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Enclosure 1

Distributed Cooperative Routing and Hybrid ARQ in MIMO-BLAST Ad Hoc Networks

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***Abstract*— Cooperation has proved to be an effective technique for improving the performance and the efficiency of wireless networks. Most of the existing work on cooperation focuses on the physical layer, with the aim of enhancing the capacity and the quality of a single link. In this paper we propose a cooperative protocol that melds physical, MAC and routing layers to increase the performance of a MIMO–BLAST ad hoc network, where nodes are allowed to transmit simultaneously. Nodes try to resolve in–range delivery of packets with an adaptive distributed Hybrid ARQ scheme to counteract interference from simultaneously active communications, while dynamic route selection is implemented for avoiding transmissions over links with harsh fading conditions. We assess the performance of our scheme through detailed simulations.**

I. INTRODUCTION

Communications in wireless networks are affected by channel variations due to multipath fading. In recent years, the design of techniques aimed at providing diversity at the receiver without the need for multiple antennas has attracted a large research effort [1]–[3]. Generally, the investigation is focused on the physical layer (PHY), and aims at improving the performance of a single link, neglecting the surrounding network. In cooperative relaying protocols, one or more nodes retransmit the source packet. The capacity and the achievable rates of fundamental relaying techniques have been characterized in [4]–[6], while practical relaying protocols have been proposed and investigated in [7], [8]. In coded cooperation, first proposed in [9], cooperating nodes send over the channel different parts of the source codeword. At the receiver side, the various codeword fragments are combined in order to enhance the probability that the original packet is correctly decoded. In [10] the derivation of the frame error rate is performed under the assumption of block fading and orthogonal channels. The performance of coded cooperation with various coding techniques has been investigated in [10]–[13]. An extension to the case of nodes equipped with multiple antennas is provided in [13]. In [14] a cooperative location–based distributed routing algorithm for wireless sensor networks is proposed, that avoids weak links through a decode-and-forward relaying scheme, where the receiver combines the source and the relay signals.

In this paper we present a cooperation scheme that efficiently manages the delivery of the packets in a multiple–input multiple–output (MIMO) multi–hop ad hoc network, where nodes are equipped with an array of antennas. Transmitters employ spatial multiplexing (SM) to increase the data rate, and receivers use a layered space–time multiuser detection (LASTMUD) algorithm [15], where signals are iteratively decoded and cancelled from the received signal in descending received power order, and not yet decoded signals are nulled by zero–forcing. To fully exploit the potential of the PHY layer, nodes are allowed to access the channel even if other communications are active in the same area. In this setting, even though the antenna array at the receiver side mitigates the fading impairments, the detection of the intended signals may suffer interference conditions and receiver overload.

We present a cooperative protocol that blends together PHY, MAC and routing layers with the aim of providing efficiency and reliability to the end–to–end delivery in a multi–hop multiple access environment. While the cooperation schemes proposed so far need a long negotiation phase and generally require substantial modifications to the system, the MIMO physical layer allows nodes to perform cooperation in a simpler way, with considerable reduction of the coordination delay and overhead. In addition, the capability of MIMO to support several simultaneous communications allows the use of multiple cooperators, without the delay introduced by TDMA.

In fact, although MIMO techniques are not strictly necessary for our proposed protocol to work, we focus on a scheme based on it since the trade off between the increased interference and the benefits granted by cooperation appears particularly interesting to analyze. In particular, cooperation is exploited to achieve a higher diversity and coding gain at the transmission level as well as a more efficient packet forwarding in the network at the routing level.

We point out that to the best of our knowledge our work is the first which considers cooperation over a complete networking system, including all levels from PHY to routing. Hence, it is difficult to make meaningful comparisons with other cooperative schemes proposed in the literature, which mainly focus on single link communications. Instead, we will compare our cooperative scheme to another cross–layer solution that does not use cooperation.

The paper is organized as follows. Section II briefly describes the physical layer. In Section III the proposed protocols are presented. Section IV shows and discusses the simulation results. Section V concludes the paper.

II. PHY LAYER DESCRIPTION

We refer to the LASTMUD transmission and reception scheme, described in [15], [16], and briefly summarized in the following, which is a specific implementation of the BLAST architecture. We assume that each node is equipped with an antenna array of N elements and is assigned a specific pseudo–random spreading sequence of N_s chips. We assume flat fading and that the channel remains constant during the transmission of a block of bits. We denote the complex channel gain between the i–th antenna of node n and the j–th antenna of node m with $h_{i,j}^{(n,m)} = \sqrt{\alpha^{(n,m)}}\phi_{i,j}^{(n,m)}$ where $\alpha^{(n,m)}$ is the path loss between node n and node m, and $\phi_{i,j}^{(n,m)}$ is a random variable accounting for fading. Even though not specifically required by the PHY, we assume symbol–synchronous transmissions for ease of notation. The symbols to be transmitted are divided among the N antennas, spread with the node spreading sequence, BPSK modulated and transmitted. The transmission power P_{TOT} is equally split among the N antennas. Assume that users $t = 1, \ldots, T$ are transmitting. Let $\boldsymbol{S}$ be the $N_s \times T$ spreading matrix, where the t–th column is the spreading sequence for node t, and let $\boldsymbol{H}_j^{(t,m)} = [h_{1,j}^{(t,m)}, \ldots, h_{N,j}^{(t,m)}]$ be the vector of the complex channel gains between the antennas of node t and the j–th antenna of node m. If $\boldsymbol{d}$ is the column vector of the data symbols simultaneously transmitted by all the N antennas of each of the T transmitters, the N_s received chips at the j–th antenna of node m are:

$$\boldsymbol{r}_j^{(m)} = \boldsymbol{S}'\boldsymbol{C}_j^{(m)}\boldsymbol{d} + \boldsymbol{\omega}_j^{(m)} = \boldsymbol{R}_j^{(m)}\boldsymbol{d} + \boldsymbol{\omega}_j^{(m)}, \tag{1}$$

where $\boldsymbol{C}_j^{(m)}$ is a diagonal square $TN \times TN$ matrix, whose non–zero elements are the channel coefficients between the N antennas of all the transmitters and the j–th antenna of m. $\boldsymbol{\omega}_j^{(m)}$ is a column vector of N_S i.i.d. complex Gaussian noise samples with zero mean and power σ^2 and $\boldsymbol{S}' = \boldsymbol{S} \otimes \boldsymbol{1}_N$, where $\otimes$ is the Kronecker product. Defining the correlation matrix

$$\tilde{\boldsymbol{R}}^{(m)} = \sum_{j=1}^{N} \boldsymbol{R}_j^{(m)H}\boldsymbol{R}_j^{(m)}, \tag{2}$$

the output of the matched filter is

$$\tilde{\boldsymbol{r}} = \tilde{\boldsymbol{R}}^{(m)}\boldsymbol{d} + \boldsymbol{n}^{(m)}, \tag{3}$$

where

$$\boldsymbol{n}^{(m)} = \sum_{j=1}^{N} \boldsymbol{R}_j^{(m)H}\boldsymbol{\omega}_j^{(m)}. \tag{4}$$

As stated before, the decoding algorithm iteratively decodes and cancels in descending received power order the signals from the total received signal. For a description of the complete receiver structure the interested reader is referred to [15].

A. Packet Coding

As introduced before, the system implements an adaptive hybrid ARQ protocol to counteract the channel variations in terms of fading and interference and provide reliability to the transmission. A packet to be transmitted is first encoded with a linear erasure code (LEC) [17], and then fragments of the obtained codeword are transmitted over the channel. LEC codes are particularly well–suited for transmissions affected by bursts of errors [18]. In this Section we briefly describe the coding system used [16]. We assume the use of this coding system at lower layers. Note that a similar techinique could also be used at the application layer [18].

Packets are encoded with the LEC defined by the triple $(n, k, \boldsymbol{G})$, where n and k are two integers with $n > k$ and $\boldsymbol{G}$ is an $n \times k$ generator matrix, with elements taken from the Galois field GF(2^r). Symbols are encoded as follows

$$\boldsymbol{p}_i = [\boldsymbol{G}]_{i,1}\boldsymbol{s}_1 \oplus [\boldsymbol{G}]_{i,2}\boldsymbol{s}_2 \oplus \ldots \oplus [\boldsymbol{G}]_{i,k}\boldsymbol{s}_k\,, \tag{5}$$

where $i = 1, 2, \ldots, n$, and $\boldsymbol{s}_i \oplus \boldsymbol{s}_j$ denotes the element-wise sum of vectors $\boldsymbol{s}_i$ and $\boldsymbol{s}_j$ in GF(2^r).

Without restriction, we consider a systematic LEC, where the original symbols are the first k coded symbols, i.e., $\boldsymbol{p}_i = \boldsymbol{s}_i$ for $i = 1, 2, \ldots, k$. Let $\mathcal{D} = \{\kappa_1, \kappa_2, \ldots, \kappa_k\}$ be the indices of the correctly decoded symbols and let $\bar{\boldsymbol{G}}_{\mathcal{D}}$ be the matrix containing the columns of $\boldsymbol{G}$ with index in $\mathcal{D}$. Since $\boldsymbol{G}$ is full-rank, $\bar{\boldsymbol{G}}_{\mathcal{D}}$ is also full rank and can be inverted in GF(2^r), to obtain $\bar{\boldsymbol{G}}_{\mathcal{D}}^{-1}$. By combining the detected symbols with $\bar{\boldsymbol{G}}_{\mathcal{D}}^{-1}$, we obtain the data symbols

$$\boldsymbol{s}_q = [\bar{\boldsymbol{G}}_{\mathcal{D}}^{-1}]_{q,1}\boldsymbol{p}_{\kappa_1} \oplus [\bar{\boldsymbol{G}}_{\mathcal{D}}^{-1}]_{q,2}\boldsymbol{p}_{\kappa_2} \oplus \ldots \oplus [\bar{\boldsymbol{G}}_{\mathcal{D}}^{-1}]_{q,k}\boldsymbol{p}_{\kappa_k}\,, \tag{6}$$

where $q = 1, 2, \ldots, k$. An interesting property of any LEC having a full-rank generating matrix is that if any k distinct coded sub-packets are correctly detected, then the entire packet can be decoded.

An L_p–bit long packet $\boldsymbol{a}$ is first split into F blocks $\mathcal{S} = \{\boldsymbol{b}_1, \ldots, \boldsymbol{b}_F\}$ of $L_b = L_p/F$ bits, referred to as systematic set. The systematic set is then encoded with a code $(V, F, \boldsymbol{G})$, with code symbols in GF(2^{L_b}), obtaining the coded set $\mathcal{C} = \{\boldsymbol{c}_1, \ldots, \boldsymbol{c}_V\}$. To each block, before transmission, a CRC code is added, that enables the receiver to know which blocks have been correctly received. If the receiver correctly decodes any F blocks of the coded set, it can retrieve the systematic set.

III. NETWORK PROTOCOL DESCRIPTION

The proposed protocol involves MAC, error control and routing, to obtain flexible and reliable delivery to the intended destination. For the sake of simplicity, we assume that time is divided in slots and that nodes start transmission only at the beginning of a slot. Moreover, transmitting nodes send short training preambles at the beginning of each slot to allow the receivers to estimate the channel coefficients and perform LASTMUD decoding.

We consider a multi–hop network, where the delivery of a packet from its source to the intended destination may require the forwarding of the packet through several relays. In this initial study, we assume that each node knows the whole path to every other node in the network.

In the rest of this section we present both the basic non–cooperative and the cooperative communication protocols. In the former, nodes try to resolve the delivery of the packet with an adaptive HARQ scheme, to counteract fading and interference. In the latter, we introduce cooperation among nodes. Through cooperation, the effectiveness of the adaptive HARQ scheme is improved by the higher diversity order provided by different node transmissions. Moreover, the main contribution of this paper is to exploit cooperation through a cooperative packet forwarding scheme, where nodes collaborate also to dynamically select routing paths with good channel conditions.

A. Basic Communication Scheme

In this subsection we provide the description of the basic non–cooperative protocol. Nodes access the channel without performing channel sensing, even if other communications are taking place in the same area.

Before DATA transmission, the source and the next hop relay perform a handshake phase. First, the source sends a request to send (RTS) packet. If the destination is available, it responds with a clear to send (CTS) packet. Please note that, unlike in 802.11 DCF, the initial handshake does not prevent neighboring nodes from accessing the channel. Control packets are assumed to be shorter than data blocks, and are sent transmitting the same bits from all N antennas. The destination sums the $\tilde{\boldsymbol{r}}$ obtained through iterative processing of the signals associated with the transmitting antennas to obtain higher reliability. We also assume that control packets are protected by a rate $1/2$ convolutional code and that the transmission of a control packet occupies a slot. The DATA packet transmission is performed only if the received signal to noise ratio (SNR) at the receiver of the signals from all the source antennas is above a certain threshold SNR_{TH}. The destination indicates in the CTS whether or not this SNR condition is met. We refer in the following to positive and negative CTS (nCTS), for a CTS where the destination indicates that the source transmission is above or below the SNR threshold, respectively. If the source receives a positive CTS, it starts the packet transmission. The transmission is divided in phases, in which the source sends out different subsets of the coded set $\mathcal{C}$, obtained through the encoding of the systematic set $\mathcal{S}$, as described in Section II-A, and the destination replies with an ACK packet, where it specifies whether or not the packet is correctly decoded, the number N_{BL} of blocks still missing for the correct decoding, and the set $\mathcal{D}_i$ of correctly decoded blocks of $\mathcal{C}$. In Fig. 1.a an example of communication is depicted. In the first phase, the source transmits the first F blocks of the coded set, i.e., the systematic set. We assume that the transmission of a block with N antennas, performed as described in Section II, has time duration equal to one slot. If the destination reports a packet decoding failure in the ACK, then the second transmission phase starts, where N_{BL} blocks randomly chosen in $\mathcal{C} \setminus \mathcal{D}_i$ are transmitted by the source, followed by a new ACK by the destination. A maximum of M_{ph} transmission phases are allowed, and if a failure is reported at the last phase, the delivery attempt is dismissed. The source performs at most M_{TX} attempts before discarding the packet. Different attempts are independend, i.e., the destination discards correctly decoded blocks at the end of each failed attempt.

The threshold SNR_{TH} is set to guarantee a success probability equal to P_S for a single delivery attempt, and is computed taking into account the maximum number of blocks sent in the various phases in the absence of interference. In particular

$$\mathrm{P}_S = 1 - \sum_{i=0}^{F-1} \binom{F\mathrm{M}_{ph}}{i} P_e^{(F\mathrm{M}_{ph}-i)} (1-P_e)^i, \qquad (7)$$

where P_e is the probability that a block is not correctly received. Equation (7) represents the probability that the receiver retrieves the packet from the received blocks, i.e., the probability that the receiver correctly decodes at least F blocks among the maximum number of blocks that the source is allowed to send during one attempt. Given that the source transmits with N antennas an L_b–bit block, P_e can be written as

$$P_e = 1 - (1 - BER)^{L_b} \qquad (8)$$

and BER can be obtained as $BER = Q\left(\sqrt{\mathrm{SNR}}\right)$.

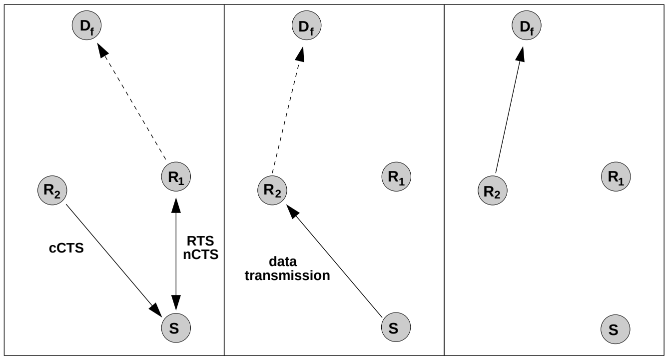

Fig. 2. Example of cooperative packet forwarding.

The SNR threshold allows nodes to avoid transmission over low success probability links. Note that this does not only result in increased efficiency, but also decreases the interference in the network, enhancing the success probability of other ongoing communications.

In order to control the interference, to adapt the access rate to the network conditions and to randomize further attempts over previously failed links, we introduce a random backoff mechanism. Link failures (not received CTS, SNR condition not met, or decoding failure at the last available transmission phase) force a source node to defer packet transmission for a number of slots B, randomly chosen in the esponentially increasing window $\left[1, 2^{N_{fails}} W\right]$, where W is the initial window size. The value of N_{fails} is updated as $N_{fails} = \min(N_{fails}^{MAX}, N_{fails}+1)$ if a failure occurs and $N_{fails} = \max(0, N_{fails}-1)$ if a packet is successfully delivered.

We consider a multi–hop network, where the delivery of a packet may require its forwarding by relaying nodes. We assume that each node knows the whole path to reach the packet destination. Routes are computed using a shortest path algorithm, where the maximum hop length is chosen such that the average SNR matches the SNR condition. In particular, if $\alpha(d)$ is the path loss between a pair of nodes at distance d, and $\phi_{i,j}$ is the complex channel gain between the i–th antenna of the first node and the j–th antenna of the second one, the average received SNR from the i–th antenna of the source is

$$E_{\phi_i}\left[\alpha(d)\frac{P_{\mathrm{TOT}}}{N}\frac{\sum_{j=1}^{N} \mid \phi_{i,j} \mid^2}{\sigma^2}\right] = \alpha(d)\frac{P_{\mathrm{TOT}}}{\sigma^2}. \qquad (9)$$

and, consequently, the maximum hop length is set to the value d for which the resulting average SNR is equal to the threshold SNR_{TH}.

B. Cooperative protocol

The system described in the previous subsection is highly adaptive to the channel conditions, in terms of fading and interference, and exploits the potential of the PHY with an

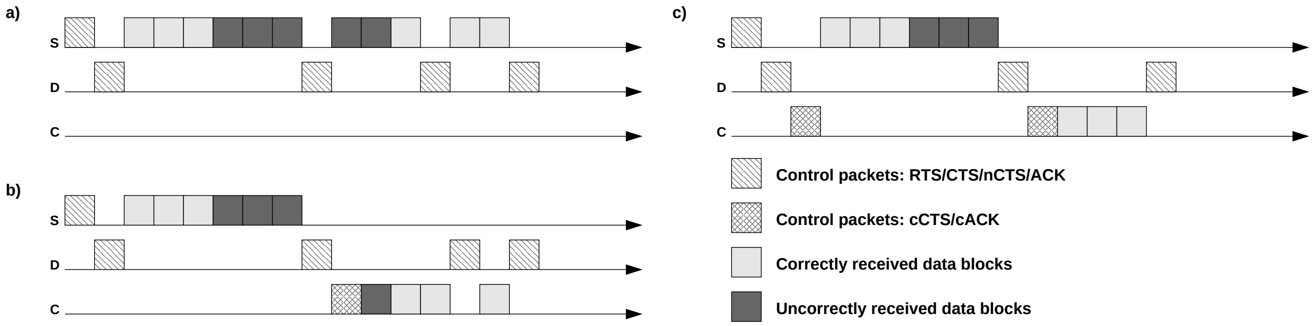

Fig. 1. Example of HARQ schemes: a) non–cooperative, b) cooperative (positive CTS) c) cooperative (nCTS).

aggressive access policy. In this subsection we present a protocol that provides a higher diversity to the system, allowing nodes to cooperate. Cooperation aims at strengthening weak links with a distributed version of the HARQ scheme, and at making packet forwarding more flexible and efficient.

Distributed HARQ Protocol: The condition on the SNR ensures that weak links are not activated, increasing the network efficiency and lowering the interference level. To enhance the packet delivery probability over links experiencing harsh channel conditions, we exploit the intrinsic broadcast nature of the wireless channel, and the capability of the PHY layer to support simultaneous transmissions. The main idea is to let nodes that have good channel conditions towards both the source and the destination help deliver the packet.

Upon receiving a negative CTS, the source node S and the destination node D stay in the receiving state for a further slot. Every node that hears the RTS/nCTS exchange, and whose links towards the source and the destination match the SNR condition, transmits a cooperative CTS (cCTS) in that slot[1], to inform S and D about its availability. If S receives a cCTS, it starts with the first transmission phase, otherwise the delivery attempt is dismissed. If D correctly receives only a subset $\mathcal{D}_1 \subset \mathcal{S}$ of blocks, and therefore is unable to recover the information packet, it sends a negative ACK. Nodes that correctly decoded the set of blocks $\mathcal{W}$ that D missed, and that have SNR towards the destination higher than the SNR of the source, start cooperation. These nodes encode $\mathcal{W}$ with a shortened version of code $(V, F, \boldsymbol{G})$, obtaining the set of blocks $\mathcal{C}'$. They then transmit a cooperative ACK (cACK) and perform the further transmission phases on behalf of the source, selecting $\mid \mathcal{S} \mid - \mid \mathcal{D}_i \mid$ blocks to be transmitted in $\mathcal{C}' \backslash \mathcal{D}_i$. A shortened version of code $(V, F, \boldsymbol{G})$ is used because the cooperators are not required to have retrieved the whole packet, in order to increase the probability that cooperation is activated. Note that, if D correctly receives at least $F - \mid \mathcal{D}_1 \mid$ blocks of $\mathcal{C}'$, it is able to retrieve the whole packet. The cACKs are necessary to inform the source of the presence of potential cooperators that have a higher success probability. If a failure occurs at the last allowed transmission phase, cooperation is dismissed, and the source schedules another attempt or discards the packet. An example of the protocol transmission scheme for the described case is provided in Fig. 1.c. In case no cACK is received, the source continues the delivery attempt as in the basic scheme.

In the case of positive CTS reception (Fig. 1.b), the source immediately starts the first transmission phase. Also in this case, if D reports a decoding failure in the ACK, available nodes that correctly decoded the source packet send out a cACK, and the protocol follows as described before.

In the described protocol, cooperating nodes may efficiently resolve the delivery of packets that would otherwise suffer harsh channel conditions and likely incur high transmission cost and long delay. Given that interference can have a different impact on the performance of the various receivers, due to correlation among different channels, cooperation may improve the efficiency of communication by providing diversity also in this case.

Cooperative Packet Forwarding: Besides the distributed HARQ scheme just described, we introduce cooperation to improve the effectiveness of packet forwarding towards destinations not directly reachable by the source. As stated in Section III-A, packets are forwarded through shortest path routes. However, the link to the next relay may be affected by harsh channel conditions.

The proposed cooperative routing protocol provides a means to dynamically select reliable links. More specifically, if the current destination R_1 of the transmission from the source S is not the final packet destination D_f, R_1 can be replaced by a cooperating node R_2. If an nCTS is sent by R_1, nodes that match the aforementioned conditions on the SNRs, and whose hop distance towards D_f is less than or equal to that of R_1, send a cCTS. Thus, S chooses among the received cCTSs the relay with the best SNR, and consequently starts the first transmission phase towards it. In Fig. 2 an example of cooperative packet forwarding is shown.

To make the forwarding scheme even more flexible, if the current transmission destination R_1 fails to retrieve the packet after a successful handshake, nodes that correctly decoded the whole systematic part indicate their availability to take charge of the forwarding in the cACK. During the second transmission phase, all cooperators transmit. If a further failure occurs, the destination selects one of the cooperators that have already decoded the whole packet by including this information in the second negative ACK. This cooperator takes the place of the source in forwarding the packet, according to its own routing path towards the final destination, and the current transmission is dismissed.

[1] Note that multiple cCTSs can be successfully decoded without collisions, due to the multiuser detection algorithm

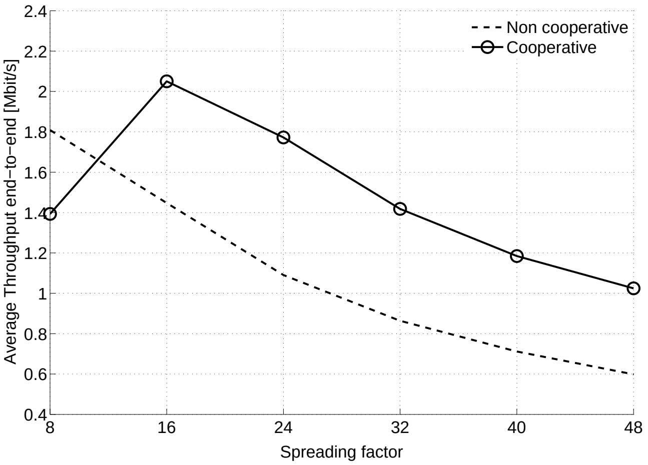

Fig. 3. End–to–end throughput for the cooperative and non–cooperative protocol as a function of the spreading factor.

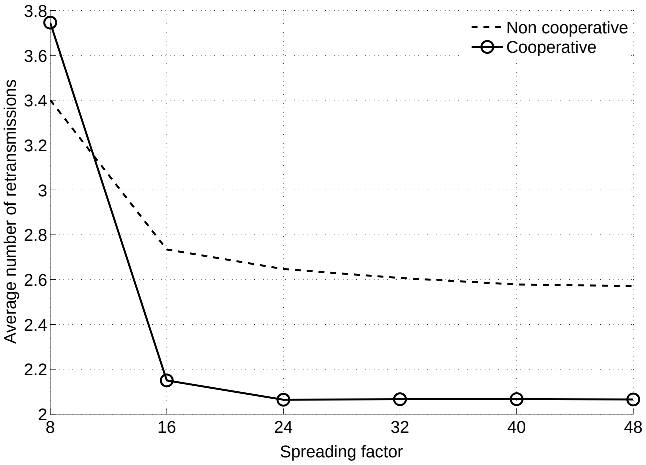

Fig. 4. Average number of delivery attempts as a function of the spreading factor.

TABLE I

SYSTEM PARAMETERS.

Phy Layer and Environment	
Modulation	BPSK
Number of array elements	2
P_{TOT}	0.25 W
Bit-rate per antenna	$7.5/N_s$Mb/s
Control pkt FEC polynomial (rate 1/2)	$133_8, 171_8$
Number of nodes	64
Topology	4 × 16 grid
Noise power σ_w^2	-170 dBm
Path loss factor β	4
Channel correlation ρ	0.9
Packet generation parameter λ	10 pkt/s per node
MAC and HARQ	
Number of blocks per packet F	8
Block length	512 bits
Erasure code parameters (n,k)	(8, 24)
Maximum number of phases M$_{ph}$	5
Maximum number of attempt M$_{tx}$	8
Initial windows W	4
N_{fails}^{MAX}	5
P$_S$	0.9
Threshold SNR$_{TH}$	9 dB
Queue length	128 pkts
Relaying queue length	64 pkts
Packet timeout from generation	10000 slots
Routing	
Maximum hop length	142 m

IV. SIMULATION RESULTS

In this Section we assess the performance of the proposed protocols through MATLAB simulations, where the previously described PHY, MAC and routing protocol are accurately reproduced. Each node has a finite FIFO queue where the packets are stored before being served. We assume that a fixed number of slots in the queue is reserved for packets to be forwarded. Packets are generated at all nodes according to a Poisson process of parameter λ packets per second per node. Each packet has destination randomly chosen among all other nodes of the network. Nodes are placed on a rectangular grid of 4×16 nodes, where the minimum distance between two nodes is set to 30 m. The simulation parameters are summarized in Table I.

The channel is slow fading and the fading coefficients for slot k are $\phi_{\ell,j}^{(n,m)}(k) = \rho\phi_{\ell,j}^{(n,m)}(k-1) + \sqrt{1-\rho^2}\xi$, where ρ is the correlation coefficient and ξ are independent complex Gaussian variables with zero mean and unit variance. The path-loss coefficient has been modeled according to Hata with $\alpha^{(n,m)} \propto [d^{(n,m)}]^{-\beta}$, where $d^{(n,m)}$ is the distance between nodes n and m; LASTMUD performance is modeled as in [19].

Fig. 3 shows the average achieved end–to–end throughput for the non–cooperative and the cooperative protocols for various values of the spreading factor N_s. It is possible to observe that for N_s greater than or equal to 16 the cooperative protocol provides a large throughput improvement. This is due to the higher number of packets delivered to their final destination. The achieved throughput decreases as the spreading factor is increased. In fact, although a greater value for N_s enhances the interference rejection capability of the PHY, and consequently increases the success ratio, the proportionally lower bit rate causes a net throughput degradation. For $N_s = 8$, the system performance is strongly reduced in the cooperative case, since the higher number of transmissions, due to multiple cooperators, results in a high failure probability, that outweighs the bit rate gain. In Fig. 4 the average number of delivery attempts per packet (referred to a single hop of the path) is depicted. For both non–cooperative and cooperative protocols, it decreases as the spreading factor is increased. The improvement is more pronounced at lower spreading factor values, while the average number of delivery attempts remains almost constant for N_s greater than 24, because for these values the performance is mainly limited by noise. As for throughput, the cooperative protocol performs better than the non–cooperative scheme, except for N_s equal to 8, where the greater interference generated by cooperation hampers the system reliability.

Our cooperative protocol also improves the effectiveness of packet delivery to distant destinations, thanks to the proposed cooperative packet forwarding scheme. Fig. 5 depicts the average end–to–end throughput achieved by a source–destination pair for different path lengths in terms of hop count. It is interesting to observe that the throughput is improved by cooperation also for single hop paths, due to the higher efficiency of the distributed HARQ scheme. Moreover, also the throughput to out–of–range destinations is greatly enhanced

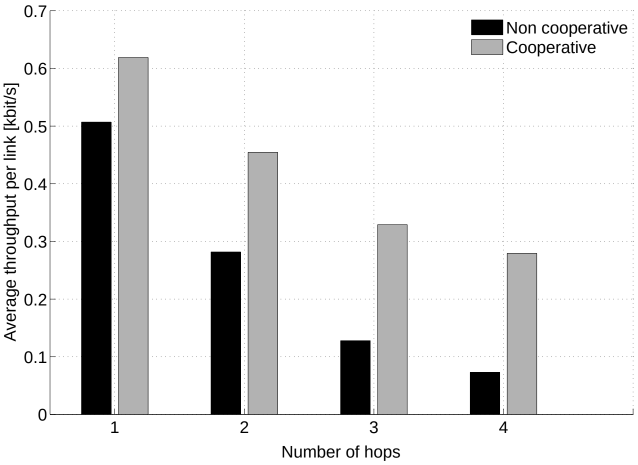

Fig. 5. End–to–end normalized throughput vs. the number of path hops for the cooperative and non–cooperative protocol, $N_s = 16$.

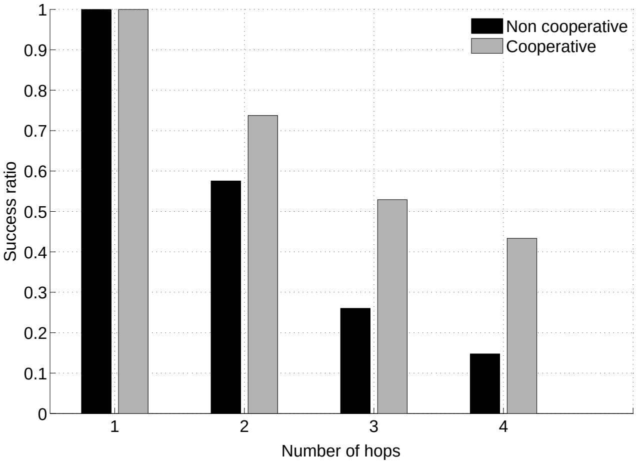

Fig. 6. End–to–end delivery success ratio vs. the number of path hops for the cooperative and non–cooperative protocol, $N_s = 16$.

by the cooperative protocol, thanks to the avoidance of links affected by fading. For instance, the throughput achieved in four-hop paths is increased by more than 200%.

Analogously, also the delivery probability towards distant destinations takes advantage of cooperation, as shown in Fig. 6. It can be seen that in both cases the success ratio decreases for paths which require more hops, although this effect is much more pronounced without cooperation. For four-hop paths the non cooperative protocol shows a delivery ratio of about 0.15, while the cooperative scheme reaches a value almost three times higher.

To sum up, these results document the advantages brought by the introduction of cooperation among nodes. While the distributed HARQ scheme improves the efficiency of in–range communications, dynamic cooperative packet forwarding provides more effective packet delivery.

The grid topology considered here is only a case study to obtain initial results. An exhaustive investigation of the proposed protocol performance for different topologies and parameters is left for future work. However, preliminary simulation results (not shown here due to space limitations) allow similar considerations as for the case presented here.

V. CONCLUSION

In this paper we have proposed a cooperative protocol involving both routing and error control for MIMO–BLAST ad hoc networks. While a distributed HARQ scheme provides reliability to the transmissions towards in–range nodes, a cooperative forwarding scheme enables dynamic route selection to avoid links affected by fading. The presented results show that the proposed protocol can greatly increase the aggregated network throughput and augment the effectiveness in the delivery of packets to distant destinations.

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