Investigating Depth-Fanout Trade-Off in WiMAX Mesh Networks

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Abstract. In the last years, Wireless Mesh Networks (WMNs) have been an emerging technology for providing cost/effective broadband Internet access. The research done insofar usually assumes that the wireless backbone of a WMN is built using IEEE 802.11 technologies. Such an approach has the drawback of leading to dense and sub-optimal deployments, due to the short transmission range of this standard. Recently standardized, the WiMAX technology is supposed to transcend this limitation by a transmission range of several miles. In particular, the *mesh mode* of the WiMAX standard enables direct communications between subscriber stations and, hence, reduces dead zones while increasing the global throughput. In this paper, we investigate the throughput capacity of a WiMAX mesh tree. More specifically, we are interested in balancing the impact of the depth of the tree with its fanout. We provide a traffic model and evaluate the WiMAX mesh tree by simulations.

1 Introduction

Wireless Mesh Networks (WMNs) [1] are an emerging two-tier architecture based on multi-hop transmission, with two fundamental objectives: to offer connectivity to end-users and to form a self-organized wireless backbone. Two types of nodes are used to fulfill these goals: *Wireless Mesh Routers* (WMR) and *Wireless Mesh Clients* (WMC). WMRs perform routing as conventional wireless routers, interconnecting and self-organizing themselves in order to form the backbone of a WMN. In addition to routing capabilities, a WMR acts also as an *Access Point* (AP) that covers a certain region offering connectivity to WMCs. WMRs may use a certain wireless technology for the backbone communication (e.g., WiMAX) and a different one to offer connectivity to end-users (e.g., WiFi). Mesh networks display salient advantages such as ubiquitous coverage, rapid and cost-efficient deployment, and robustness (see Akyildiz et al. [1] and Beyer [2] for further details). The flexibility of this architecture and the easiness of deployment make WMNs able to solve issues like dead zones, providing seamless connectivity without the needs of complicate setups.

Increasing the throughput capacity of the backbone of WMNs as well as ubiquitous connectivity is quite desirable but represents a real challenge. For instance, WMNs that use IEEE 802.11 [3] for the wireless backbone inherently suffer from reduced transmission range and low aggregate throughput capacity.

Using a transmission technology that increases the transmission range as well as the throughput capacity can alleviate these problems.

A promising technology that has both these properties is the recently published IEEE 802.16 standard [4], also called WiMAX [5]. The first release of this standard was designed to initially support only *Point-to-Point* (P2P) and *Point-to-Multi-Point* (PMP) communication mode. In a more recent release [6], the standard has been extended, introducing the *mesh mode* to let *Subscriber Stations* (SSs) communicate through multi-hop transmissions. In its basic version, the mesh mode relies on a centralized approach that organizes all the nodes of a WiMAX network in a tree structure rooted at a particular node, namely the *Base Station* (BS). The way this tree is built and the choice of the links used has a deep impact on the capacity that a WiMAX backbone may offer. For instance, the length of the links (in meters) significantly affects the bitrate. Long links can only support low bitrates, hence end-to-end throughput between source and destination may increase if relay SSs are used instead of direct communication.

In this paper we tackle exactly this point. We model the traffic demands of a WiMAX mesh tree architecture and we evaluate the trade-offs between the depth and the fanout of such a structure. Deeper trees have shorter links with higher bitrate.

In the literature can be found works that focus either on improving the scheduling algorithm [7] or in link selection and routing [8]. Both types of work aim at optimizing a single aspect of WiMAX mesh mode, which is improving concurrent transmissions for increased capacity.

Knowing the importance of allowing simultaneous transmissions in WiMAX mesh networks, we focus our work on exploring the impact of splitting direct long communications of fat trees (small depths) into multiple shorter ones (deep trees). We show by simulation that increasing the depth while reducing the fanout may increase, at least in some cases, the capacity of the WiMAX backbone even without allowing concurrent transmissions.

The rest of the paper is organized as follows. Section 2 overviews the WiMAX mesh mode and discusses the different trade-offs. Section 3 provides a traffic model for the mesh tree. Section 4 presents our simulations and discusses the results before concluding the paper in Section 5.

2 WiMAX mesh trade-offs

The IEEE 802.16 has been originally designed to support only centralized communications paradigms (i.e., P2P and PMP). Later, the mesh mode was introduced in the IEEE 802.16d [6] version of the standard. IEEE 802.16d defines the control mechanisms and management messages to establish connections in mesh network architecture. When mesh mode is employed, the network is still formed by a BS and many SSs, as shown in Fig. 1.

The traffic can now occur directly between SSs and may be relayed by intermediate nodes (both uplink and downlink). The BS can also be the gateway between the WMN backbone and the Internet. SSs (WMRs in general mesh

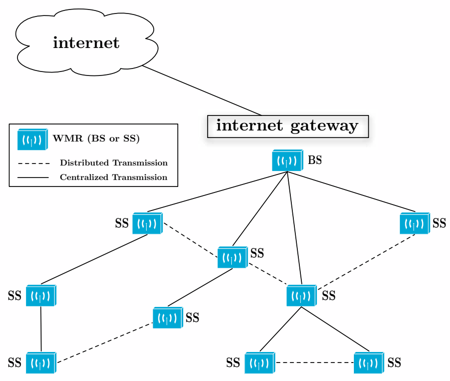
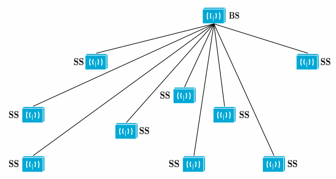
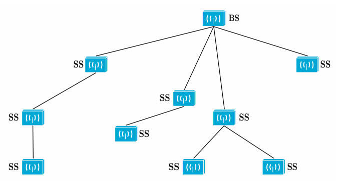


Fig. 1. WiMAX mesh mode architecture.



(a) Max fanout case.



(b) Max depth case.

Fig. 2. Depth vs. fanout in WiMAX mesh mode tree.

terminology) communicate with each other and transfer their neighbors' traffic through these links. Each SS must have at least one path towards the BS. In our study, we consider the WiMAX mesh tree on which the BS schedules the transmissions in a centralized manner. We suppose that all SSs are in the BS range and we study the depth-fanout trade-off of this architecture.

The tree depth represents the maximum number of hops needed by a SS to reach the BS, while the fanout is the width of the tree (number of children per node). We explore how the throughput capacity of a WiMAX network changes when we move gradually from an architecture that maximizes the fanout of the mesh tree (like in Fig 2(a)), toward an architecture that maximizes the depth of the mesh tree (like in Fig. 2(b)). Increasing the depth (i.e., decreasing the fanout) reduces the distance and hence increases the bitrate on the different links.[3] Moreover, it lowers the transmission power needed and hence interference decreases, which may improve spatial reuse for concurrent transmissions. However, this is beyond the scope of this paper. Reducing depth (i.e., increasing fanout) reduces the number of relay transmissions of the same data packet as well as control overhead. In the next subsection, we detail the control overhead of IEEE 802.16, before detailing the relation between bitrate and physical distance.

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[3] By distance we mean the physical distance measured in meters or kilometers.

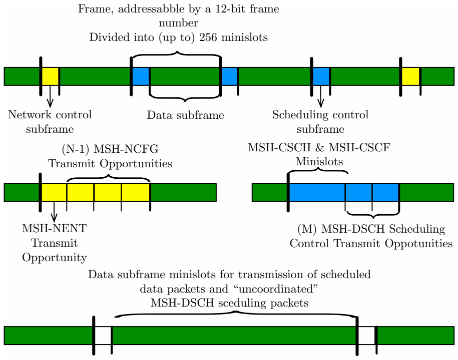

Fig. 3. WiMAX mesh frame structure.

2.1 Control overhead

IEEE 802.16 MAC layer uses *Time Division Multiplex* (TDM) to access the channel, thus using mesh frames that have fixed duration. Each frame is divided into two portions: a control subframe and a data subframe. The length of the control subframe is fixed and given by the MSH-CTRL-LEN parameter. An illustration of mesh frames is given in Fig. 3.

The scheduling in WiMAX mesh mode is performed by negotiating minislot ranges and associated channels within the data subframe. Scheduling is adaptive, based on the traffic demand for each link. In particular, two scheduling schemes are defined: *centralized* and *distributed*. The centralized scheduling is coordinated by the mesh BS and the scheduled packets are transmitted in a collision-free way within scheduling control subframes (Grants and Requests) shown in Fig. 3. Distributed scheduling is done by exchanging requests and grants in the extended neighborhood of the communicating SSs, which consists of the direct neighbors (one-hop) and their neighbors (two-hop neighbors).

In this paper, we focus on the centralized scheduling, and investigate the maximum capacity of the mesh tree by studying the depth-fanout trade-off. Centralized scheduling is performed using two main types of messages: the *Mesh Centralized Scheduling* (MSH-CSCH) message and the *Mesh Centralized Scheduling Configuration* (MSH-CSCF) message. Each node gathers its children's requests and reports them along with its own in a MSH-CSCH request to its parent. The parent node is named *Sponsoring Node* (SN) in the WiMAX terminology. The whole process repeats recursively until the requests are propagated towards the BS. The BS then determines the flow assignments and broadcasts a MSH-CSCH Grant, which is rebroadcasted by intermediate nodes until all the SS nodes in the network receive it. SSs determine their scheduling in a recursive manner by using a common algorithm that divides the frame proportionally. According to this Request/Grant procedure, WiMAX mesh networks cannot support more than 100 subscribers. Moreover, as the tree depth increases the control information reduces the available slot space for data, thus decreasing the achievable throughput. Fig. 4 shows an example of how the control time slots number in-

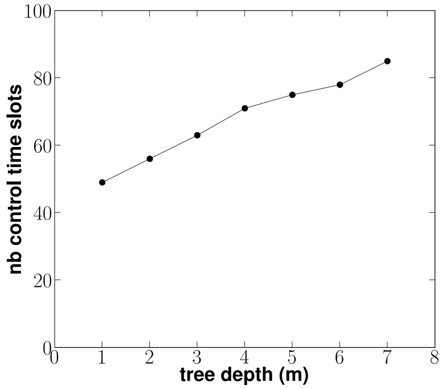

Fig. 4. Control timeslots vs. tree depth.

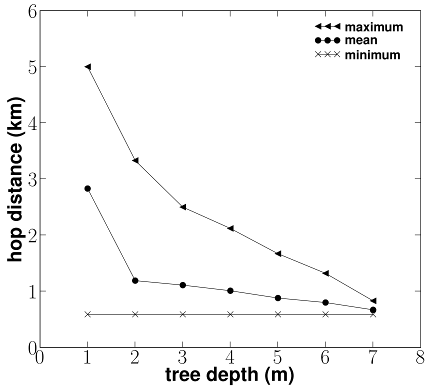

Fig. 5. Average hop distance vs. tree depth.

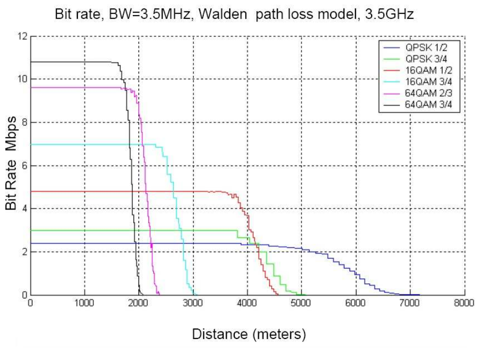

Fig. 6. Bit rate vs. distance [9].

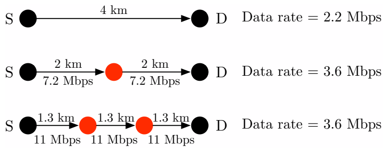

Fig. 7. Splitting links.

creases as the tree depth increases, where we assume the number of SSs is fixed and equal to 48 stations.

2.2 Bitrate vs. Distance

IEEE 802.16 standard adapts different modulations and coding techniques on different transmissions, which implicitly implies different bitrates that can be attained. In other words, the data rate decreases as the link distance increases. On the other hand, increasing the tree depth means increasing the number of hops required to reach the BS, which in turn reduces the average hop distance (in km) leading to an increase in the average link bitrate. Moreover, it also affects the transmission power needed to attain the next hop, which becomes smaller reducing the interference. In this latter case, spatial reuse can improve aggregate throughput capacity. Fig. 5 illustrates how the hop distance decreases as the depth of the mesh tree increases.

Fig. 6 illustrates how the bitrate is affected by the distance [9]. Different modulation schemes have been simulated by Betancur et al. on NS2 after implementing the PHY and the results are shown for each scheme. The highest bitrates were attained when 64 QAM 3/4 was used. However, 64QAM 3/4 cannot be used for a distance greater than 2 km. In the latter case, other modulation types are used. The most stable scheme is the Quadrature Phase Shift Keying 1/2 (QPSK 1/2), which is used for the furthest distances, but can only yield small bitrate compared to the other schemes for smaller distances.

Fig. 6 evidently shows that the overall bitrate on some long links would be better if they are split, in other words, if the communications between sources and destinations on these links utilize intermediate SSs to rely their data. Assume the source and destination are four km apart, as shown in Fig. 7. QPSK 1/2 will be used, which will only result in 2.2 Mbps bitrate. If a relay SS, located in the middle distance between the communicating nodes is used, 16QAM 3/4 can be still used and will result in 7.2 Mbps on each segment. The overall end-to-end bitrate will be 7.2 Mbps divided by two (since there is a two hops transmission), hence 3.6 Mbps. Similarly, if two relay nodes are used, then 64 QAM 3/4 can be used. The bitrate, in this case, will be about 11 Mbps on each hop, resulting in 3.6 Mbps as end-to-end bitrate (11 Mbps/3 since there is a three hops transmission).

3 Traffic model for the WiMAX mesh tree

When centralized scheduling is employed, each SS gathers its children's requests and reports them along with its own to the BS indicating the amount of resources needed in both the uplink and downlink direction. The BS receives all the requests, calculates the allocations using a common algorithm and broadcasts the grants. Requests as well as actual traffic increasingly accumulate as we approach the BS. Fig. 8 depicts the general case, where nodes are arranged into several levels (we assume m levels). An SS in level A_k has many children in level A_{k+1} and exactly one SN in level A_{k-1}. SSs in level A_1 have direct link with the BS (one hop). SSs in level A_m are the furthest from the BS (m-hops distant).

The performance of any network is strongly dependent on the traffic pattern generated by its nodes. Throughout this study, we consider that all the stations generate the same amount of uplink traffic and hence request the same amount of resources. Similarly, all the nodes request the same amount of downlink traffic. This is a reasonable assumption considering all nodes having the same average behavior. We can distinguish four types of traffic:

1. Traffic in the uplink direction towards the Internet via the BS. It is designated by u, expressed in bits per second.
2. Traffic in the downlink direction coming from the Internet via the BS. It is designated by d, expressed in bits per seconds.
3. Intra-mesh traffic in the uplink direction is the portion of the traffic that each node communicates with other nodes in the network in the uplink direction. It is designated by o, expressed in bits per seconds.

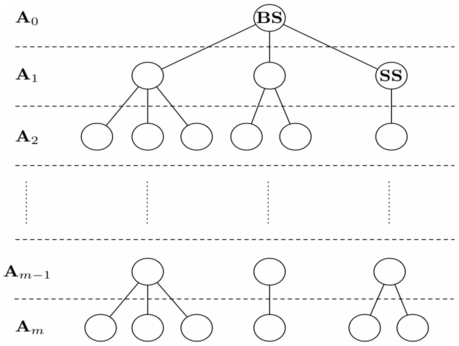

Fig. 8. Mesh tree having N nodes and m levels.

4. Intra-mesh traffic in the downlink direction is the portion of the traffic that each node receives from other nodes in the network in the downlink direction. It is designated by r, expressed in bits per seconds.

We assume that the volume of these types of traffic is the same for all nodes, since we consider long-term assumptions. In other words, we assume that all SSs are under the same conditions and have the same amount of traffic. Since each SS is a WMR, this means that, on the average, they manage a uniform distribution of WMC, each one having an equal traffic pattern profile. Thus, each SS has data to send to all the SSs in the mesh tree equi-probably, hence the quantity of data exchanged with every other node is the same in the long term.[4]

Starting from these assumptions, our objective is to calculate the aggregate throughput capacity of the mesh tree, which is the equivalent of the uniform throughput, defined as follows:

Definition 1: The *uniform throughput*, also referred to as "uniform capacity" is the maximum possible aggregate communication throughput, if all nodes communicate with all other using a common rate.

In the following sections, we give mathematical expressions of requested traffic at each link for both balanced tree and unbalanced tree. This model is used by the base station to setup schedules for different links in the mesh tree.

3.1 Model for the Balanced Tree

We define the *balanced tree* as the tree that satisfies two conditions. First, the number of children of each SN is constant. Second, the number of nodes in each level A_k is uniformly distributed among the nodes of the upper level A_{k-1} and it can be calculated as:

$$\text{Nb nodes in level } \mathrm{A}_k \;=\; (\text{nb Children per SN})^k\,. \tag{1}$$

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[4] It is worth to remark that the assumptions we made do not imply an equal uplink traffic volume and downlink traffic volume (i.e., $u \neq d \neq o \neq r$).

Nevertheless, it is more meaningful to analyze a tree that bears some deviations from these values. We call this tree *quasi-balanced.* So, we suppose that the number of children of each node is variable and we define C_a to be the average number of children. We also assume that the variance in this number is small. This is achieved by applying a routing algorithm that constructs the tree in a way to make it as balanced as possible. For instance, a new station chooses, among a set of candidate nodes, the node having the lowest number of children to be its parent. The number of nodes in level A_k is estimated as:

$$\text{Nb nodes in level } \mathrm{A}_k \;=\; (\mathrm{C}_a)^k \,. \tag{2}$$

External traffic - We first evaluate the traffic sent to or received from the Internet. We start by calculating the requests for the uplink provided that each node requests u bits per second for its own. We calculate the requests of the nodes in each level. They are increased as we approach to the BS since nodes close to it must transfer the traffic of all the nodes joined to their children's branches.

$$\begin{aligned} T_{A_i} &= (\text{Nb nodes in } \mathrm{A}_i) \times u + (\text{Average traffic from } \mathrm{A}_{i+1}) \\ &= C_a^i \times u + C_a^{i+1} \times u + C_a^{i+2} \times u + \ldots + C_a^m \times u \\ &= \sum_{k=i}^{m} C_a^k \times u \,. \end{aligned} \tag{3}$$

Furthermore, we suppose that the average traffic in any level A_i (i.e., T_{A_i}) is uniformly distributed over all nodes of this level $[(C_a)^i]$ and consequently the traffic for each node in the uplink direction U_i is estimated by:

$$U_i \;=\; \frac{u \times \sum_{k=i}^{m} C_a^k}{C_a^i} \;=\; u \times \sum_{k=0}^{m-i} C_a^k \,. \tag{4}$$

Similarly, we compute D_i, the traffic in the downlink direction:

$$D_i \;=\; d \times \sum_{k=0}^{m-i} C_a^k \,. \tag{5}$$

Intra-mesh Traffic - It designates the traffic that has both source and destination inside the mesh tree. As discussed before, each node communicates with all the nodes in the mesh tree equi-probably. This means that the quantity of data that a node exchanges with every other node is the same and it can be easily proved that the incoming intra-mesh traffic r equals the outgoing intra-traffic o. The traffic demanded by each SS in the uplink and downlink directions can be estimated as follows.

For any node SS_i in level A_i, the requested uplink traffic U_i is the sum of:

1. A portion of its own outgoing intra-mesh traffic o that goes up to other nodes via its SN. It can be expressed as:

$$\left(1 - \frac{C_i}{N-1}\right) \times o \ . \tag{6}$$

   Where N is the total number of SSs in the mesh, while C_i is the total number of SSs that use SS_i for their communications:

$$C_i \ = \sum_{k=1}^{m-i} C_a^k \ . \tag{7}$$

2. A portion of the uplink traffic of its children, each one contributing with U_{i+1} bps and, thus, producing $C_a \times U_{i+1}$ amount of traffic. Nevertheless, $\frac{C_a}{N-1}$ portion of this traffic is destined to SS_i itself, while $\frac{C_i(C_a-1)}{N-1}$ is sent downlink because the destination is in the sub-tree rooted in SS_i. Thus, the amount of intra-mesh traffic coming from its children and that needs to be forwarded uplink is

$$\left(C_a - \frac{C_i\left(C_a - 1\right) + C_a}{N-1}\right) \times U_{i+1} \ . \tag{8}$$

Hence, the total intra-mesh uplink traffic requested by SS_i is:

$$U_i = \left(1 - \frac{C_i}{N-1}\right) \times o + \left(C_a - \frac{C_i(C_a - 1) + C_a}{N-1}\right) \times U_{i+1} \ . \tag{9}$$

Similarly, we can calculate the requested downlink traffic D_i as:

$$D_i = \left(1 - \frac{C_i}{N-1}\right) \times r + \left(C_a - \frac{C_i(C_a - 1) + C_a}{N-1}\right) \times D_{i+1} \ . \tag{10}$$

3.2 Model Generalization

In section 3.1, we calculated the traffic demand in a balanced or quasi-balanced tree. In this section, we comment on a more general case where the routing paths are established without the constraints of maintaining the tree balanced. The previous analysis can still be applied, since we can calculate the two main parameters of our model: m (tree depth) and C_a (the average of the number of children per SS). Nevertheless, as the variance in the number of children increases, the error margin increases and makes the model less reliable. In order to maintain the correctness of the model, the exact number of children must be used, which may be different for every node.

4 Throughput Evaluation

We evaluate the model we proposed by implementing our own simulator in Java. We implement the centralized scheduling algorithm of the mesh mode as described in the IEEE 802.16 standard. Based on this algorithm, the BS collects the requests of all SSs in the mesh tree and allocates grants by distributing the available minislot space accordingly. Each MAC frame consists of 256 minislots. The scheduling control subframes are used by centralized scheduling (since we do not account for distributed scheduling) and the MSH-CTRL-LEN×7 OFDM symbols are allocated to transmission bursts, containing MSH-CSCH and MSH-CSCF messages. For the physical layer, we use the bitrate distance function shown in Fig. 6 [9]. In order to lower the complexity of the problem, we use only three modulation schemes, namely 64QAM 3/4, 16QAM 1/2 and QPSK 1/2.

Focusing on the impact of the tree depth m on the aggregate throughput capacity, the main parameter m varies between 1 and 7. The maximal value of the tree depth is set to 7 since the *number of hops* is a 3-bits field sent in the MSH-NCFG (Mesh Network Configuration) message. The number of nodes n is kept constant during the simulations. It is set to 49 nodes distributed on a 7×7 rectangular grid. The BS is the upper-left-corner node on the rectangular grid. The maximum distance is set to 5 km. The maximum bitrate is set to 11 Mbps.

The traffic used is uniform at all nodes. Requests are sent according to the previously defined traffic. Each node requests u bps in the uplink direction and d bps in the downlink direction (i.e., its own traffic). The intra-mesh communications also run according to our model. The BS determines flow assignments and distributes the available minislot space in two mesh frames among the SSs according to the implemented algorithm, which adapts the allocations to the available slot space.

For each value of m, a different mesh-tree is built. Since the topology we are simulating is not that huge, we construct these trees manually taking into account two fundamental parameters. First, a small variance in the number of children per node, (i.e., the number of children for each node is $C_a \pm 1$). Second, a small variance in the hop distance (measured in km). In other words, we try to establish a quasi-balanced tree.

4.1 Results

Fig. 9 shows the aggregate throughput capacity (i.e., the uniform throughput as defined earlier in section 3) for the external communication (i.e., the communication via the BS) and the internal communication (i.e., intra-mesh communication). The horizontal axis shows the tree depth, m, while the vertical axis gives the aggregate throughput, expressed in Mbps. In fact the aggregate throughput displayed here is maximal as we assume that the values of u, d, o and r are large enough, so that each scheduling process is done over two mesh frames. Two frames are used in the WiMAX mesh mode when the request exceeds the available slot space.

Looking first at the external communication (the upper curve), we note an oscillation in the aggregate throughput. It first drops down until $m = 3$, then it goes up when $m = 4$, and then down again. Three results could be derived:

1. The throughput decreases in the first part of Fig. 9 although the data rate increases on certain links. This is because it also decreases on other links

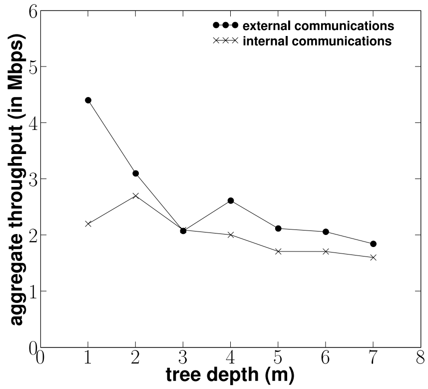

Fig. 9. Aggregate throughput vs. tree depth.

since we try, while constructing the tree, to maintain a balanced or a quasi-balanced tree. For realizing this, some links should be split into many shorter links even if the resulting multi-hop throughput between the source and destination will be smaller than the direct transmission case. So the best thing to do in order to realize the full benefit of multiple hops is to carefully split links, and to only split links that suffer from low bitrates.

2. With regards to the second part of Fig. 9, it could be easily noticed that the throughput decreases very slowly. The throughput obtained for the tree with a depth of seven is still comparable to that for a tree with a maximum of three hops. We believe that this result helps in choosing deeper trees because they shall result in a better throughput when frequency reuse is allowed. In other words, although we do not allow for concurrent transmissions, deep trees perform well. Since deep trees are better suited for simultaneous transmissions, because of path diversity and higher number of disjointed links, we believe that they should result in a higher throughput.
3. It is quite clear that the mesh tree with the depths of four and five performs better than that with a depth of three even without allowing for simultaneous transmissions. This can be justified by the longer links in the latter.

For the intra-mesh communication (the lower curve), it is clear that there is a kind of stability in the maximum aggregate throughput. The best possible throughput can be obtained when $m = 2$.

5 Conclusions and Future Work

In this paper, we proposed a model to study the capacity of WiMAX WMN backbone. Our model takes into account both intra-mesh (i.e., when source and destination are both on the local mesh tree) and external traffic (i.e., either the source or the destination are somewhere in the Internet). For both traffic types, we modeled the demands of each node when a uniform traffic distribution was considered. We observed through simulations that the aggregate throughput capacity of deep trees was comparable to that of trees with small depths. Furthermore, it exceeded this throughput in some situations. We believe that better throughput capacity can be obtained if long link communications are thoughtfully split into multiple short-link communications. This will be a future improvement for this work.

Our current efforts aim at comprehensively studying the impact of depth-fanout tradeoff when concurrent transmissions are allowed. Furthermore, distributed scheduling was not considered in our analysis and is also object of study. We conjecture that employing the centralized and distributed scheduling together may further increase the overall capacity. In this case, optimizing the number of time slots used by each scheduling scheme becomes a key issue.

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