Performance Incentives for Cooperation between Wireless Mesh Network Operators

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***Abstract*—Low transmission rate links are bottlenecks that degrade the performance of Wireless Mesh Networks (WMN), especially when they co-exist with high-rate links. In this paper we investigate the incentives for mesh node sharing between different operators. Such cooperation aims to replace low-rate links with multiple higher rate links, and is induced solely from the improved performance that can be achieved through cooperation, even when the WMN operators act in their own self-interest. We present an analytical framework that can identify when the cooperation is expected to be beneficial for both operators, and estimates the expected performance gains in different scenarios, which include single/multi-channel and single/multi-radio cases. Analytical results indicate that there are cases where cooperation can yield significant performance improvements for both WMNs. The analytical results are validated with simulation experiments.**

I. Introduction

In Wireless Mesh Networks (WMN), low transmission rate links create bottlenecks that degrade the end-to-end throughput. Additionally, the co-existence of low and high-rate links operating in the same channel can degrade the throughput of the latter due to the well-known performance anomaly [1].

The objective of this paper is to investigate the incentives for cooperation between operators of 802.11 WMNs with overlapping coverage. Of course, such cooperation can also result from agreements that involve monetary exchange or interconnection agreements similar to those that exist between telephony operators. However, the focus of our work is on the cooperation incentives due *solely* to the improved performance that cooperation yields for *both* wireless networks. The existence of such performance improvement incentives have important implications, since they can trigger cooperation between operators that act in their own self-interest. The analysis of such incentives is fundamentally different from the investigation of the performance improvements that can be obtained with relaying, since the latter considers only the total performance, whereas in our work the improvements *for each* operator determine the incentives for cooperation.

To investigate when such performance improvements arise and to quantify the corresponding gains, we propose a simple model for estimating the end-to-end throughput of a multihop WMN that captures rate diversity. Throughput approximation methods that capture rate diversity have been used in works, which however consider only the case of a single wireless hop [2][3][4]. Our modeling framework suggests that there can be significant performance improvements, and identifies the specific cases where they appear. In any case, the modeling framework presented in this paper can be used to capture the tradeoff between dense deployments of a single operator, and sparser single operator deployments where different operators cooperate. Such tradeoffs are important, since the deployment of additional nodes by a single operator can be costly or difficult due to various deployment constraints.

We investigate both the case where there is a limited number of channels available, forcing mesh nodes to operate in the same channel, and the case where there are many orthogonal channels available. It is common to have more than three transmitters on the same channel within range of each other [5]. Hence, the three orthogonal channels available in 802.11b/g are not sufficient to assign orthogonal channels to all interfering links in dense deployments. In second case, namely the existence of sufficiently enough orthogonal channels, the usage of the available orthogonal channels is constrained by the number of radios available in each mesh node. This is applicable to 802.11a that operates in the 5 GHz band. We investigate the case of one, two, and three radio mesh nodes. The contributions of this paper are the following:

- We present a end-to-end throughput estimation model for multihop WMNs, that accounts for rate diversity.
- We apply the above model to identify and quantify the improved performance that can be achieved with the cooperation of WMNs.
- The analysis considers the single-channel case, the multi-channel multi-radio case and the existence of capacity constraints due to links outside the WMN.
- We validate the analytical model by comparing the gains it estimates, with results from simulation.

The rest of the paper is organized as follows. Section II presents the analytical throughput model. Section III presents analytical investigations that identify and quantify the potential gains from cooperation. Section IV compares the analytical model with simulation results using NS-2. Finally, Section V describes related work and Section VI concludes the paper.

II. Throughput Model

Consider two WMNs, A and B, and an overlapping part of these networks that consists of a sequence of four nodes, A_1, B_2, A_2, and B_1. Under saturation conditions, network A

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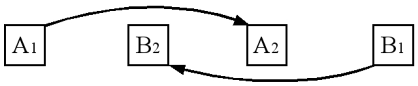

Fig. 1: No cooperation (*Case a*).

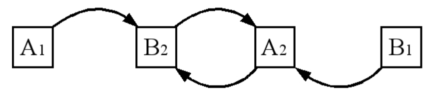

Fig. 2: Cooperation (*Case b*).

has traffic originating from node A_1 and destined to node A_2, while B has traffic originating from node B_1 and destined to node B_2. When the WMNs do not cooperate, which in the remainder of the paper will be referred to as *case a* (Fig. 1), there are two flows from A_1 to A_2, and from B_1 to B_2. On the other hand, when the two WMNs cooperate (Fig. 2), nodes B_2 and A_2 act as relays for the two traffic flows belonging to A and B, respectively. As a result, the end-to-end flow of network A traverses two hops, A_1B_2 and B_2A_2, and that of network B traverses two hops, B_1A_2 and A_2B_2; we will refer to this scenario as *case b*. Observe that there are two transmitters contending for the channel in *case a*, while there are four transmitters in *case b*.

$Gain_K$, is the metric we use in order to evaluate when the cooperation of the WMNs (*case b*) is beneficial for network K, which is either A or B. It is defined as the ratio of the long-term end-to-end throughput, X, of a WMN in *case b*, over that of *case a*. $Gain_K > 1$ indicates that for network K the cooperation is beneficial, i.e. the network achieves higher end-to-end throughput compared to the throughput it achieves when there is no cooperation. When $Gain_K > 1$ for both $K = A, B$, then cooperation is beneficial for both networks.

We denote d_{ij} the distance between the nodes i and j, and assume that all nodes are in the same contention area. We also assume that there is a rate adaptation mechanism, and consider the function $R(d)$ that gives the rate for different distances d. For the analytical investigations in Section III, we consider a specific model for $R(d)$. The analytical throughput model presented in this section can consider any rate function.

The throughput model considers the function $T(p, R)$, which denotes the expected duration for the transmission of a frame with payload size p, when the transmission rate is R. If we disregard all overheads, this function is given by

$$T(p, R) = p/R\,. \tag{1}$$

The last expression captures a key property of wireless networks: the packet transmission time is higher for nodes with a smaller transmission rate. In Section III-B we present an expression for $T(p, R)$ that includes all protocol overheads.

Next we present the analytical throughput model for Figs. 1 and 2, for single and multiple channel scenarios.

A. Single Channel

First, we assume that every mesh node operates on the same channel. This scenario can be the case for dense networks, where the number of orthogonal channels is limited, e.g. for 802.11b wireless networks operating in the 2.4 GHz band.

Case a **(no cooperation):** In this case, Fig. 1, the two WMNs do not cooperate but share the same wireless channel. The long-term throughput of each WMN can be approximated by

$$X^a = \frac{p}{T(p, R(d_{A_1A_2})) + T(p, R(d_{B_1B_2}))}\,, \tag{2}$$

where p is the frame payload size, and $T(\cdot)$ is given by (1). The above expression approximates the shared wireless channel as a round robin system, where each node A_1 and B_2 transmits one frame in consecutive rounds. This approximation is accurate in long-term because 802.11's DCF protocol provides long-term fairness.

Case b **(cooperation):** In this case, Fig. 2, a frame is forwarded across two hops to reach the destination. We now have four contending transmitters, A_1, A_2, B_1, and B_2, and the long-term end-to-end throughput of each WMN can be approximated by

$$X^b = \frac{p}{T(p, R(d_{A_1B_2})) + 2 \cdot T(p, R(d_{B_2A_2})) + T(p, R(d_{B_1A_2}))}\,, \tag{3}$$

where, for simplicity, we have assumed that $R(d_{ij}) = R(d_{ji})$.

Substituting the above equations for X^a and X^b, we obtain the $Gain$ expression that captures a key tradeoff in the scenario considered in this subsection: Cooperation can allow transmissions at higher rates, since the distances $d_{A_1B_2}, d_{B_2A_2}, d_{B_1A_1}$ are smaller than $d_{A_1A_2}$ and $d_{B_1B_2}$, but double transmissions are required for the end-to-end forwarding of each frame. Positive incentives for cooperation will exist if the improvements due to the higher transmission rates outweigh the overhead of forwarding each frame twice. Finally, note that the gain for both WMNs is the same, since they share the same channel.

B. Multiple Channels

Next we assume that a sufficient number of orthogonal channels are available, so that every link can operate on a different channel. This scenario applies to 802.11a networks operating in the 5 GHz band. Although there can be many available channels, the number of radios available in each mesh node can be a limiting factor for their usage. For this reason, we next distinguish the cases where each mesh node has one, two, or three radios.

Case a **(no cooperation):** When the WMNs do not cooperate, links A_1A_2 and B_1B_2 can operate on a different channel. Hence, the two networks do not contend with each other. The long-term throughput for each WMN is approximated by

$$X_A^a = \frac{p}{T(p, R(d_{A_1A_2}))}\,, \;\; X_B^a = \frac{p}{T(p, R(d_{B_1B_2}))}\,. \tag{4}$$

The above equations are independent of the number of radios in each mesh node, since each mesh node has a link to only one neighboring node.

Case b **(cooperation):** The contention for channel access depends on the number of radios available in each mesh node.

Single-radio nodes: The case of cooperation for single-radio nodes is similar to the single channel scenario presented in the previous subsection. Therefore, the end-to-end throughput is given by (3). This scenario does not favor cooperation, since cooperation reduces the number of different orthogonal channels the WMNs operate. The experiments in Section III indicate that there can still be cases where cooperation is beneficial, but the gains are very small.

Two-radio nodes: This is the common case for wireless mesh devices, which typically have three radio, one for client access and the other two for mesh node connectivity. Now, links A_1B_2, B_2A_2, and A_2B_1 can operate on a different channel. There is a single flow on links A_1B_2 and A_2B_1, and two flows with opposite direction on link B_2A_2 where two transmitters, A_2 and B_2, contend for the same channel.

The maximum throughput for each of the two flows traversing the middle link B_2A_2 can be approximated by

$$X^b_{B_2A_2} = \frac{p}{2 \cdot T(p, R(d_{B_2A_2}))} , \quad (5)$$

where as before we have assumed that $R(d_{ij}) = R(d_{ji})$. The maximum throughput on links A_1B_2 and B_1A_2 can be approximated by

$$X^b_{A_1B_2} = \frac{p}{T(p, R(d_{A_1B_2}))} , \; X^b_{B_1A_2} = \frac{p}{T(p, R(d_{B_1A_2}))} \quad (6)$$

If $X^b_{B_2A_2} < X^b_{A_1B_2}, X^b_{B_1A_2}$, then both flows are constrained by the shared link B_2A_2, and have equal throughput $X^b_{B_2A_2}$, given by (5).

In the general case, and assuming without loss of generality that $X^b_{A_1B_2} < X^b_{B_1A_2}$, the end-to-end throughput of the flow for each WMN can be estimated from

$$X^b_A = \min(X^b_{A_1B_2}, X^b_{B_2A_2}) , \; X^b_B = \min(aX^b_A, X^b_{B_1A_2}) \quad (7)$$

where factor $a \geq 1$ is the ratio of the number of frames sent by network B over the number of frames sent by network A, in the same time interval. If the flow of network A is constrained by its first hop, i.e. $X^b_{A_1B_2} < X^b_{B_2A_2}$, then this flow will use less than its maximum throughput share on link B_2A_2. Whether the flow from network B can utilize the excess capacity depends on $X^b_{B_1A_2}$, as indicated in (7). The factor a in this case can be estimated from

$$X^b_A = \frac{p}{(a+1)T(p, R(d_{B_2A_2}))} , \quad (8)$$

where $X^b_A = X^b_{A_1B_2}$, which is given by (6). The denominator in the last equation depicts that within one sharing round of link B_2A_2, network A transmits one frame while network B transmits $a \geq 1$ frames.

Three-radio nodes: Now, a different channel can be assigned for each direction in the middle link, B_2A_2. The throughput of each direction can be approximated by

$$X^b_{B_2A_2} = \frac{p}{T(p, R(d_{B_2A_2}))} .$$

The throughput for links A_1B_2 and B_1A_2 is given by (6). Hence, the long-term end-to-end throughput of each WMN can be estimated by

$$X^b_A = \min(X^b_{A_1B_2}, X^b_{B_2A_2}) , \; X^b_B = \min(X^b_{B_2A_2}, X^b_{B_1A_2}) .$$

For each of the multiple channel scenarios we can estimate the gain for both networks, substituting the pairs X^a_A, X^b_A and X^a_B, X^b_B for the case of no cooperation and cooperation, respectively. Note that the gain for the two networks may differ, hence there can be scenarios where cooperation is beneficial for only one of the networks.

C. Capacity Constraints

An important application of WMNs is to serve as access to wired networks, such as the Internet. It is not uncommon that the interconnection of a WMN to the wired network is a bottleneck. This can be the case for DSL connections, whose speed can be significantly lower than the maximum throughput supported by 802.11a/g; as it depends on the distance of the subscriber to the provider's office where DSLAMs are located. In this section we extend the throughput model presented in Section II, when there are constraints that are due to links external to the WMN.

Assume that the interconnection of WMNs A and B to a wired network has maximum capacity C_A and C_B, respectively. Without loss of generality, we assume that $C_A < C_B$. Next we extent the single and multi-channel throughput models to account for capacity constraints external to the WMN.

Single Channel: The end-to-end throughput for A and B is

$$X^{C_A} = \min(C_A, X) , \;\; X^{C_B} = \min(C_B, kX^{C_A}) , \quad (9)$$

where X is the throughput that is estimated by the model in Section II-A, for either the *case a* or *b*. If $C_A < X$, then A uses less than its maximum share of the wireless channel, and B can potentially obtain a larger share. Factor $k \geq 1$ is the ratio of the number of frames sent by B over the number sent by A, in the same time interval. In the case of no cooperation, factor k satisfies the equation

$$X^{C_A} = \frac{p}{T(p, R(d_{A_1A_2})) + kT(p, R(d_{B_1B_2}))} , \quad (10)$$

and in the case of cooperation, factor k satisfies

$$X^{C_A} = \frac{p}{T(p, R(d_{A_1B_2})) + (k+1)T(p, R(d_{A_2B_2})) + kT(p, R(d_{B_1A_2}))} , \quad (11)$$

where X^{C_A} is given by (9).

When both capacity constraints, C_A and C_B are lower than the throughput X^a given by (2), then the cooperation cannot be beneficial. Moreover, when both throughput constraints are greater than the throughput X^b given by (3), then the constraints do not affect cooperation, and the gains can be estimated by the model in Section II-A.

Multiple Channels: We focus on the two-radio mesh node scenario; the extension to the other scenarios can be performed in a similar manner. When there is no cooperation, the end-to-end throughput for WMNs A and B is

$$X^{a,C_A} = \min(C_A, X^a_A) , \;\; X^{a,C_B} = \min(C_B, X^a_B) , \quad (12)$$

where X^a_A and X^a_B are given by (4). When the two networks cooperate, they share the middle link B_2A_2. The end-to-end throughput for networks A and B is now

$$X^{b,C_A} = \min(C_A, X^b_A) , \; X^{b,C_B} = \min(C_B, X^b_{A_1B_2}, kX^{b,C_A}) \quad (13)$$

where X_A^b is estimated by (7) and $X_{A_1B_2}^b$ is estimated by (6). Factor k satisfies the equation

$$X^{b,C_A} = \frac{p}{(k+1)T(p, R(d_{B_2A_2}))} ,$$

where X^{b,C_A} is estimated by (13).

III. Analytical Investigations

In this section, we present a series of investigations using the above models. Our goal is to identify situations where there are performance incentives for cooperation between mesh operators, and quantify the corresponding throughput gains. We begin by discussing the physical layer model and the protocol overhead model considered in this Section.

A. Physical Layer Model

The analytical models of Section II consider the transmission rate, which is a function of the distance between the transmitter and receiver, since it depends on the path loss between the two. We consider the link budget equation for estimating the signal power at the receiver.

In the experiments, we consider 6 dBi omnidirectional antennas and transmission power 24 dBm and 14 dBm for 802.11a and 802.11b, respectively. These values are in agreement with the EIRP indoor and outdoor limits for the EU. The path loss is calculated using the equation $PL = P_1 + 10 \cdot \log_{10} d^n$,where d is the distance between the receiver and the transmitter in meters, n is the loss exponent and P_1 is the path loss for the first meter. We take P_1 to be 47 dB in 802.11a and 40 dB in 802.11b. This difference occurs due to the (almost) double frequency of 802.11a. We also assume that the antenna and cable losses are negligible (or are included in the antenna gains). A successful packet transmission requires that the received signal power is higher than the receiver sensitivity threshold. We use the sensitivity thresholds of Cisco's Aironet 1240AG access point [22].

All the experiments in this section consider the path loss exponent $n = 3$. The path loss model using this exponent, and the sensitivity thresholds in [22], give a maximum transmission range at the minimum rate equal to 368 meters for 802.11a, and equal to 541 meters for 802.11b.

B. Protocol Overhead

The protocol overhead is important to precisely estimate the average throughput. A zero overhead, as assumed in (1), provides an upper bound of the throughput gains. For the analytical and simulation experiments we consider an overhead model based on the theoretical maximum throughput estimation in [21]. In this section we discuss this overhead model, and extend the backoff overhead to account for multiple contending transmissions. Note that the overhead model does not capture collisions; its accuracy is evaluated using simulation in Section IV.

We consider the standard DCF protocol without RTS/CTS. The time for transmitting one frame consists of five components: T_{DIFS}, T_{SIFS}, T_{ACK}, T_{BO}, and T_{DATA}. The IFS delays are defined by the standard. T_{ACK} is the time for transmitting an acknowledgement. Finally, T_{DATA} is the time for transmitting one frame, which includes the MAC and physical layer headers, and the frame payload.

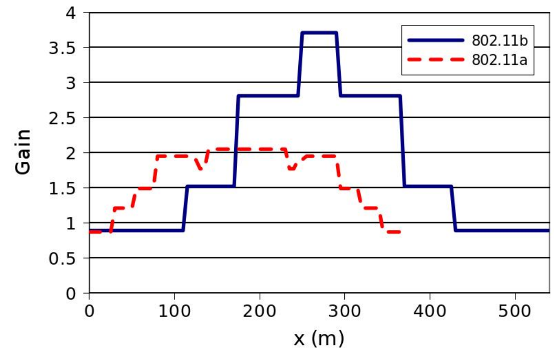

Fig. 3: Throughput gain as a function of $x = d_{A_1B_2}$; $d_{A_1A_2} = d_{B_1B_2} = d_{max}$, single channel.

Based on the above, we can define $T(p, R)$ that appears in the models of the previous section as follows:

$$T(p, R) = T_{DIFS} + T_{SIFS} + T_{ACK}^R + T_{DATA}^{p,R} .$$

Note that the backoff time T_{BO} is not included in the above expression, since it is not an overhead that needs to be added to each frame transmission. Rather, it needs to be added to the denominator of the throughput expressions presented in the previous section. When there are multiple contending transmitters, their backoff counter decreases simultaneously, since the backoff counter freezes when a transmission is sensed. As long as no collision occurs, the total backoff delay is independent of the number of contending transmitters, and depends only on the maximum number of frames a single transmitter sends in the time interval over which the throughput is estimated. Hence, the backoff delay is qT_{BO}^1, where T_{BO}^1 is the average backoff delay when there is only one transmitter, and q is the maximum number of frames sent by a single transmitter. The value of q is 1 in all the equations presented in Section II, except for (8), (10) and (11) where $q = a$.

For the values of T_{DIFS}, T_{SIFS}, T_{BO}^1, T_{ACK} and T_{DATA} we refer the reader to [21]. In all the experiments we consider payload size $p = 1500$ bytes.

C. Single Channel

In this section we investigate the gains in the single channel scenario of Section II-A. We denote with d_{max} the maximum transmission range, which is 368 m for 802.11a and 541 m for 802.11b. In the first experiment we set $d_{A_1A_2} = d_{B_1B_2} = d_{max}$. Fig. 3 shows the end-to-end throughput gain for each WMN that is achieved with cooperation, as a function of $x = d_{A_1B_2} \in [0, d_{max}]$. Observe that for both versions of 802.11 the best case scenario occurs when the distance $d_{A_1B_2}$ is approximately half of d_{max}. When the distance $d_{A_1B_2}$ is small, i.e. nodes A_1 and B_2 are close, then there are small or no advantages from cooperation, since the distance between A_1 and A_2 is close to that between B_2 and A_2, see Fig. 2, hence the throughput achieved by these links is similar. Moreover, when the distance between A_1 and B_2 is close to d_{max},

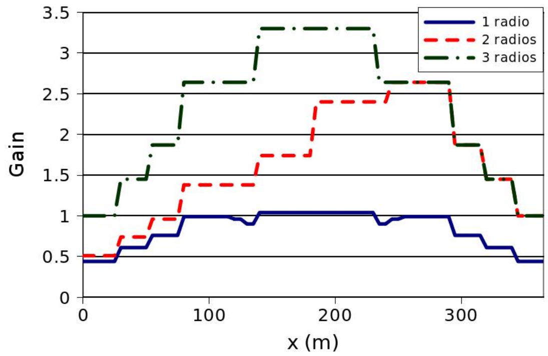

Fig. 4: Throughput gain as a function of $x = d_{A_1B_2}$; $d_{A_1A_2} = d_{B_1B_2} = 368$ m, 802.11a.

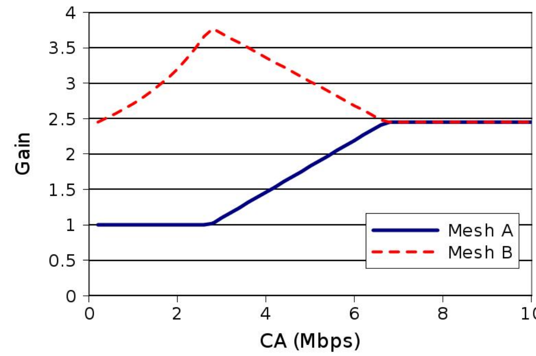

Fig. 5: Throughput gain as a function of C_A; $d_{A_1B_2} = 270$ m, $d_{A_1A_2} = d_{B_1B_2} = 541$ m, single channel, 802.11b.

then the throughput achieved by links A_1B_2 and A_1A_2 is similar, and again there are small or no gains from cooperation. The above explains the symmetry of the throughput gains in Fig. 3 around the distance $x = d_{A_1B_2} \approx 270$ meters for 802.11b and $x = d_{A_1B_2} \approx 184$ meters for 802.11a.

Observe that the gain in 802.11a is lower than in 802.11b, however the improvements in terms of the absolute throughput is larger. This is partially due to the differences in the protocol overhead, and the larger number of intermediate transmission rates in 802.11a. Additionally, note that the range of values $x = d_{A_1B_2}$ with respect to the maximum range, that yield positive gains is larger than the corresponding range in the case of 802.11b. Observe in 802.11a that as $x = d_{A_1B_2}$ increases from zero to $368/2 = 184$ meters, the throughput gain increases, except for a small drop at approximately 130 meters. This occurs because the rate for links A_1B_2 and A_2B_1 decreases, before the rate for link A_2B_2 increases.

D. Multiple Channels

Next, we present experiments for the multiple channel scenario in Section II-B. We focus on 802.11a, since it has more orthogonal channels available, which makes the multiple channel scenario more likely. We repeat the same experiment for the case of single, 2, and 3-radio mesh nodes. In particular, we set $d_{A_1A_2} = d_{B_1B_2} = d_{max} = 368$ meters, and investigate the throughput gain for various distances $x = d_{A_1B_2} \in [0, d_{max}]$. In all the experiments, the throughput gain for the two WMNs is equal, since the topology is symmetric.

Figure 4 shows the throughput gain for multi-radio mesh nodes. As discussed in Section II-B, the single-radio case does not favor cooperation, since cooperation increases the wireless channel contention. However, Fig. 4 shows that there exist cases with a positive throughput gain, but this gain are very small (less than 5%). In the case of 2-radio mesh nodes, the WMNs share link B_2A_2. The maximum throughput gain occurs when the capacity of this shared link is twice the capacity of edge links, which are used only by one network; the latter occurs when $x = d_{A_1B_2} \approx 250$ meters, in which case $d_{B_2A_2} \approx 118$ meters. Comparison of the multi-radio experiments indicates that the gains are higher for mesh nodes with more radios, which allows them to use more channels.

E. Throughput Constraints

The following experiment refers to the single channel model with capacity constraints discussed in Section II-C. We set $d_{A_1A_2} = d_{B_1B_2} = d_{max} = 541$ meters and $d_{A_1B_2} = d_{max}/2$, which yields the highest gain in the first experiment of Section III-C.Fig. 5 shows the throughput gain for different values of C_A. This figure contains three regions with a different behavior of the gain for networks A and B: For $C_A < 2.5$ Mbps, there are no gains for network A. Interestingly, observe that as C_A increases, the gain for network B increases, indicating that when there is a higher contention, which occurs when C_A increases since network A can transmit more traffic, cooperation yields larger improvements. For 2.5 Mbps $< C_A <$ 6.5 Mbps, there is a positive gain for network A, which increases as the capacity constraint increases; at the same time, the gain for network B decreases. Finally, for $C_A > 6.5$ Mbps, C_A is larger than the maximum capacity supported by the WMN, hence does not affect the gain, which is the same for both WMNs.

IV. Simulation Evaluation

In this section we present simulation experiments based on NS-2, to validate the throughput model and verify that it can accurately estimate the throughput gains that are achieved through cooperation. We extended the default NS-2 to adapt the transmission rate according to the the signal strength.

We consider the single channel scenario, whose throughput model is presented in Section II-A. Note that this scenario has the most transmitters contending for channel access; this observation together with the fact that the proposed throughput models do not account for collisions, makes this the most likely scenario, among all the scenarios considered in this paper, to exhibit inaccuracies of the analytical model. Also, we consider 802.11b. The distances $d_{A_1A_2}$ and $d_{B_1B_2}$ were selected so that the corresponding links achieved transmission rate 1 Mbps. Moreover, the distances $d_{A_1B_2}$, $d_{B_2A_2}$, and $d_{A_2B_2}$ were set so that the corresponding links achieved the transmission rates which correspond to different throughput gains in Fig. 3. The simulation results are the average of 100 runs with the same parameters. The experiments used UDP traffic in saturation conditions, and each run had duration 15 seconds. Fig. 6 shows that the analytical results for the

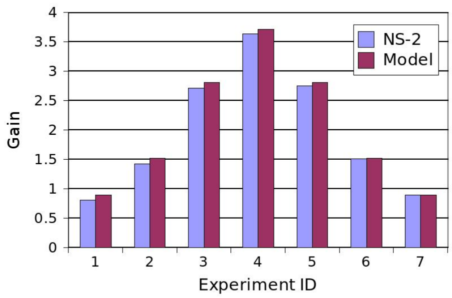

Fig. 6: Gain based on analysis and simulation.

throughput gain closely match the corresponding simulation results, verifying that the analytical throughput model can accurately estimate the throughput gains.

V. Related Work

In this section we briefly summarize related work. We stress that apart from [6] related work does not focus centrally on the performance-oriented incentives that can motivate cooperation, which is the focus of the current paper. Rather, one line of work investigates approaches for improving the performance in wireless networks, whereas another line of work considers approaches for inducing cooperation.

In [6], the authors argue that operators would benefit if their APs were enabled to cooperate and form a single virtual access network that manages available radio resources in a globally optimal way. However, this approach does not investigate the gains from cooperation for each individual network/operator, which determine the incentives for cooperation they have.

Relay nodes can be used to mitigate the performance anomaly of 802.11 [7][8][9][10]. In [8] the authors propose a centralized protocol where the access point which assigns relay nodes. In [9], nodes increase their performance by replacing one low-rate transmission with a sequence of two high-rate transmissions. In [10], high-rate nodes opportunistically turn themselves into repeaters for low-rate nodes when they expect that it will be beneficial for all parties. The nodes are assumed to cooperate to achieve a common goal. Another direction tries to implement time-fairness by minimizing the time that low-rate transmissions use the shared wireless channel [11][12]. However, this method has the disadvantage of being unfair towards low-rate links. Routing metrics such as ETT [13], WCETT [13] and CATT [14], take the transmission rate into account. Routing protocols using these metrics would choose to route traffic through high-rate links, avoiding low-rate links. All the above works focus on a single network, while we focus on the co-existence of WMNs that belong to different operators, which act in their own self-interest, and not towards achieving a common goal.

MANETs is a field where cooperation is important since nodes act in their own interest. However, related work focuses on ways to enforce cooperation either using virtual currency [15][16][17] or punishments [18][19]. A key idea and motivation for our work is that such mechanisms are not required in overlapping WMNs, when performance improvements alone can provide sufficient cooperation incentives.

Finally, our prior work [20] has investigated handover incentives between WLANs with overlapping coverage. This work considered the performance in the case of single hop wireless links, whereas the current paper investigates cooperation incentives in multihop WMNs.

VI. Conclusion

In this paper we have investigated the incentives for cooperation between WMN operators, due solely to the performance improvements that cooperation yields for both operators. The analytical framework presented can identify when such improvements exist, and quantify them. The analytical models include cases of single channel operation, multiple channel operation with multi-radio mesh nodes, and the case of capacity constraints external to the WMN. The accuracy of the models has been verified with simulation.

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