XIV del 1 al 5 de diciembre de 2008
CONVENCIÓN CIENTÍFICA
DE INGENIERÍA Y ARQUITECTURA

ANIVERSARIO 44 cujae 2008

An On-demand Scheduling Mechanism for TDMA based Wireless Mesh Networks

Nico Bayer*, Bangnan Xu*, Veselin Rakocevic+, Joachim Habermann°

*Deutsche Telekom/T-Systems, Darmstadt, Germany, Nico.Bayer@t-systems.com
+School of Engineering and Mathematical Sciences City University, London, UK
°University of Applied Sciences Friedberg, Germany

***Abstract*— Wireless Mesh Networks (WMNs) are seen as a means for providing last mile connections in a flexible and cost effective manner, due to the multi-hop as well as self-configuration and self-organising capabilities. Recently it was shown, that WMNs based on the IEEE 802.11 standard are not able to meet the carrier-grade requirements of a network operator. This is mainly caused by the random MAC protocol. It is generally regarded, that TDMA MAC protocols are better suited to provide carrier-grade services, due to their controlled access nature and the explicit resource reservation. This paper proposes an on-demand scheduler for TDMA based WMNs. This scheduler is integrated into the coordinated distributed scheduling framework of the IEEE 802.16 mesh standard. Results of the performance investigation will discussed for the clique network scenario and TCP traffic. Also the influence of the recently proposed ConstExp optimisation and the DynExp mechanism on the performance of the on-demand scheduler will be analysed.**

***Key Words* — carrier-grade, IEEE 802.16, multi-hop, scheduling, TDMA, WiMAX, wireless mesh.**

I. Introduction

WMNs are increasingly becoming a viable solution for network operators to realise broadband wireless Internet access in a flexible and cost efficient manner [1]. The main characteristic of a WMN is the ability to communicate between nodes over multiple wireless hops in order to increase the radio coverage, to cover shadowed areas, and to enhance system performance. Due to this multi-hop communication, network connectivity between stations that are outside each others transmission range is enabled. This is completely in contrast to traditional single-hop networks in which communication between two stations can only happen in case both stations are within each others transmission range.

Typically, WMNs have a hierarchical setup. The core of the WMN is the wireless backbone which is formed by Mesh Points (MPs). A MP is a node which fully supports mesh relaying, meaning that it is capable of forming an association with its neighbours and forwarding traffic on behalf of other MPs. This backbone infrastructure is self-configuring and self-healing. To realise multi-hop communication in the backbone, a multi-hop routing protocol is running on each MP. To provide client access to the mesh network, special types of MPs are necessary: the Mesh Access Points (MAPs). MAPs are MPs extended with the functionality to offer non-mesh capable client devices a connection to the WMN. The top of the hierarchy constitutes a Mesh Point Portal (MPP). The MPP bridges traffic between different WMNs or connects the WMN to the Internet. Any traffic entering or leaving the WMN towards the Internet has to pass through one of those MPPs.

The promises of WMNs have triggered advances at various levels. Firstly, vendors are pushing their proprietary mesh products. Secondly, community mesh networks grow to provide connectivity and capacity. Thirdly, research testbeds are in development. Finally, standardisation activities are focusing on multi-hop mesh networks for broadband wireless access, including Institute of Electrical and Electronics Engineers (IEEE) 802.11s and the IEEE 802.16 [2] initiatives.

However, from a network operator's point of view such a network also needs to fulfil carrier-grade requirements. Recently it was shown that random access protocols (e.g.

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)) are not able to provide carrier-grade services in highly loaded situations. In fact controlled access protocols based on Time Division Multiple Access (TDMA) are well suited and enable high Quality of Experience (QoE) even in highly loaded networks. However, TDMA based Medium Access Control (MAC) protocols are complex and especially the scheduling mechanism has much influence on the network performance. In this paper the coordinated distributed scheduling framework as defined by the IEEE 802.16 mesh standard is adopted and the on-demand scheduler is proposed. By the means of simulations, the performance of the on-demand scheduler is analysed for the clique scenario. In detail, the influence on Transmission Control Protocol (TCP) throughput will be investigated. Recently, in [3] and [4] we proposed two mechanisms to increase the performance of the distributed scheduler. The influence of these mechanisms on the on-demand scheduler performance will also be discussed.

The rest of the paper is organised as follows: Section II presents the TDMA frame structure used within this paper. Section III discusses the coordinated distributed scheduling framework as specified by the IEEE 802.16 standard. Also the on-demand scheduler proposed by this paper is handled in detail. Section IV is about the simulation environment as well as the simulation scenario and parameters. In addition, the performance evaluation metrics are defined. Section V discusses the simulation results and analyses the performance of the on-demand scheduler. Finally Section VI concludes this paper.

II. Mesh TDMA Frame Structure

The TDMA frame structure used within this paper is based on the IEEE 802.16 standard (see Figure 1). The length of the TDMA frame is defined by the *Frame Length (FL)* parameter (e.g. 4 ms, 10 ms) and the frame is divided into the control-subframe and the data-subframe.

Slots in the *control-subframe* are called Transmission Opportunities (TOs) and they are used only for the transmission of signalling messages. A TO consists of seven Orthogonal Frequency Division Multiplex (OFDM) symbols and the length of the control-subframe in TOs is defined by the *MSH_CTRL_LEN* parameter. The control-subframe serves several functions: the network control in which specific slots can be used by new nodes for initial joining of the mesh network, periodic broadcasting of network configuration messages to distribute the network configuration within the whole network and the scheduling control in which messages belonging to the scheduling mechanism can be transmitted. The *Scheduling Frames* parameter defines how many frames can be used for schedule control between two frames for network control in multiples of four frames.

Slots in the *data-subframe* are called mini-slots (MSs) and they are mainly used for the transmission of data packets. The scheduling mechanism is responsible for allocation and reservation of MSs in the data-subframe. A schedule allocation in the data-subframe consists of one or more MSs. A series of MSs allocated for a mesh station is called a burst in which a station can send one or more MAC packet data units (PDUs).

To coordinate the usage of MSs in the data-subframe the standard defines two scheduling frameworks: centralised and distributed. These two techniques do not necessarily have to be independently implemented in the network; a network is free to implement both techniques concurrently. The *centralised scheduler* applies a two-way-handshake to request and grant resources in the data-subframe. In particular, normal MPs request resources from the MPP and the MPP grants TOs among all requesting nodes.

Using the *distributed scheduler*, MPs compete for bandwidth based on the two-hop extended neighbourhood of the two communicating MPs, where a neighbourhood includes all the one-hop neighbours of a given MP. Distributed scheduling can be further divided into coordinated distributed scheduling and uncoordinated distributed scheduling. Coordinated distributed scheduling allows mesh nodes to transmit distributed scheduling signalling messages (MSH-DSCH) requesting bandwidth in the control-subframe in a collision-free manner, whereas for uncoordinated scheduling, MSH-DSCH messages are sent in free MSs of the data-subframe where they may collide. MPs are free to use either method for distributed scheduling. The *MSH_DSCH_NUM* parameter defines how many TOs in the control-subframe are reserved for the coordinated distributed scheduler.

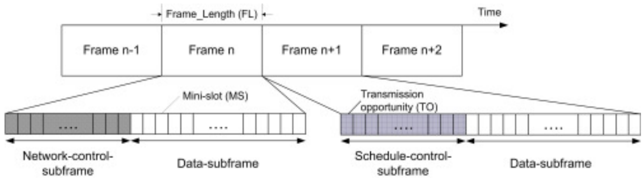


FIGURE 1
TDMA FRAME STRUCTURE

This paper adopts the coordinated distributed scheduling framework as it was found for instance in [5] that the centralised approach has several shortcomings, e.g. scalability, reliability, etc. However, the IEEE 802.16 standard does not define the exact scheduling rules and mechanisms. Therefore, in Section III after presenting the distributed scheduler in detail, the paper proposes the on-demand scheduler that can be compared with the Distributed Coordination Function (DCF) of the IEEE 802.11 standard but works in a collision-free way.

III. The Distributed Scheduling Framework and the On-demand Scheduler

In the distributed scheduler, in order to reserve bandwidth for data transmission between two MPs, whether for direct communication or communication to the MPP, a three-way handshake mechanism is used. Messages of this handshake are sent within information elements (IEs) of MSH-DSCH messages. In order to explain the three-way handshake method, the example network shown in Figure 2 will be used.

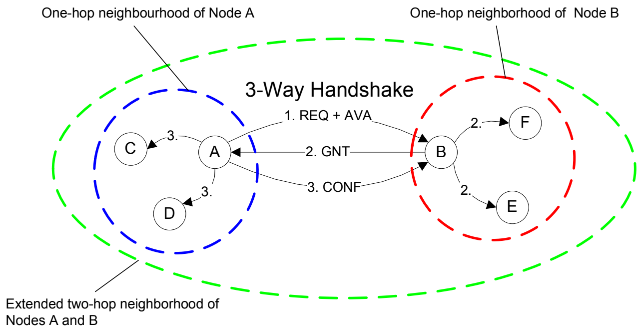


FIGURE 2
THREE-WAY HANDSHAKE OF THE DISTRIBUTED SCHEDULER

If node *A* has data to send to node *B*, node *A* will initiate the three-way handshake by sending a request (REQ) carried within the MSH-DSCH{Request} IE together with an availability (AVA) which is carried in the MSH-DSCH{Availability} IE to node *B* listing the required bandwidth and available MSs of node *A*. All one-hop neighbours of node *A*, namely nodes *C* and *D* also receive these messages and in order to avoid that MSs are assigned multiple times, they mark these MSs as unavailable. Node *B* will choose enough MSs from that list to fulfil the bandwidth requirement and will reply with a grant (GNT) carried within the MSH-DSCH{Grant} IE listing the MSs to be used for communication between nodes *A* and *B*. All the nodes in the one-hop neighbourhood of node *B*, namely nodes *E* and *F*, will also receive the GNT and know to reserve the MSs (mark the MSs as unavailable) used between nodes *A* and *B*. Node *A* must now send a confirmation (CONF) (which is simply a copy of the GNT) in order to confirm the receipt of the original GNT. Therefore, all the nodes in the one-hop neighbourhood of node *A*, nodes *C* and *D*, will receive the CONF and reserve those MSs. It is only after node *A* has transmitted the CONF that it can begin to send data using the allocated MSs. Through the three-way handshake method, the extended two-hop neighbourhood is defined. The extended two-hop neighbourhood defines the area in which MSs may not be reused. However, stations are free to reuse resources outside of this area. The mesh distributed scheduler does not define any method for assigning MSs, so MSs are free to be reused outside of the extended two-hop neighbourhood in which they are being used.

While the framework on how to request and assign bandwidth is defined by the IEEE 802.16 standard, the scheduling mechanisms defining the rules and policies on how to request/assign bandwidth are left undefined. Therefore, in Section III-B the on-demand scheduler is proposed that works similar to the CSMA/CA mechanism of the IEEE 802.11 standard but in a collision-free way. Before, in Section III-A the election based transmission timing (EBTT) mechanism is discussed that is responsible for the transmission timing of MSH-DSCH messages belonging to the distributed scheduler.

A. The Election based Transmission Timing (EBTT) mechanism

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 TO 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

$$H = 2^{\exp+4} \qquad (1)$$

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 TO with all of its two-hop neighbours using information about the next transmission interval of these nodes 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 TOs that includes *nxmt* and is defined as follows:

$$2^{\exp} * mx < nxmt \le 2^{\exp} * (mx+1) \qquad (2)$$

The *mx* parameter has a size of 5 bits and can identify exactly 32 blocks, where every block consists of $2^{\exp}$ C-DSCH TOs. *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. Details about the mesh election-algorithm as well as the EBTT mechanism can be found in [2], while improvements as well as corrections are proposed in [3] and [4].

B. The on-demand scheduler

As mentioned before, the distributed scheduler defines the scheduling framework including the TWHS as well as the EBTT mechanism responsible for the transmission timing of MSH-DSCH messages. However, the exact scheduling mechanism as well as the resource coordination scheme is left undefined. Within this section the on-demand scheduling mechanism is proposed that is comparable to the DCF of the IEEE 802.11 standard but works in a collision-free way. It is characterised by:

- MSs are requested on demand, which means, that a mesh node only requests resources in case it has received one or more data packets. These packets can be received either from the upper layer (mesh node has generated packets itself), from a neighbouring mesh node or from a client associated to the mesh node.

- To avoid that one user claims all MSs, the number of MSs that can be requested in each request is limited to θ.
- The number of future frames, in which a node is allowed to request for MSs is limited to *FrLo*. This avoids the waste of resources and large delays for new connections. It also eases the harmonisation of different scheduling mechanisms and thus different traffic types.
- Granter sends a GNT only in case the resources, listed in the AVA are available.
- If a GNT was not received within the last cycle, the requester sends a new REQ with different resources listed in the AVA.

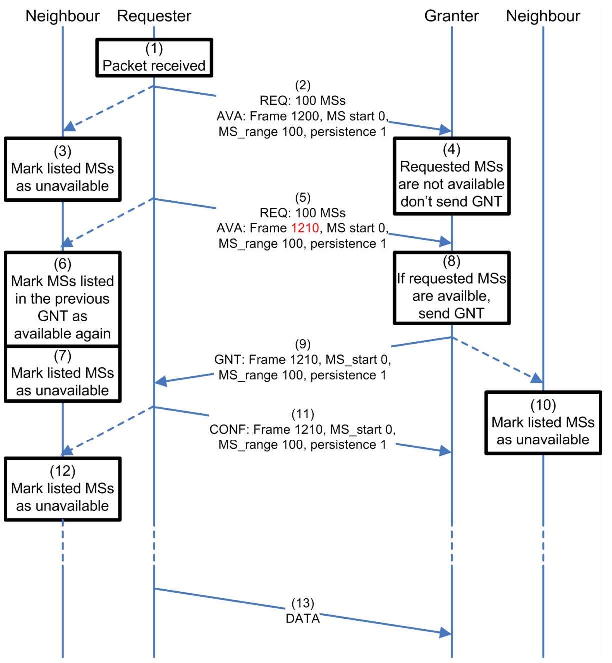


FIGURE 3
MESSAGE EXCHANGE PROCEDURE FOR THE ON-DEMAND SCHEDULER

The message exchange procedure for the on-demand scheduler is shown in Figure 3 in which the requester receives a data packet (1) and sends a REQ (2) in which it requests 100 MSs to transmit the packet. An AVA is sent along with the REQ which indicates that in frame with number 1200 the slots 0-99 are free and can be used for transmission. Persistence 1 indicates that this counts only for frame 1200. All nodes that receive these messages (except the granter) mark the listed resources as unavailable (3) in order to avoid that MSs are assigned twice within the extended two-hop neighbourhood of the requester. In the present example, the slots listed in the availability message are not free at the granter side (4). Thus, a GNT is not sent. In this case, the requester waits for a specific time and in the case a GNT has not been received, it resends the REQ together with an AVA (5). However, the available MSs listed in the availability message are for frame 1210. All nodes that receive these messages release the previously as unavailable marked resources (from the previous request/availability) (6). Again, the resources listed in the current availability messages are marked as unavailable (7). These resources are also free at the granter side (8) and therefore, a GNT is created and broadcasted (9). The GNT indicates that node *A* can use the MSs 0-99 in frame 1210 for transmission. Every node that receives the GNT (except the requester) marks the listed resources as unavailable (10) in order to avoid collisions. Finally, the requester confirms with a CONF (11) (again, all direct neighbours mark the listed resources as unavailable (12)) and transmits its data packet(s) within the MSs (13).

IV. SIMULATION ENVIRONMENT

To investigate the concepts presented in this paper a simulation module based on the IEEE 802.16 mesh mode has been developed for network simulator NS-2 [6]. The developed MAC module comprises the TDMA frame structure discussed in Section II as well as the on-demand scheduler as described in Section III-B. In the routing layer the Optimized Link State Routing (OLSR) protocol [7] is used to realise multi-hop communication. As interference due to spatial reuse is a very important issue in WMNs, the PHY layer was enhanced and now considers interference calculations to get more realistic simulation results. Furthermore, Automatic Repeat Request (ARQ) mechanisms are not used in simulations.

A. Scenario

For the performance investigation performed in this paper a simple clique topology has been selected. The clique topology as shown in Figure 4 with variable number of nodes (*N*) is a special topology in which all nodes are one-hop neighbours of each other. Thus, the number of neighbours is equal for all nodes in the network.

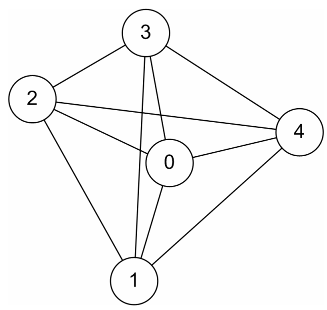


FIGURE 4
CLIQUE TOPOLOGY (EXAMPLE WITH N = 5)

B. Simulation parameters

Parameters used for simulations are listed in Table I.

C. Performance evaluation metrics

In the following, several performance metrics used throughout this paper are defined.

1) Three-way Handshake duration:

The average three-way handshake duration ($\overline{Dtwhs}$) evaluation metric is defined as the average time required by the three-way handshake procedure to establish a data schedule between two neighbouring nodes, see Figure 5.

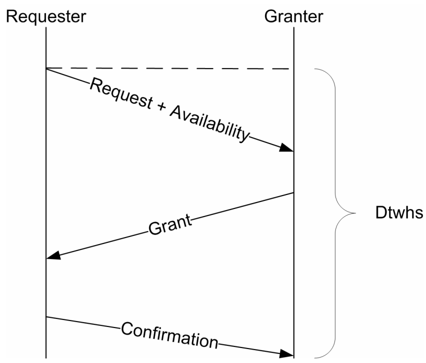


FIGURE 5
DEFINITION OF THE TWHS DURATION (DTWHS)

Dtwhs can be expressed in TOs ($Dtwhs_S$) or time ($Dtwhs_T$). Equation 3 is used to get the average three-way handshake duration for every node.

$$\overline{Dtwhs_j} = \frac{\sum_{i=1}^{p} Dtwhs_{j,i}}{p} \quad (3)$$

Here, p is the number of successfully performed TWHSs by node j. Equation 4 is then used to compute $Dtwhs_{netw}$, which is the average TWHS duration across all nodes in the network that have performed at least one TWHS (M).

$$\overline{Dtwhs_{netw}} = \frac{\sum_{j=1}^{M} \overline{Dtwhs_j}}{M} \quad (4)$$

2) *Amount of granted resources:*

The average amount of granted resources ($\overline{G}$) evaluation metric can be seen as a meter for the performance perceived by an application. It can be expressed in number of granted MSs (G_{MS}) or granted bandwidth (G_{BW}). The average number of granted resources per node is defined as follows:

$$\overline{G_j} = \frac{\sum_{i=1}^{q} G_{j,i}}{q * \tau} \quad (5)$$

Here, q is the number of grants assigned to node j, τ is the MSH-DSCH transmission interval and $\overline{G_{j,i}}$ is the amount of resources granted to node j in Grant i. Equation 6 is then used to compute the average amount of assigned resources across all nodes in the network that have received at least one grant (L).

$$\overline{G_{netw}} = \frac{\sum_{j=1}^{L} \overline{G_j}}{L} \quad (6)$$

Parameter	Value
TDMA frame length (FL)	4 ms
Control-subframe fraction	$\approx 33\%$
Mini-slots per data-subframe ($\#S$)	110
MSH_DSCH_NUM	4
MSH_CTRL_LEN	7
$Scheduling\_Frames$	2
Modulation-coding scheme used	QPSK_1/2
Propagation model	IEEE SUI shadowing
Terrain/a/b/c/σ_s	A/4.6/0.0075/12.6/0
Noise power (P_N)	-100 dBm
Antenna: type/height/gain	omni/8 m/1
Transmission distance	230 m
Tx power/Frequency(f)/Channel BW	35 dBm/3.5 GHz/10 MHz
FTP packet size	500 bytes
On-demand scheduler: $\theta/FrLo$	$\#S$/20
Simulation: iterations/duration	20/50s
Routing protocol	OLSR
Queuing discipline	FiFo
$exp^{max}_{MPP}/exp^{max}_{ACT}/exp^{max}_{SN}/exp^{max}_{IN-ACT}$	0/0/2/7
Contention threshold (ψ)	10

TABLE 1
SIMULATION PARAMETERS

V. RESULTS

In this section the performance of the EBTT mechanism together with the on-demand scheduler is evaluated using the simulation environment and parameters as discussed in Section IV. The purpose is to investigate the basic characteristics of these mechanisms. Therefore, the clique scenario is selected in which all nodes are direct neighbours of each other and use equal values for *exp*. A single TCP session is simulated between two nodes and the number of nodes in the network (N) is varied in order to find how the EBTT mechanism scales. First, the results for the basic EBTT mechanism are presented followed by the results for the extended EBTT mechanism.

A. *Results for the basic EBTT mechanism*

Results for basic EBTT mechanisms are displayed in Figure 6. $\overline{Dtwhs_{S,netw}}$ as a function of the network size is drawn in Figure 6(A). Results show that if N increases, the TWHS duration increases as well, as more nodes compete for channel access which in turn increases the probability for a node to loose the competition for a TO. This means, that nodes will lose more TOs before *nxmt* is found in which the next MSH-DSCH message can be transmitted. Also increasing *exp* increases *Dtwhs* as this means a larger *H*. The increased network contention in larger networks has more influence on *Dtwhs* for small *exp* values, while for large *exp* values, the influence can be neglected and *Dtwhs* is more or less constant. An other observation is that by increasing N the distance between the different curves shrinks. The reason for this is that the network contention increases exponentially and that the increased contention with small *exp* values compensates the decreased *H* and at some point a smaller *exp* value will show worth performance compared to a larger *exp* value.

In Figure 6(B), the number of granted MSs ($\overline{G_{MS,netw}}$) is drawn vs. the number of nodes in the network. The trend of the previous results is also reflected here. For large *exp* values, G_{MS} remains constant and is not influenced by the number of nodes in the network. This effect can be used by the network operator to provide minimum service guarantees, e.g. a minimum bandwidth, independent of *N*. Small *exp* values generally have a better performance compared with large *exp* values. However, for small *exp* values, G_{MS} rapidly drops by increasing *N*. As a consequence, it is expected that the maximum achievable bandwidth in dense network parts is smaller compared to sparse network parts even if only one data connection is running and all other nodes are not transmitting any data. This is a severe problem as MPPs mostly have a central location in order to cover many nodes. Thus, they will have many competing neighbours which results in poor network performance.

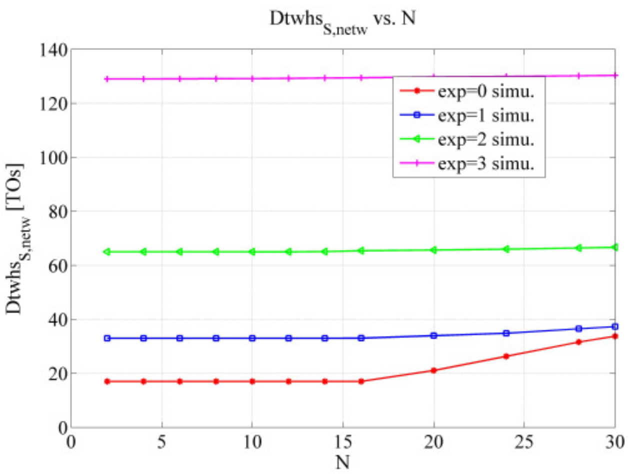
To overcome this scalability problem, enhancements have recently been defined. In the following sections the influence of these mechanisms on the performance of the on-demand scheduler is analysed.

B. *Results for the extended EBTT mechanism*

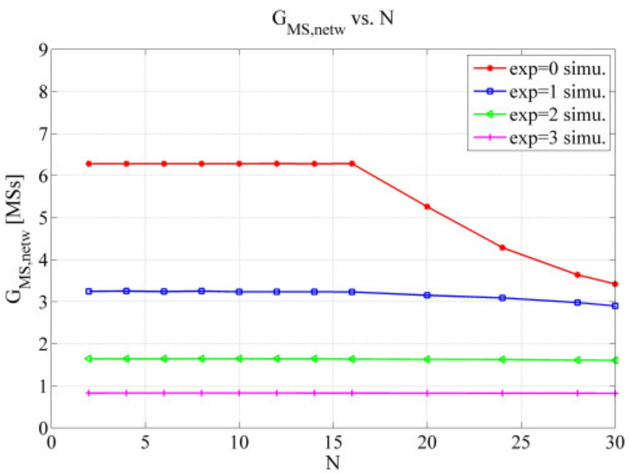
This section analyses the influence of the extended EBTT mechanism on the performance of the on-demand scheduler. The extended EBTT mechanism comprises the *ConstExp optimisation* [3] and the *DynExp mechanism* [4]. Both parts are investigated separately. For all simulations presented in this section, the *exp* value was fixed to 0.

1) *Results for the ConstExp optimisation*

The results of the ConstExp optimisation for the clique scenario are presented in this section while details of ConstExp can be found in [3]. Figure 7(A) shows $\overline{Dtwhs_{S,sink}}$ vs. the network size for different values of *cexp*. It is obvious, that a reduced *cexp* value significantly reduces *Dtwhs* in small

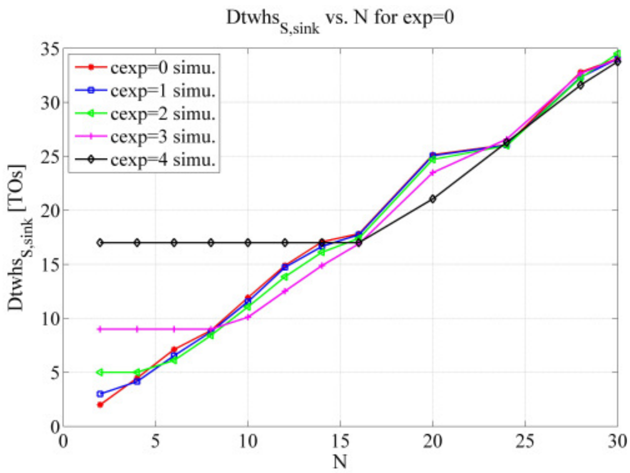


(A)
AVERAGE TWHS DURATION ($\overline{DTWHS_{S,NETW}}$)

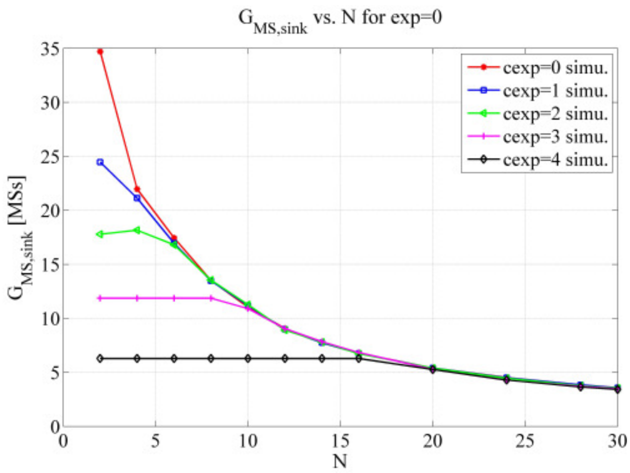


(B)
AVERAGE AMOUNT OF GRANTED MSS ($\overline{G_{MS,NETW}}$)

FIGURE 6
PERFORMANCE OF THE BASIC EBTT MECHANISM TOGETHER WITH THE ON-DEMAND SCHEDULER VS. THE NUMBER OF NODES INTHE NETWORK (N) FOR DIFFERENT VALUES OF EXP AND THE CLIQUE TOPOLOGY



(A)
AVERAGE TWHS DURATION ($\overline{DTWHS_{S,SINK}}$)



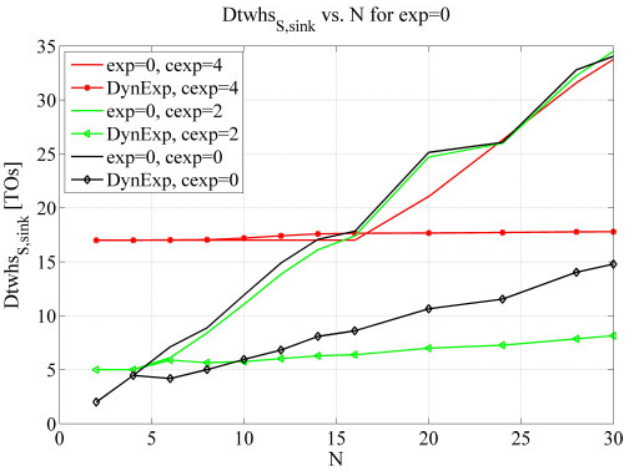
(B)
AVERAGE AMOUNT OF GRANTED MSS ($\overline{G_{MS,SINK}}$)

FIGURE 7
PERFORMANCE OF THE CONSTEXP OPTIMISATION TOGETHER WITH THE ON-DEMAND SCHEDULER VS. THE NUMBER OF NODES INTHE NETWORK (N) FOR DIFFERENT VALUES OF CEXP, EXP=0 AND THE CLIQUE TOPOLOGY

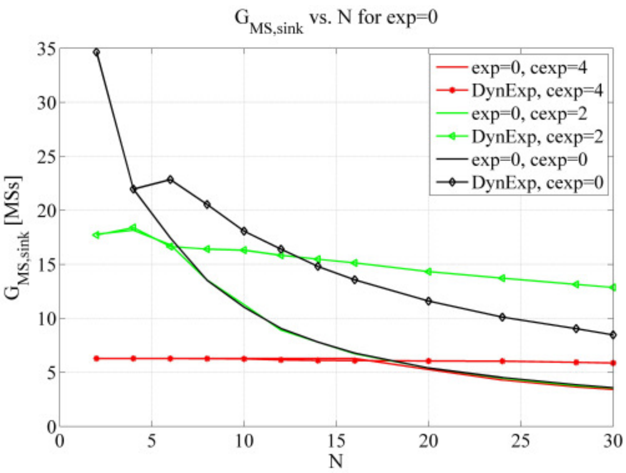
networks. For example *N = 2* and *cexp = 0* ensures that the duration of the TWHS can be reduced from approximately 17 TOs for the basic configuration with *cexp = 4* to approximately 2 TOs. However, this effect is nearly eliminated for larger networks in which the advantage of a decreased *Xmt_Holdoff_Time* is dashed by the increased contention caused by small *cexp* values.

Figure 7(B) presents the performance of the TCP connection by drawing the number of granted MSs by the traffic sink to the traffic source as a function of the network size. It is obvious, that the ConstExp optimisation is able to significantly increase the performance in small networks. For instance, if *N = 2*, the performance with *cexp = 0* is approx. 6 times the performance of *cexp = 4*. However, this performance improvement decreases with increasing *N* and disappears completely for large networks.

It can be summarised, that the ConstExp optimisation is able to improve the performance in sparse mesh networks. However, the *cexp* value should be selected with care by the network operator as it has much influence on the network performance.



(A)
AVERAGE TWHS DURATION ($\overline{DTWHS_{S,SINK}}$)



(B)
AVERAGE AMOUNT OF GRANTED MSS ($\overline{G_{MS,SINK}}$)

FIGURE 8
PERFORMANCE OF THE DYNEXP MECHANISM TOGETHER WITH THE ON-DEMAND SCHEDULER VS. THE NUMBER OF NODES INTHE NETWORK (N) FOR DIFFERENT VALUES OF CEXP, EXP=0 AND THE CLIQUE TOPOLOGY

2) Results for the DynExp optimisation

Results for the DynExp mechanism and the clique scenario are discussed in this section. The configuration of DynExp can be found in Table I and details of this mechanism are available in [4]. This mechanism is able to significantly reduce the duration of the contention phase of active nodes and thus the duration of the TWHS as shown in Figure 8(A). For small network sizes the DynExp mechanism shows no improvement as enough TOs are available and contention can be neglected. However if the network size increases DynExp can reduce *Dtwhs* for all *cexp* values. It can also be seen that at some point the performance of the DynExp mechanism with *cexp=0* is worth compared to *cexp=2*. This is simply due to the fact, that for smaller *cexp* values, the contention is so high, that many nodes have already increased their *exp* up to exp^{max} and further improvements are not possible. Of course a carefully selection and configuration of the various parameters like exp^{max} would certainly further improve the performance, also for small *cexp* values. However, the optimisation of the exp^{max} values for the different node states is not the focus of this paper and subject for future work.

Figure 8(B) provides a summary and draws the amount of granted MSs as a function of the network size in order to give an estimation of the network performance. It can be seen that the larger the network becomes the more performance gain can be achieved with the DynExp mechanism.

VI. CONCLUSIONS

In this paper the on-demand scheduler has been proposed that is integrated into the coordinated distributed scheduling framework defined in the IEEE 802.16 standard. By the means of simulations it was found that increasing the number of nodes in the network decreases the performance of the network. This means, that increasing the density of the network decreases the performance, even if the new nodes joining the network do not transmit any data packets. The ConstExp optimisation and the DynExp mechanism are approaches aiming to improve the performance. The influence of these mechanisms on the performance of the on-demand scheduler have also been analysed in detail. It was found, that ConstExp is able to improve the performance especially in small networks while DynExp is able to improve the performance in dense networks.

REFERENCES

[1] V. Gunasekaran and C. Harmantzis, "Affordable Infrastructure for Deploying WiMAX Systems: Mesh v. Non Mesh," in Vehicular Technology Conference, 2005. VTC 2005, May 2005.

[2] The Institute of Electrical and Electronics Engineers. IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems, IEEE Std 802.16-2004. IEEE, 2004.

[3] N. Bayer, D. Sivchenko, B. Xu, V. Rakocevic, and J. Habermann, "Transmission timing of signalling messages in IEEE 802.16 based Mesh Networks," in Proc. European Wireless Conference 2006 (EW '06), Athens, Greece, April 2006.
[4] N. Bayer, B. Xu, V. Rakocevic, and J. Habermann, "Improving the performance of the Distributed Scheduler in IEEE 802.16 Mesh Networks," in Proc. IEEE 65th Vehicular Technology Conference 2007 Spring (VTC '07-Spring), Dublin, Ireland, April 2007.
[5] S.-Y. Wang, C.-C. Lin, H.-W. Chu, T.-W. Hsu, and K.-H. Fang, "Improving the Performances of Distributed Coordinated Scheduling in IEEE 802.16 Mesh Networks," IEEE Trans. Veh. Technol., vol. 57, no. 4, pp. 2531–2547, 2008.
[6] S. McCanne and S. Floyd, "ns Network Simulator," http://www.isi.edu/nsnam/ns/.
[7] T. Clausen and P. Jacquet (editors) and C. Adjih and A. Laouiti and P. Minet and P. Muhlethaler and A. Qayyum and L.Viennot, "Optimized Link State Routing Protocol (OLSR)," RFC 3626, October 2003, Network Working Group. [Online]. Available: http://ietf.org/rfc/rfc3626.txt
[8] J. Robinson and E. W. Knightly, "A Performance Study of Deployment Factors in Wireless Mesh Networks," in INFOCOM, 2007, pp. 2054–2062.

Nico Bayer Nico Bayer received his diploma degree in Electrical Engineering and Information Technology from the University of Applied Sciences of Friedberg in 2003. Since 2003 he is working for T-Systems Enterprise Services GmbH in the department of "Mobile and Wireless Solutions" in Darmstadt, Germany. He is involved in different national R&D projects in the fields of mobile communications, mesh networks and Fixed/Mobile Convergence (FMC). During his activities, he is working towards a PhD thesis on "Scheduling mechanisms for Carrier Grade Wireless Mesh Networks".

Bangnan Xu is a Research Expert at T-Systems, Deutsche Telekom, leading various research projects in ad hoc/mesh networks, seamless IP mobility, fixed & mobile convergence, and next generation access networks. His current research interests include Next Generation Mobile Network (NGMN, 3GPP LTE SAE), Next Generation Network (NGN, ETSI TISPAN), IMS and beyond, packet optimised fixed & mobile converged (FMC), and Quadrupple play services. He received his Ph.D. in Electrical Engineering and Information Technology from Aachen Univ. of Technology (2002), as well as M.Sc. (1989) and B.Sc. (1986) degrees in Electrical Engineering from Dalian Maritime University. From 1989 to 1996, he was a lecturer on communication systems in Dalian Maritime University. Before joining T-Systems in 2001, he was with the chair of Communication Networks, Prof. Dr.-Ing. B. Walke, Aachen Univ. of Technology, Aachen, Germany. He holds several patents in multihop communications, ad hoc routing, and seamless IP mobility. He has authored and coauthored many technical papers, three of them granted with Best Paper Award.

Veselin Rakocevic MIEEE is currently a Senior Lecturer at City University, London, UK, where he leads the Mobile Networks Research Group. His main research interests include wireless ad hoc networks, quality of service in mobile networks, and network reliability. He published over 25 papers in journals and conferences and is a member of the TPC for a number of conferences, including IEEE Globecom, MASS and WCNC. He holds a PhD in Telecommunications from University of London, UK and a Dipl-Ing degree in Electronic Engineering from University of Belgrade, Serbia.

Joachim Habermann (Senior Member IEEE) received the Msc. and Ph.D. degrees in electrical engineering from Darmstadt Technical University, Germany in 1979 and 1984. In 1984 he joined ABB research centre in Baden, Switzerland, where he worked in the Telecommunications department in the area of mobile communications. Since 1990 he is Professor at the University of Applied Sciences Giessen-Friedberg/Germany.