Opportunistic Relay Selection in Cooperative Systems With Dirty-Paper Coding

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***Abstract*—This paper investigates an optimization of the conventional relay selection for multirelay environments. In contrast with previously reported selection schemes, where a selected relay accesses the channel in a dedicated cooperative slot, the proposed scheme recovers the bandwidth loss of the half-duplex constraint by allowing two relays to simultaneously access the channels. Based on an appropriate dirty-paper coding (DPC) technique among relays, the proposed scheme enables a relay to establish communication with the destination at the same time that another relay forwards the data from the source. It is proven that the interplay between relay selection and the superposition DPC weight factor provides a tradeoff between relaying and new data performance. Hence, an appropriate codesign of the superposition DPC parameter and opportunistic relay selection can achieve efficient communication for the new data without affecting the relaying performance. The proposed scheme is compared with conventional relaying approaches, and its enhancements are provided through theoretical studies and numerical results.**

***Index Terms*—Cooperative diversity, decode-and-forward, dirty-paper coding, opportunistic selection, relays.**

I. Introduction

COOPERATIVE diversity is an efficient technique to combat fading in wireless communications. It is based on the broadcast nature of the wireless medium and allows terminals, which are in the coverage area of a transmission, to create a virtual receiver/transmitter antenna array. Since the work of Sendonaris *et al.* [1], which introduced the notion of cooperative diversity, a number of relaying protocols have been proposed in the literature [2]–[8] for different system configurations.

For multirelay systems, a multiple retransmission of the source data can significantly improve the diversity gain of the system. This process can be performed in different orthogonal channels, which results in a data rate loss, or by allowing a simultaneous relay transmission via distributed space-time codes (DSTCs) at the cost of higher complexity [3]. Recent research has shown that an appropriate relay selection incurs no performance loss compared with multiple-relay transmissions in terms of diversity–multiplexing tradeoff (DMT) and outage probability and results in a lower complexity than DSTC approaches [9], [10]. However, due to the half-duplex constraint, relay selection still requires two orthogonal channels to accomplish cooperation.

The recovery of the data rate loss in cooperative systems is a hot research topic in the literature. Existing solutions overlap simultaneous transmissions (i.e., two transmissions) to overcome the half-duplex limitation. In superposition techniques, a relay simultaneously behaves as a transmitter and relay by using a part of its power to transmit new data and another part for relaying data [11]. Other solutions assume multiple-relay configurations where the relays take turns helping the source to mimic a full-duplex relay [12]. Furthermore, space-time code (STC) techniques allow the transmitters to keep transmitting new data during the cooperative slot [5], [7]. Finally, another approach that has recently been proposed in the literature is the consideration of dirty-paper coding (DPC) [13], [14] among relays. DPC allows a relay to transmit new data at the same time that another relay assists the source transmission. In [15], the authors use DPC design to support multiple data streams in a multihop environment. In [16], the authors present a practical DPC scheme for a basic four-node interference channel. However, in both schemes, DPC design optimization (superposition factor) is not taken into account, and relay selection issues are not discussed.

In this paper, we combine DPC design and opportunistic relay selection under a cooperative diversity concept. The proposed approach uses superposition modulation as our "embodiment" of DPC by analogy with [17] and [18]. Based on a clustered decode-and-forward (DF) relay configuration [2], a new cooperative strategy is investigated that allows two well-selected relays to simultaneously access the channel. In the case in which at least two relays can decode the source signal, one relay assists the source transmission by acting as a conventional relay, and the other transmits new data by using DPC. In contrast to the previous works where DPC is used without parameterization, here, we take into account the superposition weight factor, and we study its impact on the performance of the simultaneous links. In addition to this parameter, the incorporation of DPC design with the relay-selection policy is also discussed. Both parameters provide a tradeoff between relaying and new data performance and introduce an optimization problem. It is proven that an appropriate design of these parameters yields a performance similar to the conventional opportunistic relay selection by jointly maximizing the performance of both the relaying link and the new data link. The proposed scheme is appropriate for systems that operate a conventional relay-selection mechanism and can be viewed as an efficient way to improve

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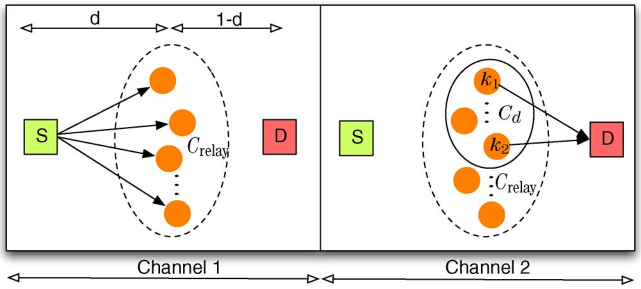

Fig. 1. System model and the related communication scenario (the source–destination link is blocked, and communication is performed via relays); S: source, D: destination, C_{relay}: cluster of relays, C_d: Decoding set, and d: distance $S \to C_{\text{relay}}$.

their performance without complicated structural modifications. The investigated selection-based cooperative protocol is compared to conventional relaying approaches, and its enhancements are provided by theoretical and simulation results. To the best of our knowledge, the codesign of DPC and opportunistic relay selection is reported in this paper for the first time.

The main contributions of this paper are twofold.

1) A new relaying scheme that uses the principles of DPC to overcome the half-duplex penalty of the cooperative relaying is proposed. The new approach allows two relay nodes to simultaneously access the channel, where one relay assists the source communication (conventional relaying), and another relay transmits its own data.
2) The interplay between relay selection and the superposition DPC factor introduces a tradeoff between relaying and new data transmissions. An optimization problem that ensures a performance similar to the conventional selection (CS) scheme and simultaneously provides an efficient communication for the new data is formulated. The solution of this optimization problem allows the proposed scheme to be viewed as an optimization of the conventional relay selection.

This paper is organized as follows. Section II introduces the system model and gives an overview of the related conventional approaches. Section III presents the proposed cooperative protocol and analyzes its performance in terms of outage probabilities. Numerical results are shown and discussed in Section IV followed by concluding remarks in Section V.

II. System Model

The system model consists of one source S, one destination D, and a cluster C_{relay} of K DF relays. Fig. 1 schematically presents the considered system model. To focus on the relaying link, a direct link $S \to D$ is not available, and the source can communicate with the destination only via the relays. This system model follows the description in [9], [10], and [19], where the direct path between the source and destination is blocked by an intermediate wall, while relays are located at the periphery of the obstacle (around the corner). Relays cannot simultaneously transmit and receive, and therefore, communication is performed in two orthogonal channels. In the broadcasting channel, the source transmits its data and the relays that can successfully decode the source signal form a decoding set $C_d \subseteq C_{\text{relay}}$. In the cooperative channel and according to the cooperative protocol, some selected relays $k \in C_d$ assist the source to deliver its data to the destination. In contrast to "pure" relay approaches, where relay nodes only assist the source transmission, here, we assume that the relay nodes are active network elements and always have data to transmit to the common destination D. This assumption refers to cellular networks with relaying abilities or sensor networks where sensors collaborate to transmit their observations to a fusion center. A slow flat block Rayleigh fading environment is assumed, where the channel remains static for one coherence interval (two slots) and independently changes in different coherence intervals with a variance equal to $\sigma_{i,j}^2$ for the link $i \to j$. Furthermore, additive Gaussian noise is assumed with unit variance. Moreover, we assume a uniform power allocation scheme, i.e., the total transmit power (defined as P_0) in each transmission time slot remains the same, and each terminal transmits with equal power. The path-loss attenuation is taken into account by assuming a simple linear geometry where power $(\sigma_{i,j}^2 \propto d_{i,j}^{-\beta})$ is decreased proportional to $d^{-\beta}$, where $d_{i,j}$ is the Euclidean distance between terminals i and j, and β is the path-loss exponent ($\beta = 2$ in our simulations). Perfect knowledge of the instantaneous SNR for the links $k \to D$ is assumed at the relays (but not in the source) [10], which allows reactive opportunistic relay selections and motivates the proposed DPC design. It is worth noting that the reactive selection takes into account only the relay–destination links and has the same outage performance as the proactive selection that decides based on the best end-to-end path between the source and the destination [9], [10]. Furthermore, although for the sake of simplicity, a single-destination channel model is assumed [20], the proposed analysis can be straightforwardly extended to an interference channel model (i.e., two destinations) [21]. It is worth noting that DPC is a theoretical tool that gives some interesting bounds about capacity. The practical implementation of the proposed scheme could involve interference-cancellation techniques and advanced signal processing methods that are not in the scope of this paper.

A. Conventional Methods

1) Distributed Space–Time Code: According to this solution, all the relays that successfully decoded the source signal (for all $k \in C_d$) participate in the cooperation by using a DSTC. The cooperative link becomes equivalent to a conventional multiple-input–single-ouput system with $|C_d|$ transmitting antennas. Due to the considered slot-based power constraint, the total transmitted power is equally distributed among the transmitting nodes. The DSTC approach provides diversity benefits at the destination, but its implementation requires *a priori* knowledge of the decoding nodes, which is critical for practical applications. The instantaneous capacity (for $|C_d| > 1$) can be written as

$$C_{\text{DSTC}} = \frac{1}{2} \log \left(1 + \frac{P_0}{|C_d|} \sum_{k \in C_d} |h_{k,D}|^2 \right) \qquad (1)$$

where $h_{i,j}$ denotes the channel coefficient for the link $i \to j$. A performance analysis of this protocol can be found in [2].

2) Conventional Selection: In contrast to the DSTC approach, where all the decoding nodes ($k \in C_d$) participate in the cooperation, in the CS, only one node relays the source data by using all the available power. The CS provides benefits that are similar to those of the DSTC scheme in terms of outage probability and DMT but has a lower complexity due to its distributed implementation. Based on the above system assumptions (DF relays), for the considered system model, the CS scheme refers to a reactive opportunistic selection [9], [10]. The reactive approach decides based on the relay–destination links and takes into account only the relays that have successfully decoded the source transmission. It has a similar performance with the proactive selection (which decides based on the best source–relay and relay–destination links) but minimizes the cooperation overhead as instantaneous feedback for the source–relay links is not required. In this case, the selected node is decided based on the cooperative slot and corresponds to the relay that has the best instantaneous relay–destination link. The CS can be expressed as [10]

$$C_{\text{CS}} = \frac{1}{2}\log\left(1 + P_0|h_{k^*,D}|^2\right) \tag{2}$$

$$\begin{aligned} P_{\text{out}}^{(\text{CS})} &= \Pr\{C_{\text{CS}} < R_0\} \\ &= \sum_{k=0}^{K}\binom{K}{k}\left[1-\exp(-\Theta)\right]^{(K-k)} \\ &\quad \times \exp(-\Theta)^{(k)}\left[1-\exp(-\Lambda)\right]^{k} \end{aligned} \tag{3}$$

where C_{CS} denotes the instantaneous capacity, $P_{\text{out}}^{(\text{CS})}$ is the outage probability, R_0 is the required spectral efficiency, $k^* = \max_{k \in C_d}\{\gamma_{k,D}\}$ denotes the selected relay, $\gamma_{i,j}$ is the instantaneous SNR for the $i \rightarrow j$ link, $\Theta = (2^{2R_0} - 1)/P_0 d^{-\beta}$, and $\Lambda = (2^{2R_0} - 1)/P_0(1-d)^{-\beta}$, with $d \equiv d_{S,k}$ and $d_{S,D} = 1$ (normalized distance). The optimization of this protocol, as well as its enhancement with new capabilities, is the basic goal of this paper.

III. Relay Selection and Dirty-Paper Coding

A. Proposed Scheme

Although opportunistic selection techniques provide diversity benefits with a lower complexity than DSTC, they still suffer from data rate loss. Due to the half-duplex constraint, the selected relay cannot simultaneously transmit and receive, and thus, two slots are required to accomplish communication. The proposed scheme is based on the conventional relay selection and recovers this suboptimal bandwidth utilization by transmitting two data flows during the cooperative slot. More specifically, if for a source transmission, the cardinality of the decoding set is $|C_d| > 1$ (at least two relays can decode the signal), a DPC design can be used to allow two relays to simultaneously access the channel. Fig. 1 (channel 2) depicts the simultaneous transmission of the two relays. One relay is used as a conventional relay node to deliver the source data to the destination, and the second one transmits its own data to the common destination. Based on the fact that one relay retransmits the decoded source data to accomplish cooperation, the other one uses this information as an *a priori* known interference at the transmitter to apply dirty-paper precoding to its own data. According to the DPC principles, the transmission of the new data is interference free but causes interference to the relaying link. The considered DPC technique for fading channels can be found in [21] and yields a capacity region for the simultaneous transmissions that is equal to

$$\begin{aligned} &R_{k_1}(\alpha, k_1, k_2) \\ &\quad \leq \frac{1}{2}\log\left(1 + \frac{\left(\sqrt{P_0/2}|h_{k_1,D}| + \sqrt{\alpha P_0/2}|h_{k_2,D}|\right)^2}{1 + (1-\alpha)|h_{k_2,D}|^2 P_0/2}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} &R_{k_2}(\alpha, k_2) \\ &\quad \leq \frac{1}{2}\log\left(1 + (1-\alpha)|h_{k_2,D}|^2 P_0/2\right) \end{aligned} \tag{5}$$

where k_1, $k_2 \in C_d$ are the selected node for the relaying transmission and the new data transmission, respectively, R_j is the maximum data rate for the jth node transmission, and $h_{i,j}$ is the channel coefficient for the $i \rightarrow j$ link. As can be seen from (4) and (5), the superposition DPC factor α and the selection of the relay nodes (k_1, k_2) have a critical impact on the performance of the system. These parameters introduce a tradeoff between the relaying and the new data link, and their interplay corresponds to an interesting optimization problem. The basic question here is to define the optimization target of the system and to propose a theoretical framework that efficiently solves the considered optimization problem.

It is worth noting that the consideration of two transmitting data flows during the cooperative slot mitigates the bandwidth loss of the orthogonal relaying transmission (two data flows in two time slots) and allows a DPC design that controls the interference. This system model focuses on these two optimization targets and clearly presents the enhancements of the proposed scheme. In addition to this purpose, a multirelay transmission seems to limit the advantages of the proposed scheme. More specifically, the scenario in which many relays transmit the source signal requires a higher decoding set ($|C_d| > 2$) without improving the performance of the relaying transmission due to the considered power constraint. This scenario decreases the application interest of the proposed scheme and refers to the topologies where the relay is closer to the source. On the other hand, the scenario that many relays transmit new data during the cooperative slot corresponds to a conventional multiaccess channel with interference. In this case, the interference is not known at the transmitters, and thus, a DPC design cannot be applied.

1) Optimization Problem: The basic motivation of the proposed scheme is to simultaneously support two independent data flows without affecting the conventional opportunistic relay selection. Therefore, the optimization target is to improve as much as possible the performance of the new data link by supporting a performance similar to the opportunistic selection for the relaying data. This behavior makes the new data link "transparent" to the CS protocol and is regarded as an optimization of the conventional approach. If the outage probability is the performance metric of the system, the optimization problem under question can be written as

$$\min_{\alpha,k_1,k_2} \left\{ P_{\rm out}^{(k_2)}(\alpha,k_2) \right\}$$
$$\textbf{s.t.} \begin{cases} P_{\rm out}^{(k_1)}(\alpha,k_1,k_2) - P_{\rm out}^{(\rm CS)} = \delta \\ |C_d| > 1 \end{cases} \qquad (6)$$

where R_0 is the required spectral efficiency, $P_{\rm out}^{(\rm CS)}$ denotes the probability of the conventional opportunistic selection [see (3)], $P_{\rm out}^{(j)}(\cdot) = \Pr\{R_j < R_0\}$ is the outage probability for the jth relay (the analytical expressions are given in Section III-B), and δ denotes the tolerated deviation from the true value. As the optimization target of the proposed scheme is to not affect the outage performance of the relaying link, the parameter δ is equal to zero by default. However, for some configurations, the value $\delta = 0$ cannot provide a solution for the optimization problem ($P_{\rm out}^{(k_1)}(\alpha,k_1,k_2)$ converges to $P_{\rm out}^{(\rm CS)}$ without crossing over it) or corresponds to $\alpha = 1$ and, therefore, zero capacity for the new data link. In this case, $\delta > 0$ ensures a solution for the optimization problem for all the cases and increases the application interest of the proposed scheme. It is also worth noting that for the cases in which $\delta \neq 0$, the parameter δ always takes small values ($\delta \simeq 0$) and, thus, has a negligible impact on the system performance. High values of δ correspond to systems where an efficient tradeoff between the simultaneous transmissions is the optimization target. This approach is beyond the scope of this paper and could be considered for future work.

2) Toward the Optimal Solution: Due to the considered slot-based power constraint, the two selected relays transmit with half the power of the CS scheme ($P_0/2$—symmetric power allocation). As the optimization target is to provide a relaying performance similar to the conventional opportunistic scheme, an opportunistic selection (selection based on the best relay–destination link) is the appropriate policy for the relaying data. This policy protects the relaying link from interference and maximizes the numerator in (4) by boosting the term, which is independent of $\alpha < 1$. Furthermore, a close inspection of the considered optimization problem shows that it holds for high values of $\alpha (\alpha \to 1)$. Low values of α increase the interference and limit the power and diversity gain of the relaying link.[1]

On the other hand, the selection of the second relay node does not affect the performance of the relaying link for high values of α. More specifically, for high values of α, the diversity gain [in the numerator of (4)] is dominated by the first relay node that has been selected based on the best relay–destination link. The selection of the second node (i.e., based on the second-best link) provides only a power gain in (4) and, thus, becomes less critical for the relaying link.[2] In this case, the selection of the second node seems to be more important for the new data link. The selection of this node based on an opportunistic relay selection among the remaining $(|C_d| - 1)$ relays can maximize the performance of the new data link and is the appropriate selection policy for the second relay node. Therefore, an appropriate relay-selection policy can be written as

$$k_1 = \arg_{k \in C_d} \max\{\gamma_{k,D}\}$$
$$k_2 = \arg_{k \in \{C_d - k_1\}} \max\{\gamma_{k,D}\}. \qquad (7)$$

The last issue in the considered optimization problem is the definition of the parameter α. This problem requires the solution of the equation $P_{out}^{(k_1)}(\alpha,k_1,k_2) - P_{\rm out}^{(\rm CS)} = \delta$ for $\alpha \in [0,1]$, where the two probabilities are given in (3) and (8), respectively. If this equation has more than one solution, and Δ is the set of these solutions, the appropriate α that solves the considered optimization problem is $\alpha^* = \min\{\Delta\}$. The considered equation can be numerically solved by defining the minimum crossover point between the two outage probabilities. However, to simplify the computations and provide some analytical results, a simplified expression of the $P_{\rm out}^{(k_1)}$ is proposed in Appendix. We note that in the case that $|C_d| = 1$, the proposed scheme becomes identical to the CS strategy, and a new data transmission is not possible.

We note that although Alamouti schemes or beamforming strategies achieve capacity [22] and seem to be appropriate solutions for the transmission of the two independent data flows (for the considered channel model), here, we are interested in systems that operate a conventional relay selection. The proposed scheme recovers the bandwidth loss of the conventional relay selection protocol without modifying its basic mechanism. The related DPC optimization is "transparent" to the first relay node that uses a conventional relay selection, and it is locally applied to the second node. Therefore, it is viewed as an optimization of the conventional relay selection and can be implemented to predesigned relay selection systems without complicated structural modifications. Furthermore, the proposed scheme can be straightforwardly applied to an interference channel model that consists of two separate destinations for the two independent data flows [21].

B. Performance Analysis

1) Relaying Data: In the case that only one relay can decode the source signal, the protocol corresponds to a single relaying transmission. Furthermore, as a direct link is not available between the source and the destination, the transmission is blocked for the case that no relay can decode the signal. Therefore, the outage probability of the relaying link can be written as

$$P_{\rm out}^{(k_1)} = \underbrace{p_{{\rm out}|1} \cdot p_1}_{\text{single transmission}} + \underbrace{\sum_{k=2}^{K} p_{{\rm out}|k} \cdot p_k}_{\text{DPC design}} + \underbrace{p_0}_{\text{non link}} \qquad (8)$$

[1]The term $(\sqrt{P_0/2}\mu + \sqrt{\alpha P_0/2}\psi)^2/(1+(1-\alpha)\psi^2 P_0/2)$ with μ, $\psi \in \Omega$ approaches $P_0\xi^2$ with $\xi = \max \Omega$ as $\alpha \to 1$ and $\mu = \xi$.

[2]This behavior is related to the selection diversity concept where the selection of the best diversity branch has a similar diversity gain with the consideration of all the diversity components [10].

where

$$p_k = \Pr\{|C_d| = k\} = \binom{K}{k} \exp\left(-\frac{(2^{2R_0}-1)k}{P_0 d^{-\beta}}\right) \times \left[1-\exp\left(-\frac{2^{2R_0}-1}{P_0 d^{-\beta}}\right)\right]^{K-k}$$

$$p_{\text{out}|k} = \Pr\left\{\text{outage}\big||C_d| = k\right\} = \begin{cases} 1-\exp\left(-\frac{2^{2R_0}-1}{P_0(1-d)^{-\beta}}\right), & \text{if } k=1 \\ \Upsilon(k,\alpha), & \text{if } k>1 \end{cases} \tag{9}$$

where the function $\Upsilon(\cdot)$ is given in Appendix.

2) New Data: According to the proposed protocol, a new data transmission is performed if at least two relays can decode the source signal. Accordingly, the performance of the new data link can be written as

$$P_{\text{out}}^{(k_2)} = \underbrace{\sum_{k=2}^{K} p_{\text{out}|k} \cdot p_k}_{\text{DPC design}} + \underbrace{\sum_{k=0}^{1} p_k}_{\text{non link}}$$

$$\begin{aligned} p_{\text{out}|k} &= \Pr\left\{\text{outage}\big||C_d| = k\right\} \\ &= \Pr\left\{\frac{1}{2}\log\left(1+\frac{P_0(1-\alpha)|h_{k_2,D}|^2}{2}\right) < R_0\right\} \\ &= \Pr\left\{|h_{k_2,D}|^2 < \frac{2(2^{2R_0}-1)}{P_0(1-\alpha)}\right\} \\ &= \left[1+(k-1)\exp\left(-\frac{2(2^{2R_0}-1)}{P_0(1-\alpha)(1-d)^{-\beta}}\right)\right] \\ &\quad \times \left[1-\exp\left(-\frac{2(2^{2R_0}-1)}{P_0(1-\alpha)(1-d)^{-\beta}}\right)\right]^{(k-1)} \end{aligned} \tag{10}$$

where the above expression is obtained by applying order statistics [selecting the second best among k independent identically distributed (i.i.d.) exponential random variables][3] [23].

According to the previous discussion, the considered optimization problem holds for high values of α. Although this property still supports nonzero communication rates (nonzero capacity) for the new data link ($\alpha \neq 1$) and, thus, the proposed scheme consists of an optimization of the CS for all the cases, it is obvious that its outage probability is maximized as $\alpha \to 1$. To increase the interest of the proposed DPC scheme and improve the quality of service (QoS) for the new data link, a lower spectral efficiency is required for the new data. As the required spectral efficiency for the new data link is decreased, the related outage performance is improved for the same value of α. This assumption corresponds to the network configurations with different QoS requirements and asymmetric data rates. We note that although a spectral efficiency R_0 is used for the new data to aid the clarity of the analysis, simulation results in Section IV validate the interest of the proposed scheme for lower data rates.

[3]Let X_i with $1 \leq i \leq k$ be i.i.d. random variables. The cumulative distribution function (cdf) of the $(k-1)$th-order statistic is equal to $F_{X_{(k-1)}}(x) = \sum_{j=k-1}^{k}\binom{k}{j}F_X(x)^j(1-F_X(x))^{k-j} = F_X(x)^{k-1}[k(1-F_X(x))+F_X(x)]$, where $F_X(x)$ denotes the cdf of X_i.

IV. Numerical Results

Computer simulations were carried out to validate the performance of the proposed schemes. The selected performance metric is the outage probability for both the relaying and the new data link, where according to [24], the outage probability dominates the error probability at the high SNRs. Spectral efficiency is counted in bits per channel per use (BPCU), and the reference SNR represents the received SNR for a hypothetical direct link $S \to D$.

Figs. 2 and 3 plot the outage probabilities versus the DPC superposition factor for different node selection strategies and for the relaying link and the new data link, respectively. The simulation parameters are $K = 4$ users, $R_0 = 2$ BPCU (also $R_0 = 1$ BPCU for the new data link), $d = 0.8$, and $\delta = 10^{-4}$. The E_b/N_0 value is set to 20 dB in our model, which corresponds to the source–destination link, but recall that the source–destination link is neglected in capacity equations. As can be seen for $\alpha \geq 0.8$, the proposed DPC approach approximates the performance of the CS scheme by allowing communication for the new data (nonzero capacity). More specifically, for $\alpha \geq 0.8$, the selection policies that use the best instantaneous relay–destination link for relaying approximate the CS. Therefore, the best relay–destination link serves the relaying data as in the conventional opportunistic selection policy. On the other hand, the selection of the second relay has no impact on the performance of the relaying link. For high values of α, the interference [in (4)] becomes negligible, and due to the opportunistic selection of the first node, the diversity gain is independent of the relay selection. In this case, as the best relay is not available for the new data transmission, the selection policy that maximizes the performance of the new data link is based on the second-best instantaneous relay–destination link. According to the considered optimization problem, a parameter $\alpha = 0.8$, as well as a selection policy that uses the best relay–destination link for relaying and the second-best link for the new data, is the appropriate parameterization of the system. This value maximizes the capacity of the new data link and, thus, optimizes its outage behavior. Furthermore, Fig. 3 shows the impact of a lower spectral efficiency on the outage performance of the new data link. As can be seen, a spectral efficiency equal to $R_0 = 1$ BPCU provides a lower outage probability and improves the quality of the link. This result validates the point that the proposed scheme becomes more important for applications with different QoS where some nodes transmit in lower rates than other ones.

In Fig. 4, we compare the outage performance of the relaying and new data links versus the SNR. The conventional STC approach, a direct noncooperative link, and the CS are used as reference protocols. The simulation environment is similar to the previous one, and $\alpha = 0.8$ is used for the proposed DPC approach. The first important observation is that opportunistic-selection-based schemes outperform STC protocols with a related SNR gain of 4 dB. This result is in line with previously

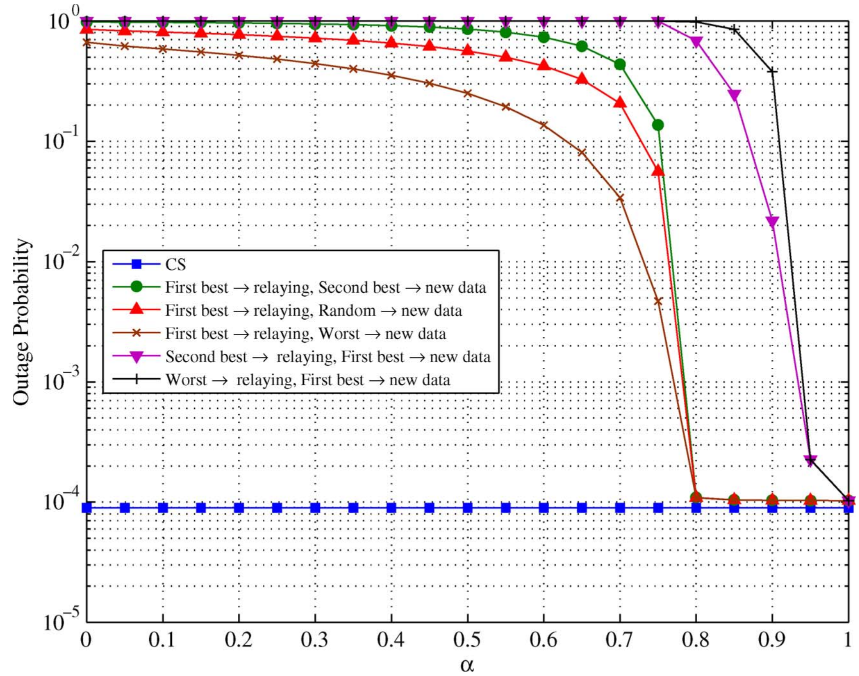

Fig. 2. Outage probabilities for the relaying link versus parameter α for different selection schemes: $R_0 = 2$ BPCU, $E_b/N_0 = 20$ dB, $d = 0.8$, $\delta = 10^{-4}$, and $K = 4$ users.

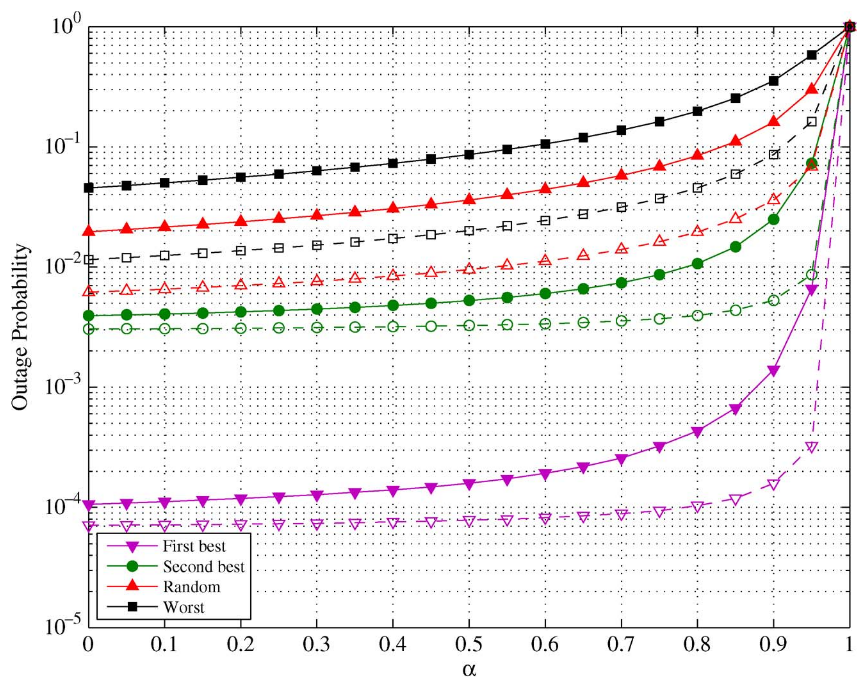

Fig. 3. Outage probabilities for the new data link versus parameter α for different selection schemes: Lines $R_0 = 2$ BPCU, dashed lines $R_0 = 1$ BPCU; $E_b/N_0 = 20$ dB, $d = 0.8$, and $K = 4$ users.

reported work and validates that relay selection seems to be a suitable solution for practical systems [10]. In addition to this observation, it can be seen that the proposed DPC scheme provides a performance similar to that of the CS scheme for all the SNRs. The parameter α is a global optimal value for all the SNR regimes (independent of SNR) and approximates the selection performance for all the cases. However, the most important result is the performance of the new data relaying link. As can be seen, the relay can establish an efficient communication with the destination with a performance that is about 5 dB lower than the STC protocol for the relaying data. Accordingly, its performance is improved as the required spectral efficiency decreases. A spectral efficiency equal to 1 BPCU offers a further gain of 2 dB.

In Fig. 5, we deal with another system configuration where the cluster C_{relay} is closer to the source. More specifically,

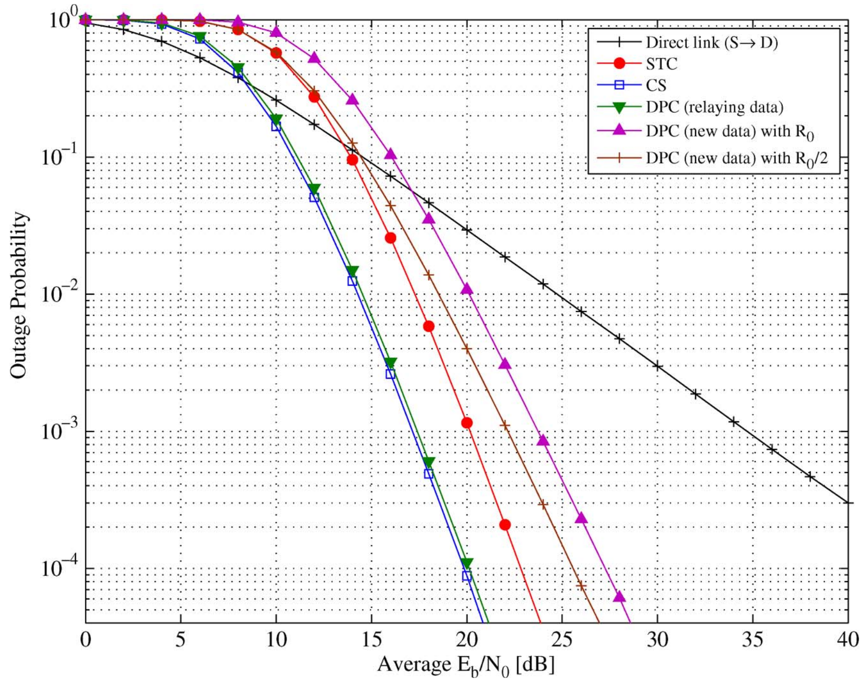

Fig. 4. Outage probabilities versus E_b/N_0 for the direct link (reference), STC, CS, and proposed schemes (relaying and new data): $R_0 = 2$ BPCU, $d = 0.8$, $\delta = 10^{-4}$, $\alpha = 0.8$, and $K = 4$ users.

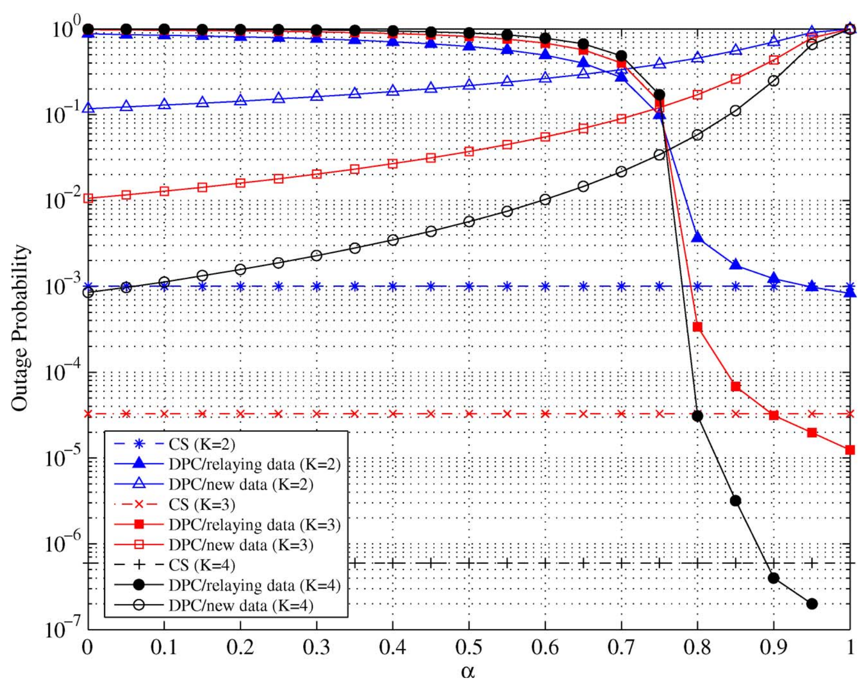

Fig. 5. Outage probabilities for the relaying link and the new data link versus parameter α for different numbers of relays: $R_0 = 2$ BPCU, $E_b/N_0 = 25$ dB, $d = 0.2$, $\delta = 0$, and $K = 2, 3, 4$ users.

we plot the outage performance of the relaying and the new data links for the CS and the proposed scheme. The simulation parameters are $K = 2, 3,$ and 4 users, $d = 0.2$, $\delta = 0$, and $E_b/N_0 = 25$ dB. In this case, the crossover point between the CS and DPC approaches yields an optimal superposition DPC factor equal to $\alpha = 0.9$. As can be seen, this optimal value (crossover point) is also independent of the number of users and, thus, depends only on the geometry of the system (d). Furthermore, as d is decreased (the cluster is closer to the source), the optimal value of α is increased to overcome the higher path loss, and therefore, the new data link becomes less efficient (the scale factor $(1 - \alpha)$ is decreased). To visualize this behavior, in Fig. 6, we compare the performance of the relaying and new data links versus the SNR for $\alpha = 0.9$, $d = 0.2$, $R_0 = 2$

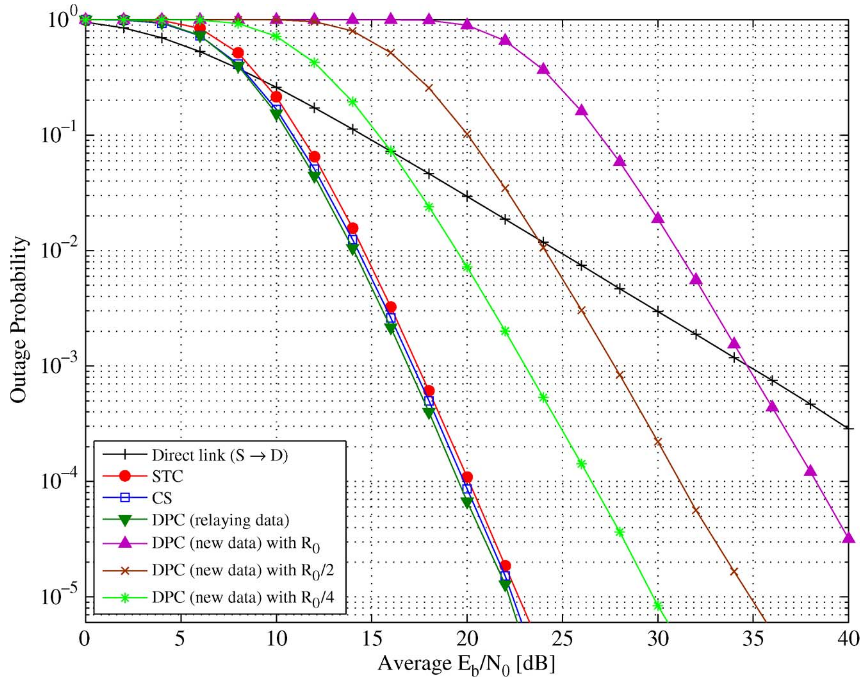

Fig. 6. Outage probabilities versus E_b/N_0 for the direct link (reference), STC, CS, proposed schemes (relaying and new data): $R_0 = 2$ BPCU, $d = 0.2$, $\delta = 0$, $\alpha = 0.9$, and $K = 4$ users.

BPCU (also $R_0 = 1, 0.5$ BPCU for the new data link), and $K = 4$ users. As can be seen, in this case, the DPC relaying link approaches the performance of the conventional opportunistic selection, but the performance of the new data link is decreased. When the cluster C_{relay} is closer to the source, the path loss between the relay and the destination becomes stronger and degrades the performance of the selection scheme (a performance similar to STC) by simultaneously decreasing the reliability of the DPC approach. However, at a high SNR ($E_b/N_0 >$ 35 dB), the performance of the new data link outperforms the performance of the (hypothetical) direct link. In addition to this observation, it can be seen that as the spectral efficiency of the new data link decreases, the related outage performance is improved. Based on the above results, it seems that the location of the cluster C_{relay} closer to the destination maximizes the interest of the proposed scheme as the outage performance of the new data link is improved.

In Fig. 7, we study the outage probability of the relaying link versus the parameter α for different selection schemes and different topologies. The selection strategies considered are those that have been described in the simulation results of Fig. 2. Based on the presented curves, the considered relay policy (best link $\rightarrow$ relaying data, second best $\rightarrow$ new data) is the appropriate solution for all the cases. This observation is in line with our previous simulation results and validates the point that the selection policy that solves the considered optimization problem is independent of the parameter d. This figure also presents the corresponding values of the parameters α and δ. It shows that α takes values in the interval [0.8, 0.9] and demonstrates that the parameter δ always takes very small values. Furthermore, Fig. 8 compares the different cooperative protocols by using as a performance metric the total achievable capacity. For the proposed DPC scheme, the capacity is defined as the sum capacity of the relaying and new data links. As can be seen, the proposed DPC approach provides a higher capacity than the conventional schemes, and its gain increases as the SNR increases (different slopes at high SNRs). This result shows that the proposed approach provides a higher overall system capacity and more clearly verifies the enhancements of the proposed scheme.

Finally, in Fig. 9, a comparison between simulation and analytical results is provided for both relaying and new data. The simulation parameters are $R_0 = 2$ BPCU, $K = 3$ users, $E_b/N_0 = 30$ dB, and $d = 0.2, 0.5, 0.8$. From the presented curves, it can be seen that the theoretical analysis efficiently approximates the true performance for both cases. More specifically, the analysis for the new data link perfectly fits with the simulation results. As far as the relaying performance is concerned, it is shown that the proposed approximation is reliable for a low α and a higher d (i.e., $d = 0.5, 0.8$) but becomes an upper bound for a combination of a high α and a small d (i.e., $d = 0.2$). The justification of this behavior is based on the simplified expression in Appendix, which holds for a high d. However, according to the above discussion, the proposed DPC method is suitable for scenarios where the cluster of relays is closer to the destination (the performance of the new data link is improved). For these scenarios, the proposed approximation is reliable and can provide an analytical computation of the required parameter α.

V. Conclusion

In this paper, we have incorporated the DPC design and the reactive opportunistic selection for DF clustered cooperative systems. In contrast with the conventional opportunistic selection, where only one relay transmits the data of the source,

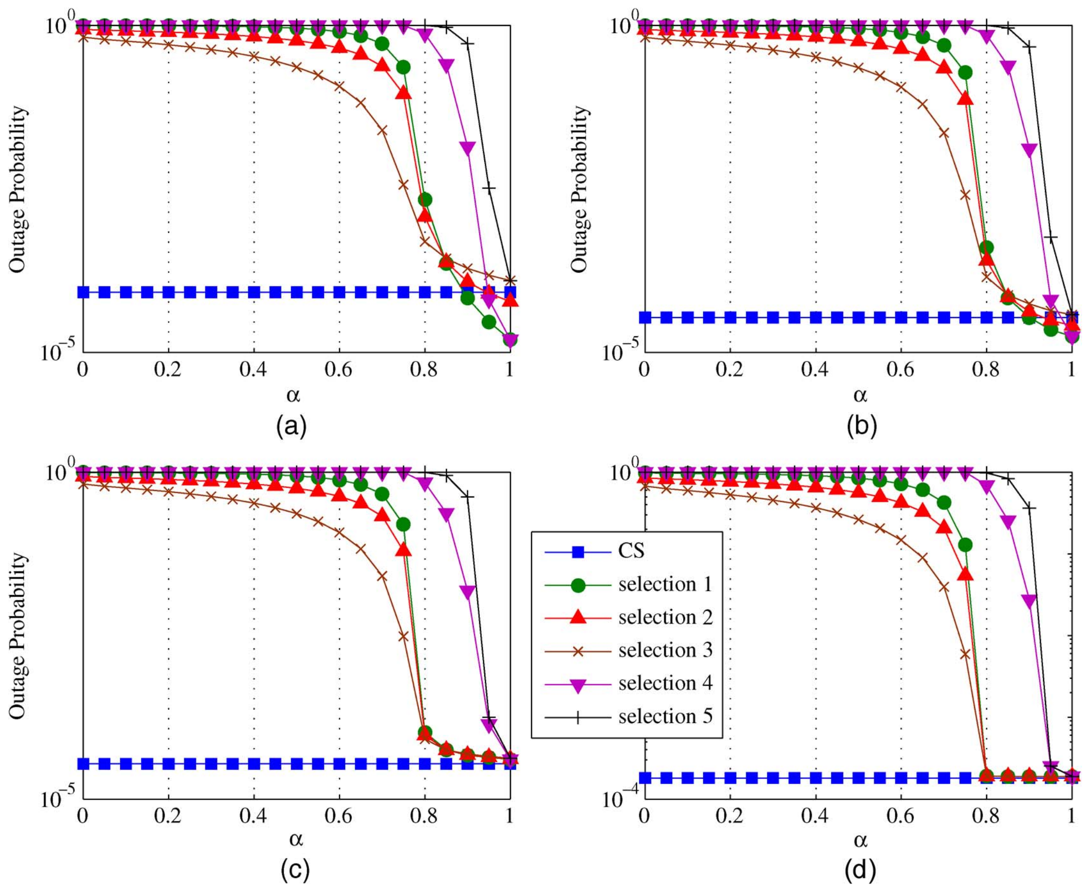

Fig. 7. Outage probabilities for the relaying link versus parameter α for different selection schemes (see Fig. 2) and different distances: $R_0 = 2$ BPCU, $E_b/N_0 = 20$ dB, and $K = 4$ users. (a) $d = 0.2 \Rightarrow \delta = 0$, and $\alpha = 0.9$. (b) $d = 0.4 \Rightarrow \delta = 0$, and $\alpha = 0.9$. (c) $d = 0.6 \Rightarrow \delta = 10^{-5}$, and $\alpha = 0.9$. (d) $d = 0.9 \Rightarrow \delta = 0$, and $\alpha = 0.8$.

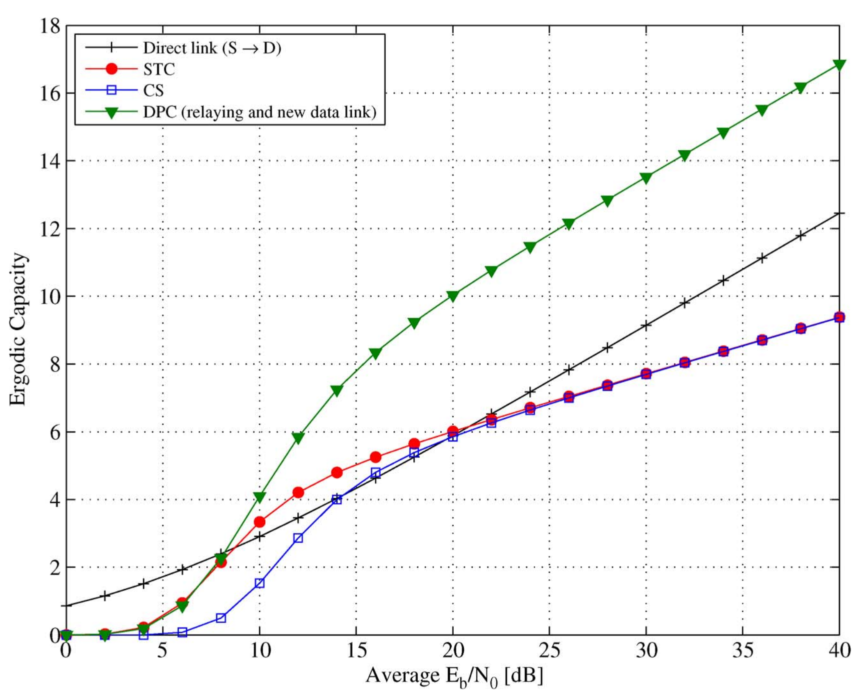

Fig. 8. Ergodic capacity of the different protocols versus E_b/N_0: $R_0 = 2$ BPCU, $\alpha = 0.8$, $d = 0.8$, $\delta = 10^{-4}$, and $K = 4$ users.

the proposed solution allows one more node to simultaneously transmit its own data with the relaying link. We have proved that an appropriate definition of the superposition DPC weight factor, as well as the selection of the two transmitting nodes, achieves a performance that is similar to that of the conventional opportunistic selection for the relaying data while

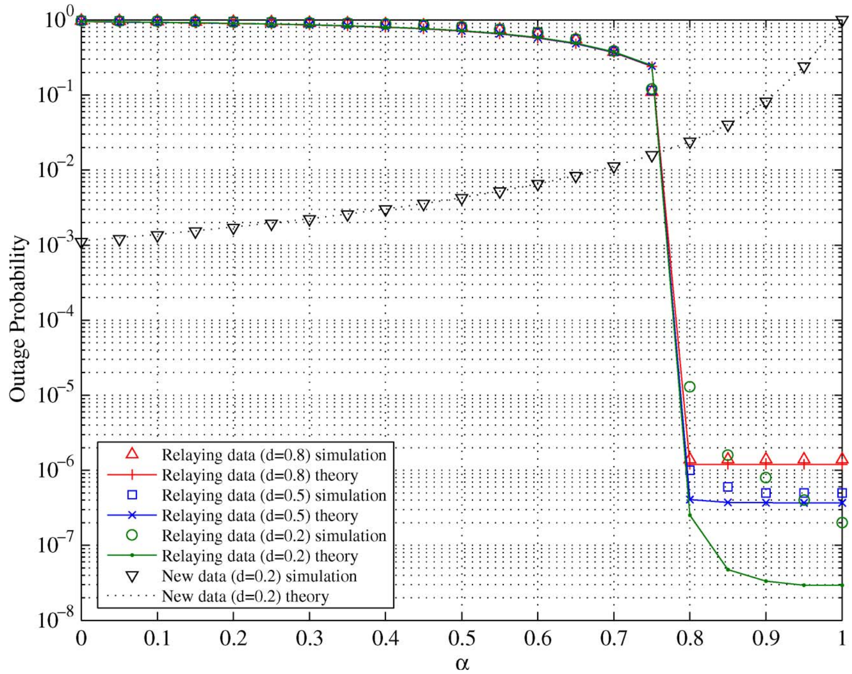

Fig. 9. Comparison between analytical and simulation results for relaying and new data versus the parameter α: $R_0 = 2$ BPCU, $d = 0.2, 0.5, 0.8$, $E_b/N_0 = 30$ dB, and $K = 2$ relays.

simultaneously offering an efficient performance for the new data link. The parameterization of the system depends only on the geometry, and thus, it is suitable for practical applications. It has been shown that the proposed optimization is suitable for topologies where the cluster of relays is closer to the destination. The enhancements of the proposed DPC design have been shown by numerical results and computer simulations. The application of the proposed analysis to interference channel models could be a promising topic for future investigation.

Appendix
DPC Scheme and Relaying Data

We assume that X and Y are the best and the second best, respectively, among $k > 1$ exponential distributed i.i.d. random variables with parameter $\lambda = (1-d)^{\beta}$. If $F_X(\cdot)$ and $f_Y(\cdot)$ are the cdf and the probability density function (pdf) of X and Y, respectively, the conditional outage probability of the relaying link, given that k relays have decoded the source transmission, can be expressed as

$$\Upsilon(k,\alpha) = \Pr\left\{\frac{1}{2}\log\left(1+\frac{\left(\sqrt{P_0X/2}+\sqrt{\alpha P_0 Y/2}\right)^2}{1+(1-\alpha)P_0Y/2}\right)\leq R_0\right\}$$

$$=\Pr\left\{\frac{\left(\sqrt{X}+\sqrt{\alpha Y}\right)^2}{2/P_0+(1-\alpha)Y}\leq 2^{2R_0}-1\right\}$$

$$=\Pr\left\{X\leq \underbrace{\left(\sqrt{\frac{2Z}{P_0}+(1-\alpha)ZY}-\sqrt{\alpha Y}\right)^2}_{\Delta\tau\stackrel{\Delta}{=}\Omega}\right\}$$

$$=\begin{cases}\int_0^\infty F_X(\Omega)f_Y(y)dy, & \text{if } Z\geq\frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha}\\ \int_0^\rho F_X(\Omega)f_Y(y)dy, & \text{if } Z<\frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha}\end{cases}$$
$$\simeq\begin{cases}\int_0^\infty F_X(\tilde{\Omega}y)f_Y(y)dy, & \text{if } Z\geq\frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha}\\ \int_0^\rho F_X(\tilde{\Omega}y)f_Y(y)dy, & \text{if } Z<\frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha}\end{cases}\tag{11}$$

where $Z = 2^{2R_0}-1$, $\rho \stackrel{\Delta}{=} -(2Z/(P_0[(1-\alpha)Z-1-\alpha-2\sqrt{\alpha}]))$, and $\tilde{\Omega}\stackrel{\Delta}{=}(\sqrt{(1-\alpha)Z}-\sqrt{\alpha})^2$. The limits of the above integral arise from the considered constraint $X \geq Y$. More specifically

$$X\geq Y \Rightarrow \left(\sqrt{\frac{2Z}{P_0}+(1-\alpha)ZY}-\sqrt{\alpha Y}\right)^2\geq Y$$
$$\Rightarrow \sqrt{Y}+\sqrt{\alpha Y}\leq\sqrt{\frac{2Z}{P_0}+(1-\alpha)ZY}$$
$$\Rightarrow \frac{2Z}{P_0}+\left[(1-\alpha)Z-1-\alpha-2\sqrt{\alpha}\right]Y\geq 0$$
$$\Rightarrow \begin{cases}Y\geq 0, & \text{if } (1-\alpha)Z-1-\alpha-2\sqrt{\alpha}\geq 0\\ Y\leq\rho, & \text{if } (1-\alpha)Z-1-\alpha-2\sqrt{\alpha}< 0.\end{cases}\tag{12}$$

To simplify the computations, we assume that for high SNRs, the term $2Z/P_0$ in Ω is negligible $((2Z/P_0) \ll (1-\alpha)ZY)$. This approximation simplifies the analytical results and holds for high SNRs (P_0) and lower values of α. Furthermore, as the random variable Y depends (inversely) on the relay-destination distance $\propto (1-d)^{-\beta}$, the above approximation is improved as d increases, which corresponds to topologies where the relays are closer to the destination.

In this case, (11) can be written as (13), shown at the top of the next page, where we have used the binomial theorem

$$\Upsilon(k,\alpha) = \begin{cases} \int\limits_0^\infty \left[1-\exp(-\lambda\tilde{\Omega}y)\right]^k (k-1)k\lambda\exp(-2\lambda y)\left[1-\exp(-\lambda y)\right]^{(k-2)}dy, & \text{if } Z \geq \frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha} \\ \int\limits_0^\rho \left[1-\exp(-\lambda\tilde{\Omega}y)\right]^k (k-1)k\lambda\exp(-2\lambda y)\left[1-\exp(-\lambda y)\right]^{(k-2)}dy, & \text{if } Z < \frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha} \end{cases}$$
$$= \begin{cases} k(k-1)\lambda\sum_{i=0}^{k}\sum_{j=0}^{k-2}\binom{k}{i}\binom{k-2}{j}\frac{(-1)^{i+j}}{\lambda(\tilde{\Omega}i+2+j)}, & \text{if } Z \geq \frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha} \\ k(k-1)\lambda\sum_{i=0}^{k}\sum_{j=0}^{k-2}\binom{k}{i}\binom{k-2}{j}\frac{(-1)^{i+j}}{\lambda(\tilde{\Omega}i+2+j)}\left[1-\exp\left(-\lambda\rho[\tilde{\Omega}+j+2]\right)\right], & \text{if } Z < \frac{\alpha+1+2\sqrt{\alpha}}{1-\alpha} \end{cases} \quad (13)$$

$(x+y)^n = \sum_{m=0}^{n}\binom{n}{m}x^{n-m}y^m$ and order statistics (best and second best) [23].

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