

Medium Access with Adaptive Relay Selection in Cooperative Wireless Networks

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Abstract—We specify and evaluate a protocol for cooperative relay communications in wireless networks targeted for low-budget and energy-constrained off-the-shelf hardware. The protocol located at the Medium Access Control (MAC) layer integrates radio resource reservation, relay selection, and packet flow. Performance is evaluated with different parameters, such as node density, channel coherence time, and data packet size. Higher network-wide reliability and throughput compared to noncooperative protocols can be achieved in dense networks and unreliable channels. At the same time, throughput does not degrade in sparse networks or good channel conditions.

Index Terms—Wireless communications, relaying, relay networks, cooperative networks, medium access protocols

1 INTRODUCTION AND MOTIVATION

COOPERATIVE diversity intends to combat the effects of small-scale fading in wireless communications [1], [2]. Many studies focus on information theoretical and physical layer aspects, such as link capacity, coding, and relay positioning in simple scenarios often with only three nodes (see, [1]–[8]). The study of cooperative diversity in large networks and the design of link-layer protocols enabling the use of relays has found less attention (see, [9]–[13]). We believe that cooperative diversity will not be implemented in practice until protocols supporting the physical layer to exploit the benefits of diversity are designed and properly specified. To this end, we focus on the design of Medium Access Control (MAC) protocols for cooperative relay systems and specify design blocks of a MAC protocol that can be readily incorporated into existing wireless systems.

The challenge of designing a cooperative MAC protocol is that the overhead caused by setting up cooperation — relay selection and other signaling traffic — should not consume the provided benefit. It is essential that nodes follow certain principles in transmitting packets such that collisions are avoided if possible. Similarly, all signaling traffic of cooperative diversity have to adhere to the medium access rules. Setup and execution of cooperative diversity must be fast enough to react to the dynamics of the channel. Relay selection might also need access to information held by the physical layer, e.g., residual battery, received signal-to-noise ratio.

Most existing approaches of integrating cooperative diversity in MAC protocols have certain drawbacks. Some proposals select relays based on information from the past and can neither react to fast changing channels nor to node movements (see [10], [12]). Others assume special transceivers supporting Distributed Space Time Codes (D-STC) or Code Division Multiple Access (CDMA) for simultaneous packet transmissions (see [11], [12]), and/or offer adaptive data rates (see [10], [14], [15]). In certain applications, such transceivers are infeasible due to their costs, energy consumption, or size constraints. Moreover, most works do not consider the time overhead for exchanging relay selection criteria or do not discuss efficient ways to integrate the required signaling packets into the existing packet flow.

We introduce a cooperative MAC protocol that does not impose such restrictions. We propose the CoRe-MAC (Cooperative Relaying Medium Access Control) protocol which builds on Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) with RTS (Request-To-Send) and CTS (Clear-To-Send) handshake and extends the mechanisms for handling transmission failures by space-time diverse channels. We pay special attention to the feasibility for low-budget off-the-shelf hardware and its backward compatibility to CSMA/CA. This enables the operation of heterogeneous networks, where some nodes use CoRe-MAC and others CSMA/CA, and hence facilitates integration of CoRe-MAC in existing networks. Unless otherwise noted, CSMA/CA refers to CSMA/CA with RTS and CTS. Moreover, we focus on keeping the overhead of CoRe-MAC compared to CSMA/CA at a minimum for good channel conditions. In CoRe-MAC, the destination of a transmission attempt decides to enable cooperation based on the quality of its link to the source (see cooperation on demand). The overhead of CoRe-MAC is low, even if a destination enables cooperation and direct transmission succeeds. The

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Manuscript received 24 May 2013; accepted 27 June 2013. Date of publication 25 July 13; date of current version 22 July 2014.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier 10.1109/TMC.2013.97

expense of enabling cooperation is the energy consumption of candidates listening to the DATA transmission from the source. CoRe-MAC keeps this cost small by applying two concepts: *relay selection with early retreat* and *prioritized candidate set*. In relay selection with early retreat only those neighbors of source and destination that are likely to support the communication attempt by cooperation listen to the DATA transmission [16]. The newly proposed prioritized candidate set limits the number of nodes that listen to DATA transmissions to a previously selected subset of neighbors. The prioritized candidate set, however, does reduce not only the energy costs but also the relay selection delay.

The contributions of this article are as follows:

- Specifying a MAC protocol for cooperative relay communications that integrates relay selection, neighbor estimation, and medium access.
- Providing a throughput-oriented design built on reactive relay selection, which
 - does not introduce additional overhead if the direct channel condition is good, or the network is sparse such that no relays are available, and
 - performs significantly better if the direct channel quality is bad.
- Providing methods to form and use a prioritized candidate set to increase the energy and time efficiency of cooperative relaying.
- Showing how to efficiently integrate a neighbor cardinality estimation method into the relay selection process to infer about potential relays.
- Evaluating the protocol under certain assumptions.

A mathematical analysis of the protocol is intractable, due to the complexity. Therefore, we analyze the parameters affecting the performance of CoRe-MAC via simulations using an open source simulator, whose results can easily be validated. As a supplement, we provide Specification and Description Language (SDL) graphs of different phases of CoRe-MAC as a means for testing and validation, which also enables implementation of CoRe-MAC in other simulation platforms. We claim that CoRe-MAC is among the most comprehensively specified and analyzed MAC protocols for enabling cooperative diversity.

The remainder of this article is structured as follows. Section 2 summarizes existing work. Section 3 provides an overview of design considerations of CoRe-MAC. Section 4 describes CoRe-MAC in detail, explaining different phases of the cooperative communication process and discussing the node behavior in these phases. Section 5 evaluates the performance of CoRe-MAC compared to CSMA/CA in terms of channel coherence time, network topology, data packet size, and spatial re-usability. Parts of this article are contained in the doctoral thesis of the first author [17].

2 RELATED WORK

This section describes papers on cooperation in the MAC layer addressing similar issues as CoRe-MAC. Network layer and relay selection aspects are not contained due to space constraints but can be found in [17].

2.1 Preliminary Work

Some concepts used in this article were introduced in our earlier papers [16], [18]. A preliminary version of CoRe-MAC appears in [18], where CSMA/CA is enhanced with relay selection assuming that nodes are *aware* of the node density in the network. Adaptive relay selection in [16] is among the first that exploited an approach with energy considerations. Channel-state information is used for relay selection, and as many others, a proactive relay selection method is proposed to save energy. We use the energy saving concepts (i.e., cooperation on demand and relay selection with early treat) of [16] and apply it to a reactive relay selection method that (i) uses recent information; (ii) does not initiate cooperation unless it is necessary; and (iii) uses only those relays that can help the source-destination pair. Moreover, we now propose a *prioritized candidate set selection* to reduce the number of relay selection requests, saving time and energy. We also incorporate a neighbor cardinality estimation [19] to maximize the number of distinct relay applications and hence maximize the probability of selecting a relay. Such fast neighbor estimation is not used in any other cooperative relaying work. We aim at minimal data exchange for cooperation setup to reduce the protocol overhead and its impact on throughput.

2.2 Cooperative MAC Protocols

Related work regarding cooperative MAC mainly extends CSMA/CA. This is due to the fact that CSMA/CA (with and without RTS/CTS) represents one of the most investigated MAC protocols. Moreover, the handshaking used to reserve the channel for source S and destination D can be exploited in several ways in cooperative protocols, e.g., deciding on using cooperation based on the channel quality between S and D and determining the cooperation gain of certain nodes.

Cooperative Medium Access Control (CoopMAC) [10] aims to increase the overall throughput in a network by applying dynamic routing in the MAC layer. Each node maintains a table which contains expected feasible data rates to all neighbors via direct link and the fastest indirect link (via another neighbor). Nodes update the table entries by overhearing the data traffic in their vicinity. When a node S wants to transmit a packet to a neighbor D , it determines whether a direct or indirect transmission via a node R is more time efficient. If the direct transmission is faster, S uses standard CSMA/CA. Else, S uses this helping node to communicate with its destination. CoopMAC does not apply cooperative relaying to mitigate small scale fading effects, nor is it able to adjust to fast channel changes or node movements. It is only applicable to radio architectures offering adaptive data rates, where the transmission via a helper node is strictly faster than the direct transmission.

In Cooperative Medium Access Control with Automatic Relay Selection (CMAC/ARS) [14], S and D provide their neighbors with information about the quality of their current connection and the desired data rate. Based on this information, neighboring nodes decide whether the data

exchange between S and D requires cooperation. In case of cooperation, D selects a new relay for each cooperative transmission. CMAC/ARS uses a contention window of fixed size for the relay selection where each candidate transmits an application packet in a randomly chosen slot. If the contention window is too small or too many relay candidates are available, the selection is prone to fail due to collision.

Cooperative Diversity Medium Access Control (CD-MAC) [12] exploits cooperative relaying not only for the data transmission but also for the exchange of handshake signals. Initially, node S starts using standard CSMA/CA. Only if D does not react, S uses cooperation. In that case S sends the RTS (Request-To-Send) to a neighbor. Then, this neighbor and S use D-STC to simultaneously send the RTS to D . Node D recognizes the cooperative transmission and uses a neighbor to respond in a similar way. Each node selects the neighbor from which it has received packets with the highest signal-to-noise ratio (SNR). CD-MAC does not ensure that a relay node is currently in transmission range of S and D . Each unanswered RTS-packet triggers a cooperation process. However, D could also ignore an RTS if it is blocked by other transmissions. Schemes using D-STCs rely on the knowledge of the channel state information (CSI) between transmitting and receiving nodes to decode the original packet. It is unclear how CD-MAC accomplishes this. Moreover, decoding D-STCs requires a special receiver architecture.

Cooperative Medium Access Control (C-MAC) [11] represents a complex MAC protocol which uses two different access schemes. It uses CSMA/CA to manage the channel access of nodes and applies CDMA such that multiple relaying nodes can transmit simultaneously their data to the destination. The complexity of the protocol as well as its requirements reduce its practical feasibility considerably. For instance, it is difficult to ensure equal power constraints for received signals of a CDMA scheme in ad-hoc networks.

r -DCF [15] modifies the distributed coordination function (DCF) of IEEE 802.11 to enable use of relay for better bandwidth utilization. The scheme exploits the multi-rate support of IEEE 802.11 and allows data transmission over a relay node if the achievable data rate is better than the direct link. The protocol enhances RTS/CTS handshake with a triangular handshake between the source, destination, and relay nodes, which requires explicit feedback from the relay nodes and the source-destination pair. The nodes need to keep a relay table to pick a relay that can provide a higher rate.

Extending MAC protocols to facilitate cooperative diversity is not limited to CSMA/CA. Shea *et al.* [20] propose a cross layer design which combines cooperative diversity, routing and a Slotted-ALOHA access. Nodes that have successfully overheard the data transmission and can provide a route to the destination that is shorter than or equal to the original route indicate their willingness to cooperate. Source then chooses a relay to forward the data.

There is also recent work that aims to analyze MAC protocol design for distributed cooperative wireless

networks [21] and for wireless sensor networks [22]. Existing attempts of integrating cooperative diversity in MAC protocols are promising and indicate that gains can be observed in real world networks. However, the solutions have certain drawbacks: they refrain from certain phases of cooperative diversity, e.g., relay selection; select relays based on probably outdated information; require much overhead; or have restrictions which make solutions infeasible in real world applications. In addition to addressing these issues, in this article, we also incorporate neighbor demographics estimation [19] into the MAC protocol, which allows the system to maximize the chances of selecting a relay.

3 BASIC DESIGN PRINCIPLES

It is known that networks with cooperative relaying require different MAC protocols than those without. Channel reservation needs to be extended in space and time for relaying. MAC also needs to account for relay selection, since potential relays might not be known a priori in dynamic networks. CoRe-MAC addresses relay selection and resource reservation. It is designed with backward compatibility to CSMA/CA in mind and adheres to the defined medium access rules. A discussion on this compatibility is in Section 4.

In the following, we present the basic design principles. Unless we otherwise noted, the source and destination nodes are called S and D , respectively.

3.1 Relay Selection

Relay selection has great impact on the achievable performance of cooperative MAC protocols. Schemes using proactive relay selection (see [9], [10]) select relays before the direct transmission. To ensure the reception of the DATA, relays need to reserve the channel in their surrounding. Thus, whenever the direct transmission succeeds, those reservations unnecessarily block other communications and degrade the overall throughput. Use of reactive relay selection (see [23], [24]) can avoid such over reservations at the expense of more complex signaling and increased energy consumption.

CoRe-MAC employs reactive relay selection. It has no additional signaling overhead compared to CSMA/CA during good channel conditions. Another advantage is that it prioritizes direct transmissions to cooperative ones. Relay candidates do not reserve the channel during direct transmission. Only if the candidates have received the DATA and D requires support, they become active and might block other communication. A major drawback of reactive relay selection is that it requires all relay candidates to listen to the DATA from S . Depending on the used energy saving options, this can tremendously increase the energy consumption compared to cooperative relaying using proactive selection.

We address this issue by using *cooperation on demand* and *relay selection with early retreat*. Using cooperation on demand, D decides to enable cooperation depending on the channel state between S and D . If D enables cooperation, relay selection with early retreat ensures that only those

TABLE 1
List of Used Signaling Packets

Abr.	Name	bytes
RTS	request-to-send	20
CTS	clear-to-send	14
ACK	acknowledgment	14
CCTS*	cooperative-clear-to-send	16
CACK*	cooperative-acknowledgment	14
ECR*	extend-channel-reservation	14
AFR*	apply-for-relay	14
SFR*	select-for-relay	20
BUSY*	busy-tone	-

nodes that are likely to support the communication between S and D remain candidates. Furthermore, CoRe-MAC supports prioritized candidates, i.e., nodes that participated in the relay selection process for $\{S, D\}$ before and are known by D . It uses this set of candidates as the nodes which need to overhear the DATA transmission.

In CoRe-MAC, we select one relay in the end, regardless of the number of relay candidates. Use of multiple relays to assist communication has been considered in [9], [23], [25], where the authors state that selecting the best relay for a communication pair is more efficient than using all available ones. The reasoning is that if the best node fails all other would fail anyway. In addition, use of multiple relays to assist communication imposes stricter hardware requirements. Therefore, in this article, we focus on one relay.

3.2 Resource Reservation

Let us consider a MAC protocol that implements virtual carrier sensing in CSMA/CA as defined in IEEE 802.11; i.e., CSMA/CA [26] reserves the channel in the vicinity of S and D using request-to-send (RTS) and clear-to-send (CTS) packets. In a cooperative scenario, such MAC needs to regard relay selection and cooperative transmission. Hence, S and D have to reserve the channel in their vicinity for relay selection, direct transmission, and cooperative transmission. Besides S and D , also the relay may require a channel reservation in its vicinity. Intuitively, resource reservation for cooperative relaying imposes additional overhead to the communication scheme and needs to be handled carefully. Whether cooperation is required or not depends on the channel condition but remains in general a probabilistic event. If cooperation is enabled but not needed, channel reservation of source, destination, and relay hinders other nodes from using the channel and negatively affects the overall network throughput. Therefore, although cooperative relaying is a means to overcome fading effects, it should not negatively influence the throughput during good channel conditions which we expect most of the time.

We have chosen the signaling packets of CoRe-MAC accordingly, which are summarized in Table 1. Moreover, we ensure that CoRe-MAC operates in heterogeneous networks with some nodes supporting only CSMA/CA (compatibility to CSMA/CA), and hence, the packet lengths are in compliance with IEEE 802.11. Those marked with * are newly introduced packets compared to CSMA/CA. While CSMA/CA and CoRe-MAC devices can coexist,

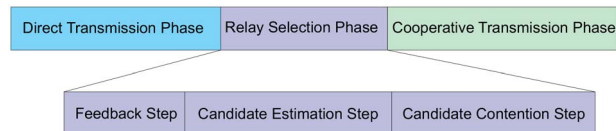


Fig. 1. Phases of CoRe-MAC.

CoRe-MAC devices have a larger access to the network resources (in time and space) due to potential relay utilization. The CoRe-MAC nodes are expected to hold the channel longer for a given packet if cooperation is enabled with the use of ECR. On the other hand, as simulation results will show, since the source retransmissions are reduced, the expected time to deliver a packet is also reduced (resulting in a higher throughput). While costs and benefits of deploying CoRe-MAC are analyzed, a fairness study in a heterogeneous network between CSMA/CA and CoRe-MAC nodes is beyond the scope of this article.

3.3 Protocol Phases

Fig. 1 shows the three phases of CoRe-MAC. In direct transmission phase, D decides on enabling cooperation and S transmits the DATA packet. If cooperation was enabled and the direct transmission failed, D selects a relay in the relay selection phase. CoRe-MAC splits this phase into three steps:

- The *feedback step* allows the destination to collect information about the availability of candidates. If no candidates are available, the destination aborts the cooperation process and requests a retransmission from the source. Hence, CoRe-MAC should not perform worse than CSMA/CA in sparse networks where nodes have hardly any neighbors which can act as relays.
- The *candidate estimation step* estimates the number of available candidates of a communication attempt.
- With this knowledge, candidates adjust their transmission probability in the *candidate contention step* to maximize the number of relay applications received by D .

The destination chooses, based on the application, the current relay and a set of prioritized candidates for further cooperations. Finally, the selected relay R forwards the DATA packet to D during the cooperative transmission phase.

4 PROTOCOL DESCRIPTION

4.1 Overview of Standard CSMA/CA With RTS/CTS

Fig. 2 shows a packet exchange of CSMA/CA [27], [28]. Light gray boxes are physical channel assessment periods; dark gray bars represent active channel reservations of nodes.

When S has a DATA packet to transmit, it first has to wait until the communication channel is free. If S detects a free channel, it proceeds depending on the previous reception success of S . After a corrupt packet reception, nodes have to defer from accessing the channel for at least t_{EIFS} . A new communication attempt needs to be at least t_{DIFS} apart from a previous one.

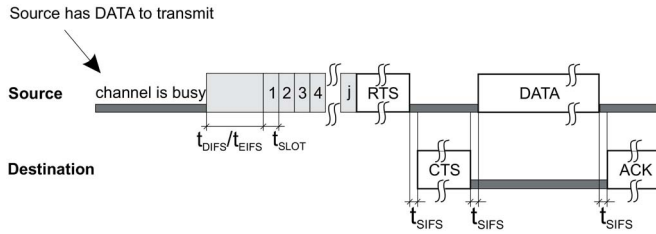


Fig. 2. Packet exchange in CSMA/CA with RTS/CTS.

Node S observes the channel for the duration of $j t_{\text{slot}}$ (see small light gray boxes in Fig. 2). If some other node starts a transmission within communication range of S during this time, S suspends the observation until the channel is free for at least t_{DIFS} again. When the observation timer expires, S transmits its RTS packet. RTS reserves the channel for the whole duration from the time destination needs to reply with a CTS packet to the reception of ACK. Besides reserving the channel, RTS informs the intended destination D about the pending DATA packet and its transmission duration.

Node D replies with a CTS if it is not blocked by other transmissions in its vicinity. The CTS reserves the channel in the neighborhood of the destination for the duration of the DATA packet transmission from S . If S does not receive this CTS it assumes a collision and increases its contention window counter (CW_{counter}) and its small retry counter src . If src reaches a maximum value src_{max} , S drops the DATA packet. Else, S tries to start the transmission again. If S receives the CTS it starts the DATA transmission. Besides delivering the data to D , the DATA packet also reserves the channel to allow S to receive an ACK from D in response.

After reception of the DATA, D informs S about its decoding success using an ACK packet. If the DATA transmission is not successful, i.e., S does not receive a positive ACK, it increases its CW_{counter} and its large retry counter lrc . The source retransmits the DATA packet until the lrc reaches a maximum value lrc_{max} . If this happens, S drops the DATA and informs the next higher layer about the delivery failure.

4.2 Direct Transmission Phase of CoRe-MAC

Fig. 3 illustrates the packet exchange in CoRe-MAC during the direct transmission phase. For the node behavior in this phase see Fig. 19 in Appendix B, which is available in the Computer Society Digital Library at <http://doi.ieeecomputersociety.org/10.1109/TMC.2013.154>.

The direct transmission phase consists of the channel reservation of $\{S, D\}$, the direct packet transmission, and if transmission was successful, the ACK from D . Moreover, D decides on enabling cooperation, and a set of potential relaying candidates is formed.

CoRe-MAC behaves similar to CSMA/CA during the direct transmission phase. The difference is that D exploits the received SNR of the RTS to estimate the expected packet error rate (PER) of the direct DATA transmission, based on the used modulation scheme and data packet size. It uses a threshold Θ to decide whether the direct channel is in a bad or good state, i.e., if cooperation should be enabled or not.

If the channel is in a good state, D replies with a CTS and disables cooperation for the following DATA transmission. In this case, the whole communication process is equivalent

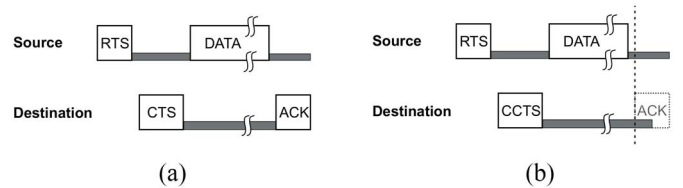


Fig. 3. Packet exchange/channel reservation during direct transmission phase. (a) Cooperation disabled. (b) Cooperation enabled.

to CSMA/CA. Neighboring nodes of S and D may optionally switch off their radio during the DATA transmission, depending on energy saving options (not analyzed in this article).

If the estimated PER reveals a bad channel condition, however, D replies with a cooperative-clear-to-send (CCTS). This packet informs S and potential relay candidates that D requests to enable cooperation. The CCTS contains additional information for the cooperation process: 1 byte information about expected PER for the direct channel and 1 byte to identify a prioritized relay set. Clearly, 1 byte is too small to name each member of this set. However, it is enough to inform neighbors about the number of nodes in this set and a short sequence number identifying the set. Candidates verify based on locally stored information whether they are members of this prioritized relay set based on the combination of the sequence number and the addresses of S and D . If D enables cooperation and direct transmission is successful these 2 bytes represent the total overhead of CoRe-MAC compared to CSMA/CA. This overhead is not significant compared to the overall DATA packet transmission time.

Let us briefly discuss the threshold Θ . CoRe-MAC aims to keep the PER between any S - D pair below Θ but does not try to make transmissions as reliable as possible at the expense of additional overhead. A smaller value of Θ enables cooperation more often than a larger one. While a small Θ can negatively affect the throughput between S and D in proactive relay selection, in a reactive selection it affects exclusively the energy consumption in the network—neighbors are more often requested to overhear the transmission of S .

CoRe-MAC addresses energy efficiency of reactive relay selection with the following methods. First, cooperation on demand reduces the time that neighbors have to overhear the direct DATA transmissions. Second, with relay selection with early retreat, the initial candidate set comprises all nodes which have received the RTS and CCTS packets. Those nodes exploit the PER information provided in the CCTS and determine expected PERs to S and D based on the received SNR values of RTS and CCTS (see Fig. 19(c)). Let PER_{SD} , PER_{SC_i} and PER_{DC_i} be the expected PERs for the DATA transmission for the links S - D , S - C_i and D - C_i , respectively, with C_i denoting the i^{th} candidate. Candidate C_i retreats from the cooperation process if

- 1) $PER_{SC_i} \geq 0.6$,
- 2) $PER_{DC_i} \geq 0.6$,
- 3) $PER_{SD} \leq 1 - ((1 - PER_{SC_i}) \cdot (1 - PER_{DC_i}))$.

Rules 1 and 2 ensure that candidate C_i has at least a 40% chance of receiving the DATA from S and can deliver it to D .

The value 0.6 is determined through exhaustive simulations [17]. Rule 3 ensures that the cooperative link via C_i is better than the direct one. These rules aim to prevent nodes which can hardly support the communication between S and D from participating in cooperation and avoid unnecessarily increasing the overall energy consumption. Finally, CoRe-MAC provides the option to limit the number of overhearing nodes to the cardinality of a prioritized candidate set (see relay selection phase). The members of this set identify themselves by the information provided in the CCTS packet. Members of that set, however, also retreat if their channel conditions to S and D are not sufficient based on the retreating rules.

An ACK from D completes the direct transmission phase and the complete transmission attempt if the packet transfer from S to D was successful. The transmission attempt ends also if D has not enabled cooperation but did not receive the DATA from S . If D has enabled cooperation and has not received the DATA packet from S , D defers its ACK transmission, which triggers a time-out event at S and the relaying candidates. Candidates which have failed in receiving the DATA packet from S quit the cooperation process.

Summing up, CoRe-MAC requires the following adaptations to CSMA/CA during the direct transmission phase:

- The RTS packet needs to reserve the channel for a longer period to account for a CCTS response of D .
- The CCTS packet needs to be introduced. It is two bytes larger than the standard CTS packet and reserves the channel for a longer period. This extended reservation is shorter than an ACK and has no effect on the throughput if direct transmission succeeds.

4.3 Relay Selection Phase of CoRe-MAC

CoRe-MAC conducts relay selection only if the direct transmission failed and D enabled cooperation. The relay selection starts if D does not transmit an ACK after the direct transmission. In such a case, S and potential relaying candidates do not detect any channel activity within t_{SIFS} after the DATA. The relay selection itself consists of three steps.

4.3.1 Feedback Step

Relay selection should only be performed if necessary. For instance, if there are no candidates, it does not make sense to start a selection process. On the other hand, a previously selected relay could, depending on the coherence time of the channel and the node mobility, be *re-used*. To this end, CoRe-MAC uses the feedback step to gather information about the availability of prioritized candidates or new candidates at D . In this context, availability means that a given candidate has received the DATA from S without error. Fig. 4 illustrates the packet sequence during the feedback step. For the node behavior see Fig. 20 in Appendix B, available online.

The feedback step starts right after the direct transmission phase. Relay candidates use busy tone (BUSY) transmissions (illustrated by gray-frames in Fig. 4) to indicate their DATA reception success. The duration of a BUSY is t_{SLOT} . It is enough time only to detect activity on the

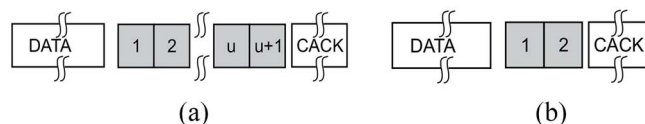


Fig. 4. Packet sequence during feedback step. (a) With prioritized relay set. (b) Without prioritized relay set.

channel. Nodes which receive a BUSY and do not participate in the cooperative communication attempt assume an erroneous packet transmission and refrain for t_{EIFS} from accessing the channel.

In the feedback step, we distinguish two cases based on the content of the CCTS packet (see Figs. 4, 20):

- 1) The CCTS contains information about a prioritized relay set with cardinality u : The first u BUSYS of the feedback step are reserved for nodes in the set to report their availability. The feedback sequence is equal to the ordering of the candidates at selection time as described in the contention step (Fig. 4(a)). Thus, there is no collision at this step, since each candidate has their own slot number.
- 2) The CCTS contains no information regarding a prioritized relay set: all candidates transmit in the first slot of the feedback step a BUSY to indicate their availability (Fig. 4(b)). There is collision in this case, but this step is to indicate their presence only.

Finally, if there are candidates, all former candidates and S transmit a BUSY to block any communication in their surrounding for another t_{EIFS} period.

If no candidates are available, S also stays silent; i.e., D does not observe any BUSY transmissions during the candidate feedback slots. In this case, D stays silent which informs S about the failed transmission attempt. This implies that, if D has utilized a prioritized candidate set, no member of this set was able to help D — they were not allowed by their neighbors, had bad channel conditions, or had moved out of transmission range of S and/or D . Regardless, D does not rely again on this prioritized candidate set and will select a new relay and a new prioritized candidate set in the next cooperation attempt with S .

If D learned about the availability of relay candidates, it ends the feedback step by sending a cooperative-acknowledgment (CACK) (Fig. 20(b)).

If no prioritized candidate set exists, D uses the CACK to inform S and the available candidates to proceed with the next relay selection steps. The CACK packet reserves the channel until the end of the contention step.

If a prioritized candidate set exists, D chooses the best member as current relay and includes its decision (i.e., the slot number of the selected relay) in the CACK transmission. Node D determines the best member based on the received signal strength of the observed BUSYS during the feedback step. We call this kind of relay selection *fast relay selection* since its overhead in time is much smaller than a selection out of all available candidates. The CACK packet reserves the channel for the overall remaining cooperation process.

4.3.2 Estimation Step

The success of contention-based relay selection depends on the contention window size, the number of candidates, and

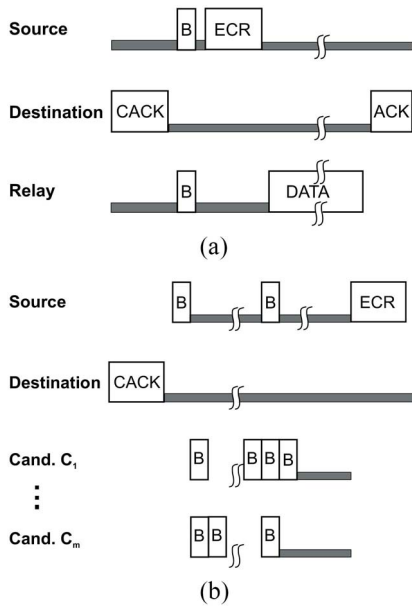


Fig. 5. Packet exchange/channel reservation during estimation. (a) Prioritized candidate selected as relay. (b) $\{S, D\}$ do candidate estimation.

their access probability. For a fixed contention window size, the access probability which maximizes the success probability of the relay selection depends on the number of competing candidates. This number varies over time due to node mobility and fading.

The purpose of the estimation step is to quickly estimate the number of available relaying candidates for $\{S, D\}$ such that the relay selection succeeds with high probability. The estimation step is important for dense networks where the number of candidates is considerably higher than the contention window size. If the number of candidates is small, however, the estimation step might not bear any benefits but increases the cooperation delay. To this end, CoRe-MAC can optionally skip the estimation. Finally, CoRe-MAC skips the estimation if a prioritized candidate set is available. Commonly, the estimation step ends by S transmitting an extend-channel-reservation (ECR).

Fig. 5 illustrates the packet exchange during the estimation step of CoRe-MAC. For the node behavior in this step see Fig. 21 in Appendix B, available online.

We distinguish between three realizations of the estimation step based on the outcome of the feedback step:

- 1) Node D utilized a prioritized candidate set and chose a relay R out of this set: S and R transmit simultaneously a BUSY after the CACK reception (see Fig. 5(a)). These transmissions prevent other nodes to access the channel for t_{EIFS} . A candidate estimation is not needed and skipped.
- 2) Node D needs to choose a new relay but is unaware of the number of candidates. We can use the Non-Adaptive Neighbor Estimator (NAE) from [19] to estimate the relay candidate cardinality. This estimator does not require data packet exchange, is simple, and is fast for relaxed accuracy demands. It is based on probabilistic trials, where the basic principle is to infer about the number of neighbors by counting the

number of empty slots in a contention window. To initiate an estimation process, the node broadcasts a Neighbor Query message. This message typically contains an access probability p_e and number of BUSY slots s_e as parameters. Each node receiving the Neighbor Query responds in each of the t_{SLOT} -length s_e slots with probability p_e . In such a contention strategy, the probability of having empty slots is:

$$P_0 = (1 - p_e)^n \quad (1)$$

where n is the number of participating nodes. To estimate n , it is sufficient to estimate P_0 and solve for n in (1). To do so, a query node counts the number of empty slots e in a frame with s_e slots. The relative frequency is $\hat{P}_0 = \frac{e}{s_e}$. Thus, an estimate for n is [19]:

$$\hat{n} = \frac{\ln\left(\frac{e}{s_e}\right)}{\ln(1 - p_e)}. \quad (2)$$

The NAE requires a certain operation range for n , such that the likelihood of having no empty slots or having all empty slots is negligible. The access probability is chosen such that (i) this requirement is satisfied; (ii) a desired estimation accuracy is achieved; and (iii) the number of slots is minimized. Algorithm details can be found in [19].

The actual estimation process is as follows (see Figs. 5(b), 21(a), and (c)). Node S transmits a BUSY right after the CACK transmission. This transmission serves two purposes. First, it reserves the channel in vicinity of S for t_{EIFS} . Second, it informs potential candidates that S is aware of the ongoing cooperation process. All candidates which do not receive the BUSY transmission of S exit the cooperation. Next, all remaining candidates transmit one BUSY simultaneously to indicate their presence. If S and D do not observe any channel activity during this period, they quit the communication attempt. Otherwise, the estimation process starts. Depending on the operation range, CoRe-MAC uses multiple contention frames of size s_{e_i} with $\sum_i s_{e_i} = s_e$. During each contention frame, each candidate transmits a BUSY in each slot with probability p_{e_i} . Node S counts the slots without channel activity e_i and estimates the number of candidates based on s_{e_i} , p_{e_i} , and e_i . During the estimation process, S has to transmit every $k_{occupy} = \lfloor t_{EIFS}/t_{slot} \rfloor$ slots a BUSY to keep other nodes in its vicinity from accessing the channel.

We point out that the actual upper bound of the estimation is a design parameter of CoRe-MAC. It can be chosen to be a fixed value at deployment time, or it can be adjusted dynamically based on observations like outcome of previous rounds of estimations or data traffic monitoring.

- 3) Optionally, it is possible to skip the estimation but use a fixed access probability during the contention window of the relay selection. The intention to skip the estimation needs to be signaled by the CACK of

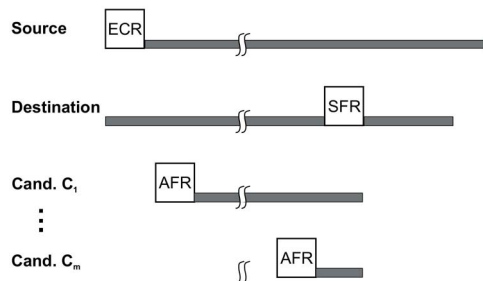


Fig. 6. Packet exchange/channel reservation during contention step.

D. Right after the CACK reception, S transmits an ECR packet to inform all candidates to transmit in the contention step with a given probability.

Besides signaling the end of the estimation step and broadcasting the number of candidates, the ECR reserves the channel in the vicinity of S for the remaining duration of the cooperation. This duration depends on the feedback step. If a prioritized candidate is selected as relay, the contention period is skipped, and the remaining cooperation consists of DATA from R and the following ACK from D . If a relay has to be selected, S reserves the channel for the contention step.

4.3.3 Contention Step

CoRe-MAC processes the contention step only if D has to select a new relay. Fig. 6 illustrates the packet exchange during the contention step. For the node behavior in this step see Fig. 22 in Appendix B, available online.

This step consists of s slots, where each slot can hold a complete apply-for-relay (AFR) with the same duration as CTS. Each candidate chooses randomly a slot and transmits during this slot with probability

$$p = \min\left(\frac{s}{\hat{n}}, 1\right), \quad (3)$$

where \hat{n} is the estimated candidate cardinality provided in the ECR packet (see Appendix A, available online). The probability p is chosen such that the probability that there is at least one noncolliding AFR is maximized; i.e., while AFRs may collide, the likelihood that at least one will go through is maximized. Node D observes the channel during the contention window, and logs its error-free AFR receptions together with the corresponding received SNR values (see Fig. 22(a)).

The selection phase fails if D does not receive any AFR during the contention step. Node D quits cooperation and S has to retransmit the DATA.

The selection phase is successful if D receives one or more AFRs. In this case, D sorts the received AFRs according to their received SNR values at the end of the contention window. Node D chooses the node from which it received the AFR with the highest SNR as relay for the current cooperation attempt. Node D selects all nodes from which it received AFRs as prioritized candidates for future communication attempts with S . The contention step ends with a select-for-relay (SFR) from D . This packet names the current relay and prioritized candidate set (i.e., sequence

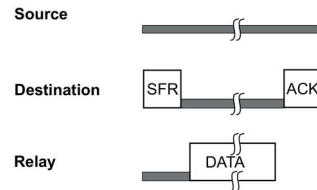


Fig. 7. Packet exchange/channel reservation in cooperative transmission.

of its error-free slots) for future attempts. Furthermore, it reserves the channel for the cooperative transmission step.

4.4 Cooperative Transmission Phase of CoRe-MAC

The cooperative transmission contains the DATA transmission from the selected relay and, if successful, the ACK from D (see Figs. 7, 23 in Appendix B, available online).

The cooperation is successful if D receives the DATA correctly from R . Only then, D uses the relay set for future transmission attempts. As a last step of a successful communication attempt, D informs S about the transmission success via an ACK. If the transmission from R is not successful or if R does not transmit at all, the cooperation fails and the communication attempt has to be repeated.

4.5 Protocol Summary

Fig. 8 summarizes the overall packet exchange of nodes using CoRe-MAC if cooperation is enabled and required. The phases are illustrated by individual background colors. Fig. 8(a) illustrates the packet exchange if no prioritized candidate set is yet available or not used. The dashed lines indicate feedback, estimation, and contention step in the relay selection phase. If D reverts to a prioritized candidate set, the duration of the relay selection phase decreases significantly (Fig. 8(b)). In this case, the feedback step duration increases slightly to allow prioritized candidates to report their availability to D , the estimation phase duration shrinks significantly, whereas the contention phase is skipped completely.

The additional overhead of CoRe-MAC are CCTS packets and the relay selection phase. CCTS is 2 bytes longer than CTS and is used only if D decides to need help from potential relays. It does not have significant impact on throughput. In the relay selection phase, to minimize overhead we use BUSYs in feedback and candidate estimation steps. First explicit packet exchange is in the contention step, which is eliminated if at least one relay in the prioritized candidate set is available. Further time overhead, e.g., extended channel reservation, can be compensated with fewer source retransmissions, depending on direct channel state. To evaluate the impact of these steps on system performance, Section 5 analyzes different versions of CoRe-MAC.

4.6 Backward Compatibility

While CoRe-MAC adheres to the medium access rules of CSMA/CA with RTS/CTS, the question of backward compatibility to existing systems employing CSMA/CA (in particular IEEE 802.11) arises due to introduction of new

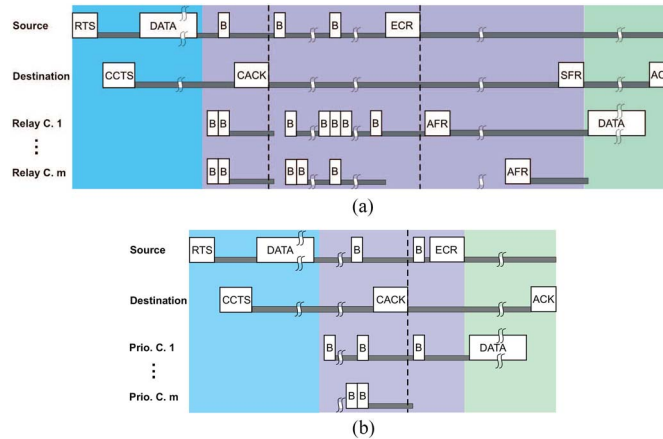


Fig. 8. Packet exchange/channel reservation of CoRe-MAC. (a) D selects a relay out of all potential candidates. (b) D uses a prioritized candidate set.

packet types. The header in the general 802.11 frame format contains the Frame Control Field [27], which in turn contains information required for the MAC to interpret all subsequent fields of the MAC header (including frame type and subtype). Not all bit combinations are used for the subtype field in the current standard. For CoRe-MAC nodes, subtypes for the new control packets in Table 1 need to be defined.

Considering a network with both CoRe-MAC and non-CoRe-MAC (i.e., CSMA/CA) nodes, CSMA/CA nodes are simply *not potential relays* for CoRe-MAC nodes, whereas for CSMA/CA nodes, CoRe-MAC nodes, like any other CSMA/CA node, listen to the channel and follow the defined packet exchange rules. When a non-CoRe-MAC S wants to communicate with a CoRe-MAC D , it would be very beneficial in terms of network resource usage that cooperation is not initiated by D if the channel is bad. To achieve that, D would need to know that S is a non-CoRe-MAC node. A simple, *but not the only*, way to do this in an 802.11 network is to utilize the `From DS` subfield of the Frame Control Field. This field is set to 0 for control packets. When a CoRe-MAC S sends an RTS, it can simply flip this bit to 1, whereas a non-CoRe-MAC S would leave it 0. With this bit flip, a CoRe-MAC D would know whether S is a cooperative node or not. When S is a CoRe-MAC node and D not, then D would respond to the received RTS with a standard CTS regardless of the channel condition.

If we consider an 802.11 network with basic CSMA/CA (no RTS/CTS handshake), non-CoRe-MAC nodes do not send an RTS. A CoRe-MAC destination would interpret the packet from the Frame Control Field. If a CoRe-MAC node sends an RTS to a basic CSMA/CA node, the corresponding node would respond by a CTS according to the standard [27]. The communication would then commence, without any problems with the protocol in both cases.

Finally, if cooperation is enabled by D (i.e., both S and D are CoRe-MAC nodes), `BUSY` tones will be transmitted in the relay selection phase. Since `BUSY`s are just indicators of channel activity, i.e., there is no packet exchange, non-CoRe-MAC nodes will interpret the channel as busy once they hear the `BUSY` and follow the medium access rules of 802.11, and CoRe-MAC nodes will participate in the relay selection if they meet the requirements.

With the above strategy, whenever S is a non-CoRe-MAC node (with or without RTS/CTS), cooperation would not be initiated by D , and the communication would commence in the same way as an all CSMA/CA network. To illustrate this, we include a simplified network that has a CSMA/CA S/D (with RTS/CTS) in our performance analysis.

5 PERFORMANCE EVALUATION

This section evaluates CoRe-MAC by comparing its performance with CSMA/CA via simulation. We use the wireless sensor network simulator JProWler [29] for its open source and fast simulation performance. We extend JProWler by our own implementations of CSMA/CA and CoRe-MAC and the Rayleigh fading model of [30]. This model generates fading coefficients which are correlated in time and thus enables us to investigate the impact of the coherence time on the performance of cooperative diversity.

We simulate the exchange of all signaling and DATA packets. We assume low-end radios with fixed symbol rate and a fixed energy per symbol value, i.e., it does not support power adjustment. The radio supports Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK). BPSK-modulated packets experience a lower bit error rate (BER) than QPSK-modulated packets due to the fixed energy per symbol assumption. Our protocol implementations use BPSK for signaling packets and QPSK for DATA packets. Hence, signaling packets to prepare communication and cooperation are less prone to transmission errors than DATA packets. For simplicity, we do not assume any channel coding.

Fig. 9 shows the basic simulation scenario. It consists of a dedicated pair of source and destination nodes, with potential relays distributed around them randomly with node density ρ per transmission coverage area. The distance d_{th} represents the maximum signal detection distance of a node in an Additive White Gaussian Noise (AWGN) channel model, i.e., the distance between S and D after which D experiences $SNR \leq \gamma_{th}$.

S has constantly DATA to send. Each simulation run simulates 10 s of communication. For each parameter set, we conduct 1 000 runs with different deployments of potential

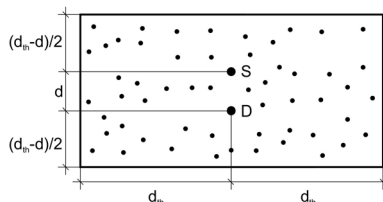


Fig. 9. Simulation scenario: a single communication pair.

relay nodes and adopt the average values. We also indicate the 90%-confidence interval of the obtained average values.

Table 2 summarizes the main simulation parameters used for evaluations unless mentioned otherwise.

Besides the default CoRe-MAC scheme as described above, we present results of CoRe-MAC versions with different options/limitations. Our motivation is to show the gains offered by some of the features of CoRe-MAC and to elaborate on their benefits in certain settings. Table 3 summarizes the protocols compared by simulations and their basic behavior. For reference, we also present the performance of basic CSMA/CA (without RTS/CTS), where relevant. The following performance criteria are used:

- *Retransmission rate of S* as the ratio of the number of DATA packets sent by S minus the number of DATA packets received at D to the number of sent DATA packets by S. The packets transmitted by the relay are included in the throughput computation.
- *Throughput* as the number of DATA packets received at D per second, where all time overhead due to additional packets are included.
- *Cost of cooperation* as the average number of candidates that has to listen to each DATA transmission of S. In a noncooperative scheme, neighbors of S and D could save energy by avoiding listening to their DATA packets, e.g., by switching their radio into sleep mode.
- *DATA dropping probability* as the ratio of the number of dropped to the total number of dropped and received DATA packets. Node S drops a DATA packet, if either its small retry counter src or its large retry counter lrc reaches its maximum value.

TABLE 2
Simulation Parameters

SNR at transmitter side	36 dB
average received SNR at D	15 dB
path loss exponent ν	2.2
SNR detection threshold	1.5
coherence time	200 ms ¹
symbol rate	128 000 symbols/s
modulation	BPSK/QPSK
DATA size	1500 bytes
t_{SIFS}, t_{SLOT} ²	16 μ s, 8 μ s
t_{DIFS}	$t_{SIFS} + 2 t_{SLOT}$
t_{EIFS}	$t_{SIFS} + t_{DIFS} + t_{ACK}$ ³
src_{max}	7
lrc_{max}	4
node density ρ	50 m ⁻²
Θ	0.001
s	6

¹ see [31] for indoor coherence time measurements

² t_{SLOT} is also the transmission duration of a BUSY

³ t_{ACK} is the transmission duration of an ACK packet

TABLE 3
MAC Protocols Considered in the Evaluation

basic CSMA/CA	standard noncooperative CSMA/CA protocol without RTS/CTS
CSMA/CA	standard noncooperative CSMA/CA protocol with RTS/CTS
CoRe-MAC	CoRe-MAC as described in the previous section
CoRe-MAC-NE	CoRe-MAC without candidate estimation step: all candidates transmit during the contention window an AFR packet.
CoRe-MAC-NPC	CoRe-MAC without candidate estimation step and prioritized candidate set: for each cooperative transmission, D selects a relay out of the complete candidate set.

- *Relay selection periodicity* as the average number of DATA transmissions from S between two candidate contention steps. A larger number represents fewer selections and thus less overhead of CoRe-MAC.
- *Probability that cooperation succeeds* as the likelihood that D receives successfully a DATA packet from its relay given that D has enabled cooperation and not received the corresponding DATA packet from S.

5.1 Impact of Protocol Parameters

Let us first focus on the parameters of CoRe-MAC. To this end, we fix the distance d such that the average received SNR from S at D is 15 dB. We choose the remaining simulation parameters as listed in Table 2.

5.1.1 Cooperation Threshold Θ

Fig. 10 shows various performance results as a function of the cooperation threshold Θ .

The value Θ represents the desired retransmission rate of S. If the expected PER of the direct link is higher than Θ , D

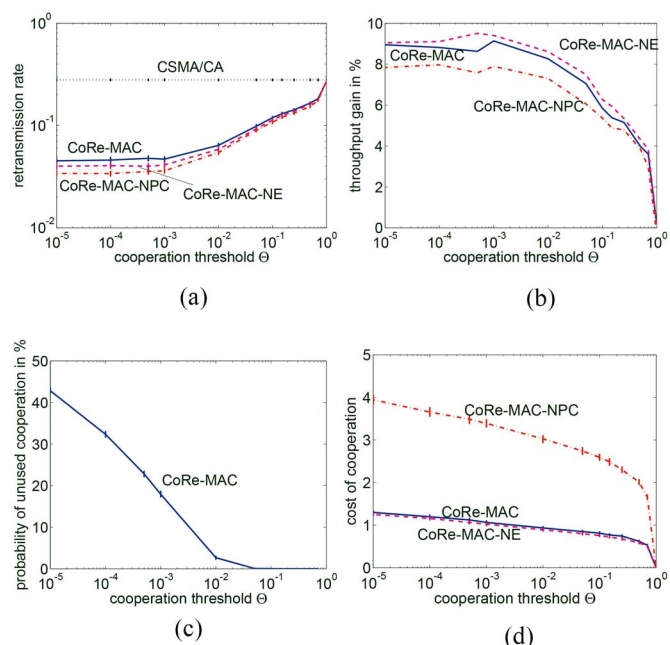


Fig. 10. Performance metrics as a function of Θ . a) Retransmission rate of S. b) Throughput gain compared to CSMA/CA. c) Cooperation enabled, not needed. d) Cost of cooperation.

enables cooperation with the intention to keep the retransmission rate below Θ . For $\Theta = 1$, CoRe-MAC never uses cooperation and hence becomes CSMA/CA. With decreasing Θ , D enables cooperation more often. For $\Theta \geq 0.001$, we observe a considerable impact of Θ on the retransmission rate (see Fig. 10(a)) and the throughput performance (see Fig. 10(b)). Smaller values of Θ improve neither the retransmission rate nor the throughput. For all CoRe-MAC versions, we observe a one-to-one relation between Θ and the retransmission rate for $\Theta \geq 0.1$. For $\Theta < 0.1$, relays cannot sustain the desired PER; the retransmission rate of S saturates for $\Theta \leq 10^{-3}$. The retransmission rate of CoRe-MAC and CoRe-MAC-NE is worse than that of CoRe-MAC-NPC. The reason is that CoRe-MAC-NPC chooses its relay always out of the entire set of candidates. A throughput comparison of the CoRe-MAC schemes reveals, however, that the schemes using the prioritized candidate set perform better. This performance difference is due to the faster selection with prioritized candidates.

Fig. 10(c) illustrates the probability that D has enabled cooperation but receives the DATA packet already during the direct transmission phase as a function of Θ . For $\Theta \geq 0.1$, D uses cooperation most of the time if it has enabled it. For smaller Θ -values, the probability of enabling cooperation without needing it increases considerably. In this region, cooperative relaying using proactive relay selection would lose some of its throughput gains, since the invested time of relay selection and channel reservation does not pay off and reduces the achievable throughput. The throughput gain of CoRe-MAC, however, does not worsen in this region.

Although a too small Θ -value has hardly any negative impact on the throughput of CoRe-MAC, we should nevertheless be careful in choosing it. The costs of enabling cooperation in a cooperative diversity scheme using reactive relay selection is mainly the additional number of candidates that have to listen to the DATA transmission of S . CoRe-MAC addresses this issue by using cooperation on demand, relay selection with early retreat, and a prioritized candidate set. Cooperation on demand is controlled by the Θ -value. For $\Theta = 1$, cooperation is never enabled and no candidate has to listen to the DATA transmission of S . For $\Theta = 0$, cooperation is always enabled. However, the number of candidates listening to the DATA transmission is kept low by using a prioritized relay set and relay selection with early retreat. Thus, while the cost of cooperation only gradually increases with decreasing Θ for CoRe-MAC using the prioritized candidate set, the number of candidates which have to listen to the DATA transmission of S increases much faster for CoRe-MAC-NPC (see Fig. 10(d)). For instance, for $\Theta = 10^{-5}$ and CoRe-MAC, one node besides D listens to each DATA transmission of S , while this number increases to 4 for CoRe-MAC-NPC. Note that all CoRe-MAC schemes here use cooperation on demand and relay selection with early retreat. Our observations regarding Θ motivate us to choose $\Theta = 0.001$ for further analysis.

5.1.2 Contention Window Size s

Let us now focus on the contention window size s of the relay selection phase. Fig. 11 indicates the influence of s on

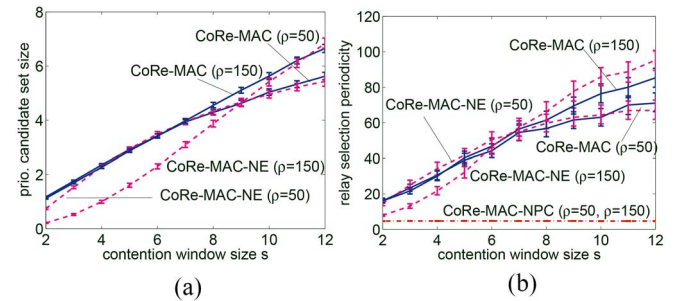


Fig. 11. Performance metrics as a function of s for $\rho = \{50, 150\} \text{ m}^{-2}$. (a) Expected number of received AFRs. (b) Relay selection periodicity.

the expected number of AFR receptions per candidate contention and the relay selection periodicity of CoRe-MAC for $\rho = \{50, 150\} \text{ m}^{-2}$. A large value of s increases the likelihood that D receives more AFR packets. Intuitively, this increases also the probability of selecting a better relay and having a large prioritized candidate set (note that the cardinality of the prioritized candidate set is also an indicator for the number of relay candidates that can help and could contend). However, large s increases the delay of the relay selection phase. Candidate estimation step of CoRe-MAC allows candidates to adjust their AFR transmission probability during the contention period such that the number of received AFR packets at D is maximized. In CoRe-MAC-NE, all candidates transmit an AFR in the contention step. For $\rho = 50 \text{ m}^{-2}$, there is a difference in the number of received AFR packets between CoRe-MAC and CoRe-MAC-NE for $s < 4$ (see Fig. 11(a)). In this scenario and $\rho = 50 \text{ m}^{-2}$, the average number of candidates is 9. The closer s gets to 9 the smaller the difference between CoRe-MAC and CoRe-MAC-NE becomes. For $s \geq 9$, both schemes end up using an access probability of 1 and achieve similar selection results. For $\rho = 150 \text{ m}^{-2}$, the average number of candidates increases to 30. While the expected number of received AFR packets of CoRe-MAC is similar for $\rho = 50 \text{ m}^{-2}$ and $\rho = 150 \text{ m}^{-2}$, it drops considerably for CoRe-MAC-NE and small s -values. CoRe-MAC-NE hardly ever succeeds in selecting a relay for high ρ and small s -values, since most of the AFR transmissions collide. This also holds for CoRe-MAC-NPC.

The relay selection periodicity of CoRe-MAC is independent of ρ and increases with s (see Fig. 11(b)). Simply put, the larger the prioritized candidate set is the rarer the events that no member of this set can support D occur. Intuitively, the relay selection periodicity of CoRe-MAC-NE heavily depends on ρ . While CoRe-MAC-NE achieves a similar periodicity as CoRe-MAC for $\rho = 50 \text{ m}^{-2}$ beyond $s = 2$, this number increases to 8 for $\rho = 150 \text{ m}^{-2}$. For $s \geq 9$ and $\rho = 150 \text{ m}^{-2}$, we observe that CoRe-MAC-NE achieves a higher relay selection periodicity than CoRe-MAC. This is due to the sloppy candidate estimation of CoRe-MAC which occasionally overestimates the number of potential relays and hence uses a too small transmission probability for the AFR. Since CoRe-MAC-NPC has to select a new relay for each cooperative transmission, its relay selection periodicity is the shortest and is independent of ρ and s .

Fig. 12 shows the throughput gain compared to CSMA/CA as a function of s . For $\rho = 50 \text{ m}^{-2}$ (see

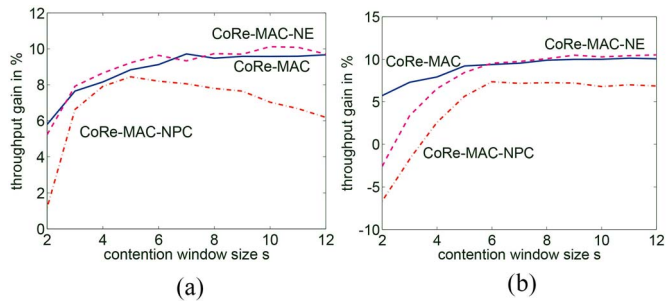


Fig. 12. Throughput gain compared to CSMA/CA as a function of s . (a) $\rho = 50 \text{ m}^{-2}$. (b) $\rho = 150 \text{ m}^{-2}$.

Fig. 12(a)), the candidate estimation pays off for $s < 3$ and results in a higher throughput gain than skipping the estimation step. For $s \geq 3$, the candidate estimation step imposes mainly an additional delay. The negative impact on throughput, however, is small due to the large relay selection periodicity. The throughput gain saturates for CoRe-MAC and CoRe-MAC-NE at 10.5% (for $s \geq 6$) in the depicted range. Intuitively, larger values of s decrease the throughput gain again, since CoRe-MAC spends more time in the relay selection process. We cannot observe this trend in the given range due to the large relay selection periodicity. For higher node density (see Fig. 12(b)), the candidate estimation becomes more important and its benefits outweigh its overhead. Regarding throughput CoRe-MAC-NPC performs always worse than versions using the prioritized candidate set due to the frequent relay selections.

We draw the following conclusions regarding the contention window size s . CoRe-MAC needs a minimum value of s such that the relay selection of D is successful. The cardinality of the prioritized candidate set depends on s and the node density. The benefit of a large prioritized candidate set is a larger relay selection periodicity. Knowledge of candidate cardinality bears definitely advantages. In situations where the number of candidates is similar to s , the candidate estimation step can be disabled to increase throughput. Alternatively, S could acquire its degree information (e.g., by monitoring the network activities), and use this information as an estimation of n . For dynamic networks and in the absence of topology information regarding the average number of available relay candidates, we recommend performing the estimation step.

In the following, we aim to provide D with at least two candidate applications for each selection step. Therefore, we choose $s = 6$ hereafter.

5.2 Impact of Network Properties

Let us now investigate the impact of different network parameters on the performance of CoRe-MAC.

5.2.1 Node Density ρ

First, we consider the impact of the node density ρ on various performance metrics of the CoRe-MAC schemes and CSMA/CA (see Fig. 13). The retransmission rate of S (see Fig. 13(a)) and the throughput (see Fig. 13(b)) of the CoRe-MAC schemes improve with increasing ρ for

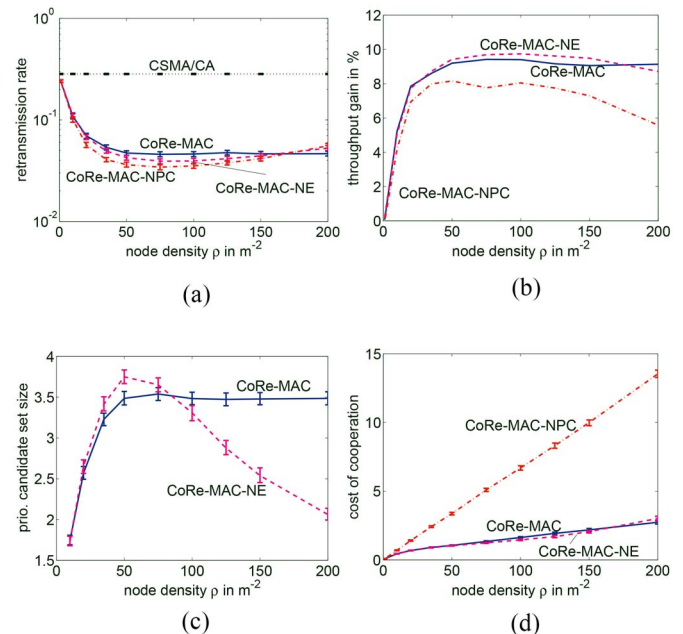


Fig. 13. Performance metrics as a function of ρ . (a) Retransmission rate of S . (b) Throughput gain compared to CSMA/CA. (c) Cardinality of prioritized relay set. (d) Cost of cooperation.

$\rho \leq 50 \text{ m}^{-2}$. For $\rho > 50 \text{ m}^{-2}$, there exists a relay for each cooperation attempt of $\{S, D\}$. The retransmission rate and the throughput of CoRe-MAC saturates. The throughput gain of CoRe-MAC-NPC declines with further increasing ρ due to the increasing probability of failing relay selections. Although CoRe-MAC-NE experiences similar relay selection success as CoRe-MAC-NPC, its throughput does not decline as fast. CoRe-MAC-NE benefits from the fact that once selected a relay is re-used via the prioritized candidate set.

Fig. 13(c) illustrates the cardinality of the prioritized candidate set of CoRe-MAC and CoRe-MAC-NE. For $\rho \leq 30 \text{ m}^{-2}$, this value is similar for both schemes. For $30 \leq \rho \leq 70$, CoRe-MAC-NE can resort to a larger set size than CoRe-MAC. The sloppy node estimation of CoRe-MAC results occasionally in a too small transmission probability of AFRs. For $\rho > 80 \text{ m}^{-2}$, however, the number of colliding AFRs increases for CoRe-MAC-NE which in turn reduces the set size of prioritized candidates. We observe benefits of the prioritized candidate set in Fig. 13(d), which shows the cost of cooperation. This value increases only gradually for CoRe-MAC and CoRe-MAC-NE using a prioritized set while it increases linearly with ρ for CoRe-MAC-NPC.

The examined node densities correspond to a total of 4-368 nodes uniformly distributed in the area shown in Fig. 9. These values cover a wide range of network sizes. With the introduction of large-scale wireless sensor networks, Internet of Things, and cyber-physical systems, we believe large node densities will be of more interest for networks of the future and are worth analyzing.

5.2.2 DATA Packet Size

Fig. 14 summarizes the impact of the DATA packet size on the retransmission rate and throughput performance of CoRe-MAC with and without prioritized candidate set.

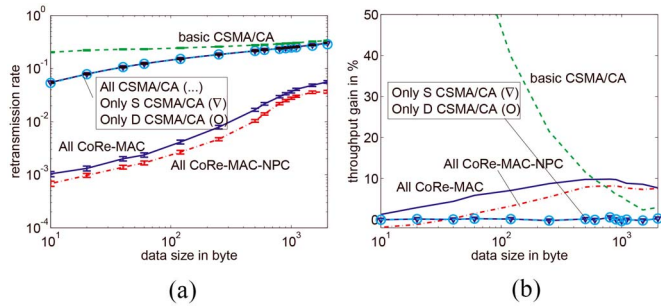


Fig. 14. Performance metrics as a function of the DATA size. (a) Retransmission rate of S. (b) Throughput gain compared to CSMA/CA.

To illustrate, the protocol behavior in case of a heterogeneous network, we also analyze the cases, where only S is a CSMA/CA node and where only D is a CSMA/CA node, both of which perform the same as an all CSMA/CA network, as expected.

The retransmission rate increases for larger DATA packet size (no channel coding is used). CoRe-MAC reduces the retransmission rate compared to both basic CSMA/CA and CSMA/CA (with RTS/CTS) considerably. The difference, however, becomes smaller for increasing packet sizes. Again, the CoRe-MAC version which selects a relay out of the entire candidate set performs better than the one which restricts the relay selection to a prioritized set.

Fig. 14(b) shows the throughput gains of CoRe-MAC and basic CSMA/CA to CSMA/CA as a function of the DATA packet size. As expected, basic CSMA/CA has significant gains over CSMA/CA and CoRe-MAC for smaller data sizes due to the overhead of RTS/CTS mechanism. In our analysis, we count the total additional overhead of CoRe-MAC required to setup and use cooperation. Intuitively, for small packets this overhead cannot be neglected. With increasing sizes, this overhead gets less significant which explains why the throughput gain first increases with increasing packet size although the retransmission rate shows the opposite behavior. However, even for DATA packets of the size of an RTS packet, CoRe-MAC achieves a higher throughput than CSMA/CA (with RTS/CTS). For the chosen parameter settings, we observe the highest gains for DATA packets of size 600 bytes. For larger packet sizes, the cooperation gain can no longer compensate the increasing PER of the DATA packets. For large packet sizes, the throughput difference between the CoRe-MAC versions vanishes. The higher delay of the longer relay selection of CoRe-MAC-NPC becomes less significant because of the DATA size and because its lower retransmission rate gets more important. For larger data sizes, basic CSMA/CA also cannot cope with high PERs.

5.2.3 Coherence Time

Wireless link quality fluctuates significantly due to the dynamic nature of the network (mobility, multi-path fading, etc.). Therefore, it is beneficial to explore how the channel characteristics affect cooperation. To capture the effect of channel status as well as node mobility in a small

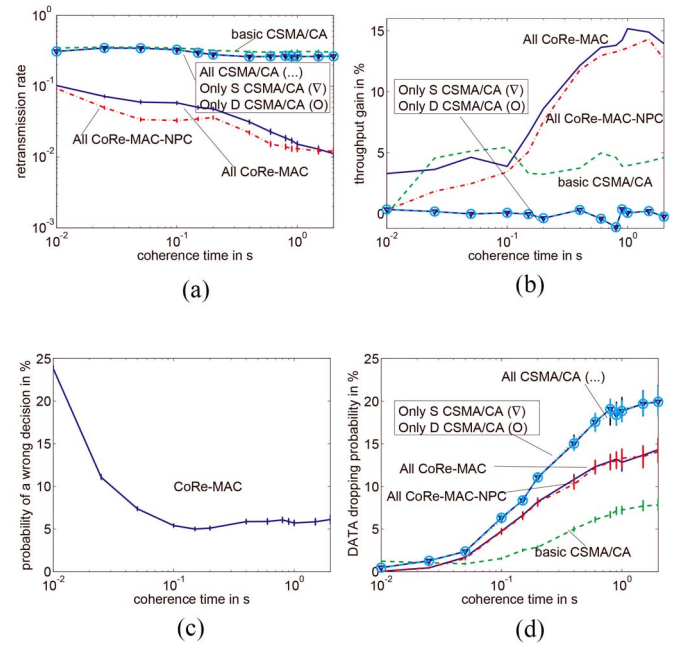


Fig. 15. Performance metrics as a function of the channel coherence time. (a) Retransmission rate of S. (b) Throughput gain compared to CSMA/CA. (c) Probability of a wrong decision. (d) DATA dropping probability.

time-scale (without specifying any mobility models), let us analyze the performance of CoRe-MAC with respect to the channel coherence time. Fig. 15(a) indicates the retransmission rate of CoRe-MAC, CoRe-MAC-NPC, and CSMA/CAs as a function of the coherence time. While the retransmission rates of both CSMA/CAs are mainly independent of the coherence time, the retransmission rate of the CoRe-MAC schemes improve with increasing coherence time. Node D decides about enabling cooperation based on the channel state at RTS reception. This channel state, however, hardly ever represents the situation experienced during DATA transmission in case of short channel coherence times. For short coherence times, it is likely that D disables/enables cooperation but requires/does not require it afterwards, i.e., makes a wrong decision (see Fig. 15(c)). For short coherence times, the retransmission rate of CoRe-MAC-NPC is better than the one of CoRe-MAC since it chooses for each cooperative transmission a new relay from all available candidates. With increasing coherence time, this advantage to CoRe-MAC shrinks. The prioritized candidates' channel states to S and D stay longer in a good state. Beyond a coherence time of 1 s, the retransmission rate of CoRe-MAC is better than the one of CoRe-MAC-NPC. Selecting a relay out of the prioritized candidate set is in general more robust against signal packet failures. That is why CoRe-MAC-NPC's retransmission rate is worse due to occasionally occurring selection failures.

Looking at the throughput in Fig. 15(b), we see that CoRe-MAC provides gains compared to CSMA/CA even for fast changing channels. The reason is that CoRe-MAC uses a reactive relay selection approach, and hence does not invest time to prepare cooperation in situations it is not needed.

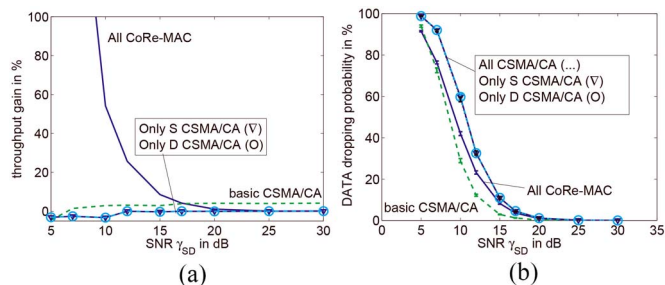


Fig. 16. Performance metrics as a function of average received SNR γ_{SD} at D . (a) Throughput gain compared to CSMA/CA (b) DATA dropping probability.

Fig. 15(d) illustrates the probability of dropping a packet as a function of the channel coherence time. For fast varying channels, the probability of dropping a packet is for all considered schemes nearly 0 (higher for basic CSMA/CA). For increasing coherence time, the time the channel stays in a particular state — either good or bad — increases. Time diversity cannot mitigate bad channel states and the number of lost DATA packets increases. CoRe-MAC performs better than CSMA/CA (with RTS/CTS) but worse than basic CSMA/CA (since for CoRe-MAC data packets can be dropped due to dropped signaling packets as well). If the channel is in a deep fade which does not allow any signaling between S and D , CoRe-MAC fails. The heterogeneous communication pairs behave as the all-CSMA/CA network.

5.2.4 Distance between S and D

Next, we investigate the performance of CoRe-MAC for different distances d between S and D . We use the average received SNR γ_{SD} as distance measure in Fig. 16. At small distances between S and D (i.e., high SNR regions), cooperation is hardly ever needed and hence is disabled by D . This results in similar throughputs of CoRe-MAC and CSMA/CA (with RTS/CTS) above 25 dB (see Fig. 16(a)). With increasing distance, i.e., decreasing average received SNR, the throughput gain of CoRe-MAC increases. At low SNR values, the gain of CoRe-MAC is considerable. This region, however, is not suitable for any communication since most of the DATA packets are dropped (see Fig. 16(b)). We observe the benefit of CoRe-MAC with respect to basic CSMA/CA as well in throughput for low SNR regions. In high SNR regions, due to the RTS/CTS overhead basic CSMA/CA performs slightly better. The heterogeneous communication pairs behave as the all-CSMA/CA network.

5.2.5 Spatial Re-Usability

Let us now focus on the spatial re-usability of the communication medium in CoRe-MAC. Simulation results indicate a gain in throughput and a reduction of the retransmission rate of CoRe-MAC compared to CSMA/CA for a single communication pair $\{S, D\}$. In CoRe-MAC using cooperation and in cooperative relaying in general, at least one additional node besides S and D is invoked in their communication process. Moreover, during the cooperation setup, i.e., relay selection and additional channel reservation, even more nodes transmit signaling packets. It is not intuitive

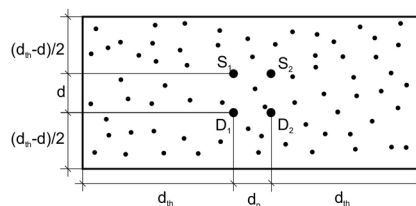


Fig. 17. Simulation scenario: two communication pairs.

whether cooperation, even though it increases the throughput of a single link, is able to improve the overall network throughput compared to noncooperative schemes. Note that we analyze the performance of a MAC-layer relay on a link-by-link basis (i.e., not end-to-end multi-hop links). Since only one communication pair can exist (depending on the interference level) in the transmission range of S and D , adding more and more communication pairs in the $S - D$ transmission area may not provide any extra information. A relevant and important issue in this case is how a selected relay would affect transmissions outside the transmission range of the $S - D$ pair. Therefore, we use the simplified scenario illustrated in Fig. 17 to elaborate on the network performance of CoRe-MAC.

This scenario features two dedicated pairs of source and destination nodes with potential relays being distributed around them uniformly randomly with a node density ρ . The distance between source and destination node is for both pairs d and the distance between the two communication pairs is d_p . Nodes S_1 and S_2 have DATA constantly to send to D_1 and D_2 , respectively. Each simulation run covers 10s of network traffic. For each parameter setting, we simulate 1000 runs with different potential relay nodes deployments and adopt the average values. We fix d to a value which corresponds to an average received SNR $\gamma_d = 15$ dB and vary the distance between the two communication pairs d_p .

Fig. 18(a) shows the overall throughput, i.e., the average number of received DATA packets per second at D_1 and D_2 , of both CSMA/CAs and CoRe-MAC as a function of the average received SNR $\gamma_{S_1S_2}$ at S_2 transmitted from S_1 . At first, we see that CoRe-MAC delivers more DATA packets than both CSMA/CAs. For large distances between the communication pairs, i.e., for small $\gamma_{S_1S_2}$ -values, both communication pairs transmit simultaneously without interfering with each other. This is true for both CSMA/CAs and CoRe-MAC. For small distances between the communication pairs, the throughput of all schemes drop to values which are more than a half of their peak values. If the channel of one communication pair is in a bad state which does not allow any communication, the other one can utilize the channel more often and vice versa. The two communication pairs start interfering with each other around $\gamma_{S_1S_2} = 1.5$ dB. There, the impact on CoRe-MAC is higher than on CSMA/CA due to following reasons. First, the reactive relay selection of CoRe-MAC inherently prioritizes direct transmissions — candidates do not reserve resources until they are selected as relay. This results in a considerable reduction of available relay candidates in the

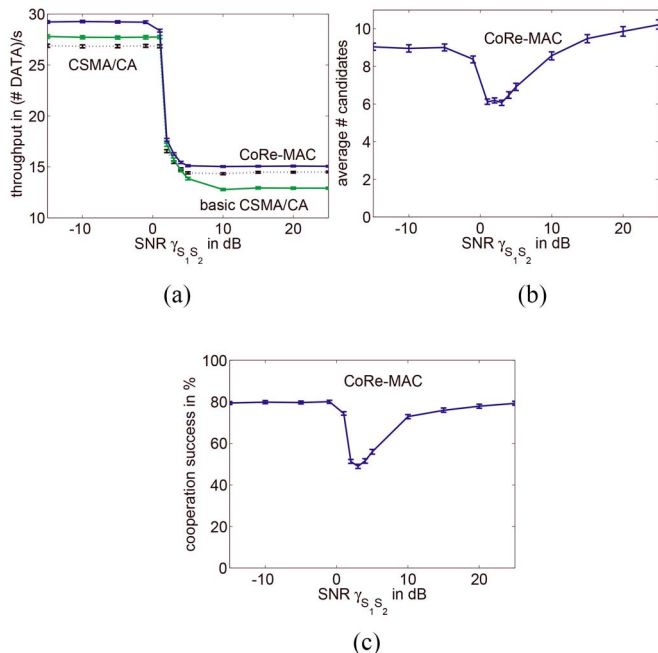


Fig. 18. Performance metrics as a function of $\gamma_{S_1 S_2}$. (a) Throughput. (b) Average number of candidates. (c) Probability of cooperation success.

region where both communication pairs are only in interference range of each other (see Fig. 18(b)). Second, the mutual interference of the communication pairs reduces the cooperation success probability (see Fig. 18(c)).

Regarding the average number of candidates, we observe that this number is higher for high $\gamma_{S_1 S_2}$ -values than for low ones. For instance, at $\gamma_{S_1 S_2} = -10$ dB each communication pair can choose on average among 9 candidates its relay where as it can choose among 10 nodes at $\gamma_{S_1 S_2} = 25$ dB. This is due to the fact that the communication pairs are potential relay candidates of each other for high $\gamma_{S_1 S_2}$ -values.

We can draw the following conclusions from this simulation. CoRe-MAC increases the throughput of single links in a network compared to CSMA/CA. If these links are not causing interference to each other, i.e., if the links are either far apart from each other or quite close such that they are aware of each other, CoRe-MAC increases the throughput. Interference among communication pairs reduces the performance of CoRe-MAC. CoRe-MAC, however, does not negatively affect the overall network throughput. Further improvements can be done on the spatial re-usability by employing spatial-aware relay selection mechanisms [32] or enhancements on IEEE 802.11 DCF [33].

6 CONCLUSION

We introduced and discussed a new cooperative MAC protocol, called CoRe-MAC, which builds on CSMA/CA and extends the mechanisms for handling transmission failures by space/time diverse channels. We paid special attention to the feasibility of the protocol for low budget off-the-shelf hardware and its backward compatibility to CSMA/CA with RTS/CTS as defined in IEEE 802.11, allowing easier integration of CoRe-MAC in existing networks. Moreover, we focused on keeping the overhead of

CoRe-MAC compared to CSMA/CA at a minimum for good channel conditions and keeping the cooperation cost low via relay selection on demand with early retreat and a prioritized candidate set. Performance studies showed that CoRe-MAC performs similar to CSMA/CA in good channel conditions but offers gains in retransmission rate and throughput for transmissions over unreliable links. The performance of CoRe-MAC depends on the node density, channel coherence time, and data packet size. Simulations revealed that CoRe-MAC does not only increase throughput of a single link but also can increase network-wide throughput. This work is a first step toward cooperation in large networks. With simple but representative scenarios, we aimed at clearly specifying and evaluating a cooperative MAC protocol.

ACKNOWLEDGMENTS

This work was partly funded by the KWF, ERDF, and Government of Austria under Lakeside Labs grant 20214/15935/23108.

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