Abstract—WiMax/802.16 mesh network is an emerging infrastructure that offers a cost-effective deployment for high-speed wireless broadband access to the backhaul network. However, as in most wireless multi-hop networks, WiMax/802.16 mesh suffers from interference that decreases considerably the throughput and spatial reuse of the network. Interference in WiMax/802.16 mesh is a result of several phenomena, namely concurrent transmissions in the neighborhood and data collisions (that need to be avoided) at a receiver from transmitting nodes that are outside the range of each other (hidden terminal nodes).

In this paper, we study the problem of Minimizing Interference (MI) in WiMax/802.16 mesh centralized scheduling networks by appropriately routing end connections and assigning slots to them. The proposed model includes the effect of hidden terminal nodes as well as the interferences coming from neighboring nodes. Results show that power-aware routing and adequate frame size selection yield better network performance, a consequence of the improved network spatial reuse.

I. INTRODUCTION

The IEEE WiMax/802.16 is a promising technology for broadband wireless metropolitan area networks (WMANs) as it can provide high throughput over long distances and can support different qualities of services. WiMax/802.16 technology [2] [3] ensures broadband access for the last mile. It provides a wireless backhaul network that enables high speed Internet access to residential, small and medium business customers, as well as Internet access for WiFi hot spots and cellular base stations [7]. It supports both point-to-multipoint (P2MP) and multipoint-to-multipoint (mesh) modes.

P2MP mode is similar in WiMax/802.16 networks and in cellular networks: radio frequency (RF) links are between the base station (BS) and subscriber stations (SSs). A subscriber station must be within the communication range and line-of-sight (LOS) of the BS with single hop connections. On the other hand, in the WiMax/802.16 mesh mode, as in most wireless mesh networks, SSs can communicate with the BS and with each other through multi-hop routes via other intermediate (sponsor/relay nodes) SSs. WiMax/802.16 mesh networks are now favored for several reasons: they extend the BS network coverage; they provide high bandwidth assignment to end clients (even distant ones) located at SSs which are not necessarily in the LOS of the BS, i.e., compatibility with non-LOS (NLOS) environments. However several challenges remain, namely efficient routing and scheduling strategies (with appropriate power aware scheme) are needed in order to reduce interference coming from neighboring nodes and avoiding collisions due to hidden terminal nodes.

The IEEE WiMax/802.16 mesh mode of operation uses time division multiple access (TDMA) technology where each frame is divided into 256 time slots. The first 16 time slots form a control subframe and the others define a data subframe. Two types of scheduling exist for WiMax/802.16 mesh mode: (i) centralized scheduling, and (ii) distributed scheduling. In this paper, we focus on centralized scheduling where the BS collects the requests from all SSs through mesh centralized scheduling (MSH-CSCH) request messages, and then assigns time slots to the granted connections. Scheduling decisions (time slot assignments) are propagated by the BS to all SSs through MSH-CSCH grant messages.

In order to achieve high network efficiency and better spatial reuse in these multihop wireless mesh networks (WiMax/802.16 mesh), multiple neighboring transmissions may be scheduled concurrently. Accordingly, some constraints on resource reuse must be considered in order to guarantee correct network operation. Moreover, these multihop mesh networks suffer, too, from hidden terminals as pointed out in [4], which could seriously degrade the network performance. Dynamic transmission power control and PHY (physical) data rate adaptation are effective mechanisms for dealing with these issues. In a power control scheme, a sender varies its transmission power on a slot by slot basis to meet the signal to interference plus noise (SINR) ratio at the receiver. Similarly, to deal with the interference generated by concurrent transmissions, a sender may reduce its PHY transmission rate to a more robust one.

An interference-aware WiMax/802.16 mesh is discussed in [9]; the proposed interference-aware algorithm chooses a path consisting of nodes with the least blocking metric, where the blocking metric is equal to the number of neighbors including the non transmitting ones. However, power-aware mechanisms (which help to reduce interference considerably) with connection slot assignment were not addressed.

Clearly, in a high density wireless mesh network, it is important to schedule multiple transmissions concurrently so that higher efficiency can be achieved. These multiple transmissions may however interfere with one another (co-channel
or asynchronous interference) either causing excessive frame loss or resulting in lower transmissions rates at the senders. In both cases, performance degradation is inevitable. Note that since we are assuming a WiMax/802.16 based mesh network, frame loss due to collisions (or synchronous interference) needs to be avoided and this is due to the TDMA property of WiMax. Therefore, in order to obtain better network efficiency (throughput), we deem it necessary to perform a suitable slot allocation that minimizes the interference (asynchronous) in the network while maximizing the number of concurrent transmissions.

In this paper, we propose a mathematical model that minimizes interference, called MI model, in WiMax/802.16 mesh networks, where the effect of the interference from neighboring transmissions and hidden terminals are incorporated. In this Interference-Hidden aware (IH-aware) model, the BS centrally performs time slot allocation for SSs (according to their bandwidth demands) taking into account the interferences each SS yields on its neighboring SSs, as well as avoiding the collisions that may arise from hidden terminals (SSs outside the transmission range of each other send data to a common SS neighbor at the same time). Hence, the MI model developed finds the best network configuration (optimal routing and to 0 otherwise. For instance, a voice connection has a bandwidth of \(64000\) bps and consumes \(w_k = 1\) time slot per \(T_{\text{scheduling}}\).

Let us next define the variables that will describe the routing of the granted connections. It corresponds to a set of decision variables defined as follows. First, for each connection \(k \in K\), we have \(x_k\) that is equal to 1 if \(k\) is routed through \(p, p \in P_k\), and to 0 otherwise. Next, in order to express properly the constraints, we need the additional following variables: \(x_k^e\) equal to 1 if connection \(k\) is routed through link \(e = (u, v)\), and equal to 0 otherwise; \(x_k^e\) equal to 1 if connection \(k\) is granted, and 0 otherwise, for \(k \in K\).

Let note that:

\[
x_e^k = x_{uw}^k = \sum_{p \in P_k} \delta_{up}^e x_{up}^k = \sum_{p \in P_k} \delta_{up}^e x_{up}^k \leq 1 \quad \text{for} \quad e = (u, v) \in L, k \in K;
\]

\[
x_k^e = \sum_{p \in P_k} x_k^e \leq 1 \quad \text{for} \quad k \in K.
\]

C. Power Aware- PowAware Scheme

We define \(\gamma_{w'u'}\) as follows: \(\gamma_{w'u'} = \begin{cases} 1 & \text{if } d_{w'u'} \geq d_{w'u}, \\ 0 & \text{otherwise} \end{cases}\). The \(\gamma\) parameter is used in the PowAware scheme, where sufficient power \(Q\) is transmitted from one node to its neighbor without interfering with a farther neighbor \((Q = \varepsilon d_{ul}^\beta)\), where \(\varepsilon\) is the amplifier transmitter and \(\beta\) is the path loss exponent. This is in contrast to the MaxPow scheme, where a node always transmits with its maximum coverage power \(Q_{\text{max}}\) (which is proportional to \(\varepsilon\)), and thus affecting all its neighboring nodes \(Q_{\text{max}} = \varepsilon D^\beta\).

D. Time slot allocation constraint IH-aware

Let us assume that a scheduling period \(T_{\text{scheduling}}\) is divided into two sub periods, one which is used for routing only uplink connections, and the other which is used only to route downlink connections. Note that uplink and downlink RF-links are always present during the whole scheduling period.

We now estimate, for the uplink and downlink connections (CN is a variable that can take either values UL uplink or DL), the overall number of used time slots on RF link \(e = (u, v) \in L\) in order to establish a time slot consumption constraint. We have (as it will be explained in the subsequent examples):

1) the connections that transit through a RF link \(e = (u, v) \in L\), i.e., connections that are generated by \(u\) and
connections where $u$ is a sponsor node. They consume:

$$\sum_{k \in K_{\text{CN}}: u = s_k} w_k \sum_{p \in P_k} \delta_{u,v}^k \cdot x_p^k + \sum_{u' \in N(u)} \sum_{k \in K_{\text{CN}}} w_k \sum_{p \in P_k} \delta_{u'}^u \delta_{u,v}^k \cdot x_p^k + \sum_{u' \in N(u)} \sum_{k \in K_{\text{CN}}} w_k \sum_{p \in P_k} \delta_{u'}^u \delta_{u,v}^k \cdot x_p^k$$

(1)

2) The connections that interfere with $e = (u, v)$, i.e., connections that are generated by $u$ but do not transit through $(u, v)$, and connections that do not transit through $(u, v)$ but where $u$ is a sponsor (relay) node. They consume:

$$\sum_{k \in K_{\text{CN}}: u = s_k} w_k \sum_{u' \in N(u) \setminus \{v\}} \sum_{p \in P_k} \delta_{uu'}^u \delta_{u,v}^k \cdot x_p^k + \sum_{u' \in N(u)} \sum_{k \in K_{\text{CN}}} w_k \sum_{p \in P_k} \delta_{uu'}^u \delta_{u,v}^k \cdot x_p^k \times \sum_{u' \in N(u)} \delta_{uu'}^u \delta_{u,v}^k \cdot x_p^k$$

(2)

3) The connections that go through $v$ but do not transit through $(u, v)$, i.e., slots consumed on $e = (u, v)$ to avoid collisions owed to the hidden terminal nodes (which only occur in the uplink given the routed tree property of WiMax/802.16 mesh centralized scheduling [2]):

$$\sum_{u' \in N(v); u' \neq u} \sum_{k \in K_{\text{CN}}} w_k \sum_{p \in P_k} \delta_{u'u}^u \cdot x_p^k$$

(3)

4) And finally the connections that are received at node $u$, i.e., connections destined to node $u$ (4) and connections that are interfering at node $u$ (5) (which only occur in the downlink given the routed tree property of WiMax/802.16 mesh centralized scheduling [2]), to preserve the half duplex property of WiMax/802.16 mesh nodes where a particular node cannot transmit and receive at the same time:

$$\sum_{u' \in N(u)} \sum_{k \in K_{\text{CN}}} w_k \sum_{p \in P_k} \delta_{u'u}^u \cdot x_p^k$$

(4)

$$\sum_{u' \in N(u)} \sum_{k \in K_{\text{CN}}} w_k \sum_{v' \in N(u')} \sum_{p \in P_k} \delta_{uu'}^u \delta_{u,v'}^k \cdot x_p^k \cdot [\gamma_{u'u'}^u]$$

(5)

Observe that in the PowAware scheme, the terms inside $[']$ are added in (2) and (5). This corresponds to the situation where a node is transmitting to a closer neighbor node, it will use the exact sufficient power such that farther neighbor nodes will not receive the interfering signal.

We suppose that $N_{\text{UL}}$ slots in a $T_{\text{scheduling}}$ (scheduling period time) are available on a RF-link $e = (u, v) \in L$ for the uplink connections. The time slot IH-aware (interference and hidden terminal aware) consumption on a RF link $e = (u, v) \in L$ for uplink connections ($\text{CN} = \text{UL}$) is defined as:

$$(1)^{\text{UL}} + (2)^{\text{UL}} + (3)^{\text{UL}} + (4)^{\text{UL}} \leq N_{\text{UL}}^{\text{slots}}.$$  

(6)

Similarly we formulate the IH-aware constraint for the downlink connections ($\text{CN} = \text{DL}$) where $N_{\text{DL}}^{\text{slots}}$ TDMA slots are available on a RF-link $e = (u, v) \in L$.

$$(1)^{\text{DL}} + (2)^{\text{DL}} + (4)^{\text{DL}} + (5)^{\text{DL}} \leq N_{\text{DL}}^{\text{slots}}.$$  

(7)

We mention that, from constraints (6) and (7), the BS performs the adequate slot assignment to avoid collisions due to hidden terminal nodes to occur and to encounter interference between concurrent neighboring transmissions. It also guarantees that at a particular time a receiving node receives only data destined to it without receiving any neighboring interference at the same time (refer to Figures 1 and 2).

### E. Illustrative Examples

Figures 1 and 2 illustrate the time slot allocation constraint for three downlink connections (4, 5, 6) respectively for the MaxPow and the PowAware schemes. The (‘R’) notation is in order to maintain the half duplex property where a subscriber station SS cannot transmit and receive at the same time. In addition, we suppose that $|e_2| > |e_4| > |e_1| > |e_5| > |e_3|$ (|e| is the distance of RF link e). We show for each slot, the corresponding connection (4, 5 or 6) that is transmitted (in black), or generating interference (in gray) on a particular RF-link. Finally, on those same figures, an edge represents a bidirectional RF-link and each connection consumes one slot on a particular RF-link.

In Figure 1 (MaxPow) and Figure 2 (PowAware) the downlink connections (4, 5, 6) use the following routing paths:

4) BS $\rightarrow$ SS$_{\text{Se}}$ $\rightarrow$ SS$_{\text{Sc}}$ $\rightarrow$ SS$_{\text{Ca}}$

5) BS $\rightarrow$ SS$_{\text{Se}}$ $\rightarrow$ SS$_{\text{Sc}}$ $\rightarrow$ SS$_{\text{Cb}}$

6) BS $\rightarrow$ SS$_{\text{Se}}$ $\rightarrow$ SS$_{\text{Cd}}$.

Figure 2 demonstrates how the PowAware scheme enables spatial reuse. Indeed, when SS$_{\text{Se}}$ is transmitting to SS$_{\text{Sc}}$ (connection 6) data on downlink edge $e_3$, no interference slots are caused on downlink edge $e_2$ in Figure 2, since $|e_3| < |e_2|$. However, for the MaxPow scheme shown in Figure 1, we observe an interference slot (denoted by 6 in gray) on downlink edge $e_2$ which causes SS$_{\text{Sc}}$ to receive the interfering signal. Moreover this interfering signal received at SS$_{\text{Sc}}$ consumes a slot on downlink edges $e_4$ and $e_5$ illustrated by the ‘R’ in gray (Figure 1) since at that moment SS$_{\text{Sc}}$ is receiving the interference signal and is unable to transmit owed to the half duplex property of a subscriber station. This will have impact on the transmissions of connections 4 and 5 that are postponed by one time slot on downlink edges $e_4$ and $e_5$ as shown in Figure 1 (MaxPow) when compared with PowAware scheme illustrated by Figure 2.

Finally, when comparing the overall number of slots wasted for interference between the MaxPow scheme (Figure 1) and the PowAware scheme (Figure 2), seven slots are saved by the PowAware scheme.

### III. MINIMIZING INTERFERENCE (MI) MODEL

#### A. Objective and Constraints of the MI model

As explained before, in order to achieve better network efficiency, one needs to reduce the interference. Hence our
The objective is to minimize interference:

$$\min \left\{ \sum_{e=(u,v) \in L} ((2)_{UL} + (2)_{DL} + (3)_{UL} + (5)_{DL}) \right\}$$

(8) minimizes the number of interfering slots, potential collision slots owed to hidden terminal nodes and half duplex slots (that are caused by interference received and which prevent a node from transmitting) for all RF-links in the network and with respect to both uplink and downlink connections.

The constraints are as follows:

Each connection (uplink or downlink) $k \in K$, if granted, must be routed on one route $p \in P_k$:

$$\sum_{p \in P_k} x_p^k \leq 1 \quad k \in K.$$  

(9)

Service providers are bound to achieve and maintain a minimum grade of service GoS (connections to be granted):

$$\sum_{k \in K} \sum_{p \in P_k} x_p^k \geq \text{GoS}.$$  

(10)

The flow conservation for uplink WiMax connections are:

$$\sum_{j \in V_n} \sum_{p \in P_k} \delta_{p}^{ij} x_p^k - \sum_{j \in V_n^c} \sum_{p \in P_k} \delta_{p}^{ij} x_p^k =
\begin{cases} 
0 & \text{if } v_i \in V \setminus \{ s_k, \text{BS} \}, \\
-1 & \text{if } v_i = s_k, \\
1 & \text{if } v_i = \text{BS}.
\end{cases}$$  

(11)

Note that in an uplink WiMax connection $k \in K_{UL}$, $d_k = \text{BS}$. Similarly, flow conservation constraints must also be enforced for downlink connections. Moreover, we allow no more than $n_{\text{hops}}^{UL}$ per uplink connection.

$$\sum_{p \in P_k} \sum_{e \in p} \delta_{p}^{de} x_p^k \leq n_{\text{hops}}^{UL} \quad k \in K_{UL}.$$  

(12)

Similarly, we allow no more than $n_{\text{hops}}^{DL}$ per downlink connection. In the experiments, we take $n_{\text{hops}}^{UL} = n_{\text{hops}}^{DL} = 5$. This value of 5 hops is chosen after some thorough experiments which showed that every node in our network could be reached with a path with at most 5 hops.

In addition, we formulate the following constraints (13) and (14) to preserve the rooted tree property for WiMax/802.16 mesh centralized scheduling for both uplink and downlink connections respectively:

$$\sum_{k \in K_{UL}} \sum_{p \in P_k} x_p^k \sum_{v' \in \text{N}(u)} \delta_{p}^{vu'} \leq 1 \quad u \in V$$  

(13)

$$\sum_{k \in K_{DL}} \sum_{p \in P_k} x_p^k \sum_{v' \in \text{N}(u)} \delta_{p}^{vu'} \leq 1 \quad u \in V$$  

(14)

Finally, we add the time slot interference-hidden terminal based constraints (6) and (7) for every RF-link $e = (u, v) \in L$, uplink connections and downlink connections respectively.

IV. EXPERIMENTAL RESULTS

We implemented the MI mathematical model which we developed in the two previous sections in C++, and solved it using the CPLEX package (version 9.1.3). Uplink sources and downlink destinations of the connections are uniformly distributed over the set of SSs. The set of potential routes is defined as follows. As defined in the IEEE WiMax/802.16 Standard [2] for the mesh centralized scheduling, we compute a single random shortest path (referred as SinglePath) between each SS node and the BS, in order to have a tree structure. We also compute 5 alternate paths between each SS node and the BS (referred as MultiPath). Note that even with multi-path, the tree structure property is always satisfied [2] due to constraints (13) and (14).

In Section IV-B, we perform experiments on two schemes, the PowAware scheme and the MaxPow scheme. Within each scheme we shall consider the SinglePath and the MultiPath.

A. Network and Traffic Instances

We generated a random real-like WiMax/802.16 mesh network, with a single base station (BS) with a transport capacity of 2 Gbps and 55 subscriber stations (SSs). We assumed 270 bidirectional potential radio links between some pairs of SSs within transmission range of each other. The resulting network was depicted in previously done work [5] [6]. Note that WiMax/802.16 [2] can support BSs requiring from 75 Mbps up to multi-Gbps performance [1].

We consider 4 classes of traffic uniformly distributed over the number of uplink and downlink connections. These four classes are voice connections (V), slow data connections (S),
fast data connections ($F$), and backbone connections ($B$). Experiments have been conducted on a traffic instance of 200 connections consisting of:

- 100 voice connections with $b_k = 64$ kbps, $w_k = 1$ slot;
- 50 slow data connections with $b_k = 1$ Mbps, $w_k = 3$ slots;
- 30 fast data connections with $b_k = 10$ Mbps, $w_k = 24$ slots;
- 20 backbone with $b_k = 100$ Mbps, $w_k = 240$ slots.

### B. Validation and Experimental Results

The number of granted connections GoS, associated with each traffic class is $\text{GoS}_a = \sum_{k \in K_a} x^a_k,$

where $a \in A = \{(V), (S), (F), (B)\}$. We set the grade of services as follows: $\text{GoS}_V \geq 80\% \times |K_V|$ (where $|K_V| = 100$ the total number of voice connections), and $\text{GoS}_V \geq \text{GoS}_S \geq \text{GoS}_F \geq \text{GoS}_B$.

In addition, the network throughput is defined as:

$$\text{Network Throughput} = \sum_{k \in K} x^k \times b_k.$$  

The term “link used” refers to a RF-link that has at least one connection that transits through it. In Table I we observe that higher GoS is reached with the PowAware scheme when compared with the MaxPow scheme. For instance, in the PowAware scheme, 2 more backbone ($B$) connections are granted when compared with the MaxPow scheme. This is attributed to the fact that in PowAware lower transmission power is used in the network, which indeed results in lesser level of interference which promotes more concurrent transmissions and hence better spatial reuse. Clearly, in order to increase the network efficiency, it is crucial to associate power aware mechanisms with the scheduling algorithm of the BS.

In Figure 3, we plot the overall Interference Bandwidth Wasted per link used vs the Network Throughput. The curve (without marks) illustrates the case where Minimizing the Interference is omitted (NMI) while in the other curves Minimizing Interference (MI) is used. As shown in the figure, less Interference Bandwidth is wasted when comparing MI to NMI for the MaxPow SinglePath scheme and for the same Throughput. Hence, MI reduces Interference, allowing therefore multiple concurrent transmissions in the neighborhood. Similar results, though not shown, are achieved when comparing MI to NMI for the PowAware SinglePath scheme. Moreover, Figure 3 shows that within a particular scheme (MaxPow or PowAware), MultiPath reduces Interference when compared to SinglePath for a particular Throughput (GoS) since MultiPath provides load balancing by escaping bottleneck nodes. Finally, PowAware scheme reduces the overall Interference when compared to the MaxPow scheme for a same Throughput, and most importantly PowAware achieves a higher Throughput (GoS) as discussed earlier in Table I (see Figure 3).

![Fig. 3. Bandwidth wasted owed to overall Interference per link used (y-axis) Vs Network Throughput (x-axis)](image)

### C. Variation of the frame size

The experimental results obtained in the previous section were associated with a frame duration of 5 ms. We vary the frame duration (WiMax/802.16 mesh supports frame durations between 2.5 ms to 20 ms [8]) and conduct experiments using a 1000 voice connection traffic, for the centralized mesh scheduling with the MI PowAware-MultiPath scheme. Results are compared with respect to the Bandwidth wasted owed to overall Interference per link used and Maximum Network Throughput for different frame durations. We assume the same scheduling period $T_{cycle} = T_{scheduling} = 100$ ms for all different frame durations, and use a BS of 75 Mbps (37.5 Mbps for uplink and 37.5 Mbps for downlink).

Table II shows the total number of slots (note that $N_{UL}^{slots} = N_{Total}^{slots} = N_{Total}/2$ per $T_{cycle}$, the slot size, the number of slots $w_k$ used per voice connection and the bandwidth wasted per voice connection owed to the slot allocation, for different frame durations. Note that for slots assigned to each voice connection (a voice connection has a data rate of 64000 bps), bandwidth is wasted but with different amount when varying the frame duration as shown in Table II.

Table III shows that when reducing the frame duration till 3 ms, higher GoS and (Throughput) is achieved, since as shown in Table II, decreasing the frame size till a 3 ms duration reduces the bandwidth wasted owed to the voice slot assignment. However, if the frame size is reduced more than 3
TABLE II
TOTAL NUMBER OF SLOTS ($N_{Total}$) (UPLINK AND DOWNLINK) PER $T_{cycle}$, SLOT SIZE, NUMBER OF SLOTS $w_k$ PER VOICE (V), AND BANDWIDTH WASTED BW PER VOICE, FOR DIFFERENT FRAME DURATIONS

<table>
<thead>
<tr>
<th>Frame duration</th>
<th>$T_{frame}$</th>
<th>$N_{Total}$</th>
<th>Slot size in bps</th>
<th>$w_k$</th>
<th>BW in bps</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 ms</td>
<td>1200</td>
<td>62500</td>
<td>2</td>
<td>61000</td>
<td></td>
</tr>
<tr>
<td>10 ms</td>
<td>2400</td>
<td>31250</td>
<td>3</td>
<td>29750</td>
<td></td>
</tr>
<tr>
<td>5 ms</td>
<td>4800</td>
<td>15625</td>
<td>3</td>
<td>14125</td>
<td></td>
</tr>
<tr>
<td>4 ms</td>
<td>6000</td>
<td>12500</td>
<td>6</td>
<td>11000</td>
<td></td>
</tr>
<tr>
<td>3 ms</td>
<td>8000</td>
<td>9375</td>
<td>7</td>
<td>1625</td>
<td></td>
</tr>
<tr>
<td>2.5 ms</td>
<td>9600</td>
<td>7812.5</td>
<td>9</td>
<td>6312.5</td>
<td></td>
</tr>
</tbody>
</table>

TABLE III
ASSOCIATED MAXIMUM GoS = GoS$^V$ (MAXIMUM NUMBER OF VOICE (V) CONNECTIONS GRANTED) REACHED FOR DIFFERENT FRAME DURATIONS

<table>
<thead>
<tr>
<th>Frame duration</th>
<th>$T_{frame}$</th>
<th>GoS$^V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 ms</td>
<td>399</td>
<td></td>
</tr>
<tr>
<td>10 ms</td>
<td>507</td>
<td></td>
</tr>
<tr>
<td>5 ms</td>
<td>684</td>
<td></td>
</tr>
<tr>
<td>4 ms</td>
<td>703</td>
<td></td>
</tr>
<tr>
<td>3 ms</td>
<td>776</td>
<td></td>
</tr>
<tr>
<td>2.5 ms</td>
<td>737</td>
<td></td>
</tr>
</tbody>
</table>

ms, for instance 2.5 ms, the GoS (and Throughput) decreases instead of increasing (see Table III), since shortening too much the frame size yields higher bandwidth wasted owed to voice slot allocation (refer to Table II 3 ms and 2.5 ms where respectively 1625 bps is wasted on the last slot of the 7 slots assigned per voice connection and 6312.5 bps is wasted on the last slot of the 9 slots assigned per voice connection). Furthermore, in Figure 4, we illustrate the Bandwidth wasted owed to the overall Interference per link used Vs the Maximum Network Throughput (GoS) associated with different frame durations. As depicted in this figure, the 3 ms frame size achieves the highest Network Throughput and the least Interference Bandwidth Wasted per link used. Thus there is a one-to-one relationship between choosing the appropriate frame size (3 ms in our case) that result in the least slot bandwidth waste (per voice connection) and minimizing Interference in the network which in turn leads to higher Throughput. This is explained by the fact that, the less slot bandwidth is wasted (per voice connection) the more the free bandwidth is available which will result into better routing and scheduling BS decisions in order to minimize interference. Hence power aware mechanisms coupled with a suitable frame size selection results in better exploiting the network resources; and that is due to the lower bandwidth wasted when performing the slot allocation.

V. CONCLUSION

This paper presented a novel efficient Minimum Interference (MI) design approach, with an interference and hidden terminal aware slot allocation for WiMax/802.16 centralized scheduling mesh networks. The slot allocation proposed, enables the BS to avoid collisions between hidden terminal nodes, and encounters interference from concurrent neighbor receiving nodes, and encounters interference from concurrent neighbors, and encounters interference from concurrent neighbors. It also guarantees reception of data without interference from the neighborhood. Two schemes were investigated, namely the PowAware scheme where each node transmits with just enough power to reach its next neighbor receiving node, and the MaxPow scheme where each node transmits with its maximum coverage power. The impact of PowAware scheme over MaxPow scheme with respect to the interference and spatial reuse (higher GoS reached when PowAware was assumed) is shown. Moreover, interference is decreased when multi-path is chosen instead of single path, within a particular scheme, owed to the load balancing provided by multi-path. Finally, the benefits (higher throughput and less interference) of choosing the appropriate frame size in presence of connections for which an amount of bandwidth is wasted with respect to the slot assignment (e.g. voice connection) were evaluated.

REFERENCES


Fig. 4. Bandwidth wasted owed to overall Interference per link used vs Maximum Network Throughput associated with different frame sizes.