# IEEE 802.16 Mesh Schedulers: Issues and Design Challenges

**Najah A. Abu Ali, UAE University**
**Abd-Elhamid M. Taha and Hossam S. Hassanein, Queen's University**
**Hussein T. Mouftah, Ottawa University**

## Abstract

IEEE 802.16 mesh mode defines three types of resource scheduling: coordinated centralized, coordinated distributed, and uncoordinated distributed. While the standard defines the required procedures and messages for each scheduler, it does not offer encouraging means to provide performance, reliability, or QoS. In this article we outline the issues of IEEE 802.16 mesh schedulers. We also survey representative proposals and qualitatively evaluate them against these issues. More critically, we identify key challenges that have not been addressed so far in the literature to motivate work in this area of research.

IEEE 802.16, also known as Worldwide Interoperability of Microwave Access (WiMAX), is a promising and attractive alternative to last mile wired access where wiring can be physically or economically infeasible. The IEEE 802.16 standard allows for backhauling by providing an optional mesh connectivity mode in addition to the inherent point-to-multipoint (PMP) connectivity. The key difference between PMP and mesh is that communication in PMP mode is based on direct connection between the base station (BS) and subscriber stations (SSs), while in mesh mode multihop communication is allowed, and traffic can be routed through other SSs or occur directly between SSs.

The cornerstone to efficient operation of WiMAX mesh networks is scheduling, which plays an important role in providing quality of service (QoS) guarantees and averting congestion. The objective of this article is to overview the scheduling mechanisms defined in the standard and survey key proposals in the literature. Where possible, we offer a qualitative comparison between the different proposals. Our higher aim is to outline the challenges and highlight open issues that have been overlooked by the proposals. More critically, we identify substantial opportunities in designing practical and efficient schedulers to resolve outstanding issues.

The standard defines three scheduling mechanisms to schedule resources in the mesh mode, all of which are time-division multiple access (TDMA)-based: coordinated centralized, coordinated distributed, and uncoordinated distributed. Each mechanism accommodates specific types of communications and potentially offers different levels of guarantees. For instance, coordinated centralized scheduling is aimed at Internet traffic flowing in and out of the network through the gateway BS, while the distributed mechanisms accommodate intranet traffic. A BS in centralized scheduling gathers resource requests from all the mesh SSs within a certain hop range. It then determines the amount of resources to grant to each link in the network in both downlink and uplink, and relays these grants through SSs within one-hop range. In distributed scheduling all nodes, including the BS, coordinate their transmissions in their two-hop neighborhood and broadcast to all their neighbors their available resources, their requests, and their grants to requested resources. Additionally, distributed scheduling can be established by directed uncoordinated requests and grants between two nodes. Hence, communicating nodes are required to ensure collision-free transmission within two hops. Note that in the mesh node the terms uplink and downlink characterize traffic moving toward and away from the BS, respectively, whether directly or through multiple hops.

## Preliminaries

In this section we offer an overview of the general messages and parameters involved in WiMAX mesh operation. For reference, Table 1 details messages and scheduling parameters utilized in mesh mode.

Figure 1 shows the structure of a mesh frame comprising two subframes: control and data. In IEEE 802.16, scheduling computes the range and position of minislots in a frame. A minislot is a unit of bandwidth allocation equivalent to a certain number of physical slots. The duration of a minislot is fixed, and each minislot contains a specific number of orthogonal frequency-division multiplexing (OFDM) symbols. The data rate attainable in a minislot depends on the coding and modulation schemes utilized at transmission time.

There are two types of control subframes, each equal to `MSH-CTRL-LEN` in length: schedule control and network control. The latter is signaled periodically and further comprises two messages: `MSH-NENT` and `MSH-NCFG`. The schedule control subframe is partitioned into two subframes. The first is of a length equal to `MSH-CTRL-LEN` less `MSH-DSCH-NUM`, and is used for exchanging centralized scheduling messages, `MSH-CSCH` and `MSH-CSCF`. The second subframe is of length `MSH-DSCH-NUM` and is used for exchanging coordinated distributed scheduling messages (`MSH-DSCH`). All transmissions in the

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| Message/parameter | Description |
|---|---|
| MSH-CTRL-LEN | Dictates the length of the overall control subframe. |
| MSH-NENT | Mesh network entry message. |
| MSH-NCFG | Mesh network configuration message. |
| MSH-DSCH-NUM | Dictates the length of the distributed control subframe. |
| MSH-CSCH | Mesh centralized schedule message, utilized for requesting and granting allocations in centralized scheduling. |
| MSH-CSCF | Mesh centralized schedule configuration messages. |
| MSH-CSCH-DATA-FRACTION | Dictates the length of the centralized data subframe. |
| MSH-DSCH | Mesh distributed schedule messages, utilized for requesting, granting, and confirming allocation in coordinated distributed scheduling. |
| XmtHoldoffExponent | A configurable parameter used in calculating XmtHoldoffTime. |
| XmtHoldoffTime | Dictates the number of MSH-NCFG, MSH-CSCH, etc transmit opportunities after NextXmtTime during which an SS cannot transmit such messages. |
| NextXmtMx | A configurable parameter used in calculating NextXmtTime. |
| NextXmtTime | Dictates the next MSH-NCFG or MSH-DSCH eligibility interval for a neighbor and is computed as the range (number of transmission opportunities): $2^{\text{XmtHoldoffExponent}} \times \text{NextXmtMx} < \text{NextXmtTime} < 2^{\text{XmtHoldoffExponent}} \times (\text{NextXmtM} + 1)$<br>A node is considered eligible for transmission during this range, but not before. |
| EarliestSubsequentXmtTime | Estimates the earliest time after NextXmtTime an SS is eligible to transmit a MSH-message, and calculated by: NextXmtTime + XmtHoldoffTime. |

Table 1. *Mesh mode messages and scheduling parameters.*

control subframe are sent using quaternary phase shift keying (QPSK)-1/2 modulation over the broadcast channel. Data is transmitted in the data subframe. The size of a data minislot is computed by

$$\left\lceil \frac{\text{OFDM Symbols per frame} - 7 \times (\text{MSH-CTR-LEN})}{256} \right\rceil.$$

Similarly, the data subframe is partitioned into centralized and distributed data subframes.

### Coordinated Centralized Scheduling

Two schedules are required for centralized operation, one for the control subframe and one for the data subframe. In scheduling the control subframe, the BS computes a breadth-first topology-based tree to a predefined hop distance from the BS. The BS then broadcasts the tree along with an ordered SSs list by transmitting a MSH-CSCF message in a new control subframe to its one-hop children. Each SS in turn propagates the MSH-CSCF until it is received by the last SS in the scheduling tree. Assuming all SSs in the network are time synchronized, any SS can compute its control schedule through extracting the tree from the MSH-CSCF. This is done by knowing the SS ordered list and from which SS the MSH-CSCF message is received.

In scheduling a centralized data subframe, a parameter called MSH-CSCH-DATA-FRACTION dictates the number of data subframe minislots dedicated to centralized scheduled data. Given the routing tree, MSH-CSCH requests are sent by every node except the BS, while MSH-CSCH grants are issued by the BS and relayed by each SS with children. After receiving all MSH-CSCH messages, the BS computes the uplink and downlink bandwidth grants to each SS in the network. The BS then encodes this information in MSH-CSCH grant messages propagated downstream using the downstream control scheduler. The grant messages do not contain the actual schedule; rather, each SS computes the global schedule using the same procedure used for control subframe scheduling. Figure 2 shows an example of centralized scheduling. Note that in the example SS1 is scheduled to send its uplink message before receiving from its children, which results in an ordering delay.

If the length of the schedule computed by the BS exceeds the length dictated by MSH-CSCH-DATA-FRACTION, the minislot reservations are proportionally scaled down to fit one frame. If the scaling down results in infeasible allocations, the schedule is spread over two frames instead. A form of fairness is achieved through proportionally scaling down reservations and insisting that every active SS participates in any given frame. However, the scaling down does not cater to the diverse QoS requirements of different SSs or their queue lengths.

### Issues with Coordinated Centralized Scheduling

Closely examining the standard's description of coordinated centralized scheduling, the following issues can be noted.

*Spatial Reuse* — There are two types of interference collision-free scheduling must avoid. Primary interference occurs when an SS is scheduled for more than one function at the same

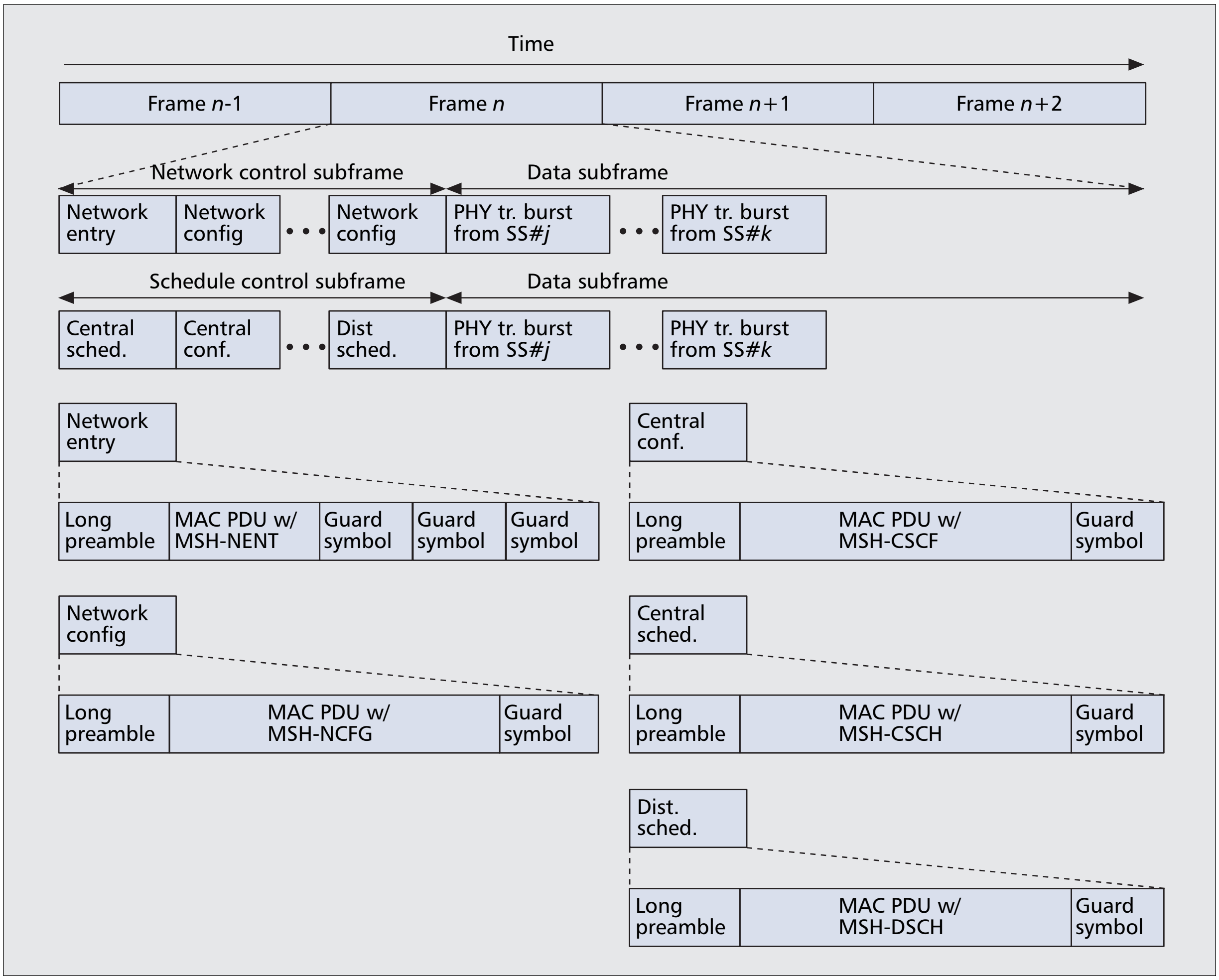


**Figure 1.** *Frame structure of the IEEE 802.16-2004 mesh mode.*

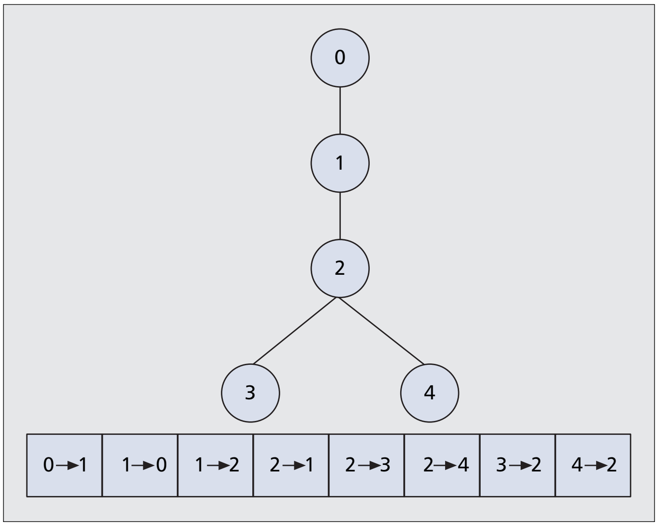
time (e.g., simultaneously receive and send, or send two separate messages to two receivers). Secondary interference occurs when a receiver is affected by a nearby transmission in which it is not involved. Spatial reuse is achieved when secondary interferences are identified and avoided while increasing network utilization (i.e., when two or more noninterfering links are simultaneously scheduled). A major shortcoming in the standard's scheduler is that it does not employ spatial reuse. Addressing this, Wei *et al.* [1] propose interference-aware routing and scheduling mechanisms. From the BS, the route selected to reach an SS is the one with the least *blocking* (i.e., the one that interferes with the fewest links). The scheduler iteratively assigns time intervals to the SS with the maximal demand. The scheduler then searches for nonblocking SSs, if any, and assigns the same slot for the one with the next maximal demand. This is repeated until all the demands are satisfied. We note that the algorithm is not readily applicable to the standard's framing and communication structure as it may schedule an SS more than once in a frame. Also, the number of symbols allocated may not be sufficient to accommodate the data and preamble, rendering an allocation useless. Han *et al.* [2] propose a scheduling scheme that grants access to SSs based on their relative demand. Each slot is assigned a service token. The objective of the service token is to reduce the schedule length. When a link is assigned a time slot in the schedule, the transmitter's service token is decreased by one while the receiver's service token is increased by one. In all, the scheduler attempts to achieve spatial reuse through allowing as many links as possible to be utilized in each slot. Again, the proposal allows one SS to transmit more than once in a frame, which increases the overhead as the standard mandates that each data transmission has two or three OFDM guard symbols. Moreover, the algorithm does not verify if an SS's grant exceeds the transmission overhead.

*Scheduling Tree* — In the standard, the routing tree is computed using a breadth-first algorithm. If a node has more than one child, the schedule is assigned to the child with the least ID, as shown in Fig. 2. The standard, however, does not specify a routing algorithm. Proposals focusing on this issue consider an integrated scheduling and routing problem. For example, Jin *et al.* [3] develop uplink routing and scheduling algorithms aimed at maximizing throughput. For routing, the authors propose two algorithms. Maximum Parallelism Routing attempts to increase spatial reuse in a breadth-first constructed tree where links may be weighted according to the number of packets at the transmitting SS. The second algorithm, Minmax Degree BFS Tree, produces a breadth-first tree such that the maximum degree is minimized. For scheduling, the authors select links based on four criteria: randomness, number of packets at the SSs, distance from the base station, and link scheduling. We note that the proposed algorithms are suitable for constant bit rate (CBR) traffic as they are based on the assumption that the number of packets and their transmission delays are known in the mesh network. However, the algorithms are not suitable for variable bit rate (VBR) and/or variable packet length traffic.

*QoS Validity* — In the standard's scheduler, QoS provisioning is performed link by link without considering end-to-end QoS requirements. Shetiya and Sharma [4], perhaps the only work

|  | Standard | Wei *et al.* [1] | Han *et al.* [2] | Jin *et al.* [3] | Shetiya *et al.* [4] | Djukic *et al.* [5] |
|---|---|---|---|---|---|---|
| Routing algorithm | × | √ | √ | √ | √ | × |
| Spatial reuse | × | √ | √ | √ | × | √ |
| Channel quality | × | × | √ | × | √ | √ |
| >1 transmission per frame per SS | × | √ | √ | √ | × | × |
| QoS validity | × | × | × | × | √ | Partially, by minimizing TDMA sequencing delay at planning stage. |
| Ordering delay | × | × | × | N/A (uplink only) | N/A (uplink only) | √ |
| Frame utilization | × | × | × | √ | √ | × |

■ Table 2. *A comparison between proposals for coordinated centralized scheduling.*



■ Figure 2. *A sample routing tree with a transmission schedule ordered according the standard's coordinated centralized scheduler.*

addressing this issue, consider providing end-to-end QoS guarantees for different types of Internet traffic at the granularity of one connection. For example, for User Datagram Protocol (UDP) traffic, both CBR and VBR, they detail how to assign the minimum number of slots at each SS along the path given that the bounds for end-to-end packet dropping probability are preserved. For TCP traffic, the authors consider measures for minimum throughput and fairness in allocating excess capacity.

*Channel Quality* — Even though the standard mentions adaptive modulation and coding (AMC) to best exploit channel quality, the centralized scheduler does not utilize AMC, potentially leading to either underutilization or corrupt messages. Literature proposals address this problem by allotting minislots to SSs based on the links channel condition. For example, the authors in [4] develop a dynamic programming framework to derive several optimal uplink and downlink schedules with different objectives aimed at different types of service. Their Adaptive Fixed Allocation Scheme, for instance, assign SSs a fixed number of slots based on their average rates as well as the channel condition of the relative link. Current proposals, however, do not specify how to partition the centralized data subframe into uplink and downlink slots.

*Ordering Delay* — For a relay to be successful, an SS must first receive the data to be forwarded. If an SS is scheduled to send before it receives, the received data must wait for another schedule length, as shown in Fig. 2. Djukic and Valaee [5] propose a schedule to minimize the ordering delay. The authors focus on the TDMA round-trip delay resulting from maintaining delivery sequence across the path. The schedule is produced by operating a Bellman-Ford algorithm on a conflict graph where the network links are vertices and the edges indicate conflicts, with the edge costs indicating the delay.

*Synchronization* — The performance of the standard's scheduling algorithm is dependent on global time synchronization, which is achieved during the ranging process by sending the timing information in the `MSH-NCFG` messages. However, `MSH-NCFG` is scheduled by the coordinated distributed scheduling discussed below. Accordingly, some SSs may not have a chance to send these massages in the appropriate frames, resulting in a synchronization drift.

*Number of Channels* — A single channel data scheduling is assumed in the standard, and there are currently no proposals to increase the network bandwidth by scheduling links using different channels.

*Isolation* — When granting an SS less than requested reservation (either for its own traffic or forwarded requests), it is not clear in the standard what portion of the grant is dedicated to the SS or for relaying to other (downstream or upstream) SSs.

*Hop Range* — In the standard, SSs sending requests to the BS must be within the hop range dictating the tree depth when routes are compute. As there are bounds on the number of transmission opportunities in the centralized portion of the control subframe and the maximum schedule length (two frames), the exact hop range in a network needs to be carefully selected.

*Frame Utilization* — The standard assigns minislots to SSs without considering their queue length.

### Discussion

A qualitative comparison of the proposals discussed above is shown in Table 2. The proposals were compared based on the issues they address. Two noteworthy observations can be made: first, not all the issues presented above are addressed by the proposals; second, in most of the proposals there is an inherent deviation from the standard's capabilities and limitations. For example, the manner in which data minislots are assigned is based on transmission opportunities with guard minislots. This means that for centralized scheduling, slot-by-slot transmission or interval allocation requires additional care.

We conclude this section by pointing at viable directions of investigation:

- At the planning stage, a mechanism is required to select an appropriate depth for the routing tree, especially since the number of allotted transmission opportunities in the centralized control subframe is related to the tree depth and affects the utilization of the centralized data subframe.
- In scaling down reservations to fit the grants into the data subframe, a static proportional factor is assumed. It should be feasible to scale down different demands based on QoS of individual SSs.
- Synchronization is affected by the probability that an SS will get a transmission opportunity using coordinated distributed scheduling. An algorithm is required to improve or at least control this probability.
- The standard accommodates directional antennas and multichannel settings. Exploiting these accommodations will result in substantial performance improvements.
- Frame partitioning needs to be studied more closely and optimized based on the traffic dynamics of the network. This includes partitioning the control and data subframes into centralized and distributed slots, and partitioning the data subframe into uplink and downlink data minislots.
- WiMAX mesh networks will mainly be used as backhaul networks handling aggregated traffic. There need to be means, specific to WiMAX, to manage aggregate traffic while preserving their end-to-end QoS requirements.

## Coordinated Distributed Scheduling

As in coordinated centralized, two schedules are required for the operation of the coordinated distributed schemes. The first relates to scheduling control messages where SSs express their requirements and grants, and confirm the grants they have received. This is performed in the `MSH-DSCH-NUM` portion of the control subframe. The second schedule is concerned with the rules dictating the outcome of the request-grant-confirm dialog and affects the coordinated distributed portion of the data subframe.

An example of request-grant-confirm dialog is shown in Fig. 3. Once an SS seizes a transmission opportunity in the distributed portion of the control subframe, it sends its available schedule along with requested data transmission opportunities. In the event that the grantor receives the request, it tries to seize a transmission opportunity in the control subframe to send a grant `MSH-DSCH` along with the granted data slots. The time until a grant is transmitted depends on the result of the distributed election algorithm. Once transmitted, the requestor and other SSs who hear the grant message will update their schedules. To confirm the grant, the requester must seize the channel and send a confirm `MSH-DSCH` before the end of the control subframe; otherwise, the data transmission opportunity will be lost.

*Scheduling Control Messages in Coordinated Distributed* — To schedule MSH-NCFG and MSH-DSCH messages in the control subframe, an SS runs a distributed algorithm called the election algorithm. The algorithm is designed such that for SSs in the same neighborhood it would yield the same result (i.e., which SS wins the next control transmission opportunity).

In their `MSH-DSCH` messages, SSs relay two parameters, *NextXmtMx* and *XmtHoldoffExponent*. An SS would also relay these parameters to its one-hop neighbors. Using this information, an SS would be able to compute its NextXmtTime (i.e. its next `MSH-DSCH` eligibility interval, which is computed to be in the range $2^{\mathrm{XmtHoldoffExponent}} \times \mathrm{NextXmtMx} < \mathrm{NextXmtTime} < 2^{\mathrm{XmtHoldoffExponent}} \times (\mathrm{NextXmtMx} + 1)$. Also computed is the SS's *EarliestSubsequentXmtTime* which estimates the earliest time after NextXmtTime an SS is eligible to transmit a `MSH-DSCH`.

A neighboring SS is added to the election algorithm if:

- Its NextXmtTime interval includes the transmission opportunity.
- Its EarliestSubsequentXmtTime is less or equal to the transmission opportunity.
- Its NextXmtTime is not known.

After determining the competing SSs, the local SS runs the mesh election algorithm, which is a pseudo-random number generator with the SS's ID, IDs of competing SSs, and the transmission opportunity as input. If the local SS's generated number is the highest, it wins the transmission opportunity. Otherwise, the SS repeats the procedures for the next transmission opportunity.

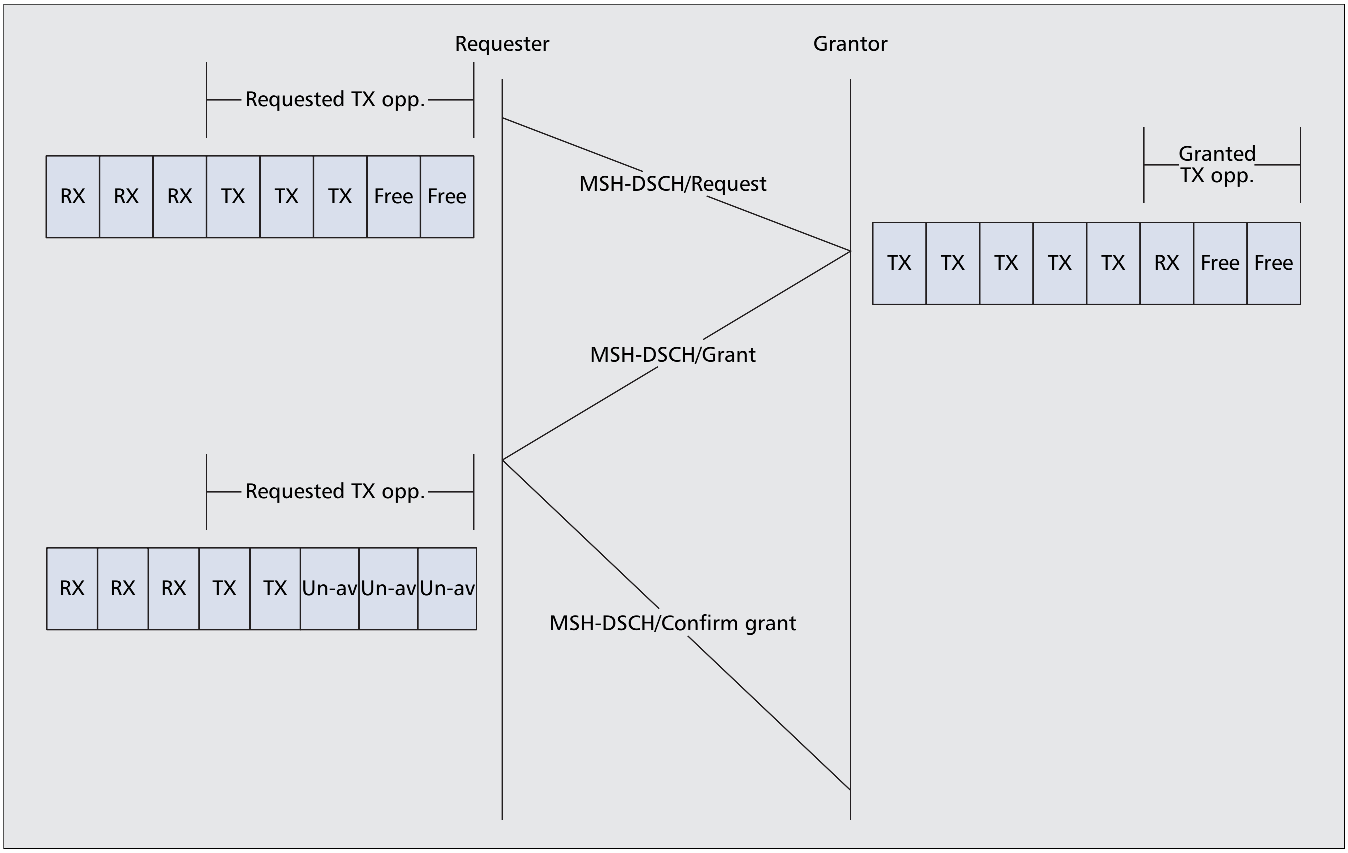
*Coordinated Distributed Data Scheduling* — The minislots available for coordinated distributed data scheduling comprise unutilized minislots in the centrally scheduled data subframe, as well as any minislots not occupied by the current centralized schedule. SSs compete for these minislots using a three-way handshake. First, the requesting SS sends a request `MSH-DSCH` packet containing data minislots available in its schedule, as shown in Fig. 3. The receiver then replies with an `MSH-DSCH` grant indicating which of these data are also available at the receiver's side. The requesting SS then broadcasts an `MSH-DSCH` confirming the grant with the copy of the granted minislots. In this manner all neighbors will update their information about the scheduler by allocating these minislots for this requester. However, the standard does not specify a specific scheduler for the coordinated distributed mechanism.

### Issues with Coordinated Distributed Scheduling

We identify the following issues with the standard's coordinated distributed scheduler.

*Holdoff Time Effect* — The exact effects of XmtHoldoffExponent on the control schedule in the standard are not clear. Cao *et al.* [6] investigate this effect by analyzing the performance of the standard's coordinated distributed scheduler. They model the number of transmission times of a certain SS as a stationary and ergodic renewal process, and assume the processes are identically independent at each SS. They consequently derive steady-state expressions for the average number of transmission opportunities between `MSH-DSCH` messages. In their simulation the authors observe the request-grant-confirm dialog under identical and nonidentical holdoff exponents and given different SS densities. As expected, smaller exponents lead to fewer intermessage slots. The authors, however, do not comment on the effect of increased contention due to small exponents

*Fairness* — The election algorithm is inevitably unfair since an SS may not have an opportunity to send its control messages based on the result of the election algorithm. More crucially, an SS winning an election algorithm may seize all available data minislots in a neighborhood. In [7], to enhance fairness, Bayer *et al.* propose a bound on the bandwidth that can be granted at any given time. As for controlling the request-



■ Figure 3. *An example of a request-grant-confirm dialog between two SSs in a neighborhood.*

grant-confirm dialog time, the authors suggest giving different SSs different exponent values based on their roles. This differentiation becomes particularly useful as the network density increases since it results in significant increases in throughput. The authors also suggest further differentiation based on QoS requirements.

*QoS* — Ideally, the coordinated distributed data scheduler provides hop-by-hop QoS statistical guarantees. However, depending on the transmission success probabilities of an `MSH-DSCH`, QoS requirements may not be guaranteed at all. As mentioned above, Bayer *et al.* [7] attempted to address this issue by controlling the request-grant-confirm dialog time to provide for differentiation based on the QoS requirements of individual SSs.

*Scalability* — The number of SSs in the neighborhood affects the performance of the algorithm by decreasing the access probability of SSs. Zhu and Lu [8] note that the "collision-free" design of the coordinated distributed operation presumes that no interference exists beyond a transmitting SS's second hop. In reality, the transmission may affect farther links. This is partially accommodated in the standard as it allows the involvement of third-hop neighbors in settling transmission opportunities. The improvement, however, comes at the cost of overhead, less access probability, and further delays. The authors investigate the performance of coordinated distributed scheduling under different propagation models: free space, two-ray, and irregular terrain. As expected, the scheduling interval increases as the extended neighborhood grows. More important, however, is that collisions occur even when 10 hops are involved. The authors also note that substantial reductions occur when using large holdoff exponents; however, these reductions result in longer scheduling intervals.

*Data Scheduler* — The standard defines the scheduling mechanism for control subframes. However, no definition is given for data scheduling. Most proposals in literature concentrate on scheduling `MSH-DSCH` messages but give no or little consideration of scheduling the actual data itself. In [9] Djukic and Valaee discuss a distributed variant of their work proposed in [5] to schedule data minislots. Despite the canonical complexity of the authors' algorithm, the authors claim that the practical performance of their algorithm is attractive. Makarevitch [10] discusses basic implementations where the bandwidth assigned to an SS is based on the number of SSs in the network. Alternatively, assignments can be based on the number of flows for which the SS is responsible relative to the total number of flows in the network. The author proposes an algorithm that assigns slots first to the SS with the maximal request. To reduce signaling, an internal slot assignment based on finite fields is used to bound conflict ratios. While the author discusses possible mapping on a WiMAX frame, the standard may not accommodate the sequence and relay of information required for the author's proposal. Based on the proposal, the SS may transmit more than once in a frame, which may increase overhead and decrease frame utilization.

*Attempt Frequency* — An SS competes periodically to seize transmission opportunity in the control subframe whether or not it has data to send.

*Handshake Priorities* — If an SS receives a grant to which it cannot reply (e.g., not enough control transmission opportunities remaining or because of competition), the data transmission opportunity could be wasted. Furthermore, as the minimum holdoff value is 16, and it is mandated that an SS back off after transmitting each `MSH-DSCH`, the duration of grant-confirm cycle may become intolerably long.

| | **Standard** | **Cao *et al.* [6]** | **Bayer *et al.* [7]** | **Djukic *et al.* [9]** | **Maka *et al.* [10]** |
|---|---|---|---|---|---|
| Attempt frequency | × | N/A | As in [Cao05] | × | × |
| Holdoff time effect | × | N/A | √ | × | × |
| QoS | × | Note relation between holdoff exponent and QoS | As in [Cao05] | × (proposal for BE traffic only) | No validation, just meets required slots |
| Scalability | × | N/A | √ | × | Partial, by having a topology-independent scheduler |
| Fairness | × | × | √ (limits granted bandwidth) | × | × |
| Handshake priorities | × | Associated with number of nodes, holdoff exponent, and topology | √ | × | × |
| Data scheduler | × | × | × | √√ | √ |

■ Table 3. *A comparison between proposals for coordinated distributed scheduling.*

*Control Subframe Length* — The precise effect of `MSH-DSCH-NUM` on the performance of the network is unclear and, in certain instances, may yield an unusable and small number of control transmission opportunities.

### Discussion

Table 3 provides a qualitative comparison between the above surveyed works on coordinated distributed scheduling. Note that the work in [6] is not a proposal per se; rather, using modeling and simulation, it offers insights on the performance of the standard's scheduler. Also noteworthy is that not many proposals analyze the control and data schedulers together. The work in [6–8] addresses the scheduling of control messages, while the work in [9, 10] offers data schedulers. We note that not all the issues outlined above have been addressed. It is also not clear whether the proposals are accommodated within the standard. For example, the proposal in [10] advocates a controllable percentage of collisions, while the standard forbids any collision resulting from coordinated centralized and distributed schedulers.

We conclude this section by pointing out possible directions of investigation:

- Many potential benefits can be gained if the schedules for both coordinated modes were jointly computed.
- A comprehensive QoS framework is required to provide statistical guarantees in coordinated distributed operation; otherwise, only best effort traffic can be supported.
- The mesh election algorithm may be enhanced to adapt to the number of SSs in a neighborhood. Moreover, the algorithm may be improved to give higher priority to an SS sending a grant confirmation message.
- Due to holdoff time and competition, an SS may receive several requests before being able to send a grant message. Hence, a mechanism is required to decide on which requests to grant.
- To ensure fairness, the number of data slots requested by an SS needs to be dynamically limited based on the load in the network neighborhood.

## Uncoordinated Distributed Scheduling

Uncoordinated `MSH-DSCH` messages are the only control messages exchanged during a data subframe. SSs employ uncoordinated distributed scheduling to compete for empty data minislots not scheduled by the coordinated schedulers. The uncoordinated `MSH-DSCH` packets are always transmitted on the "base" channel. As in coordinated distributed scheduling, SSs exchange a three-way handshake to schedule data slots with the difference that collisions are tolerated between uncoordinated `MSH-DSCH` messages.

To the best of our knowledge, no proposals have been made for the uncoordinated distributed scheduler. This could be due to the scheduler's definition in the standard, where it is mandated that uncoordinated contentions must not collide with schedules set by coordinated schedulers. There is also the fact that contention-based access has been exhaustively researched in other venues (e.g., slotted ALOHA and variants).

## Conclusions

Schedulers defined in IEEE 802.16 for the optional mesh mode (coordinated centralized, and distributed and uncoordinated distributed) lack the capability to provide fair, efficient, and QoS-guaranteed operation. In this article we attempt to identify issues impeding the realization of IEEE 802.16-based wireless broadband backhauls. We also survey representative proposals targeted toward enhancing the standard's performance. In general, the proposals are few and do not resolve most of the major issues outlined herein. Certain proposals also drift from the standard's mandates in messaging and frame structure. Finally, we elaborate on specific challenges that, if overcome, would lead to substantial performance gains.

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## Biographies

NAJAH ABU ALI (najah@uaeu.ac.ae) is currently an assistant professor at the College of Information Technology of United Arab Emirates University. She had a postdoctoral fellowship at the Computer Science School of Queen's University, Kingston, Canada, from January 2006 to August 2006. She is currently a collaborator member within the telecommunications research team at the same school. She received her B.S. and M.S. degrees in electrical engineering in 1989 and 1995, respectively, from the University of Jordan, Amman, and her Ph.D. degree in computer networks from the Electrical Engineering Department of Queen's University. Her research interests comprise wired and wireless communication networks; specifically, analytical and measurement-based network performance management, and QoS and resource management of virtual private networks, cellular networks, and backhaul wireless mesh networks. She has published her work at several conferences, and has served as a reviewer and a Technical Program Committee member for several conferences and journals.

ABD-ELHAMID M. TAHA [M] (taha@cs.queensu.ca) received his B.Sc. and M.Sc. in electrical engineering from Kuwait University in 1999 and 2002, and his Ph.D. from the Department of Electrical and Computer Engineering of Queen's University in September 2007. He is currently a post-doctorate fellow at the School of Computing, Queen's University. He has authored several publications including journals, refereed conference papers, and book chapters. He has also served as a Technical Program Committee member of multiple international IEEE conferences and symposia, and as a reviewer for respected journals, magazines, and conferences. His areas of interest include radio resource management in wireless and mobile networks, especially in the context of wireless overlays with heterogeneous access and wireless mesh networks. He is a member of ComSoc and ACM.

HOSSAM HASSANEIN [SM] (hossam@cs.queensu.ca) is a professor of computer science at Queen's University. He is a leading researcher in the areas of broadband, wireless, and variable-topology networks architecture, protocols, control, and performance evaluation. Before joining Queen's University in 1999, he worked at the Department of Mathematics and Computer Science at Kuwait University (1993–1999) and the Department of Electrical and Computer Engineering at the University of Waterloo (1991–1993). He obtained his Ph.D. in computing science from the University of Alberta in 1990. He is the founder and director of the Telecommunication Research Laboratory in the School of Computing at Queen's, where he currently supervises 20 graduate students. He has more than 250 publications in reputable journals, conferences, and workshops in the areas of computer networks and performance evaluation, and has organized and served on the Program Committees of a number of international conferences and workshops. He serves as the Secretary of the IEEE Communication Society Technical Committee on Ad Hoc and Sensor Networks. He was the recipient of the Communications and Information Technology Ontario Champions of Innovation Research award in 2003. In March 2007 he received a best paper award at the IEEE Wireless Communications and Networks Conference.

HUSSEIN MOUFTAH [F'90] (mouftah@site.uottawa.ca) joined the School of Information Technology and Engineering of the University of Ottawa in 2002 as a Tier 1 Canada Research Chair Professor, where he became a University Distinguished Professor in 2006. He was previously with the Electrical and Computer Engineering Department at Queen's University (1979–2002), where he was a full professor and department associate head. He has six years of industrial experience mainly at Bell Northern Research of Ottawa (now Nortel Networks). He served as Editor-in-Chief of *IEEE Communications Magazine* (1995–1997) and IEEE ComSoc Director of Magazines (1998–1999). He is the author or coauthor of five books and more than 800 technical papers and nine patents in the area of broadband packet switching networks, optical and mobile wireless networks, and QoS over the Internet. He is the joint holder of five best and/or outstanding paper awards. He has received numerous prestigious awards, such as the 2007 RSC Thomas W. Eadie Medal, the 2006 IEEE Canada McNaughton Gold Medal, the 2006 EIC Julian Smith Medal, the 2004 IEEE ComSoc Edwin Howard Armstrong Achievement Award, the 2004 George S. Glinski Award for Excellence in Research of the University of Ottawa Faculty of Engineering, the 1989 Engineering Medal for Research and Development of the Association of Professional Engineers of Ontario (PEO), and the Ontario Distinguished Researcher Award of the Ontario Innovation Trust. He is a Fellow of the Canadian Academy of Engineering (2003) and the Engineering Institute of Canada (2005).