Impact of Relay Gain Allocation on the Performance of Cooperative Diversity Networks

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***Abstract*— We consider a wireless network with one source/destination pair and several linear amplify-and-forward relays. The influence of the gain allocation at the relays on the performance in cooperative relay communication links is analyzed. We present an optimal gain allocation which results in a coherent combining of all signal contributions at the destination and maximizes the instantaneous throughput of the link.**

If the channel state information (CSI) at the relays is limited cooperative diversity schemes can be used. We show that the right choice of the amplification gains is crucial to achieve high outage throughput.

I. Introduction

The use of diversity in the spatial and temporal dimension to mitigate the effects of fading and therefore to increase the reliability of radio links in wireless networks is a well known technique for systems with co-located antennas (space-time coding). Recently a new form of realizing spatial diversity has been introduced in [1] and [2] called *cooperative diversity* or *user cooperation diversity*. The main idea is to use multiple single antenna nodes as a virtual macro antenna array, realizing spatial diversity in a distributed fashion. In such a network several, maybe idle, nodes serve as relays for an active source/destination pair. Relays can be classified as either *decode-and-forward* (DF) or *amplify-and-forward* (AF) relays. AF relays, which are considered in this work, only retransmit an amplified version of their received signals. This leads to low-complexity relay transceivers and to lower power consumption since there is no signal processing for decoding procedures.

Future generation WLANs will accommodate heterogeneous nodes with data rate requirements ranging from 1Mbps to 1Gbps. For complexity reasons low end user nodes may have only one antenna. High end user nodes will feature multiple antennas to improve throughput and coverage. The extended use and range of deployment will lead to a high node density. This makes cooperative signalling schemes as presented in [1], [2] an attractive option for such systems.

Previous work on cooperative relaying can also be found for example in [3] where a general information theoretic framework about relaying channels is established. In [4] a cooperation scheme for two users communicating with a base station by using existing channel coding methods is proposed. In [5] the outage and the ergodic capacity behavior of different relaying protocols is analyzed. In [6] it is shown how the capacity of ill-conditioned MIMO channels can be improved by cooperative relay nodes that act as active scatterers. A distributed implementation of the Alamouti space-time coding scheme is presented in [7]. In the distributed case this scheme is not able to make the effective channel orthogonal, but still achieves diversity. Unfortunately, full rate orthogonal space-time block codes for more than two antennas which can be assigned to cooperative relay networks (more than two relays) are not available.

In [8] we presented a simple cooperative diversity scheme for $L \geq 2$ AF relays. Essentially the block fading time-invariant channel is translated into a time-variant channel by introducing *time-variant and relay-specific linear signal processing* (e.g. by the introduction of phase offsets) at the relays. This transformation of spatial diversity into temporal diversity can be utilized by an outer code and is available for an arbitrary number of relay nodes by an outer code as presented in [9] or [10]. This cooperative diversity scheme is easy to implement and therefore leads only to a small extension in signal processing power at the relays.

In the present work we focus on the allocation of amplification gains at the relays. In [8] we already mentioned the near-far effect which results from the relative position of the relays to source and destination. As an example if a relay is far away from the source or in a deep fade the received SNR is low. If this relay is near to the destination, the amplified noise will dominate the resulting SNR at the destination. Therefore a gain allocation which depends on the SNR at the relay is necessary.

We present an optimal gain allocation resulting in a coherent combining of the signal contributions at the destination. For this gain allocation we consider the signaling overhead which is required to maintain the CSI at the relays as prohibitive. Thus, we present further suboptimal gain allocations which require only partial CSI at the relays.

The remainder of the paper is organized as follows. In the next section the system model is introduced. The optimal gain allocation is derived in section III. In section IV our cooperative diversity approach is presented and the effects of a suboptimal gain allocation on the performance is analyzed. Performance results are presented in section V. Conclusions are given in the last section.

Notation: We shall use bold uppercase letters to denote matrices and bold lowercase letters to denote vectors. Further $(\cdot)^T$, $(\cdot)^\dagger$ stand for transpose and Hermitian transpose of a matrix, respectively. $\mathrm{diag}[a, \ldots, z]$ denotes a diagonal matrix with the elements $a, \ldots, z$ on its main diagonal, $\mathbf{I}$ is an identity

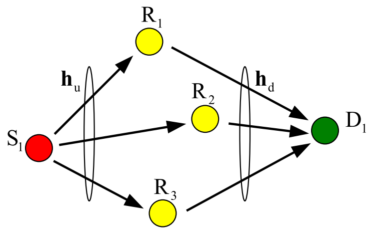

Fig. 1. Two-hop cooperative relaying network with single antenna nodes

matrix. $\mathrm{E}[\cdot]$ is the expectation operator.

II. System Model

In the following we derive a system model for cooperative relaying, assuming that communication takes place over two-hop links. Such a system is depicted in Fig. 1. In our scenario user mobility is low and the channel coefficients are constant over the latency time scale of interest. We assume that the channel is time-invariant over at least one burst of N_B symbols (block fading).

We assume L amplify-and-forward relays assisting the communication link. In such a link the transmission of one data packet from the source S to the destination D occupies two time slots. In the first slot the source transmits the data packet to the destination and to the relays. During the second slot the relays retransmit an amplified version of the received signals to the destination.

We denote the channel between the source and the relays as *uplink*, and the channel between the relays and the destination as *downlink*. The channel coefficients of the uplink are stacked in the vector $\mathbf{h}_\mathrm{u}$. The complex conjugates of the downlink channel coefficients are stacked in $\mathbf{h}_\mathrm{d}$. h_0 denotes the channel coefficient between source and destination. We consider frequency-flat fading. For our analysis we assume the channel coefficients as i.i.d. complex normal random variables $h_i \sim \mathcal{CN}(0, \gamma_i)$. The variance γ_i comprises path loss and shadowing effects.

At time instance k in the first time slot the source S sends the symbol $s^{(k)}$ with average transmit power P. The received signal at the destination D and at all relays R_l is given by

$$r^{(k)} = h_0 s^{(k)} + w^{(k)} \tag{1}$$

$$\mathbf{y}^{(k)} = \mathbf{h}_\mathrm{u} s^{(k)} + \mathbf{m}^{(k)}, \tag{2}$$

where $w^{(k)} \sim \mathcal{CN}(0, \sigma^2)$ and $\mathbf{m}^{(k)} \sim \mathcal{CN}(\mathbf{0}, \sigma_\mathrm{R}^2 \mathbf{I})$ denote the AWGN contributions at the destination and the relays, respectively.

Fig. 2 shows the system model of an AF relay. $\phi_{\mathrm{LO},l}$ represents the phase offset of the local oscillator (LO) at the relay R_l relative to a given reference phase. This phase offset is required in the system model, because LOs of all relays may be free running. In this case $\{\phi_{\mathrm{LO},l}\}$ are i.i.d. random variables. Only if there is a *global phase reference*, i.e., all LOs are phase synchronized, $\phi_{\mathrm{LO},l}$ is equal to zero for all l.

The factor g_l is the amplification gain at relay R_l. The lth Relay transmits with power P_{R_l}. With the gain matrix $\mathbf{G} = \mathrm{diag}\,[g_1, \ldots, g_L]$ and the phase reference matrix $\mathbf{\Phi} =$

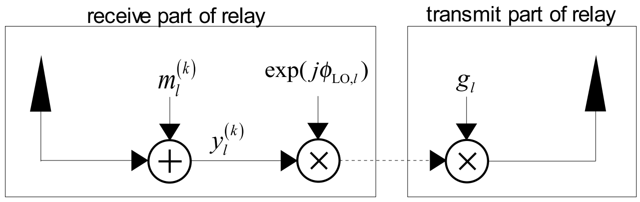

Fig. 2. System model of amplify-and-forward relay

$\mathrm{diag}\left[\exp(j\phi_{\mathrm{LO},1}), \ldots, \exp(j\phi_{\mathrm{LO},L})\right]$ the received signal at the destination in the second time slot is given by

$$r^{(k+1)} = \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{y}^{(k)} + w^{(k+1)} \tag{3}$$

$$= \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{h}_\mathrm{u} s^{(k)} + \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{m}^{(k)} + w^{(k+1)}. \tag{4}$$

The instantaneous throughput (per complex dimension) for a link described in (1) and (4) is given by

$$C_\mathrm{I} = \frac{1}{2}\log_2\left(1 + \frac{P}{\sigma^2}|h_0|^2 + \frac{P|\mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{h}_\mathrm{u}|^2}{\sigma^2 + \sigma_\mathrm{R}^2 \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{G}^\dagger \mathbf{h}_\mathrm{d}}\right). \tag{5}$$

The factor $1/2$ accounts for the two channel uses required by the relay traffic pattern.

III. Cooperative Beamforming

If perfect up- and downlink CSI and a global phase reference are available at the relays the optimal gain coefficients g_l result in a coherent combining of the signal contributions at the destination. In [11] a coherent combining scheme for sensory networks is presented as *distributed beamforming*. This scheme only assumes coherent phases of all signal contributions at the destination but equal transmit power at each relay. This is not optimal for maximizing (5). Due to the relative positions of the relays in the network the transmit power of each relay has to be optimized, too.

To derive the optimal gain coefficients we split g_l into the two factors b_l and a_l, i.e., $g_l = b_l \cdot a_l$. The factor b_l denotes the compensation of the uplink with

$$b_l = \sqrt{\frac{1}{P|h_{\mathrm{u},l}|^2 + \sigma_\mathrm{R}^2}}. \tag{6}$$

The factor a_l contains the transmit power and the phase of relay l. Furthermore, we define the vector $\mathbf{a} = [a_1^*, \ldots, a_L^*]^T$ with $\mathbf{a}^\dagger\mathbf{a} = P$ and the matrices $\mathbf{H}_\mathrm{d} = \mathrm{diag}\,[h_{\mathrm{d},1}, \ldots, h_{\mathrm{d},L}]$ and $\mathbf{B} = \mathrm{diag}\,[b_1, \ldots, b_L]$. Thus, we can write the SNR-term of the second time slot in (5) as

$$\frac{P\ |\mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{\Phi}\mathbf{h}_\mathrm{u}|^2}{\sigma^2 + \sigma_\mathrm{R}^2 \mathbf{h}_\mathrm{d}^\dagger \mathbf{G}\mathbf{G}^\dagger \mathbf{h}_\mathrm{d}} = \frac{P\ \mathbf{a}^\dagger \mathbf{H}_\mathrm{d}\mathbf{B}\mathbf{h}_\mathrm{u}\mathbf{h}_\mathrm{u}^\dagger \mathbf{B}^\dagger \mathbf{H}_\mathrm{d}^\dagger \mathbf{a}}{\sigma^2 + \sigma_\mathrm{R}^2 \mathbf{a}^\dagger \mathbf{H}_\mathrm{d}\mathbf{B}\mathbf{B}^\dagger \mathbf{H}_\mathrm{d}^\dagger \mathbf{a}} \tag{7}$$

$$= \frac{P\ \mathbf{a}^\dagger \mathbf{Q}_\mathrm{ud}\mathbf{a}}{\mathbf{a}^\dagger\left(\frac{\sigma^2}{P}\ \mathbf{I} + \sigma_\mathrm{R}^2 \mathbf{Q}_\mathrm{d}\right)\mathbf{a}}. \tag{8}$$

Fractions as in (8) are maximized by the dominant eigenvector of the general eigenvector problem

$$\mathbf{Q}_\mathrm{ud}\mathbf{a} = \lambda_\mathrm{max}\left(\frac{\sigma^2}{P}\ \mathbf{I} + \sigma_\mathrm{R}^2 \mathbf{Q}_\mathrm{d}\right)\mathbf{a}. \tag{9}$$

Due to the fact that $\left(\frac{\sigma^2}{P}\,\mathbf{I}+\sigma_{\rm R}^2\mathbf{Q}_{\rm d}\right)$ is invertible, it is also possible to express this optimization problem by the specific eigenvector problem

$$\left(\frac{\sigma^2}{P}\,\mathbf{I}+\sigma_{\rm R}^2\mathbf{Q}_{\rm d}\right)^{-1}\mathbf{Q}_{\rm ud}\mathbf{a}=\lambda_{\max}\mathbf{a}. \tag{10}$$

Since the matrix $\mathbf{h}_{\rm u}\mathbf{h}_{\rm u}^{\dagger}$ has rank one we can observe from (7) that $\mathbf{Q}_{\rm ud}$ has also rank one. Furthermore, $\mathbf{Q}_{\rm d}$ is a diagonal matrix. Therefore, we can give a_l explicitly as

$$a_l=\alpha\tilde{a}_l=\alpha\left(\frac{\sigma^2}{P}+\sigma_{\rm R}^2|h_{{\rm d},l}|^2|b_l|^2\right)^{-1}b_l h_{{\rm d},l}^* h_{{\rm u},l}^* \tag{11}$$

with

$$\alpha=\sqrt{\frac{P}{\sum_{k=1}^{L}|\tilde{a}_l|^2}}. \tag{12}$$

Note that, up to the power normalization factor α, a_l depends only on its corresponding uplink and downlink channel coefficient.

With a_l and b_l it is now possible to maximize (5) subject to the condition that the sum of all relay transmit powers is equal to P.

IV. Cooperative Diversity

Unfortunately, for cooperative beamforming, a substantial signaling overhead is required to phase-lock all LOs of all nodes (i.e. establish a global phase reference) and to maintain the CSI of all relays. We consider this overhead prohibitive, i.p., if the number of relays is large.

If there is no downlink CSI available at the relays one way to increase the reliability of the link is to use transmit diversity methods. For this reason we short review our proposed cooperative diversity scheme of [8]. It requires only very limited uplink and no downlink CSI.

A. Cooperative Diversity by Time-Variant Relay Processing

Our cooperative diversity scheme [8] can be summarized as follows: the linear processing at the relays is time-variant, which results in a time-variant equivalent source/destination channel coefficient (i.e. a time-variant SNR at the destination). The spatial diversity offered by the L relays is then translated into temporal diversity.

The number of relays limits the maximum achievable diversity order to L, because there are only L independent downlink channel realizations. To exploit this temporal diversity the input signal sequence is precoded by a linear block code (matrix multiplication) of length $N_{\rm B}=L$ as presented in [9] and [10].

1) Orthogonal Phase Signature Sequence: We proposed two different processing strategies at the relays. The first uses a time-invariant gain c_l and a relay-specific time-variant phase offset $p_l^{(k)}$ (phase signature sequence). I.e., at time instance k relay l has the gain $g_l^{(k)}$ given by

$$g_l^{(k)}=\underbrace{\sqrt{\frac{P_{{\rm R}_l}}{P|h_{{\rm u},l}|^2+\sigma_{\rm R}^2}}}_{c_l}\underbrace{\exp\left(j\varphi_l^{(k)}\right)}_{p_l^{(k)}}. \tag{13}$$

The phase offsets $p_l^{(k)}$ are derived from the columns of a FFT matrix. Therefore, the phase signature sequences are orthogonal. Usually, the transmit power of the relays is set to be equal at all relays: $P_{{\rm R}_l}=P_{\rm R}=P/L$

2) Relay Switching: The second processing strategy is motivated by antenna switching, so that at each time instance k only one relay transmits one precoded symbol to the destination. As an example for switching with $L=2$ relays the sequences for relay $l=1$ and $l=2$ are $\{g_1^{(1)},g_1^{(2)}\}=\{c_1,0\}$ and $\{g_2^{(1)},g_2^{(2)}\}=\{0,c_2\}$, respectively. The transmit power of the relays usually is set to $P_{{\rm R}_l}=P_{\rm R}=P$. It is obvious that relay switching leads to a time-variant channel.

B. Cooperative Spatial Multiplexing

If the source and destination have multiple antennas it is possible to use the relays in a way that spatial multiplexing gains can be achieved, even if all relays have only one antenna and the propagation environment is pure line-of-sight (LOS) [6]. To achieve spatial multiplexing gain it is mandatory that more than one relay is active at the same time to serve as active scatterers. Therefore, it is not possible in combination with the relay switching scheme, because each effective source-relay-destination channel matrix has rank one.

C. Impact of Gain Allocation

In the following we analyze the impact of the gain allocation at the relays on the performance of our cooperative diversity scheme. Due to the relative position of the relays to source and destination and its associated path loss the choice of c_l has a crucial impact on the system performance and on the achieved diversity order. In the case that one relay is far away from the source or in a deep fade and simultaneously near to the destination, the relay mainly amplifies noise, which dominates the resulting SNR at the destination. We show that the impact of the relative position is different for both cooperative diversity schemes.

To highlight the effect of the gain allocation on the throughput we consider that the destination receives only in the second time slot the signals from the relays and assume the local oscillators to be phased locked, i.e. $\{\phi_{{\rm LO},l}\}=0$.

1) Orthogonal Phase Signature Sequence: The instantaneous throughput (normalized to the blocklength $N_{\rm B}=L$) of the orthogonal phase signature sequence processing is given by

$$C_{\rm I}=\frac{1}{2L}\sum_{k=1}^{L}\log_2\left(1+\frac{P\left|\sum_{l=1}^{L}h_{{\rm d},l}g_l^{(k)}h_{{\rm u},l}\right|^2}{\sigma^2+\sigma_{\rm R}^2\sum_{l=1}^{L}\left|h_{{\rm d},l}\right|^2\left|g_l^{(k)}\right|^2}\right). \tag{14}$$

To clarify the exposition we assume that the downlink of all relays is an AWGN channel. In this case each relay has the same opportunity to contribute its signal at the destination.

Thus, the SNR-term in the logarithm of (14) simplifies to

$$\frac{P\left|\sum_{l=1}^{L} g_l^{(k)} h_{\mathrm{u},l}\right|^2}{\sigma^2 + \sigma_{\mathrm{R}}^2 \sum_{l=1}^{L} \left|g_l^{(k)}\right|^2} = \Gamma. \tag{15}$$

Furthermore we assume that the uplink coefficient of relay $l = i$ has much lower variance compared to the other uplink coefficients, i.e. $\gamma_i \ll \gamma_{j\neq i}\ \forall j \in [1, L]$. In this case the average SNR at the destination can be upper bounded by

$$\mathrm{E}_{\{h_\mathrm{u}\}}[\Gamma] \leq \mathrm{E}_{\{h_\mathrm{u}\}}\left[\frac{P\left|\sum_{l=1}^{L} g_l^{(k)} h_{\mathrm{u},l}\right|^2}{\sigma_{\mathrm{R}}^2 \sum_{l=1}^{L} \left|g_l^{(k)}\right|^2}\right] \approx \frac{L \cdot P \cdot \gamma_i}{\sigma_{\mathrm{R}}^2} \tag{16}$$

which is the L-fold SNR of relay i. In the orthogonal phase signature processing scheme all relays are active in each time instance of the second slot. Therefore we can conclude that relay links with a weak uplink limit the performance of the orthogonal phase signature processing scheme.

The choice of c_l as in (13) is very sensitive to deep fades, because it would result in a large amplification gain. One strategy to prevent these large gains c_l is to require a minimum received $\mathrm{SNR}_{\mathrm{min}}$ at the relays. If relay l does not fulfill this requirement it can either be turned off $(c_l = 0)$ or the amplification gain can be set to a maximum amplification threshold $c_l = c_{\mathrm{max}}$. The threshold c_{max} is the gain, relay l would use if the SNR is equal to $\mathrm{SNR}_{\mathrm{min}}$. Note, that if relay l is turned off one order of diversity is lost, because the degrees of freedom are reduced by one.

The other strategy to circumvent low SNR at the destination is to choose c_l more resistant to short deep fades with respect to small scale fading. One choice would be

$$c_l = \sqrt{\frac{P_{\mathrm{R}_l}}{P\gamma_{\mathrm{u},l} + \sigma_{\mathrm{R}}^2}}, \tag{17}$$

where only the mean received signal power at the relay is used as denominator, rather than the actual magnitude of the uplink channel coefficient.

2) Relay Switching: For the relay switching scheme the instantaneous throughput is given by

$$C_\mathrm{I} = \frac{1}{2L}\sum_{k=1}^{L} \log_2\left(1 + \frac{P\left|h_{\mathrm{d},k} c_k h_{\mathrm{u},k}\right|^2}{\sigma^2 + \sigma_{\mathrm{R}}^2 \left|h_{\mathrm{d},k}\right|^2 |c_k|^2}\right). \tag{18}$$

It can be seen, that the SNR at the destination of each time instance only depends on one relay link. It can be concluded that one weak relay link does not affect the performance as much as in the phase signature processing scheme. Therefore, the relay switching scheme promises a higher robustness to unbalanced SNRs at the relays and therefore higher performance gains.

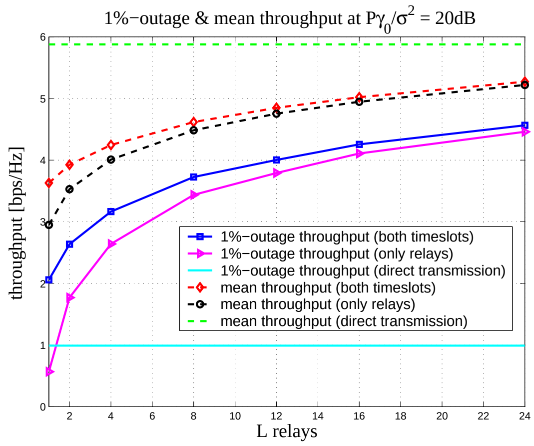

Fig. 3. 1%-outage and mean throughput for *cooperative beamforming* and *direct transmission*

V. Simulation Results

In this section we present the performance of our proposed relay processing schemes, i.e., the cooperative beamforming scheme and the two cooperative diversity schemes.

Simulation Setup: We consider a network where L relays are placed at random uniformly distributed on a disk with radius $r = 750$ wavelength $(= 45\mathrm{m}$ at 5Ghz). Source and destination are placed fixed on the border of this disk on opposite sides. We assume channel coefficients which include path loss and small scale-fading:

$$h_k = \frac{1}{d^{\beta/2}} \cdot x_k. \tag{19}$$

Here, d is the distance between the two nodes, x_k is a $\mathcal{CN}(0,1)$ complex random variable and $\beta = 2$ is the path loss exponent. Thus, the variance of the channel coefficient is $\gamma_k = d^{-2}$. In the simulations averaging is done over the positions of the relays as over the random variable x_k. We assume equal noise variances at relays and destination, i.e., $\sigma^2 = \sigma_{\mathrm{R}}^2$.

In the cooperative diversity scheme we assign the same power to all relays, i.e. $P_{\mathrm{R}_l} = P_\mathrm{R} = P/L$. Note, that in the case of the additional threshold rule ($\mathrm{SNR} < \mathrm{SNR}_{\mathrm{min}}$) the relays might not use all of their assigned transmit power, so that the total network power is less than P.
In the cooperative beamforming case the assigned transmit powers can differ at each relay. Only the sum of all transmit powers is P.

Results: In Fig. 3 the 1%-outage and mean throughput for cooperative beamforming vs. the number of relays are shown. Two relay traffic patterns are considered: the destination receives signals from the destination and the relays (both time slots) or only in the second slot (only relays). As reference a direct communication between source and destination without relays (direct transmission) is assumed. It can be seen that the outage throughput of the cooperative beamforming scheme is superior to the direct transmission scheme.

The increase of the mean throughput of cooperative beamforming is due to the increasing array gain of the number

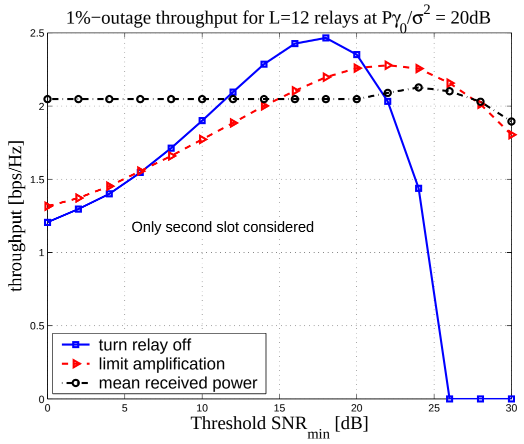

Fig. 4. Effect of threshold $\mathrm{SNR}_{\mathrm{min}}$ on 1%-outage throughput for *cooperative diversity: orthogonal phase signature sequence* for $L = 12$ relays

TABLE I

Mean number of relays which fulfill $\mathrm{SNR}_l \geq \mathrm{SNR}_{\mathrm{min}}$; $L = 12$

$\mathrm{SNR}_{\mathrm{min}}$ [dB]	14	16	18	20	22	24	26
$\bar{L}$	10.9	10.3	9.5	8.3	7.0	5.3	3.8

of relays L. However, to achieve the mean throughput of the direct transmission scheme a large number of relays would be needed.

In Fig. 4 the influence of the threshold $\mathrm{SNR}_{\mathrm{min}}$ at the relays on the 1%-outage throughput of the orthogonal phase signature cooperative diversity scheme is depicted. Three different approaches for $L = 12$ relays are shown. The first approach is to determine the amplification gain c_l as in (13) and to turn off the relay if it does not fulfill the requirement that the SNR is at least equal to the threshold $\mathrm{SNR}_{\mathrm{min}}$ (turn off relay). The second approach also determines the amplification gain c_l as in (13) and limits it to $c_l = c_{\mathrm{max}}$ (limit amplification). The third approach uses an amplification gain c_l as in (17) and limits it as the second approach (mean received power).

It can be seen that the first approach achieves the highest 1%-outage throughput at a $\mathrm{SNR}_{\mathrm{min}} = 18$ dB. From Table I it can be seen that $\bar{L} = 9.5$ out of 12 relays are used in average to achieve the outage throughput. As mentioned above, for each turned off relay one order of diversity is lost. With the second and the third approach no diversity is lost since no relay is turned off. Only the transmit power is limited.

Fig. 5 shows the 1%-outage and mean throughput for the relay switching cooperative diversity scheme vs. the number of relays. The dashed lines depict the mean throughput for the relay switching. Obviously, the number of relays has no influence on the mean throughput because no array gain can be achieved.

The solid lines and the dotted lines depict the 1%-outage throughput for the relay switching and the orthogonal phase signature sequence scheme, respectively. Gain allocation (17) is used for the dotted lines because in comparison to Fig. 4 it achieves almost the same performance with respect to the threshold $\mathrm{SNR}_{\mathrm{min}}$. Unfortunately, the outage throughput is below the relay switching scheme. Nevertheless, as mentioned in section IV-B, the advantage of this scheme is that it can be

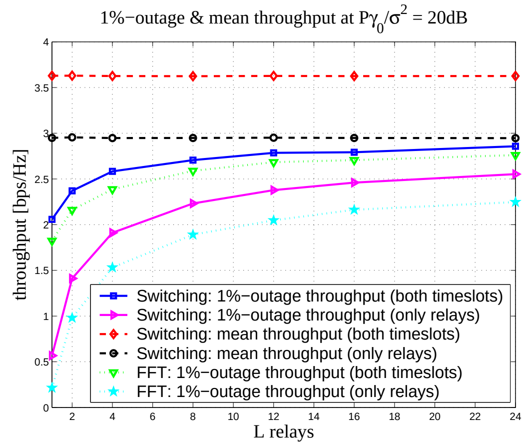

Fig. 5. 1%-outage and mean throughput for *cooperative diversity: relay switching* with gain allocation (13) (solid and dashed lines); 1%-outage throughput for *cooperative diversity: orthogonal phase signature sequence* (dotted lines) with gain allocation (17)

used to achieve spatial multiplexing gain in cooperative links.

VI. Conclusions

In this paper we analyzed the impact of the gain allocation at the relays in cooperative relay communication links. We presented a optimal gain allocation which results in a coherent combining of all signal contributions at the destination. This scheme maximizes the instantaneous throughput of the link.

Cooperative diversity schemes can be used if the CSI at the relays is limited. We showed that the right choice of the amplification gains is crucial to achieve a good performance.

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