Improving the Performance of the Distributed Scheduler in IEEE 802.16 Mesh Networks[1]

Nico Bayer, Bangnan Xu
T-Systems Enterprise Services GmbH
64295 Darmstadt, Germany
{Nico.Bayer, Bangnan.Xu}@t-systems.com

Veselin Rakocevic
School of Engineering and
Mathematical Sciences
City University, London, UK

Joachim Habermann
University of Applied Sciences
Giessen-Friedberg
61169 Friedberg, Germany

***Abstract*— Wireless mesh networks are a viable solution to provide broadband wireless access (BWA) in a cost efficient and flexible manner. The IEEE 802.16 standard is currently one of the most interesting BWA standards. Besides the popular point-to-multipoint mode it defines an optional mesh mode. This paper evaluates the performance of the coordinated distributed scheduler (C-DSCH), defined by the IEEE 802.16 standard for mesh mode. Analytical as well as simulation results show, that this mechanism has a scalability problem that leads to poor performance in dense networks and aggravates QoS provisioning. To solve this, a dynamic adaptation mechanism is proposed, that is able to reduce the contention and to enhance the performance (throughput) in dense networks.**

I. Introduction

Wireless mesh networks (WMNs) are a viable solution to realise broadband wireless Internet access in a flexible and cost efficient manner as these networks are easy to install and can be extended quickly, simply by adding new mesh nodes. Thus, WMNs can be used to extend cell ranges, cover shadowed areas, and enhance system throughput. QoS support in such networks is essential to support voice, video and data ("Triple Play") services. The mesh mode in the IEEE 802.16 standard [1] is a promising approach, able to fulfil these requirements. Like other IEEE standards it defines the PHY layer and the MAC layer. For the mesh mode the use of OFDM is defined for frequencies between 2 and 11 GHz and the MAC layer is based on time division multiple access (TDMA) to support multiple users.

This paper evaluates the performance of the coordinated distributed scheduler (C-DSCH) defined by the IEEE 802.16 standard for mesh mode operation. An analytical model as well as simulations are used for these purposes. The mathematical model presented in this paper is an enhancement of the model presented in [2]. For the simulator a custom IEEE 802.16 mesh module has been developed for the network simulator NS-2 [3].

It was found that the C-DSCH mechanism has a scalability problem that leads to poor performance in dense networks and aggravates QoS provisioning. This scalability problem results from the election based transmission timing mechanism (EBTT) which is responsible for scheduling the transmission of signalling messages used by the C-DSCH mechanism. This paper proposes a dynamic adaptation mechanism to counteract the scalability problem and to reduce the network contention in order to enhance the performance in dense networks.

The rest of the paper is organised as follows. Section II provides an overview of the IEEE 802.16 mesh mode TDMA frame structure as well as the distributed scheduling mechanism. Section III presents a mathematical model and a performance analysis of the distributed scheduler. In particular, the influence on the maximum achievable throughput per node is evaluated. Section IV proposes a dynamic adaptation mechanism able to enhance the performance of the distributed scheduler in dense networks. Also the improvements of UDP throughput in multi-hop scenarios is evaluated. Finally, Section V concludes the paper.

II. The IEEE 802.16 Mesh Mode

A. TDMA frame structure

In IEEE 802.16 mesh mode the length of the TDMA frame is defined by the $Frame\_Length$ parameter and the frame is divided into the control-subframe and the data-subframe. 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 (time slots). Transmission opportunities in the data-subframe are called minislots (MSs). According to [1], the length of a MS (S_{MS}) is calculated with the following formula:

$$S_{MS} = ceil\left[\frac{(\#_{Symb} - MSH\_CTRL\_LEN \cdot 7)}{256}\right] \quad (1)$$

In this formula, $\#_{Symb}$ represents the number of OFDM symbols per frame and depends on the channel bandwidth and the frame length. Furthermore, the (MSH_CTRL_LEN) parameter is a network parameter and stands for the number of transmission opportunities in the control-subframe. It 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

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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 mesh subscriber stations (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. The first part is for messages that belong to the centralised 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 $MSH\_CTRL\_LEN - MSH\_DSCH\_NUM$.

B. The Coordinated Distributed Scheduler

The assignment of transmission opportunities in the data-subframe is managed by a scheduling mechanism. The IEEE 802.16 standard defines two scheduling principles: centralised and distributed. This paper concentrates on the coordinated distributed scheduling mechanism (C-DSCH) which employs a three-way handshake to request, grant, and confirm transmission opportunities in the data-subframe. These Requests, Grants, and Confirmations are carried within MSH-DSCH messages that are sent within the C-DSCH part of the schedule-control-subframe. This paper analyses the transmission timing of these MSH-DSCH messages, as it has much influence on the overall network performance.

The transmission timing of MSH-DSCH messages is based on the election based transmission timing (EBTT) mechanism. This mechanism supports distributed coordinated transmission timing of periodic broadcast messages in a multi-hop network without explicit schedule negotiation. It provides collision-free and fair transmissions within the two-hop neighbourhood of each node. A transmission time is similar to a specific transmission opportunity and both expressions are used synonymously in this paper.

A node calculates the next transmission time ($nxmt$) during its current transmission time ($cxmt$). The standard defines, that after the $cxmt$ a node is not allowed to transmit for the $Xmt\_Holdoff\_Time$ (H). H is defined as

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

in which exp is the $Xmt\_Holdoff\_Exponent$ parameter that is managed by every node itself and has a size of three bits. Thus, exp can have a value between 0 and 7. After H, a node has to compete for a transmission opportunity with all of its two-hop neighbours using information about the next transmission interval of these nodes and as well as their exp values. A mesh election is held among this set of eligible competing nodes and the local node until the $nxmt$ is found. Finally, the node must include information about the next transmission time into the current MSH-DSCH message, in order to inform all two-hop neighbours and to avoid collisions of MSH-DSCH messages. Therefore, the local node compresses the $nxmt$ in the next eligibility interval $nxmti$, which is a series of one or more C-DSCH transmission opportunities that includes $nxmt$ and is defined as follows:

$$2^{exp} \cdot mx < nxmt \leq 2^{exp} \cdot (mx + 1) \tag{3}$$

The mx parameter has a size of 5 bits and can identify exactly 32 blocks, where every block consists of 2^{exp} C-DSCH transmission opportunities. mx is set to the number of the block that includes the $nxmt$ of the node. The first block starts at $cxmt$. If $nxmt$ is far from $cxmt$, the mx value is large. Thus, mx is appropriate to be used as a contention indicator.

Details about the mesh election-algorithm as well as the EBTT mechanism can be found in [1].

III. The MSH-DSCH Transmission Interval and its Influence on Network Performance

From the description in Section II, it follows that the MSH-DSCH transmission interval (number of C-DSCH transmission opportunities between subsequent MSH-DSCH messages) of node k (τ_{S_k}) depends on the $Xmt\_Holdoff\_Time$ (H_k) and the number of slots in which a node lost the election against the competing neighbours (S_k):

$$\tau_{S_k} = H_k + S_k \tag{4}$$

H_k can be determined easily, as it is simply the $Xmt\_Holdoff\_Time$ and can be calculated using Formula (2). However, the determination of S_k is much more complicated as it depends on many parameters like the number of competing neighbours as well as the exp values that they use. In [2] the following formula is proposed to calculate S_k which can be solved using fixed point iteration:

$$E[S_k] = \sum_{j=1, j\neq k, exp_j \geq exp_k}^{N_k^{known}} \frac{2^{exp_j} + E[S_k]}{2^{exp_j+4} + E[S_j]} + \left(\sum_{j=1, j\neq k, exp_j < exp_k}^{N_k^{known}} 1\right) + N_k^{unknown} + 1 \qquad k = 1, ..., N \tag{5}$$

In this formula, N_k^{known} represents the number of competing neighbours whose next transmission timing is known to node k and $N_k^{unknown}$ are competitors whose next transmission timing is not known to node k. It can be seen that if the number of competing neighbours of node k increases, S_k and thus τ_{S_k} increase as well. From this, it follows that in sparse networks mesh nodes can request bandwidth much more flexibly than in dense networks as the interval between subsequent MSH-DSCH messages of a node is much smaller.

More important than the number of C-DSCH transmission opportunities between MSH-DSCH messages is the time between subsequent MSH-DSCH transmissions of a node (τ_T).

This time depends on the network parameters $Frame\_Length$ (υ), MSH_DSCH_NUM (Γ) and $Scheduling\_Frames$ (ς). These parameters influence the density of C-DSCH transmission opportunities and thus τ_T. They have been discussed in detail in Chapter II-A.

Formula (6) calculates the time between subsequent MSH-DSCH transmissions (τ_{T_k}) of node k based on τ_{S_k} and the network parameters.

$$\tau_{Tk} = \tau_{Sk} \cdot \frac{\upsilon \cdot (\varsigma \cdot 4 + 1)}{\varsigma \cdot 4 \cdot \Gamma} \quad (6)$$

The analytical evaluations presented in this section are based on a collocated scenario (all nodes are one-hop neighbours), in which all nodes use static and identical exp values. Thus, Formula (5) is simplified, as $N_k^{unknown} = 0$ and $E[S_k] = E[S_j]$. Furthermore, Formula (5) was found to be imprecise for sparse networks, as it does not consider the fact, that unless $N \leq \frac{2^{exp+4}}{2^{exp}} = 16$, enough transmission opportunities are available and that contention can be neglected. Thus, the resulting formula to calculate τ_T is:

$$\tau_T = \begin{cases} (H+1) \cdot \frac{\upsilon \cdot (\varsigma \cdot 4+1)}{\varsigma \cdot 4 \cdot \Gamma} & \text{for } N \leq 16 \\ \left(H + (N-1)\frac{2^{exp}+E[S]}{2^{exp+4}+E[S]} + 1\right) * \frac{\upsilon \cdot (\varsigma \cdot 4+1)}{\varsigma \cdot 4 \cdot \Gamma} & \text{for } N > 16 \end{cases} \quad (7)$$

Besides the analytical model, a simulator based on the IEEE 802.16 mesh mode has been developed for network simulator NS-2. The Optimized Link State Routing (OLSR) protocol [4] is used for routing. The results presented in this section are performed using a grid scenario with varying number of nodes in which the mesh base station (M-BS) is placed in the middle of the grid. To realise a collocated scenario, the distance between neighbouring nodes is set to 50 m. Table I lists the parameters used for the simulations as well as for the mathematical analysis.

Parameter	Value
Scenario	Grid - 5, 17, 37, 65 nodes
Frame length (υ)	10 ms
MSH_CTRL_LEN	10
MSH_DSCH_NUM (Γ)	5
Scheduling_Frames (ς)	2
Max. transmission range	$\approx$ 560 m
Contention threshold (ψ)	15
Max. requestable MSs (θ)	165
Bytes per OFDM symbol (ρ)	108 (64-QAM_3/4)
Symbols per MS (S_{MS})	1
exp_{BS}^{max}	0
exp_{Act}^{max}	0
exp_{SN}^{max}	2
exp_{BS}^{max}	7

TABLE I
PARAMETERS FOR SIMULATIONS AND CALCULATIONS

Figure 1 shows the MSH-DSCH transmission interval for different network sizes and different exp values obtained through the analytical approach based on Formula (7), as well as simulations. It can be seen, that simulation and analytical results match very well and that increasing the exp parameter raises the interval between subsequent MSH-DSCH messages since the $Xmt\_Holdoff\_Time$ is increased. Furthermore, increasing the node density raises the transmission interval due to the increased network contention and the fact that nodes will lose more transmission opportunities before $nxmt$ is found. Comparing the results for $exp = 0$, it can be seen, that τ_T for $N_k = 64$, is more than three times larger compared to $N_k = 16$. A further observation that can drawn is that large exp values lead to constant transmission intervals and are more robust against increased network contention.

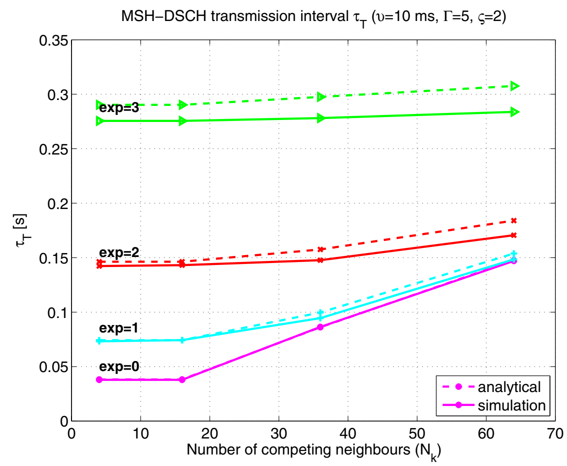

Fig. 1. MSH-DSCH transmission interval τ_T in collocated scenario with static exp usage for different network sizes

This scalability problem of the IEEE 802.16 mesh mode is a serious problem for QoS provisioning as it influences the delay, jitter and bandwidth of data packets. For instance, best effort traffic should be scheduled on a per packet basis without any continuous reservations. This means, that a node only requests as much bandwidth (resources), needed to deliver all packets that are currently in its queue. Thus, these packets can only be transmitted after the three-way-handshake has been performed. To avoid users requesting all available slots and thus blocking other users, the number of slots that can be requested within one request phase is limited (θ). Thus, the maximum bandwidth that can be achieved, depends on a frequency at which a node can send requests, (within MSH-DSCH messages) τ_{Tk}, as well as the information density, which is a product of θ, the number of bytes that can be transmitted within one OFDM symbol (ρ) and the number of OFDM symbols per minislot (S_{MS}) and is calculated with:

$$BW_k = \frac{\theta * \rho * S_{MS}}{\tau_{Tk}} \quad (8)$$

In Figure 2, the maximum bandwidth between neighbouring nodes is shown, again for the collocated scenario, with static and identical exp values. For meaningful results, the bandwidth is expressed in MSs per second assigned by the BS to the requester in order to transmit its data packets. Therefore, Formula (8) is simplified and S_{MS} and ρ are set to 1. The network configuration is equal to the configuration described above. Again, the simulation and analytical results match very well and are in line with the results in Figure 1. It can be seen that, for small exp values, the maximum bandwidth decreases rapidly as the number of neighbours increases. This means that the maximum bandwidth in dense network parts is smaller compared to sparse network parts. This is a severe problem as M-BSs mostly have a central location in order to cover many nodes. Thus, they will have many competing neighbours which results in poor network performance. Furthermore, the bandwidth using large exp values is more stable as the network contention has not as much influence.

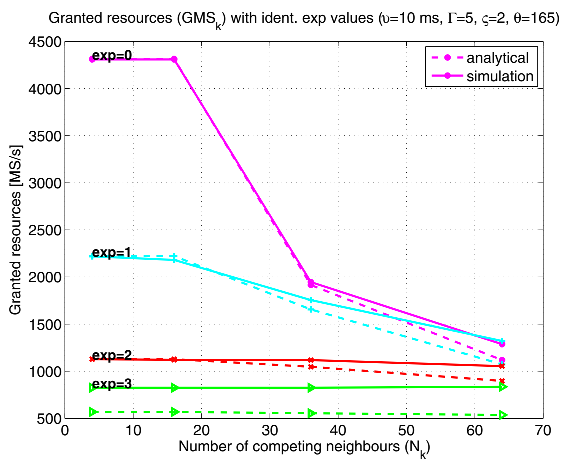

Fig. 2. Maximum granted MSs between neighbouring nodes in collocated scenario with static exp usage for different network sizes

To overcome this scalability problem, enhancements are needed in order to improve the performance of the IEEE 802.16 mesh MAC layer in dense networks. In [5], an optimisation is presented, able to improve the performance of the distributed scheduler in sparse networks by decreasing H. In dense networks, the network contention is the dominating factor. Thus, the next section presents a mechanism aiming to increase the network performance by decreasing the network contention.

IV. The DynExp optimisation mechanism

From Formula (5) it can be seen that increasing exp and thus H reduces the network contention. Therefore, instead of using a static exp value Section IV-A proposes an enhancement of the EBTT-mechanism, DynExp, that dynamically adapts the exp parameter on every node in order to reduce the network contention. Section IV-B contains simulation results that show the performance improvements of DynExp.

A. DynExp details

The general idea of this mechanism is that nodes that are currently not sending, receiving or forwarding data packets use large exp and thus large H values. However, nodes that do transmit/receive/forward data packets or nodes that have been selected by the routing protocol as potential forwarding nodes use small exp and thus small H values. For this purpose, several node states are defined:

- Mesh base station (M-BS): This is a normal base station node.
- Active node (ACT): This is a node that is part of an active route and does send, receive or forward data packets.
- Sponsoring node (SN): This node is not part of an active route but has been selected as a potential forwarding node by at least one of its neighbours.
- Inactive node (IN-ACT): This is a node that is not part of an active route and thus does not send, receive or forward data packets.

Depending on these node states, different maximum exp values are defined:

$$0 \leq exp^{max}_{M-BS} \leq exp^{max}_{ACT} < exp^{max}_{SN} < exp^{max}_{IN-ACT} \leq 7$$

As M-BSs are traffic aggregation points, they need small MSH-DSCH transmission intervals and thus use small exp^{max}_{M-BS} values. This also applies to ACTs and they use small exp^{max}_{Act} values as well. To support different traffic classes exp^{max}_{Act} could be further divided between realtime and non-realtime traffic. However, in this paper only BE (best-effort) traffic is considered. SNs are not part of an active route, thus, they do not need very small transmission intervals. However, as they are potential forwarding nodes, the interval should not be too large in order to reduce the connection setup time. Inactive nodes have the lowest priority and thus, use the largest interval. For the determination of the node status, a cross-layer approach is applied, using routing layer information.

During network operation, mesh nodes need to adapt their exp values according to the network contention and the exp^{max} values according to the node's status. The increment mechanism considers the node's status as well as the network contention. As contention indicator, the mx value is used. Nodes only increment their exp value up to maximum value exp^{max}. The increment mechanism is initiated in the following cases:

- A node's mx value, that has been calculated for the $nxmt$ has exceeded a specified threshold (ψ).
- A node has detected that one of its neighbours used an mx value that exceeded a specified threshold (ψ).

The decrement mechanism considers only the change of the node status and is initiated in the following cases in which nodes change their status to a higher priority status:

- An IN-ACT, SN, ACT changes its status to a M-BS.
- An IN-ACT or SN changes its status to an ACT.
- An IN-ACT changes its status to a SN.

The whole mechanism is shown in Figure 3.

B. Performance analysis

To evaluate the improvements of the proposed mechanism, simulations based on the scenario presented in the previous section are repeated. Again the network configuration listed

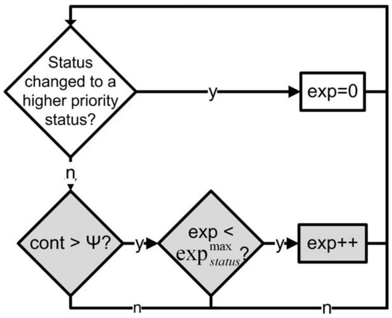

Fig. 3. Dynamic exp adaptation mechanism

in Table I is used. To realise multi-hop scenarios, the distance between neighbouring nodes is set to 275 m. One UDP connection with different number of hops is simulated between one M-SS and the M-BS. All other nodes do not transmit any data packets to mitigate cross-traffic influences.

The improvements of the DynExp mechanism on the network performance is depicted in Figure 4. This figure compares the maximum UDP throughput with and without DynExp optimisation for different node densities as well as different number of hops. It can be seen, that the DynExp mechanism has no influence in the 5 node scenario, as network contention can be neglected. However, in dense networks, it is able to increase the UDP throughput significantly in single-hop as well as multi-hop scenarios. This can be explained by a decreased network contention and thus a decreased MSH-DSCH transmission interval. Furthermore, it can be seen that compared to the single-hop scenario, the multi-hop scenarios can achieve comparable results. The reason for this observation is simply the fact that the maximum requestable bandwidth is limited and thus, enough resources are available which can be used for the multi-hop communication. Of course in an overloaded scenario, in which all stations have traffic to send, DynExp will show no improvements. Anyway, in such a case the mesh performance will be bad. Thus, admission control mechanisms are needed to avoid this.

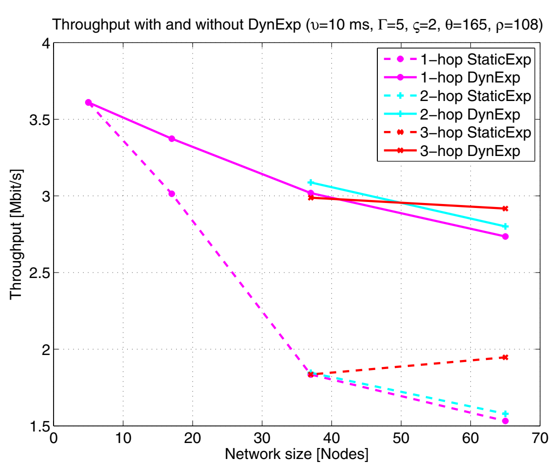

Fig. 4. Single-hop and multi-hop UDP throughput with and without DynExp optimisation in grid scenario with different network sizes

To confirm that the DynExp mechanism is able to reduce the network contention, Figure 5 compares the MSH-DSCH transmission interval (τ_T) of the M-BS with and without DynExp optimisation for the 65 node scenario. It can be seen, that the DynExp mechanism is able to decrease the MSH-DSCH transmission interval significantly, as inactive nodes increase their exp values and thus increase H in order to decrease the network contention.

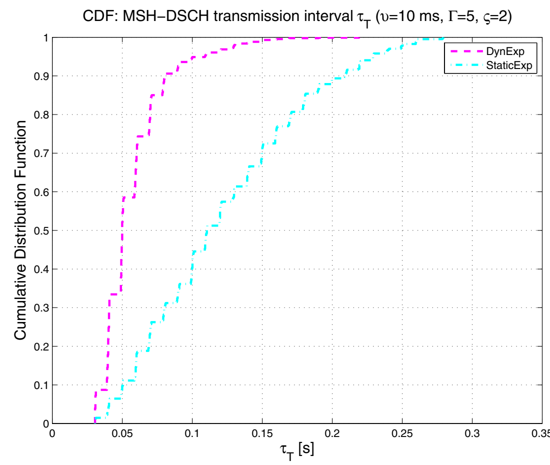

Fig. 5. Cumulative distribution of M-BS MSH-DSCH transmission interval for grid scenario with 65 nodes with and without DynExp optimisation

V. Conclusion

This paper presents an analysis of the distributed scheduler (C-DSCH) defined in the IEEE 802.16 standard. A mathematical model as well as simulations are used for these purposes. It was found, that the C-DSCH mechanism has a scalability problem that leads to poor performance in dense networks. To overcome this, the DynExp optimisation is proposed, which is able to decrease the contention in dense networks by dynamically adapting the $Xmt\_Holdoff\_Time$ on every node based on the network contention as well as the node status. In particular, the improvements of DynExp on the network throughput is investigated for single-hop and multi-hop scenarios.

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