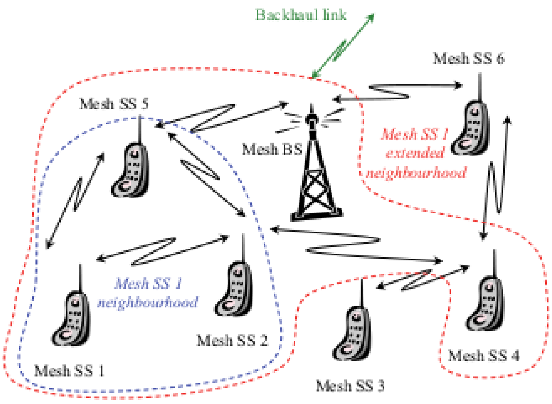

Figure 4.2 *Mesh topology*

Centralised Scheduling

In addition, when the centralised scheduling is implemented, the Mesh BS shall gather resource requests from all the Mesh SSs within a certain hop range. It shall determine the amount of granted resources for each link in the network and communicate these grants to all Mesh SSs within the hop range. The actual schedule is computed by an individual SS based on the grant messages.

All communications are in the context of a link between two nodes. One link shall be used for all the data transmissions between the two nodes. QoS is provisioned over links on a message-by-message basis. Each unicast message has service parameters in the header [3]

The Mesh specification included in IEEE 802.16j is promising network architecture, however it is not utilised very often. The Mesh appears to be the most expensive architecture to be built, because each node requires a router. At the same time it is the most robust because each node has multiple pathways available to it. The Mesh may also eliminate the need for backhaul, which in many cases is the biggest cost in setting up a wireless broadband network [24] .

4.3 Overhead Evaluation and Efficiency Analysis

The MAC overhead can be evaluated by means of determining the efficiency of the MAC layer. According to [15] and [16] the MAC efficiency can be defined as the ratio of the net throughput on MAC layer and the throughput per OFDM symbol as shown in *equation (1)*:

$$\eta = \frac{\Theta_{MAC\text{-}net}}{\Theta_{OFDM\ symbol}} \tag{1}$$

The net throughput on the MAC layer is defined by *equation (2)*. It is the ratio of the total number of payload bits, i.e. without all MAC overhead, in a frame to the frame duration $\boldsymbol{T_{frame}}$.

$$\Theta_{MAC\text{-}net} = \frac{\sum payload\ bits}{T_{frame}} \tag{2}$$

The throughput of an OFDM symbol is given by:

$$data\ rate = \frac{number\ of\ uncoded\ data\ bits\ per\ OFDM\ symbol}{OFDM\ symbol\ duration} \tag{3}$$

The throughput of an OFDM symbol in a more symbolic way can be calculated as:

$$\Theta_{OFDM\ symbol} = \frac{(N_{used} - N_{pilot}) \cdot N_{cbps} \cdot C}{T_{symbol}} \tag{4}$$

where N_{used} is the number of used OFDM subcarriers, N_{pilot} is the number of OFDM pilot subcarriers, N_{cbps} is the number of coded bits per allocated symbol (e.g. $N_{cbps} = 6$ for 64-QAM) and C is the code rate.

The number of uncoded bytes per symbol (BpS) is given as:

$$BpS = \frac{(N_{used} - N_{pilot}) \cdot N_{cbps} \cdot C}{8} \tag{5}$$

Higher modulation used for individual OFDM subcarriers, which results in higher N_{cbps}, together with higher code rate affect both $\Theta_{MAC\ net}$ and $\Theta_{OFDM\ symbol}$. Therefore we propose to evaluate the MAC layer efficiency as the ratio of OFDM symbols used for payload transmission in a frame to the total number of OFDM symbols in a frame as given in *equation (6)*. Letter L in the following equation always means length expressed as a number of OFDM symbols.

$$\eta = \frac{L_{net\ payload}}{L_{frame}} \tag{6}$$

The number of symbols in a frame does not depend on the modulation or coding, as defined by equation (7).

$$L_{frame} = \left\lfloor \frac{T_{frame}}{T_{symbol}} \right\rfloor \tag{7}$$

4.3.1 MAC Efficiency in PMP Topology

In this section the MAC layer efficiency of the PMP topology is assessed. Our goal is to express the $L_{net\ payload}$ value and put it into *equation (6)*. The uplink sub-frame consists of symbols used for ranging (L_{RNG}) and bandwidth requests (L_{BW}) and then of symbols containing UL physical layer PDUs. The length of the frame in OFDM symbols, when assuming one UL PHY PDU per subscriber station, can be written as:

$$\begin{aligned} L_{frame} &= L_{DL\ subframe} + L_{UL\ subframe} = \\ &= L_{DL\ PHY\ PDU} + L_{RNG} + L_{BW} + \sum_{i=1}^{N_{SS}} L_{UL\ PHY\ PDU\ i} \end{aligned} \qquad (8)$$

Downlink Subframe

The DL sub-frame contains only one DL PHY PDU, which consists of the two-symbol long preamble and one-symbol Frame Control Header (FCH), then followed by the DL bursts. The DL burst #1 is different from other DL bursts (if present), since it contains broadcast MAC messages. These broadcast messages comprise DL-MAP, UL-MAP, DCD and UCD messages. *Figure 4.3* depict the structure of those messages. Their presence means less space for payload transmission, which means that longer broadcast messages decrease the MAC layer efficiency. The overhead in bytes introduced by the broadcast messages when assuming that all of them are present in the frame can be calculated as:

$$OH_{DL\ burst\ \#1} = OH_{DL-MAP} + OH_{UL-MAP} + OH_{DCD} + OH_{UCD} + 4 \cdot OH_{MAC\ PDU} \qquad (9)$$

$OH_{MAC\ PDU}$ from *equation (9)* is equal to 10 bytes. Six bytes are taken by the Generic MAC header and four bytes by CRC, which is mandatory for OFDM physical layer. The lengths of individual MAC management messages will follow.

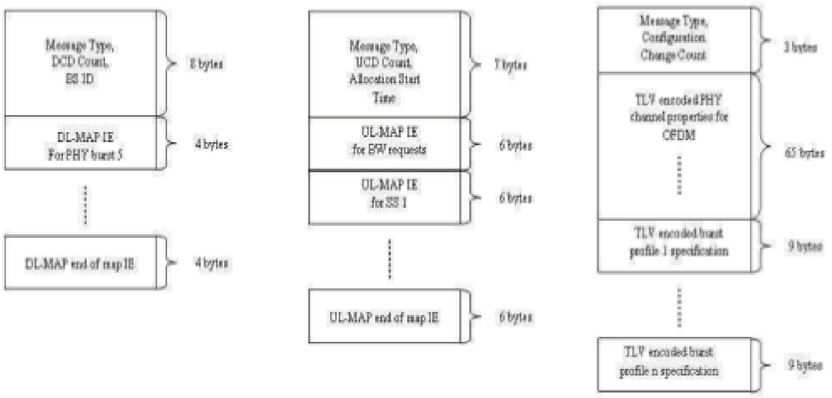

Figure 4.3 *Message structure: DL-MAP (left), UL-MAP (middle) and DCD/UCD (right)*

For our purposes it is necessary to express the length of the overhead in DL burst #1 in OFDM symbols, which can be done by using *equation (10)*, where *BpS* is the number of uncoded bytes per OFDM symbol, as specified by *equation (5)*.

$$L_{DL\ burst\ \#1} = \frac{OH_{DL\ burst\ \#1}}{BpS} \tag{10}$$

The resulting number of bytes available for transmission of data MAC PDUs can be calculated using *equation (11)*. L_{LP} (long preamble) and L_{FCH} are 2 symbols and 1 symbol respectively.

$$L_{DL\ data} = L_{DL\ subframe} - L_{LP} - L_{FCH} - L_{DL\ burst\ \#1} \tag{11}$$

DL-MAP MAC Management Message

The DL-MAP message defines the access to the downlink information. It is a fixed part that is created by 8 bytes at the beginning. After this fixed part, several information elements (IEs) defining the fifth and further DL bursts are present. The first four DL burst are specified in the DLFP burst. Another IE is at the end of the DL-MAP message. Each of these IEs is 4 bytes long (see Figure 4.3). The overhead in bytes introduced by the DL-MAP message is described by *equation 9.1*. $N_{DL\ burst}$ is the number of downlink bursts in the frame.

$$OH_{DL-MAP} = 8 + 4 \cdot \left(N_{DL\ burst} - 3 \right) \tag{9.1}$$

UL-MAP MAC Management Message

The UL-MAP message allocates access to the uplink channel. The length of the fixed part is for this message 7 bytes. The following IEs are 6 bytes long. One IE is used for every UL burst, i.e. for every subscriber station (see Figure 4.3). The resulting overhead in bytes can be found in *equation (9.2)*. N_{SS} is the number of transmitting subscriber stations.

$$OH_{UL-MAP} = 7 + 6 \cdot \left(N_{SS} + 2 \right) \tag{9.2}$$

DCD MAC Management Message

The DCD message is transmitted periodically by the MBS to define the characteristics of a downlink physical channel. Three bytes construct the fixed part of the message, the rest of the message is formed by the TLV tuples. Numerous TLV encodings are defined to describe the downlink channel properties and the burst profiles. Each burst profile definition occupies 9 bytes (see Figure 4.3).

The resulting overhead caused by the DCD message is defined by *equation (9.3)*. $N_{DL\ burst\ profiles}$ represents the number of downlink burst profiles used.

$$OH_{DCD} = 68 + 9 \cdot N_{DL\ burst\ profiles} \tag{9.3}$$

UCD MAC Management Message

The UCD message is similar to the DCD, but it describes the uplink physical channel. The fixed part comprises 6 bytes. TLV part without definition of burst profiles is 32 bytes long and each burst profile used occupies additional 12 bytes (see Figure 4.3) [3] The UCD overhead can be evaluated as in *equation (9.4)*. $N_{UL\ burst\ profiles}$ represents the number of uplink burst profiles used.

$$OH_{UCD} = 38 + 12 \cdot N_{DL\ burst\ profiles} \tag{9.4}$$

Uplink sub-frame

The uplink sub-frame contains slots for ranging, which are mainly used during the initial network entry or re-entry during handover. The number of bytes used for bandwidth requests can be calculated according to *equation (12)*. N_{SS} is the number of subscriber stations. We assume that every SS sends one BW request every frame.

$$OH_{BW} = N_{SS} \cdot OH_{MAC\ PDU} \tag{12}$$

Expressed in OFDM symbols, *equation (12)* can be written as:

$$L_{BW} = \frac{N_{SS} \cdot OH_{MAC\ PDU}}{BpS} \tag{13}$$

We obtain the resulting number of OFDM symbols available for transmission of data MAC PDUs from the following equation:

$$L_{UL\ data} = L_{UL\ subframe} - L_{BW} - N_{SS} \cdot L_{SP} \tag{14}$$

4.3.2 MAC Efficiency in Mesh Topology

Network topologies using the mesh mode can be quite varying. The mesh SS may have direct links between each other and traffic for other mesh SSs can be routed across these links. There are innumerable possibilities how the topology can look like.

In order to evaluate the MAC overhead, a particular topological model is needed, for this case we propose using a tree topology since it simply provides the multi-hop environment. Each node in the tree, except of the last level of nodes that have the highest hop count from the root node, has $\boldsymbol{a}$ children. The number of hops from the root node to another node is marked as $\boldsymbol{h}$. The maximum number of hops is designated $\boldsymbol{h}_{max}$. *Figure 4.4* shows the proposed tree topology.

Subsequently, based on the topology proposed, we need to make a traffic assumption. Let's define that only the root node, the mesh BS, is connected to the core network and the end-to-end connections occurs between the mesh SSs and some unspecified nodes outside this network and not between individual mesh SSs. It means that data for nodes in the lower parts of the tree is routed through SSs on higher levels. The mesh frame of the message does not have clearly separated downlink and uplink, however it consists of the control sub-frame and the data sub-frame. The Schedule control sub-frame contains distributed and centralized scheduling messages.

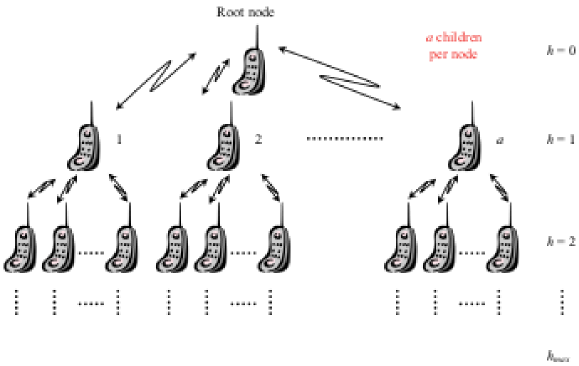

Figure 4.4 Tree-like scenario in Mesh

Centralised Scheduling (CS)

The length of the control sub-frame using CS in OFDM symbols depends on the number and length of CS bursts. It has to be a multiple of 7 OFDM symbols. The length of control sub-frame is given in *equation (15)*.

$$L_{control\ subframe} = 7 \cdot \left\lceil \frac{a \cdot L_{CSCH}}{7} \right\rceil \tag{15}$$

We assume that the requests are collected from the lower levels and passed on to the mesh BS (refer to *Figure 4.4*). Then the mesh BS responds with the appropriate grants. The intermediate mesh SSs take their part of the grants and forward the rest down the tree. The requests and grants messages appear in equal quantity.

The number of request bursts in a frame is equal to the number of children per node, i.e. a. Number of bursts does not depend on the hop count h from the root node, but their size does. The same stands for the number of the grant bursts. There are always a grants, one for each of node's children. Thus, a frame contains either a bursts with requests from the children or a bursts containing grants for them.

The L_{CSCH} parameter can be evaluated using *equation (16)*. L_{CSCH} consists of the MSH-CSCH MAC management message, the long preamble (L_{LP}) and one guard symbol (L_{guard}). It is transmitted always using the QPSK 1/2 modulation/coding, which means 24 uncoded bytes per OFDM symbol.

$$L_{CSCH} = \frac{OH_{MSH-CSCH} + OH_{MAC\ PDU\ Mesh}}{BpS_{QPSK1/2}} + L_{LP} + L_{guard} \qquad (16)$$

The overhead of MAC PDU for Mesh topology $OH_{MAC\ PDU\ Mesh} = 12$ bytes. It is two bytes longer than for PMP, because it contains the mesh sub-header. Overhead in bytes caused by the MSH-CSCH is specified as follow.

MSH-CSCH MAC Management Message

The mesh CS message, MSH-CSCH, is used by the mesh BS to broadcast the centralized schedule. All nodes with hop count lower than specified have to forward this message to their neighbours with a higher hop count. In the calculation we assume that the maximum hop count for forwarding is the same as the $\boldsymbol{h_{max}}$ parameter. The MSH-CSCH message is also used by the mesh SSs to request bandwidth from the mesh BS. The nodes report individual traffic demand requests of each child node further from the mesh BS, as well.

The message has a fixed part which in total has 4 bytes. The information carried by this part includes e.g. *Message Type, Grant/Request Flag,* and *Configuration Sequence Number* or *NumFlowEntries* fields. The *Grant/Request Flag* indicates whether MSH-CSCH serves as a grant or a request, *Configuration Sequence Number* refers to the configuration number in the MSH-CSCF message. *NumFlowEntries* specifies the number of flow entries which describe individual demands of the lower nodes in the routing tree. *NumFlowEntries* in *equation (17)* is denoted as $\boldsymbol{N_{flow}}$. It can be calculated as:

$$N_{flow}(h) = \sum_{i=0}^{h_{max}-h} a^{i} \qquad (17)$$

$N_{flow}(h)$ expresses the number of lower nodes which are found on a branch under node on level h – 1. The parameter ***h*** means that the number of flow entries is calculated for a link with position ***h*** from the root.

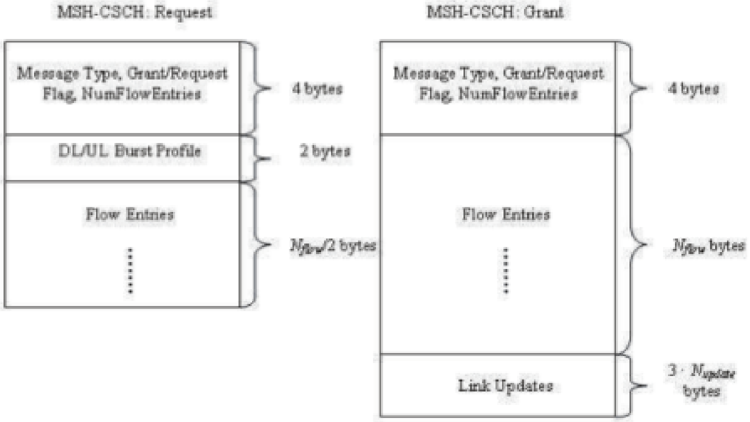

Figure 4.5 *MSC-CSCH message structures*

If the MSH-CSCH message serves as a grant, the fixed part includes another 2 bytes used for designation of the neighbour that define the uplink and downlink burst profiles. Then the part dependent on the number of flows follows. For a grant message each flow entry occupies 1 byte, for a request message half of a byte. For grants, another part specifying link updates is transmitted. It is used in case when the number of changes is too low to trigger a MSH-CSCF broadcast [3]

The structure of the MSH-CSCH: Request and MSH-CSCH: Grant messages can be seen in *Figure 4.5*. As the requests and grants appear in the same ratio, so the corresponding overhead of MSH-CSCH: Request; and MSH-CSCH: Grant messages are evaluated in as.

$$OH_{MSH-CSCH} = 5 + \frac{3}{4} N_{flow} \qquad (18)$$

Distributed Scheduling (DS)

Distributed Scheduling consist of coordinated and uncoordinated scheduling. In this work we concern only coordinated-DS. The uncoordinated type is mainly suitable for fast link setups, which is out of our concern. Using the DS, the length of the control sub-frame can be written as in *equation (19)*. There is a difference in the number of scheduling bursts in a frame. We assume that the chosen node transmits one scheduling burst of length $L_{DSCH\ high}$ and every child node transmits one scheduling burst of length $L_{DSCH\ low}$.

$$L_{control\ subframe} = 7 \cdot \left\lceil \frac{a \cdot L_{DSCH\ low} + L_{DSCH\ high}}{7} \right\rceil \qquad (19)$$

The lengths of a DS burst $L_{DSCH\ low}$ and $L_{DSCH\ high}$ can be calculated as follow:

$$L_{DSCH} = \left\lceil \frac{OH_{MSH-DSCH} + OH_{MAC\ PDU\ Mesh}}{BpS_{QPSK1/2}} \right\rceil + L_{LP} + L_{guard} \qquad (20)$$

These two lengths differ from each other only because of different number of neighbours. Each burst consists of the mesh DS message, MSH-DSCH, which has the long preamble (L_{LP}) and one guard symbol (L_{guard}). It is again transmitted using the QPSK 1/2 modulation/coding, which means 24 uncoded bytes per OFDM symbol.

MSH-DSCH MAC Management Message

The MSH-DSCH, carried in the DS bursts, is transmitted at a regular interval to inform all the neighbours of the schedule of the transmitting station. It is used to convey resource requests (MSH-DSCH: Request) and grants (MSH-DSCH: Grant) to the neighbours and also to inform the neighbours about available free resources (MSH-DSCH: Availability) that can be used to send grants. The average overhead introduced by MSH-DSCH messages is defined by *equation (21)* as follow:

$$OH_{MSH-DSCH} = 6 + 3 \cdot (N_{neigh} + 1) + 4\frac{1}{8} \cdot (N_{ext\ neigh} + 1) \qquad (21)$$

4.3.3 Total Efficiency

By using *equations (8), (11)* and *(14)* it is possible to obtain the total number of OFDM symbols available for MAC PDUs as given by *equation (22)*.

$$L_{data} = L_{frame} - L_{LP} - L_{FCH} - L_{DL\ burst\ \#1} - L_{BW} - N_{SS} \cdot L_{SP} \qquad (22)$$

Another important overhead introduced by the MAC layer are the generic MAC headers and CRCs of the data PDUs. We suppose that the frame is fully used, the number of MAC PDUs ($N_{MAC\ PDU}$), which without considering fragmentation fit into one frame, is given by *equation (23)*:

$$N_{MAC\ PDU} = \left\lfloor \frac{L_{data}}{k} \right\rfloor \tag{23}$$

where k is the length including the generic MAC header and CRC of the MAC PDU in bytes. Applicable lengths are from 11 bytes (1 byte of payload) to 2047 bytes. The maximum length is restricted by the capacity of the Length field of the generic MAC header, which is 11 bits. Using the number of MAC PDUs in a frame, the number of OFDM symbols utilized for the data MAC PDUs overhead can be calculated, as given by *equation (24)*.

$$L_{data\ MAC\ PDU\ OH} = \frac{N_{MAC\ PDU} \cdot 10}{BpS} \tag{24}$$

The number of OFDM symbols usable for the payload of the data MAC PDUs – SDUs from higher layers is given by *equation (25)*:

$$L_{net\ payload} = L_{data} - L_{data\ MAC\ PDU\ OH} \tag{25}$$

Using the *equation 6*, efficiency on the MAC layer can be finally calculated for both scenario PMP and Mesh.

4.4 Results in MAC Efficiency

4.4.1 PMP Topology

According to the standard, four primitive parameters are defined to characterize the OFDM symbol:

- BW – nominal channel bandwidth,
- N_{used} – number of used subcarriers,
- n – sampling factor, in conjunction with BW and N_{used} determines the subcarrier spacing and the useful symbol time,

- G – ratio of CP time to useful time.

Using these primitive parameters other derived parameters are identified:

- N_{FFT} – smallest power of two grater than N_{used},
- Sampling frequency; $F_s = \lfloor n \cdot BW / 8000 \rfloor \cdot 8000$,
- Subcarrier spacing; $\Delta f = F_s / N_{FFT}$,
- Useful symbol time; $T_b = 1/\Delta f$,
- CP Time ; $T_g = G \cdot T_b$,
- OFDM symbol time; $T_s = T_b + T_g$,
- Sampling time; T_b / N_{FFT} .

Possible values of G are 1/4, 1/8, 1/16 and 1/32. The sampling factor has different values for bandwidths that are being multiples of different frequencies.

N_{used} is specified as 200 which mean that N_{FFT} is 256. Therefore the number of lower frequency guard subcarriers is equal to 28, the number of higher frequency guard subcarriers is 27. Thus, together with the DC carrier, the number of null subcarriers is 56 [4] . After subtracting 8 pilot subcarriers, there are 192 subcarriers available for data transmission.

The numerical values of the OFDM parameters, which are used to obtain the resulting efficiencies and haven't been presented before are T_{frame} and T_{symbol}. T_{frame} is defined by the standard IEEE802.16e-2005 and have values from 2.5 ms to 20 ms. The third highest value, T_{frame} = 10 ms, is chosen for the calculations. T_{symbol} can be calculated using *equation (26)*, with substituting the following: G = 1/4, BW = 20 MHz and n = 144/125. These values are allowed by the standard for license-exempt bands. Bandwidth of 20 MHz and the ratio of the cyclic prefix to the useful symbol time are both the largest allowed. The final symbol duration is then 13.89 µs.

$$\begin{aligned} T_s &= T_b + T_g = (1/\Delta f) + G \cdot T_b = (1/\Delta f) \cdot (1+G) = \\ &= (N_{FFT} / F_s) \cdot (1+G) = \left[N_{FFT} / (\lfloor n \cdot BW / 8000 \rfloor \cdot 8000) \right] \cdot (1+G) \end{aligned} \qquad (26)$$

Besides the main parameter, which is the number of subscriber stations (***N***N_{ss}), other variables are chosen for the evaluated efficiency. These are the *length of the* *data MAC PDUs* ***(k)***, *modulation/coding used*, and *number of burst profiles* ***(BPs)***.

MAC PDU length

The length of the data MAC PDUs plays an important role for the efficiency value. The shorter the PDU is, the bigger part of it is occupied by the generic MAC header and CRC bytes, which for lower lengths significantly decreases the efficiency. The modulation QPSK 1/2 is assumed in the simulation. 1 DL burst profile and 1 UL burst profile is also considered.

In *Figure 4.6*, results for different number of subscriber stations (N_{ss}) are shown. It can be seen that the efficiency rises rapidly for smaller ***k*** values (approx. up to 100 bytes). After this point, the efficiency increases only gradually and for ***k*** values of 1000 bytes and more it is almost constant. At the same time it can be seen that for a certain MAC PDU length the largest number of subscriber stations has the lowest efficiency.

For higher number of subscriber stations, it obviously comes into effect for a lower initial PDU length. Nevertheless, the higher number of subscriber stations means lower efficiency.

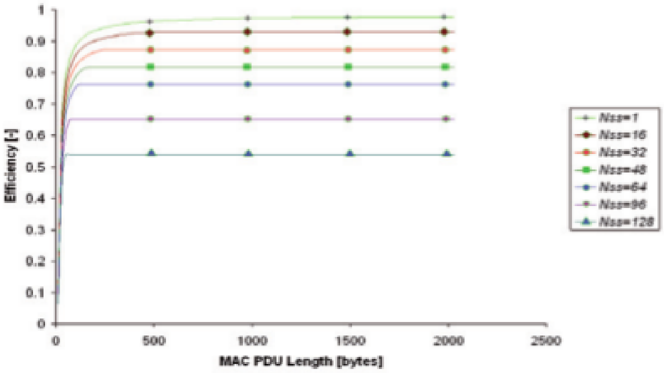

Figure 4.6 *MAC efficiency in PMP – paramater PDU length, parameter number of subscriber station* (N_{ss})

Various modulations and coding

The influence of modulation and coding is presented when using 1 DL burst profile, 1 UL burst profile and fixing the MAC PDU length to 1024 bytes. When assuming this length or higher, the influence of the number of subscriber stations is much more noticeable than the influence of the PDU length.

Based on *Table 3.2*, the efficiencies are calculated for six most common modulations/coding of them, omitting only the most robust BPSK 1/2 modulation. The modulation/coding types are numbered as in *Table 3.2*.

Figure 4.7 shows that higher modulations usage means lower MAC overhead. That is due to the fact that the PMP broadcast messages don't have to be transmitted by the most robust modulation/coding. When a modulation/coding with a higher, number of bytes per symbol is used the messages occupy a smaller portion of the PMP frame. For a higher number of subscriber stations the difference in efficiency for different modulations increases, because the more SSs are connected, the more OFDM symbols are used to send them and the more is consequently saved.

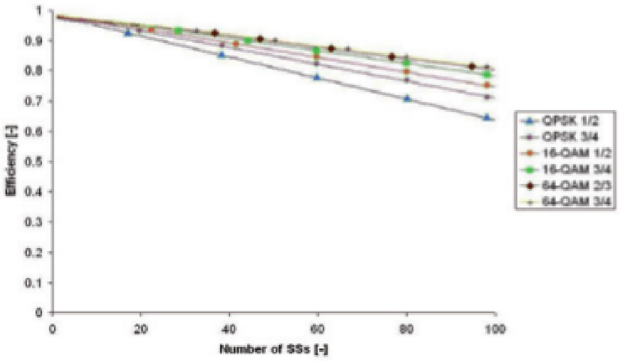

Figure 4.7 *MAC efficiency in PMP – parameter modulation type.*

It is obvious that lower modulations mean lower efficiency variations when assuming different number of subscriber stations. The higher modulation is able to keep the efficiency high. That is caused by the fact that higher modulations slightly compensate the influence of growing broadcast messages.

Various number of burst profiles

Another parameter, which affects performance on the MAC layer, is the number of burst profiles (BP). We assume that the MAC PDU length is 1024 bytes and more uplink and downlink burst profiles are specified. For UL/DL burst profile 1 modulation/coding 1 is used, for UL/DL burst profile 2 modulation/coding 2 is used, etc. Maximum number of burst profiles is 6, since 6 most common modulations are used.

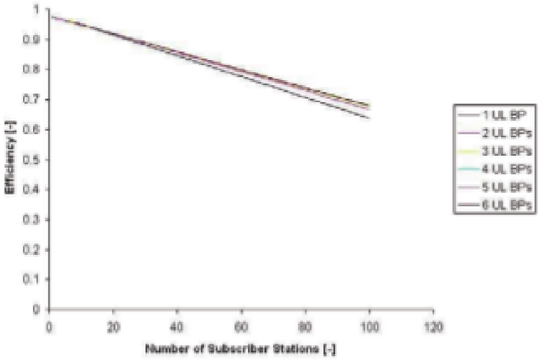

Figure 4.8 *MAC efficiency – various number of subscriber stations (**N_{ss}**), parameter burst profiles (**BPs**).*

Since the broadcast messages are assumed to be always transmitted using QPSK 1/2 modulation, using more burst profiles has only the influence of decreasing the efficiency because of additional overhead to define these BPs. This extra overhead is relatively small (approx. 6% between 1 BP and 6 BPs).

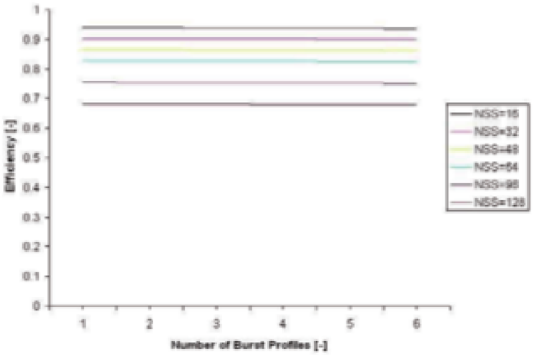

Figure 4.9 *MAC efficiency in PMP – various number of burst profiles, parameter number of subscriber stations (**N_{SS}**).*

Figure 4.8 shows that the lower number of burst profile gives the lowest efficiency when N_{ss} is higher. On the other hand, *Figure 4.9* depicts the fact that the BPs has a minor impact on MAC efficiency for particular number of subscriber stations. When the network has a lower number of subscriber stations then they will have a better efficiency.

4.4.2 Mesh Topology

The equal values of additional parameters in *section 4.4.1* were taken for the analysis of MAC efficiency in mesh topology. In the same occasion as in PMP topology, *length of the data MAC PDUs*, *modulation/coding used*, and *number of burst profiles* are considered as the evaluated parameters for efficiency.

First, let's discuss the results for the shortest and longest MAC PDUs allowed and for several lengths in between, as shown in *Figure 4.10*. It can be seen that both CS (top) and DS (bottom) have a quite similar characteristics since the efficiency is decrease when the length of PDU is decreased. For CS, the efficiency decrease linearly, however, overhead per SS is much higher. When assuming e.g. 100 SSs, the MAC layer efficiency is only around 0.3. On the other hand, the DS can support only up to 14 SSs with the efficiency lower than CS. It is caused by the fact that all SSs are members of one extended neighbourhood and have to coordinate their transmission with each other, using the MAC management messages.

Next results discussion, as shown in *Figure 4.11*, are about the MAC efficiency where the CS (top) and DS (bottom) also have similar characteristics when modulations took part as the overhead parameter. For CS, since the control sub-frame of the mesh frame is defined to always use QPSK 1/2 modulation/coding, only the data sub-frame can be transmitted with different modulation/coding setting. Higher modulation enables more MAC PDUs to fit into one frame.

However, the efficiency remains the same, because the ratio between the MAC PDU overhead and a given PDU length is constant, e.g. when assuming k = 1024 bytes, the efficiency stays the same for all possible modulations. In this analysis, the

PDU length is shortened for higher number of SSs. For higher modulation, limiting the length for higher number of SSs give effect the lower efficiency.

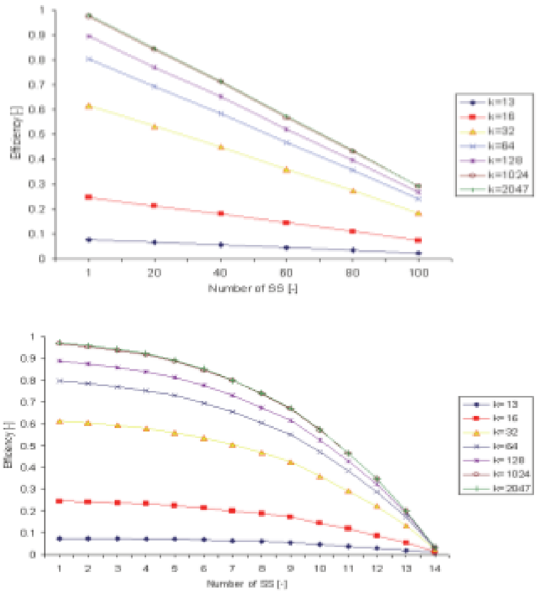

Figure 4.10 *MAC message efficiency in mesh, Centralised Scheduling (top) and Distributed Scheduling (bottom), various PDU lengths (**k** parameter).*

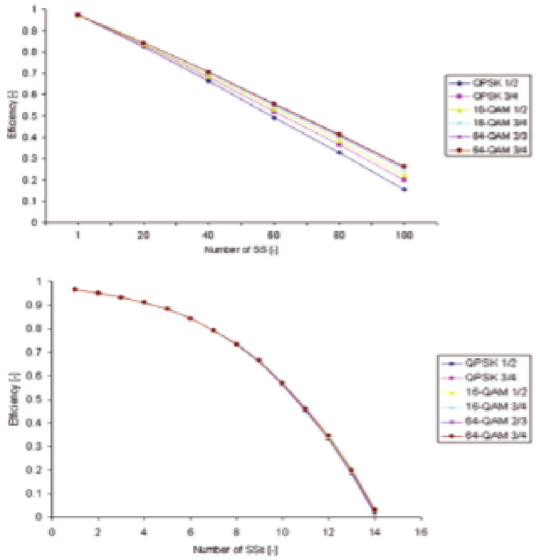

Figure 4.11 *MAC message efficiency in mesh, Centralised Scheduling (top) and Distributed Scheduling (bottom), various modulations (modulation parameter).*

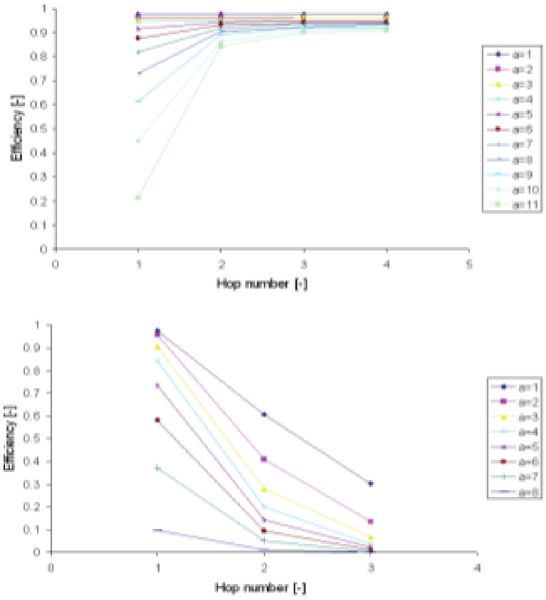

Figure 4.12 *MAC message efficiency in mesh, unrestricted bandwidth (top) and restricted bandwidth (bottom), various number of hops and node levels (**a** and **h** parameters).*

Finally, the MAC efficiency on links corresponding to individual hops is depicted in *Figure 4.12*. It is quite interesting and seems to be vague since the efficiency is higher on links further from the root node (see figure on top). The reason is due to the fact that less request and grant messages are transmitted there. Unrestricted bandwidth allocation also affected to the high efficiency in low level of hops. Figure on the bottom depicts the opposite results when a restricted bandwidth is applied in lower level of hops. However, it is obviously confirmed that children (SSs) per node introduce notably higher overhead, which results in lower efficiency.

The last *Figure 4.13* shows the efficiency performance of MAC management message in PMP topology and Mesh topology in both CS and DS. When concerning different number of subscriber stations, the PMP mode is the most efficient than Mesh CS and Mesh DS *(see section 4.4.1)*.

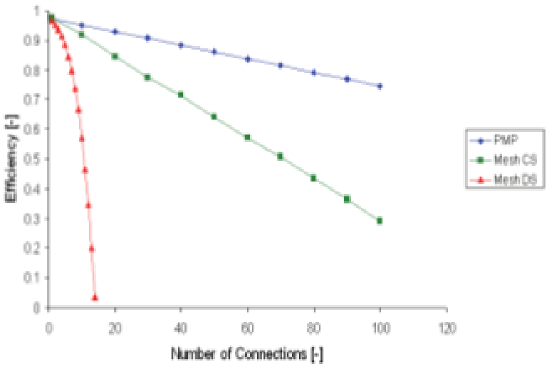

Figure 4.13 *The comparison of MAC efficiency between PMP topology and Mesh topology.*

4.5 Conclusions

In this chapter the analytical derivation of the IEEE 802.16 MAC management message overhead and efficiency in PMP and mesh topology is presented. Performance on the MAC layer has been analyzed.

The PMP mode is well suited for higher number of subscriber stations compare to Mesh mode. Using the QPSK 1/2 modulation and MAC PDU length of 1024 bytes, the efficiency on the MAC layer for 100 subscriber stations connected to the base station is around 75%. On the other hand, the mesh mode is a good option when low numbers of SSs are employed and building a PMP network would be too complicated. When considering the mesh mode, the selection of the right scheduling method is also crucial. As it can be seen from the results, CS brings less overhead than the DS version. The DS showed lower efficiency when calculating the overhead for presented scenarios in comparison to the centralized one, but if the traffic takes place mainly between individual Mesh subscriber stations, the efficiency may be better.

The data MAC PDU length is the parameter that highly influences the MAC layer performance. Obviously longer PDUs mean less MAC overhead. Especially for the PMP mode, transmitting the broadcast message with higher number of bytes per symbols gives more space to the data MAC PDUs transmission. Thus, the usage of higher modulation/coding can reduce the MAC overhead.

Introducing some changes to the IEEE 802.16 standard, for example defining more space saving TLV tuples for some of the management MAC messages could also bring some minor savings, but as the standard already experienced a gradual evolution and being implemented in many real-life applications, it does not make any sense to call for its change.

Chapter 5

The Improvement of MAC Functionality

5.1 Introduction

IEEE 802.16e mobile broadband wireless access system has the stations that might be fixed, nomadic or mobile. Regarding the mobility, the node association procedure is critical for network entry as well as network re-entry during handover. The flexibility and utilisation of MAC protocols scheduling have an important role. The standard provides the Partition Scheme as the scheduling mechanism which separates the allocation of minislots for scheduling. However, minislot can not be flexibly reserved for centralised and distributed scheduling.

The handover is an integral part of all mobile wireless systems. Continuous connection during user movement among cells is allowed due to handover procedure, but on the other hand, the handover brings a significant increase of MAC overhead and also causes an increase in delay of packet delivery to the destination user. Based on the emerging 802.16j proposals, it is very probable that in the next versions of WiMAX recommendations (IEEE 802.16m) the same types of handovers will be defined. Accordingly, the general principles (with regards to the requirements of new standards) of handover will be adopted from 802.16e.

In this chapter, the improvement of MAC functionality is considered. In the first part (*section 5.2*), the work is allied to MAC common part sub-layer (MAC-CPS) by utilised the partition scheme mechanism. The mesh mode is observed since it provides the centralised and distributed scheduling. The second part (*section 5.3*) relates to the service-specific convergence sub-layer (SS-CS) by determining the efficient scanning process of handover procedure.

5.2 Utilisation of Node Association in Mesh Mode

The MAC header of 802.16 is divided into two parts i.e Generic MAC (GM) and Bandwidth Request (BR). GM is dealing with transfer data or MAC massages. In addition, BR has responsibility on sending bandwidth request packets to a BS. In the legacy single connection of MS to BS, the connection management including node association and network entry seems have no critical issue. However, on the contrary, there are some issues when the extended connection and network such as multi-hop network, multiple and mesh connection is present. What would happen when a BS is connected to multiple MSs? How can it manage the connection?

In mobile WiMAX based on IEEE 802.16e standard, a MS are allowed to send data only at scheduled time which is decided by BS. The BS communicates to all MSs in the beginning of each frame in uplink map (UL-MAP). According to the standard, number of bandwidth allocation procedures and QoS are provided. However, particular scheduling method and reservation technique are not standardised.

In TDMA mode, the data transfer has been scheduled by time. The time is divided between frames separated by guard time. Each frame is further divided between uplink (UL) sub-frame and downlink (DL) subframe. The UL sub-frame once again divided between three periods namely ranging period, bandwidth contention period and data uplink period. UL-MAP contains duration of these periods including time slots for each MS to send data to BS in uplink sub-frame. In uplink direction, MSs send data to BS in corresponding allotted slots. Any MS is not allowed to use any other MS’s uplink slots for data transfer. Therefore, to accomplish MS requirements the slots allocation is needed.

5.2.1 MAC Scheduling and Quality of Service

In order to have a better support for QoS requirements, the standard defines key parameters like delay, minimum reserved bandwidth, bandwidth request mechanism and flow type association. However it is still not clear how the parameters would be employ, also when and where they should be used to obtain maximum QoS. It can be assumed that the implementation of an appropriate scheduling algorithm is the best way to support maximum application in parallel on this system.

Scheduling has to be done in directions, uplink and downlink. Downlink scheduling seems relatively easy because BS has all packets and their status. In contrast, the uplink scheduling seems more complex since it has various parameters such as numbers of client (MSs or RSs), delay bounds, associated flows and bandwidth requirements of each flow. In spite of different constraints between downlink and uplink direction, the different scheduling algorithm may or may not be implemented in both direction [31] .

Additionally, it is necessary to investigate if the system require two scheduling components (at BS and at MS), or only single component of scheduling sitting at the BS can properly schedule all traffic. The IEEE 802.16 standard supports four different flow classes for QoS and the MAC supports a request-grant mechanism for data transmission in uplink direction. These flows are associated with packets at MAC level. Each connection has a unique flow type associated with it. The IEEE 802.16 standard does not define any slot allocation criterion or scheduling algorithm for any type of service. A scheduling module is necessary to design UL-MAP to provide QoS for each SS. Slots assignment for connections is done by BS and included the same in UL-MAP. The IEEE 802.16 standard supports many traffic types (data, video, voice) with different QoS requirements. The 802.16 standard also defined the following four types of service flow with distinct QoS requirement [4]

- Unsolicited Grant Services (UGS)
- Real-Time Polling Services (rtPS)
- Non-Real-Time Polling Services (nrtPS)
- Best Effort (BE) Services

As described on IEEE 802.16e standard, each flow has its distinct QoS parameters. For UGS flow bandwidth request is not needed but for other flows queue length (incremental or aggregate) at MS is included in bandwidth request packet to represent the current demand. Bandwidth is always requested on a per connection basis. The IEEE 802.16e defines the following two ways for allocation of bandwidth grants [4] :

- Grant per Connection (GPC) Bandwidth is allocated to a connection and MS uses this grant only for this connection.
- Grant per Subscriber Station (GPSS) MS granted bandwidth aggregated into a single grant. This MS needs more intelligent to distribute this grant into various flows, running at this MS.

5.2.2 Scheduling Mechanism

This section points up the partition scheme mechanism which is described on the IEEE 802.16 standard. We illustrate the centralised and distributed mechanisms as well as the node association in a network topology with relay capability (multi-hop environment).

Partition Scheme Mechanism

Obviously, in relay system the mesh mode topology is adopted. In IEEE 802.16 standard, the *Time Division Multiplexing* (TDM) radio access technology between clients (RSs and MSs) and between the clients and the mesh BS is taken on. A radio channel is divided into *physical slots* (PSs) using time sharing and multiple PSs are grouped as a frame. *Figure 5.1* shows the frame structure of mesh MAC frame.

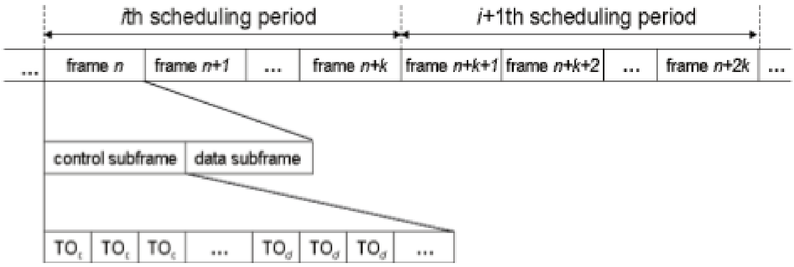

Figure 5.1 *The frame structure of mesh network based on IEEE 802.16e.*

As described in [13] , a frame is allocated for the purposes of control and management (control subframe) and information (data subframe). In the control subframe part, the signalling message is carried by the Transmission Opportunities (TOs). The TO for centralized scheduling is denoted as **TO$_c$**, additionally the **TO$_d$** is denoted for distributed scheduling.

The scheduling is to schedule minislots to serve different clients. The numbers of **TO$_c$**s and **TO$_d$**s in a control subframe are configurable. On the other hand, the data subframe carries the user data and is further divided into 256 minislots. The transmission rate that the minislot can provide is assigned as r bits/sec. According to standard, the rate is not fixed but depends on several factors (e.g., channel coding, modulation, frequency band, etc) [4] . A minislot has a property called "*minislot reuse*" by which it can be reused by multiple clients as long as the clients are geographically separated or they do not interfere each other.

The data traffics in the wireless mesh network can be divided into two categories [20] : intra-network traffic and inter-network traffic. Intra-network traffics are the traffics between two or more clients in the same wireless mesh network (i.e. MS to RS/BS, RS to BS, and vice versa). In addition, internetwork traffics are the traffics between the clients via different BSs, or the traffics from/to backhaul applications. A data subframe can simultaneously carry the intra and inter-network traffic data. The distributed scheduling mechanism is assigned for minislot allocation for the intranetwork traffic and the centralised scheduling mechanism is for the internetwork traffic. It is important to carefully schedule the minislots in a data subframe for both kinds of traffics to optimise minislot utilisation.

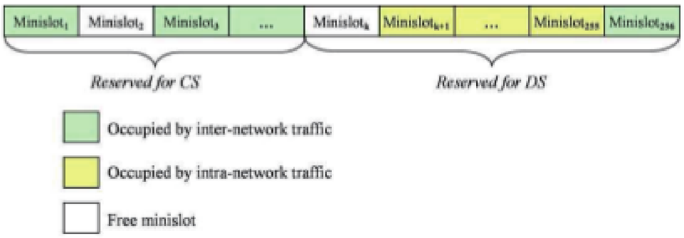

Figure 5.2 *IEEE 802.16 Partition Scheme.*

IEEE 802.16 recommends to partition a data subframe into two parts for the two scheduling mechanism which is known as the "*partition*" scheme. However, this may not be the best solution due to the fact that the partitioned boundary may not precisely capture the traffic pattern, and the minislots may not be fully utilized. *Figure 5.2* shows the partition scheme mechanism. The first 128 minislots are assigned for inter-network traffic purposes. The rest 128 minislots are assigned for intra-network traffic.

Centralised Scheduling (CS)

The CS mechanism for the communication between the BS to MSs has been specified on the IEEE 802.16e standard. The scheduling mechanism could also be adopted to make mobile possibility on relay station (mobile relay-MR). The BS acts as a scheduler and determines transmission and reception minislots for each client station (MS/MR). A scheduling tree rooted at the BS is established for the routing path between each client and the BS. A scheduling tree is denoted as follow and depicted on *Figure 5.3* below.

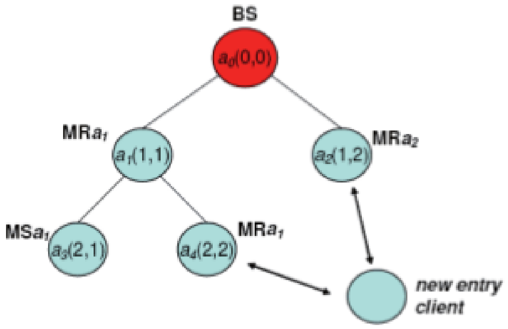

Figure 5.3 *The scheduling tree of node association in centralised scheduling.*

The tree (***T***) can be written as follow:

$$T = \{a_0(k_{a_0}, n_{a_0}), a_1(k_{a_1}, n_{a_1}), a_2(k_{a_2}, n_{a_2}), \ldots, a_i(k_{a_i}, n_{a_i}), \ldots\} \qquad (27)$$

where k_{a_i} is the layer number, n_{a_i} is the position number in layer k_{a_i}, and (k_{a_i}, n_{a_i}) is the index number of the node. The index number of BS is (0,0).

Before a client executes the registration procedure to join the network, it selects a network node with smallest layer number from all neighbouring network nodes as the *candidate node*. Then the client sends the registration message (network entry procedure) to the mesh BS through the candidate node. Upon receipt of the registration message, the BS sets the new entry client as the child of the candidate node in the scheduling tree, updates the scheduling tree, and then broadcasts the scheduling tree to all Stations. By completing the procedure, the new entry client obtains a node ID.

The CS consists of two stages. In the first stage, the BS collects bandwidth requests from all client stations. In the second stage, the BS calculates and then distributes the transmission and reception schedule to all Stations. The time period for exercising the two stages is called as *scheduling period*. The schedule assigned in the i^{th} scheduling period is referenced in the $i + 1^{\text{st}}$ scheduling period as shown in *Figure 5.1*. Take *Figure 5.2* as an example, where MR_{a_i} ($i = 1, 2, 3, 4$) requests transmission rates, R_{u,a_i} and R_{d,a_i} for data transmission to and data receipt from the BS respectively. The MR_{a_i} first checks whether the number n_{f,a_i} of free minislots is smaller than $\left[\frac{R_{u,a_i}}{r}\right] + \left[\frac{R_{d,a_i}}{r}\right]$. If so, MR_{a_i} quits the CS. Otherwise, it exercises as follows: Based on the scheduling tree, the client station with larger k_{a_i} and smaller n_{a_i} transmits the UL signaling messages first, while the client station with smaller k_{a_i} and smaller n_{a_i} relays the DL signaling message first.

Distributed Scheduling (DS)

Additionally, the distributed scheduling will be assigned when client station CS_{a_s} has data to be transmitted with transmission rate R to its neighbour CS_{a_r}. The CS_{a_s} first checks whether n_{f,a_s}, is smaller than $\left[\frac{R}{r}\right]$. If so, CS_{a_s} quits the distributing scheduling. Otherwise, the scheduling is performed to reserve minislots for data transmission as shown in Figure 5.6. Then, after the execution of DS, CS_{a_s} can transmit data to CS_{a_r} in the reserved minislot without collision [32]

5.2.3 Flexibility and Utilised MAC Messages

Based on the scheme from previous section, the MAC massages flows for CS and DS mechanism can be seen on *Figure 5.4* and *Figure 5.5* respectively.

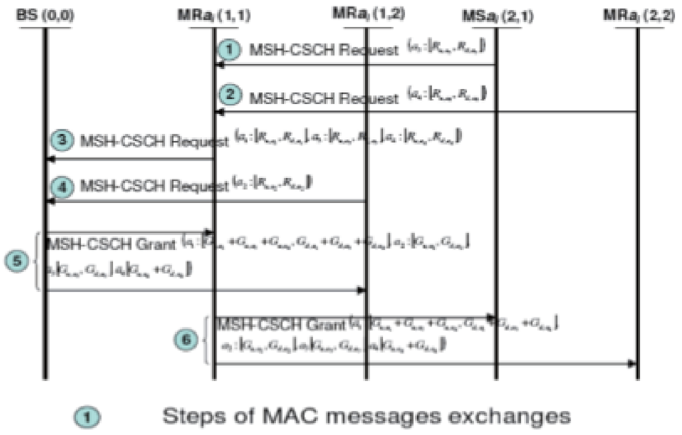

Figure 5.4 *MAC massages exchanges for centralised scheduling.*

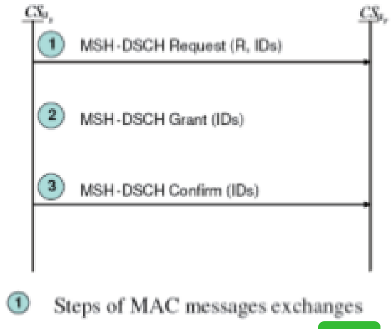

Figure 5.5 *MAC massages exchanges for distributed scheduling.*

The combination of centralised and distributed mechanism for node association MAC scheduling also have the positive effects since the minislot allocation can be more flexible and its utilisation is increased, as shown in *Figure 5.6*.

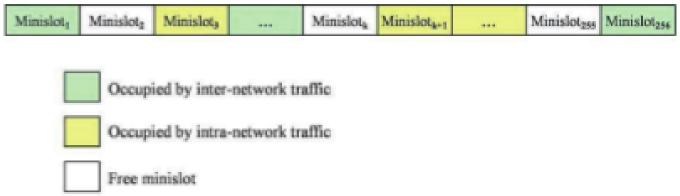

Figure 5.6 *Flexible and utilised minislots by combination of CS and DS mechanism.*

5.3 Scanning Efficiency on Handover Procedure

According to [4] , the handover procedure can be divided in two stages as depicted in *Figure 5.7*. Stage that is executed before handover, called *Network Topology Acquisition*, contains network topology advertisement and MS scanning. In this stage, the Mobile Station (MS) investigates and collects information about neighbourhood base stations of its Serving BS. During the scanning phase, the MS seeks a suitable handover to the target BS or Relay Station (RS) that are suitable to be added to the Diversity Set. The Diversity Set is a list of the BSs/RSs, which are involved in the handover procedure in case of *Macro Diversity Handover* (MDHO) or *Fast Base Station Switching* (FBSS).

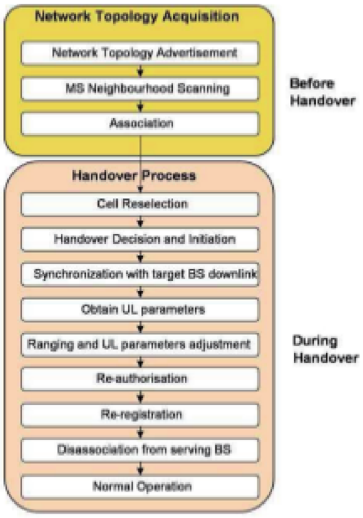

Figure 5.7 *Two stages of Handover Procedure based on IEEE802.16e.*

The scanning is realized in the “scanning intervals” which interleave the normal operation of MS. Once the scanning phase is completed, the MS sends results to its serving BS. The reported results can be delivered by two report types. The first one is “event trigger report”, in which MS sends reports based on a defined trigger, such as carrier-to-interference-and-noise ration (CINR), receive signal strength indicator (RSSI), relative delay, or round trip delay (RTD). In this type of report, the measurement report is sent to the serving BS after each measurement case. In the second type of report, “periodic report”, the MS sends reports periodically.

The results of scanning are used in the next stage of handover procedure called *Handover Process*. The first step is *cell reselection*. In this step, possible target BS is selected based on signal quality and offered QoS. Then, *handover decision* and *initiation* process can be initialized if all conditions and requirements for handover are met follow. The first step of handover process is ended by performing the synchronization to the new Target BS. However, before the synchronization is done the connection(s) to the serving BS has to be closed first.

As soon as the downlink synchronization is done, the MS can start the next step of handover: *network re-entry* procedure. The network re-entry consists of three substeps i.e. *ranging*, *re-authorization* and *re-registration*. In the ranging process the MS obtains information about uplink channel via UL-MAP and UCD messages. The Ranging is followed by authorization and registration of MS to the target BS. If successful, the MS can start normal operation.

5.3.1 MAC Management Overhead in Handover

The total handover overhead is given by the summarization of length of all handover MAC management messages exchanged during the handover procedure. Generally, the total handover overhead is affected by following parameters:

- Frequency of handovers (number of handovers per time interval)
- Sequence of exchanged messages
- Length and structure of MAC messages

Frequency of handovers

The number of handovers per a time interval depends on numbers of MSs and BSs/RSs, speed of MSs, the trajectory of MSs and the setting of cells' boundary. The number of MSs and BSs/RSs in a network and speed of MSs are random and cannot be changed or influenced without impact on users QoS. In contrast, the boundary of cells (or range of BS' areas) can be effected by network parameters setting (threshold levels, relative or absolute thresholds, hard handover threshold hysteresis, etc) [33]

Sequence of exchanged messages during handover

The sequence of management messages is different (but analogical) for different types of handovers. Additionally, the message sequence can even be different for the same types of handover; e.g. in case of different conditions or handover requirements. Moreover, the message sequence depends on the initiator of handover procedure (BS or MS). The MAC management message sequence can be modified by network parameter setting up such as periodicity of MS scanning of neighbourhood BSs/RSs or scanning results reporting.

Length and structure of MAC messages

The length of most MAC management messages vary with respect to handover conditions, or types and requirements [4] . The length of messages is affected by proper setting up of handover parameters (BS cell range, thresholds, etc.). For example, the length of messages during scanning phase depends on the number of recommended BSs to scan.

5.3.2 Minimization of MAC Management Overhead

Reducing the Scanning Time

In network topology acquisition stage, in fact, there is only one BS that can be selected as target BS for handover. The result obtained from the scanning process may become invalid because of the changing of neighbour BS's channel quality.

Consequently, if the scan or association process occupies too many resources, the throughput significantly decreases. Furthermore, the standard does not clearly state the scanning time. If the scanning is not done with proper timing, channel condition of neighbour BSs may be changed. That would make the scanning process results useless. *Figure 5.8* shows the exchanges of MAC management message in the handover procedure.

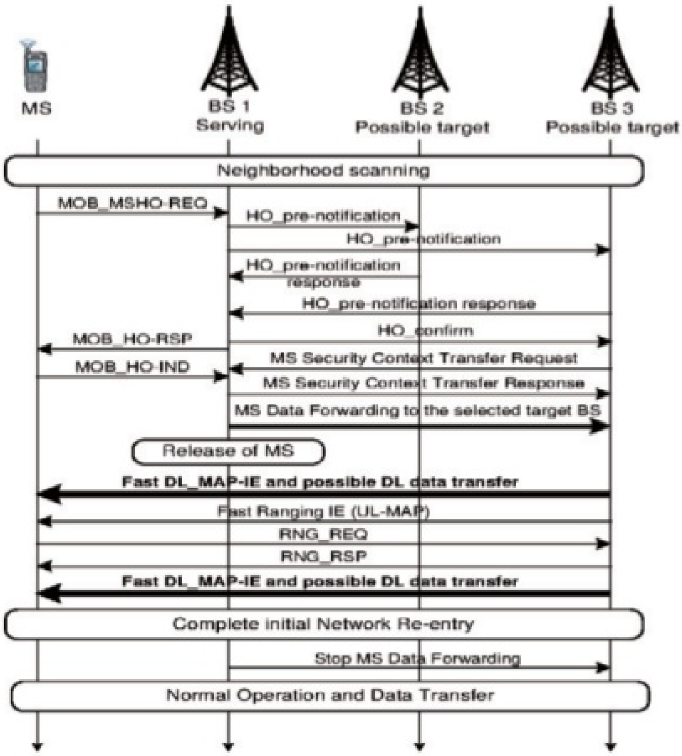

Figure 5.8 *MAC Management Message exchanges within the handover.*

These two parts of handover procedure contribute to the overhead in 802.16m. Fortunately, there are several schemes that can be implemented to cope with these issues. The main wastes of resources are represented by redundant scanning and association processes of neighbour BSs. To resolved the issues we propose the single BS scanning scheme, target BS fast ranging and the pre-registration mechanism.

Single BS scanning scheme can be achieved by exploiting the target BS estimation algorithm, in which a MS only scans or associates to the neighbour BS with the best CINR. In the mean time, target BS uses a Fast_Ranging_IE message to grant a dedicated uplink ranging opportunity to MS in its broadcasting UL-MAP message. So, the MS does not need to do contention-based ranging. Finally, the pre-registration is deployed, in which target BS obtains the service flow and authentication information of this MS through backbone network before handover. To analyze the performance of efficient scanning scheme, we consider four types of scanning as described in [18] .

The first type is denoted as $\boldsymbol{Scn_{\_1}}$ and it is defined as scanning process of BSs by MS without association. In this scanning type, the MS is only requested to obtain downlink synchronization with the target BS in order to get information about quality of target BS's physical channel. The scanning time can be calculated as:

$$Scn_{\_1} = n \times T_{Sync} \tag{28}$$

where $\boldsymbol{n}$ is denoted as the number of neighbor BSs that need to be scanned and $\boldsymbol{T_{Sync}}$ is the average time required for downlink synchronization.

The second type is $\boldsymbol{Scn_{\_2}}$ and it is defined as scanning process of BSs by MS without coordination. A MS requires the downlink synchronization as well as the execution of contention resolution-based ranging. The $Scn_{\_2}$ can be calculated as:

$$Scn_{\_2} = n \times \left(T_{Sync} + T_{Cont\_res}\right) \tag{29}$$

where $\boldsymbol{T_{Cont\_res}}$ is defined as the average time required for contention resolution-based ranging (see *equation 32* for the calculation).

The third type of scanning is denoted as $\boldsymbol{Scn_{\_3}}$ and it is defined as scanning process of BS by MS with coordination. A MS requires the downlink synchronization and the execution of fast ranging process. The scanning time can be calculated as:

$$Scn_{\_3} = n \times \left(T_{Sync} + T_{Rng}\right) \tag{30}$$

where T_{Rng} is the average time required for fast ranging (see *equation 33* for the calculation).

Finaly, the fourth type of scanning is denoted as $Scn_{\_4}$ and it is defined as scanning process of BS by MS with network assisted association reporting mode. The scanning process is similar to $Scn_{\_3}$. The difference is that the target BS does not send RNG-RSP message directly to the MS. The RNG-RSP message is firstly sent to the serving BS through backbone network. Then, the serving BS packs all RNG-RSP messages from scanned neighbor BSs into one MOB_ASC-REPORT message and sends it to the MS either during interleaving scanning intervals or normal operation time. Thus, the average time required for fast ranging is assumed to be a half of that for a contention-based ranging. The scanning time for this type of scanning can be calculated as:

$$Scn_{\_4} = n \times \left(T_{Sync} + \left[\frac{1}{2} \times T_{Rng} \right] \right) \qquad (31)$$

More details concerning different type of scanning processes can be found in reference [18]

Performance Analysis of Scanning Time

In this section we analyze the performance of scanning process. Based on system description document, we assumed a 20 ms super frame of IEEE802.16m is divided into 4 equally-size frames, where the frame length is assumed to be 5 ms [34] . The ratio of cell load (R_{Load}) is assumed to be $0 \leq R_{Load} \leq 100\%$. The T_{Cont_res} depends on the CINR and ratio of cell load. According to [17] the T_{Cont_res} is set to approximately 75 ms and 150 ms when the ratio of cell load is 0% and 50% respectively. Since the ranging collision probability is higher as ratio of cell load increases, then T_{Cont_res} can be approximated as:

$$T_{Cont\_res} = 75 + \left(\left[150 \times R_{Load} \right] \times 2 \right) \qquad (32)$$

The average time required for fast ranging (***T_{Rng}***) is also assumed to be directly proportional to the ratio of cell load. The ***T_{Rng}*** is set to approximately 25 ms and 50 ms when the ration of cell load is 0% and 50% respectively [17] . It can be calculated as:

$$T_{Rng} = 25 + ([50 \times R_{Load}] \times 2) \qquad (33)$$

The average time required for authorization (***T_{Auth}***) is relatively longer than the other times since it is the time needed by target BS to obtain the authorization information of MS from the authorization server. ***T_{Auth}*** is assumed to be 150 ms [18] . Finally, the average time required for registration (***T_{Reg}***) is assumed to be 2 frames. The considered values of delays in our paper are summarized in *Table 5.1*.

Table 5.1 *Time paramaters in IEEE802.16m scanning process.*

Time required	**Notation**	**Typical value**
Synchronization	***T_{Sync}***	2 frames
Contention resolution-based ranging	***T_{Cont_res}***	hundredth of ms
Fast ranging	***T_{Rng}***	tenth of ms
Authorization	***T_{Auth}***	150 ms
Registration	***T_{Reg}***	2 frames

The results of scanning time performance with respect to cell load and number of neighbour BSs are depicted in *Figure 5.9* and *Figure 5.10*. The discussion of the results will be followed in *section 5.3.3.*

Handover Interruption Time

The handover interruption time in 802.16e systems is caused by switching of MS from its serving BS to the target BS, the same description is assumed for 802.16m. The system profile of 802.16m also designed the maximum interruption time for handover i.e. 30 ms for intra-frequency and 100 ms for inter-frequency [35]

When the MS crosses a boarder of cells between the serving BS and target BS, the connection with the serving BS is closed. After that, a new connection with the target BS is established. Notice that after closing the connection and before setting up the new one, the MS has no connection to the network for a short time. During the interruption, packets must be routed from the serving BS to the target BS. After establishing of the connection between the MS and the target BS, packets are again sent to MS. The packets are delayed due to re-connection (network re-entry) of MS to the target BS [36]

The total interruption time during the handover process depends on the deployed handover strategy. The standard specifies four handover strategies (*Table 5.2*, [4]).

Table 5.2 *Handover strategies.*

Handover strategy	Description
HO_1	Handover with contention-based ranging
HO_2	Handover with fast ranging
HO_3	Handover with contention-based ranging and pre-registration
HO_4	Handover with fast ranging and pre-registration

In case of *HO_1,* prior receiving HO-IND message with handover start or service release indicator, serving BS does not inform the target BS to provide dedicated ranging opportunity for MS. During the network re-entry, if collision occurs, MS executes random backoff algorithm and obtain a ranging opportunity through contention. Furthermore, the target BS does not obtain the MS's registration information such as authorization or service flow information from backbone network. Hence, the handover delay of *HO_1* can be calculated as:

$$D_{HO\_1} = T_{Sync} + T_{Cont\_res} + T_{Auth} + T_{\mathrm{Reg}} \tag{34}$$

The *HO_2* includes the fast ranging phase, but the target BS does not obtain the MS's registration information from the backbone network. Therefore, the MS has to execute a re-authorization and re-registration process. The *HO_2* handover delay can be calculated as:

$$D_{HO\_2} = T_{Sync} + T_{Rng} + T_{Auth} + T_{Reg} \tag{35}$$

In case of *HO_3*, the contention-based ranging and pre-registration schemes are adopted. The target BS obtains the MS's registration information from the backbone network. Despite the target BS knows the MS's information, it requires to sent REQ-RSP message including CID updating information to the MS. Therefore the average time for pre-registration is assumed to be a half of the average time of whole registration process. The handover delay of *HO_3* is given as:

$$D_{HO\_3} = T_{Sync} + T_{Cont\_res} + \frac{T_{Reg}}{2} \tag{36}$$

The last type of handover, *HO_4*, adopts the fast ranging and pre-registration schemes. The target BS provides a dedicated ranging opportunity to MS and obtaining the service flow and authorization information of the MS from backbone network. The target BS also requires to send REQ-RSP message including CID update information the MS. Thus, the average time required for registration is assumed to be half of complete registration. The handover delay of *HO-4* can be calculated as:

$$D_{HO\_4} = T_{Sync} + T_{Rng} + \frac{T_{Reg}}{2} \tag{37}$$

The results of handover interruption time of four handover strategies are shown in Figure 5.11 and Figure 5.12. The results are discussed in section 5.3.3.

5.3.3 Analysis of Efficiency

Based on the presented results in section 5.3.2.2 and 5.3.2.3, analysis of efficiency of scanning process and handover interruption time is discussed.

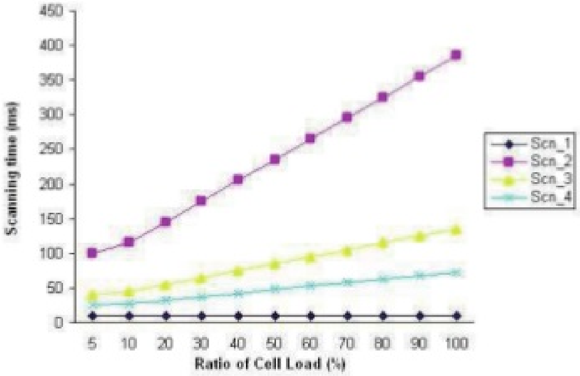

Figure 5.9 The scanning performance in various ratio of cell loads.

Figure 5.9 shows that the ratio of cell load has significant impact on the scanning time for some of scanning types. In case of the scanning without association ***(Scn_1)*** the scanning time remains constant even though the different cell loads increase. This is due to the fact that a MS only needs to synchronize with the target BS to learn the quality its physical channel. For other three scanning mechanisms, the scanning time increases as the cell load increases.

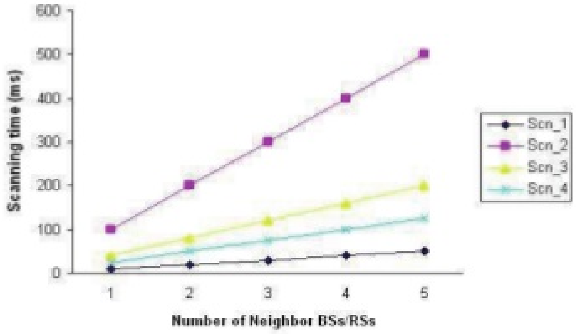

Figure 5.10 *The scanning performance in various numbers of BS/RS.*

From *Figure 5.10*, it can be observed that the number of neighbour BSs affects the duration of scanning time. For the ratio of cell load of 5%, and 5 neighbor BSs, the increase of scanning time is almost linear to the increase of number of neighbour

BSs. The scanning without association ($\boldsymbol{Scn}_{\_1}$) also has a better performance than the ones in all cases.

Impact of different frame duration on the scanning time is shown in *Figure 5.11*.

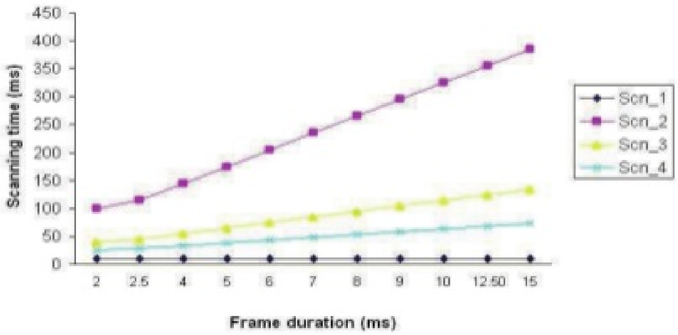

***Figure* 5.11** *The effect of frame duration on the scanning time.*

As can be observed, the scanning time linearly increase as the number of frame growing. Again, the scanning type $\boldsymbol{Scn}_{\_1}$ gives better results since it has the lowest scanning time (10 ms).

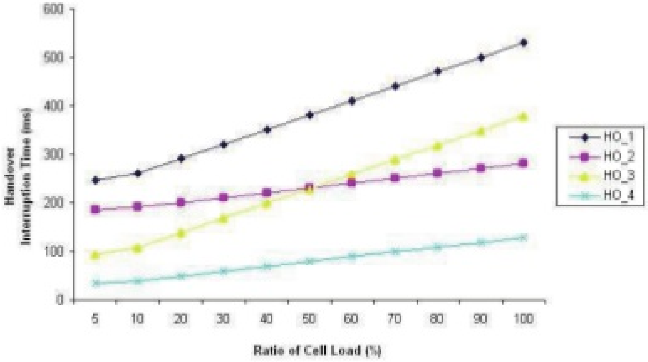

***Figure* 5.12** *Handover interruption time in various handover strategies.*

Figure 5.12 indicates that the performance of handover interruption time depends on several conditions such as the cell load and frame duration. Handover with fast ranging and pre-registration (*HO_4*) seems to be the only handover strategy that can fulfilled the IEEE802.16m's requirements since it can reach the interruption time around 34 ms.

5.4 Conclusions

There are many interesting aspects that can be performed in order to improve the MAC functionality in IEEE802.16 wireless broadband system. In this work we contemplated two aspects i.e. the utilisation of mesh MAC messages based on IEEE 802.16e standard and the scanning process of handover procedure based on IEEE802.16m. The first aspect much more related to the MAC functionality on MAC Common Part Sub-layer (MAC-CPS), and the second one is laid on the Service-Specific Convergence Sub-layer (SS-CS)[2].

The IEEE 802.16e standard has provided the partition scheme mechanism by dividing fixedly the 256 minislots for centralised and distributed scheduling. However, the partitioned boundary may not precisely capture the traffic pattern since the relay stations with multiple connections in mesh topology is obtainable, therefore the minislots may not be fully utilised. The use of combine centralised and distributed mechanism is more flexible and effective in utilisation of minislots.

Meanwhile, the handover's scanning process of IEEE802.16m is analysed in order to fulfil future requirements. Since the standard is still under development, we assumed similar handover procedure as described in IEEE802.16e. But, we are considering the 802.16m's system profiles in our analysis. The analysis focuses on scanning time and handover interruption time. Based on our analysis, there are some inefficient issues in 802.16e's handover procedure which is critical for 802.16m. These are redundant scanning and association process of neighbour BSs. Additionally, the defined handover strategies also contribute the overhead in handover procedure. Based on the result, it is suggested to employ the scanning process without association since it has the lowest scanning time. Moreover, the

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[2] The third MAC sub-layer, Security Sub-layer, is out of our consideration in this work. See Chapter 3 for detail description of SS-CS, MAC-CPS and SS.

handover with fast ranging and pre-registration is favourable since it has the lowest interruption time.

The IEEE802.16m standard is designed to support high speed mobility of user therefore the handover process seems can be occurred very frequently. In this case, the scanning process in handover procedure may play an important role. In the next chapter, we present the description of handover in high speed mobility and investigate the employment of mobility prediction on handover procedure.

Chapter 6

Mobility Prediction for Optimised Handover Procedure

6.1 Introduction

The oncoming amendments, IEEE 802.16j and IEEE 802.16m, introduce multi-hop mobile relays and advanced air interface, including advanced base station (ABS) and advanced mobile station (AMS) concepts to WiMAX. Both fulfil the IMT-Advanced requirements (ITU-R M1645) enabling the data rates up to100Mbps for mobile users and 1Gbps for fixed users. Indeed, these data rates require a higher spectral efficiency and larger bandwidth. The total channel bandwidth required by IMT-advanced systems by year 2020 is estimated to reach up to 1.2 GHz or even 1.7 GHz [6] [7] [8] .

The IEEE802.16m has amended the legacy MAC layer structure by dividing it into two sublayers only, i.e. *convergence sublayer* (SS-CS) and *common part sublayer* (MAC-CPS). The MAC-CPS is further classified into *Radio Resource Control and Management* (RRCM) functions and medium access control (MAC) functions. The RRCM functions fully reside on the control plane. The MAC functions reside on the control and data planes. The Mobility Management is one of MAC function's blocks. The Mobility Management block supports and defines the functionality related to handover procedure.

All today's mobile systems and a big part of the IEEE wireless systems implement a handover procedure to support the user's mobility. The handover, in one side, allows communication during user's movement in the network. On the other side, it significantly increases the signalling overhead in the network. One of the challenges in handover procedure is the handover decision mechanism. The common metrics for handover decision mechanism include Carrier to Interference-and-Noise

Ratio (CINR), Receive Signal Strength Indicator (RSSI) and Quality of Service (QoS). However, those metrics are quite demanding to deal with advanced handover requirement, for instance the fast handover to support high speed mobility. Therefore, the new handover decision mechanism metrics is necessary to be determined.

In this chapter, we introduce our proposal on the enhancement of handover strategy in IEEE802.16m standard by exploiting the mobility prediction. The Markov chain random modelling is used for the prediction of user's next positions. Upon knowing the user's position in advance, the system is able to estimate to which BS the MS will be connected to. Therefore, all handover procedures can be prepared in advanced as well. Accordingly, the MAC overhead due to handover interruption time can be minimised.

6.2 Mobility Prediction

The mobility prediction mechanism often provides the investigation how MSs physically move. In typical mobile networks, MSs expose some degree of regularity in mobility patterns. For example, a car travelling on a road is likely to follow the path of the road and a tram travelling across the city is likely to maintain its heading routed in the rail track and also maintain its speed for some period of time. On the other hand, the pedestrian may be moving in more random pattern but relatively in constant speed. By exploiting a mobile user's random and non-random travelling pattern, we can predict the future state of the user's position and provide a transparent network access during the period of handover. Furthermore, by using the predicted information, we can reduce the number of control packets needed to reconstruct routes and thus minimize overhead. Knowing in advance where a MS is heading allows the system to take proactive steps and the unexpected negative impact of handovers can be mitigated.

6.2.1 S-MIP Prediction

The Seamless handover architecture for Mobile IP (S-MIP) is a quite typical method employed to predict the mobility [37] In S-MIP, the handover is initiated by MS that observes a poor quality connection. When the poor condition occurred, the MS informs its serving BS that the current connection should be handed over to a new BS. The serving BS is assumed to be able to determine the new target BS based on information provided by both the candidate target BS (via backbone) and MS itself. The reported signal strengths are used to determine the MS location by using the triangulation method [38]

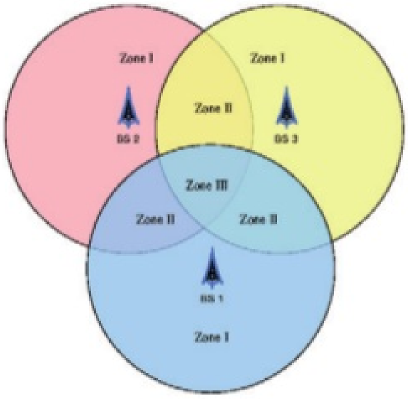

Figure 6.1 *Positioning based on S-MIP.*

Figure 6.1 shows possible MS's locations in multi-cell environment:

- *Zone I*: The handover is not likely performed since the MS is under the coverage of particular BS.
- *Zone II*: The MS is under coverage of two BSs, thus the triangulation method cannot be applied. Since it is located in the intersection of two coverage area, the BS has two distinct points toward the BSs. In S-MIP, only one BS should be chosen to maintain the wireless connection, another BS can be discarded.
- *Zone III*: The MS position can be found by applying the triangulation method. Once the MS is located, the serving BS tries to determine whether:
    - the MS is moving linearly towards another BS and handover procedure should be performed, or
    - the MS is moving stochastically near the border of the zone covered by currently serving BS, no handover required, or

- the MS should stay connected as it is, i.e. no handover should be initialised

The condition of determining the counter-measures are likely to be different for each case. If the MS moves linearly, the handover can be initialised. On the other hand, if the MS moves stochastically, the target BS cannot be reliably determined yet, and the MS should stay connected as it is now until the serving BS determines to which target BS the MS should be newly attached.

6.2.2 Path Prediction

The position and velocity information of a MS can obviously help to estimate where the MS is heading. The monitoring of MS's trajectory can be done either by GPS or by applying positioning methods such as Time Difference of Arrival (TDOA) at the neighbouring BSs, or triangulation method [38] [39] [40] .

In position-based path prediction method, the MS is assumed be able to regularly send its position to its serving BS (e.g., every 1s). A BS maintains the database of roads[3] of served MSs. Each road is supposed to be linear (bends are approximated by linear segments). A BS evaluates and records the average time to transit each road, so the probability of transition from one segment to another is modelled as a second-order Markov process.

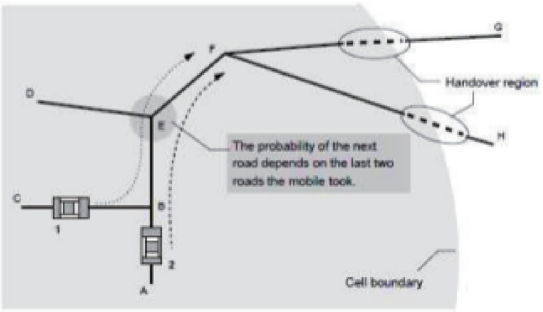

Figure 6.2 *Position-based prediction using road topology information [40]*

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[3] The road information can be extracted from a digital map service.

As can be shown in *Figure 6.2*, once the MS arrives at the *E* junction, the BS computes the probabilities that MS1 and MS2 continue their way towards *D* or *F* junctions. Since, the last two roads they followed are different <*CB, BE*> and <*AB, BE*>, those probabilities are estimated independently.

Handovers of all MSs are continuously monitored, so the locations where handovers usually appear can be marked. Using the history of handovers, the likely path of a MS can be estimated in advance, so both the handover probability and the remaining time before handover can be derived.

6.2.3 User Movement Prediction

Transition Probability Matrix

Our analysis of mobility prediction is derived from Markov process. As depicted in *Figure 6.3* below, let's consider a MS connected to its serving BS has a random motion, which means the MS has possibility to move from its original position to any directions. Based on *Markovian* characteristic, the movement may be start from any position in its original cell e.g. at point (x,y). It has probability to move to any other cells/positions or stay at the current position, which also means the *state* of the MS is changing. The transition probability from *state (i)* to state *(j)* is only based on current state [40]

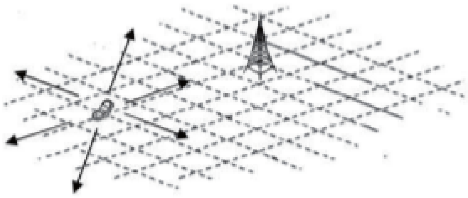

Figure 6.3 *Single cell environment.*

In a single cell environment, the state probability transition can be neglected since the MS stays under coverage of the same serving BS (there is no possible handover). On the other hand, in multi-cell environment, the handover occurs as the MS moving. Thus, there are several cells/positions to where the MS moves on. The number of cells that involve in the prediction process is denoted as *N states*. If a *markov chains* process has *N states*, then the dimension of the *transition probability matrix* (**P**) will be *N* x *N*. The structure of transition probabibly matrix is shown in *equation (39)*.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \tag{39}$$

Since the probability of transitioning from state *i* to some state *j* must be 1, so that:

$$\sum_j P_{i,j} = 1 \tag{40}$$

The elements values of a transition probability matrix are derived from a diagram that called *state markov chains diagram*. *Figure 6.4* shows how a state markov chains diagram generates a transition probability matrix.

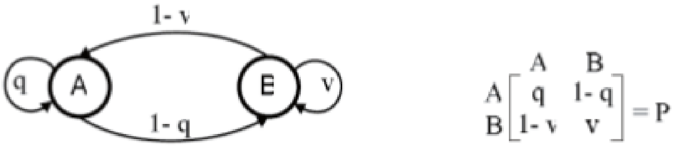

Figure 6.4 *State markov chains diagram and transition probability matrix.*

Now, let's consider the three cells (3 states) scenario of a mobile network as shown in Figure 6.5. The environment consists of one serving BS$_A$, and two target BSs (BS$_B$ and BS$_C$). The MS has three states probability i.e.:

(a) the MS stays in current position, i.e. $\boldsymbol{A} \rightarrow \boldsymbol{A}$,

(b) the MS moves from the serving BS A to the target BS B, i.e. $\boldsymbol{A} \rightarrow \boldsymbol{B}$,

(c) the MS moves from the serving BS A to the target BS C, i.e. $\boldsymbol{A} \rightarrow \boldsymbol{C}$.

The total probability of (a), (b) and (c) summation must be equal to 1. Based on these states probability, the transition probability matrix for BS$_A$ can be generated. The same way can be done to base BS$_B$ and BS$_C$.

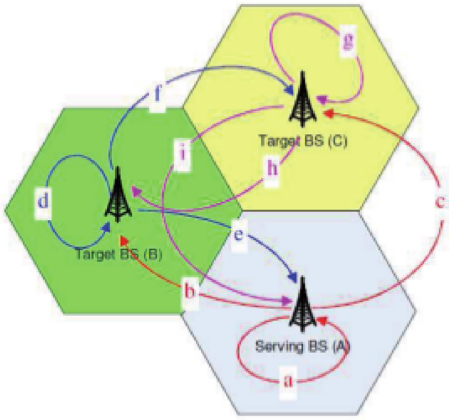

Figure 6.5 *The transition probability of multi-cell scenario.*

The state markov chain diagram shown in *Figure 6.5* generates the following transition probability matrix:

$$P = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \qquad (41)$$

The *next transition probability* ($\mathbf{P_n}$) from serving BS to target BS can be calculated as:

$$\mathbf{P_n} = [\mathbf{P_{n-1}}] \text{ x } [\mathbf{P}] \qquad (42)$$

where $\mathbf{P_{n-1}}$ is denoted as current transition probability matrix, **n** is denoted as number of states transition. Since the number of states transition depend on number of base stations involved, so **n** can be also denoted as number of BSs. According to *equation (42),* when **n** is equal to 1, there is no transition (no handover), then the next transition probability ($\mathbf{P_1}$) is equal to the original transition probability (**P**), or $\mathbf{P_1} = \mathbf{P}$. Since the multi-cell scenario is considered, the minimum number of **n** should be equal to 2. Therefore, the general term for transition probability matrix can be addressed as $\mathbf{P_1} = \mathbf{P}$ and $\mathbf{n} = 2, 3, 4....$

Initial Distribution

Another required ingredient to construct the Markov chains is called the *initial distribution* (**p**). It is given as a row vector to describe how many or what part of the objects are in each state in the beginning. Using this vector, we can find out how many or what part of the objects are in each state at any later time [41] [42]

In the purpose of mobility prediction, the initial distribution matrix consists of the actual number of MSs in each BS area, or the percentage of MSs in each BS area, or the initial probability of MSs in their particular states, or other parameters such as the minimum/maximum speed of MS ($\boldsymbol{v_{min}}$, $\boldsymbol{v_{max}}$), the distance (**d**), etc. If we consider the dimension 3x3 of the transition probability matrix **P** (as in *equation (41)*), then the initial distribution matrix, **p**, can be determined as:

$$p = \begin{bmatrix} j & k & l \end{bmatrix}$$

where *j, k* and *l* can be represented each conditions or parameters such as speed, distance, etc. If the row of **p** represents coordinates of the object (MS), then the prediction of object position in 2D (flat area) or 3D (inside the building) can be determined as:

$$\begin{array}{c} x \\ y \end{array}\begin{bmatrix} \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{bmatrix} = p \qquad\qquad \begin{array}{c} x \\ y \\ z \end{array}\begin{bmatrix} \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{bmatrix} = p$$

The position of MS after one step movement or one step state transition ($\boldsymbol{p_1}$) can be expressed as **p x P**. Similarly, the position of MS after n transitions is given as:

$$p_n = [p] \times [P_{n-1}] = [p_{n-1}] \times [P] \tag{43}$$

Simulation Rules

In the simulation we manage some assumptions[4] regarding the MS's mobility. The movement of MS is approximated based on *equation (43)*. The size of simulation area is 6,25 Km^2 (2500m x 2500m). *Table 6.1* provide overview parameters used in simulation.

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[4] Some assumptions are not completely accurate, but if we did not make assumptions to generalize the problem, we would not have the ability to approximate a solution to the problem. We just need to make sure that our assumptions are reasonable.

Table 6.1 *Simulation parameters and predefined scenario.*

Parameter	**Value**
Number of BS [number of state]	3
Number of MS [-]	10
Number of state transition [n]	15
BS height [m]	32
MS height [m]	2
Distance between position - $\boldsymbol{d}$ [m]	10
LOS/NLOS path loss model [-]	802.16m urban microcell
Mobility model [-]	Random waypoint
MS velocity [km/h]	$V_{min} = 5$, $V_{max} = 20$
Size of simulated area [m^2]	2500 x 2500 (6.25km^2)

The distance ($\boldsymbol{d}$) is defined as the distance from current position to the next position. It is assumed to be uniform ($\boldsymbol{d_{min}} = \boldsymbol{d_{max}}$) and has predefined value. The MS is assumed will moving, with the predefined speed, to the next state which has the highest probability. The serving BS_A and target BS_B and BS_C are placed within the simulated area. The target BS_B and BS_C have the highest probability value. In case of the both target BSs have a same probability value, we predefined the state priority, in which the target BS_C has highest priority than target BS_B. On the other hand, the other target BS outside the simulated area is assumed to have the lowest probability value.

In addition, though the random waypoint mobility model is used in the prediction process, it can be assumed that a MS does not walk randomly, but rather several paths could be followed.

Number of transition probability matrices used in the simulation is shown in *Table 6.2*.

Table 6.2 Transition probability matrixes.

Matrix	Value	Matrix	Value
tpm_{-1}	$\begin{bmatrix} 1/3 & 1/3 & 1/3 \\ 1/3 & 1/3 & 1/3 \\ 1/3 & 1/3 & 1/3 \end{bmatrix}$	tpm_{-2}	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$
tpm_{-3}	$\begin{bmatrix} 0 & 1/3 & 2/3 \\ 2/3 & 0 & 1/3 \\ 1/3 & 2/3 & 0 \end{bmatrix}$	tpm_{-4}	$\begin{bmatrix} 0 & 1/3 & 2/3 \\ 1/3 & 2/3 & 0 \\ 2/3 & 0 & 1/3 \end{bmatrix}$
tpm_{-5}	$\begin{bmatrix} 2/5 & 2/5 & 1/5 \\ 2/5 & 2/5 & 1/5 \\ 2/5 & 2/5 & 1/5 \end{bmatrix}$	tpm_{-6}	$\begin{bmatrix} 1/6 & 2/6 & 3/6 \\ 1/6 & 2/6 & 3/6 \\ 1/6 & 2/6 & 3/6 \end{bmatrix}$
tpm_{-7}	$\begin{bmatrix} 1/6 & 2/6 & 3/6 \\ 3/6 & 1/6 & 2/6 \\ 2/6 & 3/6 & 1/6 \end{bmatrix}$	tpm_{-8}	$\begin{bmatrix} 1/4 & 1/4 & 2/4 \\ 2/4 & 1/4 & 1/4 \\ 1/4 & 2/4 & 1/4 \end{bmatrix}$
tpm_{-9}	$\begin{bmatrix} 2/5 & 2/5 & 1/5 \\ 1/5 & 2/5 & 2/5 \\ 2/5 & 1/5 & 2/5 \end{bmatrix}$	tpm_{-10}	$\begin{bmatrix} 1/3 & 1/3 & 1/3 \\ 2/3 & 1/3 & 0 \\ 1/6 & 2/6 & 3/6 \end{bmatrix}$
tpm_{-11}	$\begin{bmatrix} 1/6 & 3/6 & 2/6 \\ 1/4 & 2/4 & 1/4 \\ 1/3 & 0 & 2/3 \end{bmatrix}$		

6.3 Results

Each MS is simulated with different transition probability matrixes as stated in *Table 6.2*. The forms of movement, as the result of simulation, are classified into five direction categories based on the MS's final position: *toward target* BS_B *(B)*, *toward target* BS_C *(C)*, *back to the original position (reside)*, *outside the movement area (out)* and *toward the cell's boundary (border)*. Beside, some errors have also occurred on the simulation result. The final positions of the MSs for each transition probability matrix are listed in *Table 6.3*.

The simulation provided many figures of MS's movements. For a comfortable appearance, we made a simplification, redraw the results and plotted them into one Cartesian coordinate system as shown in *Figure 6.6*.

As can be seen from *Figure 6.6*, majority of MSs are predicted to reach the target BS_C (52%), it is due to the simulation rule that set the priority to target BS_C once the element value of transition probability matrix between BS_B and BS_C are same. In addition, there is also the fact that the element value for BS_C (in the third column of transition probability matrix, see *equation (41)*) has larger values than BS_A and BS_B (the first and second column). Moreover, 14.5% of MSs is predicted to reach the target BS_B, where 13.6% of the MS arrived at the cell boundary and 8.2% is predicted reside on the current position. About 5.5% of the MSs is predicted moving outside the movement area. Finally, 6.2% of the prediction results are found as errors

Table 6.3 *Prediction results of MS's direction after several movements.*

	MS 1	MS 2	MS 3	MS 4	MS 5	MS 6	MS 7	MS 8	MS 9	MS 10
$tpm_{\_1}$	C	C	C	C	C	C	C	C	C	C
$tpm_{\_2}$	C	Out	-	B	C	C	C	C	C	B
$tpm_{\_3}$	C	border	out	border	border	border	C	border	border	Border
$tpm_{\_4}$	C	C	C	B	C	C	C	C	B	B
$tpm_{\_5}$	B	B	B	B	B	B	B	B	B	B
$tpm_{\_6}$	C	C	C	C	C	C	C	C	C	C
$tpm_{\_7}$	C	C	out	border	border	border	C	border	border	Border
$tpm_{\_8}$	C	reside	out	reside	reside	out	C	border	C	Out
$tpm_{\_9}$	C	reside	out	reside	reside	reside	C	reside	reside	C
$tpm_{\_10}$	-	C	C	border	C	B	-	C	-	-
$tpm_{\_11}$	C	C	C	C	C	C	C	C	C	C

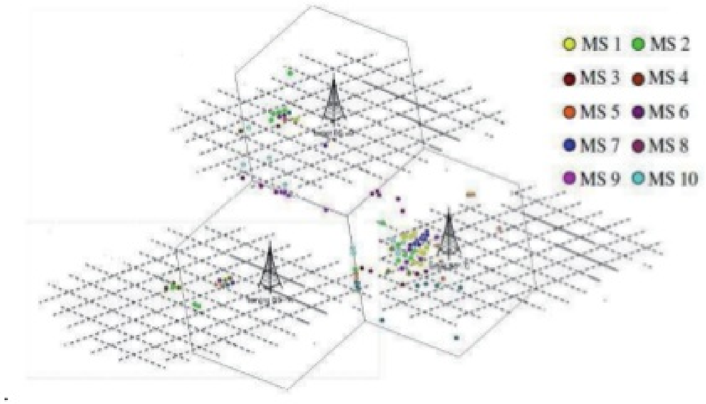

Figure 6.6 *The mobility prediction results - final position of the MSs.*

Additionally, the statistical prediction shows several forms of MS' movement. We classify the movement forms into four categories: *linear*, *reside*, *random* and *patterned*. The forms of movement are depicted in *Figure 6.7*.

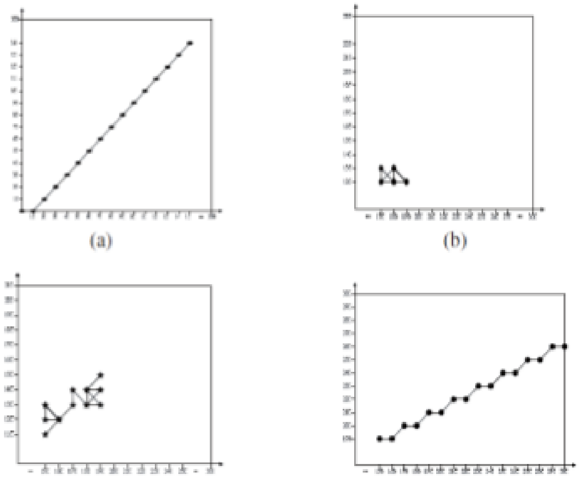
(a) (b)
(c) (d)

Figure 6.7 Various forms of MS's movement: (a) Linear, (b) Reside, (c) Random and (d) Patterned.

Those generated movement forms are mainly influenced by the transition probability matrix and speed of the MS's. Linear form is generated when the MS is moving in a relatively low speed. Reside form means the MS is back to its original position after several transitions. It is also generated by a low speed of the MS. The random form, on the other hand, is generated by a high speed of MS. In this form of movement, some uncertain directions are occurred until the MS reaches its final position. The high speed of MS is also generated the patterned form where the MS is moving in a specific pattern toward next positions until reach the final position. *Table 6.4* shows the movement form of each MS corresponded to the value of transition probability matrix.

Table 6.4 The forms of MS movement as the result of mobility prediction.

	MS 1	**MS 2**	**MS 3**	**MS 4**	**MS 5**	**MS 6**	**MS 7**	**MS 8**	**MS 9**	**MS 10**
$tpm_{\_1}$	linear	Linear	linear	linear	linear	linear	linear	Linear	linear	linear
$tpm_{\_2}$	linear	Linear	linear	linear	linear	linear	linear	Linear	linear	linear
$tpm_{\_3}$	linear	Random	reside	random	random	random	random	Random	random	random
$tpm_{\_4}$	linear	Linier	linier	linier	linier	linier	linier	Linier	linier	linier
$tpm_{\_5}$	linear	Linear	linear	linear	linear	linear	linear	Linear	linear	linear

$tpm_{\_6}$	linear	Linear	linear	linear	linear	linear	linear	Linear	linear	linear
$tpm_{\_7}$	linear	Random	reside	random	random	random	random	Random	random	Random
$tpm_{\_8}$	linear	Patterned	reside	patterned	patterned	patterned	patterned	random	patterned	reside
$tpm_{\_9}$	linear	Patterned	linier	patterned	patterned	patterned	random	patterned	patterned	patterned
$tpm_{\_10}$	reside	Reside	reside	reside	reside	reside	Reside	reside	reside	reside
$tpm_{\_11}$	linear	Linear	linear	linear	linear	linear	Linear	linear	linear	linear

6.4 Proposed Handover Decision Strategy

Since the handover procedure in IEEE802.16m may be initiated by either the BS or the MS, therefore two handover strategies i.e. proactive and reactive handover [21] [22] , are proposed to be applied to trigger the handover.

Proactive Handover

Principle of proactive handover is shown in *Figure 6.8*. In the proactive handover scenario, the handover may occur any time before the level RSSI of current BS reaches the handover hysteresis threshold (HHT). When the mobility prediction is deployed, a fixed probability threshold (FPT) is set up. The FPT corresponds to the level of RSSI for which the mobility prediction mechanism is triggered. Whereas, the HPT corresponds to the RSSI level for which the handover might be executed. Once the prediction result is acquired, the handover can be preceded any time between FPT and HHT.

The proactive handover strategy attempts to estimate network characteristics of a specific position before the MS reaches that position. The MS discovered that the new target-BS's RSSI overpasses the origin one from its serving-BS. The MS calculates the time left before the normal handover is triggered, then triggering the handover earlier before HHT. This strategy can minimize packet loss and high latency during handover.

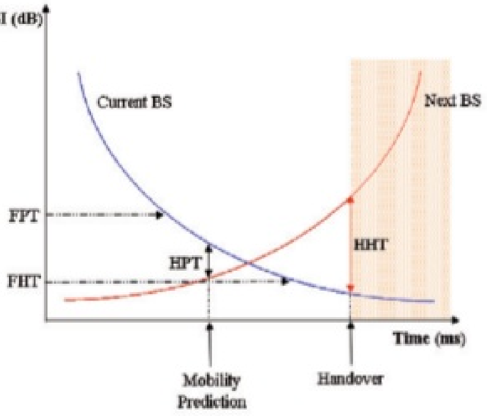

Figure 6.8 *The principle of proactive handover [21].*

Reactive Handover

Reactive handover, on the other hand, tends to postpone the handover as much as possible, i.e. the handover is initialized either if FHT < HHT (see *Figure 6.9*) or if the UE fully loses signal from the source-MBS.

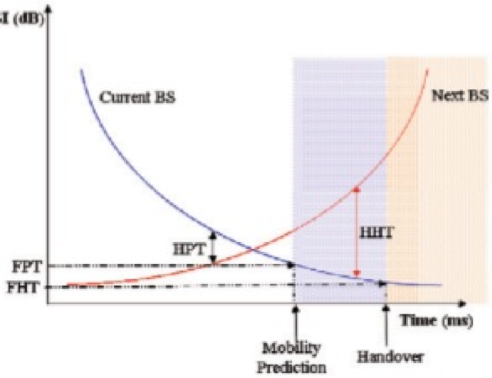

Figure 6.9 *The principle of reactive handover [21].*

Due to the possibility and supported of high speed mobility of IEE802.16m's user, the MS in the system may encounter the very frequent and unnecessary handover since the MS moves from one BS to other BS repeatedly. To mitigate the generated overhead of handover, the reactive handover scenario is applied. Reactive handover tends to postpone the handover as long as possible, even though it has discovered the new RSSI signal. The handover is triggered only when the MS (almost) lose its serving-BS signal or when the most probable position of the MS is predicted.

6.5 Conclusions

The high speed of user mobility is supported in the IEEE806.16m version. A MS in high speed is most probably moving from one cell to other cell repeatedly which cause the very frequent handovers. As a result, the system overhead (i.e. the interruption of data transfer) will significantly increase. The currently specified handover mechanism in the standard IEEE802.16e only considers portable and nomadic mobility of users. Therefore, the handover mechanism and procedure must be enhanced to avoid the frequent interruptions or unexpected disconnections.

In this chapter we introduced the movement prediction mechanism as an additional metric for handover decision procedure. Knowing the current position and velocity of an MS can obviously help to estimate where the MS is heading, thus the next position of MS to where the handover might be performed can be predicted.

In this handover decision procedure, it is assumed that the MS is able to periodically send its position to the serving BS (e.g., every 1s) during its moving. In the mean time, the serving BS maintains database of all possible target BSs to where the handover might be performed. The probability of transition from one cell to another is modeled as a Markov process. Using this method, the likely path of a MS can be estimated in advance, so both the handover probability and the remaining time before handover can be derived.

Upon receiving the prediction result, serving BS seeks all possible target BSs. One of the neighbouring BS is assigned as the predicted target BS, to where the handover is triggered. Serving BS then performs coordination with the predicted target BS via backbone. If the target BS is available for handover, the MS will proceed the handover process (see *Figure 5.7* on section 5.3 for handover process procedure).

Finally, the procedure of handover can be optimised by selecting the most appropriate handover decision strategy, either the proactive handover or reactive handover.

Chapter 7

Contribution of the Work

The research work contributions are summarised as follows:

- Analysis of MAC management messages (presented in Chapter 4)
    - Notify the aspects that influence the MAC overhead i.e. length of MAC PDU, packet modulation/coding scheme and number of burst profile.
    - Introduce the efficiency evaluation methods of MAC management messages in PMP topology based on IEEE802.16-2005 and mesh topology based on IEEE802.16-2004.
    - Proposal of Centralised Scheduling for mesh topology in multi-hop scenario.
    - Suggestion to utilise the TLV part of the message as optimal as possible.
- Improving MAC functionality on MAC-CPS in IEEE802.16j (presented in Chapter 4)
    - Proposal of CCD (Combined Centralised and Distributed) scheduling mechanism and the algorithms for flexible and effective utilisation of minislot of mesh MAC frame.
    - Proposal of indexing method in node association procedure for multi-hop scenario.
    - Modification of MAC message exchange sequences in both centralised and distributed scheduling.
- Improving MAC functionality on SS-CS in IEEE802.16m (presented in Chapter 4)
    - Proposal of single BS scan in network topology acquisition stage of handover procedure in order to avoid the redundant scanning process and reducing the scanning time.

  - Proposal of "scanning without association" as the scanning type on handover procedure to obtain the lowest scanning time.
  - Proposal of "handover with fast ranging and pre-registration" as the handover type on handover procedure to obtain the minimal handover interruption time.
  - Modification of MAC message exchange sequences in handover procedure.
- Optimization of handover strategy in IEEE802.16m (presented in Chapter 6).
  - Introduce a new mechanism and new metric for providing optimised handover procedure in IEEE802.16m. The mechanism is the mobility prediction based on Markov's chain method for estimating the next position of the MS, therefore to where the MS may be handover can be predicted in advance.
  - Introduce two new handover strategies i.e. proactive and reactive handovers for providing the optimised handover decision in IEEE802.16m. These strategies can be applied to prevent the very frequent and unnecessary handovers in the case of high speed mobility of the MS.

Technical and theoretical achievements of this work are appropriately adapted to derive contributions to influence relevant standardisation activities, mainly in IEEE 802.16j/m standard bodies. We have submitted two contribution papers to IEEE802.16 Task Group j (TGj) and IEEE802.16 Task Group m (TGm). The contributions are for the development of IEEE standards 802.16j Air Interface for Broadband Wireless Systems-Multihop Relay Specification and 802.16m Advanced Air Interface for Fixed and Mobile Broadband Wireless Access System.

Furthermore, major parts of the work have been used as the research and technical achievements in FP6 IST-EU Fireworks Project and FP7 IST-EU Rockets Project.

The works can be positioned within state-of-the art wireless technology through dissemination activities. Also contributes for the development and improvement of wireless network engineering, technology and expertise and as a reference for future works.

Chapter 8

Conclusion and Future Direction

8.1 Conclusion

In this work, we have investigated the efficiency of medium access control (MAC) layer on multi-hop multi-cell broadband wireless system based on IEEE802.16d-2004, IEEE802.16e-2005, IEEE802.16j-2009 and the upcoming IEEE802.16m. We have presented the method on analysing the MAC overhead and introduced some approaches to deal with several aspects, both by means of theoretical and by simulations. In addition, we have presented the mobility prediction method in order to optimised one aspect of MAC functionality that is handover.

We have started off by considering the physical aspect of MAC management messages in IEEE802.16d. As the standard supported point to multipoint (PMP) and mesh topology, the overhead and efficiency analysis were considered in both topologies. Some essential MAC management messages which involve in handover process were analysed. Moreover, the MAC PDU length of the message, the modulation scheme and number of hop are considered as the performance parameters. The PMP mode showed the suitability in high number of subscriber stations. On the other hand, the mesh mode is a good option when the network has low numbers of subscriber stations. Still in mesh mode, due to the traffic scenario implemented in our simulation, the centralised scheduling showed higher efficiency than the distributed scheduling. Number of hops influenced the efficiency performance of CS and DS. Additionally, in general the length of MAC PDU of the message and the modulation scheme are very much influenced the MAC layer performance. Longer PDU and higher modulation reduced the MAC overhead. Since the physical anatomy of the MAC message is already fixed, thus our recommendation is to use the TLV tuples of the messages as efficient as possible by adding some advanced purposes of the messages.

The work has been extended by investigating the improvement of MAC functionality. The investigation included the functionality on MAC Common Part Sub-layer (MAC-CPS) and Service-Specific Convergence Sub-layer (SS-CS). We brought the utilisation of the frame packet's minislots for Mesh centralised and distributed scheduling on IEEE802.16d/j as the improvement aspect for MAC-CPS. The 802.16d standard provided the partition scheme mechanism by dividing fixedly the 256 minislots. However, since the introducing of relay station in 802.16j, the partitioned boundary is not precisely capture the traffic pattern. It caused the very low utilisation of using minislots. We changed the fixed partition scheme with the flexible use of minislots in the subframe, which mean the minislots in a subframe have been shared for both centralised and distributed scheduling, thus the waste un-used minislots can be prevented.

In addition, the scanning process of handover procedure on IEEE802.16e/m was considered for the SS-CS. Since the 802.16m is still under development, in this work we considered the parameters based on 802.16m's system profiles, while the handover procedures is still based on 802.16e. Some inefficient issues, which are critical for 802.16m, were discovered i.e. redundant scanning and association processes of neighbour BSs. They increase the overhead of handover and rise the handover interruption time far above the 802.16m's requirements. We improved the handover procedure by deployed the scanning process without association and proposed the handover with fast ranging and pre-registration which fulfilled the 802.16m's requirements.

Finally, the MAC functionality is optimised and enhanced by introducing the movement prediction as an additional metric for handover decision procedure. The movement prediction predicted the next position of the MS and estimate where the MS is heading, therefore the BS to where the MS might be connected can be predicted as well. This method provides the fast and effective handover, reduce the handover interruption time, and mitigate the unnecessary frequent handover for user who moving in high speed. The method can be adopted to fulfil the handover procedure required by IEEE802.16m.

8.2 Future Directions

We consider our work on the efficiency of MAC layer as a milestone along this direction, and many research and technological development problems need to be addressed in the future.

The proposed movement prediction as a new metric in handover procedure seems quite promising. Along with the legacy Received Signal Strength Indication (RSSI) and Quality of Service (QoS), movement prediction results enhanced the decision policy of handover to be more effective. Nevertheless, further work on how to integrate the new metric in to handover procedure of IEEE802.16m and how the PHY/MAC can be cooperated in term of this metric need to be done. We have been assuming only a few number of target BSs to where the handover might be attached, so the implementation of large numbers of target BS needs to be considered. The impact of large number of target BS and large number of MS needs to be investigated as well. Moreover, it is also worth to study the movement prediction when implemented in the different technology platform such as 3GPP LTE/LTE-A or in the Femtocell network.

Moreover, once the target BS can be predicted, so the strategy for handover can be enhanced. The handover procedure may be initiated by either the BS (network) or the MS. In the conclusion of Chapter 6, we proposed to implement the proactive or reactive as the handover strategy. The future work may include the impact of proactive or reactive handover with the quality of service. The investigation of its performance on the 3G/4G networks as well as the Femtocell network need to be investigated.

Finally, for the future works we also suggest exploring and exploiting the efficiency of MAC layer of broadband wireless system based on IEEE802.16 families and 3GPP LTE/LTE-A in femtocell network. As the emerging network environment, the femtocell may include plenty of femto access points (home BS or home eNodeB) in their network. With the low power and small coverage area, the user terminal might either lost its connectivity very often or handover from one access point to other access point very frequently. It is quite a challenge to provide the robust MAC layer functionality.

Related Publications

1. **A. Ulvan** and R. Bestak "*The Analysis of Scanning Time in IEEE802.16m's Handover Procedure*", In Proceeding of The 16th International Conference on Systems, Signal and Image Processing (IWSSIP 2009), Chalkida, Greece, June 2009.
2. **A. Ulvan**, M. Ulvan, R. Bestak, "*IEEE802.16 MAC Management Messages: The Overhead and Efficiency Analysis in Mesh Topology*", in Proceedings of the 2009 Malaysia International Conference on Communication (MICC 2009). Kuala Lumpur, Malaysia, 2009.
3. **A. Ulvan** and R. Bestak, "*The Efficiency Performance on Handover's Scanning Process of IEEE802.16m*", In Proceeding of 14th IFIP Personal Wireless Communication (PWC'2009) Conference, Gdansk, Poland, 2009.
4. **A. Ulvan**, M. Ulvan, R. Bestak, "*The Enhancement of Handover Strategy by Mobility Prediction in Broadband Wireless Access*", in Proceedings of the 2009 Networking and Electronic Commerce Research Conference (NAEC 2009). Dallas, TX: American Telecommunications Systems Management Association Inc., 2009, p. 266-276. ISBN 978-0-9820958-2-9.
5. **A. Ulvan**, V. Andrlik, R. Bestak, "*The Overhead and Efficiency Analysis on WiMAX's MAC Management Message*". The Internetworking Indonesia Journal, Vol.1/No.1, Spring 2009, ISSN: 1942-9703.
6. M. Ulvan, R. Bestak, **A.Ulvan**, "*The Study of IMS Functionality in Femtocell Environment*", in Proceedings of the 2009 Malaysia International Conference on Communication (MICC 2009). Kuala Lumpur, Malaysia, 2009.
7. **A. Ulvan**, M. Ulvan, R. Bestak, "*Optimised Handover Strategy in Broadband Wireless Access by Mobility Prediction*", in *Telecommunication Systems Journal*. (Accepted to be published in spring 2009 volume).
8. **A. Ulvan**, V. Andrlik, R. Bestak, "*The analysis of IEEE 802.16e MAC Layer Overhead and Efficiency in PMP Topology*", in Proceeding of IEEE Wireless and Optical Communication Network (WOCN), 2008. ISBN: 978-1-4244-1980-7. Include Engineering Index (EI) and EI Compendex and IEEE Xplore™ IEEE Catalogue Number: CFP08604-CDR.
9. **A. Ulvan**, M. Ulvan, R. Bestak, "*Improving the flexibility and Utilisation of Node Association Procedure in Mesh Mode Based on IEEE802.16e*", in Proceeding of Indonesian Students Scientific Meeting (ISSM 2008), Delft, The Netherland, 2008. ISSN: 0855-8692.
10. **A. Ulvan**, D. Ribiero, R. Bestak, "*Multiple Cell Partitions for Increasing CDMA-Based Cell Capacity*", in Proceeding of 13th IFIP Personal Wireless Communication Conference, Toulouse, France, 2008.

11. M. Ulvan, **A. Ulvan**, R. Bestak, "*Mobile IP in Next Generation Intelligent Network*", in Proceeding of Research in Telecommunication Technology (RTT 2008) Conference, Bratislava, Slovak Republic, 2008.
12. **A. Ulvan** and R. Bestak, "*Analysing the Flexibility and Utilisation of Node Association MAC Scheduling Mechanism Based on IEEE802.16e*". In Proceeding of Research in Telecommunication Technology 2007 [CDROM] Zilina, 2007, pp. 420-424. ISBN 979-80-8070-735-4.
13. **A. Ulvan** and R. Bestak, "*Transmission Performance of Flexible Relay-based network on the Purpose of Extending Network Coverage*". Personal Wireless Communication. New York, Springer, 2007. pp.99-106 ISBN 978-0-387-74158-1.
14. **A. Ulvan** and M. Ulvan, "*IP Multimedia Subsystem – IMS : Converged Network Architecture for the Intelligent Interaction of Network Applications and Services*", in Proceeding of The International Workshop on Digital Technology, 2007. ISBN 978-80-8070-786-6.
15. **A. Ulvan**, "*Increasing the CDMA-based Cell Capacity for Urban Area With Cell Partition*", in Proceeding of Research in Telecommunication Technology, 2006. Proceeding, Vol.1, pp 176 – 181. ISBN 80-8070-637-9.
16. **A. Ulvan** and R. Bestak, "*Transmission Performance of Flexible Relay-based Wireless Network*", in Proceeding of The 3rd International Workshop in Digital Technology. 2006.

Contribution to the IEEE Standards:

1. **A. Ulvan**, R. Bestak, "Optimized Handover Mechanism for High Speed Mobility", Contribution to session #66 IEEE 802 LMSC Plenary Session. 15-18 March 2010, Orlando, Florida, USA. Standard No. IEEE C80216m-10_0032.
2. **A. Ulvan**, Z. Becvar, J. Zelenka and R. Bestak, "Using the Relative Thresholds in Handover Procedure", Contribution to session #47 802.16 relay TG, 5th Task Group Meeting on Multihop Relay in IEEE 802.16. 15-18 January 2007, London, UK, IEEE C80216j-07_086.

Project Reports (public deliverables):

1. Rocket IST-EU, 5D1, "Mechanisms for increasing the efficiency of MAC/PHY protocols". 2009
2. Rocket IST-EU, 5D2, "Specification of a reconfigurable MAC/PHY protocol and guidelines for its application". 2009.
3. Fireworks IST-EU, 3D1,"Design and Specification of MAC in Relay-based Cooperative Networks". 2008

4. Fireworks IST-EU, 3D2,"Specification for the Enhanced WMAN and MLAN MAC Protocol". 2008
5. Fireworks IST-EU, 3D3,"Performance Evaluation and Final Specification of the Enhanced MAC Protocol". 2008
6. Fireworks IST-EU, 2D2, "Advance Radio Resources Management Algorithm in Relay-Based Networks". 2007

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Definitions, acronyms and abbreviations

3 G-LTE	3rd Generation – Long Term Evolutions
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
AC	Admission Control
A/D	Analogue-to-Digital
AAS	Adaptive Antenna Systems
ADSL	Asymmetric Digital Subscriber Line
AES	Advanced Encryption Standard
ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
BP	Burst Profile
BpS	Bytes per Symbol
BPSK	Binary Phase-Shift Keying
BS	Base Station
BW	Bandwidth
BWA	Broadband Wireless Access
BWS	Broadband Wireless System
CDMA	Code Division Multiple Access
CI	CRC Indicator
CID	Connection Identifier
CP	Cyclic Prefix
CPS	Common Part Sub-layer
CRC	Cyclic Redundancy Check
CS	Convergence Sub-layer
CSCH	Centralized Scheduling
CTS	Clear to Send
D/A	Digital-to-Analogue
DC	Direct Current
DCD	Downlink Channel Descriptor
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DHCP	Dynamic Host Configuration Protocol
DIUC	Downlink Interval Usage Code
DL	Downlink
DLFP	Downlink Frame Prefix
DL-MAP	Downlink Map
DSCH	Distributed Scheduling
DSR	Dynamic Source Routing
DVB-T	Digital Video Broadcasting - Terrestrial
E1	E-carrier level 1
EC	Encryption Control
EKS	Encryption Key Sequence

ESF	Extended Sub-header Field
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FCH	Frame Control Header
GHz	Gigahertz
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordinator Function
HCS	Header Check Sequence
HiperMAN	High Performance Radio Metropolitan Area Network
HT	Header Type
HUMAN	High-speed Unlicensed Metropolitan Area Network
ID	Identifier
IDFT	Inverse Discrete Fourier Transform
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
LAN	Local Area Network
LEN	Length
LOS	Line of Sight
LP	Long Preamble
LR-PAN	Low Rate Personal Area Network
LSB	Least Significant Bit
MAC	Media Access Control Layer
MAN	Metropolitan Area Network
Mb/s	Megabits per Second
MCS	Modulation and Coding Scheme
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MSB	Most Significant Bit
MSH	Mesh
MSH-CSCF	Mesh Centralized Scheduling Configuration
MSH-CSCH	Mesh Centralized Scheduling
MSH-DSCH	Mesh Distributed Scheduling
MSH-NCFG	Mesh Network Configuration
MSH-NENT	Mesh Network Entry
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OH	Overhead
OSI	Open Systems Interconnection
PDU	Protocol Data Unit
PHS	Payload Header Suppression
PHY	Physical Layer

PICS	Protocol Implementation Conformance Specification
PMP	Point to Multipoint
PPP	Point-to-Point Protocol
PPPoE	Point-to-Point Protocol over Ethernet
PRBS	Pseudo-random Binary Sequence
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
RNG	Ranging
RS	Reed-Solomon
RTG	Receive-Transmit Turnaround Gap
RTH	Real-Time HCF Controlled Channel Access
RTS	Request to Send
Rx	Receive
SAP	Service Access Point
SC/SCa	Single Carrier
SDU	Service Data Unit
SNMP	Simple Network Management Protocol
SP	Short Preamble
SS	Subscriber Station
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TFTP	Trivial File Transfer Protocol
TLV	Type-Length-Value
TTG	Transmit-Receive Turnaround Gap
Tx	Transmit
UCD	Uplink Channel Descriptor
UIUC	Uplink Interval Usage Code
UL	Uplink
UL-MAP	Uplink Map
VLAN	Virtual Local Area Network
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network


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