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REPORT TITLE: Marco Levorato, Stefano Tomasin, Michele Zorzi, "Coded Cooperation for Ad Hoc Networks with Spatial Multiplexing", IEEE International Conference on Communications (ICC), Glasgow, Scotland, UK, June 24 2007 - June 28 2007.

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1. AGENCY USE ONLY ( Leave Blank)		2. REPORT DATE March 2007	3. REPORT TYPE AND DATES COVERED <b>Reprint 01 June 2004 - 31 March 2007</b>	
4. TITLE AND SUBTITLE Coded Cooperation for Ad Hoc Networks with Spatial Multiplexing <b>Error! Not a valid bookmark self-reference.</b>			5. FUNDING NUMBERS  <b>W911NF0410224</b>	
6. AUTHOR(S) Marco Levorato, Stefano Tomasin, Michele Zorzi				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of California. San Diego 9500 Gilman Drive, La Jolla, CA 92093-0407</b>			8. PERFORMING ORGANIZATION REPORT NUMBER  <b>N/A</b>	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)  U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER  <b>N/A</b>	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE  <b>N/A</b>	
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14. SUBJECT TERMS			15. NUMBER OF PAGES 6	
			16. PRICE CODE <b>N/A</b>	
17. SECURITY CLASSIFICATION OR REPORT <b>UNCLASSIFIED</b>	18. SECURITY CLASSIFICATION ON THIS PAGE <b>UNCLASSIFIED</b>	19. SECURITY CLASSIFICATION OF ABSTRACT <b>UNCLASSIFIED</b>	20. LIMITATION OF ABSTRACT  <b>UL</b>	

# Coded Cooperation for Ad Hoc Networks with Spatial Multiplexing

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**Abstract**—In this paper we design a network based on cooperative spatial multiplexing (SM), capable to adaptively support terminals with multiple antennas and multiple cooperating nodes. Our proposal overcomes limitations of existing cooperative networks based on space-time block codes (STBC), i.e., their need for symbol synchronization and signalling overhead for cooperation setup. Furthermore, the presented cooperation scheme is designed with the aim of improving the overall network performance, while most of the proposals in the literature focus on single link performance. SM is integrated with decision-feedback multiuser receivers for both the non-cooperative and the cooperative phases in order to maximize the use of radio resources. The cooperation efficiency is further enhanced by using a hybrid automatic repeat request (ARQ) mechanism for error control, implemented with linear erasure packet codes. Also in this case, the packet-based coding allows to have no signalling overhead for cooperation. Extensive results are provided, obtained by simulation of the complete PHY and MAC layers for a realistic network scenario with several nodes.

## I. INTRODUCTION

The main idea behind cooperative diversity is to organize a virtual antenna array by coordinating the transmission of the same data packet from many nodes thus gaining the well-known advantages of multiple antennas systems [1]. A first cooperative architecture is relaying, whereby a cooperating node retransmits the data packet upon a failed transmission. This approach, in which only one node transmits at any given time, was initially studied in [2], [3] and then further extended for coded systems in [4]. A more elaborate cooperative architecture provides that upon a failed transmission both the source and the cooperating node retransmit the data packet at the same time. In this case space-time block codes (STBC) [5] may be used for the simultaneous transmissions [6], [7]. In [8], an Alamouti scheme is used for cooperation, while time division multiple access (TDMA) is used for multiuser access and the energy saving of cooperation is investigated. A semi-analytical tool is provided in [9] for the evaluation of energy and delay efficiency of a cooperative network based on STBC. An information theoretic analysis is proposed in [10], where it is shown that for simple networks with a transmitter, a receiver and one or more cooperators, most of the gain of space-time coding may be achieved through cooperation among nodes.

The use of STBC for cooperation has two major drawbacks: first, symbol synchronization among cooperating nodes is typically necessary and may be infeasible for non-infrastructure

networks [7]; second, the used STBC depends on the number of nodes cooperating for a single transmission, with the consequent need for significant signalling overhead among the participating nodes. Moreover, the interaction between the physical (PHY) and medium access control (MAC) layers is usually not included in the analysis of cooperative networks. Indeed, either TDMA is used for multiple access [3], which however reduces the network throughput, or simple networks are analyzed with only three or four nodes [10], or the description of the MAC layer is ignored [11].

In this paper, we address the problem of designing an effective cooperation protocol from a networking perspective. The performance of the cooperative schemes is deeply affected by the considered MAC protocol. For instance, the effectiveness of cooperation is connected with both the presence of nodes available for cooperation and the efficiency of the negotiation phase. In this paper we propose a cooperation protocol that takes into account the features of a MAC protocol specifically designed for the underlying PHY layer.

While most of the literature considers nodes with a single antenna, there is a rising interest in ad hoc networks with multiple antennas [12], [13], as pursued by the forthcoming wireless local area networks (W-LAN) standard [14]. For cooperative diversity in a network where nodes are equipped with multiple antennas, we design a PHY and MAC architecture with the aim of maximizing the achieved rate while relaxing the limits of symbol synchronization requirements of STBC. In our proposal, spatial multiplexing (SM) is used both to allow simultaneous independent transmissions from multiple nodes, and in the cooperative phase, when several nodes may collaborate for the transmission of the same data packet. In order to improve the performance of cooperation, a hybrid automatic repeat request (HARQ) mechanism is used, based on linear erasure codes (LEC) [15]–[17]. SM and LEC favor a flexible cooperation among nodes with no signalling overhead between the cooperating nodes and/or the source. Since receivers implement the layered space-time multiuser detection (LASTMUD) architecture [18], we denote the resulting system as layered packet coded cooperative system (LPCCS).

A further distinguishing feature of this work is in the assessment of the performance of the proposed cross-layer design taking into account a detailed description of both PHY and MAC layers, including fading channel characteristics,

LASTMUD processing, interference characteristics, erasure packet coding and cooperative MAC protocol. The complete simulation ensures realistic results, without the inaccuracies that, for example, may stem from modeling MIMO nodes as single-antenna devices with a fictitious channel gain [19].

## II. PHYSICAL LAYER DESCRIPTION

Transmission at the PHY layer includes forward error correction (FEC) integrated with ARQ. FEC is implemented by linear erasure codes (LEC) [20] applied to groups of symbols rather than to individual bits. As investigated in [15], packet coding is particularly useful in transmissions affected by bursty interference or noise, which is the case of a LPCCS transmission, since several nodes transmit simultaneously, affecting entire packets with interference. Moreover, LEC allows flexible cooperation among nodes, as described in the next Section.

**Packet coding.** A LEC is defined by the triple  $(n, k, \mathbf{G})$ , where  $n$  and  $k$  are two integers with  $n > k$  and  $\mathbf{G}$  is an  $n \times k$  generator matrix, with elements taken from the Galois field  $\text{GF}(2^r)$ . Let us consider a data packet of  $M$  symbols belonging to  $\text{GF}(2^r)$ . For LEC encoding, the data packet is first split into the  $k$  sub-packets  $\mathbf{p}_q$ ,  $q = 1, 2, \dots, k$ , that are encoded into  $n$  sub-packets, each with  $M/k$  symbols, as follows

$$\mathbf{c}_i = [\mathbf{G}]_{i,1}\mathbf{p}_1 \oplus [\mathbf{G}]_{i,2}\mathbf{p}_2 \oplus \dots \oplus [\mathbf{G}]_{i,k}\mathbf{p}_k, \quad (1)$$

where  $i = 1, 2, \dots, n$ , and  $\mathbf{a} \oplus \mathbf{b}$  denotes the element-wise sum of vectors  $\mathbf{a}$  and  $\mathbf{b}$  in  $\text{GF}(2^r)$ . Without restriction, we consider a systematic LEC, providing the data sub-packets as the first  $k$  coded sub-packets, i.e.,  $\mathbf{c}_i = \mathbf{p}_i$  for  $i = 1, 2, \dots, k$ . Coded sub-packets  $\mathbf{c}_i$  for  $i = k+1, k+2, \dots, n$  are the *parity sub-packets*.

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. Let  $\mathcal{C} = \{\kappa_1, \kappa_2, \dots, \kappa_k\}$  be the indices of the correctly decoded sub-packets and let  $\bar{\mathbf{G}}_{\mathcal{C}}$  be the matrix containing the columns of  $\mathbf{G}$  with index in  $\mathcal{C}$ . Since  $\mathbf{G}$  is full-rank,  $\bar{\mathbf{G}}_{\mathcal{C}}$  is also full rank and can be inverted in  $\text{GF}(2^r)$ , to obtain  $\bar{\mathbf{G}}_{\mathcal{C}}^{-1}$ . By combining the detected sub-packets with  $\bar{\mathbf{G}}_{\mathcal{C}}^{-1}$ , we obtain the data sub-packets

$$\mathbf{p}_q = [\bar{\mathbf{G}}_{\mathcal{C}}^{-1}]_{q,1}\mathbf{c}_{\kappa_1} \oplus [\bar{\mathbf{G}}_{\mathcal{C}}^{-1}]_{q,2}\mathbf{c}_{\kappa_2} \oplus \dots \oplus [\bar{\mathbf{G}}_{\mathcal{C}}^{-1}]_{q,k}\mathbf{c}_{\kappa_k}, \quad (2)$$

where  $q = 1, 2, \dots, k$ .

In LPCCS, each coded sub-packet has a cyclic redundancy code (CRC) that allows the receiver to understand which sub-packets have been correctly detected. Hence, if the receiver has correctly decoded any  $k$  distinct coded sub-packets, it can retrieve the entire data packet by the properties of LEC. We further exploit the decoding property of LEC to enhance the cooperation strategy. This is achieved by transmitting the systematic part of the code (i.e., the original data sub-packets) in the first transmission, while the parity sub-packets are transmitted by the source and all the cooperating nodes in the cooperative phases, through a hybrid ARQ mechanism.

**Transmitter description.** We consider nodes equipped with  $N$  antennas. According to the LASTMUD scheme of [18], the sub-packet to be transmitted is modulated with a real constellation and spread by a node-specific pseudo-random spreading sequence. The spread block of  $S$  symbols is split among the  $N$  antennas so that  $N$  transmissions of  $S/N$  symbols are active in parallel.

As a transmission scenario we consider a flat fading channel and we indicate with  $h_{\ell,j}^{(n,m)}(t)$  the complex channel gain between the transmit antenna  $\ell$  of node  $n$  and the  $j$ th receiving antenna of node  $m$  at the discrete chip-time  $t$ . Nodes are in fixed positions and the channel gain can be factorized into two terms, one accounting for the path-loss between nodes  $n$  and  $m$ , and the other accounting for fading between two specific antennas, i.e.,

$$h_{\ell,j}^{(n,m)}(t) = \alpha^{(n,m)}\phi_{\ell,j}^{(n,m)}(t). \quad (3)$$

Since nodes transmit simultaneously, the signal at the output of a receiving antenna is the superposition of signals coming from the antennas of all transmitting nodes. Let  $\mathcal{N}$  be the set of transmitting nodes and let  $d_{\ell}^{(n)}(t)$  be the symbol from the  $\ell$ th antenna of node  $n$  and received at time  $t$  by node  $m$ . Even if symbol synchronization is not required, for the sake of a simpler notation we will consider synchronous transmissions in the following. The received signal at time  $t$  on antenna  $j$  of a generic node  $m \notin \mathcal{N}$  can be written as

$$r_j^{(m)}(t) = \sum_{n \in \mathcal{N}} \sum_{\ell=1}^N h_{\ell,j}^{(n,m)}(t)d_{\ell}^{(n)}(t) + w_j^{(m)}(t), \quad (4)$$

where  $j = 1, 2, \dots, N$ , and  $w_j^{(m)}(t)$  is an additive Gaussian noise term having zero mean and variance  $\sigma_w^2$ .

We assume that all transmissions have the same total power  $P_{\text{TOT}}$ , i.e., when  $N$  antennas are used, the power of each data signal is  $E[|d_{\ell}^{(n)}(t)|^2] = P_{\text{TOT}}/N$ .

**Receiver description.** The LASTMUD receiver performs multiuser detection, where the information from the different transmitting antennas is extracted in sequence. At each stage, the signal from one antenna is detected, and its remodulated version is subtracted from the received signal in order to improve the detection performance at the next stage. A receiving node detects not only the signals intended for itself (*data signals*), but also signals transmitted to other nodes (*interfering signals*) generating strong interference. In general, if many interfering signals are correctly decoded and canceled, data detection is more reliable. However, resource constraints may force a node to detect only a subset  $\mathcal{N}' \subseteq \mathcal{N}$  of the incoming signals.

In particular, define the column vector collecting the samples received at all the antennas of node  $m$  at time  $t$  as

$$\mathbf{r}^{(m)}(t) = [r_1^{(m)}(t), r_2^{(m)}(t), \dots, r_N^{(m)}(t)]^T. \quad (5)$$

Let  $\mathbf{d}^{(m)}(t)$  be the vector collecting the data chips received at time  $t$ , as transmitted by antennas in  $\mathcal{N}'$ . Also, let  $\mathbf{H}^{(m)}(t)$  be the matrix of channel gains seen by node  $m$ . In particular, the  $j$ th row of  $\mathbf{H}^{(m)}(t)$  collects the channel gains between all

the transmitting antennas in  $\mathcal{N}'$  and the  $j$ th antenna of node  $m$ . Lastly, let  $\mathbf{i}^{(m)}(t)$  be the  $N$ -size vector collecting both the noise and the interference seen by the receive antennas of node  $m$  due to transmitting antennas not in  $\mathcal{N}'$ . Then the received vector can be written as

$$\mathbf{r}^{(m)}(t) = \mathbf{H}^{(m)}(t)\mathbf{d}^{(m)}(t) + \mathbf{i}^{(m)}(t). \quad (6)$$

In order to extract the sufficient statistics for decoding, the receiver applies a matrix filter matched to the channel [13], [18] on the received vector, i.e.,

$$\tilde{\mathbf{r}}^{(m)}(t) = \mathbf{H}^{(m)H}(t)\mathbf{r}^{(m)}(t), \quad (7)$$

where  $H$  is the Hermitian operator. Then, the signals from antennas in  $\mathcal{N}'$  are detected in sequence by first combining the elements of  $\tilde{\mathbf{r}}^{(m)}(t)$  with suitable weights that minimize the interference, and then despreading the signal. The interference due to the detected stream is cancelled from  $\tilde{\mathbf{r}}^{(m)}(t)$  so that detection of the following streams is more reliable. For further details on the LASTMUD receiver, the interested reader is referred to [18].

### III. NETWORK AND MAC PROTOCOL DESCRIPTION

The traditional MAC protocols for ad hoc networks, e.g., those belonging to the IEEE 802.11 standard family, are not able to effectively manage the proposed PHY layer. In fact, the capability to support multiple simultaneous transmissions makes collision avoidance too conservative. Thus, we propose a new protocol whose design specifically accounts for the underlying PHY layer.

We organize transmissions in time slots, with duration equal to the transmission time of a sub-packet. At the beginning of each slot, transmitting nodes send short training sequences that allow receiving nodes to estimate the channel.

When a node wants to send a data packet to another node, it transmits a request-to-send (RTS) packet at the beginning of a slot. If the intended destination is available, i.e., it is not already involved in another communication, and it has successfully decoded the RTS, it responds with a clear-to-send packet (CTS) in the following slot. We observe that in the considered network the initial handshake phase does not force neighboring nodes to silence, but is used for improving the protocol efficiency. In fact, a failed handshake avoids long data packet transmissions to unreachable or engaged destinations, while on the other hand the RTS/CTS exchange prevents neighboring nodes from starting a communication with the transmitting node. Control packets, i.e., RTSs, CTSs, ACKs, are shorter than data sub-packets and have a small impact on the communication efficiency. Still, their reception is of paramount importance for the network performance, thus we assume that they are transmitted using only one antenna at full power  $P_{\text{TOT}}$  and that they are protected by a convolutional code of rate  $1/2$ . If the control packet exchange is successfully accomplished, the source node starts the transmission of the DATA packet as described in the following.

#### A. Hybrid ARQ with packet coding

After the handshake, the source node uses the following  $k$  slots to transmit the  $k$  systematic sub-packets of the data packet. Using CRC, the destination checks the correctness of the received sub-packets and transmits an acknowledge packet (ACK) containing the total number of correctly detected sub-packets.

The decoding load at the receiver side possibly changes in each slot, since interfering transmissions may start or terminate during a communication. Hence, the decoder performance depends on the number, the spatial separation and the power of the received signals. In order to effectively compensate for these fluctuations, we use an adaptive hybrid ARQ scheme based on LEC. As stated before, the ACK packet includes the total number of correctly received sub-packets. If the destination node correctly receives all the  $k$  sub-packet, the communication ends. Otherwise, the source node transmits  $N_{\text{unsucc}}$  redundancy sub-packets, where  $N_{\text{unsucc}}$  is the number of incorrectly received sub-packets. The redundancy sub-packets are randomly chosen among coded sub-packets, not including the systematic part. After this second transmission phase, the destination node transmits a second ACK. If  $N_{\text{unsucc}}$  is still greater than zero, a new transmission of  $N_{\text{unsucc}}$  redundancy sub-packets starts. Our algorithm continues the redundancy-plus-ACK phases until the receiver acknowledges a number of sub-packets greater than or equal to  $k$ , or until the number of redundancy transmissions reaches a fixed maximum ( $M_{fec}$ ). The proposed Hybrid ARQ technique effectively controls the coding gain under time-varying conditions without channel knowledge at the transmitter. In fact, redundancy is provided only for failed transmissions, while higher data rates are used on good links.

Fig. 1.a depicts an example of hybrid ARQ, where the communication between the source and the destination is affected by a burst of packet errors, due to bad channel conditions or to excessive interference.

In order to control the network load we introduce a random back-off mechanism at the transmitter. Link failures (i.e., not received CTS from destination, not received ACK or not complete ACK reception after the last FEC transmission) force a source node to defer any transmission for a number of slots randomly chosen in the exponentially increasing window  $[1, 2^{(N_{\text{fail}}-1)}W]$ , where  $N_{\text{fail}}$  is defined as the minimum between the number of consecutive failures and a maximum value fixed to  $M_{\text{fail}}$ , and  $W$  is the initial window value. After a correct packet reception,  $N_{\text{fail}}$  is set to  $\max(N_{\text{fail}} - 1, 0)$ . Furthermore, in order to increase the probability of transmitting an RTS packet when the intended destination is not involved in another communication, each sub-packet and control packet header includes the duration of the communication they belong to. In the following, we refer to the previously described system as layered packet coded system (LPCS). LEC is particularly suited to the described system. Nevertheless, the use of other codes, for example convolutional or turbo codes could be envisioned.

## B. Cooperation protocol

The performance of LASTMUD depends on channel conditions and interference, especially when the interfering signals are much more than the number of receiving antennas. In this case, the packet error rate may widely vary, according to fading and interference conditions. A means of preserving the network performance would be to lower the coverage range, activating only short-distance links with low path loss. As a consequence, packet delivery would require a larger number of hops which may result in a lower network efficiency. We propose instead to let nodes cooperate to overcome adverse channel conditions even on long distance links. In designing the cooperation scheme we aim at keeping a high protocol efficiency, avoiding the introduction of a negotiation procedure for cooperation. The goal of cooperative transmission is to provide redundancy sub-packets through independent spatial channels, in order to lower the number of FEC phases and to increase the probability of a correct reception.

The PHY layer based on SM and LASTMUD is naturally suited for a cooperative MAC protocol. In fact, destination nodes decode multiple data sub-packets for interference cancellation purposes, and have already a means to follow multiple simultaneous transmissions coming from different cooperating nodes. With our cooperation protocol, nodes may cooperate provided that they correctly decode the data packet. In this case, cooperating nodes can apply the packet coding technique obtaining the same coded set as the source. Upon reception of the ACK packet, cooperating nodes act as additional communication sources, transmitting redundancy sub-packets randomly chosen in the coded set. Cooperation ends upon reception of an ACK to  $k$  sub-packets or when the number of FEC transmissions reaches the maximum. Note also that cooperation is active only when the data packet is not completely decoded by the destination, so that nodes do not spend resources for good links.

Note that the receive node can easily detect cooperating transmissions with no modification of the LASTMUD architecture. Moreover, the source node does not require to adapt to cooperation, since each cooperating node operates independently. Moreover, several nodes could cooperate for the same transmission, without any need for negotiation, even though in this case the destination may experience a higher load.

Even though every node that correctly decodes the packet is eligible for cooperation, this may not be convenient for nodes that have a bad channel towards the destination. To avoid re-transmission from a node that may be further away from the destination than the source, the cooperating candidate compares the signal to noise plus interference ratio (SNIR) of the cooperator-destination link ( $SNIR_{CD}$ ) with the SNIR of the source-destination link ( $SNIR_{SD}$ ). Cooperation starts only if  $SNIR_{CD} > SNIR_{SD}$ . For this purpose, an estimate of  $SNIR_{SD}$  is included in each CTS packet. In Fig. 1.b, an example of cooperative communication is shown. The described system is referred to in the following as layered

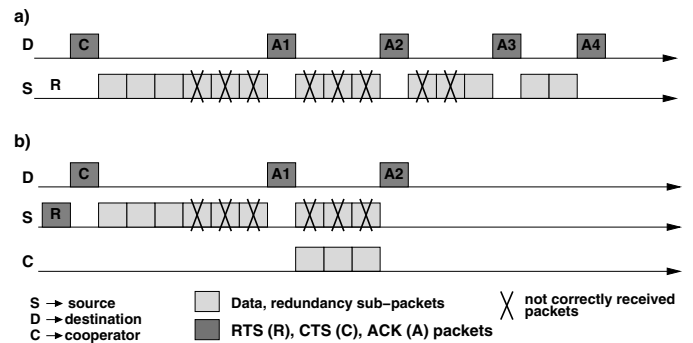


Fig. 1. Example of a) non cooperative communication, b) cooperative communication.

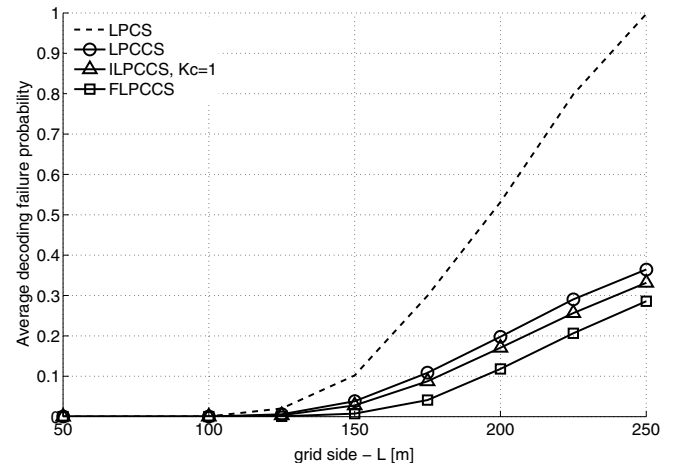


Fig. 2. Average decoding fails ratio (after all permitted redundancy phases) as a function of  $L$ ,  $\lambda = 120$  pkt/s per node.

packet coded cooperative system (LPCCS).

We should point out that when a node is cooperating, it cannot be involved in any other communication, thus potentially degrading the node throughput. On the other hand, cooperation increases the success probability. In order to evaluate the trade-off between node and network throughput, we consider two further versions of LPCCS:

- **Forced LPCCS (FLPCCS)**: an idle node  $C$  that correctly decodes an RTS/CTS exchange and matches SNIR requirements for cooperation is forced to maintain the idle state until  $D$  transmits the first ACK, or until  $C$  fails to decode a sub-packet.
- **Idealized LPCCS (ILPCCS)**: ILPCCS provides that only  $K_C$  nodes are chosen for cooperation out of those available. The selected nodes are those with the highest SNIR toward the destination. This scheme requires a coordination effort among the nodes. We considered the setting  $K_C = 1$  neglecting the coordination overhead.

## IV. SIMULATION RESULTS

We have assessed the performance of an LPCCS network by simulating both PHY and MAC layers for each node. All simulation parameters are reported in Table I. Nodes are on a grid of size  $L \times L$ , and the transmission channel is assumed to be fixed for the slot duration. The channel is slow fading and

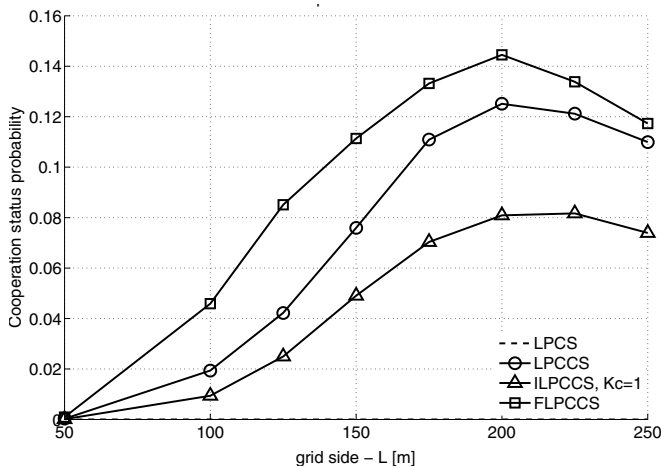


Fig. 3. Average fraction of time used for cooperation as a function of  $L$ ,  $\lambda = 120$  pkt/s per node.

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  $\rho$  is the correlation coefficient and  $\xi$  are independent complex Gaussian variables with zero mean and unit variance. The path-loss coefficient has been modeled according to Hata with  $\alpha^{(n,m)} \propto [d^{(n,m)}]^{-4}$ , where  $d^{(n,m)}$  is the distance between nodes  $n$  and  $m$ , with an average per antenna SNR of 20 dB at the distance of 35 m. Each node has a limited FIFO queue and packets are generated according to a Poisson process of parameter  $\lambda$  packets per second per node. LASTMUD performance is modeled as in [21].

Fig. 2 shows the average probability of packet uncorrect decoding after the last allowed transmission of redundancy as a function of the grid size. Cooperative protocols enable a greater communications reliability than LPCS. Note that FLPCCS has the lowest failure rate, due to the greater cooperation effort required. ILPCCS selects the cooperator with the highest SNR among the set of the candidates, thus it is expected to provide redundancy with the best average channel conditions, involving only one node in cooperation. Thus, a low level of interference due to cooperative transmissions is generated in the network and nodes are less engaged for cooperation. Nevertheless, LPCCS shows a failure rate very similar to ILPCCS, without need for coordination.

Fig. 3 shows the average fraction of time used for cooperation. The cooperative effort grows as the grid size is increased. This is due to the greater failure probability of the first transmission, and thus a greater need for cooperation, but also to a lower decoding probability of the sub-packets coming from cooperators. Since also the probability of successfully decoding potential cooperators decreases as the distance between the nodes increases, the time spent for cooperation decreases for large grid sizes.

In Fig. 4 the average throughput as a function of the arrival rate per node  $\lambda$  is depicted for a grid size of  $150\text{m} \times 150\text{m}$ . The throughput is calculated over the completely received and acknowledged packets. We remark that the throughput of both cooperative and non-cooperative protocols outperforms a more conservative MAC, where a single node is enabled to

transmit at a time. In fact, in this case the maximum achievable throughput is 937.5 kbit/s. LPCCS and ILPCCS increase the throughput by about 30% with respect to LPCS at high load. ILPCCS outperforms LPCCS because it achieves a similar failure rate with a greater efficiency. FLPCCS shows poor throughput performance, since nodes are kept idle for most of the time leading to a higher delay.

Fig. 5 shows the average percentage of not-acknowledged sub-packets as a function of the FEC phase index. Use of cooperation dramatically decreases the number of not-acknowledged sub-packets. Thus the number of FEC phases is reduced and the probability of decoding the data packet within  $M_{fec}$  FEC phases is increased. Note that FLPCCS has the strongest impact, but requires a large number of cooperators per communication, so that the overall efficiency is lower. Note also that ILPCCS and LPCCS have similar performance, even though LPCCS gets a little advantage due to the higher number of cooperators per transmission.

As a concluding remark we note that coverage range, reliability and related costs are key parameters in determining the network performance. The coverage range is of paramount importance for reducing the number of hops required to reach the destination. A great amount of redundancy coming from multiple cooperators or from different FEC phases possibly enhances the decoding probability, but could hamper the efficiency, especially when the channel state and the receiver load are correlated in time. On the other hand, too low an amount of redundancy, or the lack of potential cooperators, yields a high number of packet retransmissions due to the lower decoding probability, increasing the delivery delay. The results on the average throughput summarize the balances among these phenomena and show that ILPCCS achieves the best performance. From results not shown here for lack of space we have also observed that FLPCCS has the highest delay, since it keeps nodes idle in order to enable them to cooperate, and that ILPCCS yields a lower cooperation cost than LPCCS, because of the selection of the highest SNR cooperator.

## V. CONCLUSIONS

We have proposed a network architecture for cooperative diversity among nodes with multiple antennas. An adaptive HARQ technique and flexible cooperation mechanisms are jointly used to efficiently recover from adverse channel and receiver load conditions. The protocols are designed with a network perspective, including traffic dynamics, interference and interactions among nodes. The proposed schemes have also the remarkable advantage of not requiring signalling for setting up the collaboration and of allowing a variable number of nodes to cooperate. Moreover, the use of SM in the cooperative phase does not require symbol synchronization among cooperating nodes. Performance results confirm the advantage of cooperation and provide a useful insight into the interaction between the PHY and MAC layers for a network with several nodes, a variable size, and operating at various loads.

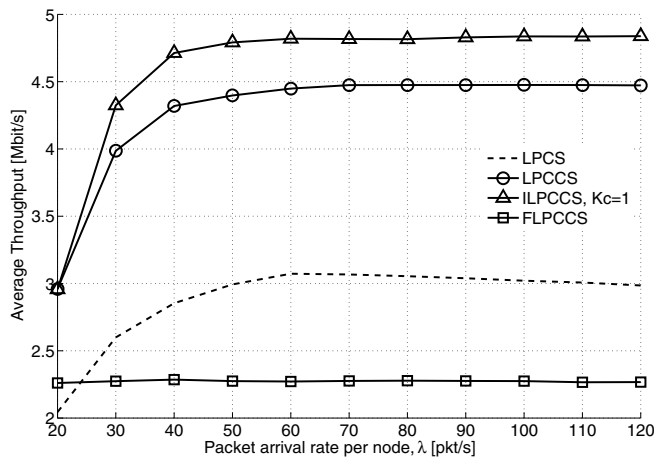


Fig. 4. Average throughput as a function of the average packet arrival per node,  $L = 150$  m.

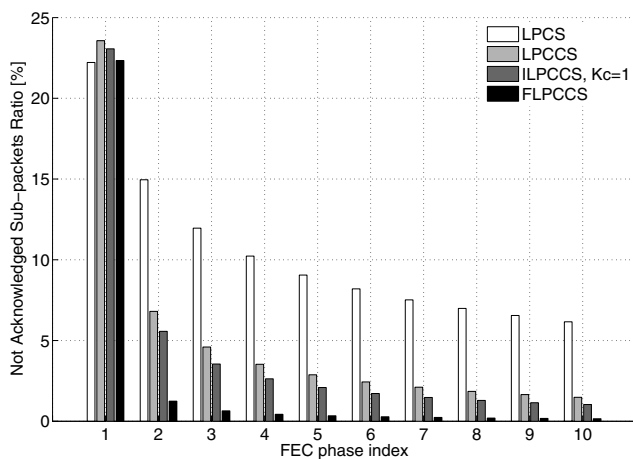


Fig. 5. Average ratio of not-acknowledged sub-packet as a function of the redundancy phase index,  $\lambda = 120$ ,  $L = 150$ m.

TABLE I  
PARAMETERS FOR SIMULATION

Parameter	Value
Number of nodes	36
Network topology	$L \times L$ square
Modulation	BPSK
Number of array elements	2
$P_{TOT}$	0.25W
Noise power $\sigma_w^2$	-170dBm
$\rho$	0.9
Sub-packets per packet ( $N_P$ )	8
Sub-packet length	512bit
Bit-rate per antenna	468.75 Kb/s
Erasure code parameters ( $n, k$ )	(8, 24)
Spreading factor	16
Signaling FEC polynomial (rate 1/2)	133 <sub>8</sub> , 171 <sub>8</sub>
Packet retransmissions	8
$M_{fec}$	10
$K_{cod}$	1
$M_{fail}$	4
Queue timeout	4096 slots
Queue length	64 pkts
Simulation slots	250000

## ACKNOWLEDGMENT

This work has been supported in part by the U. S. Army Research Office under MURI grant no. W911NF-04-1-0224.

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