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COOPERATION TECHNIQUES FOR WIRELESS SYSTEMS FROM A NETWORKING PERSPECTIVE

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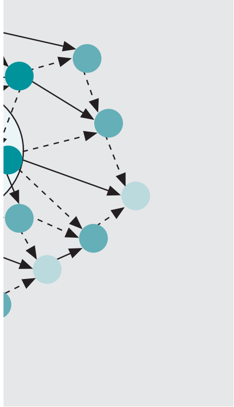

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ABSTRACT

The impact of fading and other impairments in wireless channels can be counteracted by leveraging communication diversity and introducing cooperative paradigms, where third-party nodes contribute to assist the communication. In this article we describe and evaluate two possible cooperative approaches, cooperative relaying and coded cooperation. Different from existing works where similar evaluations are mainly performed investigating a single link, we take a network-wide perspective to evaluate the effects of cooperation not only where it is performed but also on other links. We focus on a multiple-input multiple-output ad hoc scenario and show that the improvement brought by cooperative routing and coded cooperation is not always sufficient; in certain cases the former can be ineffective if no proper relay can be selected, and the latter leads to an overall increase of interference, thus worsening the quality of surrounding links. However, we suggest that these two features can be combined in an advantageous manner in order to mutually overcome their problems. Such a joint solution is shown to achieve a significant improvement over the two individual approaches. We conclude by discussing future evolutions of the cooperation paradigm, including both cooperative routing and coded cooperation, and their advanced implementation issues.

INTRODUCTION

The pervasive diffusion of mobile network devices has significantly increased the need for reliable and high-performance wireless communications. Two main aspects characterize the physical layer of wireless networks. On one hand, the use of wireless terminals is desirable for mobility and ease of deployment. On the other hand, the radio channel is known to be strongly influenced by multipath fading and interference problems.

To improve this situation and achieve reliability at the upper layers when relying on a wireless physical layer, many researchers have proposed the adoption of cooperative paradigms [1–3]. This means that one or more intermediate nodes intervene in the communication between a transmitter and a receiver so that either the communication is rerouted over a better path, or the original link is kept in use but its quality is strengthened thanks to diversity provided by these cooperators.

The former approach is known as *cooperative* (or opportunistic) *routing* [1, 4]. In the simplest version, one intermediate node simply acts as a relay between the transmitter and the receiver. However, if the communication between transmitter and receiver is part of a multihop transmission, it may be rerouted over an entirely new path that no longer involves this receiver. To this end, a distance metric is needed to verify that the selection of a given intermediate node as the next hop still sends the message toward the end-to-end destination and not further away from it. Additionally, a negotiation phase is also required where intermediate nodes can volunteer as next hops whenever the link from the transmitter to the intended receiver does not guarantee sufficiently high quality.

The latter technique instead utilizes cooperative diversity based on coded transmissions. For this reason, we refer to it as *coded cooperation* [3, 5]. The rationale of this approach is that the original communication link is still kept, but intermediate nodes try to overhear the transmission and reinforce its quality during a retransmission phase. This means that if the message is not correctly received and thus a retransmission is dictated, not only does the original transmitter resend it, which would correspond to a plain automatic repeat request (ARQ) approach, but also intermediate nodes that were able to overhear the packet do so. Moreover, they properly encode the information so that the multiple transmissions can be combined at the receiver's side to improve the link quality. Therefore, cooperative intermediate nodes bring two separate benefits: they allow alternative links with different quality to be exploited (i.e., space diversity) and also introduce coding gain, the same advantage that hybrid ARQ (HARQ) has over traditional ARQ techniques [5, 6].

Inspired by theoretical findings showing the

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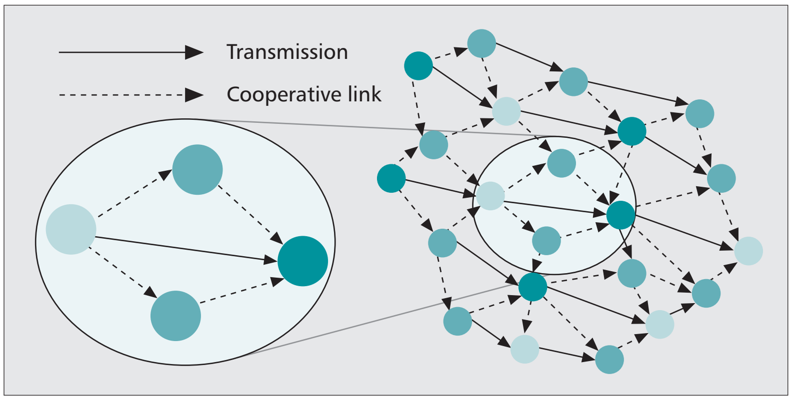

Figure 1. *Cooperation from the network perspective.*

benefits of cooperation in wireless networks [2], both these approaches have recently attracted a great deal of attention in the research community. However, we believe that many studies tend to evaluate them in local scenarios with small topologies and simplified assumptions about medium access control (MAC) or networking issues. In this article we aim to provide a description of these techniques from a network-wide perspective in order to determine whether the advantages brought by cooperation can be exploited in wireless networks, which new problems or challenges they introduce, and how they can be addressed and solved. To gain some visual insight of the new dimension we add to the problem, consider Fig. 1. Standard cooperative approaches focus on scenarios like the left part of this figure, where a single-hop transmission is locally aided by some casual cooperators, whereas we consider a scenario where all nodes apply cooperative paradigms, as shown in the right-hand part. This implies that the effects of cooperative actions are not only local; for example, cooperative relays assisting a communication can in turn find new cooperators to carry the packet on toward the final destination.

The originality of our investigation is twofold. We focus at first on implementation details at the medium access and network layers, describing possible strategies to practically achieve cooperation (including opportunistic routing, coded cooperation, or both). Moreover, we evaluate the performance of different cooperative approaches from the network viewpoint. For example, node density has an impact on which of the two aforementioned solutions is preferable. Coded cooperation may suffer in crowded networks, as multiple transmissions locally improve link quality but cause an interference increase for neighboring connections. Conversely, opportunistic routing may not be effective in sparse networks, as it might be difficult to find how to reroute a packet.

This leads us to the idea of combining these approaches, to exploit the cooperation paradigm in a comprehensive manner. Actually, we show that even a simple joint approach which tries to use opportunistic routing first, and employs coded cooperation when the former is not viable, achieves a great improvement over each of the two individual approaches. Such a result opens up the possibility of defining advanced techniques, which merge together cooperative routing and coded cooperation, so as to take full advantage of the cooperation paradigm.

Finally, we observe that the study of these issues can lead to further considerations, which appear as interesting directions for future research. In many related papers cooperation is assuredly granted, as it was assumed to come from the goodwill of wireless users. Indeed, one may doubt if cooperation among wireless terminals is likely to occur unless it is properly encouraged and rewarded. This is supported by many studies that apply, for example, game theory to wireless networks [7]. From a selfish standpoint, cooperative nodes have nothing to gain and everything to lose; the benefits of cooperation are evident only at a global level, not locally. Surely, evidence of the increased welfare in a cooperative network can be convincing for some of the wireless users, and mechanisms to promote cooperation among them can be used. However, in order to analyze these behaviors it is in our opinion mandatory to include medium access and networking details, as done in the present article, to determine where and how cooperation can be introduced.

SYSTEM DESCRIPTION

Before proceeding with the description of cooperative techniques, we give an overview of the system considered in this article. We focus on an ad hoc network with multiple-input multiple-output (MIMO) terminals. Besides this being a viable possibility per se, considering a MIMO system simplifies the introduction of cooperative features within the MAC protocol, which is decoupled from issues related to simultaneous link activations and/or collision resolution. As a side note, one could also infer that MIMO terminals can be a good choice for cooperative networks, at least if this possibility is not prevented by size and complexity limitations.

However, this choice is not restrictive or mandatory, as the approaches and the conclusions drawn in the following also apply to some extent to other kinds of networks, in particular to different types of multiple access, provided that some mechanism for handling interference from multiple users is available. For example, one can take a simplified approach, where interference is modeled through collisions, and still enable cooperation as shown in [8], where a network using a MAC on carrier sense multiple access with collision avoidance (CSMA/CA) is investigated.

The numerical evaluations will focus on the MIMO-BLAST receiver presented in [9], which is particularly suitable for our scenario, as it can successfully decode a number of incoming signals even larger than the number of receiving antennas, provided that signal decoding through successive interference cancellation is able to overcome the residual interfering power.

Hereafter, we use the following notation to represent nodes involved in the cooperation process. Cooperation techniques are actuated on a generic single-hop transmission from A to B; these nodes will be called *transmitter* and *receiver*, respectively. However, since we take a network-wide perspective, these nodes are not, in general, the end source and destination of the multihop route, but only the tail and head of an intermediate hop. We denote the end-to-end source and destination with S and D, respectively. A generic intermediate node between A and B, which can act as a *cooperator*, will be referred to as C. When multiple potential cooperators are present, they are called C_1, C_2, and so on. We will sometimes need to indicate how *far* from each other two generic nodes X and Y are. Thus, we assume the existence of a given distance metric $\ell(X,Y)$, satisfying obvious relationships of being non-negative, zero if and only if $X = Y$, and subject to triangular inequality. This metric is used by all nodes to create a routing table to any other node in the network; thus, we require that B is the next hop on the shortest path route from A to D according to the routing table induced by the distance ℓ. More generally, every node knows its own distance to the final destination D; this will be used, for example, to determine whether or not a cooperator is closer to D than the transmitter. The definition of a proper distance metric ℓ is one of the most studied topics at the network layer, and many suitable definitions have been identified. A trivial choice for $\ell(X,Y)$ is the hop count between X and Y; alternatively, specific metrics proposed in the literature for wireless multihop networks can be employed [10].

Finally, we outline the MAC protocol employed in the rest of the article. It is a simplified version of the mechanism described in [4] and can be integrated with additional signaling to solve collisions, negotiate cooperative behavior, and so on (all of these elements are orthogonal and can be superimposed on the proposed framework without any modification). The idea of this specific MAC protocol follows the same motivations for introducing cooperation in the network: to overcome problems related to wireless links with time-varying (bad) quality. A possible approach is to check the link status in advance before transmitting over it. This would allow, whenever possible, avoiding routing packets over bad quality paths and at the same time keeping the number of retransmissions limited. With a similar philosophy, we also remark that another cause of problems over radio links is the inability of a transceiver, due to the half-duplex nature of the wireless medium, to receive messages while transmitting. Thus, it could also be useful if, prior to forwarding a packet, the transmitter checked the next hop's availability to receive. We assume that this can happen through a proper handshake phase, where a request-to-send (RTS) packet is transmitted by A, followed by a clear-to-send (CTS) reply from B if the transmission can safely take place. In spite of these names, which are similar to those of the packets exchanged in a CSMA/CA approach, the goal of this handshake is not to silence transmissions from neighboring nodes, as MIMO systems can handle the presence of simultaneous transmissions. Instead, there are two advantageous features in the proposed exchange. First, upon reception of a CTS, the transmitter knows that the receiver is available and not busy transmitting to another destination. This aspect is often neglected in local single-hop scenarios, but becomes important when larger network topologies are considered. Second, the RTS can be used to estimate the received signal strength; similarly, the CTS piggybacks feedback information about the link quality, such as physical gain estimates [11]. This makes it possible to evaluate the power required to achieve a target error probability over the link, or even to detect that bad link quality is completely preventing a successful transmission. In the following we summarize this channel state information through a signal-to-noise-plus-interference ratio (SNIR) value between the nodes involved.

We can also assume, as is usually done, that RTS and CTS packets are significantly shorter than data packets, and can be protected by strong error-correcting codes. Thus, a CTS reporting a bad channel condition is still audible at the other side, even though a data packet would not be, unless the same strong code is used (which may be feasible for a short control packet, but not for a data packet).

To sum up, we stress that, regardless of specific implementation details, there are two fundamental issues that need to be addressed by a cooperative MAC [12]. First of all, receiver B needs to be informed of A's intent to transmit. Moreover, B needs to report some feedback to A that allows the transmitter (and also neighboring potential cooperators) to evaluate whether cooperation is required. These two elements are necessary and sufficient to implement our two investigated cooperation approaches, as shown in the next sections. Finally, we require that if the CTS indicates bad link quality, node A defers the transmission and waits for cooperation from neighboring nodes. The specific way in which these nodes cooperate depends on the scheme used, and is described in more detail in the following.

COOPERATIVE ROUTING

A first form of cooperation over multihop paths can be applied at the routing level [1, 4]. This occurs when the CTS from node B reports a bad channel condition, indicated by a SNIR value between A and B, denoted $SNIR(AB)$, lower than the threshold $SNIR_{th}$ that guarantees the target error probability. Whenever $SNIR(AB) < SNIR_{th}$, node A does not transmit any packet to B, but waits for an additional time slot during which intermediate nodes that are idle, and therefore listen to the handshake, may volunteer to become cooperative relays.

Figure 2 graphically represents a network where the elements of cooperative routing (direct links and opportunistic hops) have been highlighted. To participate as a cooperative relay, node C must be able to listen to both the RTS and CTS. From the RTS it can estimate the SNIR between itself and the source, $SNIR(AC)$, and also derive the distance $\ell(A,D)$ of node A from the final destination D, since the RTS contains the identifier of these nodes. From the CTS, which piggybacks the $SNIR(AB)$ value, it may learn whether the quality of the source-destination direct link is poor. If this is the case, node C checks the following two conditions to

The idea of this specific MAC protocol follows the same motivations for introducing cooperation in the network, i.e., to overcome problems related to wireless links with time-varying (bad) quality.

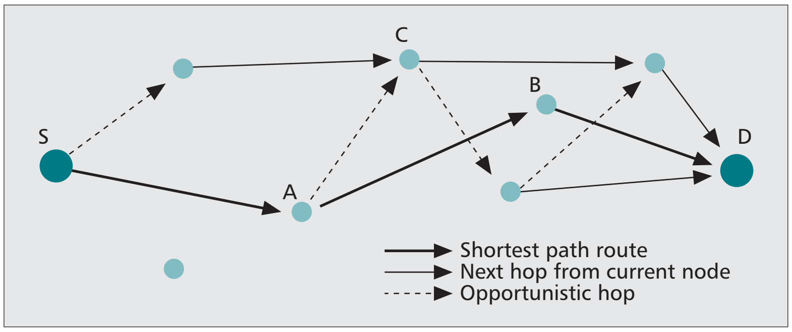

Figure 2. *Cooperative routing.*

determine whether or not to contribute:

1 The value of $SNIR(AC)$ must be above $SNIR_{th}$.
2 C should represent an advancement toward the final destination D.

Note that C is not required to know the whole route exactly, just its own distance to the destination.

Condition 1 means that the channel between A and C is good enough, and it is also better than the one between A and B, which is below threshold. Condition 2 expresses that, even though the route is changed, the packet is still advancing toward D. In the following ℓ is chosen as the hop count, and condition 2 is to be read in the sense that $\ell(C,D)$ must be less than $\ell(A,D)$; that is, C has to be chosen among the neighbors of A for which $\ell(C,D) = \ell(A,D) - 1$.

The assumption that ℓ must be decreased at every step has been chosen only for the sake of simplicity. Actually, it is possible to consider extensions where even nodes with the same distance can be accepted, provided that some form of hysteresis is introduced to avoid the packet continually moving within the same set of nodes without advancing toward D. An overview of these issues, as well as a possible solution, can be found in [13]. In the same way, it is even possible to consider cooperative paths where the distance ℓ is actually increased, provided that some advantage is envisioned (e.g., a better overall quality of the route toward the final destination D). This may be especially useful in the last hop transmission (i.e., where B and D coincide), so that cooperative relaying can only make the path longer; however, this may be useful if the direct connection has bad quality, as discussed in [14].

Several intermediate nodes C_1, C_2, … can be a cooperative next hop from A if they satisfy the aforementioned conditions. Such nodes declare their availability to take charge of the forwarding of the packet by sending a cooperative CTS (cCTS) message, which can be received by both A and B. The transmission of such a message requires an additional time slot to be left unused after the CTS. In the cCTS, node C_j indicates the value of $SNIR(AC_j)$. If exactly one cCTS is received from a single cooperator C, A begins the first transmission phase toward C, whereas node B goes idle. If multiple cCTSs are received, the transmitter selects as the next relay the node with lowest distance ℓ to the final destination D (ties possible when using, e.g., hop count are broken through random choices). Actually, alternative criteria for the position-based part can be used, as detailed in [15]. If two or more nodes satisfy this condition, the one with the best channel is chosen. When the first transmission phase starts, node A clarifies its choice by indicating the new receiver on the data blocks. Once C has received the packet, it then forwards it toward the final destination, according to its own routing table.

The cooperative routing approach implies additional overhead due to the cCTS packets. Not only do they require a modification of the access scheme as the transmitter must wait for them after a CTS reporting a bad SNIR, but also the transmission of such control packets may cause interference peaks for other surrounding nodes, as many potential cooperators might send a cCTS simultaneously. However, we expect this problem not to occur very frequently for the following reason. On one hand, the transmission of cCTS happens only when the direct link from A to B fails. As this link is chosen as belonging to the best path to D, its quality is frequently bad only if the network is very sparse; otherwise, there would have been a better choice than B as the next hop. On the other hand, the phenomenon of simultaneous transmission of cCTS messages from multiple potential cooperators causes high interference levels only if the network is dense. Thus, the impact of this phenomenon on the overall performance should be limited. Nevertheless, since we are interested in evaluating the performance in a network-wide manner, we take it into account.

CODED COOPERATION

Another possible approach to deal with bad link quality tries instead to directly improve the reliability of transmission. This may be beneficial when the link quality changes often, as the previously explained cooperative routing would make path adjustments too frequently. Taking advantage of the MIMO feature, it is possible to improve the diversity order by adding cooperative transmissions that do not replace the link from A to B, but rather strengthen it in a coded fashion. In the literature such an approach is named coded cooperation [3, 5]. Even though it is not novel itself, we frame it in an original context as we consider its impact on the whole network performance.

The main difference between cooperative routing and coded cooperation is that in the latter case third-party nodes help the transmitter without modifying the original route, and participate in the transmission after it has started. As an aside, this is also useful to improve the communication should the quality significantly degrades after the handshake phase.

Cooperators C_1, C_2, …, seek in this case to listen to the transmission from A to B and, if needed, send additional redundancy to the receiver. This improves the reliability of the transmission when the direct channel between A and B is bad. The resulting scheme, which exploits the broadcast nature of wireless communications, appears as a distributed version of HARQ and requires the following additional MAC procedures.

Node A begins the transmission by sending an RTS packet. If the CTS sent back by B indicates that the SNIR between the nodes, $SNIR(AB)$, is above threshold, no cooperation is requested. Otherwise, nodes C_1, C_2, …, which overhear both signaling packets, can participate in a cooperative manner. This happens if they satisfy the condition $SNIR(AC_j) > SNIR_{th}$, whereas it is no longer required that these nodes are closer than A to the final destination D. In fact, these cooperators will not become next-hop relays, a role still retained by B. Incidentally, note that this choice is the only viable one in many cases, for example, when B and D coincide, or when none of the Cs is a good relay by itself. At this point, the coded cooperation scheme proceeds as represented in Fig. 3.

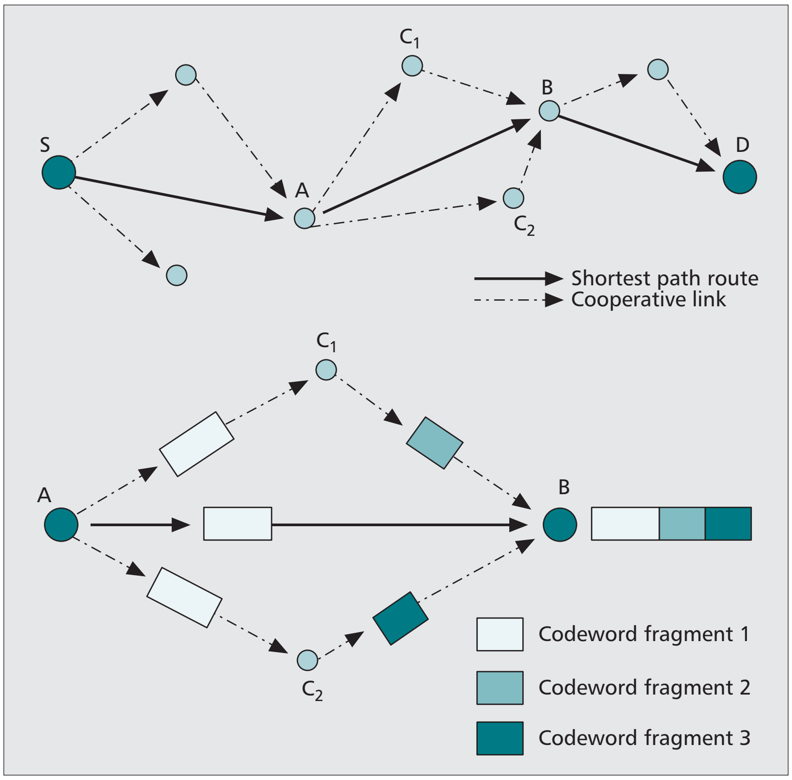

Figure 3. *Coded cooperation.*

Once A receives the CTS from B, it starts the transmission toward it, in spite of the bad channel conditions. Nodes C_1, C_2, … can decode the data blocks sent by A. After this first transmission, to which B would reply with a negative acknowledgment (NACK) message, they participate in subsequent retransmissions by sending coded versions of the packet. This means that instead of having all nodes retransmitting an identical copy of the data block, every cooperator sends an encoded version of it, obtained in a distributed manner. To this end, many equivalent schemes may be used; the only important aspect is that the receiver can attain correct reception if the received information content is at least that of the whole data block.

Note that this approach is better than letting all the C_js send the same packet. In this case, if the same part of the data block is incorrect for all the retransmissions, B is still unable to decode part of the data. Instead, different coded versions can be combined to obtain a coding advantage. The situation is similar to the advantage offered by HARQ over conventional ARQ.

We also observe that this scheme can be extended, since it is not necessary to include as cooperators only nodes that are able to receive the RTS before transmission starts. As the channel conditions may be changing, it is possible that the link quality between A and B was initially good during the handshake, causing B to answer with a positive CTS, but then this condition is no longer verified during the transmission phase, causing a NACK. Cooperation from other nodes can easily begin at this point, rather than already from the start.

COMBINED SOLUTIONS

Letting all intermediate nodes C_j participate in the coded cooperation scheme may sometimes be undesirable. As an example, even though we require that they be able to correctly receive the data packet from A (i.e., $SNIR(AC_j)$ is above threshold), there is no guarantee that the link from C_j to B is good. In principle, $SNIR(C_jB)$ may be even worse than $SNIR(AB)$. In this case, the participation of such nodes brings little contribution over the non cooperative transmission case, where A alone transmits to B, while on the other hand the interference is heavily increased by the consequent multiple transmissions.

For this reason, in the following we impose another additional requirement, that is, an intermediate node C_j participates in the coded retransmission only if $SNIR(C_jB)$ is greater than or equal to $SNIR(AB)$. The choice of this particular criterion is, however, not restrictive, as other similar conditions can be applied as well, provided they satisfy the following two points: first, they must be based on local information available at the single node; second, they restrict cooperative interventions only to nodes that can really improve the transmission. In any case, our investigations show that a restriction of this kind is truly necessary to avoid interference peaks due to simultaneous transmission of cCTSs by cooperators. We stress again that this network aspect is often overlooked by many studies which focus on a single link.

More generally, one drawback of coded cooperation is that it potentially triggers retransmissions from many cooperators, which may be unnecessary. Think, for example, of the case where many intermediate nodes are good candidates for cooperation, so the help of each one of them would be sufficient to deliver the packet to B; in such a case, many useless transmissions will be activated. However, as the intermediate nodes do not have a way to negotiate their intent to cooperate and act in a distributed manner, such a problem is not trivial to avoid.

A simple possibility would be to activate the coded cooperation feature only when cooperative routing fails. To do so, we need to modify the handshake phase as follows. We impose that all nodes C_j meeting the aforementioned conditions, that $SNIR(AC_j)$ is above threshold $SNIR_{th}$ and $SNIR(C_jB)$ is greater than $SNIR(AB)$, send a cCTS. Thanks to the evaluation of the distance metric, node A is able to distinguish whether the intermediate node C_j can carry out the packet forwarding alone, or is just able to help improve the transmission to B. This distinction will be clearly specified by the transmitter in the first packet sent, which would have either B or one of the C_js as its intended receiver.

Thus, in the following, these three approaches are compared (in addition to the approach without cooperation): opportunistic routing, coded cooperation, and a joint approach consisting of the combination of opportunistic routing and coded cooperation as described above. We stress that other implementations of joint approaches are possible, e.g., by introducing a more careful selection of participants in the coded cooperation phase, which would help to further improve the performance. However, this requires more complex mechanisms, which are out of the scope of this article. For this reason, we leave them as an open direction for future research.

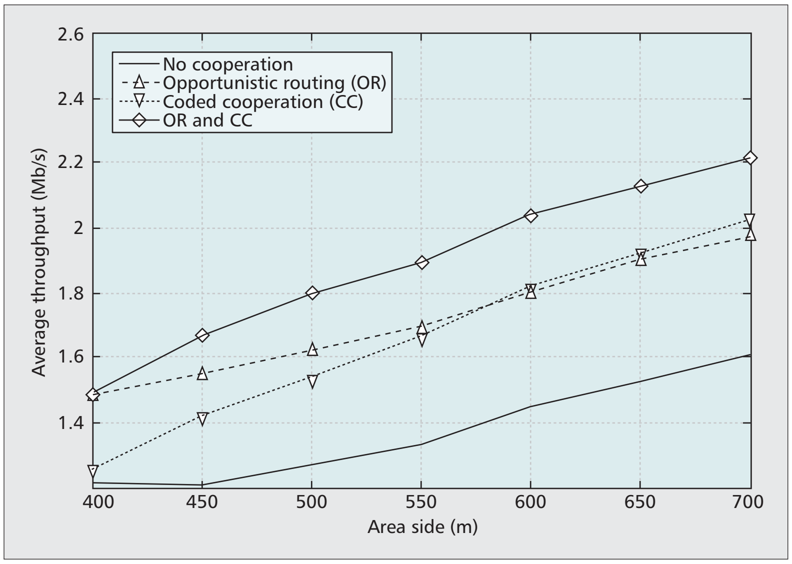

Figure 4. *Link throughput.*

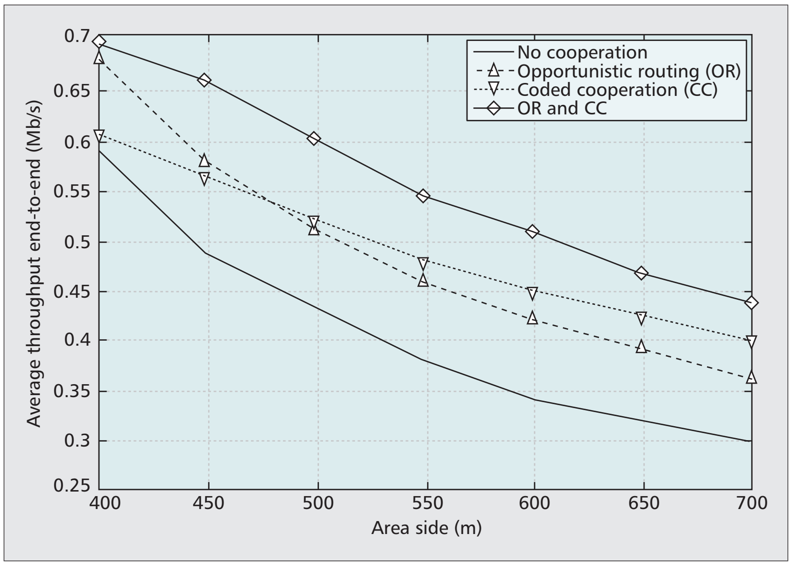

Figure 5. *End to end throughput.*

Finally, attention to the MAC and routing issues should be paid not only to evaluate the performance of the cooperative network, but also to gain a wider view of cooperation itself. For nodes that generate low amounts of traffic, cooperation may be a waste of resource, as they are aiding many neighboring transmissions with little or no benefit for themselves. Actually, similar to what happens in other fields of application of game theory, it has been shown [7] that if nodes have selfish behavior (i.e., they try to maximize their own benefit), cooperation is not favored. However, as cooperation brings advantages on a global scale, if the nodes are convinced of the utility of a trustful collaborative behavior, their egoistic approach in a repeated game may encourage cooperation instead.

To this end, several approaches are proposed, often borrowed from social sciences, exploiting, for example, bio-inspired models, such as the ones describing colonies, clans, and other collaborative behaviors that can be encountered in social networks. Even though these topics deserve a very broad analysis, which is out of the scope of this article, we stress here that an essential part of the creation of social ties is the ability to exchange messages. For example, cooperative behavior in swarms or colonies happens via exchange of pheromone, whereas clans or herds have rules to determine roles in teamwork and outcast those who misbehave. Thus, collaborative intelligence is gathered not only to take advantage of cooperation but also to determine who is part of cooperation and who is not. The exchange of control messages due to the MAC protocol not only determines a practical implementation but also supplies a concrete instrument to identify cooperative neighbors and define such societal relationships. We believe that the network-wide perspective given here better instantiates the performance evaluation together with the characterization and motivation of cooperation in a wireless scenario.

PERFORMANCE EVALUATION

To evaluate the previously described techniques we utilize a MATLAB simulator taking into account the protocol stack from the physical to the network layer, along the lines discussed in [6]. Random topologies with 100 nodes are deployed over a square area with variable size. This means that the node density can be varied by tuning the size of the deployment area, whose side ranges from 400 to 700 m. Nodes generate packets according to a Poisson process of intensity equal to 5 packets/s/node and choose their final destination at random. Data packets and control packets are 4096 and 512 bits long, respectively. Routing tables are supplied to all nodes, which are therefore aware of their next hop to any end destination.

The channel is affected by flat Rayleigh fading; the channel quality is assumed to stay constant during the transmission of any data or control packet. The channel gain between positions x and y includes a path loss term proportional to d^{-4}, where $d = d(x,y)$ is the physical distance between x and y, and a Rayleigh term that is the envelope of a complex Gaussian random variable $\phi(k)$ with zero mean and unit variance. Subsequent channel values are correlated with a coefficient $\rho = 0.9$ (i.e., $\phi(k) = \rho\phi(k-1) + \sqrt{1-\rho^2}\xi$), where ξ is an independently drawn complex Gaussian random variable with zero mean and unit variance.

Figure 4 reports the per-link throughput of the network, that is, the rate at which data is correctly transmitted to the next hop over a time unit by an average link, as a function of the side length of the square deployment area. As a general behavior, this metric increases as the network becomes sparser, since larger physical separations of links allow higher transmission parallelism. Opportunistic routing and coded cooperation improve the performance with respect to the case without cooperation. However, the former significantly enhances the throughput for high node densities, whereas the opposite is true for the latter, which gives almost no improvement in this case. As the deployment area increases, this behavior tends to revert, until ultimately for sparse networks coded cooperation outperforms cooperative routing.

Such a trend can be explained by observing that at high node densities it is easier to find a next hop in an opportunistic manner, as there are many neighbors from which to choose. Conversely, in this case coded cooperation may be counterproductive since, if adopted by all nodes, it would cause a general interference increase. As the node density decreases, it becomes more difficult to find a neighbor able to relay the packet alone, whereas coded cooperation can still be used, as it combines contributions from multiple nodes. Since the neighbors are, on average, further away, the interference increase is also less significant. Finally, observe the good behavior of the proposed combined technique, which outperforms both opportunistic routing and coded cooperation for any node density. At high node density, the advantage of this technique mainly comes from the opportunistic routing part, which has the dominant character. However, in general it is able to leverage on the advantages of both components.

Similar reasons explain what can be observed in Fig. 5, where the end-to-end throughput is plotted. First of all, observe that this metric, for all the approaches, decreases for higher size of network area. This happens because while less interference affects the links, which therefore have higher throughput if individually taken, it is also more likely that a multihop path gets stuck at a node that is unable to deliver the packets to an adequate next hop. This can happen even if opportunistic routing or coded cooperation is employed, although these techniques permit to improve the end-to-end throughput.

Observe again that opportunistic routing gives the hig/fmorehest improvement in dense networks, whereas coded cooperation is preferable when the network is sparse. Finally, the combined approach still has the best performance, as it combines the benefits of both techniques.

Figure 6 shows the average length of the hops which achieve a successful communication. This quantity is connected with the per-link throughput, as the value of this latter metric should be matched with the length of the link itself. For example, having a high link throughput may not be advantageous if the link length is significantly decreased, so that on average more links are required. Note that in general the hop length first increases with the side of the deployment area, and then saturates. This happens more or less in a similar manner for all the techniques. Moreover, cooperative routing decreases the hop length, which is explained by its opportunistic nature, as shorter links clearly have better SNIR on average. Instead, coded cooperation slightly increases the average length, as it is able to recover links that would fail if cooperation were not employed. As can be expected, our proposed combined technique has an intermediate behavior between these two cases.

Finally, in order to characterize the *transmission cost* of the compared approaches, we consider the efficiency indicator reported in Fig. 7, which is evaluated by computing the ratio of useful transmissions (those delivering a packet) over

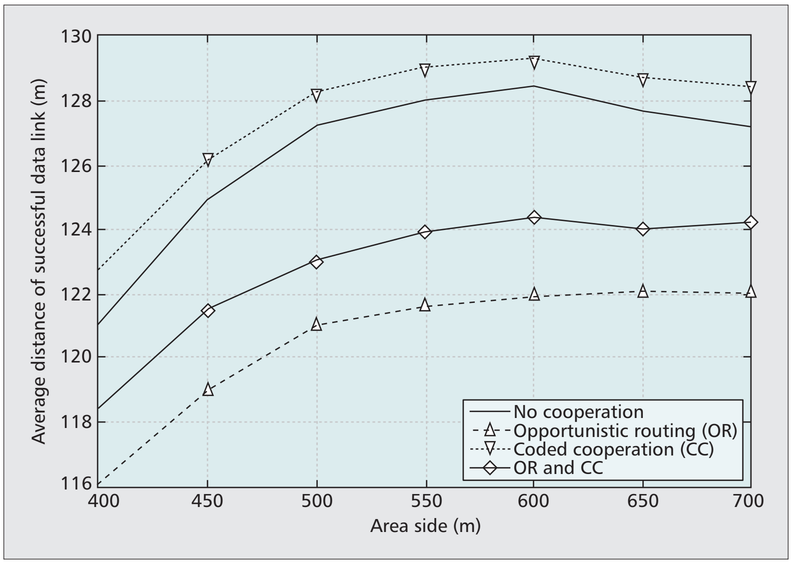

Figure 6. *Average distance of successful data link.*

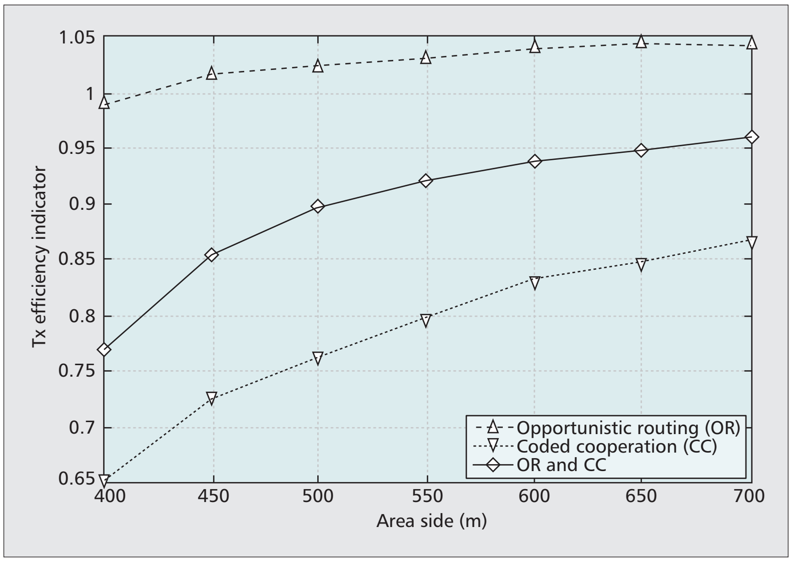

Figure 7. *Efficiency indicator (rate of useful transmissions).*

We believe that the network-wide perspective given here better instantiates the performance evaluation together with the characterization and motivation of cooperation in a wireless scenario.

the total number of transmissions (i.e., also including control packets, redundancy, and unacknowledged transmissions). The curves are normalized to the performance of the *no cooperation* case. From this comparison, an evaluation of the cost variation for the power spent in transmission can be inferred. As visible from the figure, opportunistic routing achieves a better transmission efficiency; this is actually expected, since it simply corresponds to selecting better paths. Conversely, coded cooperation increases the number of transmissions performed, and therefore the efficiency indicator decreases. However, it is remarkable that combining opportunistic routing and coded cooperation significantly decreases this additional cost. In other words, the advantages of the joint solution are achieved with just a slightly increased transmission cost; this generally depends on the node density, but for sufficiently low values (e.g., area side above 500 m, where coded cooperation is shown to be more beneficial), the cost increase is below 10 percent.

CONCLUSIONS

In this article we describe how fundamental cooperative approaches for wireless communication can be implemented in a network context, with special emphasis given to medium access and routing issues, which are often overlooked.

We also evaluate the performance of different schemes, including opportunistic routing, coded cooperation, and a novel joint approach that combines them in a simple yet effective manner. We provide numerical results to show that several network aspects affect cooperation; as an example, we verify that node density affects which of the approaches is preferable. Joint approaches not only achieve better results, combining the advantages of each strategy, but also open up the possibility of better overall management of cooperative paradigms. For this reason, they appear as a promising direction for future research.

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