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CoRe-MAC: A MAC-Protocol for Cooperative Relaying in Wireless Networks

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***Abstract*—Cooperative relaying methods can improve wireless links, but introduce overhead due to relay selection and resource reservation compared to non-cooperative transmission. In order to be competitive, a cooperative relaying protocol must avoid or compensate for this overhead.**

In this paper, we present a MAC protocol for relay selection and cooperative communication as an extension to CSMA/CA which addresses resource reservation, relay selection, and cooperative transmission while keeping the overhead in terms of time and energy low. We discuss the efficiency of this protocol for packet error rate, throughput, and message delay in a multi-hop network. Simulation results show that the protocol performs similar and without noticeable overhead compared to standard CSMA/CA for good SNR while it is able to significantly improve throughput and reliability at larger distances.

Keywords: cooperative relaying, cooperative diversity, MAC, relay selection, CSMA/CA

I. Introduction

Mobile radio communications suffer from large-scale and small-scale fading effects that attenuate the communication signal. While large-scale fading is caused by a distance-dependent path loss and shadowing effects, small-scale fading is caused by multipath propagation. For mobile receivers or transmitters, small-scale fading can cause rapid fluctuations of the received signal-to-noise ratio (SNR); if a mobile device moves only a small distance, it may experience deep fading, even if it had perfect signal reception just an instant before.

Cooperative relaying [1] is a concept, where a relay node assists the communication between two nodes when the direct link is affected by small scale fading. The information is relayed via a spatially different path which is likely not affected by the same fading effects as the direct link at the same time. Thus, using such a relay communication channel can improve the network capacity by implementing spatial diversity for the communication paths [2]. With the growing number of networked wireless devices in everyday appliances, there are more potential relay nodes within transmission range of a sender and receiver. Henceforth, cooperative relaying will gain additional importance in the near future.

Cooperative diversity is expected to be more beneficial, if the cooperative relaying protocol is designed according to the following: First, it should have a low overhead. A large number of communication attempts are expected to succeed without the need for alternative communication paths. Thus, in the case of a successful transmission, a cooperative relaying protocol should have minimal overhead in comparison to non-cooperative transmission schemes. Second, the protocol should exploit cooperative diversity to an extent that makes the effort for the more complex interaction between wireless nodes worth it. Finally, the protocol should be implementable with state-of-the-art hardware.

In this paper, we propose a novel **Co**operative **Re**laying **M**edium **Ac**cess protocol (CoRe-MAC) for wireless networks which extends the standard Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) protocol. The objective is to increase reliability and throughput of the communication if the Signal-to-Noise-Ratio (SNR) over the direct link between source and destination is below an acceptable level, while avoiding overhead to the communication if the direct transmission is successful. To this end, in the proposed protocol a reactive (on demand) relay selection is invoked only in case of transmission failures.

The remaining part of this paper is structured as follows: Section II presents related work and summarizes design options on cooperative diversity and relaying. Section III introduces the proposed CoRe-MAC protocol. Section IV provides an evaluation of CoRe-MAC and a standard CSMA/CA approach for comparison reasons in a realistic scenario. Finally, we conclude and give an outlook to future research in Section V.

II. Related Work and Design Options

Cooperative relaying can be divided into three main phases: direct transmission, relay selection, and cooperative transmission. In the *direct transmission* phase the source transmits its data, whereas destination and relay (or potential relays) try to receive it. In the *relay selection* phase a neighboring node of source and destination is selected. The *cooperative transmission* phase, where the relay forwards the data to the destination, occurs only if the destination has failed to retrieve the data from the source during the direct transmission.

The relay selection phase has a great impact on the performance of the whole cooperative relaying process [3]. The major selection criteria is the link quality of the communication participants which is typically measured by probing packets [4]–[6]. The selection can be further refined by using additional factors like residual power [7]. Note that the selection process also depends on the actual environment, i.e., it is important to know how frequently a relay needs to be selected for a given source destination pair, since a node may be a good relay at one time instant and a bad one later on. In the absence of any environment information, relays are selected for each packet anew [4]. However, relay selection is a distributed task which requires time and energy and thus introduces additional overhead. Thus, it is beneficial to explore the current realization of the channel between source and destination and to do relay selection only on demand [8].

Relay selection can be done before direct transmission (*proactive relay selection*) or after direct transmission (*reactive relay selection*). Proactive relay selection is considered to have energy advantages over reactive relay selection since only the selected relay needs to spend energy for listening to the transmission of the source [4]. However, it introduces a constant overhead to all transmissions. Moreover, the channel state may change during the direct transmission phase. The selected relay might then not be able to receive the data, or the relay link to the destination can also change considerably making successful relaying unlikely. In reactive schemes, a relay is selected only if the destination is not able to receive the data from the source and asks for assistance (cf. *iterative relaying* [2]). Thus, reactive relay selection is only done if a direct transmission fails and relaying candidates have already received the original data from the source properly. A disadvantage is that all potential relaying nodes need to listen to the transmission of the source. Since many transceivers consume the same order of energy for receiving and transmitting [9], the costs for having all neighbors of source and destination listen might not be negligible.

Recently, cooperative relaying is no longer treated as a separate task but is investigated in combination with Medium Access Control (MAC) protocols. It is beneficial to exploit channel reservation messages such as Request-To-Send (`RTS`) and Clear-To-Send (`CTS`) for probing the channel and selecting a relay [10], [11], since relays also need to make a channel reservation for the cooperative transmission phase. The main difference of our protocol compared to these proposals is that CoRe-MAC selects relays after the direct data transmission phase and thus, does not introduce additional delay to successful direct transmissions.

III. MAC-Layer Protocol for Cooperative Relaying

A. Motivation

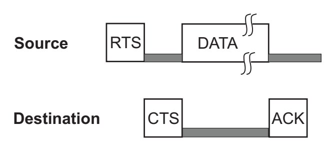
MAC changes considerably in the presence of cooperative relaying. In non-cooperative schemes, the wireless medium is reserved just in the neighborhood of source and destination for the time of the direct transmission and the acknowledgment. In cooperative relaying, however, the channel reservation needs to be extended in space and time for the relaying. This leads to reduction of the spatial re-usability of the network since the channel reservations for the relay might interfere or block other communications which otherwise could be done concurrently if the relay is not used. Furthermore, in proactive relay selection, relays are selected and the channel floor for them are reserved before direct transmissions. Whenever the direct transmission succeeds, those reservations block other communications and degrade the overall throughput.

The motivation for our protocol is that relaying is not always needed. Thus, we try to minimize the introduced overhead due to cooperative relaying. CoRe-MAC follows a reactive relay selection approach such that it behaves as standard non-cooperative protocols in the absence of link errors on the direct link in terms of throughput. Besides reducing the introduced overhead when cooperation is not needed, reactive relay selection also inherently prioritizes direct transmission with respect to cooperative ones. Our protocol also addresses the higher energy consumption of reactive schemes by determining whether cooperation can be used or not before direct transmission and by limiting the number of nodes listening to the data transmission between source and destination (see section III-D).

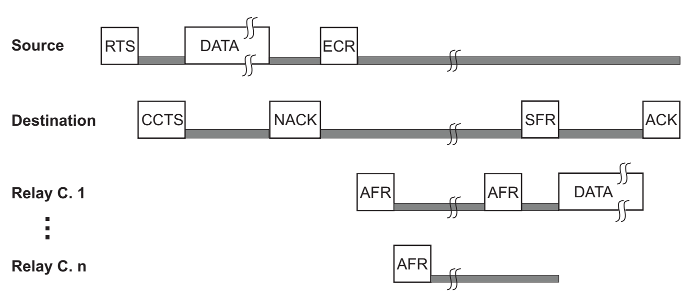
B. Protocol Description

Hereafter we refer to the channel between source-destination, source-relay, and relay-destination as SD-channel, SR-channel, and RD-channel, respectively. The multi-hop channel between source and destination via the relaying node is addressed by SRD-channel.

Fig. 1 depicts channel allocations and packet exchange for successful and failed direct transmissions and Table I summarizes the names and the size of the used signaling packets of our protocol. Packets marked with * are modified versions of standard CSMA/CA packets or newly introduced ones. The length of the packets has been chosen in compliance with IEEE 802.11. Signaling packets are sent using a lower modulation scheme that is slower, but less prone to transmission errors than the modulation of the data message. Dark bars in Fig. 1 indicate channel reservations of a particular node.



(a) no cooperation request



(b) cooperation request and process

Fig. 1. Packet exchange and channel reservation

A communication attempt starts with an `RTS` transmission from the source which is used to inform the intended destination about the duration of the `DATA` transmission and reserves the channel floor until the response of the destination is received. At reception of an `RTS`, the destination decides whether cooperation is needed or not (see section III-D). If the

TABLE I
LIST OF USED SIGNALING PACKETS

Abr.	Name	bytes
RTS	Request-To-Send	20
CTS	Clear-To-Send	14
ACK	Acknowledge	14
CCTS*	Cooperative Clear-To-Send	16
NACK*	Negative Acknowledge	14
ECR*	Extend-Channel-Reservation	14
AFR*	Apply-For-Relay	14
SFR*	Select-For-Relay	20

destination does not reply (i.e., it has not received the request or it is not allowed to answer due to another communication), a back off like in CSMA/CA is performed. Each unanswered RTS increases the *small message retry counter*. If this counter exceeds a maximum value the DATA is dropped. In Fig. 1(a) we show the message exchange and channel reservation of CoRe-MAC for the case where no cooperation is requested. The destination replies with a CTS message, which reserves the channel for the data transmission of the source. When the source receives the CTS message it starts transmitting the DATA message. The DATA message extends the channel reservation in the vicinity of the source until reception of an Acknowledge (ACK) message from the destination. Note, that there is no additional delay introduced compared to CSMA/CA. If the direct transmission fails, the *large message retry counter* is incremented. Until the value of this counter exceeds a specified maximum value, the source tries to occupy the channel for a retransmission. Otherwise the DATA message is dropped.

The message exchanges and the channel reservations if the destination decides to use cooperation are depicted in Fig. 1(b). The destination uses a Cooperative-Clear-To-Send CCTS message, which contains the information of a CTS message extended by the SNR value of the SD-channel, to inform source and neighbors that cooperation is required. The channel reservation of a CCTS lasts until the end of the DATA transmission. The reception of the CCTS triggers the same actions at the source as a CTS. Thus, if the direct transmission succeeds, there is no additional overhead in comparison to CSMA/CA, except for a 14% transmission time increase for the CCTS instead of CTS, which is not significant since the control message itself only accounts for a small part of the overall message transmission time.

When the direct transmission fails the destination uses a Negative-Acknowledge (NACK) message to inform source and relaying candidates that a cooperative transmission is necessary. The NACK extends the channel reservation of the destination until the end of the relay selection phase. Since the source needs to know the success of the cooperative transmission, it extends its own channel reservation until the expected ACK reception by broadcasting an Extend-Channel-Reservation (ECR) message. After this message the slotted relay selection process starts where relaying candidates use Apply-For-Relay (AFR) messages (see subsection III-C) to indicate their relaying readiness. These messages are also used to reserve the channel floor until the end of the relay selection phase. Reservations in the relay selection phase (i.e., those done by NACK, ECR, and AFR messages) only block nodes which are not participating in this cooperative transmission attempt to access the channel, e.g., relaying candidates are not prevented from sending their AFR messages. At the end of the relay selection phase the destination transmits a Select-For-Relay (SFR) message which selects the current relay and also extends the channel reservation until the end of the DATA transmission from the relay. At reception of the SFR the selected relay starts transmitting the overheard data from the source. Finally, the destination signals the success of the cooperation. If the cooperation attempt is not successful, retransmission from the source is invoked. In the retransmission phase the channel reservation process in Fig. 1 is repeated.

C. Relay Selection

Potential relays need to have successfully overheard the message from the source and have received the NACK message from the destination. After the NACK, there is a fixed number of slots where these relays send an AFR message with a given probability ρ in each slot. A relay selection is successful, if there is at least one slot where exactly one relay has sent its AFR. The transmission probability ρ is chosen in a way to maximize the expected number of slots with exactly one AFR message.

The probability p that out of m potential relays only one sends an AFR in a given slot is thus given by

$$p = m\rho(1-\rho)^{m-1} \,. \tag{1}$$

In order to maximize p we solve $\frac{dp}{d\rho} = 0$ yielding $\rho = \frac{1}{m}$ and $p_{max} = (1-\frac{1}{m})^{m-1}$ as solution. Performing a relay selection over s slots gives a success probability p_S of

$$p_S = 1 - (1 - p_{max})^s \,. \tag{2}$$

The number of contention slots s determines the success probably p_S. Choosing a high s increases the time overhead of the selection process. For up to 100 relaying candidates an s of 5 yields a p_S above 90 % which turns out to be a good compromise between overhead for relay selection and success rate. After the reception of one or more non-colliding AFR messages, the destination selects the best relay candidate in terms of highest received SNR in its SFR message. In case the relay selection fails, the absence of the destination's SFR tells the source to continue with a retransmission attempt for the direct transmission.

D. To Cooperate or Not to Cooperate?

The success of a transmission is a random event with the received SNR being a parameter. By looking at the current link quality one can estimate the success probability of the transmission. If this probability for the success of a direct transmission is high, relays are likely to be not needed and may pass on supporting the ongoing transmission (and overhearing it). Based on an application-dependent threshold Θ, the destination can decide at reception of the RTS whether a relay is required or not (compare *Relay Selection on Demand* [8]). The threshold Θ specifies the Packet Error Rate (PER) an application can cope with. The proposed protocol aims to keep the PER between any source destination pair below this threshold but does not try to make the transmissions as reliable as possible at the expense of the throughput. Furthermore, if cooperation is required, potential relaying nodes assess their link qualities to source and destination. Only nodes which can provide an overall PER from source to the destination which is smaller than the PER of the direct channel should be considered and should consume energy overhearing the direct transmission.

For simplicity and without loss of generality we assume Binary Phase Shift Keying (BPSK) without channel coding in the following. A received symbol y_i is given by

$$y_i = h_i \cdot x_i + n_i \ , \tag{3}$$

where x_i is the transmitted symbol, h_i is the fading coefficient which is Rayleigh distributed with parameter $\sqrt{L/2}$ and n_i is additive white gaussian noise with parameter N_0. The value L represents the path loss of the observed link and N_0 is the spectral noise density. In the case of quasi-static fading, the fading coefficient h_i is constant for the transmission of one packet. The Bit Error Rate (BER) is given by [12]

$$\mathrm{BER} = 0.5 \cdot \mathrm{erfc}\left(\sqrt{\frac{h_i^2 E_b}{N_0}}\right) \ , \tag{4}$$

with E_b being the energy per bit at transmitter side. For uncoded messages with j bits per packet calculation of the PER is straightforward and given by

$$\mathrm{PER} = 1 - (1 - \mathrm{BER})^j \ . \tag{5}$$

$$\mathrm{PER}_{\mathrm{SD}} < \Theta \ ; \tag{6}$$

$$\mathrm{PER}_{\mathrm{SD}} \geq \Theta \ ; \tag{7}$$

The PER of the source-relay and relay-destination channel is then obtained as

$$\mathrm{PER}_{\mathbf{SRD}} = 1 - (1 - \mathrm{PER}_{\mathbf{SR}})(1 - \mathrm{PER}_{\mathbf{RD}}) \tag{8}$$

where $\mathrm{PER}_{\mathbf{SR}}$ and $\mathrm{PER}_{\mathbf{RD}}$ are the PER for the source-relay and the relay-destination message transmissions, respectively.

Whenever the direct channel between source and destination provides a PER which is lower than the specified threshold value Θ, a regular CTS message is used to inform source and neighbors that no cooperation is required. In all other cases the destination uses a CCTS which additionally contains the current SNR of the direct link.

Potential relaying candidates determine the PER of the direct link by using (5) with the SNR information obtained from CCTS and control their own capability to improve the reliability of this transmission by evaluating (8) using their own link qualities measured by reception of RTS and CCTS packets. If the expected PER of the given relay channel is below the expected PER of the direct channel, the corresponding relay will listen to the transmission of the source.

TABLE II
SIMULATION PARAMETER

E_b/N_0 at transmitter side	40
path loss exponent	2.2
SNR detection threshold	1.5
coherence time	varied
data rate	250 kbit/s
message size	1000 byte
max contention slots	255
slot duration	1 ms
SIFS	0.5 ms
DIFS duration	2.5 ms
EIFS duration	5 ms
max small retries	5
max large retries	5
node density (tx range)	50

IV. PERFORMANCE EVALUATION

A. Simulator, Setting and Assumptions

We extended the wireless sensor network simulator JProwler [13] by CSMA/CA channel reservation and Rayleigh fading model. JProwler was chosen for its open source and its simulation performance.

In the simulation, we account for all control messages such as RTS and CTS as well as for DATA messages with different length. Control messages are assumed to be transmitted with half of the transmission rate of data packets and thus experience a lower BER than the transmission of the DATA messages. The simulation setup features a dedicated pair of a source and a destination node (one hop), with potential relays being distributed around them uniformly randomly with a given density. The distance between source node S and destination node D (SD-distance) is varied during an experiment run in order to infer about the protocol's performance at various signal qualities. The experiments are repeated with different deployments of the potential relay nodes until the simulation results show an accuracy of $\pm 1\%$ within a 95% confidence interval.

If not stated otherwise, we use the settings summarized in Table II in our simulations. The number of potential relaying candidates (parameter m) is assumed to be known by node D. The parameter m can be approximated based on the node density and SD-distance.

B. Simulation Results

Relay Candidates: Fig. 2 shows the number of relay candidates averaged over all transmission attempts of the source (cooperative and non-cooperative ones) and thus reflects the additional amount of data message receptions due to cooperation. If the PER of the SD-channel is above the Θ threshold, relays will not overhear the following data transmission. In the case of a small Θ, relays are often set to overhear

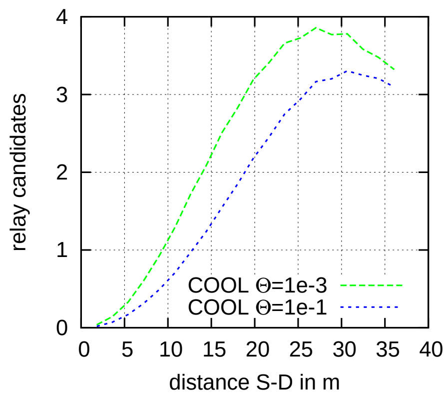


Fig. 2. Average number of potential relays

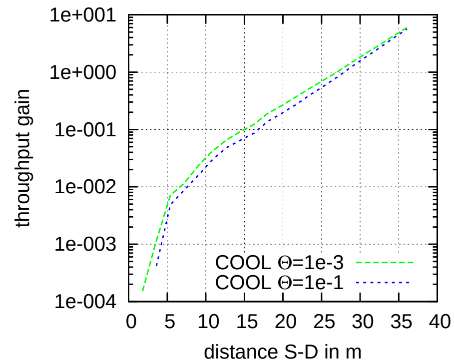


Fig. 3. Throughput Gain vs distance S-D

messages, which comes at the cost of energy consumption for the relaying nodes while listening or the non-availability of these nodes to other communications while they are listening. On the other hand, a high Θ increases the chance that relaying was not activated when a direct transmission fails. For $\Theta = 1$, a protocol without relaying is obtained. The higher the distance and the lower Θ, the more relays are activated to listen in average. For large distances, this number decreases due to the lower number of potential relays.

Throughput: Fig. 3 compares the throughput gains of CoRe-MAC to standard CSMA/CA for different Θ values. If the SD-distance is small, the probability for lost or incomplete messages is comparably low and CoRe-MAC operates mostly in the mode without relaying. Thus the performance of both protocols is similar if the SNR between source and destination is good.

With increasing distance more transmissions fail. Here, the standard CSMA/CA protocol tries to overcome this with retransmissions while CoRe-MAC uses alternative paths via relaying. Due to the coherence of the channel state, retransmissions on the direct channel tend to fail more likely than relayed transmissions, which leads to a significantly better throughput for CoRe-MAC.

For very low SNR, direct transmissions fail very often while the relaying protocol is still able to provide communication. In this case, the relaying protocol is invoked very often and the relay behaves as an additional hop between source and destination.

PER: Fig. 4 illustrates the PER, i.e., the ratio of the number of messages not received to the number of messages originated by the source, as function of different parameters. A message transfer is considered successful, if its transmission succeeds, with or without the help of relaying operations or retransmissions. In Fig. 4(a) the PER is depicted as function of the SD-distance. As expected, the PER increases with the distance. However, the relaying protocol is able to provide a lower PER, especially at large distances. Again, there is a tradeoff between Θ as activation threshold for the relays and the resulting PER.

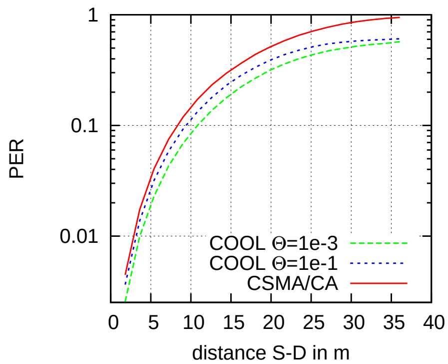
Fig. 4(b) shows the dependence of PER to the length of the data message for distance of 2 m between source and destination. With increasing message size the PER for our protocol as well as for the CSMA/CA protocol increases. This is on the one hand a result of the decreasing PER for smaller messages and on the other hand is influenced by the coherence time of the channel – for larger messages it is less likely that the channel state is coherent when doing a retransmission. Cooperative relaying is more important if the message size is large. The selection of the appropriate Θ value also depends on the message size.

The influence of the coherence time of the channel on the PER is illustrated in Fig 4(c). With increasing coherence time the PERs of the investigated protocols decrease. However, CoRe-MAC outperforms CSMA/CA for the whole range of considered coherence times. For small coherence time values, the channel changes considerably between channel reservation and `DATA` transmission, resulting in a higher PER.

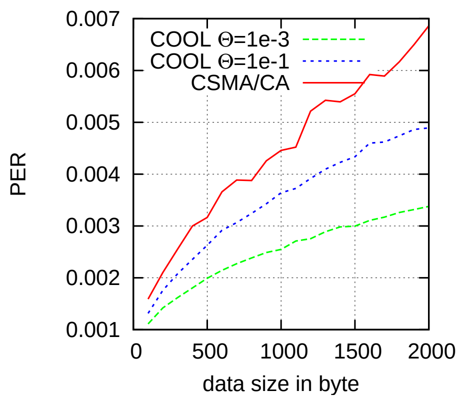
Average Delay: Since CoRe-MAC performs the relay selection only after a failure of the direct transmission we expect no extra overhead in the data transmission time in comparison to standard CSMA/CA. As criteria we use the delay, defined as the time from the start of a data transmission at the source until successful reception of the whole data at the destination. It contains signaling overhead, retransmissions, and cooperative transmissions. Fig. 5 depicts the average delay of the different protocols (with two different settings for Θ) and supports aforementioned hypothesis. The relaying protocol is able to reduce the delay in case the direct transmission fails, since on average it needs less time in relaying the message than the standard protocol needs for multiple retransmissions. For large distances, however, the average transmission time of CSMA/CA is shorter than with relaying. This is due to the case that at these distances most direct transmissions fail and do not enter the statistic. The few that are received witness a good channel condition and thus have a shorter delay than most relayed communications.

V. Conclusion

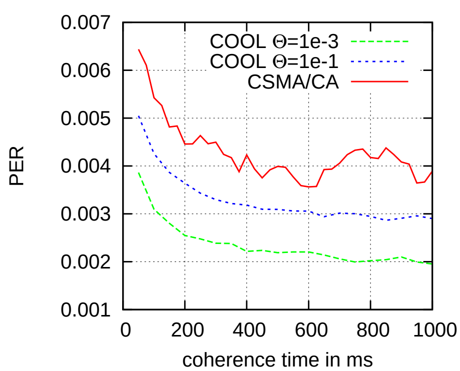
This paper presented and discussed CoRe-MAC, a MAC protocol for cooperative relaying which builds on the IEEE 802.11 mechanisms. Special attention was paid to the feasibility of the protocol for state-of-the-art systems and to the evaluation of its performance under realistic assumptions.



(a) PER vs SD-distance



(b) PER vs message size at 2 m SD-distance



(c) PER vs coherence time at 2 m SD-distance

Fig. 4. PER vs (a) distance, (b) message size, and (c) coherence time

The protocol extends the IEEE 802.11 mechanisms for handling transmission failures by space/time diverse channels. In the case the direct transmission is successful, however, our protocol comes with no additional overhead for the relay selection. Thus, for good SNR between source and destination CoRe-MAC has similar performance as the standard CSMA/CA approach. In the case of a transmission failure, e. g., due to small scale fading, our approach supports transmission via a different communication path implementing spatial diversity via a selected relay. Thus, especially for transmission over unreliable communication links, the throughput, the delay, and reliability of wireless communication can be

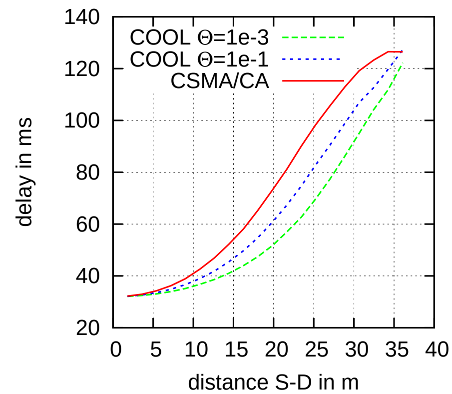


Fig. 5. Delay vs SD-distance

improved. As a next step, we plan to implement and evaluate the protocol on a hardware testbed, consisting of a cluster of wireless nodes.

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