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Hybrid DF-CF-DT For Buffer-Aided Relaying

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***Abstract*—In this paper, we maximize the expected achievable rate of buffer-aided relaying by using a hybrid scheme that combines three transmission strategies, which are decode-and-forward (DF), compress-and-forward (CF) and direct transmission (DT). The proposed hybrid scheme is dynamically adapted based on the channel state information. This includes adjusting the data rate and compression when compress-and-forward is selected. We apply this scheme to three different models of the Gaussian block-fading relay channel, depending on whether the relay is half or full duplex and whether the source and the relay have orthogonal or non-orthogonal channel access. The integration and optimization of these three strategies provide a more generic and fundamental solution and give better achievable rates than the known schemes for buffer-aided relaying. We compare the achievable rates to the upper-bounds of the ergodic capacity for each one of the three channel models.**

I. Introduction

As well-known, important capacity theorems were established for the physically degraded and reversely degraded discrete memoryless full-duplex relay channel in [1]. This topic has emerged as an important research area in the wireless communication field as well [2], [3]. Achievable rates and capacity upper-bound results for half-duplex relays in fixed-gain Gaussian channels were provided in the literature assuming non-orthogonal channel access of the source and relay [4], and also assuming orthogonal channel access [5], [6]. More recent results were provided in [7]. We know from these references that, similar to the full-duplex case [1], [8], the best known upper bounds on the capacity are the max-flow min-cut bounds, and that there are three different coding strategies that maximize the achievable rates, which are decode-and-forward (DF), compress-and-forward (CF) and direct transmission (DT) from the source to the destination. None of these three strategies is globally dominant over the other two, but rather each one of them can achieve higher rates than the others in specific scenarios depending on the qualities of the source-relay, source-destination and relay-destination channels. Furthermore, there are other contributions in the literature that consider fading relay channels. For example, the quasi-static (block-fading) half-duplex relay channel was studied, and it was shown that dynamic adaptation of the transmission strategies using DF and DT is needed in order to maximize the expected achievable rates [9]. However, CF was not considered and channel allocation was fixed beforehand and not subject to optimization therein. It is obvious that making channel allocation dynamic and subject to optimization would add to the degrees of freedom in the system design and enable achieving higher rates. Optimal channel allocation for Gaussian (non-fading) orthogonal and non-orthogonal relay channels was considered in a number of papers, and the obtained results for the best achievable schemes were based on DF only [5], [10], [4]. Recently, "buffer-aided relaying" was proposed and studied for the cases when there is no direct link from the source to the destination [11], [12], [13], and also when the direct link is available and utilized [14]. We are interested in the latter case in this work.

Having gone through many of the most important works in the literature that considered block-fading relay channels, we still believe that there is room for improvement since they all focus on dynamic adaptation of decode-and-forward relaying strategies and they do not consider compress-and-forward as well, although there are certain scenarios over which CF can be better than DF as we know from the case of fixed-gain channels. So, in this work, we consider a buffer-aided hybrid scheme that combines DF, CF and DT and switches among them dynamically based on the channel conditions, and we consider optimizing the resource allocation for this hybrid scheme to maximize the expected achievable rates. We believe that this is an important contribution to the literature since it is more generic than the known schemes and, hence, it can achieve higher rates when optimized properly.

Before we end this section, we want to mention that the concept of "buffer-aided relaying" was also considered for dual-hop broadcast channels and it was called "joint user-and-hop scheduling" since the buffering capabilities are actually needed to enable dynamic and flexible scheduling (i.e. channel allocation) among multiple users (destination nodes) and the relay [15]. Also, it was also applied to other channel models that involve relaying such as the bi-directional relay channel [16], [17], the shared relay channel [18] and overlay cognitive radio networks [19]. The list of references on buffer-aided relaying provided here is not exhaustive.

II. Block-Fading Relay Channel Models

We consider a three-node network that consists of a source (S) that wants to send information to a destination (D) with the assistance of a relay (R). We assume a Gaussian block-fading model for the channels between the nodes. We also assume that all channel blocks have the same duration (T in seconds) and bandwidth (W in Hz) and that they are large enough to

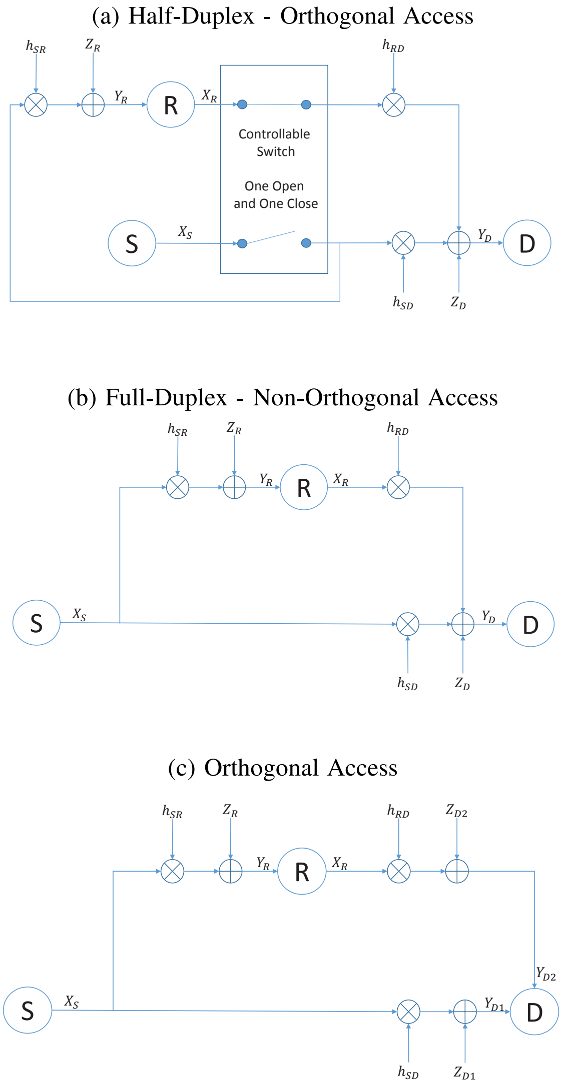

Fig. 1. Channel Models

achieve the instantaneous capacity[1]. Furthermore, we assume that the source and relay transmit using a constant (maximum) power per unit bandwidth (in Jouls/sec/Hz). We investigate three different models for the relay channel that are shown in Fig 1. We call them; (a) half-duplex – orthogonal access, (b) full-duplex – non-orthogonal access, and (c) orthogonal access. In the figure, $X_{\mathsf{S}}[k]$ and $X_{\mathsf{R}}[k]$ are the transmitted (complex field) source signal and relay signal, respectively, in channel block k. Similarly, $Y_{\mathsf{R}}[k]$ and $Y_{\mathsf{D}}[k]$ are the received signals at the relay and destination, respectively, and $Z_{\mathsf{R}}[k]$ and $Z_{\mathsf{D}}[k]$ are the added Gaussian noise at these two nodes, which are mutually independent and have circularly symmetric, complex Gaussian distribution with unit variance. Furthermore, $h_{\mathsf{SD}}[k]$, $h_{\mathsf{SR}}[k]$ and $h_{\mathsf{RD}}[k]$ are the channel complex coefficients, which stay constant during one channel block k and change randomly afterwards. The corresponding signal-to-noise-ratio (SNR) of these channels, in a given channel block k, are denoted $\gamma_{\mathsf{SR}}[k]$, $\gamma_{\mathsf{SD}}[k]$ and $\gamma_{\mathsf{RD}}[k]$, respectively, where $\gamma[k] = |h[k]|^2\bar{P}$. The probability density function (PDF) of the channel gain ($|h|^2$) over each one of the three links is a continuous function. Over each link, the receiver knows the channel complex coefficient $h[k]$ perfectly, but the corresponding *transmitter*[2] *knows only the channel gain* $|h|^2$.

The controllable switch in channel model (a) makes only one of the two nodes (source or relay) transmit (subject to optimization). In channel model (c), $Y_{\mathsf{D}_1}[k]$ and $Y_{\mathsf{D}_2}[k]$ are the received signals from the source and the relay, respectively, over orthogonal channels. Both $Z_{\mathsf{D}_1}[k]$ and $Z_{\mathsf{D}_2}[k]$ are added Gaussian noise with unit variance. We assume that the two orthogonal channels have the same size (TW).

The instantaneous (i.e. in a given channel block k) channel capacities are denoted be $C_{\mathsf{SD}}[k]$, $C_{\mathsf{SR}}[k]$ and $C_{\mathsf{RD}}[k]$ for the source-destination, source-relay and relay-destination links, respectively. For channel models (a) and (c), where we have orthogonal access, the channel capacities (per unit bandwidth) follow the well-known capacity of AWGN channels $C_x[k] = \log(1+\gamma_x[k])$, $\forall x \in \{\mathsf{SD},\mathsf{SR},\mathsf{RD}\}$. For channel model (b), where we have non-orthogonal access, the source-relay link will still be an AWGN channel. On the other hand, the source-destination and relay-destination links form a multiple-access channel (MAC). It can be proven[3] that for optimality, the destination should decode the relay's message first and then process the source's message. Thus, $C_{\mathsf{SD}}[k] = \log(1+\gamma_{\mathsf{SD}}[k])$ and $C_{\mathsf{RD}}[k] = \log\left(1+\frac{\gamma_{\mathsf{RD}}[k]}{1+\gamma_{\mathsf{SD}}[k]}\right)$.

III. Communication System Description

A. System Requirements

We investigate a hybrid communication scheme that combines three different strategies; direct transmission (DT), decode-and-forward (DF) and compress-and-forward (CF). These schemes are adapted dynamically and optimally based on the channel conditions in order to maximize the expected achievable rate. When the source transmits a new codeword, it decides (subject to optimization) if the codeword will be used for DT, DF or CF, and it adjusts the data rate (denoted by $R_{\mathsf{DT}}[k]$, $R_{\mathsf{DF}}[k]$ and $R_{\mathsf{CF}}[k]$) of the codeword accordingly. As an optimization framework, we assume that the proposed hybrid scheme uses orthogonal time-sharing of the three transmission strategies in the same channel block. The time sharing ratios are subject to optimization. For notation, $\theta_{\mathsf{DT}}[k]$, $\theta_{\mathsf{DF}}[k]$ and $\theta_{\mathsf{CF}}[k]$ denote the time sharing ratio in a given channel block k for the DT, DF and CF transmission

[1] As well-known, achieving the capacity requires infinite code length. However, with sufficiently long codewords, we can transmit at channel capacity with negligible probability of error.

[2] This assumption is stemmed from practical system design considerations. As a consequence of it, beamforming of the source and relay signals towards the destination is not feasible, and, hence, β in formulas (5) and (7) in [4] equals zero under our assumptions.

[3] The proof is omitted here for brevity. It is available in the full-version of this paper, which is available online [20].

strategies, respectively. They refer to the source transmission phase of all of these strategies.

In the DF case, the relay fully decodes the source message and it generates and stores an amount of information, denoted by $R^*_{\mathsf{DF}}[k]$ that would be sufficient for the destination to decode the source message reliably (given that the destination utilizes both the source and relay signals to decode the source codeword). For example, the relay can store a bin index (in the sense of Slepian-Wolf coding [21]) of the source message that indicates the partition at which the source codeword lies. In the CF case, the relay encodes and stores a quantized version of the received signal using, e.g. Wyner-Ziv lossy source coding [22]. The data rate of this generated message by the relay is denoted by $R^*_{\mathsf{CF}}[k]$.

In addition to the availability of the channel state information, another important requirement to support the adaptivity of the system is having unlimited buffering capability at the relay and the destination. This is because when the source transmits a new codeword and the relay decodes or compresses it, it does not forward it directly to the destination in the same or the following channel block, but it rather stores it and it adjusts its transmission rate based on the relay-destination channel quality. Thus, the relay might send the information bits that corresponds to one codeword of the source over multiple channel blocks or combine the information bits that corresponds to more than one codeword of the source. This was properly explained in [14].

B. Data Rates of CF

In CF, the data rate of the source codeword is bounded by the capacity of the single-input multiple-output (SIMO) channel assuming that the relay and destination are two antennas of the same receiver.

$$R_{\mathsf{CF}}[k] < \theta_{\mathsf{CF}}[k] \log\left(1 + \gamma_{\mathsf{SR}}[k] + \gamma_{\mathsf{SD}}[k]\right) \tag{1}$$

Notice that if $R_{\mathsf{CF}}[k] \leq \theta_{\mathsf{CF}}[k] C_{\mathsf{SD}}[k]$, then the destination can decode the source message via direct transmission and the relay does not need to forward anything. For notation, we define $\gamma_{\mathsf{CF}}[k] = \exp\left(\frac{R_{\mathsf{CF}}[k]}{\theta_{\mathsf{CF}}[k]}\right) - 1$, where the data rate is measured in nats/sec/Hz.

Theorem 1 (Rate of compressed signal at the relay): Given that $\gamma_{\mathsf{SD}}[k] < \gamma_{\mathsf{CF}}[k] < \gamma_{\mathsf{SR}}[k] + \gamma_{\mathsf{SD}}[k]$, the data rate of the encoded compressed signal by the relay must satisfy

$$\frac{R^*_{\mathsf{CF}}[k]}{\theta_{\mathsf{CF}}[k]} \geq \log\left(1 + \frac{\left(\gamma_{\mathsf{CF}}[k] - \gamma_{\mathsf{SD}}[k]\right)\left(1 + \gamma_{\mathsf{SD}}[k] + \gamma_{\mathsf{SR}}[k]\right)}{\left(\gamma_{\mathsf{SD}}[k] + \gamma_{\mathsf{SR}}[k] - \gamma_{\mathsf{CF}}[k]\right)\left(1 + \gamma_{\mathsf{SD}}[k]\right)}\right) \tag{2}$$

in order to enable the destination to decode the source message reliably.

The proof is omitted here due to space constraint. It is available in [20].

C. Optimization Problem Formulation

We write the main optimization problem in a generic form that is applied to the three channel models in Fig. 1. We want to maximize the average total achievable rate of the relay channel, which is the sum of the rates achieved by the three transmission strategies. The relay should transmit sufficient amount of rate to enable the destination to decode the source messages reliably.

$$\max_{\zeta[k]\ \forall k} \quad \bar{R}_{\mathsf{DT}} + \bar{R}_{\mathsf{DF}} + \bar{R}_{\mathsf{CF}} \tag{3a}$$

$$\text{subject to} \quad \bar{R}_{\mathsf{RD}} \geq \bar{R}^*_{\mathsf{DF}} + \bar{R}^*_{\mathsf{CF}}, \tag{3b}$$

$$R_{\mathsf{DT}}[k] = \theta_{\mathsf{DT}}[k] C_{\mathsf{SD}}[k], \tag{3c}$$

$$R_{\mathsf{DF}}[k] = \theta_{\mathsf{DF}}[k] C_{\mathsf{SR}}[k], \tag{3d}$$

$$R^*_{\mathsf{DF}}[k] = \theta_{\mathsf{DF}}[k]\Big(C_{\mathsf{SR}}[k] - C_{\mathsf{SD}}[k]\Big)^+, \tag{3e}$$

$$R_{\mathsf{RD}}[k] = \min\left(\theta_{\mathsf{RD}}[k] C_{\mathsf{RD}}[k], Q[k]\right) \tag{3f}$$

in addition to (1) and (2) (at equality).

In (3), $\bar{X} = \lim_{K\to\infty} \frac{1}{K}\sum_{k=1}^{K} X[k]$, $\forall X \in \{R_{\mathsf{DT}}, R_{\mathsf{DF}}, R_{\mathsf{CF}}, R_{\mathsf{RD}}, R^*_{\mathsf{DF}}, R^*_{\mathsf{CF}}\}$. Furthermore, $Q[k]$ is the normalized total amount of information stored in the relay's buffers at the start of channel block k, and $(x)^+ = \max(x, 0)$. $\zeta[k] = \{\theta_{\mathsf{DT}}[k], \theta_{\mathsf{DF}}[k], \theta_{\mathsf{CF}}[k], R_{\mathsf{CF}}[k], \theta_{\mathsf{RD}}[k]\}$ is the set of optimization variables for channel model (a). They are constrained by

$$\theta_{\mathsf{DT}}[k] + \theta_{\mathsf{DF}}[k] + \theta_{\mathsf{CF}}[k] + \theta_{\mathsf{RD}}[k] = 1 \tag{4}$$

Eq. (4) only applies to channel model (a). In channel models (b) and (c), $\theta_{\mathsf{RD}}[k] = 1$ over all channel blocks, and

$$\theta_{\mathsf{DT}}[k] + \theta_{\mathsf{DF}}[k] + \theta_{\mathsf{CF}}[k] = 1 \tag{5}$$

IV. Optimal Solution

We go through the main steps to be able to obtain the solution of (3).

Lemma 1 (Queue at edge of non-absorption): A necessary condition for the optimal solution of (3) is that the queue in the buffer of the relay is at the edge of non-absorption. Consequently, for $K \to \infty$, the impact of the event $Q[k] < \theta_{\mathsf{RD}}[k] C_{\mathsf{RD}}[k]$, $k = 1, \cdots, K$ is negligible. Therefore, the optimal solution will have

$$\bar{R}_{\mathsf{RD}} = \lim_{K\to\infty} \frac{1}{K} \sum_{k=1}^{K} \theta_{\mathsf{RD}}[k] C_{\mathsf{RD}}[k] \tag{6}$$

and the constraint (3b) will be satisfied at equality.

The proof follows the same steps that are given in [11, Theorem 1 and Theorem 2].

By using the Lagrangian dual problem of (3), we get

$$\max_{\zeta[k]\ \forall k} \quad \bar{R}_{\mathsf{DT}} + \bar{R}_{\mathsf{DF}} + \bar{R}_{\mathsf{CF}} - \lambda\left(\bar{R}^*_{\mathsf{DF}} + \bar{R}^*_{\mathsf{CF}} - \bar{R}_{\mathsf{RD}}\right) \tag{7}$$

where $\lambda \geq 0$ is the Lagrangian multiplier. A direct consequence of Lemma 1, in particular (6), is that the achievable rates in a given channel block k are only dependent on their respective optimization variables $\zeta[k]$. Therefore, (7) can be transformed into a number K of independent optimization problems that are solved independently.

$$\max_{\zeta[k]} R_{\mathsf{DT}}[k] + R_{\mathsf{DF}}[k] + R_{\mathsf{CF}}[k] - \lambda\left(R^*_{\mathsf{DF}}[k] + R^*_{\mathsf{CF}}[k] - R_{\mathsf{RD}}[k]\right) \tag{8}$$

and λ in all K optimization problems should be adjusted globally such that the constraint (3b) is satisfied at equality. Therefore, the optimal value of λ depends on the channel statistics of the three links SD, SR and RD.

Based on the new defined notations, we can show that (8) can be written as

$$\max_{\zeta[k]\setminus\{R_{\mathsf{CF}}[k]\}} \quad \theta_{\mathsf{DT}}[k]\phi_{\mathsf{DT}}[k] + \theta_{\mathsf{DF}}[k]\phi_{\mathsf{DF}}[k] + \theta_{\mathsf{CF}}[k]\phi_{\mathsf{CF}}[k] + \theta_{\mathsf{RD}}[k]\phi_{\mathsf{RD}}[k] \tag{9}$$

where

$$\phi_{\mathsf{DT}}[k] = C_{\mathsf{SD}}[k] \tag{10a}$$

$$\phi_{\mathsf{DF}}[k] = R_{\mathsf{DF}}[k]/\theta_{\mathsf{DF}}[k] - \lambda R^*_{\mathsf{DF}}[k]/\theta_{\mathsf{DF}}[k] \tag{10b}$$

$$\phi_{\mathsf{CF}}[k] = \max_{R_{\mathsf{CF}}[k]/\theta_{\mathsf{CF}}[k]} \quad (R_{\mathsf{CF}}[k]/\theta_{\mathsf{CF}}[k] - \lambda R^*_{\mathsf{CF}}[k]/\theta_{\mathsf{CF}}[k]) \tag{10c}$$

$$\phi_{\mathsf{RD}}[k] = \lambda C_{\mathsf{RD}}[k] \tag{10d}$$

Consequently, the optimization of $R_{\mathsf{CF}}[k]/\theta_{\mathsf{CF}}[k]$ is independent of the optimal value of the channel access ratios. It depends on the value of λ, which is a global variable that is not a function of the instantaneous channel capacities in a given channel block k. This is valid for all three channel models under consideration.

Theorem 2 (Optimal R_{CF} allocation):

Given that $0 \leq \lambda \leq 1$, then the optimal $R_{\mathsf{CF}}[k]$ allocation is given by

$$\frac{R_{\mathsf{CF}}[k]}{\theta_{\mathsf{CF}}[k]} = \max\Big(\log\left((1-\lambda)(1+\gamma_{\mathsf{SD}}[k]+\gamma_{\mathsf{SR}}[k])\right), C_{\mathsf{SD}}[k]\Big) \tag{11}$$

The proof can be obtained by solving the optimization problem (10c). The solution steps are omitted for brevity. They are available in [20].

A direct consequence of Theorem 2 is that in all channel blocks k that have $R_{\mathsf{CF}}[k] > \theta_{\mathsf{CF}}[k]C_{\mathsf{SD}}[k]$, we will have

$$\phi_{\mathsf{CF}}[k] = \log\left(1+\gamma_{\mathsf{SR}}[k]+\gamma_{\mathsf{SD}}[k]\right) + \lambda\log\left(\frac{1+\gamma_{\mathsf{SD}}[k]}{\gamma_{\mathsf{SR}}[k]}\right) + \lambda\log(\lambda) + (1-\lambda)\log(1-\lambda) \tag{12}$$

Theorem 3 (Selecting transmission strategy):

Given that $\lambda < 1$, the optimal solution will have only one transmission strategy (DF, CF or DT) selected per channel block k, and in channel model (a), either the source or the relay transmits and not both of them. The transmission strategy is selected according to

$$\xi[k] = \arg\max_{x} \quad \phi_x[k] \tag{13}$$

where $x \in \{\mathsf{DT}, \mathsf{DF}, \mathsf{CF}, \mathsf{RD}\}$ (for channel model (a)), or $x \in \{\mathsf{DT}, \mathsf{DF}, \mathsf{CF}\}$ (for channel models (b) and (c)). Thus, we get $\theta_x[k] = 1$ if $\xi[k] = x$, and $\theta_x[k] = 0$ if $\xi[k] \neq x$.

The proof is straightforward by solving (9). Notice that we assume that the channel gains are random variables with continuous probability distribution. Therefore, ϕ of each transmission strategy will also be random, and the probability that two different strategies maximize (13) in a given channel block is zero. Consequently, the solution of (9) is always unique when $\lambda < 1$.

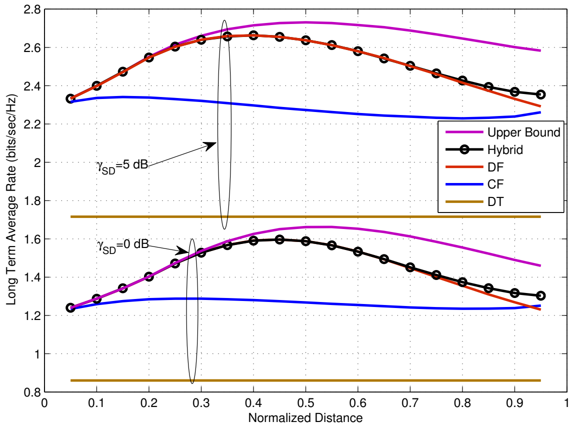

Fig. 2. Achievable rates for channel model (a).

We can also prove that we have strong duality since the time-sharing condition (refer to [23]) is satisfied in our problem. Furthermore, we can prove that, regardless of the channel statistics, the optimal value of λ that maintains the constraint (3b) at equality will satisfy $0 \leq \lambda \leq 1$. At the special case when $\lambda = 1$, which happens when the SR link is very strong, the solution will not be unique since $\phi_{\mathsf{DT}}[k] = \phi_{\mathsf{DF}}[k]$ for all values of k at which $\gamma_{\mathsf{SR}}[k] \geq \gamma_{\mathsf{SD}}[k]$. However, we can show that in this case, the optimal achievable rate will equal the capacity upper-bound. All of these proofs and extra details, including the characterization of upper bounds, can be found in [20].

V. Numerical Results

We make our numerical results assuming that the distance between the source and the destination is d_{SD}, and the relay is located on the straight line between the source and the destination such that the distance between the source and the relay is d_{SR}, and the distance between the relay and the destination is $d_{\mathsf{RD}} = d_{\mathsf{SD}} - d_{\mathsf{SR}}$. The channels between the nodes are Rayleigh block-faded, and the average channel qualities are given by this formula

$$\bar{\gamma}_x = \epsilon\left(\frac{d_x}{d_{\mathsf{SD}}}\right)^{-\alpha}, \tag{14}$$

where $x \in \{\mathsf{SR}, \mathsf{RD}, \mathsf{SD}\}$, $\alpha = 3$ is the path loss exponent, and ϵ is a constant that is related to the transmission power, antenna gains and total distance. We use two cases in the simulation, $\epsilon = 10^{0.5} \approx 3.1623$, which gives $\bar{\gamma}_{\mathsf{SD}} = 5$ dB, and $\epsilon = 1$, which gives $\bar{\gamma}_{\mathsf{SD}} = 0$ dB.

In the simulations (Figs. 2,3,4), we plot the expected achievable rates versus the normalized distance of the relay to the source $\frac{d_{\mathsf{SR}}}{d_{\mathsf{SD}}}$. Also, we compare the optimal hybrid scheme to the upper-bounds and to sub-optimal schemes that use DF and DT without CF, or use CF and DT without DF.

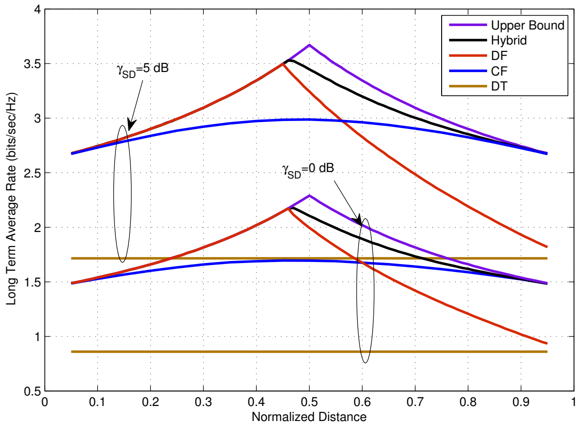

Fig. 3. Achievable rates for channel model (b).

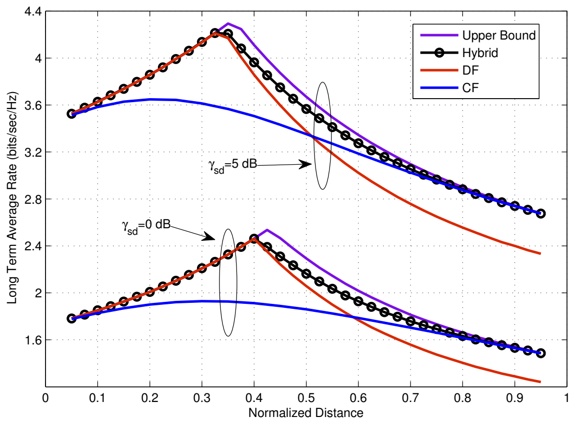

Fig. 4. Achievable rates for channel model (c).

VI. Conclusions

We showed in this paper how to integrate compress-and-forward with decode-and-forward in buffer-aided relaying systems, and we have applied that to three different models of the relay channel. For optimality, only one transmission strategy is selected in a given channel block based on the channel conditions. The optimization of the data rate for compress-and-forward is obtained using a simple closed-form formula. The numerical results demonstrated the gains of the proposed scheme.

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