WiMAX Mesh: Multi-hop Evaluation on MAC Layer Efficiency

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Abstract

This chapter focuses on the efficiency analysis of MAC management messages transferred in mesh topology in both centralised and distributed scheduling. We consider the basic IEEE802.16 MAC messages that involve in network admission process. The encountered overhead in the multihop scenario is taking into account. Topology using the Mesh model can be quite varied. The Mesh SS/MS/RS may have direct links between each other and traffic for other Mesh SSs may be routed across these links. There are innumerable possibilities how the topology can look like. Due to the considered MAC overhead and to reduce the complexity, a particular topological model is needed. In this chapter, a tree-like topology is proposed, modelled and simulated, including the assumption of the traffic. It is defined that only the root node (using centralised scheduling terminology – the Mesh BS) is connected to the core network and the end-to-end connections occurs between the Mesh SSs/MSs/RSs and some unspecified nodes outside this network. The connection between individual Mesh SSs is not considered. It means that data for nodes in the lower parts of the tree is routed through the stations/nodes on higher levels. The obtained results showed that the size of mesh frame, the bandwidth, MAC PDU size and several others parameters defined in the standard contributed on the overhead of MAC layer. In respect of the obtained results, several ways of reducing the MAC overhead can be made. The use of Mesh mode would be a waste of resources when majority of the traffic is Point to Multipoint (PMP) and transforming the network to PMP mode does not represent a vital problem. On the other hand, the Mesh mode is a good option when not so many subscriber stations are employed and building a PMP network would be too complicated. The selection of the right scheduling method is also crucial when considering the Mesh mode. Based on this work, centralised scheduling brings less overhead than the distributed mechanism. Nevertheless it introduces a single point of failure, which is the Mesh BS responsible for schedule assignments. The distributed scheduling showed lower efficiency when calculating the overhead for presented scenarios in comparison to the centralised one, but if the traffic takes place mainly between individual Mesh subscriber stations, the efficiency may be better. The result, finally, also determined the maximum number of applicable hops that still fit the performance requirements of the system.

Keywords: WiMAX, IEEE802.16, Mesh network, MAC efficiency, Multi-hop

1. Introduction

The need for an immediate access and exchanging the information has spurred enormously the development of new broadband access technologies over recent years. Wireless local area network (WLAN) in accordance with the IEEE 802.11 standard enabled spreading of wireless networking to nearly every home. The IEEE 802.16 networks, also commonly known as WiMAX, overcome some of the limitations of IEEE 802.11, e.g. limited range or insufficient Quality of Service (QoS) support, and also introduce full mobility. Using their conjunction it is possible, not only to create a solution for metropolitan and local area networks, but also support some special purposes network such as fixed, mobile and vehicular ad-hoc networks. Therefore, the broadband communication in the special circumstances or emergency systems such as military or SAR operations, or disaster early warning systems, or inter-vehicle communication, etc., which are based on mesh topology will be applicable.

The IEEE 802.16 standard aims at providing last-mile wireless broadband access. It specifies the air interface of a fixed and mobile broadband wireless access system. The standard includes the MAC and multiple PHY layer specifications [1]. Several amendments have been made on the development of the standard. The current active standard, 802.16j, supported the multihop relay and improved coexistence mechanisms for license-exempt operation [2]. While, the 802.16m (also known as WiMAX Release 2), aiming at fulfilling the ITU-R IMT-Advanced requirements on 4G systems, is still under active development [3].

In general, WiMAX supports two types of network topologie, i.e. *Point to Multipoint* (PMP) and Mesh, that provides more flexibility in network design, but it also brings an increased overhead, since scheduling and coordination of transmission becomes more difficult. In PMP, 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, used for the purpose of transporting *Medium Access Control* (MAC) management messages, is required by the MAC layer.

The Mesh specification included in IEEE 802.16 is a promising network architecture, however to date it is not utilized 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. 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.

In PMP mode, traffic occurs only between the BS and SSs/MSs/RSs, while in the Mesh mode traffic can be routed through other SSs/MSs/RSs and can occur between SSs/MSs/RSs. This can be done on the basis of equality using distributed scheduling, or using a Mesh BS that is superior, which results in centralised scheduling, or combination of both.

A Mesh BS is a system with direct connection to backhaul services outside the mesh network. All other systems of a Mesh network are called Mesh SSs/MSs/RSs. The stations with which a node has direct links are called neighbours. These stations form a (one-hop) neighbourhood. An extended neighbourhood contains all the neighbours of the neighbourhood, which mean several hops might present in the communication between the BS and the stations.

Using distributed scheduling; all nodes including the Mesh BS shall coordinate their transmissions in their multi-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 multi-hop neighbourhood. For both uplink and downlink, the mechanism of determining the schedule is the same.

In centralised scheduling, on the other hand, 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 stations within the hop range. The actual schedule is computed by an individual station based on the grant messages. According to the standard, 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.

2. Current Situation of Studied Problem

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 section, we overviewed the current research works and technological development related to the topic of this work.

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 [4], 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.

In case of wireless broadband access, the MAC performance has been analysed in several research works. The authors in [5] 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 [6]. 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 centralised/distributed scheduling and the proposed multi-hop PMP. Moreover, in [12] 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 thesis, 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 [7-9] have been performed to acquire the fast handover mechanism. In [7] 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 [8] 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 [9] 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.

3. IEEE802.16 MAC Functionality

The primary task of the IEEE802.16 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 [10]. The MAC layer does the reverse when receiving the transmission.

3.1. IEEE 802.16 – Basic Information

The IEEE 802.16 standard specifies several frequency bands to be used for operation of the IEEE 802.16 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 [1].

The standard also supports two different topologies – PMP and Mesh. The chosen topology noticeably restricts selection of the physical layer. As it is apparent from *Table 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.

Table 1. IEEE 802.16 air interface

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

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 2*.

Table 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. IEEE802.16 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 which are addressed to itself or which 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 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.

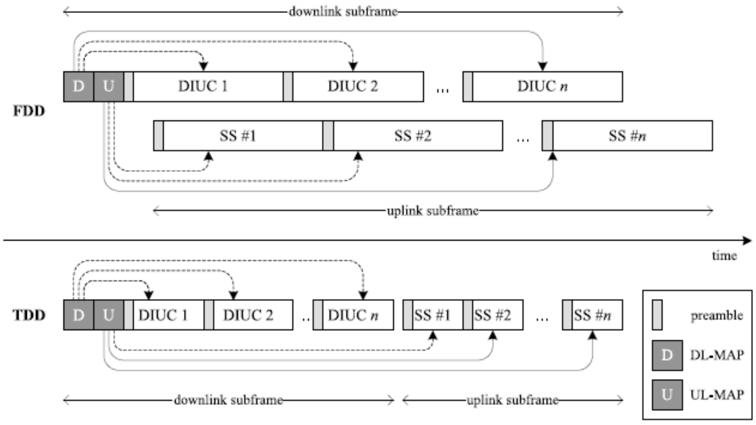

Figure 1. MAC frame structure – FDD (above), TDD (below)

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. In this article, we consider the frame structure of mesh topology only.

3.2.2. Mesh's frame structure

For the Mesh topology, a 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 2*.

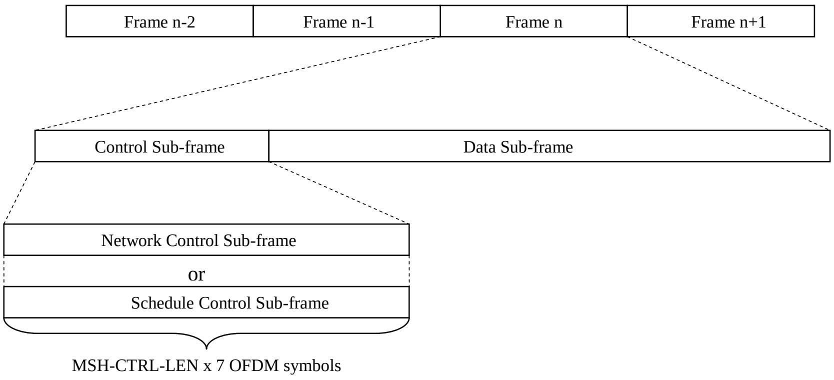

Figure 2. Basic frame structure of Mesh

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.

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

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.

3.3. 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*. 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.

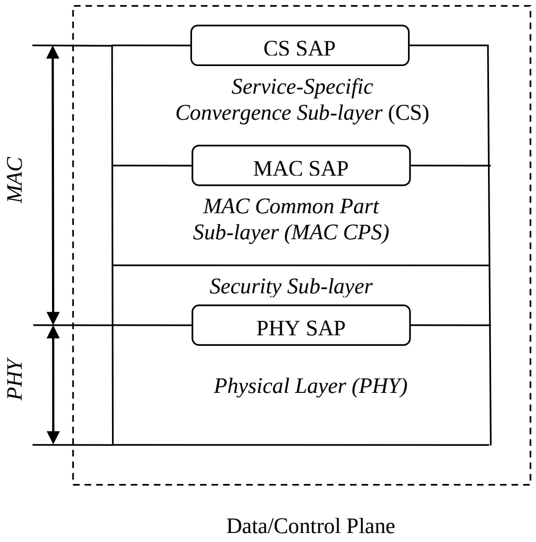

Figure 3. IEEE 802.16. Data/Control plane.

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 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 4*. 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.

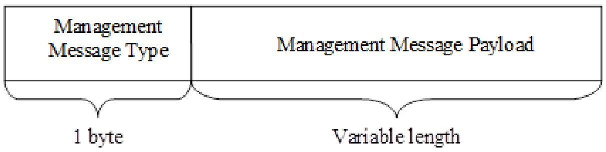

Figure 4. MAC management message structure

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.

The other way of encoding information elements into a MAC management message is by using 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.

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. In Mesh topology, there are no clearly separate downlink and uplink sub-frames, as seen in *Figure 2*. 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.

3.4.1. 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 5*.

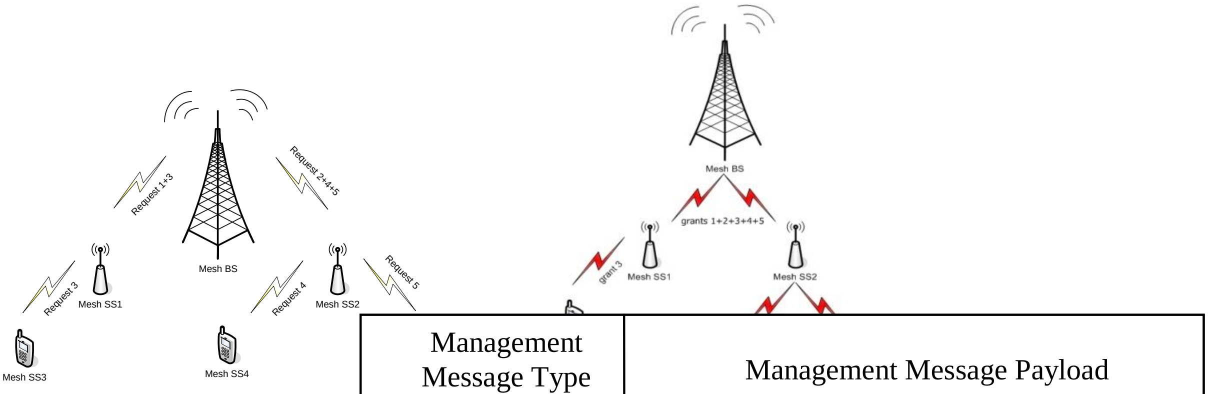

Figure 5. Flow of requests scenario in a Mesh routing tree (left); Flow of grants scenarios in a Mesh routing tree (right).

The requests and grants are distributed using MAC management messages MSH-CSCH (Mesh – Centralised 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.

3.4.2. Distributed Scheduling

Distributed scheduling is different from the centralised 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 6*. 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.

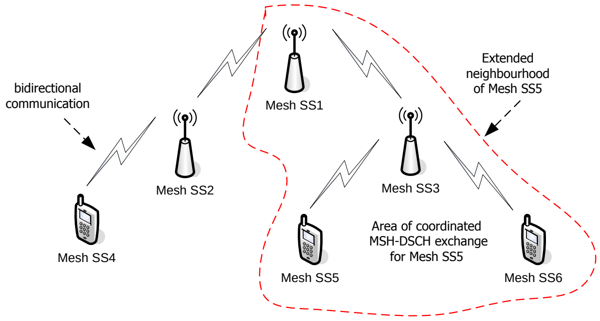

Figure 6. Illustration of coordinated distributed scheduling

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 centralised scheduling methods. The MSH-DSCH MAC management message 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.

Both distributed scheduling methods employ a three-way handshake mechanism as shown in *Figure 7*. *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 **Error! Reference source not found.**

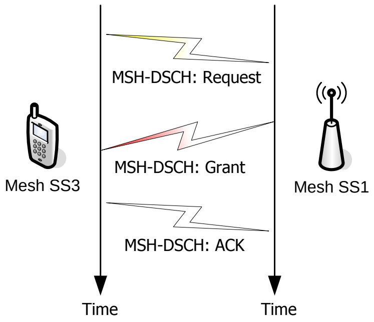

Figure 7. Distributed scheduling three-way handshake

4. Overhead and Efficiency Analysis

4.1. MAC Layer Efficiency

Mesh topology 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 *MAC* management messages.

In 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 (centralised 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 8*. 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. 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 **Error! Reference source not found.**

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 [11]

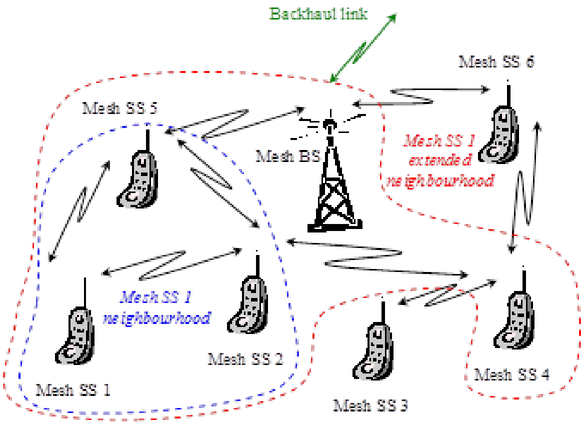

Figure 8. Mesh topology

The MAC overhead can be evaluated by means of determining the efficiency of the MAC layer. According to [6]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)*:

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

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 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:

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

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:

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

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).

$$L_{frame} = \left[\frac{T_{frame}}{T_{symbol}}\right] \tag{7}$$

4.2. MAC Efficiency in Multi-hop 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 9* shows the proposed tree-like scenario 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 centralised scheduling messages.

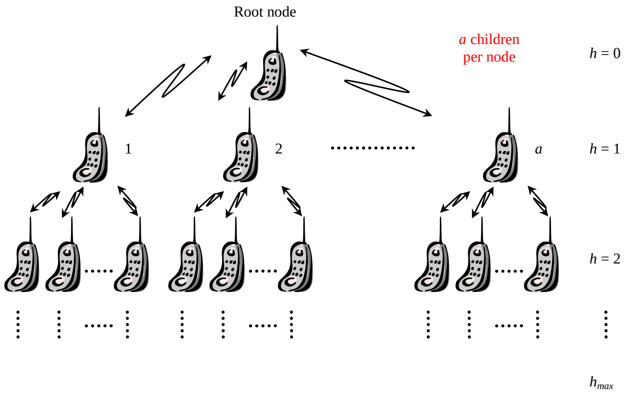

Figure 9. Tree-like scenario in Mesh

Then we need to make a traffic assumption. Let's define that only the root node (using centralised scheduling terminology – 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. *Table 3* shows the number of nodes in the neighbourhood and the extended neighbourhood for a node that is in the tree located on level *h*.

The Mesh frame described in *section 3.2.1* does not have clearly separated downlink and uplink. It consists of the control sub-frame and the data sub-frame. That means the length of the Mesh frame can be expressed as a number of OFDM symbols by *equation 8*.

$$\begin{aligned} L_{frame} &= L_{control\ subframe} + L_{data\ subframe} = \\ &= L_{centralized\ config} + L_{centralized\ schedule} + L_{distributed\ schedule} + \sum_{i=1}^{a+1} L_{PHY\ PDU\ i} \end{aligned} \qquad (8)$$

Table 3. Neighbourhood and extended neighbourhood size

Node level h	Nneigh	Next neigh
0	a	a2 + a
1	a + 1	a2 + 2a
2	a + 1	a2 + 2a + 1
…	a + 1	a2 + 2a + 1
hmax – 2	a + 1	a2 + 2a + 1
hmax – 1	a + 1	2a + 1
hmax – 1	1	a + 1

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 (9).*

$$L_{control\ subframe} = 7 \cdot \left\lceil \frac{a \cdot L_{CSCH}}{7} \right\rceil \qquad (9)$$

We assume that the requests are collected from the lower levels and passed on to the mesh BS (refer to *Figure 9).* 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 (10).* 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.

$$L_{CSCH} = \frac{OH_{MSH-CSCH} + OH_{MAC\ PDU\ Mesh}}{BpS_{QPSK1/2}} + L_{LP} + L_{guard} \qquad (10)$$

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 centralised 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 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 (11)* is denoted as N_{flow}. It can be calculated as:

$$N_{flow}(h) = \sum_{i=0}^{h_{\max}-h} a^{i} \tag{11}$$

$N_{flow}(h)$ 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.

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 **Error! Reference source not found.**[1]. 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.

$$OH_{MSH-CSCH} = 5 + \frac{3}{4} N_{flow} \tag{12}$$

Distributed Scheduling (DS)

Distributed Scheduling consist of coordinated and uncoordinated scheduling. In this thesis 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 (13)*. 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 $L_{DSCH\ low}$.

$$L_{control\ subframe} = 7 \cdot \left\lceil \frac{a \cdot L_{DSCH\ low} + L_{DSCH\ high}}{7} \right\rceil \tag{13}$$

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

$$L_{DSCH} = \left\lceil \frac{OH_{MSH-DSCH} + OH_{MAC\ PDU\ Mesh}}{BpS_{QPSK1/2}} \right\rceil + L_{LP} + L_{guard} \tag{14}$$

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 (15)* as follow:

$$OH_{MSH-DSCH} = 6 + 3 \cdot (N_{neigh} + 1) + 4\frac{1}{8} \cdot (N_{ext\ neigh} + 1) \tag{15}$$

5. Results and Discussions

The tree topology which is used to compute efficiency values for the Mesh mode using centralised and coordinated distributed scheduling methods has two main parameters. The first is the number of children per node, denoted ***a***, and the second is the maximum number of hops from the root node to the most distant node, denoted $\boldsymbol{h_{max}}$. They are together used to calculate the amount of scheduling information distributed within the Mesh network.

Since the capacity of the Mesh frame is constant in size and limited, restriction of maximum value of *a* parameter with given maximum hop count can be observed. *Table 4* contains the identified values for centralised/distributed scheduling, restricted/unrestricted MAC PDU size (denoted ***k***), and restricted/unrestricted bandwidth usage (denoted ***B/W***).

The restricted BW usage means that in the lower levels of the tree only such part of the data sub-frame can be used so that the highest link in the hierarchy leading to the root node could accommodate the traffic.

Table 4. Maximum value of children per node for various maximum hop counts

$\boldsymbol{h_{max}}$	max ***a***							
	B/W unrestricted				B/W restricted			
	CS		DS		CS		DS	
	k unrestr.	*k* restr.	*k* unrestr.	*k* restr.	*k* unrestr.	*k* restr.	*k* unrestr.	*k* restr.
2	95	23	14	12	7	23	6	12
3	26	8	14	7	3	3	3	7
4	11	4	14	4	2	2	2	4
5	7	3	14	3	1	1	1	3
6	5	2	14	2	1	1	1	2
7	4	2	14	2	1	1	1	2
8	3	2	14	2	1	1	1	2
9	2	1	14	1	1	1	1	1

In the following part, efficiency values will be presented for each of the possible combination of scheduling method, size limitation, and bandwidth limitation. Highest h_{max} that allows the $a = 4$ was chosen. Only for distributed scheduling with both *B/W* and *k* unrestricted $h_{max} = 10$ was selected even though it isn't the highest possible. For this scenario, the maximum hop number isn't limited at all. All calculation made assume QPSK 1/2 modulation and MAC PDU length of 1024 bytes.

5.1. Results on Centralised Scheduling

Figures 10 to *13* show MAC layer efficiencies on links corresponding to individual hops. Link with hop number 1 is the link between the root node and its children nodes. These figures can't be compared directly with each other, because different value of the h_{max} parameter creates different conditions on the links.

Figures 10 and *11* were obtained assuming that the bandwidth on lower levels (i.e. higher hop numbers) is not restricted. The efficiency on links further from the root node is higher because of the fact that less request and grant messages are transmitted there. More children per node introduce notably higher overhead, which results in lower efficiency.

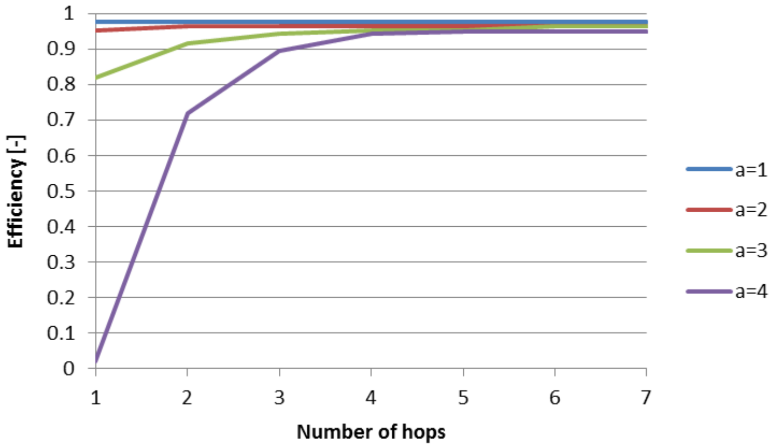

Figure 10. *Mesh efficiency on centralised scheduling (hmax = 7, parameter a)*

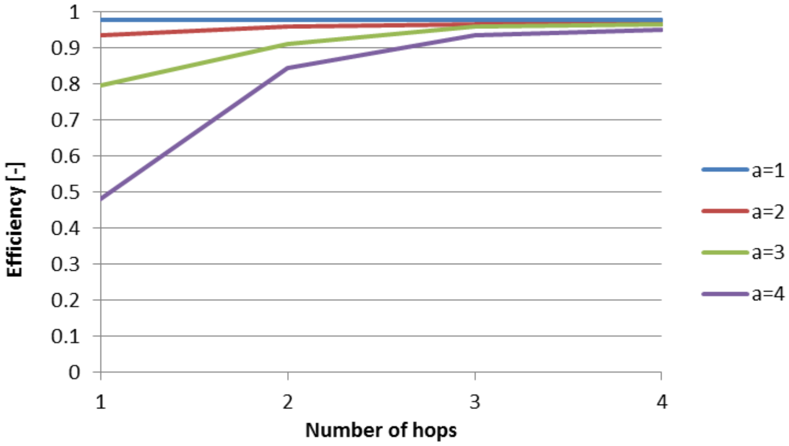

Figure 11. Mesh efficiency on centralised scheduling *(hmax = 4, parameter a, k restricted)*

When the bandwidth limitation is concerned, the efficiency for growing hop number decreases dramatically. It is not caused by the MAC overhead, which is bigger for lower number hops (as depicted in *Figures 12* and *13*), but the reason is that the higher hop links cannot be fully used, in order for the lower hop nodes to accommodate the traffic to and from them.

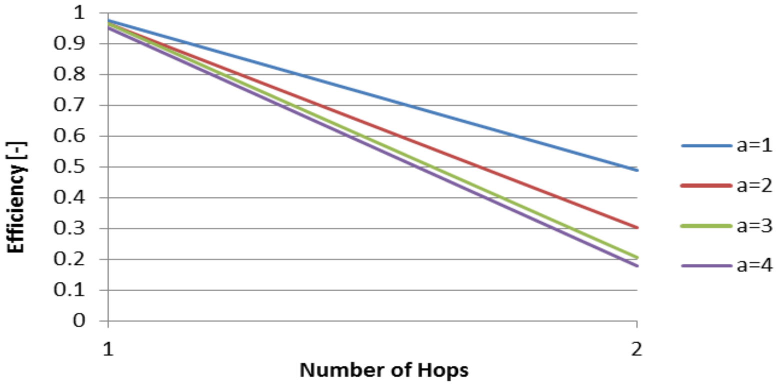

Figure 12. Mesh efficiency on centralised scheduling, *(h_{max} = 2, parameter a, B/W restricted)*

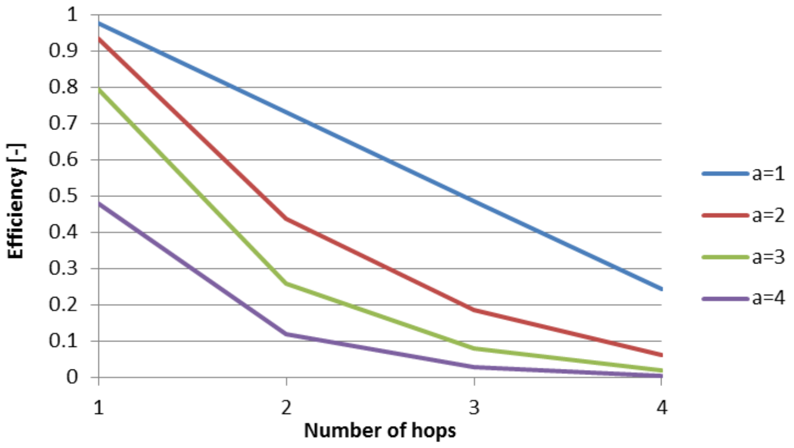

Figure 13. Mesh efficiency on centralised scheduling,*(*h_{max} *= 4, parameter a, BW restricted, k restricted)*

5.2. Results on Distributed Scheduling

In *Figure 14* we can see that the distributed scheduling when not considering *k* or BW restriction has an interesting property. The efficiency is nearly constant regardless to hop number. It is caused by the constant number of extended neighbourhood members. Only the last two hops show the small rising efficiency due to a lower number of these neighbours.

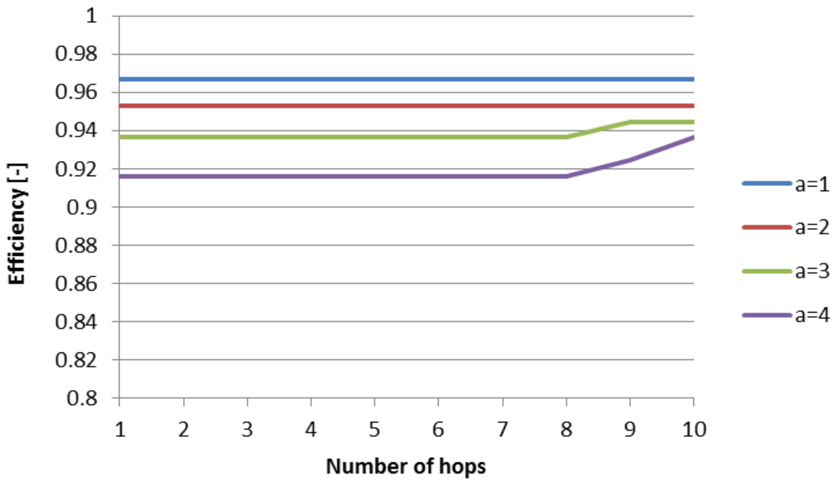

Figure 14. Mesh efficiency on distributed scheduling *(*h_{max} *= 10, parameter a, k unrestricted)*

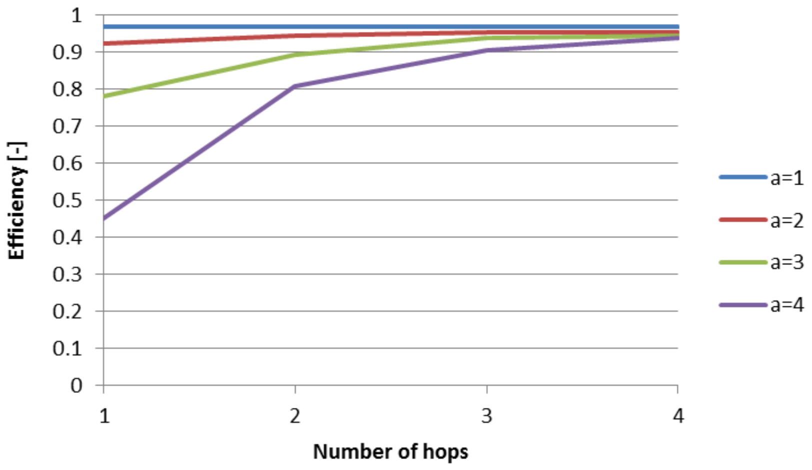

Figure 15. Mesh efficiency on distributed scheduling,*(h_{max} = 4, parameter a, k restricted)*

The scenario with *k* restricted, as depicted in *Figure 15*, shows lower efficiency for lower number hops. Since at least one UL and one DL PDU for every node in the tree is guaranteed, links on higher levels carry more MAC PDUs, which affects the amount of the overhead.

Figures 16 and *17*, showing the cases when restricted B/W is assumed, are equivalent to centralised scheduling. The MAC overhead plays a minor role, majority of the efficiency degradation is caused by incomplete usage of the data sub-frame.

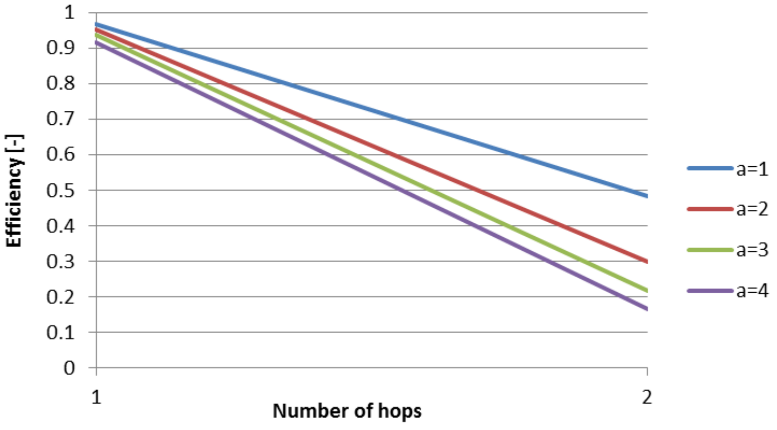

Figure 16. Mesh efficiency on distributed scheduling,*(h_{max} = 2, parameter a, B/W restricted)*

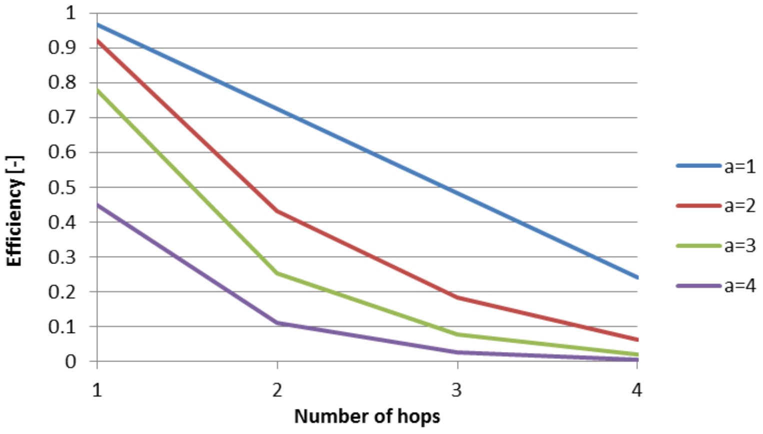

Figure 17. Mesh efficiency on distributed scheduling, *($h_{max} = 2$, parameter a, B/W restricted, k restricted)*

6. Conclusion

Performance on MAC layer of the IEEE 802.16 WirelessMAN standard was analysed. The ratio of the number of OFDM symbols usable for transmission of higher layer data to the total number of OFDM symbols per frame is highly influenced by several parameters. They include the topological mode chosen, number of communicating subscriber station, selection of coding and modulation, length of MAC PDUs, and number of defined burst profiles. Performance of the Mesh mode is mainly affected by the scheduling mechanism.

Based on the simulation results as depicted previously in *Figures 10 – 17* the performance between centralised and distributed scheduling in multihop environment can be examined. In case of unlimited bandwidth, it can be seen that centralised scheduling is more efficient than the coordinated distributed method. MAC PDU length causes efficiency degradation for lower hop numbers. In addition, when considering bandwidth limitation, the centralised scheduling also has better performance than distributed scheduling. However the character of the dependency is not mostly caused by the MAC overhead.

When comparing centralised and distributed scheduling methods defined for the Mesh mode, the centralised scheduling approach gives better results. This is valid just for our case when the tree topology is assumed and all the subscriber stations communicate end to end with a node outside examined network via the root node. Still, distributed scheduling can be more efficient than the centralised one for scenarios with prevailing local communication. Moreover it shows an interesting property of the overhead being nearly constant, independent of the hop number in the proposed tree.

It can be concluded that when considering the Mesh mode the selection of the right scheduling method is crucial. As it can be seen from the results, centralised scheduling brings less overhead than the distributed version. Nevertheless it introduces a single point of failure, which is the Mesh base station responsible for schedule assignments. The distributed scheduling showed lower efficiency when calculating the overhead for presented scenarios in comparison to the centralised one, but if the traffic takes place mainly between individual Mesh subscriber stations, the efficiency may be better.

Acknowledgement

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