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Location-based Relay Selection and Power Adaptation Enabling Simultaneous Transmissions

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***Abstract*—Relaying is a well known technique to extend coverage and improve conditions for nodes in the outer coverage region. In this paper we propose a relaying scheme that exploits the spatial separation of relay and destination pairs to improve throughput by allowing simultaneous transmissions. The proposed scheme is a cross-layer optimization for two-hop relaying that uses position information to jointly optimize relay selection and relay transmit power, maximizing Medium Access Control layer throughput. Further, in order to calculate the expected throughput, we apply a probabilistic model that takes into account MAC retransmissions and timing behavior of the IEEE 802.11 Distributed Coordination Function mode. Our results show an increase in throughput of approximately 20% is achievable for the proposed scheme when compared to two-hop relaying in the analyzed scenario.**

I. Introduction

In mobile wireless networks, the typical bottleneck when users are downloading and streaming content from the Internet, is the wireless link between the user and the Access Point (AP) [1] [2]. In particular, performance degradations will occur for all users in a wireless network if some nodes need to use a low bit-rate mode as argued in [2]. These low quality links exist to users far away from the AP. For these nodes, two-hop relaying as considered in [2] and [3] can yield better performance, since the relay effectively extends the range of the AP. In cases, where the relay-to-destination (r-d) transmissions are spatially well-separated, these r-d transmissions could be done simultaneously to increase overall throughput. This idea of simultaneous transmissions has been used for instance in [4]. In this paper, the authors improve downlink throughput near Internet gateways by using measurements to create a virtual interference map. Similarly, in [5] capacity and performance improvements of up to 22 % are achieved by interference-aware tuning of transmit power, bit rate, and carrier sense threshold.

In [1] the CCMAC protocol is proposed, which improves throughput for relay-to-AP (r-AP) transmissions. The scheme allows use of direct and two-hop transmissions, with and witout coded cooperation. A table of link quality measurements is used to keep track of which bit-rate can be used towards neighbours, as in the CoopMAC protocol [2]. As the table is based on previous observations, we expect that it is similarly sensitive to operating in mobile settings. A less movement sensitive approach would be to actively monitor and exchange link quality information as discussed in [6]. A lighter approach, proposed in [7], which requires less overhead is to exchange position information. Further, position information makes a priori interference prediction easier. This way of exploiting positioning information is explored in [8]. There an extension to the 802.11 Distributed Coordination Function (DCF) is proposed where location information is included in the RTS/CTS handshake. Using a propagation model to reduce the exposed node effect, throughput increases up to 22 %.

In this paper we propose a Relaying scheme *SimTX* that allows simultaneous relay transmissions like CCMAC [1]. Instead of using historic link measurements as CoopMAC and CCMAC [1], [2], the scheme uses position information for interference prediction as in [8], to allow it to work in settings with mobile users. Further, the scheme performs tuning of relay transmit power based on the predicted interference as in [4], [5]. Specifically, we assume that information of the positions of the mobile users is made available to the AP through a periodic collection mechanism of e.g. GPS measurements as presented in [7]. We then investigate the performance of the proposed *SimTX* relay selection scheme that exploits user positions to choose relays suited for simultaneous r-d transmissions. The scheme also selects the best relay transmit power to maximize throughput. In this paper we consider only the case of two simultaneous transmissions. However, the basic principle may be applicable for more simultaneous transmissions. For evaluation, we compare the achieved performance of the SimTX scheme to existing transmissions schemes, namely direct transmission and two-hop decode and forward relayed transmission.

II. Simultaneous Relay Transmissions

An example of the possible node layout of the considered scenario is shown in Fig. 1. Here, the two destination nodes, denoted primary and secondary, are shown in solid, and the corresponding candidate relays are shown with plusses and crosses. The relay selection is described in sec. III. For simplicity we only consider transmissions initiated from the AP to mobile nodes, and do therefore not consider potential influence from surrounding networks.

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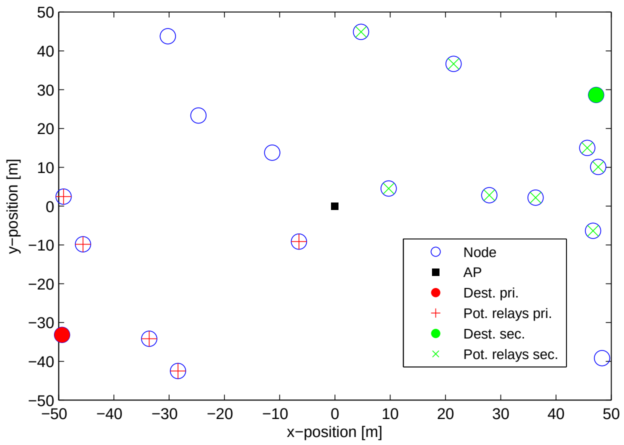

Fig. 1. Example of the node layout, with primary and secondary destination nodes and their potential relays.

The sequence of events in the case where two r-d transmissions occur simultaneously is sketched in Fig. 2. The two AP-r transmissions are done sequentially using the maximum transmit power level. For the simultaneous r-d transmissions we assume that the relay nodes can choose a power level from a fixed and discrete set. The aim of the adjustments is to limit cross-interference. We assume that the Medium Access Control (MAC) protocol is a modified 802.11 DCF, where the AP schedules transmissions in a way so that R1 and R2 can transmit simultaneously to D1 and D2, respectively. This happens immediately after the ACK for Data2 has been transmitted by R2 to the AP. If R1 does not overhear the ACK from R2, it should wait the time of an ACK, a DIFS, and a short back-off period, to allow a possible retransmission of Data2. Hereafter R2 will transmit Data2 to D2, and R1 can start its simultaneous transmission of Data1. If on the other hand R1 overhears the ACK from R2, it can safely initiate the simultaneous transmission immediately.

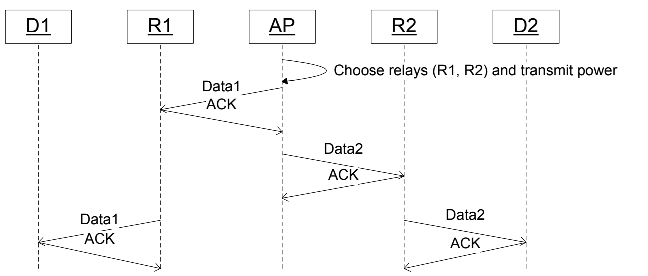

Fig. 2. D1 and D2 are the destination nodes, R1 and R2 are the relays and AP is the source of the transmissions.

The SimTX scheme requires that the carrier sense thresholds of the two destination nodes are set so that they can communicate with the AP but do not back-off when the simultaneous transmission by the other relay is ongoing. Thus, the carrier sense threshold β_{CS} of a destination node should be set as:

$$P_{\text{rx}}(d_{\text{d-r}_{\text{opp}}}) < \beta_{\text{CS}} < P_{\text{rx}}(d_{\text{d-AP}}) \qquad (1)$$

where $P_{\text{rx}}(d_{\text{d-r}_{\text{opp}}})$ and $P_{\text{rx}}(d_{\text{d-AP}})$ are the received powers at the destination from the opposite relay and AP, respectively; calculated using (3) as specified in sec. III-B. We assume that this setting is done when exchanging position information.

III. The SimTX scheme

The proposed scheme for joint relay selection and power adaptation works as a scheduling algorithm for the AP's transmit queue. In order for two packets to be suited for simultaneous transmission, their destination nodes need to be located so that the simultaneous r-d transmissions do not interfere too severely. Assuming that the AP knows the positions of all relay and destination nodes, it can evaluate the expected interference for specific choices of destination pairs. The task of the relaying scheme is therefore to schedule the packets in the queue in such a way that pairs of destination nodes that are suited for simultaneous transmissions are scheduled accordingly, and further to select the most suitable relay nodes and transmit power levels. For this we propose the following algorithm.

A. Position-aware Packet Scheduler

The proposed scheduling algorithm consists of three steps, which are explained in details in the following.

a) Form pairs: The AP picks the first packet in the transmit queue as the primary destination node. In order to have simultaneous transmissions a secondary destination node is also needed. We assume that a scheduled transmission can be upgraded to be the secondary transmission if it seems suited for simultaneous transmission. A similar approach is used in [4]. To limit cross-interference, we select the secondary node as the node that is closest to the coordinate: $(-x_{\text{pri}}, -y_{\text{pri}})$.

Since the choice of secondary destination node is not independent of the relay positions, another node could be more suited. However, to keep complexity low, we do not consider the destination node selection as a part of the optimization problem.

b) Choose potential relays: Having determined the two destination nodes, the best suited relay nodes are sought. Initially, a pre-filtering is performed to rule out unsuited relays. As potential relays we consider those where both the *AP-r* distance and the *r-d* distance are less than the *AP-d* distance:

$$d_{\text{AP-d}} > d_{\text{AP-r}} \quad \wedge \quad d_{\text{AP-d}} > d_{\text{r-d}}. \qquad (2)$$

c) Find max-throughput configuration: In this step, the algorithm solves the 4-dimensional optimization problem of finding the best configuration of relays and transmit power. It does this by computing the expected throughput of all combinations of primary and secondary candidate relays and available transmit power levels for these relays. The best configuration is the combination that has the highest throughput.

B. Throughput Model

In order to evaluate the expected throughput of different relay and transmit power configurations, we apply the throughput model presented in this section. As we are interested in comparing the performance of our proposed SimTX relaying scheme to existing transmission schemes, we consider also the expected throughput for direct transmissions as well as two-hop relaying.

For simplicity, we assume that all transmission are of the same payload length and that all entities use the same fixed modulation and coding scheme. In order to achieve comparable results, we will assume that the MAC layer is based on IEEE 802.11 DCF as described in [9].

First, we derive a model of the Bit Error Rate (BER), given node positions and transmit power levels. From this BER we estimate the throughput delivered by the MAC layer.

The received power is calculated based on the path-loss model from [10]:

$$P_{\text{rx}}(d)\ [dBm] = P_{\text{tx}} - PL(d_0) - 10\alpha \log_{10}(d/d_0) \tag{3}$$

where P_{tx} is the transmit power, $P_{\text{rx}}(d)$ is the received power at the receiver, d is the distance between transmitter and receiver, $PL(d_0)$ is the path loss at a reference distance $d_0 = 1$m, and α is the path loss exponent. We calculate the Signal to Interference and Noise Ratio (SINR) as:

$$\gamma\ [dB] = 10\ log_{10}\left(\frac{P_{\text{rx}}(d_{\text{rx-tx}})\ [mW]}{P_{\text{rx}}(d_{\text{rx-interf}})\ [mW] + N_0\ [mW]}\right) \tag{4}$$

where $P_{\text{rx}}(d_{\text{rx-tx}})$ is the received power from the main transmitter at distance $d_{\text{rx-tx}}$ from the receiver, whereas $P_{\text{rx}}(d_{\text{rx-interf}})$ is the power received from the interfering transmitter at distance $d_{\text{rx-interf}}$ from the receiver. N_0 is the assumed noise floor. In cases where only one entity is transmitting at a time, there is no interference, and $P_{\text{rx}}(d_{\text{rx-interf}})$ is set to zero.

SINR is converted into average BER for BPSK coding under the assumption of Ricean small-scale fading using theoretical expressions from reference [11]. Here, we use the matlab function `berfading` from the *Communications Toolbox*.

Having calculated the BER, we now consider the Frame Error Rate (FER).

For simplicity, this work currently does not take cross-traffic into account. Therefore, we assume in this model that the main cause of bit errors when allowing simultaneous transmissions is interference from the pair-transmission. This differs from the work of e.g. Bianchi [12], where a single collision domain is considered and simultaneous transmissions would always be seen as collisions. In our analysis, the simultaneous r-d transmission are assumed to be done in separate collision domains, though with cross-interference.

Therefore, we have three possible outcomes of a transmission attempt: 1) successful reception of a frame (s), 2) failed during DATA (fd), and 3) failed during ACK (fa).

Assuming a constant BER denoted P_{b}, the outcomes have the following probabilities:

$$P_{\text{s}} = (1 - P_{\text{b}})^{N_{\text{data}} + N_{\text{ACK}}} \tag{5}$$
$$P_{\text{fd}} = 1 - (1 - P_{\text{b}})^{N_{\text{data}}} \tag{6}$$
$$P_{\text{fa}} = (1 - P_{\text{b}})^{N_{\text{data}}} \cdot (1 - (1 - P_{\text{b}})^{N_{\text{ACK}}}) \tag{7}$$

where N_{data} and N_{ACK} are the number of bits transmitted in data and ACK frames, respectively. Notice the simplifying assumption that the ACK has the same BER as the data. In practice the BER of the ACK will be lower, as the direction is opposite of data. Thus, we expect slightly pessimistic results.

Given the constants in Table I based on [9], we calculate the average time of successful and failed transmissions as:

$$T_{\text{s}}(r) = \overline{T_{\text{BO}}}(r) + T_{\text{data}} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{DIFS}} \tag{8}$$
$$\overline{T_{\text{f}}(r)} = \left(\overline{T_{\text{BO}}}(r) + T_{\text{data}} + T_{\text{DIFS}}\right) \cdot P_{\text{fdn}} + \\ + \overline{T_{\text{BO}}}(r) + (T_{\text{data}} + T_{\text{SIFS}} + T_{\text{ACK}} + T_{\text{DIFS}}) \cdot P_{\text{fan}} \tag{9}$$

where, $P_{\text{fdn}} = \frac{P_{\text{fd}}}{P_{\text{fd}} + P_{\text{fa}}}$ and $P_{\text{fan}} = \frac{P_{\text{fa}}}{P_{\text{fd}} + P_{\text{fa}}}$ are normalization factors, and $\overline{T_{\text{BO}}}(r)$ is the average back-off time, which depends on the number of the current retry attempt r. Hence, also $T_{\text{s}}(r)$ and $T_{\text{f}}(r)$ depend on r. According to [9], the contention window (CW) is a uniform Random Variable (RV) between $CW_{\text{min}} = 15$ and $CW_{\text{max}} = 1023$. For each consecutive retry the CW is set according to:

$$CW(r) = min(1023, 2^{4+r} - 1). \tag{10}$$

We assume the average waiting time due to back-off is:

$$\overline{T_{\text{BO}}}(r) = T_{\text{slot}} \cdot \frac{CW(r)}{2} \tag{11}$$

where T_{slot} is the slot time used in IEEE 802.11.

As we have now determined the time and probability of a single successful or failed transmission, we now derive the expected throughput delivered by the MAC layer service, when taking MAC layer retransmissions into account. In IEEE 802.11 the default maximum number of retransmission attempts, here denoted R is 7. After R attempts the frame transmission fails and an error will be returned from the MAC layer without delivering the payload. In this work we only consider the MAC throughput, which may be different from the throughput achieved by overlying transport protocols and applications, due to for example time-out mechanisms as used in TCP to judge when a segment has been lost and needs to be retransmitted [13]. Let n be the retry number, and T_{tx} the RV representing the time spent on a transmission attempt:

$$T_{\text{tx}}(n) = \begin{cases} \sum_{r=0}^{n} T_{\text{f}}(r) + T_{\text{s}}(n+1) & \text{for} \quad 0 \le n \le R-1 \\ \sum_{r=0}^{n} T_{\text{f}}(r) + T_{\text{s}}(n+1) & \text{for} \quad n = R,\ \text{success} \\ \sum_{r=0}^{n+1} T_{\text{f}}(r) & \text{for} \quad n = R,\ \text{failure} \end{cases} \tag{12}$$

with outcome probabilities:

$$P_{\text{tx}}(n) = \begin{cases} (1 - P_{\text{s}})^n \cdot P_{\text{s}} & \text{for} \quad 0 \le n \le R-1 \\ (1 - P_{\text{s}})^n \cdot P_{\text{s}} & \text{for} \quad n = R,\ \text{success} \\ (1 - P_{\text{s}})^{n+1} & \text{for} \quad n = R,\ \text{failure}\ . \end{cases} \tag{13}$$

From this, we can compute the expected value as:

$$E[T_{\text{tx}}] = \sum_{n=0}^{R-1} (T_{\text{tx}}(n) P_{\text{tx}}(n)) + T_{\text{tx}}^{\text{s}}(R) P_{\text{tx}}^{\text{s}}(R) + T_{\text{tx}}^{\text{f}}(R) P_{\text{tx}}^{\text{f}}(R) \tag{14}$$

where $T_{\text{tx}}^{\text{s}}(R)$, $P_{\text{tx}}^{\text{s}}(R)$, $T_{\text{tx}}^{\text{f}}(R)$, and $P_{\text{tx}}^{\text{f}}(R)$ are the transmission time per attempt and frame delivery probability for the successful and failed cases in equations (12) and (13). The probability of a successful MAC frame delivery is:

$$P_{\text{suc}} = 1 - (1 - P_{\text{s}})^{R+1}. \quad (15)$$

For comparison we calculate the average throughput ($\frac{\text{Delivered data}}{\text{Transmission time}}$) of the primary (pri) and secondary (sec) transmissions of the considered algorithms, the MAC payload size B_{MSDU} in octets. For the direct algorithm the throughput[1] is:

$$S_{\text{dir}} = \frac{(P_{\text{suc}}^{\text{pri}} + P_{\text{suc}}^{\text{sec}}) \cdot B_{\text{MSDU}}}{E[T_{\text{tx}}^{\text{pri}}] + E[T_{\text{tx}}^{\text{sec}}]}. \quad (16)$$

In the following, we use the indices 1 and 2 to indicate the AP-r and r-d transmissions. The throughput for the two-hop relaying algorithm is calculated as:

$$S_{\text{rel}} = \frac{(P_{\text{suc}}^{\text{pri},1} P_{\text{suc}}^{\text{pri},2} + P_{\text{suc}}^{\text{sec},1} P_{\text{suc}}^{\text{sec},2}) \cdot B_{\text{MSDU}}}{E[T_{\text{tx}}^{\text{pri},1}] + E[T_{\text{tx}}^{\text{pri},2}] + E[T_{\text{tx}}^{\text{sec},1}] + E[T_{\text{tx}}^{\text{sec},2}]}. \quad (17)$$

Finally, we calculate throughput for the SimTX algorithm:

$$S_{\text{sim}} = \frac{(P_{\text{suc}}^{\text{pri},1} P_{\text{suc}}^{\text{pri},2} + P_{\text{suc}}^{\text{sec},1} P_{\text{suc}}^{\text{sec},2}) \cdot B_{\text{MSDU}}}{E[T_{\text{tx}}^{\text{pri},1}] + E[T_{\text{tx}}^{\text{sec},1}] + E[\max(T_{\text{tx}}^{\text{pri},2}, T_{\text{tx}}^{\text{sec},2})]}. \quad (18)$$

$E[\max(T_{\text{tx}}^{\text{pri},2}, T_{\text{tx}}^{\text{sec},2})]$ is calculated from the Cumulative Distribution Function (cdf) of the maximum of two independent RVs X and Y:

$$\begin{aligned} P(\max(X,Y) \le c) &= P(X \le c \text{ and } Y \le c) \quad (19) \\ &= P(X \le c)P(Y \le c) = F_Y(c)F_X(c). \end{aligned}$$

This is true for independent RVs. However, if one transmission is successful and the other fails, the single retransmission experiences a better SINR. The assumption of independence between $T_{\text{tx}}^{\text{pri},2}$ and $T_{\text{tx}}^{\text{sec},2}$ is therefore expected to result in slightly pessimistic results. The influence of this assumption is investigated by simulation in sec. IV. Consequently we get:

$$F_{T_{\text{tx}}^{(2)}}(t) = P(\max(T_{\text{tx}}^{\text{pri},2}, T_{\text{tx}}^{\text{sec},2}) \le t) = F_{T_{\text{tx}}^{\text{pri},2}}(t) F_{T_{\text{tx}}^{\text{sec},2}}(t) \quad (20)$$

where $F_{T_{\text{tx}}^{(2)}}(t)$ is the product of the cdfs of the time spent per transmission attempt on the simultaneous r-d transmissions, which is simply the elementwise product of two vectors of length $R+1$. Since $T_{\text{tx}}^{(2)} > 0$, we may compute the expectation of the maximum as:

$$E[\max(T_{\text{tx}}^{\text{pri},2}, T_{\text{tx}}^{\text{sec},2})] = \int_0^\infty (1 - F_{T_{\text{tx}}^{(2)}}(t))dt. \quad (21)$$

IV. Results and Discussion

The results are based on the parameters in Table I. In this section we will first show results of the throughput model on a single link as given by eq. (16). For different BER levels, the output of the throughput model is shown Fig. 3.

In the following, we use the throughput model to evaluate the proposed SimTX algorithm in comparison to direct transmissions and two-hop relaying. The Direct and Relaying schemes use the maximum transmit power (100mW) for all transmissions, whereas the SimTX uses the maximum transmit power (100mW) for the AP-r transmissions and variable transmit power for the r-d transmissions. The following results are calculated using the throughput model in the scenario specified in Table II.

[1]To get throughput in Mbit/s, multiply the results by $8 \cdot 10^{-6}$.

Parameter	Value
T_{slot}	10 μs
T_{SIFS}	9 μs
T_{DIFS}	34 μs
T_{data}	$20 + 4\lceil(16 + 6 + 8 \cdot (34 + MSDU))/24\rceil$ μs
T_{ACK}	44 μs
N_{data}	$(36 + MSDU) \cdot 8$ bits
N_{ACK}	112 bits

TABLE I
FRAME SPECIFICATION FOR 802.11A MAC DCF, 6MBIT/S, BPSK MODE

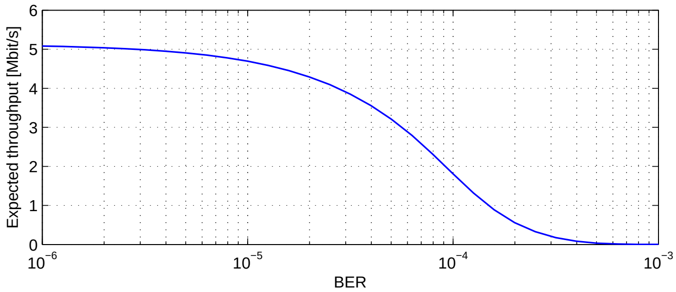

Fig. 3. Expected average throughput for Rmax=7 and $B_{\text{MSDU}} = 1024$ bytes.

Parameter	Value
Scenario size	100m x 100m
AP position	(0,0)
Number of nodes	30
Path loss exponent (α)	2.9
$N0_{\text{floor}}$	$-86dBm$
Ricean K-factor (K)	15
Bit rate	6 Mbit/s
Modulation scheme	BPSK
Max no. of retransmissions (R)	7
B_{MSDU}	1024 bytes
P_{tx} levels available	0, 5, 10, 20, ... , 90, 100 mW

TABLE II
SIMULATION PARAMETERS

Since the SimTX scheme is intended to improve relaying performance, we are not very interested in the cases where direct transmissions are always superior. Therefore we pick the primary destination nodes randomly from nodes that are at least $30m$ from the AP. Fig. 4 shows the throughput for each algorithm for different random seeds. For each seed, the throughput is calculated for an attempt to deliver a pair of packets to a primary and secondary destination node, respectively. The throughput calculation is done using eqs. (16), (17), and (18). We observe that the algorithms have different maximum throughput levels around 5, 2.6, and 3.5 Mbit/s, respectively. The Direct throughput fluctuates a lot, since some destination nodes cannot be reached in one hop. The Relaying throughput is quite steady around half of the

Direct, since it uses two consecutive transmissions. Finally, the SimTX algorithm improves the relaying performance thanks to the simultaneous transmissions.

Additionally, simulation results for the SimTX algorithm are shown to evaluate the impact of the assumptions in eq. (5) eq. (19). Specifically, in the simulation the SINR is different for data and ACK since the ACK is transmitted the opposite direction, and dependent on if the other node transmits.

The results show that the model is pessimistic as expected, expecially when the throughput is between 1 and 2 Mbit/s. As this happens quite rarely, and Relaying performs better in most of these cases, we can use the model for parameter selection.

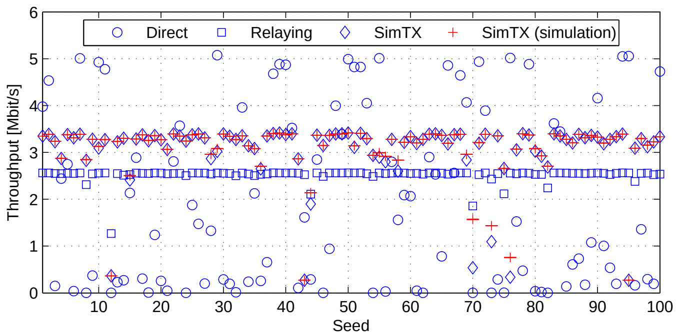

Fig. 4. Throughput for the considered algorithms and comparison of model output and simulation of the 802.11 back-off algorithm in the case of two simultaneous transmissions. 95% confidence intervals are shown for simulation results.

Fig. 5 shows a summary of the achieved throughput, when considering the cases where either Relaying or SimTX are the preferred algorithms. We see that the SimTX throughput is appr. 14% (2.45 to 2.8 Mbit/s) higher than for Relaying. If we consider the improvement from using only Relaying to using the best of Relaying and SimTX in each case, an increase of approximately 20% (2.45 to 2.95 Mbit/s) is achieved.

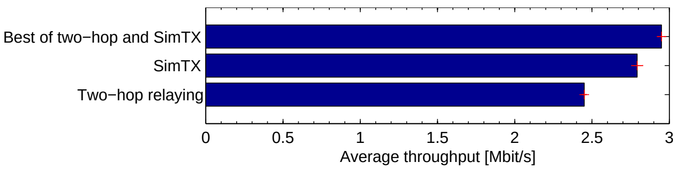

Fig. 5. Comparison of the average throughput, for cases where relaying or SimTX is preferred, including 95% confidence interval. Based on 2500 repetitions.

Since this work assumes perfect position knowledge and the considered scenario does not include cross-traffic, we would expect lower performance in a more realistic setting. But since both the Relaying and SimTX algorithms would be affected by these factors, the relative improvement could still hold.

V. Conclusions and Future Work

In this work we have proposed the SimTX algorithm that jointly optimizes the choice of relays and relay transmit power for two simultaneous r-d transmissions. For relay choice and transmit power selection, we have applied a model to calculate the expected MAC layer throughput when taking into account the BER, maximum limit of retransmissions and interference in case of simultaneous transmissions. The model allows the relaying scheme to choose the expectedly best relays and transmit power levels online.

Our results show throughput improvements of appr. 20% in the considered scenario compared to typical two-hop decode and forward relaying. That is, we have shown that two simultaneous relay-to-destination transmissions can be beneficial despite the cross-interference they induce on each other.

As our model assumes no cross-traffic, a future work item is to evaluate the performance in a realistic scenario using a simulation tool such as e.g. ns-2. Another point could be to include rate adaptation in the model so that more than a single bit-rate is considered in the cross-layer optimization. Finally, the assumption regarding perfect knowledge of node positions should be relaxed. In previous work [6], [7] we analyzed the impact of node movements and inaccurate prediction parameters on two-hop relaying schemes. It would be interesting to analyze how these factors affect the proposed SimTX scheme, since they have been found to have a noticable impact on typical decode and forward two-hop relaying.

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