A Proportionally Fair Centralized Scheduler Supporting Spatial Minislot Reuse for IEEE 802.16 Mesh Networks

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Abstract. Mesh and relay networks promise to increase the reach, capacity, and throughput of wireless communication networks. As a prominent example, the reservation-based IEEE 802.16 standard (as the basis for Worldwide Interoperability for Microwave Access WiMAX) comes with basic protocol mechanisms for an optional mesh mode as well as a relay mode of operation. This paper proposes a proportionally fair scheduler to fully utilize the potential of wireless mesh by exploiting spatial reuse. The scheduler is discussed within the setting of an IEEE 802.16 network operating with centralized scheduling in the mesh mode. We investigate the entire process of (1) bandwidth reservation, (2) calculation of the schedule and the bandwidth allocation, and (3) dissemination and activation of the schedule using an extension to the standard to allow for slot reuse. A performance analysis shows the feasibility of the proposed scheduling scheme and allows for insights into prospective future research areas in IEEE 802.16 networks.

Keywords: Wireless mesh networks, IEEE 802.16, proportional fair scheduling, spatial reuse.

1 Introduction

Networks to support wireless and mobile communications are constantly evolving towards higher data rates, scalability with respect to network coverage or number of network nodes, or improved mobility support. Extending cellular or single hop networks towards mesh or relay networks, which employ the multihop paradigm, offers a great potential for the above outlined performance improvements.

Extensions to contemporary standards for wireless communication technologies such as IEEE 802.16 ([3] [5] [6]) or 802.11 ([1] [2]) introduce the basic protocol mechanisms for mesh or relay operation. Moreover, these standards introduce the support of quality of service (QoS) using reservation-based MAC protocols. However, the aforementioned standards do only specify bandwidth

N. Bartolini et al. (Eds.): QShine/AAA-IDEA 2009, LNICST 22, pp. 556–566, 2009.

reservation mechanisms feasible for one hop operation. Moreover, they do not provide optimized algorithms and mechanisms to implement reuse-aware multihop scheduling.

To fill this gap, we contribute a proportional fair scheduler that supports slot reuse and is thus well suited for multihop operation. Using the example of the IEEE 802.16 standard we further demonstrate how to integrate multihop bandwidth reservation mechanisms into state-of-the-art wireless technologies, which allows us to implement and utilize our scheduler in realistic settings.

The remainder of this article is structured as follows. Section 2 surveys related work. In Section 3, the design and operation of the developed scheduler is described, and the integration of multihop reservation mechanisms in the IEEE 802.16 standard is outlined. As a proof-of-concept, in Section 4, we perform a simulation study that confirms the proper working of the developed mechanisms. The article is concluded in Section 5, where we highlight further open research issues.

2 Background and Related Work

Wireless Mesh Networks (WMNs) provide a flexible and cheap means to extend existing wireless network coverage and serve areas without existing network infrastructure. The IEEE 802.16 standard specifies a mesh mode of operation which permits the setup of WMNs able to support strict QoS requirements. To support QoS the mesh mode uses reservation based MAC protocols which explicitly reserve bandwidth for transmission for each link in the network. The mesh mode specifies two classes of mechanisms to enable the explicit reservation of bandwidth, centralized scheduling and distributed scheduling, respectively.

Using centralized scheduling nodes in the WMN can request bandwidth for transmissions for data flows to the mesh base station. The mesh base station can also allocate bandwidth for transmissions from itself to individual nodes in the network using centralized scheduling. However, these allocations are restricted to links included in a scheduling tree rooted at the mesh base station, which may cover a subset of the total nodes in the network. Distributed scheduling is more flexible and can be used for reserving bandwidth on any link in the WMN.

Using centralized scheduling, all the requests are are transmitted up the scheduling tree to the mesh base station, and it then computes the allocation for individual links on the tree and generates appropriate grants. These grants are relayed down the scheduling tree to the individual nodes on the tree, which then compute the actual transmission schedules from the grant messages and using the information about their position in the scheduling tree (see also explanation in Sec. 3, and for more details readers are referred to [3] and [7]).

Centralized scheduling is thus more useful and appropriate for traffic from the nodes to the mesh base station (the mesh base station, MBS, is a node which provides access to external networks) and vice versa ([8]). In this paper we will focus on centralized scheduling only. Centralized scheduling in the mesh mode has been investigated to some extent in the literature (e.g. [9] and [10]). However, solutions incorporating spatial reuse into centralized scheduling in the IEEE 802.16 mesh mode have not been studied to sufficient depth within the context of the IEEE 802.16 mesh mode of operation. The protocols specified in the standard for centralized scheduling do not support spatial reuse. One of the earliest works to look at use of spatial reuse within the mesh mode is [4]. In this paper the authors present an interference-aware scheduler for the mesh mode which permits central computation of an interference-aware schedule permitting multiple links to be activated simultaneously. However, here the entire schedule is determined centrally and also needs to be fully disseminated to the individual nodes else it is not possible for the nodes to find out how to schedule the actual transmissions. Further, although the authors suggest that they can use the centralized scheduling messages provided in the standard to apply their solution they do not specifiy any details as to how the additional reuse information will be known to individual nodes, given that the nodes are not aware of the topology of the entire wireless mesh network. Moreover, there the goal is to look towards maximizing the throughput in the wireless mesh network without considering the fairness of the bandwidth allocated to the individual links.

In this paper we investigate an extended centralized scheduler for the IEEE 802.16 mesh mode. The extended scheduler is able to schedule the centralized transmissions with spatial reuse where permissible (i.e. the same slots are used by multiple nodes where no contention would arise due to the reuse). Additionally, the allocation, and the reuse is computed by the MBS such that all nodes get a proportionally fair share of the bandwidth, and are able to fairly reuse the slots proportional to their bandwidth requirements. To the best of our knowledge, this is one of the first papers investigating extensions to the centralized scheduler in the IEEE 802.16 mesh mode to support the above goals.

3 IEEE 802.16 Reuse-Aware Proportional Fair Scheduling

This chapter presents the developed scheduler. We describe the design of the scheduler and discuss its integration into the IEEE 802.16 standard by extending it to allow for reuse-aware scheduling.

3.1 Assumptions and Requirements

For the remainder of the paper, we assume a centralized scheduling algorithm for bandwidth allocation, which is executed at the Base Station (BS) or Mesh Base Station (MBS). The scheduler operates on all bandwidth requests that are collected from the Subscriber Stations (SS) in the scheduling tree. The computed schedule, i.e., the *Minislot* allocation, is disseminated down the scheduling tree using *MSH-CSCH* messages.

Design goals for our scheduler are: proportional fairness, awareness of spatial reuse, robustness as well as good performance under heavy traffic load and scarce scheduling resources[1]. We design our scheduler as follows.

- The MBS collects the bandwidth *Requests* from the SSs in a standard-conforming manner, i.e. using *MSH-CSCH* messages that are traversing up the scheduling tree in order.
- Next, the MBS computes the schedule and allocates bandwidth to the SSs in an iterative process. First, a standard-conforming and proportionally fair bandwidth allocation is determined. Next, reuse of *Minislots* is enabled by subsequent reallocation steps.
- Finally, the MBS disseminates the bandwidth *Grants* in the network. We propose an information element extending the *MSH-CSCH* control message that enables reuse of *Minislots*.

3.2 Reuse-Aware Proportional Fair Scheduling

We describe the working of our reuse-aware, proportionally fair scheduler along the operation of the centralized scheduling in the mesh mode of the IEEE 802.16 standard. We next discuss (1) the handling of bandwidth request messages and (2) the determination of the schedule.

Handling of Bandwidth Request Messages. Following the standard, the *UplinkFlow* and *Flowscale Exponent* fields of the *MSH-CSCH Request* messages are used by the SSs to indicate their bandwidth requirements (in the *Grant* message these fields and the field *DownlinkFlow* determine the granted uplink and downlink allocations, which are carried out in units of *Minislots*). The actual data rate requirement, can be calculated as follows.

$$BW_{uplink} = UplinkFlow \cdot 2^{Flowscale\ Exponent+14}\ bits\ /s$$

Fig. 1 shows a simple multihop topology, which will serve as a sample topology to illustrate the working of the developed mechanisms. The SSs send their requests starting from the leaves of the tree. The node with the highest scheduling tree index (here SS_6) is the first SS to transmit its request. The upstream node SS_4 combines the bandwidth requirements of SS_6 with its own requirements and sends it up the tree in order, i.e., after SS_4 sends after SS_5. As a result the MBS receives two *MSH-CSCH Request* messages containing the requests of $\{SS_6, SS_4, SS_3, SS_1\}$ and $\{SS_5, SS_2\}$, respectively.

Determination of the Schedule. The schedule is calculated in a two step process: (1) a proportional fair bandwidth/*Minislot* allocation is determined; (2) a reuse-aware policy to assign the *Minislots* is carried out. For the first step, the MBS assigns *Minislots* to nodes under the two following constraints.

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[1] Note the scheduling resources are also needed for distributed scheduling in addition to centralized scheduling and should hence be used efficiently by the individual schedulers.

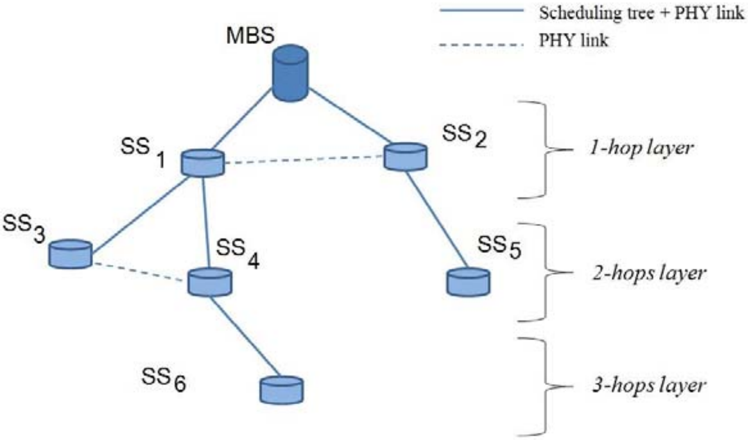

Fig. 1. PHY links and centralized scheduling tree of sample topology

- *Minislots* are allocated to single nodes and conforming to the IEEE 802.16 standard. This first allocation allows no *Minislot*reuse.
- The SSs are served in order and each SS receives a block of consecutive *Minislots*, the amount of which is proportionally fair to the total amount of requested bandwidth.

This initial assignment prevents SSs from starvation, and allows neglecting interference issues. Please note that the achievable fairness depends on the configuration of the number of permissible *Minislots* in the data subframe. The actual calculation of the schedule is straight forward. The MBS builds a table ordered according to the node indices and extracts the bandwidth requests from the different *MSH-CSCH* messages as shown in Table 1 for our example.

Next the MBS iterates over the nodes and carries out two calculations. First, guaranteeing fairness requires the evaluation of each bandwidth request in relation to the total bandwidth requested. The fair fraction of bandwidth $BWalloc_i$ for SS_i is calculated as:

$$BWalloc_i = \frac{BWreq_i \cdot BW_{total}}{\sum BWreq_j} \tag{1}$$

Where $BWreq_i$ represents the bandwidth requirement of node SS_i, $BWtotal$ is the overall amount of bandwidth to be allocated in this new schedule and the sum over $BWreq_j$ describes the bandwidth requested by all nodes except SS_i. Second the actual calculation of the corresponding amount of *Minislots* for each SS is performed:

$$Minislots_i = \left\lceil \frac{BWalloc_i}{BW_{minislot}} \right\rceil \tag{2}$$

Table 1. Example of the bandwidth requests propagated up the scheduling tree towards the BS. The higher the tree index, the earlier the corresponding *MSH-CSCH Request* is transmitted to allow for aggregation of requests.

Node: *tree index*	Bandwidth request	Bandwidth allocation
$SS_1 : 01$	$BWreq_1 + BWreq_3 + BWreq_4 + BWreq_6$	$BWalloc_1(Minislots_1)$
$SS_2 : 02$	$BWreq_2 + BWreq_5$	$BWalloc_2(Minislots_2)$
$SS_3 : 03$	$BWreq :_3$	$BWalloc_3(Minislots_3)$
$SS_4 : 04$	$BWreq_4 + BWreq_6$	$BWalloc_4(Minislots_4)$
$SS_5 : 05$	$BWreq_5$	$BWalloc_5(Minislots_5)$
$SS_6 : 06$	$BWreq_6$	$BWalloc_6(Minislots_6)$
Sum	Sum of all above $BWreq$	$BWtotal$ (Total amount of *Minislots*)

Where $BW_{minislot}$ is the number of bits that can be transmitted within one *Minislot*. Following this assignment, no node is left without *Minislot*; if the amount of data is lower than a *Minislot* payload, a single *Minislot* is allocated. The resulting allocation is illustrated in Table 1. It is important to notice that owing to the rounding up of bandwidth for the *Minislot* distribution the node served last could be assigned less *Minislots* than would be proportionally fair. We consider this last node first in our reallocation of *Minislots* to account for this.

The outlined scheme starts allocating bandwidth with the leave nodes of the scheduling tree, since for uplink traffic, the appropriate serving order is from the leave to the root of the tree. Related work discusses alternate schemes, though.

3.3 Reuse-Aware Scheduling for IEEE 802.16

As long as no reuse is intended, the implementation of the determined schedule in IEEE 802.16, i.e. the dissemination of the corresponding *MSH-CSCH Grant* messages, can follow the standard procedure. However, if we plan to allocate *Minislots* multiple times to non-interfering links, we cannot easily utilize the existing *MSH-CSCH Grant* messages, because currently the standard does not foresee reuse. Moreover, since the schedule is calculated in a distributed fashion based on the amount of *Minislots* assigned by the BS and disseminated in the *MSH-CSCH Grant*, we have to ensure that the SSs do not derive an interfering schedule if we add reuse information.

After the initial assignment of slots to the SSs, we propose to assign additional slots for reuse to the SSs that are to be utilized only if the interference constraints are fulfilled. During this second allocation, the nodes are served in the order starting from the lowest tree index, i.e. starting from the root of the tree. The algorithm to allocate *Minislots* for reuse operates as follows (Fig. 2 illustrates the reuse of *Minislots*):

- A list containing all SSs is created, $SS = SS_i$.
- For each block of allocated *Minislots* from the first round (SS_x, $mBlock_x$), a SS_y (if exists) that does not violate the interference constraints with SS_x and

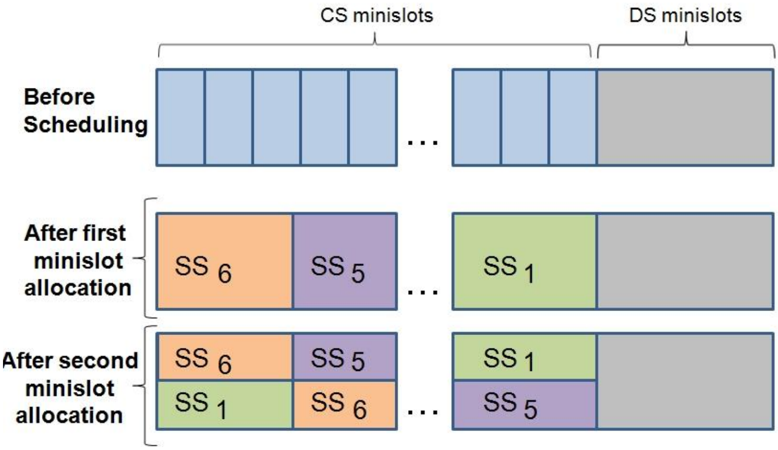

Fig. 2. Schematical operation of the reuse-aware *Minislot* allocation strategy. The example shows the reuse of *Minislot* among non-interfering links that permit for reuse (here $\{SS_6, SS_1\}$, $\{SS_5, SS_6\}$ and $\{SS_1, SS_5\}$ are node-pairs with non-interfering links).

is not already active during this allocation is selected, and another allocation (SS_y, $mBlock_x$) is performed.

The actual result of the reallocation process depends on the topology of the network, which determines the interference and reuse constraints. The obtained reuse schedule needs to be disseminated in the network. For this, it is necessary to modify the way the *MSH-CSCH* messages handle the granting process to the SSs, in order to allow for reuse. We propose to add a *Minislot* start and *Minislot* duration for the transmission (a similar mechanism is in use for the distributed scheduling in IEEE 802.16), to unambiguously indicate the *Minislot* blocks to be reused. Table 2 shows the proposed message format of the *MSH-CSCH Information Element*.

Table 2. Proposed MSH-CSCH Grant Information Element to extend the IEEE 802.16 Standard

Syntax	Size	Notes
MSH-CSCH_Grant_Info(){		
LINK ID	8 bit	
Start Frame number	4 bit	
Minislot start	8 bit	
Minislot range	8 bit	
Direction	1 bit	
Persistence	3 bit	
}		

After receiving a *MSH-CSCH Grant* message, a node processes the Information Elements that are significant for itself and retransmits the entire *MSH-CSCH Grant* message to its children. With the information included in the modified *Grant* message (see Table 2), all nodes are informed on exactly when they are allowed to transmit data for the reused *Minislots*, thus avoiding collisions due to interference.

In contrast, in the original standard the nodes are able to determine the order of transmission using the knowledge of the bandwidth allocation in combination with their own tree index, which is sufficient to determine the order of transmission only if no reuse is permitted.

3.4 Summary

The developed strategy allows for a *Minislot* allocation with a high level of fairness, while being simple and efficient at the same time. Although the described scheme does not support traffic class differentiation when making the bandwidth assignations, basic priority policies could be implemented at local level (at the individual SSs) when using the *Minislots*, by serving first to those flows which require less delay. However, thanks to the robustness of the centralized scheduler, the fairness of the proportional allocation and the performance gains of the *Minislots* reuse, a good performance results in terms of bandwidth use and latency can be expected if the network is not overloaded.

4 Proof-of-Concept in an IEEE 802.16 Mesh Network

We implemented the designed scheduler as well as the modified IEEE 802.16 protocol messages in a standard compliant IEEE 802.16 simulation environment. We utilized the mesh mode of the standard in combination with centralized scheduling. Goals of the simulation study were to confirm the proper operation of the scheduler as well as getting an estimate on the achievable performance gains over a baseline non-reuse-aware scheduler.

We use the topology shown in Fig. 1 for our analysis, which allows for reuse, but also imposes interference constraints between various branches and subbranches of the scheduling tree. We have studied various sets of workload ranging from low to very high offered traffic load between the MBS and the individual SSs (the traffic being uniformly distributed among the SSs and directed to the MBS and vice versa); the simulation parameters are given in Table 3.

In Fig. 3 and Fig. 4, we show the results for the average delay per data packet obtained under medium and high traffic load. We have chosen the delay metric, since it is an indicator of both the network performance and the proper reuse of resources; for the same amount of admitted traffic, a lower delay indicates that *Minislots* or Frames earlier in time can be utilized, for a highly loaded network the increased throughput of the network is hindering the build-up of queues for a reuse-aware scheduling scheme.

The results shown in Fig. 3 and Fig. 4 indicate that our scheduler meets the design goals, which is particularly evident for the high traffic setting shown in

Table 3. Simulation parameters and settings for the simulation study

Parameter	Setting/Range
PHY	WirelessMAN-OFDM ($N_{FFT} = 256$), *ETSI*
Channel bandwidth	14 MHz
Subcarrier	Spacing: 62,5 kHz, 192 subcarriers
Symbol time	Overall: 18 μs, without preamble/guard: 16 μs
Frame duration	20ms
Minislot duration	1111symbols
Control subframe	12 Transmission opportunites each with 4 symbols Modulation: QPSK-1/2
Data subframe	255 *Minislots* each with 4 symbols 1 *Minislot* with 7 symbols Modulation: 16-QAM-1/2

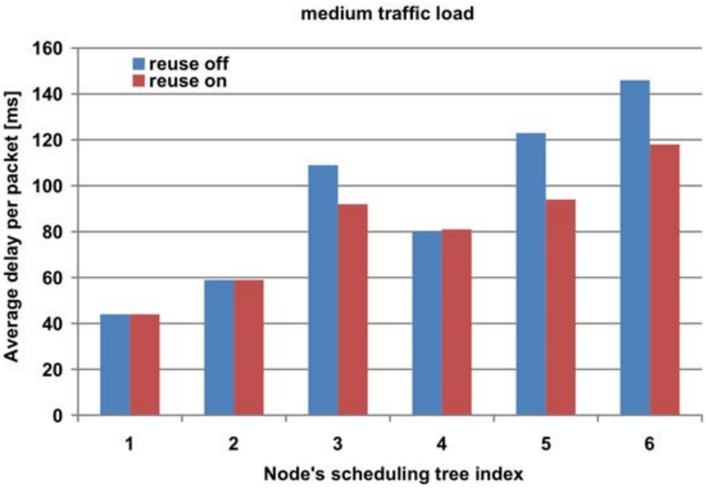

Fig. 3. Average end-to-end delay per node for reuse-aware proportional fair scheduling vs. reuse-unaware proportional fair scheduling under low traffic load

Fig. 4: the offered load can no longer be sustained for the deeper levels of the tree topology by the reuse-unaware scheme, which can be seen in the more than linear increase in delay on the two and three hop paths.

In Fig. 5 we show the differences between nodes on the same layer/tier of the topology using our algorithm. Our proportional scheduler allocates more bandwidth to nodes with more children to accommodate the potentially higher bandwidth requests of these branches of the tree. The average delay for different offered traffic loads is again an indicator for the achieved fairness of the bandwidth allocation.

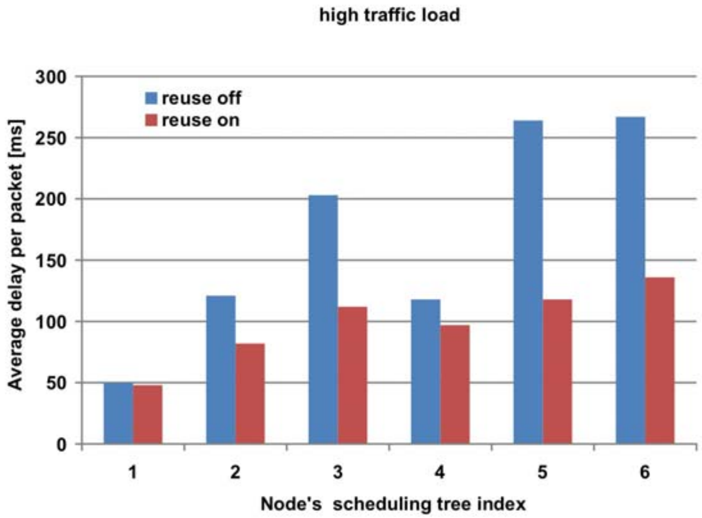

Fig. 4. Average end-to-end delay per node for reuse-aware proportional fair scheduling vs. reuse-unaware proportional fair scheduling under high traffic load

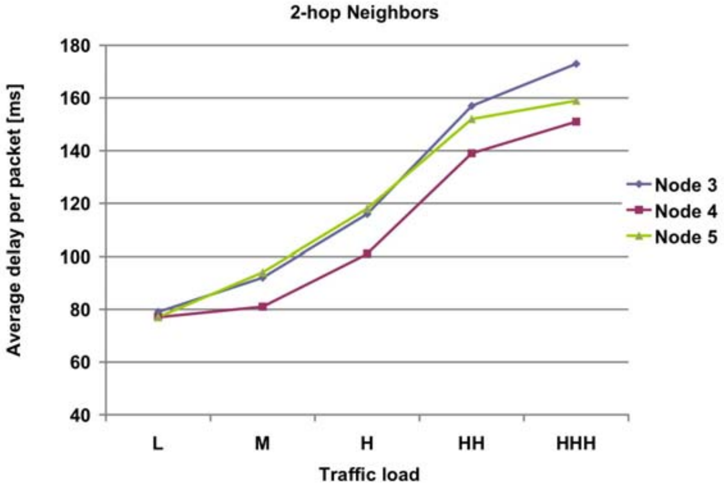

Fig. 5. Average end-to-end delay for the two hop neighbors of the MBS for reuse-aware proportional fair scheduling under varying traffic load from low (L) to very high (HHH)

We observe that our scheduler shows only small differences in delay between the nodes on the same tier of the topology. This is not the case for the reuse-unaware schemes as can be seen in Fig. 3 and Fig. 4, where we observer significantly different delays for e.g. nodes SS_3, SS_4, SS_5 which are on the same level of the scheduling tree.

5 Conclusion

We have proposed a proportionally fair scheduler to fully utilize the potential of wireless mesh and relay networks by exploiting spatial reuse. The developed scheduler can be easily be integrated with contemporary wireless technologies such as IEEE 802.16 that are following a deterministic and reservation-based MAC protocol. In the context of IEEE 802.16, our scheduler allows to maintain the basic protocol mechanisms for requesting bandwidth. The scheduling and bandwidth allocation to permit reuse have been designed and implemented. Moreover, extensions to the standard (that does not sufficiently support bandwidth reuse in its current specification) have been proposed to facilitate the dissemination of the derived schedule in a reuse supporting manner.

A performance analysis has demonstrated the feasibility of the developed schemes. The obtained results are promising and indicate significant performance gains, even in basic network topologies. Still, more advanced scheduling schemes and strategies can be foreseen, thus fully utilize the potential that has been opened up with the outlined the standard extension that permits for *Minislot* reuse in IEEE 802.16 mesh networks.

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