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Cooperative multi-hop transmission in wireless networks

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Abstract

We consider various relaying strategies for wireless networks by comparatively examining direct transmission, conventional relaying, and the novel concepts of cooperative relaying. The latter build on two inherent benefits of relaying systems: the spatial diversity offered by the relay channel, and the ability to exploit the broadcast nature of the wireless medium. Studied cooperative protocols include adaptive decode-and-forward schemes as a simple extension of conventional store-and-forward relaying systems, and more complex decode-and-reencoding schemes that realize distributed coding strategies. We provide a unifying analysis for the tractable two-hop case, before extending the consideration to multi-hop scenarios. The analysis is conducted from the perspective of communication over fading channels under limited bandwidth, energy, and end-to-end delay; main parameters include propagation loss, network geometry, and targeted end-to-end spectral efficiency. Main results indicate that (i) cooperative relaying provides attractive benefits for wireless systems whenever temporal and frequency diversity are scarce or not exploited, (ii) using just two hops is reasonable for many practical scenarios, and (iii) the advantages of the studied relaying schemes decrease for higher desired end-to-end spectral efficiency.
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Keywords: Multi-hop communications; Relaying; User cooperation

1. Introduction

Given the constraints imposed by link budget estimates for future generations of infrastructure based networks, relaying emerges as a viable option for challenging the tradeoff between transmission range and end-to-end data rate. Essentially, relays allow for reducing the end-to-end path loss between an information source and its destination. Each relay in a relay chain thereby usually relies solely on the information sent by its immediate predecessor, and the destination simply listens to the last relay in this chain. We refer to this as *conventional relaying* as it is known from ad hoc networking.

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More recently, the concepts of *cooperative relaying* have emerged. By allowing cooperation among the relays and by *combining all relays' transmissions* at the destination, the spatial diversity of relaying systems can be exploited. More generally, useful side information is taken into account that is unnecessarily discarded in conventional relaying.

In a different context, the promising concepts of spatial diversity have recently lead to intense research in the area of multi-antenna systems. While systems that use the spatial diversity offered by antenna arrays are attractive due to their simplicity, their successful use requires the integration of multiple antenna elements at terminals, and, to take full benefit, uncorrelated channels from each of them. In scenarios where these conditions cannot be met, cooperative relaying provides an alternative by "distributing" the antennas among terminals.

Cooperative relaying has also become known as user cooperation diversity, virtual antenna arrays, coded cooperation, and distributed coding.

1.1. Challenges

In small devices, the inability of RF hardware to perform simultaneous reception and transmission at the same frequency calls for assigning orthogonal channels for the receiving and transmitting paths. This so-called "orthogonality constraint" incurs a subdivision of available resources in time and/or frequency. In this paper we assume that this division is done in the time domain, which allows for designing causal, adaptive transmission concepts.

As a direct consequence of the orthogonality constraint, the transmission rate on the individual phases needs to be increased. Consider a system with limited bandwidth and end-to-end delay that transmits from source to destination at spectral efficiency R. Subdividing this transmission into k hops implies that each of the hops be operated at rate kR if the same end-to-end efficiency is to be achieved.

Other challenges include possibly increased interference that result from repeated re-emissions in relay networks, protocol complexity related to routing and scheduling, and security issues that result from relaying data via another user's terminal. Interestingly, it turns out that most of these challenges are not related to user cooperation as such, but to relaying in general.

1.2. Classification

Relay protocols can be classified according to their *forwarding strategy*:

1. *Amplify-and-forward*: Relays act as analog repeaters by retransmitting an amplified version of their received signals. The noise floor is increased.
2. *Decode-and-Forward*: Relays attempt to decode, regenerate and retransmit an exact copy of the original signal, potentially propagating decoding errors.
3. *Decode-and-Reencode*: Relays attempt to decode and construct codewords that are different from the received codewords, thereby providing incremental redundancy to a receiver that assesses the original and the re-encoded signals. Again, there is the problem of error propagation.

A synonymous term for amplify-and-forward relaying is "non-regenerative" relaying; the decoding protocols are correspondingly also referred to as "regenerative" relaying.

Further, there are different *protocol natures*:

1. *Fixed protocols*, where the relays always forward a processed version of their received signals;
2. *Adaptive protocols*, where the relays, in an attempt to balance the benefits from relaying and the drawbacks of error propagation, autonomously decide whether or not to forward;

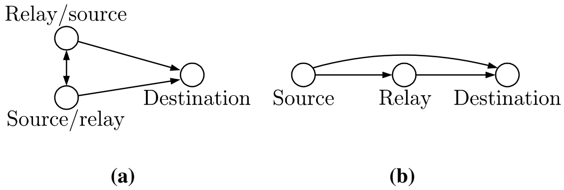

Fig. 1. (a) Symmetric vs. (b) asymmetric networks. In symmetric networks, the average channel fading (or path loss, respectively) is equal for all links from the cooperating source terminals to the destination. In asymmetric networks, the path loss reduction comes at the cost of loss of symmetry, i.e., the roles of relay and source can no longer be exchanged for the mutual benefit of both stations.

3. *Feedback protocols*, where the relays provide redundancy only when explicitly requested to do so by the destination.

Finally, one may distinguish *symmetric* and *asymmetric* scenarios as illustrated in Fig. 1. For the symmetric case, true cooperation of two source terminals is possible, whereas in the asymmetric case, one can benefit from a reduction of end-to-end path losses by sacrificing symmetry.[1]

As an example, we note that conventional relaying as done in ad hoc networks and as it is often envisaged for extending cellular networks, may be categorized as a *fixed*, *asymmetric*, *decode-and-forward* scheme.

1.3. Previous work

First interest in the relay channel dates back to the work of van der Meulen [1]. These considerations have been extended by Cover et al. by determining capacity for physically degraded relay channels [2,3]. While these examples focus on the three-terminal case, a more general approach is taken by Gastpar et al., who study the situation in which a single source–destination pair is assisted by a network of relay terminals [4,5]. More generally, the ultimate limits of ad hoc networks using conventional store-and-forward relaying are addressed in [6].

Explicit *cooperation* of neighboring nodes is first considered by Sendonaris et al. [7,8]. For noisy interuser channels and various degrees of knowledge of channel state information (CSI), they show that significant gains can be achieved over non-cooperative direct transmission. The work is later extended to orthogonal transmit and receive resources at the relay as well as alternative coding schemes that overcome the repetition-coded nature of relaying protocols [9].

In a different context, Dohler et al. investigate the possibility of forming *virtual antenna arrays* [10,11]. By examining various concepts ranging from three-terminal cooperation to the use of multiple groups of relays, each representing a virtual antenna array, they show improvements induced by the resulting diversity gains.[2]

Amplify-and-forward networks have been discussed in [12,13], where it is shown how such schemes can be understood as distributed MIMO systems.

More recently, Laneman et al. [14] propose various cooperative protocols for the three-terminal case. The conducted analysis from the perspective of outage probabilities for limited bandwidth and constrained end-to-end delay shows that relaying—even in its cooperative form—may suffer from repetition coding and the necessity of providing orthogonal resources for reception and transmission at the relays. The discussion

[1] Instead, a different form of symmetry is introduced: source and destination can communicate in both directions using the intermediate relay.

[2] However, the results are obtained for idealistic assumptions on terminal positions, required transmit powers, etc. A discussion of the feasibility of the concepts would be helpful.

focuses on *symmetric* networks. The analysis in [14] captures the significant parameters SNR (i.e., energy), path loss, spectral efficiency, and network geometry. We take a similar approach in this paper, albeit with a different focus. In [15], we have proposed a simple version of Laneman's adaptive decode-and-forward scheme that yields comparable performance to the more complex one proposed in [14]. The operation of multiple relay nodes in a two-hop scenario, using distributed space–time coding, is investigated in [16].

The work of Laneman is extended by Nabar et al. [17], who propose an additional cooperative protocol based on *receive-collision*. The basic idea is to have source and relay transmit different signals simultaneously to the destination, thereby making more efficient use of resources. These benefits come at the cost of increased complexity as orthogonal signal designs need to be deployed for transmission and the collisions need to be resolved based on multi-user detection in the receiver.

Various studies examine concepts of avoiding the repetition-coded nature of relay protocols by developing distributed coding schemes [9,18–23], which yield additional coding gains at the cost of increased complexity. In particular, various *distributed* coding techniques have been proposed. For example, Hunter et al. [24,25,19] discuss code word partitioning: codewords of N bits, containing K information bits ($R = K/N$), are partitioned into N_1 and $N_2 = N - N_1$ bits, where the N_2 bits can be determined from N_1 (parity). Two cooperating users $(1, 2)$ each broadcast their N_1 bits and a corresponding cyclic redundancy check (CRC) in a first phase, and the respective partners try to detect these. If successful, then the remaining N_2 parity bits are determined and sent by the assisting relay station in the second phase. Otherwise, i.e., if decoding failed, the terminal sends its "own" N_2 bits. The prosed scheme avoids error propagation by sending the assisting station's "own" parity bits if decoding failed. The authors suggest the use of *rate-compatible punctured convolutional codes* (*RCPC*) [26].

The first to discuss *distributed turbo coding* are Zhao and Valenti [22,21]. Janani and Hunter likewise consider this approach [27,23]. The source encodes using a rate 1/2 recursive systematic convolutional code; the relay decodes and re-encodes after *interleaving*. The destination decodes using a standard turbo decoder. This scheme clearly avoids repetition coding, therefore achieving coding gains at the cost of additional complexity. Two asymmetric cases have been studied and a comparison to the use of block codes is performed [19]. The results indicate that by using one relay in connection with a strong turbo code, one can outperform conventional repetition coding by 2 dB at a frame error rate of FER = 10^{-2}. These coding gains increase correspondingly with the use of multiple relays.

Boyer et al. are to our knowledge the first to study *multi-hop* scenarios [28]. Four different channel models and simple static cooperative protocols are examined. It is argued that the feedforward and feedback interference in multi-hop chains is a form of intersymbol interference, and can therefore be eliminated by means of classical equalization techniques. Unfortunately, the required rate increase and the challenging problems of resources assignment in multi-hop chains are not considered, and feedforward and feedback interference are assumed to be negligible in the corresponding simulations.

Finally, a contemporary overview of network-level aspects of conventional relaying is provided in [29]. An example system using conventional relaying in a Manhattan scenario is presented in [30]; the results suggest that in such scenarios, conventional relaying constitutes an attractive approach towards improving system capacity. An exemplary and comparative study of a cooperative CDMA system is presented in [31]. Capacity considerations for ad hoc networks are provided in [32].

1.4. Contribution and outline

What is missing to date is a unifying analysis and a comparative study of the different proposed concepts. In this paper, we therefore aim at contributing by examining the various approaches within a single framework. The two-hop case as the basic building block as well as multi-hop scenarios are studied. We focus on adaptive decode-and-forward and decode-and-reencode schemes as these promise the strongest potential while offering manageable complexity. It is assumed that nodes are equipped with a single antenna.

We start by outlining the protocols of interest in Section 2 before proceeding with an analysis in Section 3. We illustrate the most important tradeoffs and key characteristics of the schemes and discuss some implementations aspects in Section 4. Section 5 offers concluding remarks; the appendix collects mathematical essentials.

2. Protocols

We start by describing the protocols for the two-hop case.

2.1. Basic two-hop building blocks

2.1.1. Reference cases

Baseline models for comparison are (i) direct single-input single-output (SISO) transmission from a source node to its destination node, and (ii) transmit diversity using two antennas at the source for direct transmission to the destination according to Alamouti's scheme [33]. In many scenarios, multiple antennas cannot be implemented in a terminal, or correlation limits the resulting performance. Cooperative schemes can overcome these limitations by "distributing" the antennas among source and relay.

2.1.2. Conventional relaying

This form of relaying is the basic means of service provisioning in ad hoc networks, and it offers a further degree of freedom in the range-rate tradeoff for cellular networks. The protocol is designed to benefit from a reduction of the end-to-end path loss between source and destination by exploiting the nonlinearity of attenuation as a function of distance. The source transmits to the relay in phase one, and the relay re-transmits a *newly encoded* signal to the destination in a second phase. For decoding, the destination solely relies on the signal it receives from the relay. Since such store-and-forward relaying is often performed at layer 3, it is also referred to as "layer-3-decode-and-forward" (L3DF).

2.1.3. Adaptive decode-and-forward (AdDF)

In cooperative relaying, the destination combines the signals that have been transmitted from source and relay. The simplest solution would be to have the relay unconditionally forward to the destination. However, Laneman et al. [14] have shown that such *fixed* decode-and-forward protocols do not yield the desired diversity gains, as performance is limited by *error propagation* incurred by decoding errors at the relay. To circumvent this, adaptive protocols have been proposed.

2.1.3.1. Simple AdDF. In [15], we have suggested the following protocol. *In phase one*, the source broadcasts its information. Both relay and destination receive faded noisy versions of this signal. The relay decodes the message and, based on a cyclic redundancy check or similar measures, decides whether or not to forward the signal. *In phase two*, if the relay has decided to forward, then it re-sends a freshly encoded version to the destination, thereby providing low-complexity redundancy in the form of repetition coding. The destination combines the received version of this signal with the stored samples it has previously received from the source. We assume maximal ratio combining (MRC). Otherwise, i.e., if the relay has decided not to forward, then it simply remains silent. The destination detects this case based on the lack of sufficient signal strength, and for decoding it needs to rely on the samples stored in phase one.

2.1.3.2. Complex AdDF. A more complex "selection relaying" protocol has been suggested in [14]. It differs from the simple AdDF protocol only in the cases in which the relay has decided not to decode. This *complex AdDF* protocol prevents possible "silence" in phase two by having the source repeat its message in this second phase; the destination then combines the two versions it has received in the two phases. The resulting gains from standard repetition coding come at the cost of increased complexity as the source must have information on the decoding status of the relay. This information can be obtained by feedback or, theoretically, from channel reciprocity.

In general, AdDF protocols are simple in nature; yet, their performance is limited by their *repetition-coded* nature. The following protocols aim at overcoming this limitation.

2.1.4. Adaptive decode and re-encode (AdDR)

Recall the distributed coding techniques discussed in Section 1. The underlying idea of these re-encoding schemes is to create a new, different codeword at the relay that is sent to the destination, thereby allowing for an *accumulation of mutual information* at the destination [34,35]. By contrast, the simple repetition-coded AdDF schemes outlined above just perform an *accumulation of SNRs*. Adaptive decode-and-reencode protocols are therefore characterized by an encoding procedure at the relay that creates a different codeword than that sent by the source, and by a destination that performs the corresponding *code combining* [34].

As in the case of AdDF schemes, we will examine a simple and a complex version of the AdDR scheme. The former causes "silence" in phase two if the relay failed to decode; the latter uses feedback from the relay to indicate to the source that it shall send a different codeword in phase two.

2.2. Multi-hop schemes as extensions of two-hop relaying

So far we have considered two-hop schemes; we now generalize the discussion to the case of multi-hop transmission. To this end, we assume that a path ("relay chain") has been established by a higher-layer routing protocol, and that a certain resource is available for the end-to-end communication from the path's source to the destination.

2.2.1. Resource reuse

The orthogonality constraint calls for assigning orthogonal resources, i.e., different time slot or frequencies, for reception and transmission at a relay. For the two-hop scenarios considered so far, this has inherently led to an interference-free protocol. In multi-hop scenarios, there are two different general approaches:

No resource reuse (*NRRU*): The available resource can be subdivided into k resources, one for each of the k hops. Compared to direct transmission with rate R, links must operate at rate kR, but there is no interference between the individual transmissions in the chain.

Resource reuse (*RRU*): The available resource is subdivided into $k' < k$ resources for the k hops. The required rate of the individual links is only $k'R < kR$, but *feedforward* and *feedback* interference is incurred from *reusing* the resources in the chain. Fig. 2 shows an example. Note that the NRRU scheme is a special case of the RRU case with $k' = k$.

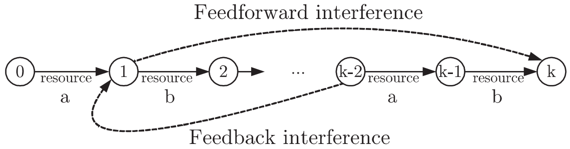

Fig. 2. Example multi-hop network with resource reuse (RRU). Node 1 transmits at resource b, thereby interfering with reception at node k. Likewise, the transmission of node $k-2$ at resource a interferers with reception at node 1.

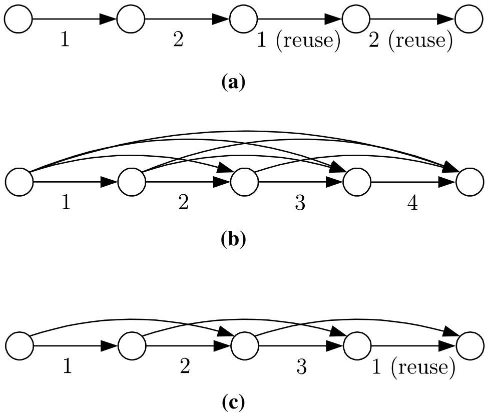

Fig. 3. Reuse of resources in various $k = 4$ RRU relaying schemes. In conventional relaying (top), the third hop can reuse the resource of the first hop, eventually requiring just two different resources to obey the hard orthogonality constraint. By contrast, *full* cooperative relaying (middle) calls for the use of four resources. Cooperative *cascaded two-hop cooperative relaying* (bottom) represents a tradeoff: it requires three resources. (a) Conventional relaying: no combining, here $k = 4$, $k' = 2$. (b) Full cooperative relaying, here combining of max. Four transmissions, $k = 4$, $k' = 4$. (c) Cascaded two-hop cooperative relaying, combining of max. Two transmissions, $k = 4$, $k' = 3$.

2.2.2. Cooperative cascaded multi-hop relaying

The basic idea of cooperative relaying in the context of multi-hop transmission is to combine previous transmissions of the relay chain at the respective receivers. For long relay chains, the implications of the orthogonality constraint would call for assigning a large number of resources and appropriate combining as illustrated in Fig. 3(b).

To save resources and to simplify the combining process, we introduce a *cascaded two-hop cooperative relaying scheme*. The idea is simple: each node in a relay chain combines just the preceding two transmissions as indicated in Fig. 3(c). Other transmissions are discarded, as they contribute to a lower extent to the combined SINR. Cascaded cooperative relaying constitutes a tradeoff between the advantages of cooperative relaying on the one hand and the challenges of combining complexity, resource allocation, and scheduling on the other hand. Note that this scheme is exactly the *concatenation of the basic two-hop building blocks* that we have discussed in the previous section; Fig. 4 depicts an example.

3. Analysis for a block fading model

3.1. Assumptions and channel model

3.1.1. Channel model

Communication takes place over *frequency flat fading* channels, so that the propagation from a node i to a node j is determined by a single channel coefficient $h_{i,j}$. These coefficients are assumed to remain constant for the duration of one block. We model the channel as Rayleigh fading, i.e., the magnitudes $|h_{i,j}|$ of the channel coefficients follow a Rayleigh distribution. Consequently, the channel powers $|h_{i,j}|^2$ are exponentially distributed.[3]

[3] In [36], we study two additional scenarios: in addition to Rayleigh channels, we investigate the no-fading AWGN case, and we examine a more relaxed energy constraint where energy is limited per node.

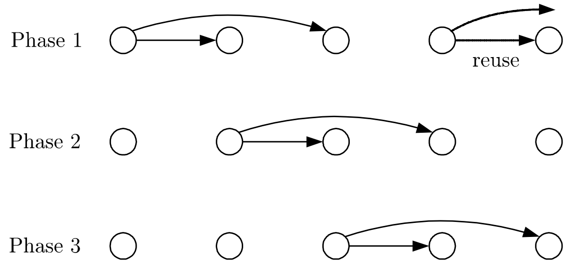

Fig. 4. Operation of the cascaded cooperative two-hop relaying scheme. It requires three phases ($k' = 3$). In this example, the first phase is reused. Relay nodes combine the transmissions from two phases before retransmission.

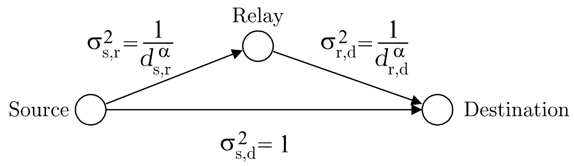

Fig. 5. Mean path losses $\sigma^2_{i,j}$ modelled by the distances $d_{i,j}$ and the path loss exponent α. The reference distance is $d_{s,d} = 1$.

To include the impact of distance-dependent path loss in this model, we note that the *instantaneous* channel attenuation is the multiplication of a deterministic path loss, say $\sigma^2_{i,j}$, with the random fading variable. This results in a single random variable with mean $\sigma^2_{i,j}$ that jointly models path loss and fading. Consequently, $|h_{i,j}|^2$ can be modelled as exponentially distributed random variables with means $\sigma^2_{i,j}$ given by the distance-dependent path losses. This model has likewise been used in [14,12].

3.1.2. Network geometry and example multi-hop scenario

We use a simple model where the path loss between nodes i and j depends on the distance $d_{i,j}$, the path loss exponent α, and a reference distance $d_{s,d}$ according to

$$\sigma^2_{i,j} = \left(\frac{d_{s,d}}{d_{i,j}}\right)^{\alpha} = \frac{1}{d^{\alpha}_{i,j}}. \quad (1)$$

Here, we assume without loss of generality that the reference distance $d_{s,d}$ between source and destination is of unit length, i.e., $d_{s,d} = 1$. Typically, $2 \leqslant \alpha \leqslant 5$. Fig. 5 illustrates the model for a two-hop scenario.

For purposes of simple exposition of the multi-hop case, we shall rely on a k-hop scenario as depicted in Fig. 3, where $k - 1$ relay nodes are equidistantly positioned on the straight line connecting source (node 0) and destination (node k). The path loss between any two neighboring nodes is then described by a gain factor

$$\sigma^2_{i-1,i} = \left(\frac{d_{s,d}}{d_{s,d}/k}\right)^{\alpha} = k^{\alpha}. \quad (2)$$

3.1.3. Energy, bandwidth, delay

We confine all our protocols to consume the same total energy per information bit that is transmitted from source to destination. Likewise, we restrict the *bandwidth* and *end-to-end delay* of the considered relay protocols to that of direct transmission.

More precisely, for direct transmission we assume a total power P to be available during a block with length T. In the case of transmit diversity, the energy is equally distributed over the two transmit antennas.

In the case of two-hop relaying, we share the energy among source and relay according to a *fraction* p_1: the source transmits with power $2p_1P$ over the period $T/2$, which leaves a power of $2p_2P$ for the relay's transmission in the second phase, where $p_2 = 1 - p_1$ and $0 \leqslant p_1 \leqslant 1$. In the multi-hop case, we equally distribute the available energy over all hops.

This strict total energy constraint enables a fair comparison with direct transmission; allowing the relays to introduce additional energy can only improve the performance. For ease of notation, we define SNR = P/N, where N is the noise power at both the relay and the destination.

3.2. Analysis of two-hop protocols

For the following analysis, we refer to the scenario as depicted in Fig. 5.

3.2.1. Direct transmission

The received signal is $y = h_{s,d}x + n$. The mutual information I_D in y and x, i.e., the instantaneous channel capacity, is

$$I_D = \log(1 + |h_{s,d}|^2 \mathrm{SNR}). \tag{3}$$

The outage event $I_D < R$ is the event that the instantaneous channel capacity I_D is insufficient to support this desired rate R. The *outage probability* is the probability of this event, $p^{(out)} = \Pr[I_D < R]$. For the exponentially distributed fading power $|h_{s,d}|^2$ of the source–destination channel, we have the outage probability[4]

$$p_D^{(out)} = \Pr[I_D < R] = 1 - \exp\left(-\frac{2^R - 1}{\sigma_{s,d}^2 \mathrm{SNR}}\right) \tag{4}$$

$$\approx \frac{2^R - 1}{\sigma_{s,d}^2 \mathrm{SNR}} \quad (\mathrm{SNR} \gg 1). \tag{5}$$

The last term is the asymptotic outage probability for large SNR, where we have used $1 - e^{-x} \approx x$ for $x \ll 1$. This result has previously been reported in [14]; we reformulated it using our notation solely for purposes of completeness.

3.2.2. Conventional relaying (L3DF)

The end-to-end capacity of this two-step transmission scheme cannot exceed the minimum of the two individual link capacities. Hence, it is given by

$$I_{L3DF} = \frac{1}{2} \min\left\{\log(1 + 2p_1|h_{s,r}|^2 \mathrm{SNR}), \log(1 + 2p_2|h_{r,d}|^2 \mathrm{SNR})\right\}. \tag{6}$$

The factor 1/2 accounts for the two-phase nature of the scheme. The outage probability $p_{L3DF}^{(out)} = \Pr[I_{L3DF} < R]$ then reads

$$p_{L3DF}^{(out)} = \Pr\left[\min\{2p_1|h_{s,r}|^2, 2p_2|h_{r,d}|^2\} < \frac{2^{2R} - 1}{\mathrm{SNR}}\right]. \tag{7}$$

We introduce for compact notation

$$g(\mathrm{SNR}) = \frac{2^{2R} - 1}{\mathrm{SNR}}. \tag{8}$$

[4] Recall that an exponential random variable u with mean σ^2 has $\Pr[u < u] = 1 - \exp(-u/\sigma^2)$.

Noting that the case of the minimum of two random variables being less than a certain value is complementary to the event that both variables are greater than this value, we develop from (7)

$$p^{(\mathrm{out})}_{\mathrm{L3DF}} = 1 - \left(\Pr[2p_1|h_{\mathrm{s,r}}|^2 \geqslant g(\mathrm{SNR})] \cdot \Pr[2p_2|h_{\mathrm{r,d}}|^2 \geqslant g(\mathrm{SNR})]\right),$$

which, using standard results for exponential random variables [Eq. (A.2)], leads to

$$p^{(\mathrm{out})}_{\mathrm{L3DF}} = 1 - \exp\left(-\left(\frac{g(\mathrm{SNR})}{2p_1\sigma^2_{\mathrm{s,r}}} + \frac{g(\mathrm{SNR})}{2p_2\sigma^2_{\mathrm{r,d}}}\right)\right) \tag{9}$$

$$\approx \frac{2^{2R}-1}{\mathrm{SNR}}\left(\frac{1}{2p_1\sigma^2_{\mathrm{s,r}}} + \frac{1}{2p_2\sigma^2_{\mathrm{r,d}}}\right). \tag{10}$$

From this result we can determine the optimum power allocation $p_1^{(\mathrm{opt})}$ that minimizes outage probability under the total energy constraint. It is found from minimizing the term in parentheses in (10) as

$$p^{(\mathrm{opt})}_{1,\mathrm{L3DF}} = \frac{1}{1 + \frac{\sigma_{\mathrm{s,r}}}{\sigma_{\mathrm{r,d}}}}. \tag{11}$$

Often, one aims at achieving a certain outage probability, and a protocol's performance is then measured by the SNR that is required to achieve this target. Here, we compare the performance of conventional relaying and direct transmission by determining the ratio of the SNRs that achieve the same outage probability by equating (5) and (10). For large SNR

$$\Delta_{\mathrm{L3DF}} = \frac{\mathrm{SNR_D}}{\mathrm{SNR_{L3DF}}} = \underbrace{\frac{2^R-1}{2^{2R}-1}}_{\text{Rate-dependent}} \cdot \underbrace{\left(\frac{\sigma^2_{\mathrm{s,d}}}{2}\left(\frac{1}{p_1\sigma^2_{\mathrm{s,r}}} + \frac{1}{p_2\sigma^2_{\mathrm{r,d}}}\right)\right)^{-1}}_{\text{path loss-dependent}}. \tag{12}$$

If this ratio Δ_{L3DF} is larger than one, then we can achieve power savings under the total energy constraint by using conventional relaying; otherwise, direct transmission is preferable. Hence, Δ_{L3DF} constitutes the *SNR gain* that conventional relaying yields over direct transmission.[5]

3.2.3. Transmit diversity

For transmit diversity using two antennas at the source and maximal ratio combining (MRC) in the receiver [33], the mutual information of the transmit diversity protocol is

$$I_{\mathrm{T}} = \log\left(1 + \left(|h^{(1)}_{\mathrm{s,d}}|^2 + |h^{(2)}_{\mathrm{s,d}}|^2\right)\frac{\mathrm{SNR}}{2}\right), \tag{13}$$

where we assume $h^{(1)}_{\mathrm{s,d}}$ and $h^{(2)}_{\mathrm{s,d}}$ to be uncorrelated but identically distributed coefficients from the two source antennas to the destination antenna, both with mean $\sigma^2_{\mathrm{s,d}}$. As shown in [14], the outage probability for large SNR can be characterized as

$$p^{(\mathrm{out})}_{\mathrm{T}} = \Pr[I_{\mathrm{T}} < R] \approx \left(\frac{2^R-1}{\mathrm{SNR}}\right)^2 \cdot \frac{2}{\sigma^4_{\mathrm{s,d}}}. \tag{14}$$

[5] Note that this result has been obtained using the approximations for large SNR (5) and (10). We will derive closed-form results for the SNR gain of other protocols as well. Yet, it is worth noting that we found by means of numerical analysis that these approximations provide very accurate results for all typical ranges of the parameters of interest (e.g., path loss exponent $2 \leqslant \alpha \leqslant 5$ and spectral efficiency $0 \leqslant R \leqslant 5$ bit/s/Hz).

From (5) and (14) we readily find the SNR advantage of transmit diversity over direct SISO transmission for large SNR

$$\Delta_{\mathrm{T}} = \frac{\mathrm{SNR_D}}{\mathrm{SNR_T}} = \frac{1}{\sqrt{2p^{(\mathrm{out})}}}. \tag{15}$$

Note that the SNR advantage depends on the desired outage probability $p^{(\mathrm{out})}$: the lower the target outage probability, the more we benefit from using diversity techniques.

3.2.4. Adaptive decode-and-forward (AdDF)

The cooperative schemes are designed to simultaneously exploit path loss savings and diversity benefits. Recall that in the AdDF protocol, the relay forwards only when it has reliably decoded, i.e., if the capacity of the source-relay link exceeds the required spectral efficiency $2R$. The decoding event D is therefore:

$$D:\ \log(1 + 2p_1|h_{\mathrm{s,r}}|^2\mathrm{SNR}) \geqslant 2R \Longleftrightarrow 2p_1|h_{\mathrm{s,r}}|^2\mathrm{SNR} \geqslant 2^{2R} - 1. \tag{16}$$

Conditioned on this event, the mutual information of the two studied AdDF protocols can be expressed as

$$I_{\mathrm{AdDF}} = \begin{cases} \frac{1}{2}\log(1 + 2p_f|h_{\mathrm{s,d}}|^2\mathrm{SNR}) & \overline{D}, \quad \text{(a)} \\ \frac{1}{2}\log(1 + 2(p_1|h_{\mathrm{s,d}}|^2 + p_2|h_{\mathrm{r,d}}|^2)\mathrm{SNR}) & D. \quad \text{(b)} \end{cases} \tag{17}$$

Again, the factor 1/2 models the two-phase nature. The first line corresponds to direct transmission from source to destination, on which the protocol relies if the relay did not decode-and-forward. If on the other hand the relay can correctly decode, then it provides additional redundancy for the destination, which then performs MRC as described by Eq. (17b). This is the desired case.

In (17a), we use the factor p_f to distinguish the different fallback strategies of the two adaptive protocol versions. Recall that in the *simple* version, we have only a fraction p_1 for direct transmission (in phase one). In the *complex* version, the source employs repetition coding in phase two, providing a total power $(p_1 + p_2)\mathrm{SNR} = \mathrm{SNR}$, so that

$$p_f = \begin{cases} p_1 & \text{Simple AdDF,} \quad \text{(a)} \\ 1 & \text{Complex AdDF (repetition coding).} \quad \text{(b)} \end{cases} \tag{18}$$

An exact expression for the outage probability is derived in Appendix A.2.2 (Eq. (A.11)). As is further discussed in Eq. (A.13), the adaptive decode-and-forward protocol achieves for large SNR

$$p^{(\mathrm{out})}_{\mathrm{AdDF}} \approx \left(\frac{2^{2R}-1}{\mathrm{SNR}}\right)^2 \cdot \frac{1}{8p_1\sigma^2_{\mathrm{s,d}}}\left(\frac{2}{p_f\sigma^2_{\mathrm{s,r}}} + \frac{1}{p_2\sigma^2_{\mathrm{r,d}}}\right). \tag{19}$$

The optimum power fraction for both protocol versions under the total energy constraint is likewise derived in the appendix. Finally, we determine the SNR gain of the adaptive protocols over direct transmission from (5) and (19) for large SNR

$$\Delta_{\mathrm{AdDF}} = \frac{\mathrm{SNR_D}}{\mathrm{SNR_{AdDF}}} = \frac{2^R - 1}{2^{2R} - 1}\left(\frac{\sigma^2_{\mathrm{s,d}}p^{(\mathrm{out})}}{8p_1}\left(\frac{2}{p_f\sigma^2_{\mathrm{s,r}}} + \frac{1}{p_2\sigma^2_{\mathrm{r,d}}}\right)\right)^{-\frac{1}{2}}. \tag{20}$$

We note by comparison to (12) that the cooperative relay protocols and conventional relaying suffer to the same extent from higher required spectral efficiencies, but the influence of network geometry is different. In particular, we see that the potential for energy savings depends in the same way on the outage probability ($\sim \sqrt{p^{(\mathrm{out})}}$) as in the case of transmit diversity (15), indicating that both cooperative protocols achieve the same *diversity order* as transmit diversity.[6]

3.2.5. Adaptive decode-and-reencode (AdDR)

Having analyzed AdDF schemes, an extension to the AdDR schemes is straightforward. Noting that they are characterized by an accumulation of mutual information instead of SNRs, we develop

$$I_{AdDR} = \begin{cases} \frac{1}{2}\sum_{i\in\mathfrak{C}} \log(1+2p_i|h_{\mathrm{s,d}}|^2\mathrm{SNR}) & \overline{D}, \quad \text{(a)} \\ \frac{1}{2}\{\log(1+2p_1|h_{\mathrm{s,d}}|^2\mathrm{SNR}) + \log(1+2p_2|h_{\mathrm{s,r}}|^2\mathrm{SNR})\} & D. \quad \text{(b)} \end{cases} \tag{21}$$

In case the relay does not decode (21a), only phase one contributes in the *Simple* AdDR scheme. This is indicated in Eq. (21) by the notation $\mathfrak{C} = \{1\}$. By contrast, in the *complex* counterpart, both phases contribute as the source transmits in phase two if the relay did not decode. The set of contributing phases contains both phases, hence one would have $\mathfrak{C} = \{1, 2\}$ in Eq. (21).

So far we have focused on two-hop schemes. We will extend our considerations by discussing how such "basic building blocks" can advantageously be used to construct multi-hop chains.

3.3. Analysis of multi-hop protocols

Recall from Section 2.2 that resources, i.e., the combination of time and frequency on which transmissions are scheduled, can potentially be reused in multi-hop chains. This may result in possible interference from transmissions within the relay chain.

As a consequence, the instantaneous signal-to-*interference*-and-noise ratios, denoted by $\gamma_{i,j}$, do not just depend on a single fading coefficient, but on all interfering transmissions and their fading contributions. Assuming that superimposing interfering signals can be modelled as AWGN,[7] we have

$$\gamma_{i,j} = \frac{|h_{i,j}|^2 kp_i P}{N + \eta_j P \Psi_{i,j}} = \frac{|h_{i,j}|^2 kp_i}{\mathrm{SNR}^{-1} + \eta_j \Psi_{i,j}}. \tag{22}$$

Here, $\Psi_{i,j}$ is the normalized interference that node j faces when receiving a contribution from node i, and η_j models the capability of node j to cancel feedback and feedforward interference ($0 \leqslant \eta_j \leqslant 1$). Again, we assume that the total energy for transmission of one bit from source to destination is constrained. Here, p_i denotes the fraction of the total available energy that is allocated to node i's transmission, with $\sum_{i=1}^{k} p_i = 1$. For equally allocated power, we have $p_i = 1/k$, and hence $kp_i = 1$. The interference $\Psi_{i,j}$ results from super-positioned signals received from non-contributing transmissions in the chain

$$\Psi_{i,j} = \sum_{l\in\mathfrak{I}_{i,j}} kp_l |h_{l,j}|^2, \tag{23}$$

where $\mathfrak{I}_{i,j}$ denotes the set of interfering nodes that transmit at the same resource as node j is receiving from i.

3.3.1. Conventional relaying

Extending the consideration in Eq. (6), the instantaneous capacity of conventional store-and-forward relaying is determined by the weakest link in the chain of k hops, i.e.,

[6] For the complex protocol without power allocation, this has been shown in [14]; we conclude that using our power allocation likewise achieves full second-order diversity. The same holds for the proposed simple protocol.

[7] Which becomes more and more appropriate as the number of interferers increases.

$$I_{\mathrm{L3DF}} = \frac{1}{k'} \min_{i=1,\ldots,k} \{\log(1 + \gamma_{i-1,i})\}. \tag{24}$$

Note the factor $1/k'$, which accounts for the k'-fold subdivision of the end-to-end resource. An analytical solution of the general case is hard to establish, but performance can be assessed using Monte-Carlo simulations of the event $p_{\mathrm{L3DF}}^{(\mathrm{out})} = \Pr[I_{\mathrm{L3DF}} < R]$.

However, for the interference-free NRRU case, where $k' = k$ and, as no reuse occurs, $\Psi_{i,j} = 0$, an analytical solution is available. Note that Eq. (22) reduces to

$$\gamma_{i,j} = |h_{i,j}|^2 k p_i \mathrm{SNR}.$$

Along the same lines as in Eq. (7), the outage probability can then be derived as

$$\begin{aligned}
p_{\mathrm{L3DF}}^{(\mathrm{out})} &= \Pr[I_{\mathrm{L3DF}} < R] \\
&= \Pr\left[\min_{i=1,\ldots,k}\{|h_{i-1,i}|^2\} < \frac{2^{kR}-1}{kp_i\mathrm{SNR}}\right] \\
&= 1 - \prod_{i=1}^{k} \Pr\left[|h_{i-1,i}|^2 \geqslant \frac{2^{kR}-1}{kp_i\mathrm{SNR}}\right] \\
&= 1 - \prod_{i=1}^{k} \exp\left(-\frac{2^{kR}-1}{\sigma_{i-1,i}^2 k p_i \mathrm{SNR}}\right) \\
&= 1 - \exp\left(-\frac{2^{kR}-1}{k\mathrm{SNR}} \sum_{i=1}^{k} \frac{1}{p_i \sigma_{i-1,i}^2}\right) && (25) \\
&\approx \frac{2^{kR}-1}{k\mathrm{SNR}} \sum_{i=1}^{k} \frac{1}{p_i\sigma_{i-1,i}^2} \quad (\mathrm{SNR} \gg 1). && (26)
\end{aligned}$$

3.3.2. Application to the example scenario

For equal power allocation $p_i = 1/k$ and equal propagation conditions as described by Eq. (2), the SNR gain over direct transmission is found from the ratio of SNRs in Eqs. (26) and (5) that achieve the same outage probability

$$\Delta_{\mathrm{L3DF}} = k^{\alpha-1} \frac{2^R - 1}{2^{kR} - 1}. \tag{27}$$

As one would expect intuitively, the SNR gain increases in the number of hops as path loss is saved. On the other hand, it decreases in the number of hops as a higher spectral efficiency per hop is required.

The *optimum number of hops* for the example scenario can be found from minimizing the term in the exponential in Eq. (25), or equivalently by maximizing Eq. (27). The result is implicitly given and can easily be determined numerically.

3.3.3. Adaptive cooperative multi-hop schemes

We now turn to analyzing the more complex cascaded cooperative schemes, where the relays autonomously decide whether or not to decode-and-forward and where the receiving nodes combine the preceding two transmissions in the chain (Fig. 3(b)). For their similar structure, one can examine AdDF and AdDR schemes in a common manner (referred to as AdDx in the following).

The mutual information in the signals transmitted at node 0 and received at node i is given by

$$I_{\mathrm{AdDx}}(i)=\begin{cases}H(x) & i=0,\\ \frac{1}{k'}\log\left(1+\gamma_{0,1}\right) & i=1,\\ \min\{I_{\mathrm{AdDx}}(i-2),I^{(2)}_{\mathrm{AdDx}}(i)\} & i\geqslant 2,\end{cases} \tag{28}$$

where the first case is the self-information of the transmitted signal at the source; the second case is the mutual information at the first node, and the last case describes the cascaded manner in which the relay chain operates for this protocol. The recursive form of Eq. (28) reflects the concatenation of two-hop building blocks, each having a capacity of $I^{(2)}_{\mathrm{AdDx}}(i)$. The capacity of such a two-hop block is given by Eqs. (17) and (21) for AdDF and AdDR, respectively. For the current notation, they read

$$I^{(2)}_{\mathrm{AdDF}}(i)=\begin{cases}\frac{1}{k'}\log(1+\gamma_{i-2,i}) & \overline{D}(i-1),\\ \frac{1}{k'}\log(1+\gamma_{i-2,i}+\gamma_{i-1,i}) & D(i-1)\end{cases} \tag{29}$$

and

$$I^{(2)}_{\mathrm{AdDR}}(i)=\begin{cases}\frac{1}{k'}\sum\limits_{p_j\in\mathfrak{C}}\log(1+p_j\gamma_{i-2,i}) & \overline{D}(i-1),\\ \frac{1}{k'}\sum\limits_{j=1}^{2}\log(1+\gamma_{i-j,i}) & D(i-1),\end{cases} \tag{30}$$

where $\mathfrak{C}=\{1\}$ for the Simple AdDR and $\mathfrak{C}=\{1,p_{i-1}/p_{i-2}\}$ for the Complex AdDR scheme.[8] As before, the decoding event at the considered block's relay is

$$D(i-1):\ \frac{1}{k'}\log(1+\gamma_{i-2,i-1})\geqslant R \tag{31}$$

$$\iff \gamma_{i-2,i-1}\geqslant 2^{k'R}-1. \tag{32}$$

The probability of outage of end-to-end communication, $\Pr[I_{\mathrm{AdDx}}(k) < R]$, is hard to analyze in closed from, for the $\gamma_{i,j}$ are constructed from more than one exponential random variable; see Eq. (22). Yet, there is a solution for the interference-free AdDF NRRU scheme; see Appendix A.2.3.

4. Results and discussion

4.1. Performance of two-hop protocols

4.1.1. Outage probability

We start our discussion by considering the optimistic case of a relay being located halfway between source and destination, i.e., $d_{s,r}/d_{s,d} = 0.5$. Fig. 6 depicts the outage probability as a function of the SNR for all protocols, for a path loss exponent $\alpha = 3.0$ and a rate $R = 2$ bit/s/Hz.

Under our strict assumptions, conventional relaying looses ≈1 dB over direct transmission according to Eq. (12). Direct transmission and conventional relaying achieve first-order diversity: the probability of outage decays by one order of magnitude for an increase of 10 dB in SNR.

[8] Here, we use a similar notation as in Eq. (21).

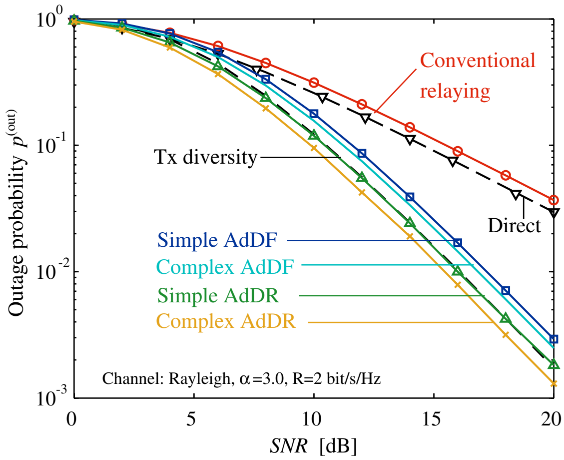

Fig. 6. Outage probability vs. SNR for a relay located halfway between source and destination. Parameters: path loss exponent $\alpha = 3.0$, spectral efficiency $R = 2$ bit/s/Hz.

By contrast, the transmit diversity scheme as well as the diversity-exploiting cooperative protocols realize second-order diversity, thereby outperforming direct transmission and conventional relaying. Note that cooperative schemes perform comparable to the transmit diversity scheme; loosely speaking, these protocols jointly exploit path loss savings and diversity gains by having one of the two transmit antennas (in the form of the relay) located between source and relay, while conventional transmit diversity has both antennas at the source and faces the full path loss from source to destination.

The similar performance of simple and complex adaptive decode-and-forward scheme suggests that the gains from repetition coding that is employed by the source in the fallback case of the *complex* protocol are not substantial. As we have observed this outcome for all other studied scenarios, we focus on the performance of the proposed simple AdDF scheme in the following.

Finally, the re-encoding AdDR protocols outperform their AdDF counterparts by ≈1.3 dB, made possible by re-encoding a different codeword instead of simple repetition coding from the relay.

4.1.2. Influence of spectral efficiency

Recall that due to the nodes' inability to receive and transmit simultaneously at the same frequency, orthogonal resources must be assigned for reception and transmission at the relay. For networks with *limited available bandwidth and delay*, this calls in turn for a more spectrum-efficient use of the available resources. The results in (12) and (20) for conventional and adaptive AdDF two-hop relaying indicate that the incurred SNR loss is

$$\frac{2^{2R}-1}{2^{R}-1}. \tag{33}$$

This loss is incurred from orthogonality and repetition; it was shown in [14] that in the high-rate regime, repetition is the dominant drawback. Conventional relaying and AdDF schemes loose 3 dB for each additional bit/s/Hz over direct transmission in the high-rate regime. The AdDR schemes potentially overcome this limitation by avoiding repetition.

More quantitatively, the resulting SNR gains are depicted in Fig. 7 for an outage probability of $p^{(\mathrm{out})} = 10^{-2}$. Conventional relaying outperforms direct transmission only for $R \leqslant 1.5$ bit/s/Hz. The Simple

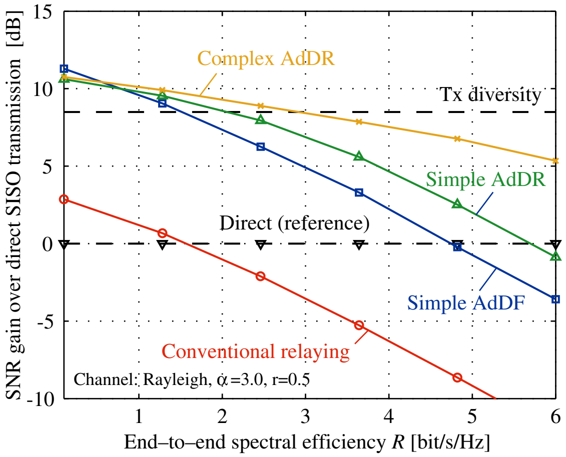

Fig. 7. SNR gain over direct transmission as a function of the end-to-end spectral efficiency R. For the considered bandwidth limited scenarios, the relay protocols suffer from the required doubled spectral efficiency. Parameters: outage probability $p^{(\mathrm{out})} = 10^{-2}$, path loss exponent $\alpha = 3.0$, relay position $d_{s,r}/d_{s,d} = 1/2$.

AdDF protocol achieves gains of ≈7 dB over conventional relaying for all spectral efficiencies; it is preferable over direct transmission up to 4.7 bit/s/Hz. The AdDR schemes yield additional benefits. However, the Simple AdDR scheme's SNR gain decreases as a function of the targeted end-to-end rate similarly to the AdDF schemes; its performance is limited by the source-relay bottleneck. The Complex AdDR protocol advantageously exhibits an SNR loss of only 1.2 dB per bit/s/Hz compared to 3 dB per bit/s/Hz of the other relaying methods, thereby achieving gains over direct transmission for all considered spectral efficiencies.

4.1.3. Influence of relay node position

To study the impact of relay node location, we now vary the position of the relay along the straight line connecting source and destination. The parameter of interest is therefore the relative distance $d_{s,r}/d_{s,d}$ from the source ($0 \leqslant d_{s,r}/d_{s,d} \leqslant 1$).

Fig. 8 depicts the SNR gains as a function of this relative distance. For the shown case of $R = 2$ bit/s/Hz and a path loss exponent of $\alpha = 3.0$ (thick lines), the simple cooperative protocol can achieve gains up to 7.5 dB over direct transmission; conventional relaying yields no gains under our strict assumptions. At the cost of additional complexity, the AdDR schemes perform best with gains of ≈9 dB. As intuition suggests, relaying yields more benefits for stronger propagation losses ($\alpha = 5.0$), indicated by the thin grey lines.

Placing the relay halfway between source and destination (or, more precisely, having a routing protocol that chooses a relay close to this location) is well-known to be the best strategy for conventional relaying as this maximizes path loss savings. The characteristics in Fig. 8 indicate that this is likewise a good choice for cooperative relaying. In addition, we note that the cooperative schemes' performance are less susceptible to the relay position than that of their conventional counterpart; this indicates that requirements for routing and relay node selection are more relaxed for cooperative relaying.[9] Note finally that the AdDF scheme can outperform the AdDR protocol for special cases; this improvement is due to the optimized power fraction; see Eq. (A.14).

[9] This discussion is detailed in [36], where we investigate the *usage regions* of the relaying schemes.

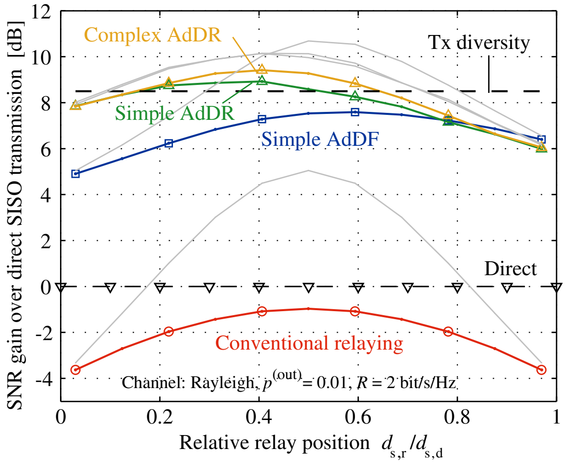

Fig. 8. SNR gain induced by a reduction of the required SNR, as a function of the position $d_{s,r}/d_{s,d}$ of a relay that is located on the straight line between source and destination, for conventional and cooperative relaying. Thick lines: path loss exponent $\alpha = 3.0$; thin, grey lines: $\alpha = 5.0$. Parameters: outage probability $p^{(out)} = 10^{-2}$, $R = 2$ bit/s/Hz.

4.2. Results for multi-hop schemes

4.2.1. SNR gain and influence of number of hops

Focusing on the interference-free NRRU protocol versions, we note that the increasing required per-link spectral efficiency kR incurs a corresponding SNR loss

$$\frac{2^{kR}-1}{2^{R}-1}.$$

On the other hand, the higher the number of hops, the more one benefits from path loss savings. Fig. 9 depicts the resulting SNR gain that the protocols of interest achieve over direct transmission as a function of the number of hops. For the shown path loss exponent $\alpha = 4.0$ and targeted end-to-end rate $R = 1$ bit/s/Hz,

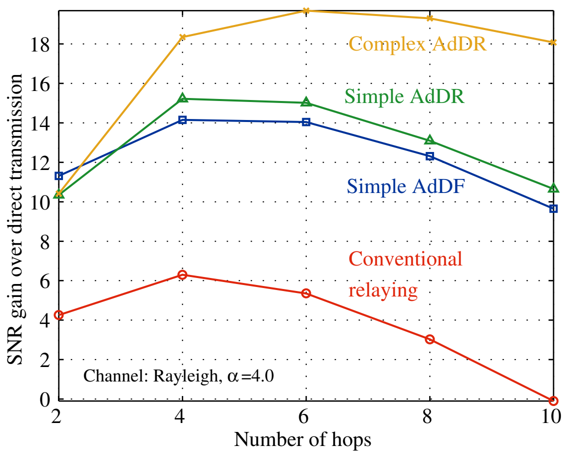

Fig. 9. SNR gain vs. number of hops in the example scenario for the interference-free NRRU scheme. Parameters: $\alpha = 4.0$, $R = 1$ bit/s/Hz, target outage probability $p^{(out)} = 10^{-2}$ (fading case).

the optimum number of hops is four for conventional relaying as well as for Simple AdDF and Simple AdDR. Complex AdDR outperforms these protocols by achieving a stronger SNR gain at an optimum hop count of six. Note that the parameters at hand favor relaying; we will see that relaying becomes inappropriate for scenarios with lower path loss exponents and higher targeted spectral efficiencies.

For the RRU schemes (results not shown), reusing resources within the relay chain in connection with interference cancellation unfolds the full potential of relaying. If full interference cancellation were possible, i.e., $\eta = 0$, then the SNR gain monotonically increases in the number of hops under our assumptions. This performance benefit results from the very fact that the reuse of resources allows for a per-link rate of $k'R$, instead of kR, whereas the path loss savings unlimitedly increase in the number of hops.

It is crucial to note, however, that a *certain minimum interference suppression is indeed required* for the protocols to function *at all*. If this interference suppression is not sufficient, then the protocols do not achieve the targeted performance. We elaborate on this subsequently.

4.2.2. Impact of interference cancellation

We have argued that cancelling feedback and feedforward interference is necessary when resources are reused in the relay chain (RRU scheme). As this interference results from the same information being transmitted from different locations, it can be regarded as intersymbol interference and may consequently be eliminated using known equalization techniques [28].

We have modelled this interference elimination by a factor η with $0 \leqslant \eta \leqslant 1$, where $\eta = 0$ corresponds to perfect cancellation and $\eta = 1$ reflects the worst case of no interference cancellation. For the example scenario with $k = 6$ equidistant hops with reuse $k' = 3$, Fig. 10 depicts the SNR gain as a function of η for various path loss exponents. For purposes of clarity, we show only conventional relaying and AdDF schemes. We note: (i) a minimum cancellation is required for the protocols to function *at all*; (ii) this minimum cancellation depends on the path loss exponent α: the lower the path loss, the lower the isolation from mutual interference, and the stronger the required cancellation; (iii) if the minimum cancellation is not achieved, then this leads to an outage probability floor that prevents the target $p^{(\mathrm{out})} = 10^{-2}$ from being reached. Reliable communication is then not possible.

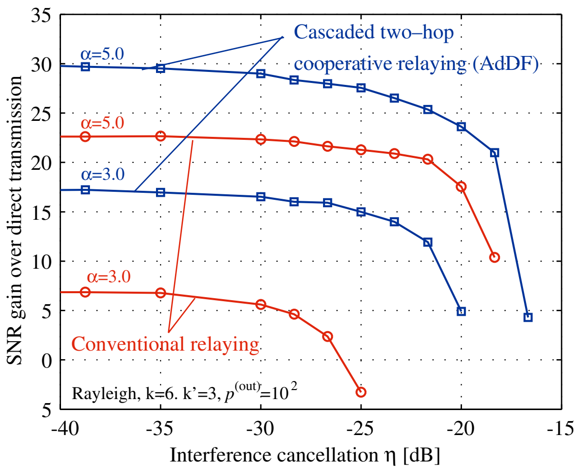

Fig. 10. SNR gain vs. interference cancellation capability in the example scenario. Parameters: Rayleigh fading, $k = 6$ hops, reuse $k' = 3$, $R = 1$ bit/s/Hz, target outage probability $p^{(\mathrm{out})} = 10^{-2}$.

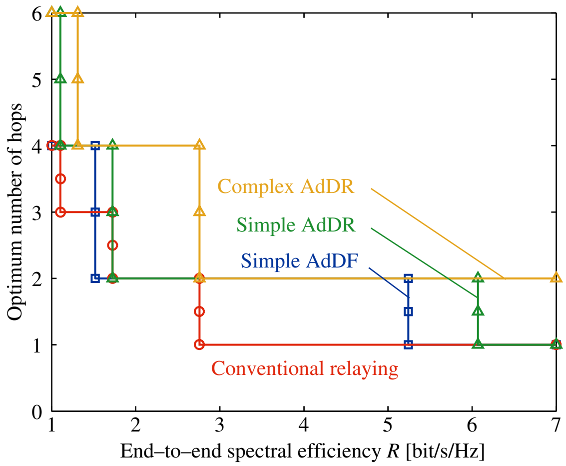

Fig. 11. Optimum number of hops in the example scenario vs. targeted end-to-end spectral efficiency. Using two hops is beneficial for the cooperative protocol for a wide range of end-to-end rates, while conventional relaying falls back to direct transmission already at lower rates (≈2.3 bit/s/Hz). Parameters: NRRU scheme, target outage probability $p^{(\mathrm{out})} = 10^{-2}$, $\alpha = 4.0$, $k = k'$.

4.2.3. *"What is the optimum number of hops?"*

We have seen that for sufficiently strong interference cancellation, the SNR gain monotonically increases in the number of hops. Hence, provided such strong interference cancellation that ensures that the desired outage probability is reached, the optimum number of hops for the resource reuse scheme (RRU) is infinity. In general, however, the optimum number of hops decreases as the interference cancellation efficiency reduces.

For the NRRU scheme, which assigns orthogonal resources for each of the hops, we discussed the trade-off between the path loss reductions from shorter hops on the one hand and increased per-link rates kR on the other hand. Fig. 11 illustrates the resulting optimum number of hops as a function of the targeted end-to-end spectral efficiency R.

The results suggest that cooperative *two-hop* schemes are optimal for a wide range of scenarios; they are applicable up to rates of 5.2 bit/s/Hz (Simple AdDF), 6.1 bit/s/Hz (Simple AdDR), and for more than 7 bit/s/Hz (Complex AdDR). By contrast, conventional relaying provides benefits only for $R \leqslant 3$ bit/s/Hz (red lines with circular markers).

More generally, a low number of hops is beneficial under our assumptions. In particular, recall that the example scenario constitutes a certain best case for relaying: nodes are equidistantly placed on a straight line, and we assumed zero power cost for reception. For realistic, more irregular scenarios, where receiving requires power, one would expect even lower numbers of hops to be most promising. Considering their simplicity, two-hop implementations emerge as a highly attractive option.

4.3. *Trends for AWGN channels*

The Rayleigh fading model discussed so far is a commonly accepted one; yet, it represents the "worst-case" fading for which our diversity-exploiting protocols will achieve significant advantages. The "best case" with respect to fading is communication over AWGN channels.

Based on the discussion in [36], where we have additionally addressed AWGN channels, we draw the following conclusions:

1. Cooperative and conventional relaying perform similarly in AWGN, as spatial diversity does not yield any benefits in non-fading environments. Compared to Rayleigh fading environments, conventional relaying improves, whereas cooperative relaying looses.
2. In AWGN scenarios, we expect to isolate the *broadcast* advantages of the cooperative protocols since we do not benefit from diversity gains. Yet, these broadcast advantages, resulting from the fact that the destination takes the original signal sent by the source into account, are almost negligible for typical path loss exponents.
3. The optimum number of hops is similar to that of Rayleigh scenarios, with a tendency to even lower optimum hop counts than for Rayleigh channels.

4.4. Applicability of results and implementation aspects

It remains to reflect on the applicability of the results and to discuss issues related to implementation in practical systems.

4.4.1. Evaluation of results

It is worth noting that using mutual information, outage probability, and SNR gain as performance measures implies perfect *link adaption*,[10] for which an improvement in effective SNR directly translates into a corresponding performance benefit. However, finite granularity of practical code rates and modulation alphabet sizes leads to link adaptation in certain discrete steps that are often referred to as "PHY modes." As a consequence of such limited adaptability in practical systems, the resulting performance of the protocols may differ to some degree from the results presented above.

Moreover, recall that we assumed a general distance-dependent path loss model. While this is a widely accepted model, it fails to cover specific, yet typical scenarios. An example is the well-known Manhattan scenario, where relay nodes can advantageously be placed at street crossings to provide coverage for areas that would otherwise be shadowed by buildings. In [30] it is shown that conventional relaying can significantly improve network capacity in such environments. Cooperative relaying does not promise significant additional returns in this case: the "direct" path from source to relay is heavily obstructed by buildings that reduce this path's relative contribution to negligible levels.

4.4.2. Implementation aspects

At the physical layer, cooperative relaying calls for *combining* from various resources—as done in ARQ mechanisms where redundancy from different time slots is taken into account. At the MAC layer, resources must be allocated such that reception(s) and transmission take place on orthogonal resources. A simplified resource allocation can be applied in two-hop networks, where conventional and cooperative relaying have identical demands.

We note that the lion's share of challenges, for example routing in mobile environments, is related to relaying itself, not to cooperation. Based on this, a viable strategy might be to *view cooperative relaying as an extension of conventional relaying*—not as a competing technology. Issues such as distributed routing, mobility management, and partly resource assignment, are challenges for both conventional and cooperative relaying, and hence should be tackled jointly. However, provisions should be made towards implementing the above listed cooperative extensions.

Then, to take full benefits from both relaying methods, operation could take place in a supplementary manner: conventional relaying serves as a means of providing coverage in areas where direct communica-

[10] We refer to link adaptation as adjusting the transmission rate to SINR conditions.

tion and cooperative relaying are not viable; for the remaining areas, cooperative relaying is used to further improve network performance.

5. Summary and conclusions

We have considered various cooperative relaying schemes and compared their performance with direct transmission, transmit diversity techniques, and conventional store-and-forward relaying. The common idea of cooperative schemes is that the destination combines the signals transmitted from source and relay, thereby exploiting the diversity of the relay channel and the broadcast nature of wireless propagation.

Our focus was on adaptive cooperative protocols, where the relays autonomously decide whether or not to retransmit so as to avoid error propagation. If the relays decide not to forward, then simple schemes are characterized by "silence"; complex schemes use feedback to indicate to the source that it should transmit instead. We discussed numerous suggested protocols that fit into this framework.

Decode-and-forward schemes (AdDF) are attractively simple by operating in a repetition-coding manner, whereas more sophisticated decode-and-reencode (AdDR) schemes create a different codeword at the relay, thereby improving performance through accumulation of mutual information instead of signal-to-noise-ratios.

We studied basic two-hop building blocks and their extension to multi-hop chains, which can advantageously be formed by concatenating such two-hop blocks. In the latter case, reusing resources is beneficial from an efficiency point of view, but it incurs mutual interference within the chain.

Under the assumption of single-antenna nodes communicating over block Rayleigh fading channels with limited energy, delay, and bandwidth, we found the following:

1. Full second-order diversity is achieved by the cooperative protocols.
2. All relaying schemes suffer as the targeted end-to-end spectral efficiency is increased: conventional and AdDF loose 3 dB per additional bit/s/Hz; by avoiding repetition coding, the AdDR schemes loose to a lower extent (1.2 dB per bit/s/Hz for the Complex AdDR).
3. The performance of cooperative schemes depends to a lower extent on the relay position than in the case of conventional relaying; this indicates more relaxed requirements for routing.
4. In multi-hop networks, reusing resources calls for a strong interference suppression capability to sufficiently eliminate interference (e.g., 20 dB for a path loss exponent 3.0 in order to achieve an outage probability of 10^{-2}). If this can be achieved, then the benefits increase in the number of hops.
5. Operating multi-hop chains without resource reuse avoids interference, but efficiency suffers. The resulting optimum number of hops is two to six, depending on end-to-end spectral efficiency and protocol.

Finally, we believe the lion's share of challenges to be related to relaying as such; cooperative relaying can come as an add-on with adjustable levels of complexity. It promises additional returns at low cost that might help in solving the challenging demands of future wireless networks.

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Appendix A. Outage probability considerations

A.1. Exponential random variables

A.1.1. Single exponential random variable

For the purpose of completeness, we recall well-known facts. The PDF of an exponential random variable u has a probability density function (PDF)

$$p_{\mathsf{u}}(u) = \begin{cases} 0 & u \leqslant 0, \\ \lambda_{\mathsf{u}} \mathrm{e}^{-\lambda_{\mathsf{u}} u} & u > 0. \end{cases} \tag{A.1}$$

The parameter λ_{u} of the distribution is related to the expected value of the random variable $E\{\mathsf{u}\}$ by $\lambda_{\mathsf{u}} = 1/E\{\mathsf{u}\}$. The distribution's cumulative distribution function (CDF) is

$$\Pr[\mathsf{u} \leqslant u] = \int_{-\infty}^{u} p_{\mathsf{u}}(x)\,\mathrm{d}x = 1 - \mathrm{e}^{-\lambda_{\mathsf{u}} u}. \tag{A.2}$$

A.1.2. Sum of two exponential variables

Assume there are two random variables u and v, each exponentially distributed with parameters λ_{u} and λ_{v}, respectively. We are interested in the PDF and CDF of the sum of the two random variables

$$\mathsf{w} = \mathsf{u} + \mathsf{v}.$$

The PDF of the sum is the convolution of the two individual PDFs

$$\begin{aligned} p_{\mathsf{w}}(w) &= \int_{-\infty}^{\infty} p_{\mathsf{u}}(u) p_{\mathsf{v}}(w-u)\,\mathrm{d}u = \int_{0}^{w} \lambda_{\mathsf{u}} \mathrm{e}^{-\lambda_{\mathsf{u}} u} \lambda_{\mathsf{v}} \mathrm{e}^{-\lambda_{\mathsf{v}}(w-u)}\,\mathrm{d}u = \lambda_{\mathsf{u}}\lambda_{\mathsf{v}} \mathrm{e}^{-\lambda_{\mathsf{v}} w} \int_{0}^{w} \mathrm{e}^{(\lambda_{\mathsf{v}}-\lambda_{\mathsf{u}})u}\,\mathrm{d}u \\ &= \begin{cases} \lambda_{\mathsf{u}}^2 \mathrm{e}^{-\lambda_{\mathsf{u}} w} w & \lambda_{\mathsf{v}} = \lambda_{\mathsf{u}}, \\ \frac{\lambda_{\mathsf{u}}\lambda_{\mathsf{v}}}{\lambda_{\mathsf{u}}+\lambda_{\mathsf{v}}} (\mathrm{e}^{-\lambda_{\mathsf{u}} w} - \mathrm{e}^{-\lambda_{\mathsf{v}} w}) & \lambda_{\mathsf{v}} \neq \lambda_{\mathsf{u}}. \end{cases} \end{aligned} \tag{A.3}$$

The CDF is then found from integration as

$$\Pr[\mathsf{w} \leqslant w] = \int_{-\infty}^{w} p_{\mathsf{w}}(x)\,\mathrm{d}x = \begin{cases} 1 - (1+\lambda_{\mathsf{u}} w)\mathrm{e}^{-\lambda_{\mathsf{u}} w} & \lambda_{\mathsf{v}} = \lambda_{\mathsf{u}}, \\ 1 - \left(\frac{\lambda_{\mathsf{v}}}{\lambda_{\mathsf{v}}-\lambda_{\mathsf{u}}} \mathrm{e}^{-\lambda_{\mathsf{u}} w} + \frac{\lambda_{\mathsf{u}}}{\lambda_{\mathsf{u}}-\lambda_{\mathsf{v}}} \mathrm{e}^{-\lambda_{\mathsf{v}} w}\right) & \lambda_{\mathsf{v}} \neq \lambda_{\mathsf{u}}. \end{cases} \tag{A.4}$$

A.1.3. Approximations

For purposes of completeness, we briefly summarize two results from [14]. Let u be an exponential random variable with parameter λ_u. Then the CDF $P_{\mathsf{u}}(u) = 1 - \mathrm{e}^{-\lambda_{\mathsf{u}} u}$ satisfies [14, (41)]

$$\lim_{x\to\infty} \frac{1}{g(x)} P_{\mathsf{u}}(g(x)) = \lambda_{\mathsf{u}}, \tag{A.5}$$

where $g(x)$ is a continuous function with $g(x) \to 0$ as $x \to \infty$. Further, let u and v be two exponential random variables with parameters λ_{u} and λ_{v}, respectively, and let $\mathsf{w} = \mathsf{u} + \mathsf{v}$. Then, the CDF $P_{\mathsf{w}}(w)$ satisfies [14, (44)]

$$\lim_{x\to\infty} \frac{1}{g^2(x)} P_{\mathsf{w}}(g(x)) = \frac{\lambda_{\mathsf{u}}\lambda_{\mathsf{v}}}{2}, \tag{A.6}$$

where $g(x)$ is defined as above. This result can be obtained by applying the rule of Bernoulli and L'Hospital to the CDF $P_{\mathsf{w}}(w)$.

A.2. Outage probabilities

A.2.1. Transmit diversity

From (13) the outage event $I_T < R$ reads

$$|h_{s,d}|^2 + |h_{r,d}|^2 < \frac{2^R - 1}{\mathrm{SNR}/2}. \tag{A.7}$$

Here, $|h_{s,d}|^2$ and $|h_{r,d}|^2$ are independent, but identically distributed exponential variables, each with parameter $\sigma_{s,d}^{-2}$. Using this in (A.4), we conclude

$$p_T^{(out)} = 1 - \left(1 + \frac{1}{\sigma_{s,d}^2}\frac{2^R - 1}{\mathrm{SNR}/2}\right) \cdot \exp\left(-\frac{1}{\sigma_{s,d}^2}\frac{2^R - 1}{\mathrm{SNR}/2}\right). \tag{A.8}$$

A.2.2. Adaptive decode-and-forward

A.2.2.1. Exact outage probability. We aim at determining the characteristic of the outage probability of the AdDF protocol. From (17), and considering the outage event $I_{AdDF} < 2R$, the outage probability becomes

$$p_{AdDF}^{(out)} = \Pr[2p_f|h_{s,d}|^2 < g(\mathrm{SNR})] \cdot \Pr[2p_1|h_{s,r}|^2 < g(\mathrm{SNR})] + \Pr[2p_1|h_{s,d}|^2 + 2p_2|h_{r,d}|^2 < g(\mathrm{SNR})] \cdot \Pr[2p_1|h_{s,r}|^2 \geqslant g(\mathrm{SNR})], \tag{A.9}$$

where $g(\mathrm{SNR})$ is defined by (8). Using (A.2) and (A.4), and denoting the parameters of the exponential random variables by

$$\lambda_u = \frac{1}{2p_1\sigma_{s,d}^2}, \quad \lambda_v = \frac{1}{2p_2\sigma_{r,d}^2}, \quad w = g(\mathrm{SNR}), \tag{A.10}$$

we obtain the outage probability as

$$p_{AdDF}^{(out)} = \left(1 - \exp\left(-\frac{g(\mathrm{SNR})}{2p_f\sigma_{s,d}^2}\right)\right) \cdot \left(1 - \exp\left(-\frac{g(\mathrm{SNR})}{2p_1\sigma_{s,r}^2}\right)\right) + \left[1 - \left(\frac{\lambda_v}{\lambda_v - \lambda_u}e^{-\lambda_u w} + \frac{\lambda_u}{\lambda_u - \lambda_v}e^{-\lambda_v w}\right)\right] \cdot \exp\left(-\frac{g(\mathrm{SNR})}{2p_1\sigma_{s,r}^2}\right). \tag{A.11}$$

A.2.2.2. Approximation for large SNR. Using the results of Appendix A.1.3, we find

$$\frac{p_{AdDF}^{(out)}}{g^2(\mathrm{SNR})} = \underbrace{\frac{1}{g(\mathrm{SNR})}\Pr[2p_f|h_{s,d}|^2 < g(\mathrm{SNR})]}_{\to 1/(2p_f\sigma_{s,d}^2)} \cdot \underbrace{\frac{1}{g(\mathrm{SNR})}\Pr[2p_1|h_{s,r}|^2 < g(\mathrm{SNR})]}_{\to 1/(2p_1\sigma_{s,r}^2)} + \underbrace{\frac{\Pr[2p_1|h_{s,d}|^2 + 2p_2|h_{r,d}|^2 < g(\mathrm{SNR})]}{g^2(\mathrm{SNR})}}_{\to 1/(2\cdot 2p_1\sigma_{s,d}^2\cdot 2p_2\sigma_{r,d}^2)} \cdot \underbrace{\Pr[2p_1|h_{s,r}|^2 \geqslant g(\mathrm{SNR})]}_{\to 1}, \tag{A.12}$$

so that for large SNR

$$p_{AdDF}^{(out)} \approx \left(\frac{2^{2R} - 1}{\mathrm{SNR}}\right)^2 \frac{1}{8p_1\sigma_{s,d}^2}\left(\frac{2}{p_f\sigma_{s,r}^2} + \frac{1}{p_2\sigma_{r,d}^2}\right). \tag{A.13}$$

From this expression, we can find the power fractions that minimize the outage probability of the AdDF protocol as

$$p_{\mathrm{AdDF}}^{(\mathrm{opt},R)} = \begin{cases} \frac{8\sigma_{\mathrm{r,d}}^2 - \sigma_{\mathrm{s,r}}^2 - \sqrt{16\sigma_{\mathrm{r,d}}^2\sigma_{\mathrm{s,r}}^2 + \sigma_{\mathrm{s,r}}^4}}{8\sigma_{\mathrm{r,d}}^2 - 4\sigma_{\mathrm{s,r}}^2} & \text{Simple AdDF,} \\ \frac{1}{1 + \frac{\sigma_{\mathrm{s,r}}^2}{2\sigma_{\mathrm{r,d}}^2 + \sigma_{\mathrm{s,r}}^2}} & \text{Complex AdDF.} \end{cases} \tag{A.14}$$

A.2.3. AdDF—the multi-hop case

Recall that for $k' = k$ and $\Psi_{i,j} = 0$, (22) simplifies to

$$\gamma_{i,j} = |h_{i,j}|^2 k p_i \mathrm{SNR} = |h_{i,j}|^2 \tilde{\gamma}_i,$$

where we have introduced the normalized SNR

$$\tilde{\gamma}_i = k p_i \mathrm{SNR} \tag{A.15}$$

to simplify the following. The outage probability can then be stated as

$$p_{\mathrm{AdDF}}^{(\mathrm{out})}(i) = \begin{cases} 0 & i = 0, \\ 1 - \exp\left(-\frac{2^{kR}-1}{\sigma_{0,1}^2\tilde{\gamma}_{0,1}}\right) & i = 1, \\ 1 - \left\{\left(1 - p_{\mathrm{AdDF}}^{(\mathrm{out})}(i-2)\right) \cdot \left(1 - p_{\mathrm{AdDF}}^{(\mathrm{out})(2)}(i)\right)\right\} & i \geqslant 2. \end{cases} \tag{A.16}$$

As for the mutual information, the outage probability is given in recursive form. A closed-form solution for the outage probability of the basic two-hop building block $p_{\mathrm{AdDF}}^{(\mathrm{out})(2)}(i)$ is provided below by Eq. (A.18). For the NRRU case, $p^{(\mathrm{out})}$ can therefore be easily determined; for the more general RRU case, Monte-Carlo simulations have been performed.

From (A.16), the outage probability is derived as

$$\begin{aligned} p_{\mathrm{AdDF}}^{(\mathrm{out})(2)}(i) &= \Pr[|h_{i-2,i}|^2\tilde{\gamma}_{i-2} < 2^{kR} - 1] \cdot \Pr[|h_{i-2,i-1}|^2\tilde{\gamma}_{i-2} < 2^{kR} - 1] \\ &\quad + \Pr[|h_{i-2,i-1}|^2\tilde{\gamma}_{i-2} + |h_{i-1,i}|^2\tilde{\gamma}_{i-1} < 2^{kR} - 1] \cdot \Pr[|h_{i-2,i-1}|^2\tilde{\gamma}_{i-1} \geqslant 2^{kR} - 1], \end{aligned} \tag{A.17}$$

which, using the previous results, leads to

$$\begin{aligned} p_{\mathrm{AdDF}}^{(\mathrm{out})(2)}(i) &= \left(1 - \exp\left(-\frac{2^{kR}-1}{\sigma_{i-2,i}^2\tilde{\gamma}_{i-2}}\right)\right)\left(1 - \exp\left(-\frac{2^{kR}-1}{\sigma_{i-2,i-1}^2\tilde{\gamma}_{i-2}}\right)\right) \\ &\quad + \left[1 - \left(\frac{1}{1 - \frac{\sigma_{i-1,i}^2\tilde{\gamma}_{i-1}}{\sigma_{i-2,i}^2\tilde{\gamma}_{i-2}}} \mathrm{e}^{-\frac{2^{kR}-1}{\sigma_{i-2,i}^2\tilde{\gamma}_{i-2}}} + \frac{1}{1 - \frac{\sigma_{i-2,i}^2\tilde{\gamma}_{i-2}}{\sigma_{i-1,i}^2\tilde{\gamma}_{i-1}}} \mathrm{e}^{-\frac{2^{kR}-1}{\sigma_{i-1,i}^2\tilde{\gamma}_{i-1}}}\right)\right] \cdot \exp\left(-\frac{2^{kR}-1}{\sigma_{i-2,i-1}^2\tilde{\gamma}_{i-2}}\right). \end{aligned} \tag{A.18}$$

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