A Novel Protocol for Cooperative Diversity in Wireless Networks

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***Abstract*: Recently, cooperative diversity has emerged as a means of providing gains from spatial diversity to devices with single antennas. Yet, the performance of these protocols remains limited in symmetric networks. In this paper, we investigate the performance of a novel "detached" cooperative diversity protocol that is designed for asymmetric networks, both in terms of outage probability and frame error rate. The influence of data rate, path loss, and network geometry on the performance of the proposed protocol is studied, and the usage region, in which cooperative schemes outperform direct transmission, is derived.**

Our results suggest that the novel cooperative diversity protocol outperforms non-cooperative transmission under a wide range of environment conditions and hence constitutes a viable option for future wireless networks.

1. Introduction

The rising demand for high data rate services in current and future wireless networks calls for advanced strategies at various layers. A frequently considered concept is the use of relay nodes to help transmit information from a source node to its destination. As an extension of this approach, *cooperative diversity* [4] or *virtual antenna arrays* [2] exploit the inherent spatial diversity of the relay channel by allowing mobile terminals to cooperate. More generally, by taking the original signal copy sent by the source node into account, such *cooperative relaying* systems exploit useful side information that conventional relaying systems unnecessarily discard as noise.

For statistically independent channels between all nodes in a single relay system, it was shown in [4] that full 2^{nd} order diversity can be achieved asymptotically, i.e. the outage probability as a function of the SNR decays with slope 2 ($\Delta = 2$) on a logarithmic scale:

$$p^{out} \propto \frac{1}{\text{SNR}^{\Delta}}, \qquad \text{SNR} \gg 1. \tag{1}$$

While this constitutes a very promising result, it has been demonstrated in [8] that for symmetric network constellations[1] the performance of cooperative schemes is inferior to that of direct transmission in the low SNR regime as well as for high spectral efficiencies. The main drawback in this context are losses due to the repetition coding nature of the proposed protocols.

In this paper, we propose a novel protocol that is designed for *asymmetric* network constellations. By exploiting the nonlinear properties of path loss, we are able to provide the relay with superior receive conditions while *at the same time* minimizing the energy needed for retransmission, i.e. the "cost" of repetition. Our results indicate that the usage region is large, for a wide range of parameters of interest. We stress the importance of this fact insofar as the presence of a sufficient number of mobile stations within the usage region is essential for the formation of cooperating user groups.

The outline of the paper is as follows: Section 2. reviews the system and channel model used for performance evaluation and gives a short overview of cooperative diversity protocols. After introducing the novel protocol in Section 3., Sections 4. and 5. analyze its performance in terms of outage probabilities and frame error rates, respectively. SNR gains over direct transmission and the size of the usage region are also investigated. Finally, we draw conclusions in section 6..

2. System and Channel Model

2.1. Introduction to Cooperative Diversity

We consider scenarios as depicted in Figure 1, which include a single relay and where all nodes feature only a single antenna. As for conventional relaying, cooperative diversity schemes suffer from the "orthogonality constraint" – the inability of current RF implementations to simultaneously receive and transmit at the same frequency. Hence, we have to divide the available channel into two orthogonal subchannels in the time and/or frequency domain. Without loss of generality, we focus on the time division case.

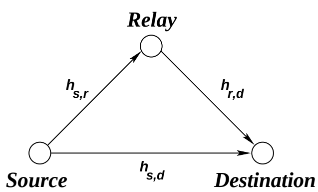

Figure 1: Illustration of a cooperative diversity scenario. The source sends a broadcast message to destination and relay. The relay then forwards an additional copy of the source message to the destination, which appropriately combines the two messages.

Cooperative diversity protocols can be classified as either amplify-and-forward or decode-and-forward. In the first case, the relay acts as an analog repeater (resulting in noise enhancement) while in the second case it fully decodes, re-encodes and retransmits the received message (and possibly propagates decoding errors). Decode-and-forward protocols are clearly favorable for implementation simplicity since amplify-and-forward style protocols require either the storage of large amounts of analog data (time division) or complicated and expensive transceiver structures (frequency division). The reader is referred to [7] for a detailed discussion of advantages and disadvantages.

[1]Throughout this paper, we will refer to a network where the links between source, relay(s) and destination experience equal *average* path loss as a "symmetric network". The term "asymmetric network" is used for all other possible network constellations.

The protocols may be further categorized into fixed protocols, where the relay always forwards (a processed version of) its received message, and adaptive protocol versions, where the relay uses a threshold rule to forward only information it deems useful for the destination. If the relay decides not to forward, the source simply uses repetition coding during the second time slot. Obviously, the source must have knowledge of the relay's decoding decision, which can for example be obtained via a dedicated feedback channel. In [8] it was shown that preventing error propagation at the relay is crucial for achieving high performance and that under practical assumptions regarding the knowledge of channel state information, adaptive decode-and-forward protocol versions offer the best trade-off between implementation simplicity and excellent performance.

2.2. Channel Model

We model all channels as Rayleigh flat fading with additive white Gaussian noise. Fading remains constant during the time required to transmit one block of data from the source to the destination (quasi-static or block fading). More specifically, $h_{i,j}$ (cf. Figure 1) are zero-mean, circularly symmetric complex Gaussian random variables, such that $|h_{i,j}|^2$ are exponentially distributed with mean $\sigma_{i,j}^2$. Phases $\angle h_{i,j}$ are uniformly distributed over $[0, 2\pi)$. Noises (after sampling at the receiver) are modeled as zero-mean mutually independent, circularly-symmetric, complex Gaussian random sequences with variance N_0.

For the path loss, we assume a log-distance model, i.e. the received power decreases linearly with distance, on a logarithmic scale. An interesting approach taken in [4] suggests to model the effects of path loss into the variance of the fading variables by observing that the SNR at a specific node j obtained by transmission from node i can be written as:

$$\begin{aligned}\mathrm{SNR}_{i,j} &= \left[\mathrm{SNR}\left(\frac{d_0}{d_{i,j}}\right)^{\alpha}\right]|h_0|^2 \\ &= \mathrm{SNR}\left[\left(\frac{d_0}{d_{i,j}}\right)^{\alpha}|h_0|^2\right] \\ &= \mathrm{SNR}|h_{i,j}|^2 \end{aligned} \qquad (2)$$

where $|h_0|$ is a fading coefficient with unit variance $\sigma_0^2 = 1$, $d_{i,j}$ is the distance between transmitter and receiver, α is the path loss exponent, and SNR is the signal-to-noise ratio attained by the transmitter at a receiver at reference distance d_0. Without loss of generality, we define $d_0 = d_{s,d}$ and therefore $\sigma_{s,d}^2 = 1$. Throughout this paper, we can now model the effects of path loss in the following way:

$$\sigma_{i,j}^2 = \left(\frac{d_{s,d}}{d_{i,j}}\right)^{\alpha} \equiv \frac{1}{r_{i,j}^{\alpha}}. \qquad (3)$$

where we have introduced the variable $r_{i,j} \equiv d_{i,j}/d_{s,d}$ as the relative (i.e., normalized) distance between two nodes. This approach allows for a convenient study of the effects of geometry on the performance of the proposed protocol.

2.3. Normalization Issues

In order to ensure fair performance comparison with direct transmission, we need to normalize all used resources, i.e. energy, time, and bandwidth. Hence, to maintain the time and bandwidth usage of direct transmission, source and relay need to transmit at double spectral efficiency in our cooperative transmission schemes.

To ensure that the *overall* transmitted energy per *information bit* is the same for all protocols, source and relay have to adjust their transmit powers appropriately. We shall elaborate more on that topic in Sections 4. and 5..

3. The Novel ”Detached” Protocol

Our aim is to design a protocol that is able to fully exploit the benefits of the non-linearity of path loss in asymmetric network constellations. Due to the broadcast nature of the wireless medium, the relay will automatically experience better receive conditions than the destination, whenever its average path loss[2] to the source is lower than that of the destination.

But cooperative transmission schemes can exploit the non-linearity in another way: whenever the relay is closer to the destination than the source, i.e., $r_{r,d} < 1$, it needs lower transmit power than the source to attain the same SNR at the destination. By adjusting the transmit power of the relay such as to attain the same SNR at the destination as the source, we can minimize the energy needed to provide the destination with a second copy of the source message. The relay obviously needs some kind of power control to be able to perform the appropriate power adjustment. However, since only long term statistics (the average path loss) need to be available, this is only a low increase in complexity.

As another modification of the original adaptive protocol [4], we refrain from letting the source repeat its message whenever the relay decides not to forward it, since repetition coding over a quasi-static channel does not yield significant benefits but increases the overall energy needed for transmission. It notifies source and destination of this event via a broadcast message, which can use a very low rate and therefore can be assumed to be reliably decoded by both.

The operation of the novel protocol, in which the relay is “detached” from the source's help is summarized as follows: First, the source transmits its message in a broadcast manner to destination and relay. If the relay was able to correctly decode this message (which can be determined by using CRC or LDPC codes that offer the inherent ability to detect decoding errors), it fully re-encodes and retransmits it, while scaling its transmit power such that it achieves the same average SNR at the destination as the source. Otherwise the source will simply continue transmission with the next message block and the destination has to rely on only a single copy of the source message. The relay's position should be

[2] Due to our log-distance path loss model, the expressions average path loss and distance are dual of each other. We will hence use them exchangeably.

chosen such that this event occurs only with low probability since in that case, the overall error rate is clearly governed by the performance of the direct link between source and destination. After having received the potentially two copies of the source message, the destination combines them constructively via maximal ratio combining to exploit the provided spatial diversity.

4. Information Theoretic Performance

4.1. Outage Probability

A commonly used information theoretic performance measure is the outage probability versus SNR. We define an outage as the event that the maximum average mutual information I between source and destination is inferior to the spectral efficiency $2R$ desired for transmission. Note the factor 2 that is due to the cooperative transmission's need to attain double spectral efficiency in order to meet normalization requirements. The outage probability is simply the probability that an outage event occurs: $p^{out} \equiv Pr[I < 2R]$.

In order to perform correct energy normalization, we need to determine the *average* energy used by the detached protocol for transmission of a single source message:

$$E_{det} = Pr_{dec}\left(P_{src}\frac{T}{2}+P_{rly}\frac{T}{2}\right)+(1-Pr_{dec})P_{src}\frac{T}{2}, \tag{4}$$

where P_{src} and P_{rly} are the transmission powers of source and relay, respectively. The first term in (4) arises from the case that the relay decodes (with probability Pr_{dec}) while the second term is equivalent to the event that the source simply continues transmission. Since it must be the aim of our protocol to minimize the occurrence of the latter event, and as it is confirmed by simulation, we can assume that $Pr_{dec} \approx 1$ and hence

$$E_{det} \approx \frac{T}{2}\left(P_{src}+P_{rly}\right) = \frac{T}{2}P_{src}\left(1+\left(\frac{d_{r,d}}{d_{s,d}}\right)^{\alpha}\right), \tag{5}$$

where the transmission power of the relay is scaled such that it attains the same SNR at the destination receiver as the source. The energy used for direct transmission is obviously $E_d = P_{src}T$ and for fair performance comparison, we need to scale the original SNR for direct transmission by E_d/E_{det} to obtain the equivalent $SNR^{'}$ used for cooperative transmission:

$$\frac{E_{det}}{E_d} = \frac{\frac{T}{2}P_{src}(1+r_{r,d}^{\alpha})}{P_{src}T} = \frac{1}{2}(1+r_{r,d}^{\alpha}) \tag{6}$$

$$\text{SNR}^{'} = \frac{\text{SNR}}{\frac{1}{2}(1+r_{r,d}^{\alpha})} = \frac{2\ \text{SNR}}{1+r_{r,d}^{\alpha}}. \tag{7}$$

The maximum average mutual information of the detached adaptive decode-and-forward protocol can now be written as:

$$I = \begin{cases} \log\left(1+\text{SNR}^{'}(|h_{s,d}|^2+|h'_{r,d}|^2)\right) & |h_{s,r}|^2 \geq t \\ \log(1+\text{SNR}^{'}|h_{s,d}|^2) & |h_{s,r}|^2 < t \end{cases} \tag{8}$$

where $|h'_{r,d}| = \sqrt{r_{r,d}^{\alpha}}|h_{r,d}|$. $t(\text{SNR}^{'}) = \frac{2^{2R}-1}{\text{SNR}^{'}}$ is a threshold defined such that reliable communication in the Shannon sense is possible between source and relay at spectral efficiency $2R$. The outage probability in the high SNR regime readily follows (please refer to Appendix A1. for further detail):

$$p_{DADF}^{out} = \frac{2\sigma_{s,d}^2+\sigma_{s,r}^2}{2\sigma_{s,d}^4\sigma_{s,r}^2}\left(\frac{2^{2R}-1}{\text{SNR}^{'}}\right)^2, \quad \text{SNR}^{'} \gg 1 \tag{9}$$

which, using $\sigma_{s,d}^2 = 1$ and $\sigma_{s,r}^2 = r_{s,r}^{-\alpha}$, leads to

$$\begin{aligned} p_{DADF}^{out} &= \frac{1}{2}\left(1+2r_{s,r}^{\alpha}\right)\left(\frac{2^{2R}-1}{\text{SNR}^{'}}\right)^2 \\ &= \underbrace{\frac{2r_{s,r}^{\alpha}+1}{2}\left(\frac{r_{r,d}^{\alpha}+1}{2}\right)^2}_{g}\left(\frac{2^{2R}-1}{\text{SNR}}\right)^2 \\ &\equiv g\cdot\left(\frac{2^{2R}-1}{\text{SNR}}\right)^2 \end{aligned} \tag{10}$$

where g is a geometry factor. Clearly, an optimum for g can be found independently of R and SNR. Unfortunately, deriving a closed form expression for the optimal position of the relay becomes too involved. However, the relay should obviously be located on the line between source and destination. By numerical evaluation, it can be found that $r_{s,r} = 1 - r_{r,d} = 0.5$ is a good approximation for a wide range of path loss exponents ($3 \leq \alpha \leq 6$, Figure 3 confirms this notion). This result corresponds to what intuition suggests and what is already widely known for relaying systems: for optimal performance, the relay should be located halfway between source and destination.

4.2. SNR Gain

What is even more important than the absolute performance of the novel protocol is its performance with respect to direct transmission. In order to obtain a meaningful measure for this expression, we will define the *SNR gain over direct transmission* as the quotient of the SNRs required by non-cooperative and cooperative transmission to attain the same outage probability.

The outage probability for direct transmission can be formulated as [4]

$$p_D^{out} = \frac{2^R-1}{\text{SNR}_D}, \qquad \text{SNR}_D \gg 1. \tag{11}$$

Solving for SNR_D yields

$$\text{SNR}_D = \frac{2^R-1}{p_D^{out}}, \qquad \text{SNR}_D \gg 1. \tag{12}$$

and applying the same to the outage probability of the detached protocol results in

$$\text{SNR}_{DADF} = \sqrt{\frac{g}{p_{DADF}^{out}}}(2^{2R}-1). \tag{13}$$

The diversity gain that comes in the form of the SNR gain readily follows:

$$\text{DG} \equiv \frac{\text{SNR}_D}{\text{SNR}_{DADF}} = \frac{2^R-1}{p^{out}}\sqrt{\frac{p^{out}}{g}}\frac{1}{2^{2R}-1}$$

$$= \sqrt{\frac{1}{p^{out} \cdot g} \frac{2^R - 1}{2^{2R} - 1}} \quad (14)$$

To obtain a more meaningful result, (14) can be expressed in a logarithmic manner:

$$\text{DG [dB]} \approx 5\Big(-\log_{10} p^{out}\Big) + \Big(4.5 - 2^{3-\alpha}\Big) - \Big(3R + 2^{2-R}\Big) \quad (15)$$

using appropriate approximations as well as the definition of g and $r_{s,r} \approx 0.5$. The maximum gain due to geometry is obviously 4.5 dB while we loose 3 dB whenever we increase the spectral efficiency by 1 bit/s/Hz, for high values of R. On the other hand, the SNR gain increases linearly with the required magnitude of the outage probability ($-\log_{10} p^{out}$). This is intuitively clear since direct transmission achieves only diversity order 1 while cooperative transmission achieves diversity order 2 (cf. Figure 2). Using equation (15), we can easily calculate the *maximum* SNR gain of cooperative over direct transmission. If we wish to achieve an outage probability of 10^{-2} at spectral efficiency 2 bit/s/Hz (equivalent to uncoded QPSK transmission) in an suburban environment with $\alpha = 3$, the maximum SNR gain, achieved when the relay is located roughly halfway between source and destination, will be approximately 6.5 dB. Figures 2 and 3 confirm this result.

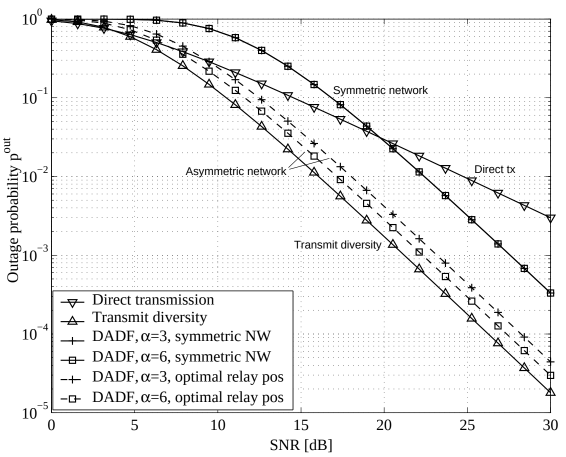

Figure 2: Performance of the detached adaptive decode-and-forward protocol in terms of outage probability versus SNR for spectral efficiency R=2 bit/s/Hz. Full second order diversity is achieved in all network constellations. The most substantial gains over direct transmission can be obtained by placing the relay halfway between source and destination (i.e., $r_{s,r} = r_{r,d} = 0.5$).

For practical purposes however, not only the maximum gain but also the size of the usage region, i.e., the size of the area for which DG ≥ 0 holds, is important. We present results regarding this subject subsequently.

4.3. Results

Figure 2 shows the outage probability of the proposed detached protocol for a spectral efficiency of $R = 2$ bit/s/Hz for different network geometries and path loss exponents. We chose $\alpha = 3$ to represent propagation conditions in rural and $\alpha = 6$ for rich scattering metropolitan and indoor environments. Direct transmission as well as a MIMO system with two transmit and one receive antenna using the well known Alamouti space time code [1] for transmission (transmit diversity system) are depicted for performance comparison. Both operate at R=1 bit/s/Hz since they are not subject to the orthogonality constraint.

We observe that in a symmetrical network, cooperative transmission suffers from a SNR loss of roughly 6 dB with respect to a transmit diversity system, compared to a prediction of 5.5 dB from [4] and matching the results for the traditional adaptive decode-and-forward protocol in practical systems obtained in [8]. By placing the relay halfway between source and destination, the novel protocol is able to fully exploit the nonlinear properties of path loss. The "cost of repetition" is greatly reduced and the SNR loss with respect to transmit diversity reduces to approximately 1.7 dB for $\alpha = 3$ and 1 dB for $\alpha = 6$. Gains from diversity increase as α grows, but saturate fast as can be seen from equation (15).

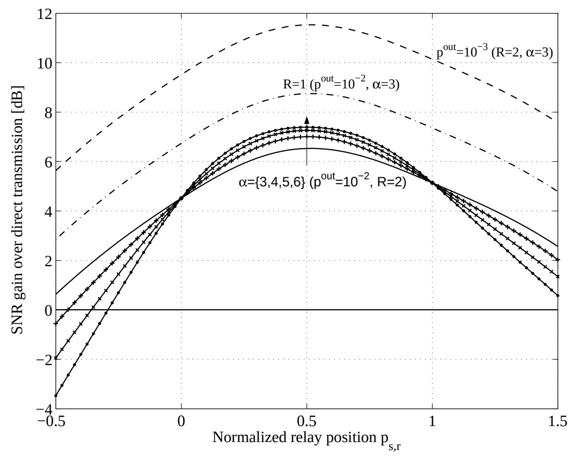

Figure 3: SNR gain of the detached adaptive decode-and-forward protocol over direct transmission. $r_{s,r}$ denotes the position of the relay between source and destination, normalized to the source-destination distance. The maximum SNR gain is obtained for $r_{s,r} \approx 0.5$, independent from α. Spectral efficiency and required outage probability have no influence on the spatial distribution of the SNR gain, which is only influenced by α.

The influence of the design parameters data rate, required outage probability and path loss exponent is depicted in Figure 3 for different network geometries, when the relay is located on the line between source and destination, i.e., $r_{s,r} = 1 - r_{r,d}$. The plotted curves confirm our analytical results: the shape of the curves is only dependent upon the relay's distance from the source and the path loss exponent. Changing spectral efficiency and/or required outage probability only results in a linear shift of the curves along the ordinate. The maximum SNR gain can be obtained if the relay is located halfway between source and destination and corresponds to the values that can be obtained from equation (15). It can also be observed that the optimal placement of the relay is slightly towards the destination and *independent of the path loss exponent*.

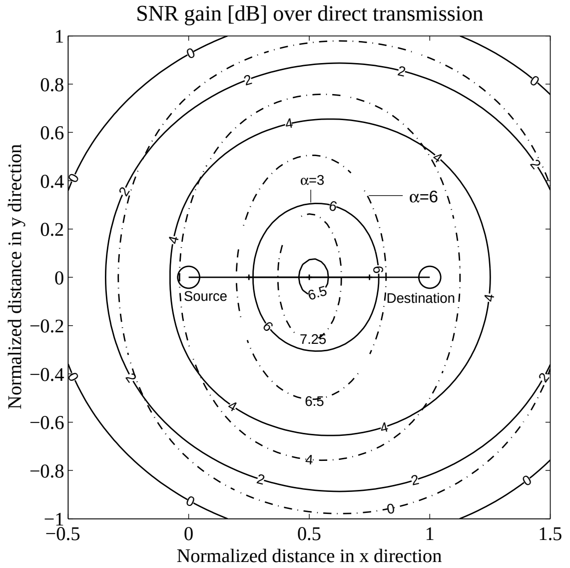

Figure 4: Usage region of the detached cooperative diversity protocol for R=2 bit/s/Hz, outage probability $p^{out} = 10^{-2}$ and $\alpha = 3$ (solid lines, rural environment) as well as $\alpha = 6$ (dash-dotted lines, indoor environment). The radius of the usage region lies in the order of the source-destination distance.

Figure 4 shows the usage region of the protocol for a spectral efficiency of 2 bit/s/Hz and an outage probability $p^{out} = 10^{-2}$. It can be observed that the central point of the usage region is located at $r_{s,r} \approx 0.5$ and that its diameter fulfills $d \approx 2.25$ for $\alpha = 3$ and $d \approx 1.75$ for $\alpha = 6$. While the maximum SNR gain increases slightly with rising α, the size of the usage region is diminished at the same time. Given the diameter of the usage region, finding a "partner" mobile handset to establish a cooperative transmission group should be an easy task for mobiles that are far away from the base station/access point while it is quite complicated for users in its vicinity.

5. Performance under Realistic Assumptions

In the following, we are interested in obtaining results for practical wireless systems, i.e. under realistic assumptions regarding modulation alphabets and receiver structures. Since our protocol works on a block transmission basis, the frame error rate can be used to obtain meaningful results. We focus on the case of uncoded transmission. However, we know from information theory that as we employ ever more powerful coding techniques, the frame error rate will finally approach the limits set by the outage probability, under our block fading conditions.

5.1. Analysis

We limit ourselves to the cases R={1,2} bit/s/Hz. Hence, BPSK and QPSK are used for the direct link while under the cooperative transmission scheme, we need to use QPSK and 16-QAM, respectively, in order to achieve the double spectral efficiency and maintain our strict normalization requirements. In the following, M denotes the constellation size, N is the block length of the source message in bits, and $\overline{\gamma}_b$ denotes the average SNR per information bit.

The overall frame error rate can be written down as:

$$P_{F,all} = (1 - P_{F,s,r})P_{F,div} + P_{F,s,r}P_{F,s,d} \qquad (16)$$

where $P_{F,s,d}$, $P_{F,s,r}$ and $P_{F,div}$ are the frame error rates in transmission from source to destination and relay and diversity transmission from source and relay to the destination, respectively. Since for uncoded transmission, the frame error probability is simply the probability that none of the bits in the block is erroneous, they can be written down as:

$$\begin{aligned} P_{F,s,d} &= 1 - (1 - P_b(M, \overline{\gamma}_b/s))^N & (17)\\ P_{F,s,r} &= 1 - (1 - P_b(M, \overline{\gamma}_b/(r_{s,r}^{\alpha} s)))^N & (18)\\ P_{F,div} &= 1 - (1 - P_{b,div}(M, \overline{\gamma}_b/s))^N & (19) \end{aligned}$$

The different bit error probabilities $P_b(M, \overline{\gamma}_b)$ for PSK and QAM can be found in Appendices A2. and A3.. s is a power scaling factor in order to ensure that cooperative and direct transmission use the same energy per *information* bit:

$$\begin{aligned} s &= \frac{1}{\overline{\gamma}_b}\Big(Pr_{dec}(\overline{\gamma}_b + \overline{\gamma}_b r_{r,d}^{\alpha}) + (1 - Pr_{dec})\overline{\gamma}_b\Big)\\ &= Pr_{dec}(1 + r_{r,d}^{\alpha}) + (1 - Pr_{dec})\\ &\approx 1 + r_{r,d}^{\alpha} \qquad (20) \end{aligned}$$

where $Pr_{dec} \approx 1$ is the probability that the relay is able to decode the source message, which approaches one in our regime of interest (SNR $\gg 1$).

Analytical evaluation of the overall frame error rate in order to find a closed form expression for the SNR gain from cooperative transmission becomes involved. However, we can use our results to calculate the FER versus SNR performance of our protocol and by comparison with the FER for direct transmission obtain the desired SNR gains.

5.2. Results

Wee see from Figures 5 and 6 that the SNR gain of the detached protocol under realistic assumptions is higher than in information theoretic analysis. The explanation for this behavior is that in uncoded transmission, the error rate between source and destination is not zero even if the channel capacity is sufficient to support the required data rate. Hence, direct transmission needs comparatively high SNRs in order to achieve the desired low error probability and the cooperative scheme largely profits from the diversity provided by the relay.

The strong influence of the network geometry is clearly visible from Figure 5 – in contrast to information theory, the optimal placement of the relay now depends on the path loss exponent α. For $\alpha = 3$ it is $r_{s,r} \approx 0.2$ while it approaches $r_{s,r} \approx 0.5$ as α rises. This illustrates the stated fact that providing the relay with superior receive conditions and maximizing the contribution of correct information over the relay path is essential for the performance of cooperative protocols in practical wireless networks. The SNR gain increases by 5 dB every time we decrease the required frame error rate by one order of magnitude – equal to information theory and again

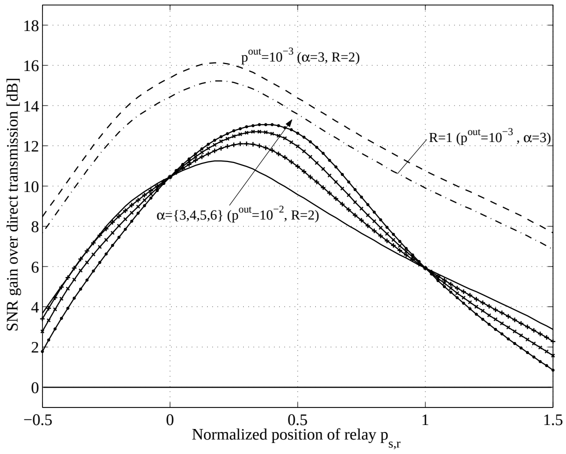

Figure 5: SNR gain of the detached adaptive decode-and-forward protocol over direct transmission for $N = 100$. The maximum SNR gain as well as the optimal relay position depend significantly on α. For low values of α, the relay should be close to the source while for high α it should be placed halfway between source and destination. Spectral efficiency and required FER have no influence on the spatial distribution of the SNR gain.

due to the first order diversity for direct and second order diversity for cooperative transmission. The influence of rate is stronger for practical wireless systems (4 dB loss in comparison to 2 dB loss from $R = 1$ to $R = 2$). Investigating this effect for higher R is beyond the scope of this paper but clearly constitutes a path for further research.

Gains from cooperative transmission tend to increase for larger block lengths (results not shown). Spectral efficiency and frame error rate have again no influence on the spatial distribution of the SNR gains, i.e., only result in a linear increase or decrease.

Figure 6 depicts the usage region of the novel detached protocol. Observe that, although *maximum* SNR gains are higher, its size is comparable to that calculated in information theoretic analysis. This is equivalent to the fact that the enhanced receive conditions of the relay play a major role in the performance. In symmetrical networks the relay faces the same receive conditions as the destination, which clearly sets harsh limits for the usage region.

6. Conclusions

We have introduced a novel cooperative diversity protocol, the detached adaptive decode-and-forward protocol and evaluated its performance from an information theoretic as well as practical viewpoint. Performance gains of several dB can be obtained within a large usage region as well as under a wide range of parameters (path loss exponent, required error rate, spectral efficiency).

Note that gains will be even more pronounced if we give up our harsh normalization requirements, i.e., allow the relay to introduce additional power and/or further delay. This is usually the case when conventional relaying (layer 3 relaying) is considered. Since conventional relaying *at its best* achieves first order diversity, it is obvious that cooperative transmission will have superior performance. Consequently, whenever the use relaying technologies is envisioned in future wireless networks, exploiting the benefits of diversity is a viable option, since it comes at relatively low additional complexity but offers significant performance enhancements.

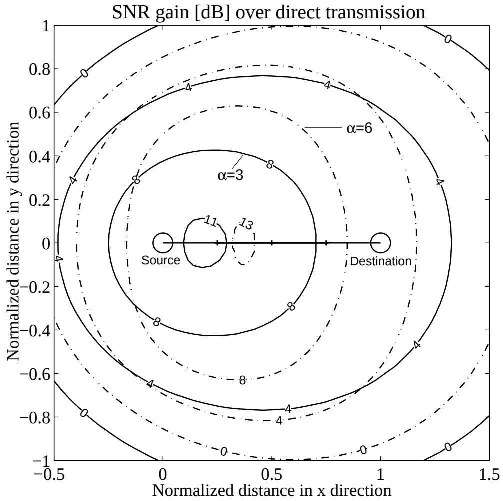

Figure 6: Usage region of the detached cooperative diversity protocol for R=2 bit/s/Hz, frame error rate $p^{out} = 10^{-2}$, $N = 100$ and $\alpha = 3$ (solid lines) as well as $\alpha = 6$ (dash-dotted lines). It is clearly more favorable to place the relay close to the source, for low values of α.

The drawback of the novel detached protocol is its implementation complexity: we need a feedback channel from relay to source and destination and we do not retain a fixed transmission rate. We are currently investigating the performance of related protocols with considerably lower implementation complexity [3]. The application of channel coding to our transmission schemes is a further path for investigation, although we may already state that, eventually, by usage of capacity-approaching codes, the performance will approach the limits set by information theory.

7. Acknowledgments

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A Appendix

A1. Outage Probability

We are interested in finding an expression for the outage probability of the detached protocol, in the large SNR regime. Remembering (8), consider the term $r_{r,d}^{\alpha}|h_{r,d}|^2$, which is the concatenation of the fading coefficient between relay and destination and the power scaling by the relay. As we have already outlined, this structure allows for modeling the power scaling (as well as the path loss) into the fading coefficient:

$$r_{r,d}^{\alpha}|h_{r,d}|^2 = \left(\frac{d_{r,d}}{d_{s,d}}\right)^{\alpha}|h_{r,d}|^2 = \frac{|h_{r,d}|^2}{\sigma_{r,d}^2} = |h_{r,d}^{'}|^2$$

where $|h_{r,d}^{'}|^2$ is the *effective* fading coefficient between relay and destination, *including* the power adjustment of the relay and hence having a variance ${\sigma'}_{r,d}^2 = \sigma_{r,d}^2/\sigma_{r,d}^2 = 1 = \sigma_{s,d}^2$. Note that power scaling and path loss are concatenated in such a way that the resulting effective fading coefficient is statistically independently, but identically distributed to the source-destination channel. This result very nicely illustrates the fact that the relay's power scaling ensures that it attains the same *average* SNR at the destination as the source. Now the outage probability can be derived easily:

$$\begin{aligned} p_{DADF}^{out} &= \Pr(|h_{s,r}|^2 \geq t)\,\Pr(|h_{s,d}|^2 + |h_{s2,d}|^2 < t) \\ &\quad + \Pr(|h_{s,r}|^2 < t)\,\Pr(|h_{s,d}|^2 < t) \end{aligned}$$

Using the approach from [4], we evaluate p_{DADF}^{out}:

$$\begin{aligned} \frac{p_{DADF}^{out}}{t^2(\text{SNR}^{'})} &= \Pr(|h_{s,r}|^2 \geq t) \\ &\quad \times \frac{\Pr(|h_{s,d}|^2 + |h_{s2,d}|^2 < t)}{t^2(\text{SNR}^{'})} \\ &\quad + \frac{\Pr(|h_{s,r}|^2 < t)}{t(\text{SNR}^{'})}\,\frac{\Pr(|h_{s,d}|^2 < t)}{t(\text{SNR}^{'})}. \end{aligned}$$

$$\begin{aligned} \lim_{\text{SNR}^{'}\to\infty} \frac{p_{DADF}^{out}}{t^2(\text{SNR}^{'})} &= 1\frac{1}{2\sigma_{s,d}^2\sigma_{s,d}^2} + \frac{1}{\sigma_{s,r}^2}\frac{1}{\sigma_{s,d}^2} \\ \lim_{\text{SNR}^{'}\to\infty} p_{DADF}^{out} &= \frac{2\sigma_{s,d}^2 + \sigma_{s,r}^2}{2\sigma_{s,d}^4\sigma_{s,r}^2}\left(\frac{2^{2R}-1}{\text{SNR}^{'}}\right)^2 \end{aligned}$$

Full second order diversity is achieved ($p^{out} \propto \text{SNR}^{-2}$).

A2. BER for SISO Links

The BER (over SNR per bit) performances of BPSK and QPSK are well known to be equal and can be found in [5]. Using [5, eq. 5.2-80] for the *symbol* error probability of QAM in AWGN channels and knowing that $P_b \approx P_s/\log_2 M$ is a good approximation for the bit error probability when using Gray mapping, we can write:

$$P_{b,AWGN} \leq \frac{4}{\log_2 M} Q\left(\sqrt{\frac{3\log_2 M\ \gamma_b}{M-1}}\right). \tag{21}$$

By averaging over the fading statistics for a Rayleigh channel, we obtain:

$$P_b = \frac{a}{2}\left(1 - \sqrt{\frac{\frac{b}{2}\overline{\gamma}_b}{1+\frac{b}{2}\overline{\gamma}_b}}\right) \tag{22}$$

where $a = 4/\log_2 M$ and $b = 3\log_2 M/(M-1)$. For 16-QAM, $a = 1$ and $b = 4/5$ from which P_b is easily obtained.

A3. BER for Diversity Links

For the sake of compactness, we only outline the solution, a more detailed derivation has been developed in [3]. We again average (21) over the fading statistics, now using the pdf of two i.i.d. Rayleigh channel fading coefficients, which after partial integration and simplifications yields:

$$P_b = \frac{a}{2}\left(1 - \sqrt{\frac{\frac{b}{2}\overline{\gamma}_b}{1+\frac{b}{2}\overline{\gamma}_b}}\ \frac{3+b\overline{\gamma}_b}{2+b\overline{\gamma}_b}\right). \tag{23}$$

By choosing $a = 1$ and $b = 2$ for QPSK and $b = 4/5$ for 16-QAM the bit error probabilities are easily obtained.

Another way is to use [5, eq. C-21], which after simplification yields the same results (for the case of QPSK).

A4. Discussion of used approximations

While $P_b \approx P_s/\log_2 M$ is only a lower bound for the exact BER and not very tight in the low SNR regime, (21) is an *upper* bound on the SER, and equally loose in the low SNR regime. Simulations show that (22) and (23) are in fact upper limits on the BER of QAM in Rayleigh fading (1 and 2 path diversity) and generally overestimate the BER by roughly $1/3$ (simulation results not shown). If on the other hand we use the exact solution for the SER of QAM in Rayleigh fading [6], the approximation $P_b \approx P_s/\log_2 M$ would in fact underestimate the real BER, just like reviewer 2 suggested.

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