# Performance of IEEE 802.16 Mesh Coordinated Distributed Scheduling under Realistic Non-Quasi-Interference Channel

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*Abstract— IEEE 802.16 is a promising standard that is expected to solve the "last mile" Internet access issue in a metropolitan area. In IEEE 802.16, several TDMA-based scheduling schemes are designed to provide "collision-free" transmission of control messages. In this paper, we investigate the performance of coordinated distributed scheduling in IEEE 802.16 Mesh Mode, under realistic non-quasi-interference model. Extensive simulation study show that, collisions may occur in practical scenarios. We observe that, the collision ratio can be as high as 20% for 2-hop extended neighborhood, and approximately 7% for 3-hop extended neighborhood, which is significant. Our study also provides an insight on how to select appropriate XmtHoldoffExponent, in order to alleviate the collisions due to accumulative interference and to limit the scheduling interval.*

**Keywords—IEEE 802.16, WiMax, Mesh Network, Distributed Scheduling, Interference, TDMA**

## 1 Introduction

The advent of IEEE 802.16 [1][2] standard is emerging as a promising broadband wireless technology to finally resolve the "last mile" Internet access in conjunction with IEEE 802.11. IEEE 802.16 originally is to provide fixed broadband access of up to 75 Mbps and typical base station infrastructure coverage of 5 miles in PMP (Point-to-Multipoint) operation mode, which is much greater than the coverage of 802.11. 802.16e has also been approved as the official standard for Mobile WirelessMAN on Dec. 7th 2005.

802.16 MAC supports two modes: PMP and Mesh, respectively. The former organizes nodes into a cellular like structure consisting of a base station (BS) and subscriber stations (SS). The channels are divided into uplink (from SS to BS) and downlink (from BS to SS), both shared among the SS's. PMP mode requires all SSs to be within the transmission range and clear line-of-sight of the BS. In PMP mode, traffic only occurs between the BS and SSs, On the other hand, in the mesh mode, an ad hoc network is formed with all nodes acted as relaying routers in addition to their sender and receiver roles, although there may still be nodes to serve as BSs and provide backhaul connectivity. In order to achieve efficient multi-hop data transmissions, the Mesh mode defines three scheduling schemes, i.e., centralized, coordinated distributed, uncoordinated distributed scheduling, which are used by control messages for various functionalities, such as to grant net entry requests, topology discovery and management, and to schedule data transmissions. Except uncoordinated distributed scheduling, which is designed to support low duty-cycle traffic scenarios with simple unreliable control message transmissions, the other two scheduling algorithms are designed to provide "collision-free" transmissions of control messages.

In this paper, we focus on the behaviors of the claimed "collision-free" coordinated distributed scheduling algorithm of IEEE 802.16 Mesh mode. We observe that the algorithm specified in the standard cannot really guarantee "collision-free" scheduling in realistic RF environments. This is due to the discrepancy between the idealized interference modeling used to develop the algorithm and the actual "non-quasi-interference" environment in real world, which will be elaborated more in Section 3. As a result of such discrepancy, substantial amount of collisions may occur in certain topology and RF environment. We propose an alternative algorithm to substitute the current coordinated distributed scheduling algorithm. Simulation shows that the proposed algorithm is able to guarantee "collision-free" scheduling in a realistic "non-quasi-interference" environment.

The remainder of the paper is organized as follows. 802.16 Mesh mode and details of coordinated distributed scheduling algorithm are described in Section 2. In Section 3, we discuss the quasi-interference issue that undermines the "collision-free" scheduling performance. In Section 4, we provide simulation results that verify such modeling discrepancy under the realistic "non-quasi-interference" scenarios and present key observations. After summarizing related works in Section 5, we conclude the paper in Section 6.

# 2 Background of IEEE 802.16 Mesh Mode

## 2.1 General Description of IEEE 802.16 Mesh Mode

Figure 1 shows the frame structure of the Mesh mode. Each frame is divided into a control sub-frame consisting of *MSH_CTRL_LEN* (0-15) transmission opportunities and a TDM data sub-frame consisting of up to 256 minislots. For high reliability, all the transmission opportunities are in fixed length of 7 OFDM symbols ($T_S$). The duration of a minislot can be derived given the frame duration ($T_F$), the number of control transmission opportunities and minislots. Table 1 shows the defined frame duration code of WirelessMAN-OFDM, which is one of four defined PHYs. There are two types of control sub-frame, i.e., schedule control sub-frame and network control sub-frame. The latter is re-occurring once for every *Scheduling_Frames*. The network control sub-frame provides basic functionality of network entry and topology management, while the schedule control sub-frame is to resolve the transmission schedule of data sub-frame. A node will not transmit in any minislot that is not reserved for its use. While reserved, each data transmission (a PHY burst with one or more MAC PDUs) may take multiple minislots, which is shown in Figure 2.

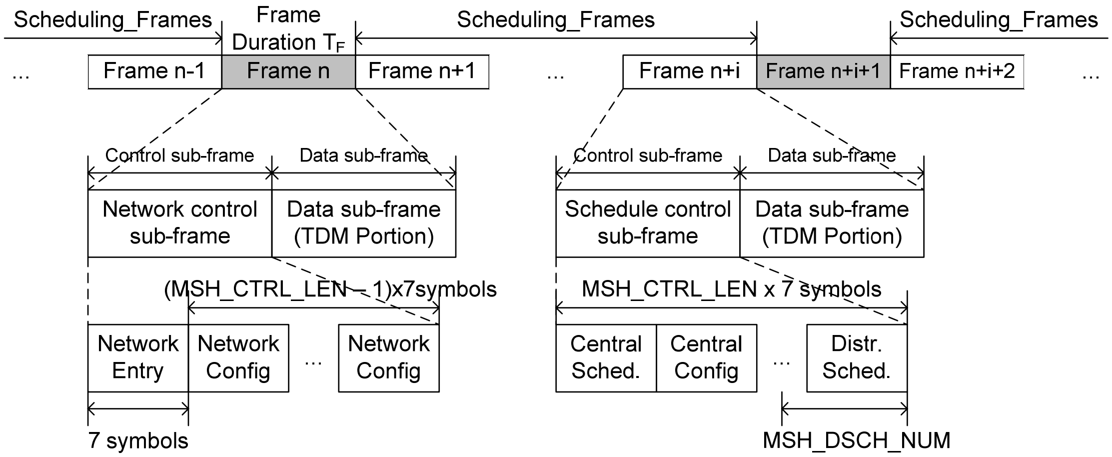

Figure 1. Mesh frame structure

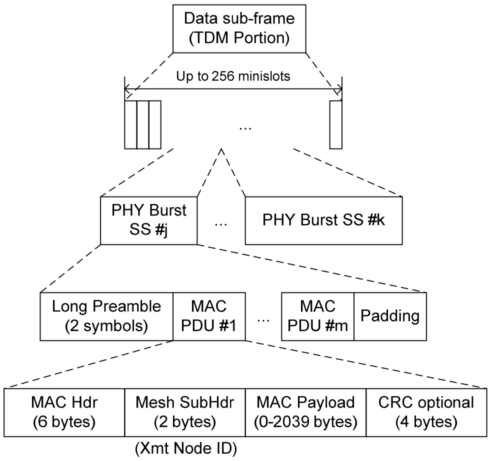

Figure 2. Data sub-frame structure

Table 1. WirelessMAN-OFDM frame duration ($T_F$ ms) codes

| Code | Frame duration (ms) | Frame per second |
|---|---|---|
| 0 | 2.5 | 400 |
| 1 | 4 | 250 |
| 2 | 5 | 200 |
| 3 | 8 | 125 |
| 4 | 10 | 100 |
| 5 | 12.5 | 80 |
| 6 | 20 | 50 |
| 7-255 | reserved | reserved |

The network control sub-frame serves primarily for new nodes that want to gain access to the network. In each network control sub-frame, the first transmission opportunity is dedicated to network entry message (MSH-NENT) in an unreliable contention-based access. A successful network entry relies on additional handshake messages between the new node and the sponsor node. The remaining (*MSH_CTRL_LEN* – 1) transmission opportunities are dedicated to network configuration messages (MSH-NCFG) in a coordinated distributed scheduling access manner. The schedule control sub-frame is used to schedule minislots for TDM transmissions in the data sub-frame. However, the access of transmission opportunities in the schedule control sub-frame itself requires certain rules, which could be centralized, or distributed, or a combination of both scheduling methods. If both scheduling method co-exist, the first (*MSH_CTRL_LEN-MSH_DSCH_NUM*) transmission opportunities within the control sub-frame are allocated for centralized scheduling messages (MSH-CSCH/MSH-CSCF), while the remaining ones are for distributed scheduling messages (MSH-DSCH).

## 2.2 Coordinated Distributed Scheduling

Due to the limit of space, we will not elaborate other scheduling algorithm in this paper. Interested readers may refer to standard specification [1] and the tutorial for more details on Mesh model [3]. Coordinated distributed scheduling is designed to achieve collision-free periodical transmissions of two types of control messages, i.e., MSH-NCFG and MSH-DSCH, respectively. Since the exact same algorithm is used independently for these two types of messages in separated slots (termed *transmission opportunities – XmtOps* – by the standard), we can simply actually analyze the behaviors of one of them, and the result is applicable to the other.

The general concept of coordinated distributed scheduling is to let nodes running the scheduling algorithm independently derive pseudo random but predictable behaviors by exchanging 2- or 3-hop (for free space environments) neighborhood schedule information with each other. Both the randomness and predictability are achieved by dynamically constructing random generator seeds for each node according to a common rule. The seed for a node is constructed based on its unique node ID and the index (or timestamp) of the candidate interested *XmtOp*. Given the neighborhood information, the random number generated locally will be the same as the corresponding one generated at the neighboring node. Therefore, predictability is achieved. In detail, by using previously scheduled transmission opportunities, nodes compute and exchange their next collision-free *XmtOp*s, as well as available schedules of their 2- or 3-hop neighbors, which is in the format of the following scheduling related parameters

$$\begin{cases} NextXmtXm :: 5bits \\ XmtHoldoffExponent :: 3bits \end{cases}$$

Given these two parameters of a specific neighbor, a node can determine an interval for *NextXmtTime* as well as *EarliestSubsequentXmtTime* of the neighbor as the following:

$$\begin{aligned} NextXmtXm \cdot 2^{XmtHoldoffExponent} &< NextXmtTime \\ &\leq (NextXmtXm + 1) \cdot 2^{XmtHoldoffExponent} \end{aligned} \qquad (1)$$

$$EarliestSubsequentXmtTime = NextXmtTime + 2^{XmtHoldoffExponent+4} \qquad (2)$$

Since the exact scheduled *XmtOp* of the neighboring node is unknown, as an implementation issue, one may define *NextXmtTime* to be the last *XmtOp* within the interval when calculating *EarliestSubsequentXmtTime*.

As shown in Figure 3, at the previously scheduled *XmtOp*, a node (namely the local node) will run an election algorithm to find its next collision-free *XmtOp*. Based on the calculated *NextXmtTime* time interval and *EarliestSubsequentXmtTime*, a node can exclude some neighboring nodes (e.g., Nbr 16 and 25 in Figure 4) from the competing neighbors of a particular candidate *XmtOp X*, which reduces the number of unnecessary idleness in the schedule and improve the utilization. For a particular candidate *XmtOp* starting from the *EarliestSubsequentXmtTime* of the local node, if the local node generates the maximum random number amongst all the eligible competing nodes, it wins this *XmtOp*. Otherwise, it will keep incrementing the candidate *XmtOp* and running the same election algorithm until it wins the election [3].

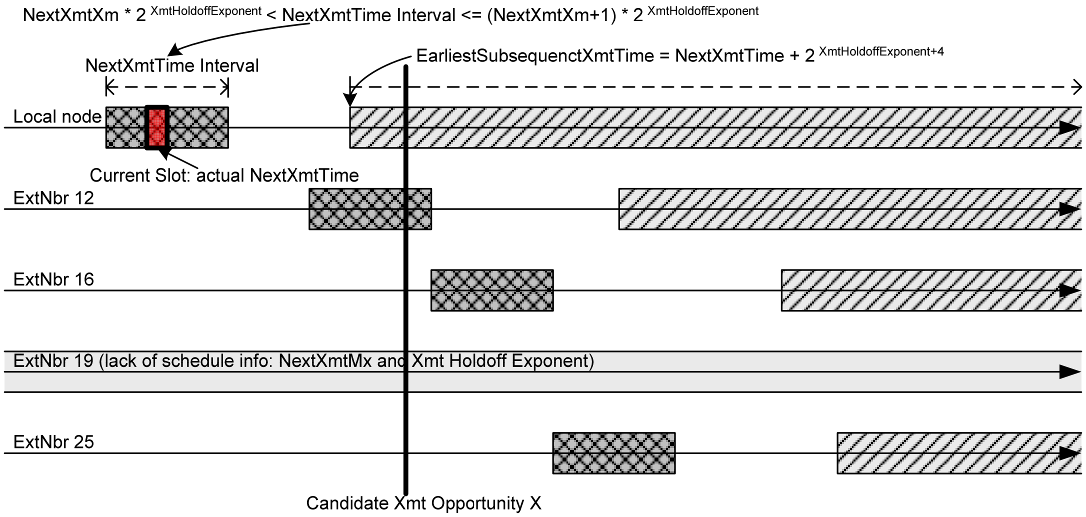

Figure 3. Coordinated distributed scheduling – Election-based approach

## 3 Quasi-Interference RF Modeling

We note that the coordinated distributed scheduling algorithm is aiming to achieve "collision-free" scheduling in a fixed environment. However, this claim is based on a simplified RF model in that wireless interference is mainly (if not only) considered if amongst nodes that are able to communicate with each other. In other words, it appears that there is no residue energy beyond a node's one hop neighborhood. This simplified RF model facilitates the construction of a wired-like link graph of wireless network. The scheduling algorithm deals with the broadcast nature of wireless communications in such a link graph that interference from direct neighbors of a receiver is considered, while accumulative interference from nodes beyond direct neighbors of the receiver are ignored. Therefore, we call this type of RF modeling the "quasi-interference" modeling, with respect to the realistic RF modeling where the energy of all propagated signals are counted regardless the upper layer network topology .

Strictly speaking, 802.16 is aware of the discrepancy between quasi-interference model and the real world. That is the reason why it provides a 3-hop ExtendedNeighborType option. Evidently the larger the extended neighborhood is, the less number of concurrent transmissions can be scheduled in the network with finite number of nodes, which leads to less spatial re-use. Nevertheless, in the following section, we clearly observe by simulation that, although it can reduce number of collisions, 3-hop scheduling still cannot guarantee collision-free completely given the fundamental limitation of the algorithm.

## 4 Simulation Study  Under Non-Qausi-Interference Scenarios

We implement the IEEE 802.16 Mesh Mode in QualNet [11], which has the capability of modeling realistic non-quasi-interference environments with a broad variety of propagation models. An OFDM system profile of Mesh MAC (ProfM3_Mesh) and 7MHz channelization at ETSI bands (ProfP3_7) has been used (for details, please refer to [1]). All performance relevant configuration parameters are listed in Table 2.

Table 2. Simulation configuration

| **PHY Profile - ProfP3_7 - WirelessMAN-OFDM PHY profile for 7 MHz channelization** | |
|---|---|
| Carrier frequency | 3.5GHz ETSI licensed band |
| Channel bandwidth | 7 MHz |
| Modulation | 64-QAM 3/4 (Assuming fixed rate) |
| $E_b/N_0$ (for BER<$10^{-6}$) | 19.0 dB |
| OFDM raw bitrates | 21.60 Mb/s (for $T_g=T_b/4$) |
| Receiver SNR threshold | 23.894 dB |
| Noise power | -97.073 dBm (2.8027e-17 mW/Hz) |
| Receiver power sensitivity threshold | -73.179 dBm (minimum performance requirement -70 dBm) |
| Transmission Power | 34.77 dBm (3W) |
| Antenna height | 1.5 m |
| Antenna gain plus all implementation losses | -5.0 dB |
| **MAC Profile - ProfM3_Mesh - WirelessMAN-OFDM Basic Packet Mesh MAC profile** | |
| Frame duration | code {0x01} $T_F$ = 4ms |
| Symbol duration | $T_S$ = 3.7037 μs |
| Minislot size | 1PS = 4 symbols |
| Control opportunity size | 7 symbols |
| Scheduling_Frames | 8 |
| MSH_CTRL_LEN | 8 |
| MSH_DSCH_NUM | 8 (all for coordinated distributed scheduling) |
| Number of minislots | 256 |

The following combinations of propagation models (i.e., Free Space, Two-Ray, ITM) and multi-hop topologies (grid, uniform distribution, actual terrain data) with 49 nodes are constructed. Please note the limited coverage of 64-QAM ¾ modulation and high data rate.

- Free space model + 49 nodes in grid formation with a grid distance of 300 m (network diameter = 8 hops)
- Free space model + 49 nodes uniformly distributed in 2.5kmx2.5km (network diameter = 10 hops)
- Two ray model + 49 nodes uniformly distributed in 2.5kmx2.5km (network diameter > 10 hops, not fully connected)
- ITM model + 49 nodes uniformly distributed in 1.1kmx1.1km mountainous terrain with relative elevation range of approximately 200 m. (network diameter = 10 hops). ITM is a terrain based RF model based on Longley-Rice model.

Identical *XmtHoldoffExponent* have been used for all scenarios presented in this paper. However, consistent results have been observed for non-identical *XmtHoldoffExponent* cases. As we mentioned in Section 2.2, we only present result for both MSH-NCFG, but the same performance can be observed for MSH-DSCH as well with the exact same scheduling behaviors. The following set of performance metrics is collected:

- Reception collision ratio (%): overall collision ratio seen at receivers (only collisions caused by interference from concurrent transmissions are counted)
- Scheduling interval (XmtOp): overall average number of corresponding transmission opportunities between two consecutive scheduled slots
- Number of extended neighbors: overall average number of neighbors in the *n*-hop extended neighborhood

Note that by carefully setting the receiver power sensitivity and SNR threshold based on bit-energy-to-noise-density ratio ($E_b/N_0$), we can identify error receptions caused by interference from concurrent transmissions (i.e., received SINR<SNR threshold, but received SNR≥SNR threshold, and received power≥receiver power sensitivity). Also note that we only collect statistics in stabilized condition, and therefore exclude collisions in transient condition.

Figure 4 shows the non-zero reception collision ratio, which verifies our analysis in Section 3. With the smallest *XmtHoldoffExponent*, nodes have high possibility to schedule concurrent transmissions beyond 2/3-hop scheduling neighborhood. Based on the idealized quasi-interference model, such spatial re-use and concurrent transmissions shouldn't cause any collision. However, we observe substantial amount of collisions for both 2-hop scheduling (up to 20.78%) and 3-hop scheduling (up to 6.76%). The reception collision ratio decreases when *XmtHoldoffExponent* increases from 0 to 4, for extend neighborhood type of 2 and 3, respectively. Note that when it decrease fast when *XmtHoldoffExponent* increase from 0 to 1 and from 1 to 2, and slowly for larger *XmtHoldoffExponent* (3 and 4). This is because for the latter, the holdoff interval (128 and 256, respectively) is substantially larger than the number of nodes in the affected interference neighborhood, even larger than the total number of nodes in the network. As a result, the probability of concurrent transmissions has already been significantly "diluted", and keeping increasing the holdoff interval does not benefit much more. This result is useful for selecting appropriate *XmtHoldoffExponent* to alleviate collisions and in the mean time still maintaining short schedule interval, which may result in optimal scheduling performance if latency due to unsuccessfully control message transmissions is considered.

Figure 5 shows the overall average schedule interval with respect to *XmtHoldoffExponent*, for extend neighborhood type of 2 and 3, respectively. Since for most cases in our simulation (except for *XmtHoldoffExponent* = 0 in 3hop extended neighborhood scenarios), the number of neighbors in the extended neighborhood, are equal or smaller than the holdoff interval, therefore, the resulted schedule interval is close to the lower bound specified by the holdoff interval (i.e., the dot lines in Figure 5(a) and (b)), which is equal to $2^{XmtHoldoffExponent}$.

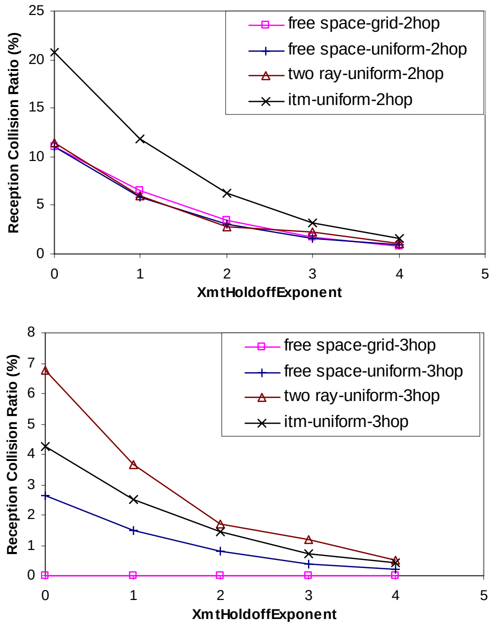

Figure 4. Reception collision ratio
(a) ExtendedNeighborhoodType = 2 hop (b) 3 hop

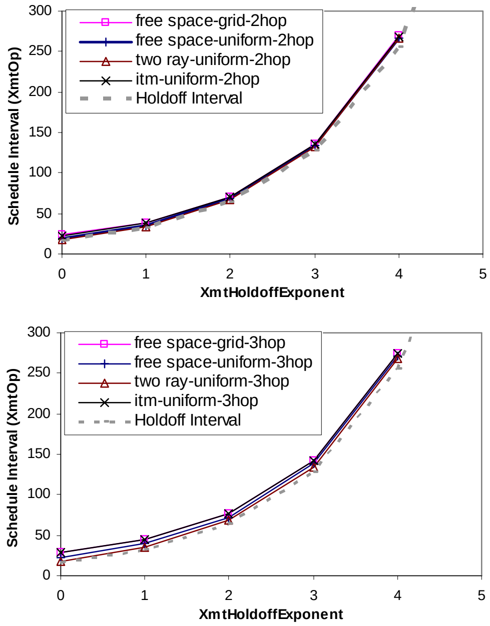

Figure 5. Schedule Interval
(a) ExtendedNeighborhoodType = 2 hop (b) 3 hop

# 5 Related Works

As relatively new standard, IEEE 802.16 has been studied much less than access technologies such as IEEE 802.11. Eklund et. al. presented an system level overview of 802.16 standards family in [4]. Redana and Lott modeled and compared the control message overhead between centralized and distributed scheduling mechanisms in [7]. From a different angle, Cao et. al. proposed a theoretic model to compute the schedule interval of 802.16 coordinated distributed scheduling in [5]. With the algorithm to grant data requests left open in the standard, the schedule interval is an important common performance metric that reflects the scheduling latency of coordinated distributed scheduling. Both general formulation and practical computable approximation under the assumption of geometric distribution of scheduling attempts after *EarliestSubsequentXmtTime* are presented. The model is validated though NS-2 simulation, which matches well with our QualNet results. Other related topics include QoS support in Mesh mode [6], and cross-layer optimization of routing based on MAC layer scheduling behaviors [8][9][10]. It's worth noting that maximizing spatial re-use and concurrent transmissions is the major idea behind many of such optimization efforts. However, most of proposed optimization schemes are based on the simplified quasi-interference model, in which accumulative interference beyond one hop of the sender is simply ignored. One example is the metric used to select the "best" neighbor to maximize concurrent transmissions at net entry [10]. Under realistic non-quasi-interference environment, the actual performance of such schemes needs more careful evaluation.

# 6 Conclusions and Future Work

In this paper, we studied the performance coordinated distributed scheduling in IEEE 802.16 Mesh mode, under realistic non-quasi-interference scenarios. We observed that, a substantial amount of collisions may exist even if the scheduling scheme can coordinate a 3-hop extended neighborhood. We also observe that, an optimal overall scheduling latency can be achieved by keeping a balance between the holdoff interval and the reception collision ratio.

In our future work, we plan to develop analytical model that is able to capture behaviors of reception collision ratio, network topology, RF propagation models, as well as scheduling parameters under the non-quasi-interference scenarios. Based on such model, we also plan to predict the overall scheduling latency with message handshake under non-quasi-interference scenarios, where collision-free cannot be guaranteed. Such result is critical for the implementation-dependent algorithms for requesting, allocating, and granting data minislots, because it will minimize scheduling failures (to schedule data transmissions earlier before the completion of required control message handshake) and delayed schedules (to schedule data transmissions too late after the completion of control message handshake).

# 7 References

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