

# Performance of transmission-time optimized relaying schemes in real-world channels

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**Abstract**—The deployment of relay stations has been proposed as a practical means to increase spectral efficiency in wireless networks. In this paper, we compare the achievable data rates of several relaying schemes using measurements at 2.45 GHz.

We investigate the decode-and-forward relay schemes described by Nabar et al. [1], which we extend by additionally optimizing transmit durations. At the transmitters, we distinguish between the availability of *instantaneous* channel state information and *average* channel SNR information.

Our data analysis indicates that (i) the deployment of relays can improve ergodic data rate at least twofold, (ii) instantaneous channel knowledge enables at most 8.7% increase in spectral efficiency over average channel knowledge, and (iii) relay selection has a large impact on the performance of cooperative networks.

**Index Terms**—Cooperative Diversity/Relaying, Virtual MIMO.

## I. INTRODUCTION

In cellular networks, the link quality is mainly limited by the link budget on the uplink. In particular, acceptable indoor coverage is often hard to achieve due to strong attenuation by building walls. In order to increase the cell coverage, the relays that are in the vicinity of the source mobile stations (MSs) can increase the signal quality, and thus the channel capacity, significantly.

As discussed in [1]–[6], the advantages of relaying techniques include the reduction of power consumption, the elimination of blind spots, and indoor coverage extension. As a result, several relaying algorithms have been proposed [1], [7]–[9]. However, many of these works have been performed under simplified assumptions regarding the channel properties, in particular in terms of path loss and shadowing correlations. In this work, we investigate the performance of a number of relay schemes from an information-theoretic point of view using performance measures and real-world measured channels. Similar works have been presented in [6], [10]. In [6], the authors concentrate on indoor schemes, while [10] focuses on outdoor-to-indoor relaying at 5.3 GHz, considering single antennas at the base station as well as single relays in mobile scenarios.

This paper extends the work of [11], where the authors analyzed the issue of power normalization, the impact of the

relay transmit power, and the potential benefits from using multiple relays for outdoor-to-indoor relay channels. However, the authors did not analyze the impact of varying degrees of channel state information at the source and relays.

In our work, we

- consider stationary uplink relay channels at 2.45 GHz;
- analyze the impact of instantaneous versus average channel knowledge at the MSs and the relays;
- maximize transmission rate in terms of transmit time allocation;
- discuss the spectral efficiency of the schemes by means of their ergodic and outage rates; and
- stress the importance of proper relay selection.

The outline of the paper is as follows. First, Section II presents the channel measurements. Then, Section III describes the relaying schemes considered, including the power constraints on the nodes. Section IV focus on time allocation optimization, considering real world measurements. Section V presents numerical results for relevant configurations and finally conclusions are given in Section VI.

## II. CHANNEL MEASUREMENTS

For our investigations, we used measurement data from the Stanford July 2008 Radio Channel Measurement Campaign [12]. The measurement scenario is shown in Figure 1.

The frequency responses between all MSs and all relays (R), all MSs and the BS, as well as between all R and the BS were measured. A total number of 120 blocks of these uplink and relay channels were recorded, where the blocks were separated in time by 250 ms. Each block is characterized by a single complex transfer function. To prevent interference from affecting the measurement, we used the band from 2.33 to 2.40 GHz, which was subdivided in 200 frequency bins. Therefore, the time-varying transfer function of each single-input single-output (SISO) link is represented by a  $120 \times 200$  matrix.

For a given link (at a given frequency), we denote the measured channel coefficient between source MS ( $s$ ) and relay ( $r$ ) as  $g_{sr}$ , the measured channel coefficient between the source MS ( $s$ ) and the destination BS ( $d$ ) as  $g_{sd}$  and the measured channel coefficient between relay ( $r$ ) and the destination BS

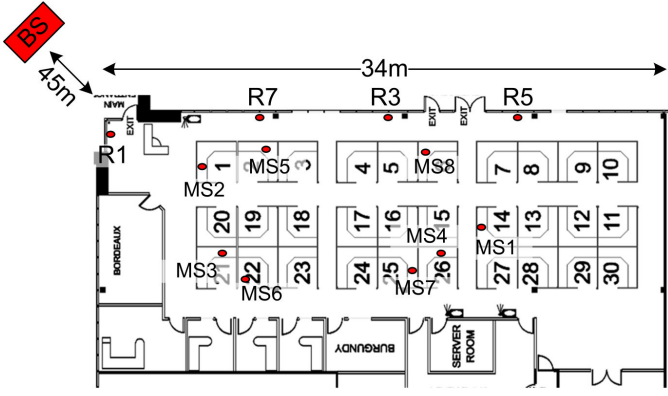


Fig. 1. Measurement scenario.

(d) as  $g_{rd}$ . The relay and destination nodes are numbered as indicated in Figure 1.

### III. RELAYING SCHEMES

We investigate three different decode-and-forward relaying schemes on the uplink (see Figure 2): (i) broadcast/multiple access (BM), (ii) broadcast/point-to-point (BP) and (iii) strictly two-hop (PP). In Figure 2, black and red arrows indicate the communication during the first and the second phase, respectively. For the first two schemes, the total transmission time  $T$  must be divided into two equal parts by design [1]. In the third scheme, we divide  $T$  into two phases of length  $\alpha T$  and  $(1 - \alpha)T$ , where  $0 < \alpha < 1$ . Naturally, we want to choose  $\alpha$  such that the resulting end-to-end data rate is maximized, given a particular kind of channel knowledge.

In the following, we describe each investigated relay scheme assuming unit power. We enforce the power constraint on a per-node basis, as opposed to a network-based power constraint [11] where the deployment of additional relays comes at the cost of reduced transmit power at the other nodes. Furthermore, we assume that the power constraint applies for each transmission phase *individually*, i.e., a node cannot save power in one phase and transmit with boosted power in a subsequent phase, but whenever it transmits, it is doing so with its full power available. This leads to a different total energy consumption for the investigated schemes. While this comparison might seem unfair, it is the most practical assumption.

#### A. Broadcast / Multiple Access

In the first phase, the source is transmitting to both the destination and the relay. In the second phase, both the source and the relay are transmitting. This scheme results in the following achievable rate

$$R_{\text{BM}} = \frac{1}{2} \min\{(R_1^{(s,r)} + R_1^{(s,d)}), R_1\}, \quad (1)$$

where

$$\begin{aligned} R_1^{(s,r)} &= \log[1 + |g_{sr}|^2/N_0], \\ R_1^{(s,d)} &= \log[1 + |g_{sd}|^2/N_0], \\ R_1 &= \log \det(\mathbf{I}_2 + \mathbf{H}_1 \mathbf{H}_1^H / N_0), \end{aligned}$$

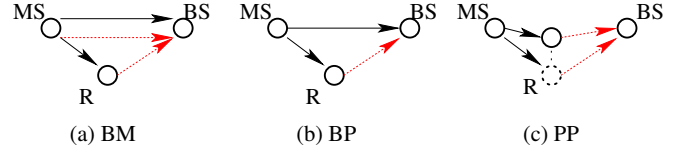


Fig. 2. Investigated relaying schemes

$$\mathbf{H}_1 = \begin{bmatrix} g_{sd} & 0 \\ g_{rd} & g_{sd} \end{bmatrix},$$

and  $g_{sr}$ ,  $g_{sd}$ , and  $g_{rd}$  describe the channel coefficients for the different links as previously defined.

#### B. Broadcast / Point-to-point

This scheme is similar to the previous one, however, the source is transmitting only in the first phase. This results in an achievable rate of

$$R_{\text{BP}} = \frac{1}{2} \min\{R_2^{(s,r)}, R_2\}, \quad (2)$$

where

$$\begin{aligned} R_2^{(s,r)} &= \log[1 + |g_{sr}|^2/N_0], \\ R_2 &= \log[1 + \|\mathbf{h}_2\|^2/N_0], \\ \mathbf{h}_2 &= [g_{sd} \ g_{rd}]^T. \end{aligned}$$

#### C. Two-hop, cooperative relays

In this scheme, the source transmits to  $n_r$  relays in the first phase. In the second phase, the relays are forwarding the message jointly to the destination. We assume that the relays do not cooperate to decode the signal from the source, but do cooperate during the transmission to the destination. For this reason, the link of the relay with the worst channel from the source MS determines the spectral efficiency on the first hop. This scheme leads to an achievable rate of

$$R_{\text{PP}} = \min\{\alpha R_3^{(s,r)}, (1 - \alpha) R_3^{(r,d)}\}, \quad (3)$$

where

$$\begin{aligned} R_3^{(s,r)} &= \min_{r \in \{1, \dots, n_r\}} \log[1 + |g_{sr}|^2/N_0], \\ R_3^{(r,d)} &= \log[1 + \mathbf{g}_{rd}^H \mathbf{g}_{rd} / N_0], \end{aligned} \quad (4)$$

and  $\mathbf{g}_{sr}$  and  $\mathbf{g}_{rd}$  are channel vectors from the source to the relays, and from the relays to the destination, respectively. Note that in this scheme, transmit time optimization is possible.

#### D. No relay

When using no relays, the following spectral efficiency is achieved for transmission

$$R_{\text{NR}} = \log[1 + |g_{sd}|^2/N_0]. \quad (5)$$

#### IV. OPTIMIZING TRANSMIT TIME ALLOCATION

To find  $\alpha_{opt}$  maximizing (3), we express this optimization problem as

$$\alpha_{opt} = \arg \max_{\alpha} \min\{\alpha R_3^{(s,r)}, (1-\alpha)R_3^{(r,d)}\}. \quad (6)$$

This is a max-min problem [13] with the solution

$$\alpha_{opt} = \frac{R_3^{(r,d)}}{R_3^{(s,r)} + R_3^{(r,d)}}. \quad (7)$$

Nevertheless,  $\alpha_{opt}$  depends on the kind of underlying channel knowledge.

##### A. Instantaneous (perfect) channel knowledge

Under ideal conditions, sources and relays have knowledge of all involved channels. This is usually not achievable in practice, but it provides an upper bound on the rate.

In this case, we compute  $R_3^{(s,r)}$  and  $R_3^{(r,d)}$  via (7) using the instantaneous channel coefficients available every 250ms in our measurements. Thus we calculate  $\alpha_{opt}$  each 250ms as well. The  $\alpha_{opt}$  found in this way will be denoted as  $\alpha_{inst}$ .

##### B. Average channel knowledge (SNR)

Here, we assume that the channels are stationary, i.e., their SNRs do not change significantly over time. These SNRs can thus be estimated and exchanged between the nodes with sufficiently small overhead, which makes this assumption practical in current communication systems.

We compute the ratio  $\alpha$  under average channel knowledge as follows. Consider one of the links with instantaneous gain  $g$ . Denoting by  $E\{\cdot\}$  the expectation operator, the ergodic capacity is

$$E\{R\} = E\{\log[1 + |g|^2/N_0]\}.$$

Using Jensen's inequality, we obtain the upper bound

$$E\{R\} \leq \log [1 + E\{|g|^2\}/N_0] = \tilde{R}.$$

Note that  $\tilde{R}$  depends only on the *average* SNR and can thus be computed by the nodes themselves. The transmit time allocation under average channel state information is then calculated analogous to (7), but with every rate  $R$  replaced by the corresponding bound on its expected value,  $\tilde{R}$ . The phase duration computed in this way will be denoted as  $\alpha_{avg}$ .

##### C. No channel knowledge

In the case of no channel knowledge at the transmitter and at the relays, 50% of the total time is allocated to each transmit period [1]. This case is denoted by the notation  $\alpha_{50} = 0.5$ .

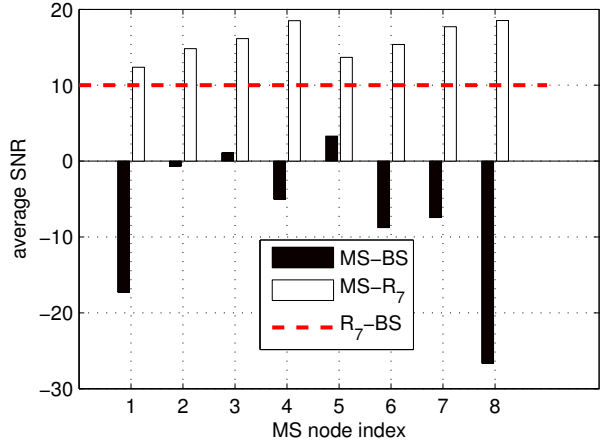


Fig. 3. SNR levels for all MS nodes.

#### V. NUMERICAL RESULTS

We normalized all channel coefficients such that the link from relay 7 to BS had an average SNR of 10 dB, while the SNRs of the other links were relative to the specific link, as described in [11].

In the following, we compare the performance of the introduced relaying schemes using our measured data. We begin with the SNR levels of the different links shown in Figure 3. The direct links from the MSs to the BS have quite poor SNR (black bars). The best relay,  $R_7$ , is used as reference and is assumed to have a SNR of 10dB (red dashed line), as discussed above. The SNRs of the indoor links between the MSs and the relays are significantly higher.

Next, we compare the different relaying schemes. From our measurements we have 200 frequency realizations, each with 120 samples in time. Initially we take the mean rate over time for each realization, and then we compute the median ergodic capacity and outage capacities over the 200 realizations. Figure 4 shows the median ergodic data rate and the 10%, 5% and 2.5% outage rates, over all the 200 realizations available, for each relaying scheme. For the PP schemes, we plot the values obtained with transmit time optimization using average channel knowledge,  $\alpha_{avg}$ . Every relaying scheme was evaluated for all source nodes, with the specified relay, e.g.  $BM(R_7)$  denotes the broadcast-multicast relaying scheme using relay  $R_7$ . It is interesting to see that even the worst relaying scheme at least doubles the data rate of the no-relay case for most cases, due to the additional power available at the relays. It can be seen that while in the three schemes  $BM(R_7)$ ,  $BP(R_7)$  and  $PP(R_7)$ , the presence of a single relay node already increases the data rate significantly, the option of using multiple relays can push the gains even further. Although the relaying scheme with the best achievable rate strongly depends on the measured channel characteristics, in general, the best median ergodic rate was obtained using two relays  $PP(R_{1,7})$ , since relays 1 and 7 are, in general, the ones with the best channels from the MSs, and the channels

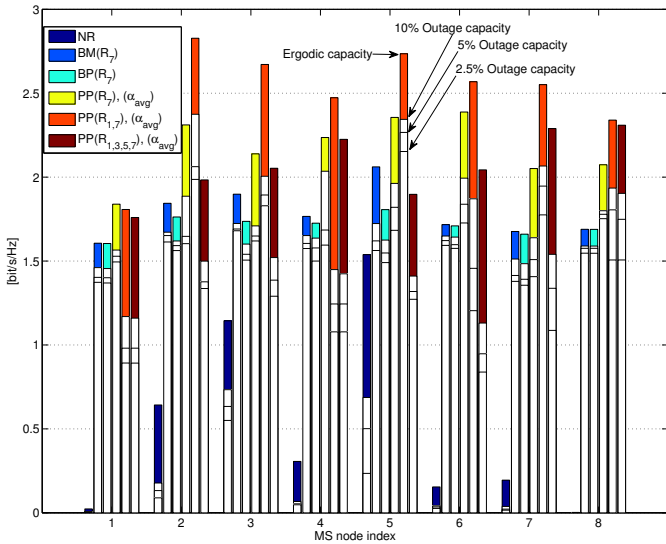


Fig. 4. Comparison between all relaying schemes using  $\alpha_{\text{avg}}$ .

to the BS are strong enough. On the other hand, using relays with bad channels from the MSs might decrease the overall spectral efficiency as seen for  $\text{PP}(R_{1,3,5,7})$ . This degradation on the achievable spectral efficiency is expected from (4), since the relay with the smallest spectral efficiency determines the performance of the first hop, and thus acts as a performance bottleneck in the whole relaying scheme. This result reinforces the importance of properly selecting the best relaying nodes.

In order to compare the spectral efficiency when using different kinds of channel knowledge ( $\alpha_{\text{inst}}$ ,  $\alpha_{\text{avg}}$  and  $\alpha_{50}$ ), Figure 5 shows the median ergodic rate and the 10% outage rate, over all realizations, for the  $\text{PP}(R_7)$  relaying scheme. It is remarkable that average channel knowledge  $\alpha_{\text{avg}}$  performs relatively close to optimum, i.e., perfect channel knowledge ( $\alpha_{\text{inst}}$ ). For our data, the penalty for average channel knowledge is at most 8.7% of the ergodic rate. This is in spite of the fact that the computation of  $\alpha_{\text{avg}}$  is based on an upper bound instead of the true expected rate.

Optimizing the phase duration based on any kind of channel knowledge, be it instantaneous or average, is clearly beneficial. As seen for MS 5, the spectral efficiency improves up to 43.45% when using  $\alpha_{\text{avg}}$ , compared to equal time allocation ( $\alpha_{50}$ ). Thus, the proposed optimization brings considerable rate enhancements for the overall relay channel, even under realistic assumptions.

Note that the PP scheme is the most simple scheme (in one transmission phase either the source or the relays transmit). However, when using transmit time allocation (even with average channel knowledge) renders this scheme superior to the others.

A drawback one can observe in Figure 5 is that the difference between the ergodic rate and the 10% outage rate tends to be larger when considering average channel knowledge ( $\alpha_{\text{avg}}$ ). However, the overall performance is still significantly better than when not using any channel knowledge.

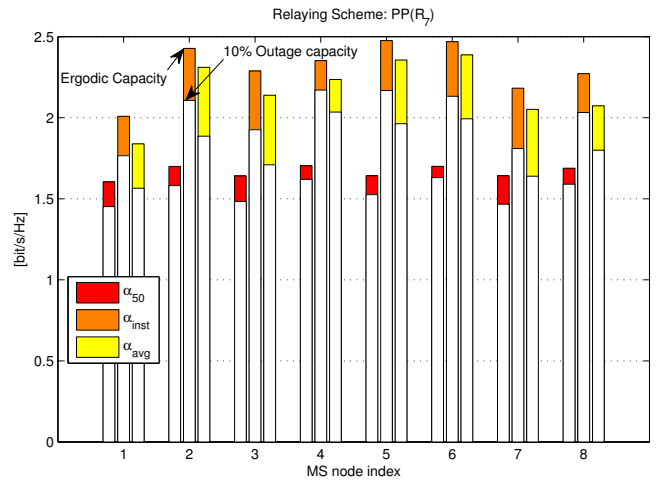


Fig. 5. Performance of different time allocation strategies.

## VI. CONCLUSIONS

We presented the spectral efficiency for indoor-to-outdoor uplink relaying schemes, based on experimental measurement data. Our findings show that relaying tremendously increases achievable data rates, particularly when the direct link has low SNR.

In our work we always considered a per-node power constraint, since relaying is intended to raise the transmit power and thus the link quality.

We optimized the transmit time allocation for a specific decode-and-forward scheme to maximize the spectral efficiency. We consider both instantaneous and average channel knowledge at the transmitters. It turned out that in both cases spectral efficiency increases significantly compared to having no channel knowledge. The performance difference between using average channel knowledge and instantaneous (perfect) channel knowledge is surprisingly small. In terms of outage rate, using average channel knowledge for optimization turned out to be slightly less robust.

Finally, our results suggest that proper relay selection is vital for increasing the spectral efficiency of relaying-based schemes, since the best performance was obtained with the relays that, in general, had the best channels from the MSs, given that the channel from the relays to the BS is good enough.

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