# 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. To achieve cooperative diversity we proposed time-variant and relay-specific phase rotations induced at each relay to make the effective channel time-variant. In the present work we show that the allocation of the amplification gains at the relays has great influence on the diversity performance and give optimal methods and low complexity extension to existing gain allocations. Furthermore, we give criteria whether a node in the network should act as relay or not.**

## I. Extended Abstract

The use of diversity in the spatial and time 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 will have a single 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] to an attractive option for such systems.

Fig. 1 depicts the considered cooperative relay network with one active source/destination pair and $L$ 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 which together establish one transmission cycle. In the first time slot the source transmits the data packet to the relays. During the second time 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*.

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 *transmission cycle* (block fading).

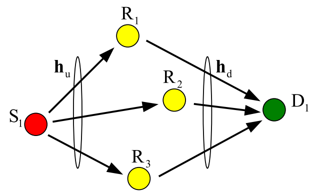


Fig. 1. 2-hop cooperative relaying network with single antenna nodes

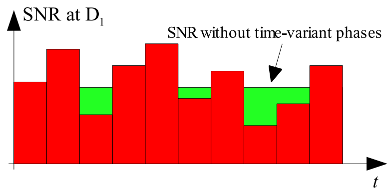


Fig. 2. Resulting time-variant SNR at the destinations

### A. Cooperative Diversity by Time-Variant Relay Processing

Our starting point is the simple cooperative diversity scheme which we proposed in [3]. It requires only very limited uplink CSI (e.g. magnitude of channel coefficient) and no downlink CSI. For clarity of exposition we briefly summarize the approach: 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). With this scheme the spatial diversity offered by the $L$ relays is transformed into temporal diversity. In a simple embodiment relay $l$ uses a time-invariant gain $a_l$ and a relay-specific time-variant phase offset $p_l^{(k)}$ (phase signature sequence). Thus, the amplification gain of relay $l$ at time instance $k$ is for example given as

$$g_l^{(k)} = a_l \; p_l^{(k)}. \tag{1}$$

Fig. 2 shows a typical time-variant destination SNR for the link $\mathrm{S}_1/\mathrm{D}_1$. The phase signature sequence consists of $N_\mathrm{B} = 10$ segments. The exploitation of this time-variance (temporal diversity) to achieve a cooperative diversity gain requires an appropriate coding scheme of the source signal. Some well suited candidates are presented in [4] and [5].

In [3] we focused on the time-variant processing at the relays and introduced two orthogonal phase signature sequences. The first is derived from the columns of a FFT matrix. This leads to

$$p_l^{(k)} = \exp\left(-j\,\frac{2\pi}{N_\mathrm{B}}\,(k-1)\,(l-1)\right) \tag{2}$$

Another simple choice is based on an identity matrix, which leads to elements expressed by

$$p_l^{(k)} = \begin{cases} 1 & \text{if } (k-l+1) \bmod L = 1 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

An example for (3) with $L = 2$ and $N_\mathrm{B} = 4$: The sequences are $[1, 0, 1, 0]$ and $[0, 1, 0, 1]$ for relay $l = 1$ and $l = 2$, respectively. It can be seen that in this case the relays are switched for each symbol which leads to a time-variant channel.

## B. Impact of Gain Allocation

Due to the relative position of the relays to source and destination and its associated path loss the choice of $a_l$ 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. Therefore a gain allocation scheme which takes this effect into account is necessary.

The capabilities of gain allocation schemes depend on the channel state information (CSI) available at the relay. Considering only CSI of the source-relay link $h_{\mathrm{u},l}$ at the relays one popular choice (e.g. in [1]) of $a_l$ is given by

$$a_l = \sqrt{\frac{P_{\mathrm{R}}}{P|h_{\mathrm{u},l}|^2 + \sigma_{\mathrm{R}}^2}} \qquad (4)$$

where $P$, $P_{\mathrm{R}}$ and $\sigma_{\mathrm{R}}^2$ is the transmit power of the source and the relay and the variance of the relays noise, respectively. We impose a total power constraint $P$ on all relays, i.e. $P_{\mathrm{R}} = P/L$. The allocation scheme (4) is very sensitive to deep fades, because in this case this scheme would result in a large amplification gain.

To prevent these large gains we propose an extension to (4) by setting an maximal amplification threshold. With this threshold gains are restricted to a specified interval $a_l \in [0,\ a_{\max}]$. The choice of $a_{\max}$ depends on the number of relays and on the network topology and needs to be optimized (see Fig. 3).

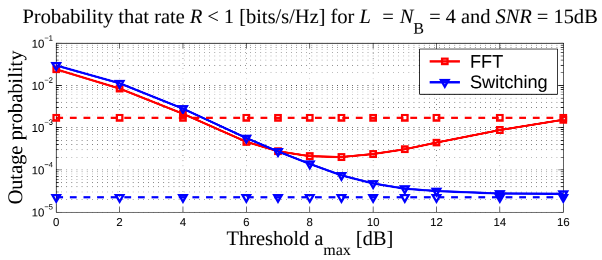


Fig. 3. Outage probability that the rate is less than 1 bit/s/Hz vs. threshold $a_{\max}$ for $L = 4$ relays and block-length $N_{\mathrm{B}} = 4$; with threshold $a_{\max}$ (solid lines); no threshold (dashed lines);

In Fig. 4 the impact of the gain allocation on the diversity performance of the in [3] proposed scheme is shown.

First we concentrate on the solid curves, which correspond to the gain allocation (4) without any additional threshold. It can be seen that only the switching method (3) achieves the full diversity order of $L+1 = 5$. The FFT phase signatures (2) achieve only a lower diversity order of two. With the additional threshold (dashed curves) the performance of the FFT phase signatures method is increased clearly.

## C. Outlook

In the present work we focus on the allocation of the time-invariant gain $a_l$ at the relays. As mentioned above this has a crucial impact on the performance of links using AF relaying.

Fig. 5 shows the system model of a AF relay. $\phi_{\mathrm{LO},l}$ represents the phase offset of the local oscillator (LO) at the relay $\mathrm{R}_l$ 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.

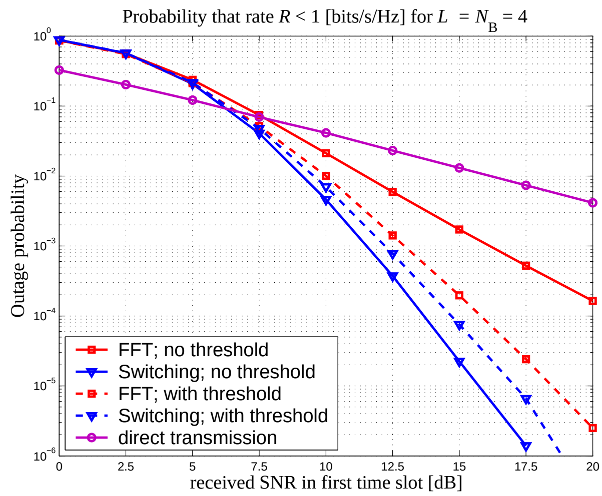


Fig. 4. Outage probability that the rate is less than 1 bit/s/Hz for $L = 4$ relays and block-length $N_{\mathrm{B}} = 4$; with threshold $a_{\max}$ (dashed lines); no threshold (solid lines); direct = no relays, source sends in every time slot

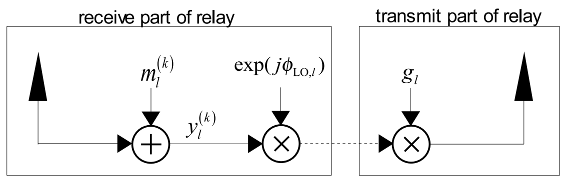


Fig. 5. System model of amplify-and-forward relay

Only if there is a *global phase reference*, i.e. all LOs are phase synchronized, $\phi_{\mathrm{LO},l}$ is equal to zero.

We consider different amount of CSI at the relays. 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. A substantial signaling overhead is required to phase-lock all LOs of all nodes (i.e. establish a global phase reference). We consider this overhead prohibitive, i.p. if the number of relays is large. Thus, we present further to the amplification-threshold extension suboptimal gain allocations which require only partial CSI at the relays and are easy to implement in a real system. We study their performance analytically and by means of simulations.

The relative position of the relays to the source and destination has an important influence on the resulting SNR at the destination. This raises the question which nodes in a network should act as relays. We will give an answer to this question in terms of SNR at the relays. Furthermore, we will show that the in [4] and [5] presented codes of diversity order $L$ are robust even if less than $L$ nodes act as relays.

## REFERENCES

[1] J. N. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, Apr. 2003. (Accepted for publication).

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part I: System description," *IEEE Trans. Commun.*, vol. 51, pp. 1927–1938, Nov. 2003.

[3] I. Hammerstroem, M. Kuhn, and A. Wittneben, "Cooperative diversity by relay phase rotations in block fading environments," in *Proc. SPAWC*, (Lisboa, Portugal), Jul. 11–14, 2004. to appear.

[4] A. Wittneben and M. Kuhn, "A new concatenated linear high rate space-time block code," in *Proc. 55th IEEE Veh. Tech. Conf.*, vol. 1, (Birmingham, Al), pp. 289–293, May 6–9, 2002.

[5] Y. Xin, Z. Wang, and G. B. Giannakis, "Space-time diversity systems based on linear constellation precoding," *IEEE Trans. Wirel. Comm.*, vol. 2, pp. 294–309, Mar. 2003.