Transmit Power Control in Wireless Mesh Networks Considered Harmful

Sebastian Max, Tinghuai Wang Department of Communication Networks (ComNets) Faculty 6, RWTH Aachen University, 52074 Aachen, Germany Email:{smxlwth}@comnets.rwth-aachen.de

Abstract—A Wireless Mesh Network (WMN) serves to extend the coverage of Access Points (APs) by means of Relay Nodes (RNs) that forward data between Mobile Nodes (MNs) and an AP. This concept reduces deployment costs by exchanging the wires between APs by a wireless backbone. Unfortunately, this also reduces capacity, owing to multiple transmissions of the same data packet on its multi-hop route.

Hence, different mechanisms to increase the capacity of WMNs are investigated, one of them being transmit power control. By limiting the transmission power, interference on other links is reduced. As a consequence, it should be possible for them to use more susceptible and thus higherrate Modulation- and Coding Schemes (MCSs), which improves the system capacity.

Unfortunately, the reduction of the transmission power has also the effect that the received signal power is reduced, which then requires more robust (lower-rate) MCSs, reducing capacity.

In this paper, we use an analytical framework to compute the upper capacity bound of Wireless Mesh Networks (WMNs) with and without transmit power control. The comparison shows that the negative influence of the power control dominates the positive.

I. INTRODUCTION

Since Wireless Local Area Networks (WLANs) have been introduced as standard in IEEE 802.11 the number of installed networks grows exponentially. The typical WLAN configuration is the Basic Service Set (BSS); one or more Mobile Nodes (MNs) associated to a fixed Access Point (AP) acting as the gateway to a wired backbone. As the service area of an AP is limited by high pathloss and restricted transmission power, multiple APs are deployed to enlarge the service area. A set of multiple interconnected APs together with its associated MNs is called and Extended Service Set (ESS).

The wired backbone connecting multiple ESSs is a major cost-factor; hence, it has been proposed to replace wires by radio, thereby introducing the WMN. In a WMN, Relay Nodes (RNs) serve to forward data to or from the nearby AP (possibly across other RNs) multi-hop from or to a MN.

A drawback of WMNs is that multihop communication consumes a multiple of the radio resources required to transmit a frame, thereby reducing capacity. As the wireless channel is shared by the transmissions ongoing on the various hops, mutual interference either requires sequential transmissions at high data rate or spatial reuse with transmissions at low data rates by using a robust Modulation- and Coding Schemes (MCSs) [1]. In this paper, we address the question if the application of transmit power control algorithm to WMNs is able to increase the system capacity. For this aim, we apply an analytical model to evaluate the upper bound system capacity in a network that uses different power control algorithms.

The paper is structured as follows: after presenting this model and the analytical methods in Section II, the transmit power control algorithms under consideration are introduced in Section III. In Section IV we evaluate the upper bound system capacity to compare the effect of the different algorithms. Interestingly, we find that using no transmit power control at all maximizes the system capacity.

II. SYSTEM MODEL

Due to space constrains, we refrain from explaining the detailed system model for WMNs here. Instead, we refer to our earlier work in [2] and describe the most important characteristics only.

Our system model of a WMN is partitioned into several layers, where each layer corresponds roughly to one layer in the ISO/OSI reference model: the physical-, the medium access control-, the network- and the "traffic"-layer which abstracts layers 4 to 7 by generating and absorbing data traffic. Additionally, two more layers are used to describe the propagation on the wireless channel (layer 0) and the network topology (layer -1).

- Layer -1: Network Topology: As capacity of a WMN is closely linked to its topology, we follow the methods from [3] to generate a realistic WMN topology according to the propagation conditions of the wireless channel model in the given service area.
- Layer 0: Wireless Channel: The channel model determines the received signal quality of a packet

transmitted from node N_i to N_j , located at position p_i and p_j , respectively. Two important factors attenuate the signal on its way: (i) the path loss and (ii) the shadowing resulting from obstructions, e. g. buildings. While the first one is modelled as a deterministic function which is inversely proportional to the distance, the latter one is expressed by a lognormal shadowing process with spatial correlation, as suggested in [4], [5].

- Layer 1: Physical Layer: The Physical Layer (PHY) model serves to decide whether or not a packet is received error-free. In our model, the probability of successful packet reception is calculated from two parameters: First, Received Signal Strength (RSS), determined by the channel model, must be high enough for correct synchronization of the receiver to the signal. Second, if simultaneous transmissions occur, mutual interference is modeled by the Signal to Interference plus Noise Ratio (SINR) at the receiver, determining the Packet Error Rate (PER).
- Layer 2: Medium Access Control: While the PHY model abstracts the characteristics of a link in the network (when, where, with what MCS can the link be used, what is its PER and throughput), the Medium Access Control (MAC) model is aimed to represent the operation of the whole network. Since the wireless channel is omni-present throughout the network, transmissions have to be scheduled collision-free. In a real network, the MAC protocol of IEEE 802.11, namely the Distributed Coordination Function (DCF) is responsible for this.

Our goal is to calculate the capacity bound of WMNs. For that purpose we assume an optimal scheduler that (i) has full knowledge about the PHY model for each link, valid for the time instant of link scheduling; (ii) controls the traffic load to each link, such that the end-to-end flow requirements are met; (iii) generates a schedule for packet transmissions taking all links and flow requirements into account and (iv) disseminates this schedule to the nodes without any costs.

As a consequence, all nodes operate under the control of an optimal scheduler that does not cause the mentioned protocol overhead. Hence, it is possible to compute an optimal schedule for carrying the traffic load in the WMN in the minimum duration possible. Thus, this schedule maximizes the network capacity. How to find an optimal schedule is described in more detail in [2], [6].

• Layer 3: Routing: WMNs have a routing sublayer in the link layer, e. g. as specified in IEEE 802.11s. It serves to find a suitable multi-hop route.

In the model, we abstract the capabilities of the

routing protocol by taking its effects on the endto-end traffic flows into account. While any MN connects to the RN or AP with the highest RSS, routing among RNs is driven by end-to-end cost, measured in the total transmission duration. Thus, the shortest routes can be compute by the help of the Floyd-Warshall algorithm.

• Layer 4+: Traffic Characteristics: A major difference between WMNs and Mobile Ad-Hoc Networks (MANETs) is the orientation of traffic flows. While in a MANET every node potentially communicates peer-to-peer with any other node, the traffic flow a WMN is directed from MNs to the Internet and vice versa. We choose to model the typical Internet traffic by assigning each MN i the load l_i , partitioned into 90% traffic downlink from the Internet and 10% uplink to the Internet.

III. TRANSMIT POWER CONTROL ALGORITHMS

In this section, we investigate the effects of using different transmit power control algorithms on the upper capacity bound in the WMN model as introduced. As candidates, we have selected three well-known algorithms, namely Local Mean Algorithm (LMA) [7], Local Minimum Spanning Tree (LMST) [8], and Max-Min Power (MMP). The power levels applied in these power control algorithms are 1, 2, 5, 10, 20, 50, 100, 200, 500 and 1000 mW.

A. Local Mean Algorithm (LMA)

To model the effects of LMA in WMNs, the following process is used [7]:

- 1) All nodes start with same initial transmission power.
- Every node periodically broadcasts a "Life"-Message.
- Upon the reception of a "Life"-Message, each node responds with a "Live-Acknowledgement"-Message.
- 4) The number of responses is counted.
- 5) If the number of responses is greater than a pre-set threshold "NodeMaxThres", the node decreases transmission power and repeats the algorithm.
- 6) If the number of responses is less or equal than the pre-set threshold "NodeMaxThres", the node does not change the transmission power and repeats the algorithm after some delay.

This algorithm is a typical power control algorithm putting emphasis on the power conservation while keeping the connectivity of the network.

As for MNs one bidirectional link to a RN or AP suffices for connectivity, "NodeMaxThres" is fixed to one for MNs. To ensure a connectivity of the WMN, "NodeMaxThres" is set to either 4 or 5 for all RNs and



Fig. 1: LMA power control with NodeMaxThresh 5

APs; of course, MN do not count towards this number as they are not capable of forwarding data. Figure 1 shows the effect of this algorithm in an exemplary network, "NodeMaxThres" is set to 5.

B. Local Minimum Spanning Tree (LMST)

In this algorithm, each node builds its local minimum spanning tree independently and only keeps on-tree nodes that are one hop away as its neighbors in the final topology. Several important properties of LMST have been determined in [8]: (i) the topology constructed under LMST preserves the network connectivity, (ii) the degree of any node in the resulting topology is bounded by 6; and (iii) the resulting topology can be converted into one with only bi-directional links (after removal of uni-directional links). Feature (ii) is desirable because a small node degree reduces interference.

LMST is composed of the following three phases: information exchange, topology construction, and determination of transmission power [8].

- Information exchange: Each AP and RN notifies its neighbors by a regular transmission of beacons; upon reception of a beacon, the RSS during reception is stored. Furthermore, each node broadcasts its current view of its neighborhood.
- Topology construction: The local Minimum Spanning Tree (MST) of AP/RN is constructed using the received neighborhood information and Prim's algorithm [9].
- 3) Determination of transmit power: Subsequently, the transmission power is reduced until all neighborhood announcements that contain the node itself are received from nodes with one hop distance in the local MST only.



Fig. 2: LMST power control

4) Topology with bidirectional links: As some links may be uni-directional after the reduction of the transmission power, [8] proposes to send unidirectional probing messages for each link, indicating that the link belongs to the local MST of the node. Upon the reception of this message, the receiver has to increase the transmission power if the link does not belong to this local MST.

Figure 2 gives a depiction for this algorithm in an exemplary network.

C. Max-Min Power (MMP)

This algorithm aims at the object that to maintain the best possible MCS of each link while decreasing the transmission power as much as possible. The following process is emulated in our framework, where we will use several notations defined in the last section:

- Information exchange: Beacons are broadcasted regularly at maximum transmission power; upon receiving a beacon its RSS is stored. Similar to LMST, each beacon contains the local view of the neighborhood; additionally, the RSS for each neighbor is transmitted.
- 2) Topology construction: After all beacons have been received, node u build its visible neighborhoods set NV_u , which is the set of nodes that node u can reach by using the maximum transmission power.
- 3) Determination of transmit power For each $v \in N(u)$, compute the minimum power needed to reach v with the highest possible MCS; this computation becomes possible as the RSS of each neighbor is known from the beacon.



Fig. 3: MMP power control

Figure 3 gives a depiction for this algorithm in an exemplary network, where the different colors for each links indicate different transmission powers.

IV. EVALUATION

Based on the WMN model introduced in Section II, the network capacity bound of a given WMN can be evaluated. A variation of the shadowing (and thus the generated network topology) and the positions of the MNs has a significant effect on this capacity. Therefore, we use its mean value computed from multiple WMNs instances that use different settings for those two parameters. Each graph shows this mean value, plus its confidence interval for a 95% confidence level.

Figure 4a shows that the capacity bound without power control outperforms that with power control algorithms LMA and LMST, and it is comparable to that with power control algorithm MMP. In Figure 4b the network capacity for a WMN where each RNs and APs is equipped with two directed receive antennas with antenna gains of 10dB. While the antenna gain significantly improves the network capacity, similar observations as before can be found concerning the performance of the transmit power control algorithms. In order to explore the possible reasons causing the bad performance of LMA and LMST, we take a deeper look at different statistics of the optimal schedule that resulted in the given system capacity.

The average number of concurrent transmissions of networks with 50 MNs, is given in Table I, which is the implicit reflection of the spatial reuse level. As listed in this table, the network with transmit power control explores more spatial reuse which enables more concurrent transmissions. Another observation is that



Fig. 4: System capacity with differed power control algorithms

TABLE I: Average number of scheduled concurrent transmissions

Power control	No rx-gain Antenna	Two 10dB rx-gain antenna
None	6.36	6.24
LMA-4	6.81	6.70
LMA-5	7.10	6.32
MMP	6.51	6.29
LMST	6.40	6.27

the networks without directed antennas enables a higher spatial reuse than with directed receive antennas.

The statistic on number of hops each route in the networks are also interesting, as shown in Figure 5. More hops in each route indicate longer routes, which will consume more resources, and counterbalance the gains explored by spatial reuse on the network capacity. We observe that WMNs employing power control use slightly longer routes than those without.

Usually, the high-rate MCS on small hops are expected to compensate the system utilization consumption



(b) Two directed antennas with antenna gain 10dB

Fig. 5: Cumulative distribution function of number of hops per route

from longer routes. As depicted in Figure 6, the MCS in the cases using power control are lower than the case without power control, except the case using MMP algorithm.

V. CONCLUSION

A fundamental question during the design of WMNs is how to schedule interfering transmissions: Either sequentially, so that each receiver is not affected by the interference, or in parallel, divided in the space domain. Clearly, transmit power control tries to optimize the second option by reducing possible interference and increasing the spatial reuse.

In this paper, we showed that the simplest power control possible - either to transmit with the maximum power or not to transmit at all - results in the maximum system capacity in comparison to all other common transmit power control strategies. This result implies that, in protocol design, it is preferable to use high data rate to improve the system capacity and abstain from transmit power control.



Fig. 6: Cumulative distribution function of selected transmission rates

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