# Transmission timing of signalling messages in IEEE 802.16 based Mesh Networks[1]

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*Abstract*: **Broadband wireless access becomes more and more important for current and future communication systems. The IEEE 802.16 (WiMAX) standard combines this technology with mesh multihop network topologies. These multihop networks can be deployed for high speed wide-area wireless networks. One key issue of mesh networking is the MAC (Medium Access Control) layer, which is used to share common channel resources (transmission opportunities) among wireless nodes. The scheduling and assignment of transmission opportunities can be realized in centralized or distributed manner. This paper analyses the IEEE 802.16 election based transmission timing (EBTT) mechanism for the coordinated distributed scheduling (C-DSCH). This mechanism is responsible for transmission timing of C-DSCH signalling messages. As the standard defines only a framework of the EBTT-mechanism this paper presents some extensions that are needed in order to guarantee a correct functionality. Furthermore, simulations using the network simulator ns2 show that the standard election mechanism does not perform well and causes a significant delay on data packets. This paper proposes new ideas to solve the problems and to reduce the packet delay.**

## 1. Introduction

The IEEE 802.16 technology [1] is the standard for future broadband wireless metropolitan area networks (WMAN). As well as other IEEE standards it defines the PHY layer and the MAC layer. The PHY layer supports single carrier (SC), OFDM and OFDMA and is defined to work in frequencies between 2-11 GHz and 10-66 GHz. The MAC layer is based on time division multiple access (TDMA) to support multiple users. Furthermore the MAC layer supports two kinds of modes, namely point-to-multipoint (PMP) mode and mesh mode. In PMP mode, communication is only possible between a base station (BS) and a subscriber station (SS). In mesh mode multihop communication is possible between mesh subscriber stations (M-SSs). From a network operator's point of view mesh networks are able to reduce costs as these networks are easy installable and can be extended fast, simply by adding new mesh nodes. Thus WMNs can be used to extend cell ranges, cover shadowed areas, and enhance system throughput.

Mesh networks are regarded as one of the key features of beyond 3G systems. Besides the 802.16 group mesh technology is in the the focus of different other IEEE standardization groups. While IEEE 802.11s [2] is working on mesh networks for wireless local area networks (WLAN), IEEE 802.15 [3] has wireless personal area networks (WPAN) in focus.

A very important factor that influences the performance of mesh networks is the assignment of available network resources. The assignment of resources can be organized in centralized or distributed manner, with the objective to optimally use the network resources and share them fairly among the mesh nodes. The IEEE 802.16 standard defines a three-way handshake mechanism that uses specific signalling messages to request, grant, and confirm available resources (bandwidth). It is obvious that the transmission timing of these signalling messages has high influence on the network performance. If the interval between two subsequent signalling messages of a node is too large, the three-way handshake will last very long and packets in the queue will get an additional delay. Furthermore M-SSs and M-BSs will not be able to react according to frequent changes in the load of network traffic.

This paper will focus on the election based transmission timing (EBTT) mechanism that is responsible to time the transmissions of signalling packets (MSH-DSCH) that belong to the coordinated distributed scheduling (C-DSCH). The EBTT-mechanism uses information about the two-hop neighbourhood to determine a specific slot (transmission opportunity) in which the local node is able to send without to risk a collision with a MSH-DSCH message of an other mesh node. As the standard defines only a framework of the EBTT-mechanism this paper proposes some extensions needed for the correct functionality. Furthermore, the standard mechanism does not perform well and causes a significant additional delay on data packets. The paper proposes some enhancements designed to overcome these problems. Simulations with the network simulator 2 (ns2) [4] show that these enhancements are able to reduce the additional packet delay noticeably.

The assignment of network resources is still an open issue in the IEEE 802.16 standard. According to our best knowledge this work is the first proposing enhancements to the IEEE 802.16 mesh mode scheduler. Related work considers the assignment of slots for data transmissions. While [7] describes a distributed mechanism with respect to QoS, [6] and [8] concentrate on centralized mechanisms. [5] describes a stochastic model of the IEEE 802.16 distributed scheduler.

The rest of the paper is organized as follows: Section 2. provides an overview of the 802.16 MAC layer in mesh mode. A detailed description of the EBTT-mechanism can be found in Section 3. Furthermore this section

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presents extensions to the election mechanism and initial results indicating the flaws of this mechanism. The next section describes enhancements to the EBTT-mechanism proposed by this paper and presents simulation results that show the achieved improvements. Finally Section 5. concludes the paper.

## 2. MAC layer overview in WiMAX mesh mode

In WiMAX mesh mode the TDMA frame is divided into the control-subframe and the data-subframe (Figure 1). While the slots of the data-subframe are mainly used for the transmission of data packets, the control-subframe is used only for the transmission of signalling messages. All transmissions in the control-subframe are sent using the most robust modulation. Both subframes are fixed in length and consist of transmission opportunities. The number of transmission opportunities in the control-subframe is a network parameter ($MSH\_CTRL\_LEN$) and can have a value between 0 and 15. Each transmission opportunity in the control-subframe has a length of seven OFDM symbols and can carry one signalling message. Two types of control-subframes exist, the network-control-subframe and the schedule-control-subframe. During frames in which the schedule-control-subframe is not scheduled the network-control-subframe is transmitted. The $Scheduling\_Frames$ parameter defines how many frames have a schedule-control-subframe between two frames with network-control-subframes in multiples of four frames. The network-control-subframe serves primarily for new terminals that want to gain access to the network. It is used to broadcast network information to all M-SSs and it provides means for a new node to gain synchronization and initial network entry into a mesh network. The schedule-control-subframe is used to transmit signalling messages for the scheduling of the data-subframe transmission opportunities and is split in two parts (Figure 2). The first part is for the messages that belong to the centralized scheduling mechanism (CSCH) and the second part is for MSH-DSCH messages that belong to the coordinated distributed scheduling mechanism (C-DSCH). The number of transmission opportunities in the C-DSCH part ($MSH\_DSCH\_NUM$) is a network parameter and can have a value between 0 and 15. Thus the length of the CSCH part is $MSH\_CTRL\_LEN - MSH\_DSCH\_NUM$.

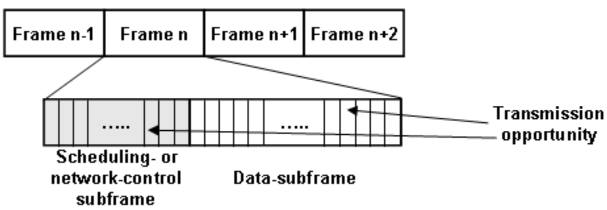


Figure 1: General mesh TDMA frame structure

The assignment of transmission opportunities in the data-subframe is managed by a scheduling mechanism.

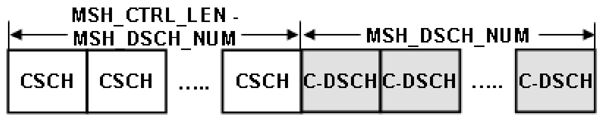


Figure 2: Schedule-control-subframe structure

The IEEE 802.16 standard defines two scheduling principles: centralized and distributed. Both employ a three-way handshake using Requests, Grants, and Confirmations that are carried within specific messages. In centralized scheduling, the MSH-CSCH message is used to carry them and the BS provides schedule configuration and assignments to all M-SSs in the network. Using the distributed scheduling mechanism the MSH-DSCH message carries the Requests, Grants, and Confirmations and all stations (M-BS and M-SSs) shall coordinate their transmissions in their two-hop neighbourhood, see Figure 3. The distributed mechanism can be further classified in coordinated and uncoordinated. In the coordinated case, the MSH-DSCH messages are sent in the C-DSCH part of the control-subframe in a collision free manner; whereas, in the uncoordinated case, MSH-DSCH messages are sent in the free slots of the data-subframe and may collide. MSH-DSCH messages are transmitted regularly by every node throughout the whole mesh network to distribute nodes schedules.

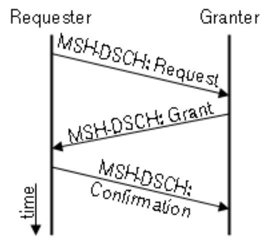


Figure 3: Three-way handshake mechanism to request, grant and confirm the assignment of transmission opportunities

This paper concentrates on the coordinated distributed scheduling mechanism and analyses the transmission timing of the MSH-DSCH messages as this has much influence on the overall network performance. Queued packets cannot be transmitted, until the node has performed the three-way handshake to request the appropriate transmission opportunities in the data-subframe. In a worst case scenario these packets will get an additional delay of three times the mean interval between subsequent MSH-DSCH messages. This effect will be impaired in multihop networks because every intermediate node has to perform the three-way handshake.

## 3. Election based transmission timing (EBTT) mechanism

The transmission timing of MSH-DSCH messages is based on the distributed EBTT-mechanism. This mechanism supports transmission timing of regular broadcast messages in a multihop, mesh network without explicit schedule negotiation. The transmission timing is collision-free within the two-hop neighbourhood of each node. Furthermore, the mechanism is completely distributed and needs no central control, it is fair and robust. A transmission time is similar to a specific transmission opportunity and both expressions are used synonymously in this paper. This mechanism is also used for transmission timing of mesh network configuration messages (MSH-NCFG). To avoid collisions of MSH-DSCH messages every node must inform its neighbours about the next MSH-DSCH transmission time. To save network resource and to reduce the signalling overhead mesh nodes do not broadcast the exact $Next\_Xmt\_Time$ ($nxmt$) but only the $Next\_Xmt\_Time\_Interval$ ($nxmti$) which is a series of one or more C-DSCH transmission opportunities. Therefore the IEEE 802.16 standard defines the parameters $Next\_Xmt\_Mx$ ($mx$) and $Xmt\_Holdoff\_Exponent$ ($exp$). These parameters are included in every MSH-DSCH message. Besides the own parameters every node also includes the parameters of all one-hop neighbours. Thus every node is able to calculate the $Next\_Xmt\_Time\_Interval$ of all nodes in the two-hop-neighbourhood. The IEEE 802.16 standard provides several definitions for these purposes. The $Xmt\_Holdoff\_Time$ ($H$) is the number of MSH-DSCH transmit opportunities after the $Last\_Xmt\_Time$ ($lxmt$) that a node is not eligible to transmit a MSH-DSCH message. It is quantized to 3 bits with a range of 16 to 2048:

$$H = 2^{exp+4} \tag{1}$$

Figure 4 shows an example for the calculation of the $Xmt\_Holdoff\_Time$ for $exp = 1$.

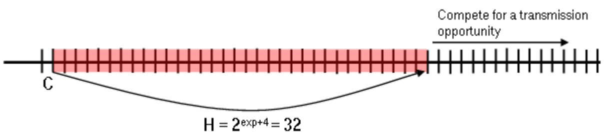


Figure 4: $nxmt$ and $H$ calculation for $exp = 1$

This Figure shows that a node has to wait a minimum of $H$ after $lxmt$ before it can send the next MSH-DSCH message. After $H$ it has to compete with its neighbours for a C-DSCH transmission opportunity in which it is allowed to transmit its next MSH-DSCH message ($Next\_Xmt\_Time$). The $Next\_Xmt\_Time$ is compressed in MSH-DSCH packets to the $Next\_Xmt\_Time\_Interval$ which consists of a series of C-DSCH transmission opportunities and comprises $nxmt$:

$$2^{exp} * mx < nxmt \leq 2^{exp} * (mx + 1) \tag{2}$$

From this it follows that the size of the $nxmti$ is $2^{exp}$. The calculation of $mx$ according to the corresponding $nxmt$ is challenging and described in detail in Section 3.1.

The $Earliest\_Subsequent\_Xmt\_Time$ ($esxmt$) is the earliest time after the $Next\_Xmt\_Time$ that this node is eligible to transmit a MSH-DSCH message:

$$esxmt = nxmt + H + 2^{exp} * mx \tag{3}$$

In figure 5 an example for the $Earliest\_Subsequent\_Xmt\_Time$ for $exp = 1$ is shown.

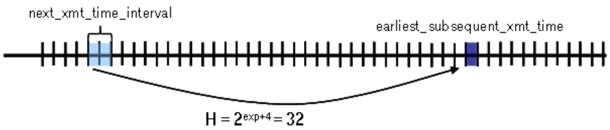


Figure 5: $esxmt$ calculation for $exp = 1$

Figure 6 gives an overview of the mechanism to determine the $Next\_Xmt\_Time$.

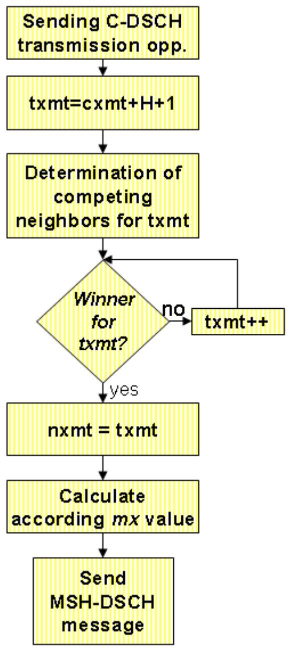


Figure 6: Overview of the mechanisms to determine $nxmt$

A node calculates its own $Next\_Xmt\_Time$ during the $Current\_Xmt\_Time$ ($cxmt$) (i.e., the transmission opportunity when a node transmits its MSH-DSCH message). Therefore the node sets the $Temp\_Xmt\_Time$ ($txmt$) to $cxmt + H + 1$. Now it has to determine the set of eligible competing nodes for this $Temp\_Xmt\_Time$ out of its neighbour table. This set will include the nodes for which:

- $nxmt$ interval of the neighbour includes the $txmt$,
- The $esxmt$ of the neighbour is $\leq txmt$,
- The $nxmt$ of the neighbour is not known.

Figure 7 summarizes these election criteria. A mesh election is held among this set of eligible competing nodes using $Temp\_Xmt\_Time$ as the seed and the node IDs of all eligible competing nodes. If the local node does not win the mesh election, $Temp\_Xmt\_Time$ is

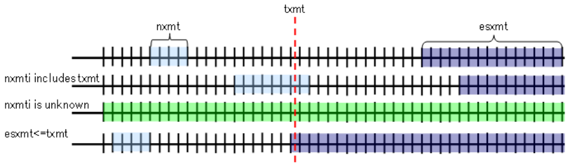


Figure 7: Competing neighbours for a specific $txmt$

set to the next MSH-DSCH transmission opportunity ($txmt = txmt + 1$). Otherwise, the local node is the winner of the mesh election and the $Next\_Xmt\_Time$ is set equal to $Temp\_Xmt\_Time$. As the election is based on the $txmt$ value and the node IDs, the result will be the same on every node. If a node is the winner for a specific transmission opportunity no other node in its two-hop-neighbourhood will win the mesh election for this transmission opportunity. A detailed description of the mesh election-algorithm can be found in [1]. After the $nxmt$ was found the node needs to calculate the corresponding $mx$ value to add it, together with the $exp$ value to the current MSH-DSCH message in order to inform its neighbours about the $Next\_Xmt\_Time\_Interval$. The calculation of the $mx$ value is challenging as it must consider a reference value in order to assure a unique $nxmti$ calculation on the neighbouring nodes. In Section 3.1. the problem is described in detail and a mechanisms is proposed that is able to handle this issue.

### 3.1. Extensions to the EBTT-mechanism

The IEEE 802.16 standard defines only a framework of the distributed scheduling mechanisms. Thus extensions are needed to guarantee a correct functionality. The consistent numbering of C-DSCH transmission opportunities and the reference point calculation for two-hop-neighbours are unstandardised. Thus this paper proposes ideas to meet these demands.

The consistent numbering of C-DSCH transmission opportunities is the basis for the correct operation of the EBTT-mechanism. As the transmission opportunity number is used as the seed value for the election-mechanism it must be equal on all nodes. In the case of an inconsistent numbering the result of the mesh election-algorithm for a specific transmission opportunity would be different on every node. Thus collisions of MSH-DSCH messages are inevitable. For a consistent numbering we propose to use Formula 4 for example to calculate the number of the current transmission opportunity ($cxmt$).

$$cxmt = \left[cfrnr - ceil\left(\frac{cfrnr}{\varsigma * 4 + 1}\right)\right] * \Gamma + past\_opps \tag{4}$$

$cfrnr$ is the current frame number and is known to all nodes as this parameter is distributed regularly within MSH-NCFG messages. Furthermore $\Gamma$ represents $MSH\_DSCH\_NUM$ and $\varsigma$ the $Scheduling\_Frames$ parameter. Both are network parameters known by every node. Finally $past\_opps$ is the number of past C-DSCH transmission opportunities within the current frame and determinable by every node itself. Thus every C-DSCH transmission opportunity (past, current and future) can be identified unique. A consistent numbering is guaranteed even for new nodes currently entering the mesh network.

The previous section describes the mechanism to determine $nxmt$ during $cxmt$. The $mx$ value is used to calculate $nxmti$ in order to inform the neighbours about the interval in which the node will transmit the next MSH-DSCH message. This calculation is challenging as the $mx$ and $exp$ parameters are relative parameters. Therefore a time reference point ($REF$) is needed. This is not an issue for one-hop neighbours as they could use the transmission opportunity in which the MSH-DSCH message was received as reference value. Two-hop neighbours have no information about the transmission time of the original MSH-DSCH message as they will receive the information forwarded by an other node. As the IEEE 802.16 standard does not define this issue we propose to use Formula 5 to calculate a reference point.

$$REF = floor\left(\frac{cxmt}{2^{exp}}\right) * 2^{exp} - H \tag{5}$$

Depending on this reference point every node can calculate the $mx$ value for the determined $nxmt$ using formula 6.

$$mx = floor\left(\frac{nxmt - REF - 1 - H}{2^{exp}}\right) \tag{6}$$

As formula 5 considers the $Current\_Xmt\_Time$ ($cxmt$) every node has to calculate the $REF$ value for $cxmt$ and adapt the $mx$ parameter of every neighbour before it adds these parameters to its own MSH-DSCH message.

### 3.2. Initial results

To find out the impact of the transmission timing parameters $mx$ and $exp$ on the MSH-DSCH transmission frequency a mathematical analysis as well as simulations are performed.

In general the number of C-DSCH transmission opportunities between subsequent MSH-DSCH transmissions of node k is $\xi_k = H_k + S_k$. $H_k$ represents the $Xmt\_Holdoff\_Time$ and $S_k$ the number of transmission opportunities after $H_k$ in which k fails the competition before it wins [5]. To determine the theoretical minimum MSH-DSCH interval ($\tau_{min}$) Formula 7 can be used. This formula describes the most simple scenario with only one mesh node and assumes that this node will always win the first C-DSCH transmission opportunity after $H$. From this it follows $S = 0$ and $\xi_{min} = H$.

$$\tau_{min} = H * \Delta \tag{7}$$

$\Delta$ represents the average time between C-DSCH transmission opportunities and is calculated with Formula 8.

$$\Delta = \frac{\upsilon * (\varsigma * 4 + 1)}{\varsigma * 4 * \Gamma} \tag{8}$$

This formula considers the network parameters $Frame\_Length$ ($\upsilon$), $Scheduling\_Frames$ ($\varsigma$) and

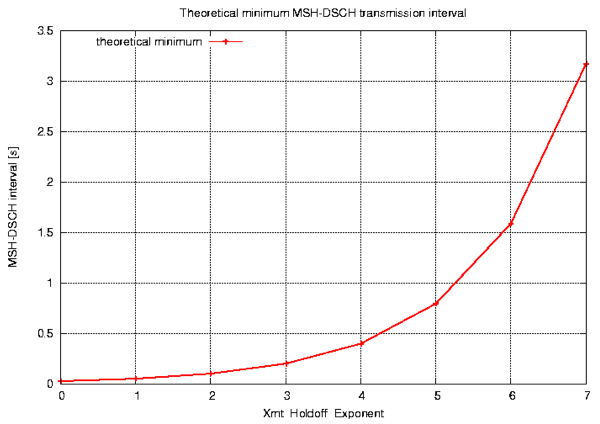


Figure 8: Analytical results on the minimum MSH-DSCH transmission interval

| Parameter | Value |
|---|---|
| Scenario | Grid 8x8+1, 65 nodes |
| Frame length | 10ms |
| MSH_CTRL_LEN | 3 |
| MSH_DSCH_NUM | 3 |
| Scheduling_Frames | 3 |
| Distance between nodes | 275m |
| Transmission range | ≈560m |
| Simulation duration | 50s |

Table 1: Simulation parameters

$MSH\_DSCH\_NUM$ ($\Gamma$). Figure 8 presents the theoretical minimum MSH-DSCH interval with different $exp$ values determined using Formulas 7 and 8.

It can be seen that increasing the $exp$ parameter of course raises the interval between subsequent MSH-DSCH messages since the $Xmt\_Holdoff\_Time$ is increased.

For more realistic results mesh scenarios with multiple mesh nodes need to be investigated. In this case a mathematical analysis can not consider all parameters which have influence on the MSH-DSCH transmission interval. Thus the network simulator ns2 is used for these purposes. Therefore we have developed a mesh module for ns2 that is based on the IEEE 802.16 standard. This module already includes the extensions described before and is able to simulate complex mesh scenarios with hundreds of nodes. The simulation parameters are listed in Table 1. As simulation scenario a equilateral grid with 64 M-SSs is selected. The M-BS is placed in the middle of the grid and the distance between neighbouring M-SS is 275m. An overview of this scenario can be found in Figure 9.

Figure 10 compares the minimum MSH-DSCH transmission interval with the average interval of all mesh nodes and the average interval of the M-BS. It is obvious that the average MSH-DSCH transmission interval of all nodes is two times higher compared to the theoretical minimum. The reason for this is that it is not guaranteed that a node will win the first transmission opportunity after $H$ as it has to compete with its one- and two-hop neighbours. Furthermore the average transmission interval of the M-BS is again two times higher compared to the average interval of all nodes. As the M-BS is placed in the middle of the grid, it is the node with the most neighbours and thus the most competitors. On this account it will lose more transmission opportunities before the $Next\_Xmt\_Time$ is found compared to nodes that are placed at the edge of the grid. This is a severe problem as M-BS will always be placed in the middle of a mesh network in order to cover many nodes. Furthermore M-BSs are traffic aggregation points as they forward packets to the Internet. Therefore they need to react fast on changing traffic demands and thus need small MSH-DSCH transmission intervals. From Figure 10 it can be seen that the actual version of the distributed scheduler is not able to fulfil these requirements.

To solve this, mechanisms and enhancements are needed that are able to reduce the MSH-DSCH transmission interval. One solution could be a mechanism that dynamically adapts the $exp$ value independently on every node. An other solution could be an optimization of the current mechanism. This optimization is the focus of this paper and will be described in the following section.

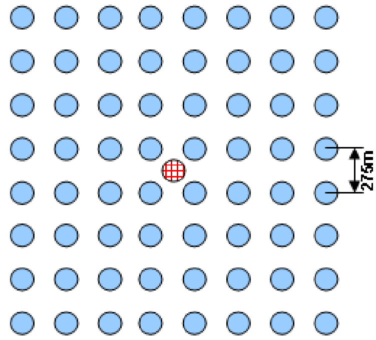


Figure 9: Simulation scenario (8x8 grid + 1 M-BS)

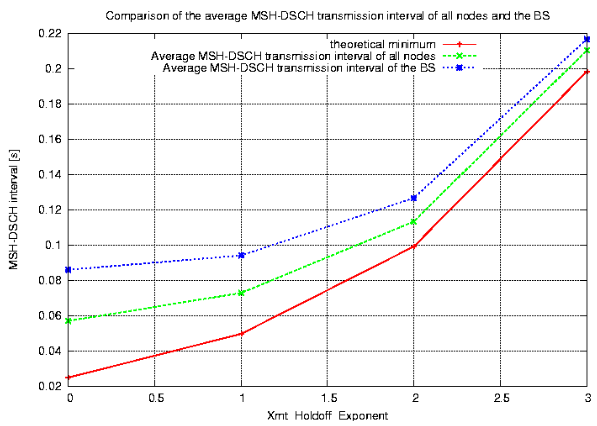


Figure 10: Simulation (scenario: grid 8x8 + 1 M-BS) and analytical results on the MSH-DSCH transmission interval

## 4. Optimized EBTT-mechanism

To reduce the interval between subsequent MSH-DSCH messages, we propose the following solution. Equation 1 calculates the $Xmt\_Holdoff\_Time$. It can

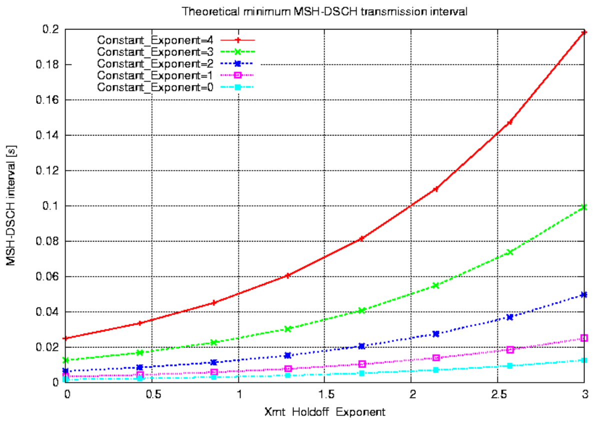


Figure 11: Analytical results on the minimum MSH-DSCH interval with varying $Constant\_Exponent$ values

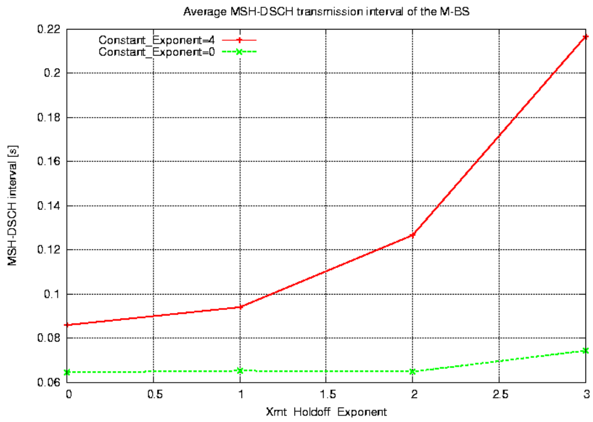


Figure 12: Simulation results on the average MSH-DSCH transmission interval of the M-BS with varying $Constant\_Exponent$ values (scenario: grid 8x8 + 1 M-BS)

be seen that even for $exp = 0$ the minimum value of $H$ is $2^4$. Even in this case a node has to wait a minimum of 16 transmission opportunities before it can send the next MSH-DSCH message. From our point of view the $Constant\_Exponent$ value of 4 is not optimal. So we propose to decrease this value. Figure 11 shows the theoretical minimum MSH-DSCH transmission interval calculated using formula 7 and 8 but in contrast to the previous results with different values for the $Constant\_Exponent$ parameter.

It can be seen that a decreased $Constant\_Exponent$ value is able to reduce the theoretical minimum transmission interval significantly. Again the network simulator ns2 is used for more realistic investigations. The simulations presented in Section 3.2. are repeated with the parameters in Table 1 but with variable values of the $Constant\_Exponent$ parameter. The simulation results presented in Figure 12 compare the average MSH-DSCH transmission interval of the M-BS using a $Constant\_Exponent$ value of 4 and 0. It can be seen that our enhancement is also able to reduce the average MSH-DSCH transmission interval in a realistic scenario significantly.

To find out the impact on data packets further simulations are performed. The current version of the mesh module in ns2 uses a basic data packet scheduler. This scheduler is not able to handle complex data traffic. Thus a simple one-hop simulation scenarios is selected. The scenario comprises a grid of four nodes with a M-BS in the middle of the grid. To determine the data packet delay the ping application of ns2 is used to measure the round trip time (rtt). The rtt is the time a packet needs from source to destination and the other way around. Only one of the M-SSs generates ping packets and sends them to the M-BS. The ping interval is 0.5s with a seed of 0.2s. Figure 13 compares the rtt using the standard and the enhanced EBTT-mechanism. It presents the rtt for every ping packet and also the regression line for a better comparability. It can be seen that the enhanced EBTT-mechanism is able to nearly half the average rtt.

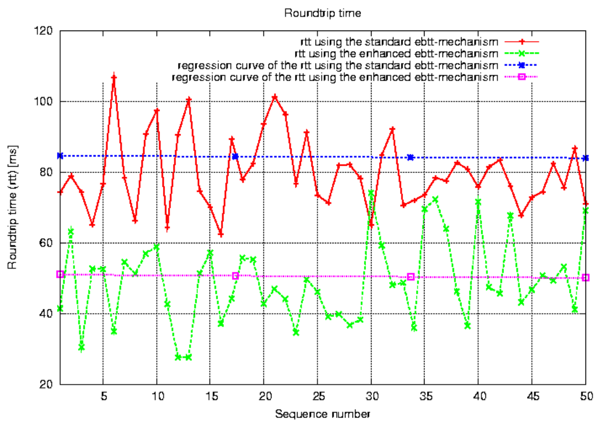


Figure 13: Simulation results on the round trip time using the standard and the enhanced EBTT-mechanism (scenario: grid 8x8 + 1 M-BS)

## 5. Conclusions

This paper describes the election based transmission timing mechanism defined in the IEEE 802.16 standard that times transmissions of MSH-DSCH messages in 802.16 based mesh networks. It presents the influence of this mechanism on the overall network performance and proposes extensions to the mechanism that are needed to guarantee a correct functionality. Using the network simulator ns2 it can be shown that in dense networks the interval between subsequent MSH-DSCH messages is very large and thus causes significant delay on data packets. The paper presents an extension to the EBTT-mechanism to solve this problem. Simulations show that the adoption of this mechanism reduces the transmission interval. Furthermore also the delay on data packets caused by the MAC layer is reduced significantly.
Our future work will consider a dynamic $exp$ adaptation mechanisms to meet QoS requirements. For example nodes with delay sensitive traffic shall use smaller $exp$ values. Nodes that are not part of an active route shall use high $exp$ values in order to reduce the competition within the mesh network. An other issue is the com-

bination of coordinated and uncoordinated distributed scheduling in order to further reduce the transmission interval. Furthermore the assignment of transmission opportunities in the data-subframe will be considered with respect on QoS constraints.

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