By combining (14) and (15), we finally obtain

$$\int_{t_j}^{t_{j+1}} e^{-ax} p_{\hat{\gamma}}(x)dx$$
$$= \frac{N}{\Gamma(m)} \left[G(\tilde{a}+1, m-1, \tilde{t}_j) - G(\tilde{a}+1, m-1, \tilde{t}_{j+1})\right]$$
$$+ \frac{N}{\Gamma(m)} \sum_{l=1}^{N-1} \binom{N-1}{l} (-1)^l$$
$$\times \sum_{k_1=0}^{m-1}, \ldots, \sum_{k_l=0}^{m-1} \left\{ \frac{G(\tilde{a}+1+l, \sum_i k_i + m-1, \tilde{t}_j)}{(k_1)!(k_2)!, \ldots, (k_l)!} - \frac{G(\tilde{a}+1+l, \sum_i k_i + m-1, \tilde{t}_{j+1})}{(k_1)!(k_2)!, \ldots, (k_l)!} \right\}.$$

■

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A Cross-Layer Approach for Cooperative Networks

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***Abstract*—This paper deals with a cross-layer approach for cooperative diversity networks, which use a combination of amplify-and-forward (AF) and decode-and-forward (DF) as a relaying strategy. Based on a well-selected ad hoc configuration, the proposed approach combines the cooperative diversity concept with a simultaneous optimization of physical, network, and multiple access control layers. The considered optimization problem requires an appropriate distribution of three roles among the network nodes, which are the diversity relays (AF concept), the intermediate router (DF and routing), and the destination (scheduling). The proposed role assignment is based on the instantaneous channel conditions between the links and jointly supports performance optimization and a long-term fairness concept. To minimize the required complexity, a partial and quantized channel feedback is also proposed. The proposed cross-layer solution is compared with conventional approaches by computer simulations and theoretical studies, and we show that it achieves an efficient performance–complexity tradeoff.**

***Index Terms*—Ad hoc networks, amplify-and-forward (AF), cooperative systems, cross-layer design, relay channels.**

I. INTRODUCTION

Cooperative diversity is a new diversity technique that was proposed in the literature as a form of a spatial diversity system [1]–[6]. It uses the broadcast nature of the wireless medium, and its basic idea is that the terminals, which are in the coverage area of a transmitter, can forward an "overheard" version of the transmitted signal. This virtual antenna array produces the desired diversity gain at the destination. Among the proposed reforward strategies, the amplify-and-forward (AF), which involves a simple scale and retransmission of the received signal by the relay nodes, seems to give a good performance and complexity tradeoff [7].

Currently, there has been a lot of interest in AF cooperative schemes, where the relay nodes are selected according to some well-defined system parameters [8]–[11]. In [12], the authors proposed a distributed relay selection for a two-hop AF system, where the selected criterion is the best instantaneous signal-to-noise ratio (SNR) composed of the SNR across the two hops. This solution extracts a diversity gain on the order of the number of relays [13] with a lower complexity than the complicated distributed space–time codes. However, a distributed relay selection is time sensitive and requires perfect time synchronization among the nodes, which is a crucial issue for practical systems. On the other hand, centralized approaches require continuous channel feedback from all the links of the network and, therefore, result in a high power consumption [14]. The related complexity is increased as the number of nodes and hops is increased. In resource-constrained wireless systems such as sensor networks [15], by monitoring the

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connectivity among the nodes locally (one hop) rather than globally, one can prolong the network lifetime.

Consideration of the instantaneous channel quality in the routing protocols can also optimize system performance [16]. Dynamic routing protocols avoid links that are in deep fades and propose alternative reliable routes from the source to the destination. The combination of the cooperative diversity concept with the channel-based routing protocols can further improve the destination quality-of-service (QoS) and the required power consumption [17].

In this paper, we study the joint combination of cooperative diversity with channel-based scheduling and routing under a two-hop AF and decode-and-forward (DF) framework. Based on a simple well-selected ad hoc configuration, we introduce an optimization problem that requires an appropriate assignment of three cross-layered roles. The proposed approach selects the relay nodes, the intermediate router, and the final destination according to the instantaneous channel conditions. This cross-layer multiple access control (MAC) decision, which incorporates information from the physical (PHY) and network (NET) layers, can optimize the system performance. Furthermore, we focus on centralized approaches that, despite the extra signaling, are more robust and less sensitive to timing synchronization than the distributed schemes. However, to overcome the problem of feedback and decrease the required complexity, a partial and quantized feedback is proposed. This feedback is limited to a qualitative description of a well-selected subset of links. The resulting performance and complexity tradeoff is analyzed by theoretical and numerical studies, and we show that the proposed suboptimal solution gives reliable results. The final issue we address is the way that the available resources are shared between the nodes. The proposed algorithm distributes the roles among the nodes with the same probability and, thus, supports the fairness concept [8], [18]. Although the presented analysis refers to a particular ad hoc configuration, it is also useful for general network structures. The considered system is the simplest one to combine the considered cross-layer issues and can be regarded as the basis of real topologies.

The remainder of this paper is organized as follows: In Section II, we describe the system model and the problem under consideration. Section III presents the proposed algorithm and its associated performance. Numerical results are given in Section IV, and Section V summarizes the key conclusions.

II. System Model

Consider a two-hop ad hoc structure consisting of one source S, two routers R_1 and R_2, and two destinations D_1 and D_2. It is assumed that the source continuously has data to transmit for both destinations (a similar scenario is assumed in [8], [9], and [19]) and that all the nodes are half-duplex and, thus, cannot simultaneously transmit and receive. The source has no direct link with the destinations, and both DF routers can be used as intermediate nodes for both destinations. This long-term routing information (two available routers) is provided by multipath-based routing protocols [20], [21] and is available for the role assignment under consideration.

The considered configuration is organized in two clusters C_1 and C_2, where each cluster corresponds to a basic three-node cooperative system. The first cluster includes the source and the two routers, whereas the second cluster includes the selected intermediate router and the two destinations. Fig. 1 schematically presents the system model. The basic goal of this particular system configuration is to present the considered cross-layer problem in a simple way. The selected topology (two hops with two nodes) is the simplest one to combine routing, scheduling, and fairness issues under a combined AF/DF cooperative framework. It is the basis of real systems, and thus, the proposed solution can be useful for practical ad hoc configurations that are characterized by many nodes and hops.

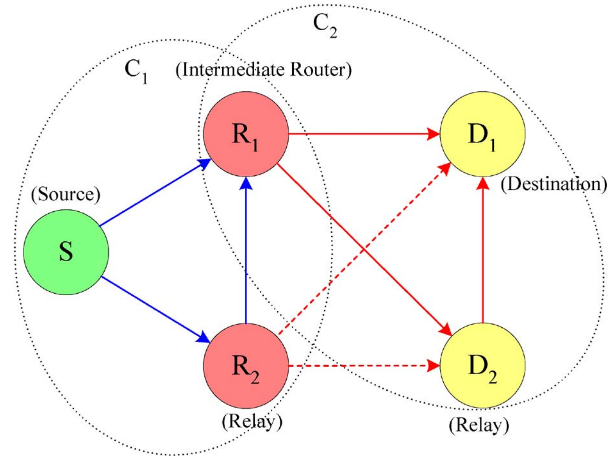

Fig. 1. System model. (Lines) Chosen routes. (Dashed lines) Possible routes. C_i: ith cluster; S: source; R_i: ith router; D_i: ith destination $(i = 1, 2)$.

In each cluster, the cooperative diversity scheme is based on the conventional orthogonal protocol [2], where each transmission is performed in a dedicated channel (i.e., different frequencies). The consideration of more complicated cooperative schemes that optimize the diversity–multiplexing tradeoff is beyond the scope of this paper [22]. Therefore, in the first cluster, the node S is the source, one router is used as an AF relay, and the other router is used as a destination. In the second cluster, the previous router destination is used as a source via DF, one destination is used as a relay, and the other destination is the final receiver. Each destination node (final receiver, intermediate router) combines multiple copies of the transmitted packet by using a maximum ratio combiner (MRC) and demodulates (decodes) the received signal. We note that despite the decoding process at the intermediate router, the proposed approach focuses on the AF policy (the diversity relays apply the AF policy). The modulation scheme is binary phase-shift keying (BPSK), but generalization to other modulation formats is straightforward. For each link $A \rightarrow B$, the channel is modeled as a zero-mean independent circularly symmetric complex Gaussian random variable with unit variance. It is assumed that the links have the reciprocity property, and thus, the forward and backward links are equivalent. Furthermore, the additive noise is represented as a zero-mean mutually independent circularly symmetric complex Gaussian random sequence with variance $\sigma^2_{A,B}$. Perfect channel estimation at each receiver is assumed. The system model can be formalized by the following equation sets:

$$\begin{aligned} y_{R_i}^{(d)} &= g_{S,R_i} x_J + n_{S,R_i} \\ y_{R_I}^{(c)} &= g_{R_{-I},R_I} \left(G_{S,R_{-I}} \cdot y_{R_{-I}}^{(d)} \right) + n_{R_{-I},R_I} \\ \tilde{x}_J(I) &= \mathrm{MRC}\left(y_{R_I}^{(d)}, y_{R_I}^{(c)} \right) \end{aligned} \quad (1)$$

$$\begin{aligned} y_{D_i}^{(d)} &= g_{R_I,D_i} \tilde{x}_J + n_{R_I,D_i} \\ y_{D_J}^{(c)} &= g_{D_{-J},D_J} \left(G_{R_I,D_{-J}} \cdot y_{D_{-J}}^{(d)} \right) + n_{D_{-J},D_J} \\ \hat{x}_J(I) &= \mathrm{MRC}\left(y_{D_J}^{(d)}, y_{D_J}^{(c)} \right) \end{aligned} \quad (2)$$

where the first set corresponds to the cluster C_1, and the second set corresponds to the cluster C_2. More specifically, $i = 1, 2$; the indexes $I, J \in \{1, 2\}$ denote the selected router and destination, respectively; the notation $-I$ denotes the complement of I ($I \in \{1, 2\}$—two values); $y_{R_i}^{(d)}$ and $y_{R_I}^{(c)}$ are the router's received signals from the source and the C_1 relay, respectively; $g_{A,B}$ and $n_{A,B}$ are the channel coefficient

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and the noise term, respectively, for the link $A \rightarrow B$; $\mathrm{MRC}(A, B)$ denotes the MRC process for the signals A and B; $y_{D_J}^{(d)}$ and $y_{D_J}^{(c)}$ denote the destination's received signals from the router and the C_2 relay, respectively; x_J denotes the transmitted signal for the Jth destination; $\tilde{x}_J(I)$ is the estimation of x_J by the Ith router; $\hat{x}_J(I)$ is the received signal at the Jth destination (passed by the Ith router in the first hop); $G_{A,B} = \sqrt{P/[P|g_{A,B}|^2 + \sigma_{A,B}^2]}$ is the AF amplification factor; and P is the transmitted power for each node.

The cross-layer problem in this paper is to decide, for each transmission, the destination node (scheduling) and the intermediate router (routing) based on the instantaneous channel conditions. Our routing optimization focuses on a short-term definition of the next-hop router among the available ones and can be regarded as a "complementary routing process" to a long-term routing scheme. More specifically, we assume that an existing long-term routing algorithm provides a set of available routers (two routers in our case) to establish communication between the source and destinations [20], [21]. This routing scheme can track variations in path loss and shadowing (average channel) but not those due to small-scale fading. The short-term routing decision under consideration is to select the most appropriate router among the available ones based on an instantaneous channel feedback. In addition to this cross-layer concept, the basic targets of our design are to optimize the aggregate performance to minimize complexity and to support a fairness concept. Here, the fairness parameter is defined as an equal distribution, on average, of the considered roles [8] among all nodes in Fig. 1. Therefore, each one-hop node becomes a router (or relay) with the same probability, and each two-hop node becomes a destination (or relay) with the same probability. Based on the aforementioned formalization, our cross-layer problem can be expressed as

$$(I_{\mathrm{opt}}, J_{\mathrm{opt}}) = \arg \min_{I,J \in \{1,2\}} \left\{ |x_J - \hat{x}_J(I)|^2 \right\}$$
$$\mathrm{Prob}\{I_{\mathrm{opt}} = k\} = \mathrm{Prob}\{J_{\mathrm{opt}} = k\} = \frac{1}{2} \text{ for } k = 1, 2. \quad (3)$$

III. Cross-Layer Approach

In this section, we present the algorithm that solves the aforementioned optimization problem. The proposed cross-layer approach incorporates opportunistic scheduling with channel-based routing and achieves fairness and optimized performance. The performance of the proposed algorithm is validated by theoretical studies, and an estimation of its computational complexity is also given.

A. Round-Robin (RR) Approach

First, we briefly present the classical RR approach that is used as a reference throughout this paper. For the considered problem, RR corresponds to a simple scheduling and routing approach that ensures the fairness concept. It does not require any feedback from the wireless medium and periodically distributes the roles (intermediate router, final destination, diversity relays) among the nodes. This resource allocation corresponds to a fair distribution of the roles. However, despite the implementation simplicity and the support of the fairness concept, not using the channel parameter gives RR a poor performance.

B. Performance Optimization

To optimize the performance, the scheduling and routing decisions have to be adapted to the instantaneous channel conditions. However, an optimal real-time adaptation requires a high degree of signaling and searching, which corresponds to an NP-complete problem for multihop configurations. Here, we propose a suboptimal solution that adapts the scheduling and routing decisions to partial feedback information. More specifically, instead of deciding on the appropriate router and destination based on global feedback from all the possible links to the source, we take the decisions hop by hop.

Therefore, first, the algorithm selects the best available DF router that will be used as an intermediate node to communicate with the destinations. This selection is based on the instantaneous channel conditions between the source and the two routers. Therefore, the router that has the best direct link is selected as an intermediate node, and the other one is selected as the cooperative AF relay for the first cluster. This decision can be regarded as a dynamic routing strategy with cooperative diversity. On the other hand, the decision of the final destination is based on the instantaneous channel conditions between the selected router and the two destinations. Therefore, the destination that has the best direct link with the selected router is the final destination, and the other one becomes the cooperative AF relay for the second cluster. This decision can be regarded as an opportunistic scheduling with cooperative diversity. Based on the aforementioned formalization, the solution that optimizes the performance can be presented as

$$I_{\mathrm{opt}} = \arg \max_{I \in \{1,2\}} \{\gamma_{S,R_I}\}$$
$$J_{\mathrm{opt}} = \arg \max_{J \in \{1,2\}} \{\gamma_{R_{I_{\mathrm{opt}}},D_J}\} \quad (4)$$

where $\gamma_{A,B}$ denotes the instantaneous SNR for the link $A \rightarrow B$.

C. Fairness Concept

The fairness concept is measured from a long-term point of view and with respect to the resource utilization (channel access, power consumption) [8], [9], [18]. More specifically, the support of fairness is translated to an equivalent distribution of the roles to each category of nodes. Therefore, from the router's point of view, the fairness concept ensures that each router can be the intermediate router (or C_1 relay) with the same probability. This consideration ensures the same power consumption for the two routers. More specifically, the intermediate router has to perform DF relaying, resulting in higher power consumption than the AF relay router. The fairness concept enforces the same power consumption for both routers, on average.

From the destination's point of view, the fairness concept ensures that each node will communicate with the source with the same probability. This consideration avoids a monopolistic use of the wireless medium (final destination), as well as a continuous unnecessary power consumption (C_2 relay).

When the channel statistics of the different links are independent identically distributed (i.i.d.) random variables ($\sigma_{A,B}^2 = \sigma^2 \; \forall \; A, B$), each link has the best instantaneous conditions (i.e., SNR) with the same probability, and thus, the fairness concept is automatically supported. However, in the case where the links have different statistics, the router and the destination with the higher average channels will be selected with a higher probability than the other ones. To overcome this problem and support the fairness concept for all the cases, we use the normalized instantaneous SNR as a criterion of the instantaneous quality of a link [8]. More specifically, instead of comparing the absolute SNR value of the direct links, we compare the difference of each instantaneous link from its average value. The considered instantaneous channel quality criterion can be expressed as

$$\bar{\gamma}_{A,B} = \frac{\gamma_{A,B}}{\sigma_{A,B}^2} \quad (5)$$

where $\bar{\gamma}_{A,B}$ is the normalized instantaneous SNR for the link $A \rightarrow B$.

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TABLE I
QUALITATIVE REPRESENTATION OF THE LINK $A \rightarrow B$ WITH N BITS

Received normalized SNR	Qualitative level
$\bar{\gamma}_{A,B} < \Gamma_1$	1
$\Gamma_{\nu-1} \leq \bar{\gamma}_{A,B} < \Gamma_\nu$	ν (for $2 \leq \nu \leq 2^N - 1$)
$\Gamma_{2^N-1} \leq \bar{\gamma}_{A,B}$	2^N

D. Complexity Discussion

The computational complexity of the proposed algorithm is related to the required overhead. In contrast with the full-feedback centralized approaches that require feedback from all the links (six links) to the source, the proposed suboptimal scheme requires a limited number of feedback packets. More specifically, the links that are involved in the decision process are the direct links between source and routers and selected router and destinations (four links). Moreover, in contrast with the full-feedback approaches that require probability computations of analytical performance for all the possible combinations to find the optimal solution, the proposed algorithm bases its decision on simple SNR comparisons.

Furthermore, another factor that is related to the feedback complexity is its numerical (digital) representation of feedback. Almost all the literature to date supposes a perfect feedback representation that is not possible for practical applications. To reduce the feedback overhead, we propose a quantized form of feedback that is limited to N bits. In this case, the feedback does not represent the absolute value of the link quality but a qualitative description based on 2^N quality levels. To have a probabilistically equivalent division of the SNR region, the switching SNR levels are given as follows:

$$\text{Prob}\{\bar{\gamma} < \Gamma_n\} = \frac{n}{2^N} \quad \Rightarrow \quad P_{\bar{\gamma}}(\Gamma_n) = \frac{n}{2^N} \quad \Rightarrow$$
$$1 - e^{-\Gamma_n} = \frac{n}{2^N} \quad \Rightarrow \quad \Gamma_n = \ln \frac{2^N}{2^N - n} \tag{6}$$

where $P_{\bar{\gamma}}(\cdot)$ denotes the cumulative distribution function (cdf) of the normalized SNR (the SNR is exponentially distributed with unit parameter for Rayleigh fading channels), and $n = 1, \ldots, 2^N - 1$. Table I summarizes the qualitative representation of a link. The quantized approach and the limited number of the required feedback bits significantly decrease the computational complexity in comparison with the conventional full-feedback centralized schemes. It is obvious that the complexity gain is more important for complex ad hoc configurations that contain many nodes and hops.

E. Performance Analysis

Based on the previous sections, we can now describe the proposed cross-layer approach. In the first phase of the proposed protocol, the source receives quantized (N bits) feedback from the two routers, which indicate the quality of their links with the source. If the two SNR values belong to different subregions, the link with the higher SNR level defines the intermediate router. In the case where the two feedback values are equivalent, the selection is based on a simple RR policy that periodically selects a router as the intermediate node. We note that RR ensures the support of fairness for the case of equivalent links. In the second phase of the protocol, the source receives (quantized) feedback from the two destinations, which describes the quality of the links from the selected router. The destination decision process is the same as for the intermediate router.

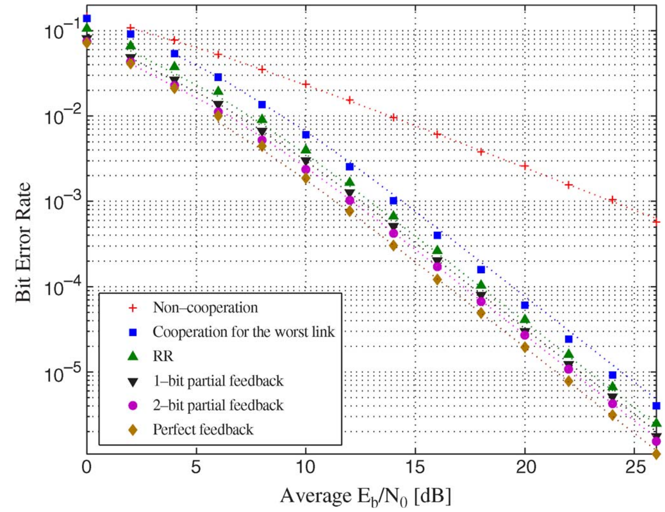

Fig. 2. BER performance for different levels of feedback. (Dotted lines) Analytical results. (Points) Simulation results. C_1 cluster with $\sigma^2_{S,D_i} = \sigma^2$.

The average error probability of the proposed protocol can be expressed as

$$P_{A,B,C}(e) = \frac{2^N - 1}{2^N + 1} P^{(\text{opt})}_{A,B,C}(e) + \frac{2}{2^N + 1} P^{(c)}_{A,B,C}(e)$$
$$P^{(D_J)}(e) = \frac{1}{2} \sum_{I=1}^{2} \left(P_{S,R_{-I},R_I}(e) + P_{R_I,D_{-J},D_J}(e) \right) \tag{7}$$

where $P^{(D_J)}(e)$ is the error probability for the D_J destination, $P_{A,B,C}(e)$ is the error probability for the cooperative links ($A \rightarrow C$, $A \rightarrow B \rightarrow C$), $P^{(\text{opt})}_{A,B,C}(e)$ denotes the error probability for the case where the direct link has the best instantaneous SNR, and $P^{(c)}_{A,B,C}$ is the error probability for the conventional case. Their analytical expressions and the related weight factors can be found in Appendixes I–III, respectively.

F. Complex Networks

The generalization of the proposed scheme for complex networks, which are characterized by many nodes and hops, is straightforward. The algorithm walks through the network in a hop-by-hop basis, and a feedback-based router and relay assignment is performed. For the ith hop, the best instantaneous direct link between the previous selected router [$(i-1)$th hop] and the available ith hop routers defines the intermediate DF router (the final destination for the last hop). The second in order direct link defines the cooperative AF relay for each hop. In the case of equivalent links, an RR policy is applied to ensure the fairness concept.

IV. NUMERICAL RESULTS

Computer simulations were carried out to evaluate the performance of the proposed cross-layer design. The simulation environment is based on the model of Section II. Fig. 2 presents the bit-error-rate (BER) performance of different feedback levels for a scenario with one hop (C_1) and equivalent links. The performance of the noncooperative scheme and cooperation for the worse direct link are used as reference. From these curves, we can see that the feedback-based approaches outperform the classical RR (no feedback). More specifically, the gain of the perfect feedback approach is equal to 2 dB, and for quantized feedback, it is equal to 0.5 dB for each used bit (1 dB for 2 bits). An important observation is that a quantized feedback with a low number

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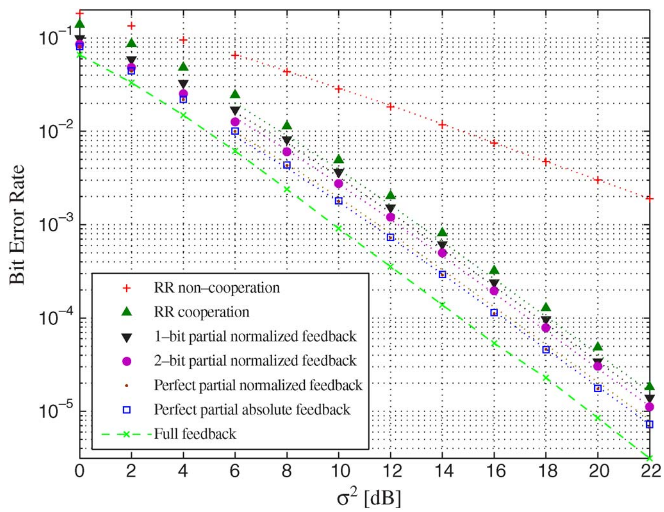

Fig. 3. BER performance for the D_1 destination and for different levels of feedback versus σ^2 (received E_b/N_0 for a subset of links). (Dotted lines) Analytical results. (Points) Simulation results. $C_1 + C_2$ clusters with $\sigma^2_{S,R_1} = \sigma^2_{R_1,D_1} = \sigma^2 + 4$ dB and $\sigma^2_{R_2,D_1} = \sigma^2 + 2$ dB, where σ^2 is the received E_b/N_0 for all the other links.

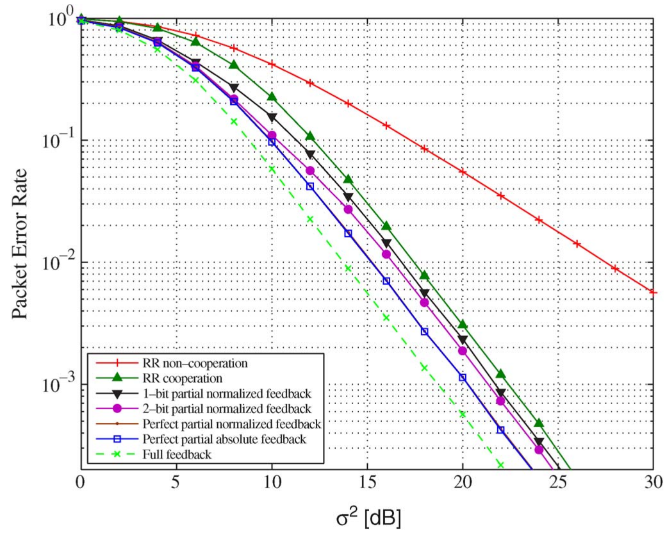

Fig. 4. PER performance for the D_1 destination and for different levels of feedback versus σ^2 (received E_b/N_0 for a subset of links). $N_b = 500$ bits, $C_1 + C_2$ clusters with $\sigma^2_{S,R_1} = \sigma^2_{R_1,D_1} = \sigma^2 + 4$ dB, and $\sigma^2_{R_2,D_1} = \sigma^2 + 2$ dB, where σ^2 is the received E_b/N_0 for all the other links.

of bits $(N = 2)$ gives a satisfactory performance–complexity tradeoff. Furthermore, the comparison between analytical and simulation results validates the presented theoretical analysis.

The following simulation results refer to the complete ad hoc configuration of Section II (C_1 and C_2) and deal with the fairness problem. Here, the different links are not symmetric, and their relation can be represented by the equations $\sigma^2_{S,R_1} = \sigma^2_{R_1,D_1} = \sigma^2 + 4$ dB and $\sigma^2_{R_2,D_1} = \sigma^2 + 2$ dB, where σ^2 is the received power (in decibels) of all the other links. Fig. 3 presents the BER performance for the destination D_1 and for different configurations of the proposed algorithm. The performance for an RR noncooperative scheme and a channel-based scheme with absolute partial feedback are given as reference results. Moreover, the performance of a full-feedback scheme, which bases the scheduling and routing decision on an analytical estimation of the performance for all the possible combinations, is also shown for comparison. From the presented curves, we can also see that the channel-based approaches outperform the RR scheme, and their gains follow our previous remarks. Moreover, we can see that the perfect feedback normalized solution has a similar performance as the perfect feedback absolute SNR solution, which suffers from a lack of fairness. Therefore, the normalized approach jointly optimizes the performance and supports the fairness concept. The comparison of the proposed algorithm with the full-feedback scheme shows a difference of about 1.5 dB at high SNRs. This difference has been expected as the proposed algorithm only uses partial channel information. However, the decrease in complexity by considering partial feedback in the scheduling and routing decision is more important than the resulting performance degradation.

Fig. 4 shows the packet-error-rate (PER) performance for the considered two-cluster simulation environment. The PER is a common performance measure for cross-layer designs and efficiently represents the interplay between layers. The considered packet size is equal to $N_b = 500$ "uncoded" bits, and the channel remains unchanged over the packet duration. The presented results validate that a 2-bit feedback provides an efficient performance–complexity tradeoff. At low SNRs ($\leq$10 dB), the achieved performance approaches that of a perfect partial feedback (absolute/normalized), and at high SNRs, the corresponding gain is similar to the BER plots.

TABLE II
FAIRNESS CONCEPT

Algorithm	R_1	R_2	D_1	D_2
RR	50%	50%	50%	50%
Normalized SNR	50%	50%	50%	50%
Absolute SNR	71.5%	28.5%	68.6%	32.4%

Table II presents the fairness behavior of the different approaches simulated in Figs. 3 and 4. From this table, we can see that the normalized channel-based approaches support the fairness concept, and thus, the probability of using a node is equal to 0.5. On the other hand, the absolute channel-based scheme gives an unfair allocation of the considered nodes. Therefore, the router R_1 is used as an intermediate router with a probability of 0.715, and the destination D_1 is used as a final destination with a probability of 0.686. The justification of these results is explained in Appendix IV.

V. Conclusion

In this paper, we have dealt with the cross-layer optimization in cooperative diversity systems, which use a combination of AF and DF as a relaying strategy. The proposed cross-layer approach incorporates channel-based routing and scheduling and supports fair resource allocation between the nodes. To decrease the required overhead, a partial and quantized feedback is proposed, which is limited to a small number of links and carries a qualitative representation of the normalized instantaneous channel conditions. The performance of the proposed scheme is evaluated by theoretical studies and computer simulations, and we show that it achieves an efficient performance–complexity tradeoff. Although the presented analysis refers to a particular well-selected ad hoc topology, they are useful for practical systems with many nodes and hops.

Appendix I
Statistical Description of the System

We consider a three-node system with one source (A), one relay (B), and one destination (C). The SNR of the direct link $(A \rightarrow C)$ follows an exponential distribution, and the SNR for the relaying link

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$(A \rightarrow B \rightarrow C)$ can be expressed via the harmonic mean distribution [23]. More specifically, the probability density function (pdf) of the two possible links can be expressed as

$$\begin{aligned} p_{A,C}(\gamma) &= \beta_{A,C} e^{-\beta_{A,C}\cdot\gamma} U(\gamma) \\ p_{A,B,C}(\gamma) &= 2\beta_{A,B}\beta_{B,C}\gamma e^{-(\beta_{A,B}+\beta_{B,C})\cdot\gamma} \\ &\quad \times \left[\frac{\beta_{A,B}+\beta_{B,C}}{\sqrt{\beta_{A,B}\beta_{B,C}}} K_1\left(2\gamma\sqrt{\beta_{A,B}\beta_{B,C}}\right) \right. \\ &\quad \left. + 2K_0\left(2\gamma\sqrt{\beta_{A,B}\beta_{B,C}}\right)\right] U(\gamma) \\ &\simeq (\beta_{A,B}+\beta_{B,C}) e^{-(\beta_{A,B}+\beta_{B,C})\cdot\gamma} U(\gamma) \end{aligned} \tag{8}$$

where $U(\cdot)$ is the unit step function; $p_{A,C}(\cdot)$ and $p_{A,B,C}(\cdot)$ are the pdfs of the direct and relay links, respectively; $\overline{\gamma_{i,j}}$ is the average SNR for the link $i \rightarrow j$; $\beta_{i,j} = 1/\overline{\gamma_{i,j}}$; and $K_i(\cdot)$ is the ith-order modified Bessel function of the second kind. We note that the aforementioned asymptotic expression can be found in [24, eq. (9.6.9)].

The pdf of the SNR in the MRC output can be expressed as

$$\begin{aligned} p_c^C(\gamma) &= p_{A,C}(\gamma) * p_{A,B,C}(\gamma) \\ &\simeq \frac{(\beta_{A,B}+\beta_{B,C})\beta_{A,C}}{(\beta_{A,B}+\beta_{B,C})-\beta_{A,C}} \\ &\quad \times \left(e^{-\beta_{A,C}\cdot\gamma} - e^{-(\beta_{A,B}+\beta_{B,C})\cdot\gamma}\right) U(\gamma) \end{aligned} \tag{9}$$

where the notation "$*$" denotes the convolution process.

Based on the aforementioned statistical description, the error probability of a cooperative system can be expressed as

$$P_{A,B,C}^{(c)}(e) = \int_0^\infty P(e|\gamma) p_c^C(\gamma) d\gamma \tag{10}$$

where $P(e|\gamma)$ is the instantaneous error probability, which is equal to $Q(\sqrt{2\gamma})$ for the BPSK case, with $Q(x)$ as the Gaussian Q-function, which is defined as $Q(x) = (1/\sqrt{2\pi})\int_x^\infty e^{-t^2/2} dt$.

APPENDIX II
COOPERATION WITH RELAY SELECTION

We suppose a basic three-node cooperative system (A, B, C) with one source A and two destinations B and C, in which one of them is the potential relay.

A. Selecting the Node With the Poorer Direct Link

In this case, the relay becomes the node that has the poorer direct link (SNR) with the source. By using the basic order-statistics theory [25], the pdf of the SNR for the source to relay link can be expressed as

$$\begin{aligned} p_r(\gamma) &= p_{A,B}(\gamma)\left(1 - P_{A,C}(\gamma)\right) + p_{A,C}(\gamma)\left(1 - P_{A,B}(\gamma)\right) \\ &= (\beta_{A,B}+\beta_{A,C}) e^{-(\beta_{A,B}+\beta_{A,C})\cdot\gamma} \end{aligned} \tag{11}$$

where $p_{i,j}(\cdot)$ and $P_{i,j}(\cdot)$ denote the pdf and cdf, respectively, for a direct link $i \rightarrow j$. Therefore, based on (8), the pdf of the SNR for the relaying link $A \rightarrow B \rightarrow C$ can be written as

$$p_s(\gamma) = (\beta_{A,B}+\beta_{A,C}+\beta_{B,C}) e^{-(\beta_{A,B}+\beta_{A,C}+\beta_{B,C})\cdot\gamma}. \tag{12}$$

Furthermore, based on (9) and (12), the pdf of the SNR (for the C destination) of the cooperative case is asymptotically given by

$$\begin{aligned} p_{c,s}^C(\gamma) &= \frac{(\beta_{A,B}+\beta_{A,C}+\beta_{B,C})\beta_{A,C}}{(\beta_{A,B}+\beta_{B,C})} \\ &\quad \times \left(e^{-\beta_{A,C}\cdot\gamma} - e^{-(\beta_{A,B}+\beta_{A,C}+\beta_{B,C})\cdot\gamma}\right). \end{aligned} \tag{13}$$

B. Selecting the Node With the Best Direct Link

In this case, the relay is the node with the best direct link (SNR). Based on [26], the pdf of the SNR for the relaying link can be expressed as

$$\begin{aligned} p_s'(\gamma) &= (\beta_{A,B}+\beta_{B,C}) e^{-(\beta_{A,B}+\beta_{B,C})\cdot\gamma} \\ &\quad + (\beta_{A,C}+\beta_{B,C}) e^{-(\beta_{A,C}+\beta_{B,C})\cdot\gamma} \\ &\quad - (\beta_{A,B}+\beta_{A,C}+\beta_{B,C}) e^{-(\beta_{A,B}+\beta_{A,C}+\beta_{B,C})\cdot\gamma}. \end{aligned} \tag{14}$$

Based on (9) and (14), the pdf of the SNR (for the C destination) for the cooperative case is equal to

$$\begin{aligned} p_{c,s}'^C(\gamma) &= \frac{(\beta_{A,B}+\beta_{B,C})\beta_{A,C}}{\beta_{A,B}+\beta_{B,C}-\beta_{A,C}} \\ &\quad \times \left(e^{-\beta_{A,C}\cdot\gamma} - e^{-(\beta_{A,B}+\beta_{B,C})\cdot\gamma}\right) \\ &\quad + \frac{(\beta_{A,C}+\beta_{B,C})\beta_{A,C}}{\beta_{B,C}} \\ &\quad \times \left(e^{-\beta_{A,C}\cdot\gamma} - e^{-(\beta_{A,C}+\beta_{B,C})\cdot\gamma}\right) \\ &\quad - \frac{(\beta_{A,B}+\beta_{A,C}+\beta_{B,C})\beta_{A,C}}{\beta_{A,B}+\beta_{B,C}} \\ &\quad \times \left(e^{-\beta_{A,C}\cdot\gamma} - e^{-(\beta_{A,B}+\beta_{A,C}+\beta_{B,C})\cdot\gamma}\right). \end{aligned} \tag{15}$$

Therefore, the related error probability expression can be written as

$$P_{A,B,C}^{(\mathrm{opt})}(e) = \int_0^\infty P(e|\gamma) p_{c,s}'^C(\gamma) d\gamma. \tag{16}$$

APPENDIX III
WEIGHT FACTORS OF (7)

We assume two direct links and K equivalent SNR regions. The total number of cases where a link can be used for direct transmission can be expressed by the following arithmetic series:

$$S_K = \sum_{k=1}^K k = \frac{K(K+1)}{2}. \tag{17}$$

The number of cases where the RR scheme is involved is equal to the number of SNR regions. Therefore, the two weight factors of (7) are given by

$$\begin{aligned} w_{\mathrm{opt}} &= \frac{S_K - K}{S_K} = \frac{K-1}{K+1} \\ w_{\mathrm{RR}} &= \frac{K}{S_K} = \frac{2}{K+1}. \end{aligned} \tag{18}$$

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APPENDIX IV
FAIRNESS CONCEPT

The fairness concept is related to the probability that each node can be selected. Therefore, based on [8], we have

$$\phi_{R_I} = \frac{\beta_{S,R_{-I}}}{\beta_{S,R_I} + \beta_{S,R_{-I}}}$$
$$\phi_{D_J} = \sum_{I=1}^{2} \phi_{R_I} \frac{\beta_{R_I,D_{-J}}}{\beta_{R_I,D_J} + \beta_{R_I,D_{-J}}} \qquad (19)$$

where ϕ_{R_I} is the probability that the router R_I can be selected as an intermediate router, and ϕ_{D_J} is the probability that the destination D_J can be the final destination. We note that for the normalized approach, $\beta_{i,j} = 1/2\, \forall\, i, j$.

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A Novel Method of Serving Multimedia and Background Traffic in Wireless LANs

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***Abstract*—Wireless local area networks (LANs) require the efficient integration of multimedia and traditional data traffic. This paper proposes the Priority-Oriented Adaptive Polling (POAP) protocol that could be used in place of the enhanced distributed channel access (EDCA) part of the IEEE 802.11e access scheme. EDCA seems capable of differentiating traffic; however, it exhibits great overhead that limits the available bandwidth and degrades performance. POAP is collision free, prioritizes the different kinds of traffic, and is able to provide quality of service (QoS) for all types of multimedia network applications while efficiently supporting background data traffic. POAP, compared to EDCA, provides higher channel utilization, distributes resources to the stations adapting to their real needs, and generally exhibits superior performance.**

***Index Terms*—Adaptive polling, medium access control (MAC), quality of service (QoS), wireless local area network (LAN).**

I. INTRODUCTION

Nowadays, voice, audio, and video have to be efficiently transmitted along with the traditional data traffic. Real-time applications require QoS because they are time bounded, while slightly unreliable connections are allowed. On the other hand, data traffic does not demand particularly low delay, but reliability is essential. Thus, modern networks should be able to meet all types of traffic requirements. The IEEE 802.11e [1] workgroup has enhanced the Distributed Coordination Function (DCF) with QoS support, proposing enhanced distributed channel access (EDCA), which is the essential part of the 802.11e

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