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Cooperative Spatial Multiplexing for Ad Hoc Networks with Hybrid ARQ: System Design and Performance Analysis

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Abstract— **For a network where each node has multiple antennas, we propose a transmission mode and a cooperation protocol, with the aim of maximizing the network throughput. The distinctive feature of the work is that the focus in both the design and the evaluation is at the network level, rather than on a single link. To this end, we propose the use of spatial multiplexing and code division multiple access (CDMA) to increase the parallelism of transmissions in the network, thus improving throughput. Cooperation is also implemented by spatial multiplexing and CDMA, together with an adaptive hybrid automatic repeat request mechanism that adapts the retransmissions to the actual channel conditions. Spatial multiplexing allows frame-asynchronous transmissions and a flexible cooperation protocol that minimizes the signaling overhead. The resulting scheme is named layered coded cooperative system (LCCS). We propose an implementation of LCCS based on linear erasure packet codes, where cooperation is transparent to the receiver, and we assess the performance of LCCS both by analyzing a simple network with three nodes and by simulating a more complex network.**

I. INTRODUCTION

COOPERATION among nodes of a wireless ad hoc network has been recently investigated for its potential to provide spatial diversity by implementing a distributed antenna array. Early examples of cooperation are fixed relaying [1]–[3] and selective relaying [4], that have been further enhanced by letting nodes cooperate only when they experience good channel conditions through *opportunistic* techniques [5]. Opportunistic routing [6] exploits the broadcast nature of the wireless channel to communicate through good links, possibly with power and rate adaptation, as in multiuser diversity forwarding (see [7], [8] and references therein). The choice of cooperative nodes then involves also scheduling issues and various solutions have been proposed, including geographic random forwarding (GeRaF) [9] and opportunistic scheduling [10], [11].

A number of issues are still open for the design and evaluation of cooperative diversity from a networking perspective. For example, the existing literature has not thoroughly addressed the dynamic behavior of a network, where cooperation is conditioned upon the availability of nodes not involved in any other transmission, which in turn depends on the adopted medium access control (MAC) technique and on the traffic statistics. In some cases, e.g. [2], transmit and cooperative phases are disciplined by time division multiple access (TDMA), which may lead to spectrum inefficiency. Moreover, at a network level a further protocol should handle the case of a failure in both the initial and the cooperative phases. Another example of MAC for cooperation is described in [12], where code division multiple access (CDMA) allows simultaneous transmissions by multiple users, and TDMA is used to discipline cooperation, thus having the same limitations as the previous scheme. Also in this case cooperative nodes are made always available by considering full-duplex terminals, which are difficult to realize in ad hoc networks. In most works, the issues of the availability of a cooperative nodes and of the bandwidth cost of a cooperative action are often ignored. In addition, the analytical investigation of cooperative mechanisms is typically limited to very simple networks with only three or four nodes [13], a scenario that lends itself to theoretical approaches but may fail to reveal more interesting behaviors at the network level.

A further problem of cooperation in a complex network is node synchronization. For example, the use of space-time block codes (STBC) [14], [15] for cooperation [4], [16], [17] typically requires symbol synchronization among cooperative nodes, which may be very expensive or even infeasible for non-infrastructured networks [17]. Moreover, STBC are designed for a specific number of transmit antennas and some signaling overhead is needed in order to coordinate or select the cooperative nodes.

Differently from the past literature on cooperation, this paper focuses on the implementation of cooperative diversity in a more complex (and more realistic) networking scenario, by considering a significant number of nodes and addressing the design of both physical (PHY) and MAC layers. The aim is the maximization of the sum of the achieved throughput of each node, in terms of correctly received useful bits per second. We consider nodes equipped with multiple antennas [18], [19], in order to address the wider interest on multi-antenna networks as shown by the forthcoming wireless local area networks (W-LAN) standard (see [20] and references therein). The distinctive feature of the proposed protocol is the integration of hybrid automatic repeat request (HARQ) with both spatial multiplexing (SM) and cooperation, to obtain a protocol that adapts spatial diversity and redundancy to the ac-

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tual network conditions. The resulting architecture implements a very flexible scheme for cooperation among nodes with no additional signaling overhead between cooperative nodes and with the source. Moreover, we remove the requirement of symbol synchronization of STBC by using SM and a layered space-time multiuser detector (LASTMUD) at the receive nodes [21]. We name the proposed system as layered coded cooperative system (LCCS). In [22] an integration of HARQ and cooperation has been considered for single antenna systems with synchronous nodes and repetition codes. We generalize this approach by considering multiple antennas per node and better codes (namely linear erasure codes, [23]) applied to the entire data packet. In [24], a technique for implementing uncoordinated cooperation is proposed, which approaches simultaneous node transmissions as a detection issue exclusively focused on the PHY layer, whereas in this paper we integrate PHY issues with HARQ and MAC.

The paper is organized as follows. In Section II we describe PHY, MAC and data link layers of the proposed network. Section III provides an analysis of the performance of LCCS for a simple network of three nodes. Numerical results obtained from this analysis, as well as from extensive simulations of a complete cooperative network with tens of nodes, are presented in Section IV. The main conclusions of the work are outlined in Section V.

II. SYSTEM MODEL

A. Spatial multiplexing and layered receiver

Each node has N antennas and is assigned a pseudo-random spreading sequence for CDMA. The bits to be transmitted are split into N streams, one for each antenna. Then, each stream is spread with the node-specific spreading sequence of N_S chips and all the antennas transmit simultaneously their spread stream on the channel.

The simultaneous transmission on all the antennas has two major consequences: *a*) the transmit power P_{TOT} must be split among the antennas, and *b*) the receiver sees the superposition of the signals coming from all the transmit antennas. As for the first point, we assume that P_{TOT} is uniformly divided among the N antennas so that each antenna transmits at a lower power than in the single antenna case, while the use of multiple transmit antennas yields an increased data rate. For the second issue of signal superposition, a LASTMUD receiver [21] is used. For the sake of a simple analysis, we consider a narrowband transmission, while the extension to a wideband scenario can be easily obtained by using, for example, orthogonal frequency division multiplexing (OFDM) with spreading in the time axis (see [25] for an overview).

Let us suppose that K nodes, denoted with indices $k = 1, 2, \ldots, K$, are transmitting. By letting $\alpha^{(k,m)}$ be the power gain due to the path-loss from node k to node m, the complex channel gain from antenna i of node k to antenna j of node m can be written as $h_{i,j}^{(k,m)} = \sqrt{\alpha^{(k,m)}} g_{i,j}^{(k,m)}$, where $g_{i,j}^{(k,m)}$ is a random variable accounting for fading.

Let $\boldsymbol{S}$ be the $N_S \times K$ matrix collecting in its kth column the spreading code of node k. Let $\boldsymbol{H}_j^{(k,m)} = [h_{1,j}^{(k,m)}, h_{2,j}^{(k,m)}, \ldots, h_{N,j}^{(k,m)}]$ be the N-size row vector of the complex channel gains from the N antennas of node k to antenna j of node m. We collect all channel vectors for antenna j of receive node m in the diagonal matrix $\boldsymbol{C}_j^{(m)}$, i.e. $\text{diag}\{\boldsymbol{C}_j^{(m)}\} = [\boldsymbol{H}_j^{(1,m)}, \boldsymbol{H}_j^{(2,m)}, \ldots, \boldsymbol{H}_j^{(K,m)}]$. Let $\boldsymbol{d}$ be the column vector of the data symbols transmitted simultaneously by all N antennas of each of the K nodes and let us define the $N_S \times NK$ matrix $\boldsymbol{S}' = \boldsymbol{S} \otimes \boldsymbol{1}_N$, where $\otimes$ is the Kroneker product and $\boldsymbol{1}_N$ is a row vector of all ones and size N. The set of N_S chips received by node m on antenna j can be written as [21]

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

where $\boldsymbol{\omega}_j^{(m)}$ is an N_S column vector of complex Gaussian noise samples with zero mean and power σ^2. A key component of our layered coded cooperative system (LCCS) is the LASTMUD receiver. The receive node m extracts a sufficient statistics for decoding by applying a matrix filter matched to the channel and summing the contributions of all the antennas. Following the derivations of [21], by defining the $KN \times KN$ correlation matrix

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

the output of the matched receiver is the KN-size vector

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

where $\boldsymbol{n}^{(m)}$ is the filtered noise and ^{H} is the Hermitian operator. Then $\tilde{\boldsymbol{r}}^{(m)}$ is processed in KN stages. At each stage, decoding of an antenna signal is performed and its interference contribution on the received signal is generated. Before decoding a new antenna, the contributions of all previously decoded antennas are removed from the received signal, in order to reduce interference. Note that a receive node may decode packets even when they are intended for other receivers, in order to reduce interference on its own packets. Further details on the LASTMUD receiver can be found in [21].

B. Medium Access Control protocol

Traditional access protocols for ad hoc networks try to avoid collisions, i.e., simultaneous transmissions in the same neighborhood that would interfere and result in data loss and waste of resources. In LCCS, instead, simultaneous transmissions are possible thanks to CDMA and SM and thus we design the MAC protocol with the aim of increasing the network throughput.

Transmission is organized in *time slots* and each data packet spans multiple slots. Each slot comprises *a*) a short training sequence used by receive nodes to estimate the channel; *b*) a header identifying the source and destination nodes and *c*) control or data bits.

Before data transmission, a handshake phase is established between the source and the destination nodes. First, the source sends a Request Packet (RP), which contains the identifiers of source, destination and packet, as well as the duration of the requested transmission. If the destination node is not already involved in another communication and successfully decodes RP, it responds with a Grant Packet (GP) in the following slot. Note that a node may receive several requests in a single slot and many granting policies could be implemented. For instance, selecting the request with the maximum received power is likely the best for link reliability, but may be unfair. However, the exploration of the best granting policy is beyond the scope of this paper, and we consider a random choice among the received requests. The handshake avoids transmission of long data packets to unreachable destinations. For the same purpose, nodes keep an *occupancy table* with the expected number of slots before a neighbor becomes idle and delay RP transmissions accordingly. Information on nodes' activity is extracted from any detected packet, including packets detected for interference cancelation purposes.

After the handshake, the source transmits the packet as described in Section II-C. The receiver reports the success or failure of the packet decoding through Feedback Packets (FP) of acknowledge (ACK) or non-acknowledge (NACK). We assume that transmission of control and data packets is performed in time-adjacent slots and that the delays due to processing and propagation are negligible.

We also assume that each control packet (RP, GP and FP) fits the duration of a single slot and therefore has a limited impact on communication efficiency. Still, their reception is of paramount importance for network performance, thus we assume that they are transmitted using only one antenna at full power P_{TOT}, and are protected by a convolutional code of rate $1/2$ with generator polynomial given in Table I.

Note that we exploit SM and CDMA for multiple access so that nodes do not perform carrier sensing before accessing the channel. For the same reason, unlike in the IEEE 802.11 distributed coordination function, in our protocol the reception of a handshake packet does not prevent nodes from accessing the channel for the duration of the forthcoming data transmission. Still, since the number of simultaneous transmissions is limited by the spreading factor and spatial properties of the channel, we include in the protocol a backoff mechanism that limits repeated transmission attempts. Link failures (i.e., GP or FP is not received, or a NACK is reported at the end of the transmission) force a source node to defer any other transmission for a number of slots B, randomly chosen in the exponentially increasing window $[1, 2^{N_{\text{fail}}} \times W]$, where W is the initial window value and N_{fail} is the minimum between the number of consecutive failures and $Max_{N_{\text{fail}}}$. At each correct detection, N_{fail} is decreased by one unlike in conventional backoff in which it is reset to zero. Preliminary simulations show that this window policy achieves a better performance and is more adaptive to network conditions than the standard technique. A detailed analysis of this issue is left for future study.

C. HARQ protocol

The performance of decoding algorithms is highly dependent on the received power, the number of incoming signals and the channel conditions. All these quantities may change in each slot and the estimation of the channel coding rate needed to successfully transmit cannot be performed in the handshake phase. In order to counteract variations in link conditions, we include in our protocol an adaptive HARQ error control scheme that combines the benefits of forward error correction (FEC) and ARQ providing *incremental redundancy*. We want to stress that the proposed protocol admits several different implementations. In this and the following Sections we outline the general characteristics of both HARQ and cooperative HARQ, whereas in Section II-E a specific implementation is proposed and discussed.

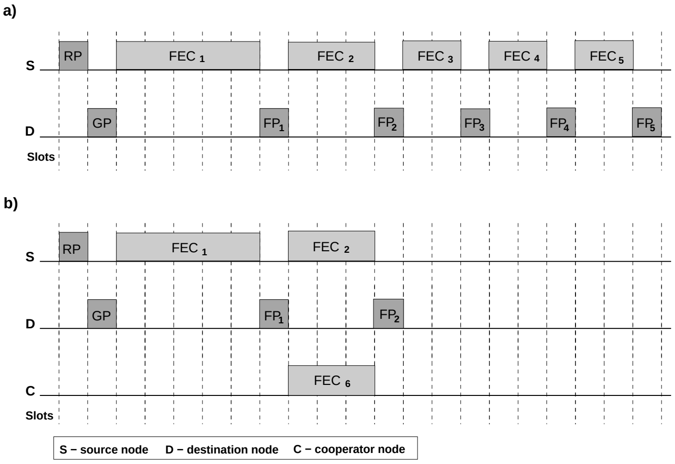

Fig. 1. Example of transmission for the non-cooperative (a) and the cooperative (b) protocol.

Each data packet is encoded with an error correcting code and transmission is performed in several FEC phases, each providing a different portion of the coded packet. In particular, at FEC phase p, a subset $\mathcal{F}_p$ of the coded bits is transmitted using one or more slots. We will discuss the choice of $\mathcal{F}_p$ and its size in Section II-E. Together with $\mathcal{F}_p$, in each phase the source node transmits checksum bits that allow the destination to understand whether or not that subset has been received correctly. In the next slot, the destination replies with an ACK or NACK, accordingly. An ACK causes the source to stop FEC phases. After a NACK at the pth FEC phase, the source transmits $\mathcal{F}_{p+1}$. If M_{fec} FEC phases have been performed and the destination still reports a failure, the source defers the transmission of the packet by B slots. After M_{tx} failed packet transmission attempts, the packet is dropped.

Fig. 1 (a) shows an example of operation of the proposed adaptive HARQ scheme, where the source performs five FEC phases. The proposed HARQ scheme effectively adapts the coding rate to the channel condition, providing incremental redundancy when the destination fails to decode the packet with the previously received parts of the codeword. The source reschedules a new delivery attempt after the failure of M_{fec} FEC phases in order to diminish the load of the network, refraining from further redundancy transmissions under bad channel conditions.

D. Cooperative HARQ protocol

Cooperation is well known to provide advantages due to spatial diversity obtained by relaying data through cooperative nodes. In our protocol, the destination node already decodes multiple streams coming from the antennas of the source as well as interfering nodes. Therefore, the proposed PHY and MAC layers can be easily adapted for cooperation by letting cooperative nodes transmit incremental redundancy simultaneously with the source. In particular, idle nodes that correctly decode the packet at the first FEC phase and receive a NACK from the destination, may cooperate by re-encoding the packet and transmitting redundancy to the destination node. Cooperation is dismissed at the reception of an ACK or after $M_{\rm fec}$ FEC phases. Observe that cooperative and source transmissions are simultaneous and have the same duration, although the transmitted subsets $\mathcal{F}_p$ may be different for the two transmitting nodes.

In Fig. 1 (b), an example of cooperative transmission is shown. It is important to remark that the channels of source and cooperative nodes are independent. Thus, in slow fading environments, the cooperative nodes may resolve the delivery more efficiently than the source. Note also that cooperation becomes active only upon a NACK, therefore avoiding unnecessary FEC phases.

Cooperator choice. In order to optimize cooperation, we let nodes cooperate only when they have a better chance than the source of being correctly decoded by the destination. In particular, each candidate node compares the signal to noise plus interference ratio (SNIR) of its own link to the destination ($SNIR_{CD}$) with the SNIR of the source-destination link ($SNIR_{SD}$) and cooperates only if $SNIR_{CD} > SNIR_{SD}$. For this purpose, the destination node includes an estimate of $SNIR_{SD}$ in each GP while $SNIR_{CD}$ is estimated through FP.

Multiple cooperative nodes. Our cooperation scheme is completely transparent to the source, and does not require additional signaling or negotiation, since the receiver is able to identify useful sub-packets by header inspection. Several nodes may cooperate for the same transmission with no need for coordination, although too many packets may overload the receivers.

It is important to observe that our protocol enables nodes to establish new links while other communications are active in their neighborhood. Thus, a drawback of our protocol is that cooperative nodes are deaf to incoming RP packets when transmitting, since we consider half-duplex terminals. Moreover, transmission of packets originated in cooperative nodes is delayed for the duration of the cooperation. This may result in throughput loss and delay degradation at the cooperative nodes. On the other hand, by providing channel diversity, cooperation yields an improved efficiency and, consequently, a lower average interference. Simulation results will show that the balance between drawbacks and advantages is in favor of cooperation for the considered scenario.

In the following, the non-cooperative protocol is referred to as layered coded system (LCS), while the cooperative protocol is referred to as LCCS.

E. Implementation by packet coding

In this Section we propose an implementation of the HARQ protocol through linear erasure codes (LEC), specifically designed for error control in packet networks. Examples of LEC are the codes of [23] and the burst erasure correction codes with low decoding delay of [26], both of which have been recently studied in a networking context in [27]. Packet coding is particularly useful in transmissions affected by bursty interference, as in our system where several nodes transmit simultaneously and interference affects entire packets.

A LEC of rate r_c is defined by the triple $(U, r_c, \boldsymbol{G})$, where U is an integer and $\boldsymbol{G}$ is a $(U/r_c) \times U$ *generator matrix*, with elements taken from the Galois field GF(2^b). For the encoding of a data packet of L_{pkt} bits, the bits are first grouped into symbols of b bits each and then split into U blocks $\boldsymbol{a}_u$, $u = 1, 2, \ldots, U$ of $M = L_{pkt}/(bU)$ symbols each. The LEC encoder generates $L = U/r_c$ coded blocks as follows

$$\boldsymbol{b}_\ell = [\boldsymbol{G}]_{\ell,1}\boldsymbol{a}_1 \oplus [\boldsymbol{G}]_{\ell,2}\boldsymbol{a}_2 \oplus \ldots \oplus [\boldsymbol{G}]_{\ell,U}\boldsymbol{a}_U \,, \tag{4}$$

where $\ell = 1, 2, \ldots, L$ and $\oplus$ denotes the element-wise sum in GF(2^b) of vectors. In the following, the coded blocks $\boldsymbol{b}_\ell$ will be denoted as *sub-packets* of the data packet. Without restriction, we consider a systematic LEC for which $\boldsymbol{b}_\ell = \boldsymbol{a}_\ell$ with $\ell = 1, 2, \ldots, U$.

An interesting property of any LEC having full-rank generating matrix is that if any U out of the L sub-packets $\boldsymbol{b}_\ell$ are correctly decoded, then the entire packet can be recovered [23]. Let $\mathcal{C} = \{\kappa_1, \kappa_2, \ldots, \kappa_U\}$ be the indices of the correctly decoded sub-packets and let $\bar{\boldsymbol{G}}_{\mathcal{C}}$ be the matrix containing the columns of $\boldsymbol{G}$ with index in $\mathcal{C}$. Since $\boldsymbol{G}$ is full-rank, $\bar{\boldsymbol{G}}_{\mathcal{C}}$ is also full rank and can be inverted in GF(2^b), to obtain $\bar{\boldsymbol{G}}_{\mathcal{C}}^{-1}$. By combining the decoded sub-packets with $\bar{\boldsymbol{G}}_{\mathcal{C}}^{-1}$, we obtain the original U data blocks

$$\boldsymbol{a}_u = [\bar{\boldsymbol{G}}_{\mathcal{C}}^{-1}]_{u,1}\boldsymbol{b}_{\kappa_1} \oplus [\bar{\boldsymbol{G}}_{\mathcal{C}}^{-1}]_{u,2}\boldsymbol{b}_{\kappa_2} \oplus \ldots \oplus [\bar{\boldsymbol{G}}_{\mathcal{C}}^{-1}]_{u,U}\boldsymbol{b}_{\kappa_U} \,, \tag{5}$$

where $u = 1, 2, \ldots, U$.

According to the general description of the previous Section, we consider that each subset $\mathcal{F}_p$ is an ensemble of sub-packets $\boldsymbol{b}_\ell$. In particular, $\mathcal{F}_1 = \{\boldsymbol{b}_\ell\}_{\ell=1,2,\ldots,U}$. Then $\mathcal{F}_p$, $p = 2, \ldots, M_{\rm fec}$, contains a variable number of sub-packets, according to the number of sub-packets that have been correctly decoded by the destination in the previous FEC phases. In particular, if the destination at FEC phase p has decoded ν_p sub-packets, with $\nu_p < U$, the NACK contains the number of missing sub-packets $H_p = U - \nu_p$, and the indices of the correctly decoded sub-packets. At FEC phase $p+1$, $\mathcal{F}_{p+1}$ contains H_p randomly selected sub-packets, excluding those correctly decoded. Note that if the NACK does not include the indices of the correctly decoded sub-packets, the same sub-packet may be re-transmitted, even if it has already been correctly decoded by the destination. Therefore, the signalling overhead is reduced at the expense of a slight coding gain reduction.

While both the source and the cooperative nodes follow the same rules for the choice of the length of the FEC sets, the index of the transmitted sub-packets is in general different. Still, since the transmission from the source and the cooperative node is not coordinated, the destination may receive multiple copies of the same sub-packet. In this case the protocol incurs a slight loss of efficiency, that could be avoided by devising more sophisticated solutions, left for future study.

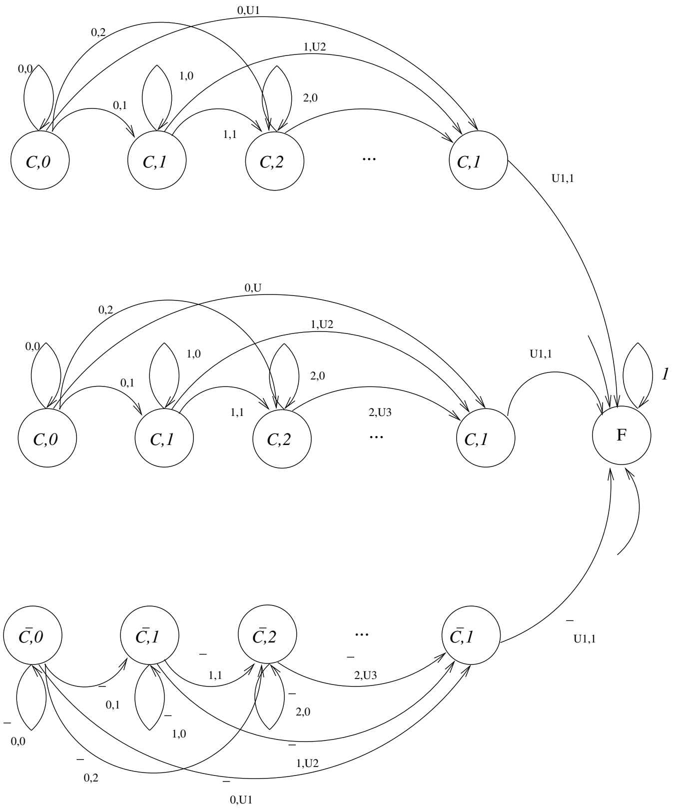

Fig. 2. Example of Markov chain for LCCS.

III. Analysis of LCCS

In order to gain some fundamental insight into the behavior of LCCS we analyze a simple network with a source node S, a destination node D, and a possible cooperative node C. This kind of analysis has been commonly used in the literature for assessing the performance of cooperative protocols [1]–[3], [13]. Node C may be in one of three states for the duration of an entire session of FEC phases between S and D: a) *idle state*, when it does not cooperate because it failed to decode the first FEC phase and it does not transmit to any other node; b) *cooperation state*, when it cooperates with S; and c) *busy state*, when it is transmitting to a node other than D. The busy state occurs with probability π_{B} and in this case node C interferes with the transmission between S and D. We do not consider here the effect of the presence of other nodes (e.g., nodes communicating with C when it is busy).

The behavior of this simple LCCS network using LEC for HARQ can be described by the Markov chain of Fig. 2, where states identify both the number of correctly decoded sub-packets ν at the end of each FEC phase and the status of node C, where (C,ν), $(\bar{C},\nu)$ and $(\hat{C},\nu)$ refer to cooperation, idle and busy status, respectively. The Markov chain has also a state F, which corresponds to the correct decoding of U sub-packets, i.e., the packet is correctly received. The first FEC phase sets the initial state of the Markov chain. Let p_ν, $\bar{p}_\nu$ and $\hat{p}_\nu$ be the probability of being in state (C,ν), $(\bar{C},\nu)$ and $(\hat{C},\nu)$ at the end of the first FEC phase, respectively. In particular, let z_ν, be the probability that node D has correctly decoded ν sub-packets in the first FEC phase, conditioned on the fact that C is not busy.

As we mentioned above, we assume that node C cooperates only if it has decoded U sub-packets, i.e., it is able to decode the entire packet. Let π_{C} be the probability that node C decodes all U sub-packets. The probability of being in state (C,ν) at the end of the first FEC phase is $p_\nu = z_\nu \pi_{\mathrm{C}}(1-\pi_{\mathrm{B}})$, $\nu = 0, 1, \ldots, U-1$. On the other hand, the probability that node D has correctly decoded ν sub-packets and node C is neither collaborating nor interfering is $\bar{p}_\nu = z_\nu(1-\pi_{\mathrm{B}})(1-\pi_{\mathrm{C}})$, $\nu = 0, 1, \ldots, U-1$.

Given that node C is busy, let $\hat{z}_\nu$, $\nu = 0, 1, \ldots, U$ be the conditional probability that node D correctly decodes ν sub-packets at the end of the first FEC phase, then the probability of being in state $(\hat{C},\nu)$ at the end of the first FEC phase is $\hat{p}_\nu = \hat{z}_\nu \pi_{\mathrm{B}}$, $\nu = 0, 1, \ldots, U-1$. The probability that node D decodes all U sub-packets in the first FEC phase is $\tilde{p} = (1-\pi_{\mathrm{B}})z_U + \pi_{\mathrm{B}}\hat{z}_U$.

The next FEC phases correspond to transitions in the Markov chain of Fig. 2 and the state is updated according to the number of new sub-packets decoded by D in each phase. For a cooperative transmission, let $q_{\nu,\mu}$ be the probability that μ sub-packets are decoded out of $U-\nu$ sub-packets transmitted by node S and $U-\nu$ sub-packets transmitted by node C. Note that $q_{\nu,\mu}$ has a different statistical description from p_ν, since in the first FEC phase only S transmits, while $q_{\nu,\mu}$ accounts for simultaneous transmissions from both S and C. When node C is idle, $\bar{q}_{\nu,\mu}$ is the transition probability from state $(\bar{C},\nu)$ to state $(\bar{C},\nu+\mu)$. When node C is busy with another transmission, the transition probabilities from state $(\hat{C},\nu)$ to state $(\hat{C},\nu+\mu)$ are indicated as $\hat{q}_{\nu,\mu}$. Lastly, transition probabilities from states (C,ν), $(\bar{C},\nu)$, $(\hat{C},\nu)$ to state F are collected into the U-size column vectors $\boldsymbol{t} = [q_{0,U}, q_{1,U-1}, \ldots, q_{U-1,1}]^T$, $\bar{\boldsymbol{t}} = [\bar{q}_{0,U}, \bar{q}_{1,U-1}, \ldots, \bar{q}_{U-1,1}]^T$ and $\hat{\boldsymbol{t}} = [\hat{q}_{0,U}, \hat{q}_{1,U-1}, \ldots, \hat{q}_{U-1,1}]^T$, respectively. ^{T} denotes the transpose operator.

From the Markov chain of Fig. 2 we capture two distinctive features of LCCS, namely a) the cooperative behavior, which is reflected into the sub-chain (C,ν), and b) HARQ, which is reflected into the U states of each sub-chain. Moreover, in LCCS there may be simultaneous transmissions to different destinations and this is reflected by the probability that node C is busy.

Let $\boldsymbol{T}$ be a $U \times U$ matrix with entries

$$[\boldsymbol{T}]_{\ell_1,\ell_2} = \begin{cases} q_{\ell_1-1,\ell_2-\ell_1} & \ell_1,\ell_2 = 1,2,\ldots,U,\ \ell_1 \geq \ell_2 \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

and let $\bar{\boldsymbol{T}}$ and $\hat{\boldsymbol{T}}$ be defined analogously to $\boldsymbol{T}$ with $\bar{q}_{\ell_1-1,\ell_2-\ell_1}$ and $\hat{q}_{\ell_1-1,\ell_2-\ell_1}$ instead of $q_{\ell_1-1,\ell_2-\ell_1}$

The evolution of the Markov chain is governed by the transition probability matrix

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{T} & \boldsymbol{0}_{U\times U} & \boldsymbol{0}_{U\times U} & \boldsymbol{t} \\ \boldsymbol{0}_{U\times U} & \bar{\boldsymbol{T}} & \boldsymbol{0}_{U\times U} & \bar{\boldsymbol{t}} \\ \boldsymbol{0}_{U\times U} & \boldsymbol{0}_{U\times U} & \hat{\boldsymbol{T}} & \hat{\boldsymbol{t}} \\ \boldsymbol{0}_{1\times U} & \boldsymbol{0}_{1\times U} & \boldsymbol{0}_{1\times U} & 1 \end{bmatrix}. \tag{7}$$

Let also $\boldsymbol{s}(u) = [\boldsymbol{s}_C(u)\,, \boldsymbol{s}_{\bar{C}}(u)\,, \boldsymbol{s}_{\hat{C}}(u)\,, s_F(u)]$ be the $3U+1$ row vector of state probabilities at the uth FEC phase, where

$\boldsymbol{s}_C(u)$ is the U row vector containing the probabilities of states $(C,0),(C,1),\ldots,(C,U-1)$. $\boldsymbol{s}_{\bar{C}}(u)$ and $\boldsymbol{s}_{\hat{C}}(u)$ are defined analogously to $\boldsymbol{s}_C(u)$ with states $(\bar{C},\nu)$ and $(\hat{C},\nu)$, respectively, instead of (C,ν). Lastly, $s_F(u)$ is the probability of being in state F. At the end of the first FEC phase, the state probabilities are

$$\boldsymbol{s}(1)=[p_0,\ldots,p_{U-1},\hat{p}_0,\hat{p}_1,\ldots,\hat{p}_{U-1},\bar{p}_0,\ldots,\bar{p}_{U-1},\tilde{p}]\,, \tag{8}$$

while at end of FEC phase u the state probabilities are $\boldsymbol{s}(u)=\boldsymbol{s}(u-1)\boldsymbol{P}$, $u=2,3,\ldots,M_{\text{fec}}$.

Since at each FEC phase node S (and C) retransmits in sequence a number of sub-packets equivalent to those that have not been decoded, the average number of sub-packets transmitted by the source after u FEC phases is

$$\tau(u)=U+\sum_{v=1}^{u-1}\sum_{\ell=1}^{U}(U-\ell+1)\{[\boldsymbol{s}_C(v)]_\ell+[\boldsymbol{s}_{\bar{C}}(v)]_\ell+[\boldsymbol{s}_{\hat{C}}(v)]_\ell\}\,,$$

where $\tau(1)=U$. Hence, the average throughput after u FEC phases is

$$T(u)=b_p\frac{s_F(u)}{T_s\cdot S_s\cdot\tau(u)}\,, \tag{9}$$

where T_s is the symbol period, S_s is the number of symbols per sub-packet and b_p is the number of data bits of one packet.

A. Transition probabilities computation

We derive the transition probabilities of the LCCS Markov chain under the following assumptions: *a*) error propagation is neglected; *b*) Rayleigh fading is assumed with unit power; *c*) channels do not change within a sub-packet transmission and are independent for each sub-packet (*block fading*) and *d*) BPSK modulation is used.

We assume that signals coming from different nodes are almost orthogonal, due to CDMA, so that the pseudo-inverse of (2) is equal to the pseudo-inverse of the correlation matrix obtained without detection of the interfering node. Still, we model the residual interference as a random vector of size NN_S. This vector is projected on the vector obtained by matched filtering (3) and despreading [21]. Assuming the spreading factor is large enough, the resulting variable is complex Gaussian distributed with zero mean and variance $1/(NN_S)$. Its squared magnitude has probability density function (pdf) $f_I(y)=NN_Se^{-NN_Sy}$, $y\geq 0$. Suppose that node D attempts to decode signals coming from a node with path loss α, under the interference from a node with path loss β. The probability of correctly decoding a block of M/N BPSK symbols at the LASTMUD stage θ is [28]

$$\zeta(\theta,\alpha,\beta)=\int_0^\infty\int_0^\infty\left[1-Q\left(\sqrt{\frac{x\alpha^2}{y\beta^2+\sigma^2}}\right)\right]^{M/N} f_H(x,\theta)f_I(y)dxdy \tag{10}$$

where $\theta=1,2,\ldots,N$, $Q(\cdot)$ is the complementary normalized Gaussian distribution function and $f_H(x,\theta)$ is the pdf of the power gain x relative to the antenna decoded at stage θ of LASTMUD. It has been shown in [28] that x is chi-square distributed with 2θ degrees of freedom, i.e.

$$f_H(x,\theta)=\left[2^\theta\Gamma(\theta)\right]^{-1}x^{\theta-1}e^{-x/2}\,,\quad x\geq 0\,. \tag{11}$$

The probability of decoding μ sub-packets out of the ℓ transmitted is

$$\varphi(\alpha,\beta,\ell,\mu)=\binom{\ell}{\mu}\left[\prod_{\theta=1}^{N}\zeta(\theta,\alpha,\beta)\right]^{\mu}\left[1-\prod_{\theta=1}^{N}\zeta(\theta,\alpha,\beta)\right]^{\ell-\mu}\,. \tag{12}$$

Let $\alpha^{(S,D)}$ be the path loss between S and D and $\alpha^{(C,D)}$ the path loss between node C and D. Let $\alpha^{(S,C)}$ be the path loss between S and C. We also assume that when C cooperates, node D first decodes signals coming from C and then those coming from S. In this case, the reception of sub-packets from C is interfered by S, while, assuming perfect cancellation in the LASTMUD receiver, the reception of sub-packets from S has no interference.

First FEC phase. In the first FEC phase U sub-packets are transmitted by the source and we have $z_\nu=\varphi(\alpha^{(S,D)},0,U,\nu)$ and $\pi_{\text{C}}=\varphi(\alpha^{(S,C)},0,U,U)$. If node C is busy, we have $\hat{z}_\nu=\varphi(\alpha^{(S,D)},\alpha^{(C,D)},U,\nu)$.

Non-cooperative FEC phases. Suppose that ν sub-packets have been correctly received, assuming that the source transmits $U-\nu$ sub-packets, the transition probability from state $(\bar{C},\nu)$ to state $(\bar{C},\nu+\mu)$ is $\bar{q}_{\nu,\mu}=\varphi(\alpha^{(S,D)},0,U-\nu,\mu)$, where $\mu=0,1,\ldots,U-\nu-1$. If C is busy, we obtain $\hat{q}_{\nu,\mu}=\varphi(\alpha^{(S,D)},\alpha^{(C,D)},U-\nu,\mu)$, where $\mu=0,1,\ldots,U-\nu-1$.

Cooperative FEC phases. If C cooperates, both S and C transmit $U-\nu$ sub-packets. Assuming that D first decodes signals coming from C and then those coming from S, the transition probabilities can be written as

$$q_{\nu,\mu}=\sum_{\ell=0}^{\mu}\varphi(\alpha^{(C,D)},\alpha^{(S,D)},U-\nu,\ell)\,\varphi(\alpha^{(S,D)},0,U-\nu,\mu-\ell)\,, \tag{13}$$

where $\mu=0,1,\ldots,U-\nu-1$.

IV. NUMERICAL RESULTS

In this Section we present and discuss the performance of the system proposed in Section II-E. Table I summarizes the values of all the parameters. We consider a transmission in the 5 GHz ISM frequency band and BPSK modulation with 99% in–band power, so that packet transmission may afford up to $7.5/N_S$ Mbps per used tx antenna and the block channel variation assumption is reasonable.

A. Analytical results

The performance of the network of Section III is evaluated in terms of throughput (9) as a function of the average SNR between S and D, $SNR^{(S,D)}=\alpha^{(S,D)}/\sigma^2$, and the average SNR between C and D, $SNR^{(C,D)}=\alpha^{(C,D)}/\sigma^2$, while we assume that the average SNR between S and C is fixed

TABLE I
PARAMETERS FOR SIMULATION

PHY Parameters	value
Modulation	BPSK
Antennas per node N	2
Spreading factor N_S	16
Bit-rate per antenna B_w	468.75 kbit/s
Operating band	5.8 GHz ISM
$P_{\rm TOT}$	0.25W
Data packet length (L_{pkt})	4096 bit
Erasure code parameters (U,r_c)	(8, 1/3)
Block length ($M = L_{pkt}/U$)	512 bit
Noise power σ^2	-170 dBm
Signaling FEC polynomial (rate 1/2)	$133_8, 171_8$

HARQ parameters	value
$M_{\rm tx}$	8
$M_{\rm fec}$	10
$Max_{N_{\rm fail}}$	6

Simulation parameters	value
Number of nodes ($K_{\rm tot}$)	36
Network topology	150 × 150 m square grid
Channel correlation ρ	0.9
Number of simulated slots	400000

Queue and backoff parameters	value
Queue timeout Q_{TO}	4096 slots
Queue length	Q_{pkt} pkt
W	4

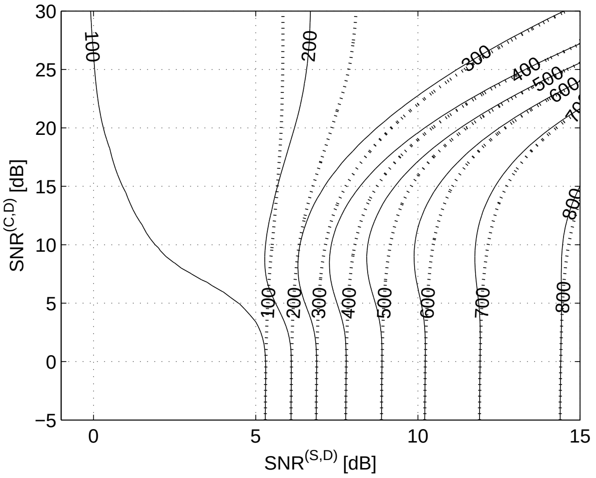

Fig. 3. Average throughput in kbit/s as a function of the average $SNR^{(S,D)}$ and the average $SNR^{(C,D)}$. $SNR^{(S,C)} = 20$ dB for LCCS (solid lines) and LCS (dashed lines).

$(SNR^{(S,C)})_{\rm dB} = 10\log_{10}[\alpha^{(S,C)}/\sigma^2] = 20$ dB. The channel is assumed block-fading with independent Rayleigh fading coefficients.

The results are obtained with PHY layer and HARQ parameters as indicated in Table I. In the throughput computation the overhead due to sub–packet header and checksum is neglected. We compare the performance of LCCS and LCS. Fig. 3 shows the isometric lines of the average throughput in kbit/s as a function of $SNR^{(S,D)}$ and $SNR^{(C,D)}$ for $\pi_{\rm B} = .2$. We plot the performance of LCCS (solid lines) and LCS (dashed lines) and we note that LCCS gains about 1 dB in $SNR^{(S,D)}$ when $SNR^{(C,D)}$ is in the range 5 to 15 dB. For a given $SNR^{(S,D)}$ and for an increasing $SNR^{(C,D)}$ we observe that initially the throughput increases, thanks to the advantage provided by cooperation. However, for very high $SNR^{(C,D)}$ we incur a throughput degradation due to the interference caused by node C when it is busy. Lastly, note that LCS sees a performance degradation as $SNR^{(C,D)}$ increases, even if it is not cooperating. This is due to the fact that when C is busy in another transmission, it interferes with the communication between S and D, and the interference power increases with the channel gain between C and D, i.e., with $SNR^{(C,D)}$. Fig. 4 shows the average throughput as a function of the busy probability $\pi_{\rm B}$ for $SNR^{(S,D)} = 6$ dB, $SNR^{(C,D)} = 10$ dB and $SNR^{(S,C)} = 20$ dB. We observe that as the busy probability increases the network becomes less cooperative.

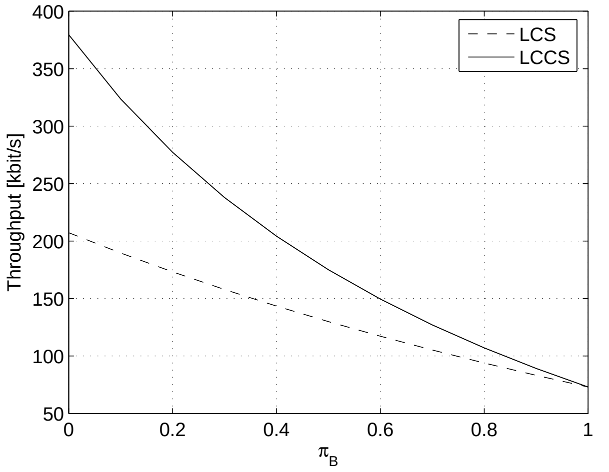

Fig. 4. Average throughput as a function of the busy probability $\pi_{\rm B}$. $SNR^{(S,D)} = 6$ dB, $SNR^{(C,D)} = 10$ dB and $SNR^{(S,C)} = 20$ dB.

B. Simulation results

A main goal of this paper is to design a cooperative system that works effectively in a simultaneous access network environment. Most of the literature, with few exceptions such as [29], shows performance for small networks with very few nodes. A distinctive feature of this work is that performance is assessed through the simulation of MAC/PHY layers of a network with tens of nodes, as reported in Table I. We set up a one–hop fully connected $L \times L$ sized grid network with $K_{\rm tot}$ nodes, providing a maximum distance between nodes equal to the coverage range measured without interference. The packet arrival for each node is a Poisson process of rate λ [pkt/s]. Packets are served with a First In–First Out (FIFO) policy and are discarded after a maximum of Q_{TO} slots spent in the queue. The queue stores at most Q_{pkt} packets. Note that each of the $K_{\rm tot}$ nodes may cooperate or operate as source or destination, and accesses the channel without any restriction but the backoff mechanism. This scenario allows to assess the protocol efficiency in balancing the resources since nodes have the option to either cooperate or transmit their own packets.

The PHY layer and the access protocol are those considered in Sections II-A and II-B, respectively. By preliminary simulations we have selected the spreading factor in order to obtain a good balance between the spectral efficiency and the

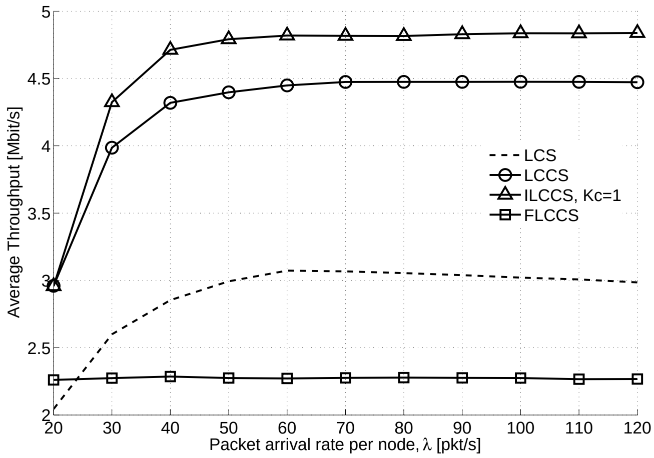

Fig. 5. Average network throughput as a function of the per node arrival rate λ for the simulation parameters of Table I.

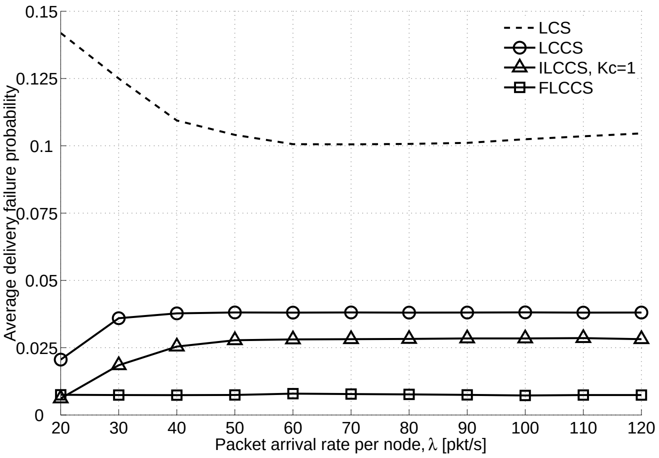

Fig. 6. Average transmission error rate as a function of the per node arrival rate λ for the simulation parameters of Table I.

interference level. Indeed, the spreading factor could be optimized in order to maximize the overall network throughput, trading off between interference level and spectral efficiency. A useful quantity to be optimized could be the information efficiency [30], [31]. However, this optimization should take into account the traffic load as well as channel characteristics and would result in an adaptive technique, which is left for future investigation.

Channel variations are described with an autoregressive moving average (ARMA) model [32], [33] and the complex fading coefficient for slot t is $g_{i,j}^{(k,m)}(t) = \rho g_{i,j}^{(k,m)}(t-1) + \sqrt{1-\rho^2}\xi(t)$ where ρ is the correlation coefficient and $\xi(t)$ are independent complex Gaussian variables with zero mean and unit variance. The path-loss has been modeled according to Hata, i.e. $\alpha^{(k,m)} \propto [d^{(k,m)}]^{-4}$, where $d^{(k,m)}$ is the distance between nodes k and m. We assume perfect channel estimation. Detection performance of LASTMUD at each receive node is assessed by the semi-analytical technique of [34].

In order to achieve a deeper understanding of the effects of cooperation on the network performance, we also consider two variants of LCCS:

- **Forced LCCS (FLCCS)**: an idle node C that correctly decodes an RP/GP exchange and matches SNR requirements for cooperation, is forced to maintain the idle state until D transmits FP, or until C fails to decode a subpacket.
- **Idealized LCCS (ILCCS)**: K_C cooperative nodes per communication are chosen among all the candidates, i.e., idle nodes that correctly receive the data packet. The K_C candidates with the highest SNR from the destination are chosen. Simulations are performed with $K_C = 1$. Note that a real implementation of the selection of cooperative nodes would require a high coordination overhead and may not be a viable solution from a protocol perspective. Nevertheless, ILCCS is provided as a guideline for protocol design and for comparison with the uncoordinated version.

Fig. 5 shows the overall network throughput, as a function of λ, where the throughput is calculated over the successfully received and acknowledged data packets. We first observe that in a fully connected IEEE 802.11 network where only one node is allowed to transmit at a given time, the maximum network throughput coincides with the maximum node throughput, which in our simulation scenario is 937.5 kbit/s for a node with two antennas. In our system instead, nodes may transmit simultaneously, achieving a higher network throughput for both LCS and LCCS, despite signaling and redundancy overhead. Moreover, both LCCS and ILCCS outperform LCS, meaning that the throughput gain due to cooperation is larger than the throughput loss due to deferring a node's own communications. Still, a balance between cooperation and non-cooperation is needed, since even FLCCS, that forces cooperation, has a lower throughput than LCCS and ILCCS. Lastly, LCCS and ILCCS perform similarly in this environment, although a totally uncoordinated behavior may result in too many cooperative nodes in more dense networks. This may be counteracted, e.g., with the identification of groups of cooperative nodes or with a probabilistic selection of cooperative nodes.

Fig. 6 shows the average probability that a destination fails to decode the data packet after M_{fec} FEC phases. All the cooperative protocols achieve a lower failure rate than LCS, since cooperative transmissions provide higher coding and diversity gains. On the other hand, when more nodes are cooperating, the interference level is increased and we observe that ILCCS obtains a lower failure probability than LCCS because it selects the best cooperative node among all the candidates and enhances coding and diversity gains while limiting the interference. Indeed, the limitation of the interference allows FLCCS to achieve the lowest failure rate among all the presented schemes. In fact, nodes that correctly decode a RP/GP exchange are forced to keep the idle state in order to decode the ongoing data transmission, and the number of simultaneous communications is lowered, so that the receiver is not overloaded.

Simulation results, not reported due to lack of space, show that the performance of the network, in terms of throughput

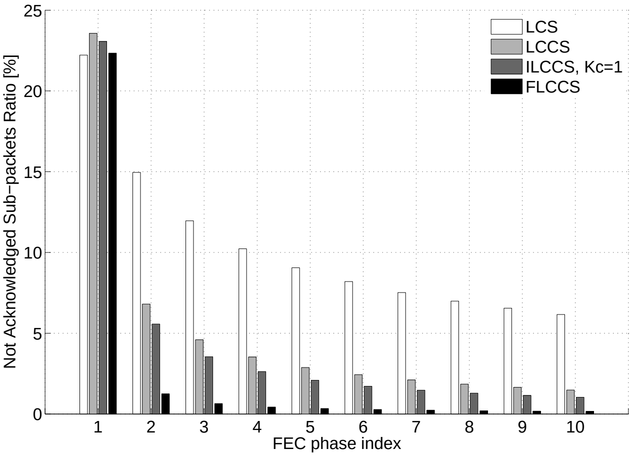

Fig. 7. Average not acknowledged sub-packets ratio after the i-th FEC phases for the simulation parameters of Table I, $\lambda = 120$ pkt/s.

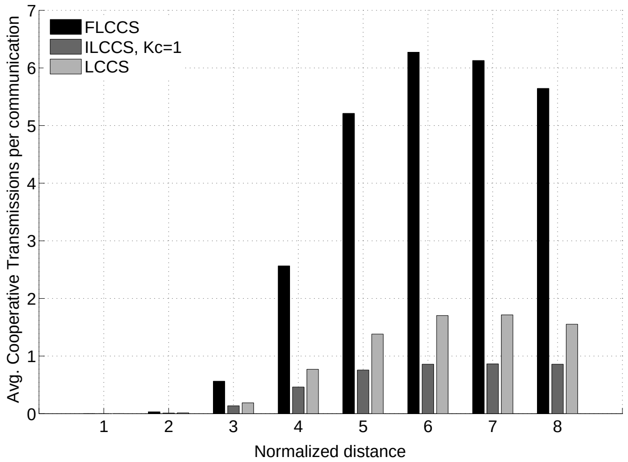

Fig. 8. Cooperative/non-cooperative retransmission ratio as a function of the distance group. The simulation parameters are shown in Table I, $\lambda = 120$ pkt/s.

and failure rate, is not very sensitive to the value of the backoff parameter W. This is due to the good balance provided by the chosen spreading factor N_S and to the effective HARQ scheme and backoff policy. However, a more aggressive choice of N_S may result in an increased dependence of the achieved performance on W. In order to provide a deeper insight into the evolution of the HARQ process, we report in Fig. 7 the average percentage of blocks needed for correct packet decoding. LCS shows a slowly exponential decrease of the percentage of missing blocks as an effect of channel correlation, because of both fading and interference. Cooperative schemes strongly reduce this percentage at the first phase in which cooperation is active (second FEC phase), providing coding and diversity gain. For the next FEC phases, the percentage decreases slowly because of channel correlation. Indeed, we have observed that most packet deliveries are resolved within the second FEC phase when a node is cooperating.

Fig. 8 shows the number of cooperative nodes per communication, as a function of the link distance normalized with respect to the minimum distance ($d_{\min}$) among nodes. Links are collected in groups, where the i–th group comprises links characterized by a source–destination distance between $(i-1) \cdot d_{\min}$ and $i \cdot d_{\min}$. We observe that all cooperative protocols have a similar behavior, with increasing cooperation within groups 1 to 6, as links experience a higher decoding failure probability at the first FEC phase and more nodes match the SNR requirements. In groups 7 and 8 the cooperation level decreases as the decoding probability decreases even for cooperative candidates.

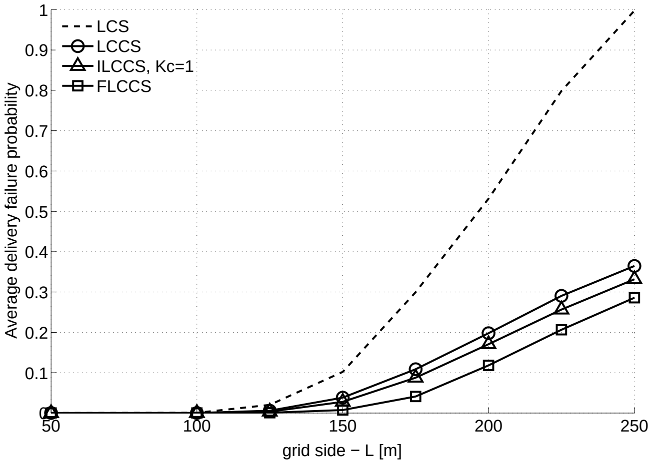

Fig. 9. Average communication success ratio as a function of the distance class. The simulation parameters are shown in Table I, $\lambda = 120$ pkt/s.

The proposed cooperative protocols increases the correct packet delivery on longer links. Fig. 9 plots the failure rate, as defined for Fig. 6, as a function of the network grid side L. LCCS, ILCCS and FLCCS soften the threshold behavior of LCS. Despite the protection offered by FEC, as the distance between the nodes increases, links quickly become less stable in LCS, while cooperative systems offer an increased reliability and sustain connectivity. Still, note that power consumption increases with the average distance between nodes, due to the higher number of FEC phases. We can conclude that cooperation is an efficient alternative to routing, as routing may lead to increased delays and further signaling overhead.

In order to evaluate the processing complexity of the considered schemes, Fig. 10 shows the complementary cumulative distribution functions (ccdf) of the number of signals (one per transmitting antenna) decoded by the receivers. For the sake of clarity, we do not include the plot associated with ILCCS, since we have verified that it behaves similarly to LCCS. We also plot the ccdf relative to the header inspection (HI) protocol, in which the receive node inspects the headers of the incoming slots and decodes the entire slot only when needed. Note that LCCS requires more decoding than LCS. On the other hand, ILCCS reduces the cooperation effort and has a lower number of decoded streams than LCCS.

V. CONCLUSIONS

We proposed the LCCS protocol, which provides high throughput by exploiting SM. When compared to other cooperation schemes, LCCS has the remarkable advantage of not requiring signaling for setting up the cooperation and of

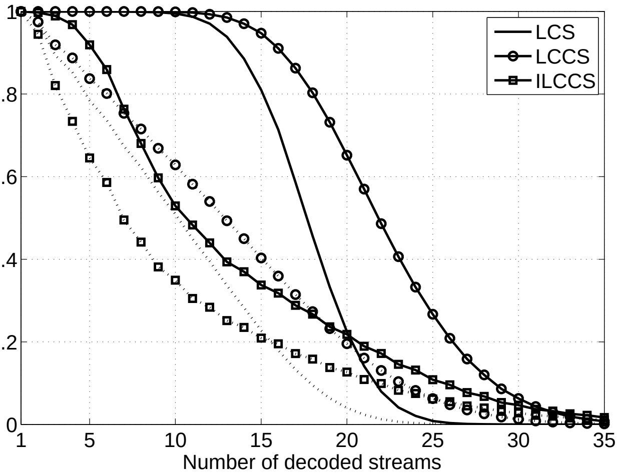

Fig. 10. ccdf of the number of decoded steams by a single receiver. HI system is represented with dotted lines. The simulation parameters are shown in Table I, $\lambda = 120$ pkt/s.

allowing a variable number of nodes to cooperate. Moreover, using SM even for cooperation does not require symbol synchronization among cooperative nodes. Our study focused on networking issues, including important aspects such as interactions among nodes, interference, PHY/MAC design, traffic dynamics, which have mostly been overlooked so far. Performance results obtained by the detailed simulation of a complex network confirm the advantages of cooperation at the network level and provide valuable insight into the interaction between the PHY and MAC layers for a network with many nodes and variable size, and operating at various loads.

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