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Measurement based investigation of cooperative relaying

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Abstract—In this paper we present measurements that involve two access points (APs) and two user terminals, each of which is equipped with 4 antennas, in an indoor office environment. The data allow for the simultaneous characterization of the multiple input-multiple output (MIMO) links from the APs to the user terminals and between the user terminals, and are, to the best of our knowledge, the first of their kind. We show that the links between user terminals are impaired by body shadowing, and have therefore much lower gains than the direct links to the APs. Moreover we investigate the statistics of the links, and their correlation. Based on these measurements, we investigate the performance of cooperative relaying in terms of rate improvement (for this analysis the data from only one AP are used). We show that a significant rate improvement can be achieved if the relaying node is free to set the power level at which it transmits, and if it is free to select which of its antennas is used to perform the relaying.

I. INTRODUCTION

In conventional cellular systems, downlink communication is achieved by the transmission of a signal from an access point to the intended receiver. If there are multiple users in the coverage area of this access point, they share the medium through separation in frequency, time, space or code.

Relaying systems employ a different strategy. Although the content of the communication is generated at the access point, it arrives to the desired receiver either directly from the access point or through other nodes that receive it and re-transmit it. These nodes are called relays, and the topic of relay communication has been receiving a lot of attention in the context of multi-hop networks, adhoc networks, sensor networks etc. The advantages of relay systems are the reduction in power consumption (or increase in system capacity for a given power consumption), the elimination of blind spots, range extension etc.

Clearly, the rate performance of the relaying and the direct communication schemes depends on various parameters such as the relative average channel gain of the direct and relay links, the difference in coding requirements on the two types of links and the channel statistics (distribution and correlations). Most of the theoretical work on relay and cooperative channels has been performed under simplified assumptions for the channel properties [2]–[4]. However, measurements show that more details need to be included in the channel models, e.g. joint versus disjoint shadowing, short term fluctuations, angular dispersion considered individually or jointly.

In this paper we present the first (to our knowledge) measurements that simultaneously characterize the links from the access point to 2 nodes within its coverage area and the links between these 2 nodes. Moreover, the nodes are mock-devices carried by human users, a fact that significantly affects the channel properties. The paper is structured as follows: in Section II we review the basic relaying principles that we will investigate. Section III describes the measurement equipment, the measurement procedure, and the initial channel characterization. Section IV shows the achievable rate improvement with relaying, while Section V additionally allows for antenna selection techniques. The results are summarized in Section VI.

II. RATE IMPROVEMENT WITH RELAY SYSTEMS: THEORETICAL ANALYSIS

In a narrowband system with additive white Gaussian noise (AWGN), the channel capacity is given by the well known Shannon Shannon formula:

$$C = \log_2(1 + SNR) \quad (1)$$

where the signal to noise ratio SNR is defined as $SNR = g \frac{P_t}{\sigma^2}$. P_t is the transmitted power, g is the instantaneous channel gain (amplification/attenuation) introduced by the physical channel, and σ^2 is the variance of the thermal (AWGN) noise at the receiver. In a real life system, the achievable spectral efficiency R is limited by the allowable amount of coding, the size of the transmitted data packets, and the allowable receiver complexity. It can be approximated as

$$R = \log_2\left(1 + \frac{1}{\gamma} SNR\right), \quad (2)$$

where the factor γ includes the effects of coding losses as in [1].

We assume that we have an access point (AP) and two user equipments, one of which acts as the destination D and the other as the relay R. The purpose is to deliver an information content from the AP to the destination D. This can be done directly from the AP or through the relay R. We investigate the following schemes, assuming that g_1 and g_2 are the channel gains from the AP to D and R respectively, and g_R is the channel gain for the link between R and D.

- 1) Direct communication with the AP

The direct link is the link between the AP and D. The maximum achievable rate for direct communication is

$$R_{cell} = \log_2\left(1 + g_1 \frac{P_t}{\gamma_{cell}\sigma^2}\right), \quad (3)$$

where γ_{cell} describes the coding loss for transmission from the AP to D, and P_t is the total transmitted power.

2) Communication using the relay link

The data that is destined for D is transmitted from the AP at a transmit power level $\lambda_c P_t$, ($0 \leq \lambda_c \leq 1$), and R receives and decodes them. The maximum rate on the link from the AP to R is

$$R_c = \log_2\left(1 + g_2 \frac{\lambda_c P_t}{\gamma_c \sigma^2}\right), \quad (4)$$

where γ_c is the coding loss for the transmission from the AP and λ_c describes the percentage of the total transmit power P_t spent on the this step¹. The relay R regenerates the information and sends it to D over the link between them, with a transmit power of $\lambda_r P_t$, ($0 \leq \lambda_r \leq 1$) (we only discuss decode, reencode and forward scenarios). The maximum rate on this link is

$$R_r = \log_2\left(1 + g_r \frac{\lambda_r P_{cell}}{\gamma_r \sigma^2}\right), \quad (5)$$

where γ_r is the coding loss, and λ_r describes the percentage of power that is spent on the relay transmission. We assume that the total network power consumed is the same as in both cases, i.e. $\lambda_c + \lambda_r = 1$. Let η_c be the percentage of time dedicated to the transmission from the AP to R. Then the rest of the time ($\eta_r = 1 - \eta_c$), the relay link is active. Clearly, the maximum achievable data rate that can be achieved in this cooperative mode of transmission (i.e. if D decodes the data based only on what it receives from R) is:

$$R_{coop} = \max_{\eta_c, \eta_r, \lambda_c, \lambda_r} [\min[\eta_c R_c, \eta_r R_r]], \quad (6)$$

such that $\lambda_c + \lambda_r = 1, \eta_c + \eta_r = 1$.

The minmax problem shown above achieves its solution for $\eta_c R_c = \eta_r R_r$, and therefore the optimal choice for η_c, η_r is $\eta_c = \frac{R_r}{R_r + R_c}, \eta_r = \frac{R_c}{R_r + R_c}$. The corresponding achievable rate via the relay node is

$$R_{coop}(\lambda_c) = \frac{R_r R_c}{R_r + R_c}. \quad (7)$$

If we assume that the relay can only transmit a certain amount of power, due to battery and/ or hardware limitations (e.g. amplifier linearity), then λ_c is fixed. If the relay node does not have such limitations, the maximization of R_{coop} involves the optimization over the variables λ_c, η_c (λ_r, η_r can be uniquely determined from λ_c, η_c). The solution of this problem is not trivial. To simplify, we assume that λ_c can vary over a predetermined set of values in the set Λ , and the relay node selects the λ_c that maximizes $R_{coop}(\lambda_c)$. Clearly,

the finer the search in λ_c , the closer the solution is to optimal. For the analysis that follows we assume that λ_c can be selected from the set $\Lambda = \{0.25, 0.5, 0.75\}$.

3) Route selection

If the data to the destination D are transmitted over the best of the direct and the relay link, then in the case of fixed λ_c the achievable rate is

$$R_{sel}(\lambda_c) = \max\{R_{cell}, R_{coop}(\lambda_c)\}, \quad (8)$$

and in the case of variable λ_c it is

$$R_{sel} = \max_{\lambda_c \in \Lambda} \{R_{cell}, R_{coop}\}. \quad (9)$$

III. MEASUREMENT DESCRIPTION

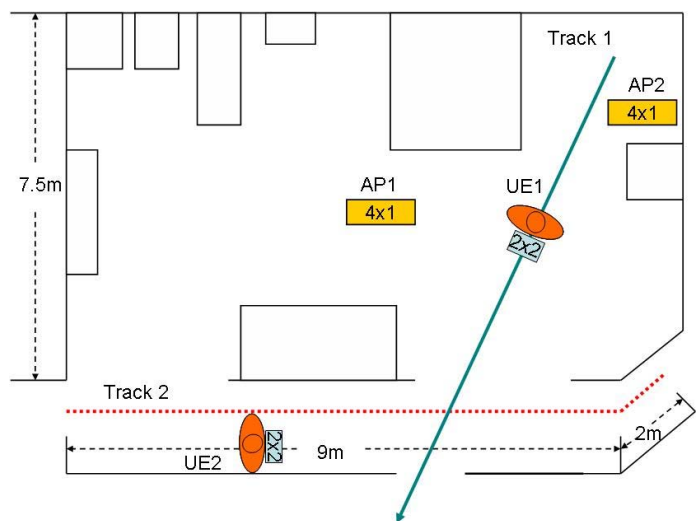


Fig. 1. Sketch of cooperative measurement scenario

The basic system for our measurements was the multiple input- multiple output (MIMO) sounder of the Antennas & Propagation Division at Aalborg University [5]. The measurements were taken at 5.2 GHz, in a scenario resembling a small open office or internet cafe, see Figure 1. The measurements involved two APs equipped with 4 $\lambda/2$ spaced monopoles and two user equipment handsets with 4 patch elements each around the rim on a 10x5x1cm shell. While the APs were transmitting and UE1 was receiving, UE2 had both Tx and Rx capability with an RF isolation of 80dB between TX and RX operation. As each terminal had 4 antennas, $4 \times 4 = 16$ possible links exist between any two terminals. For this experiment, the UEs were held by two users that walked along the lines indicated in Figure 1. This section provides representative example results from just one measurement with two persons holding the UE's in video mode (terminal in front of the user bodies), while walking. Although the measurements had a 200MHz bandwidth, we treat them here as narrowband to extract the most important channel features.

We first investigate the statistics and the relative gains of the links among the communicating entities. We normalize the measurements, so that the average gain (over measurement

¹A different mathematical approach would apply in 'amplify and forward' situations.

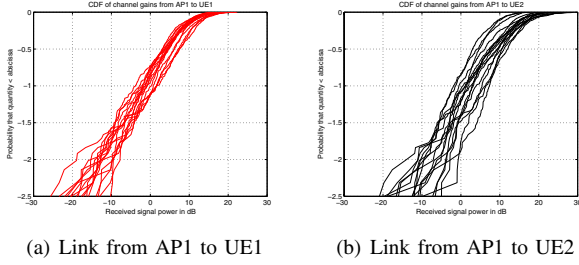


Fig. 2. CDFs of gains from AP1 to the UEs

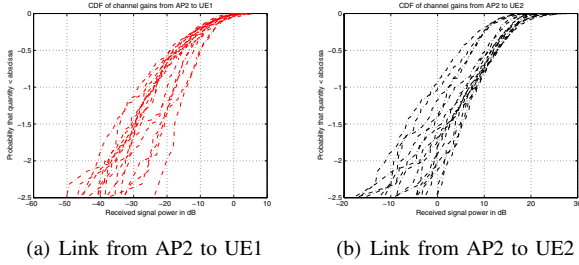


Fig. 3. CDFs of gains from AP2 to the UEs

locations and over transmit-receive antenna combinations) from AP1 to UE1 is 10dB. The short term fading distributions of all the links are shown in Figures 2, 3, 4. Clearly, the link statistics follow the Rayleigh distribution. A slight tendency for the links between the UEs to have more dynamics is visible. This is expected as a mobile-mobile link in particular situations can exhibit double Rayleigh behavior ([6], [7]).

It is clear that the links from AP1 have approximately equal gains to the two UEs, while the links from AP2 have higher gain to UE2 than to UE1. Most significantly, the links between the two UEs have significantly lower average gains than the links between UEs and APs. The explanation lays in two

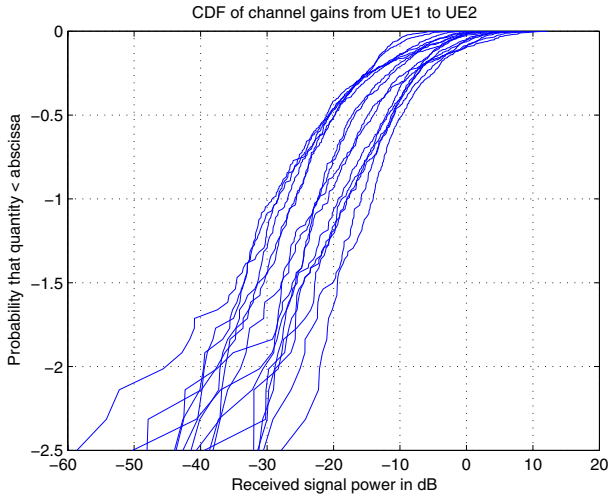


Fig. 4. CDFs of gains between UEs

types of effects. The first one is body shadowing induced by the presence of the users' torso. For example the link between AP2 and UE1 is always obstructed by the body of the user, and therefore is on average 20dB lower than the link between AP2 and UE2 despite the fact that the distance between UEs can be significantly shorter than the distance between the UEs and AP2. The second effect is the near field loading of the antennas due to the handling. [8] found terminal attenuations of about 10dB compared to free space. Thus the links between the UEs are subject to this disturbance at both ends, while it only appears at one end for the AP links. Finally, the branch powers can vary significantly (10dB) for different transmit and receive antenna combinations on the links connecting any two communicating entities. This indicates that there would be a significant benefit from antenna selection techniques. They would provide most of the diversity gain without requiring advanced processing (like maximum ratio or equal gain combining would).

TABLE I
STATISTICS OF SHORT TERM SIGNAL POWER CORRELATIONS

Links	$\langle \rho \rangle$	σ_ρ	ρ_{min}	ρ_{max}
AP-UE1	0.16	0.13	-0.12	0.54
AP-UE2	0.13	0.15	-0.17	0.57
UE1-UE2	0.10	0.16	-0.20	0.55
UE1-AP-UE2	0.00	0.07	-0.12	0.16
UE2-UE1-AP	0.01	0.16	-0.26	0.59
UE1-UE2-AP	0.11	0.11	-0.13	0.42

The short term link correlations ρ are given in Table I. It follows that all 4x4 trunks are practically decorrelated (three upper rows). Links having a UE as a common node have the tendency to exhibit slightly higher correlations than they would have if the AP were a common node. This can be explained by the near field loading on the UE side, which dominantly influences the channel state.

IV. RATE IMPROVEMENT IN SHORT RANGE RELAYING SYSTEMS

We use the measurements described in the previous section and apply to them the relaying principles developed in Section II. The analysis in [9] normalized the links so that the links from the AP to the relay and to the destination had the same average gain, and varied the average gain of the relay link. In this paper we normalize so that the average gain from AP1 to the destination is 10dB. With this normalization that preserves the relative properties of the gains, the only situation where relaying becomes a preferred option relative to direct transmission when AP2 acts as the origin, UE2 acts as the relay and UE1 acts as the destination. Therefore we only analyze these measurements.

We will not investigate the effect of different coding losses on the various types of links (origin- destination/ origin- relay/ relay-destination). Instead we set all the coding losses to 8dB. Finally for all our calculations, we assume that λ_c can be selected from the set $\Lambda = \{0.25, 0.5, 0.75\}$. Clearly, the finer

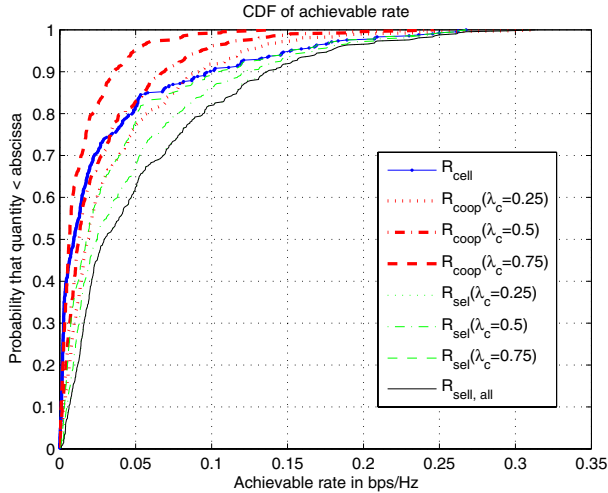


Fig. 5. Rate improvement with relaying

the search in λ_c , the better the performance of relaying will be.

The measurements involved multiple antennas at each transmitting and receiving end. The algorithms defined earlier can be generalized to multiple input- multiple output (MIMO) systems, but for our calculations we concentrate on the single input-single output (SISO) link performance.

A. Illustration of rate improvement

We select one antenna at each end of the communications links, and consider its performance as indicative of the overall link quality. Figure 5 shows that relaying can indeed improve the achievable rate. Relaying alone can do so for an appropriate choice of fixed λ_c . In this case, the optimum choice is $\lambda_c = 0.25$, i.e. when most of the energy is expended on the link from the relay to the destination. This is due to the fact that the link from the AP to the relay has a significantly higher gain. If the system can further select between direct and relayed transmission, an additional rate improvement can be achieved. Moreover, by using relaying, we introduce link diversity, which is manifested in the change of steepness of the curves. The rate advantage is more clear in the ergodic rather than in the outage sense.

Figure 6 shows the optimum selection of λ_c over the route. $\lambda_c = 0.25$ is the value that is selected most frequently. This means that in these settings, λ_c need not be updated very frequently, which reduces the feedback overhead requirements of the system.

B. Statistics of rate improvement over the possible links

Let (i,j,k) denote a system that uses the i -th AP2 antenna as the origin, the j -th UE2 antenna as the relay R, and the k -th UE1 antenna as the destination $D(i, j, k \in \{1, 2, 3, 4\})$. For each (i,j,k) we can define the percentage of time that relaying is preferred to direct transmission (for fixed or variable λ_c), and the rate improvement over the median rate of the direct link.

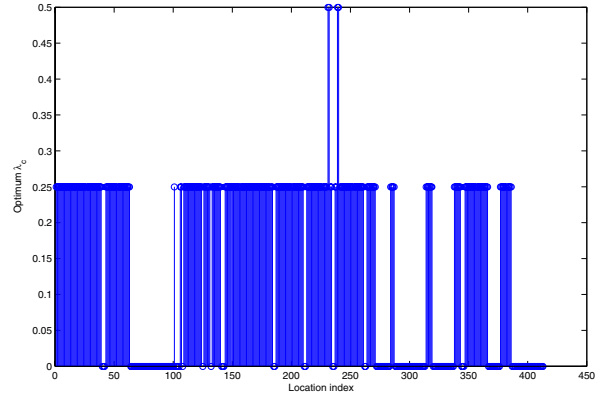


Fig. 6. Optimum λ_c

TABLE II
RATE IMPROVEMENT STATISTICS OVER THE LINKS (I,J,K)

		min	Mean	MAX
% relay usage	$\lambda_c = 0.25$	20%	40%	78%
	$\lambda_c = 0.5$	13%	34%	71%
	$\lambda_c = 0.75$	5 %	22%	54%
	Optimum λ_c	20%	41%	79%
Rate improvement	$\lambda_c = 0.25$	5%	78%	319%
	$\lambda_c = 0.5$	4%	52%	207%
	$\lambda_c = 0.75$	0%	26%	99%
	Optimum λ_c	5%	78%	319%

If we repeat these calculations for all triplets (i,j,k) , we can investigate the statistics over the possible antenna combinations. Table II shows the minimum, mean and maximum percentage of relay use, as well as the corresponding improvement in rate. Clearly, relaying is frequently used and can provide a huge rate improvement. The amount of improvement depends strongly on the choice of (i,j,k) .

V. RATE IMPROVEMENT WITH RELAY ANTENNA SELECTION

We set all the coding losses to 8dB. and assume that $\Lambda = \{0.25, 0.5, 0.75\}$.

A. Illustration of rate improvement

We again select one antenna at AP2 and one antenna at the destination UE1, but we allow the relay link to select an antenna from the possible 4 at the relay node UE2 so as to maximize the achievable rate.

Figure 7 shows that choosing the appropriate relaying antenna can significantly improve the achievable rate. The comparison of Figure 7 and Figure 5 clearly illustrates the significant benefit that can result from relay antenna selection. Indeed the relay antenna selection appears to be more effective in increasing the average achievable rate that the selection of λ_c .

Figure 8 shows the optimum selection of λ_c and relay antenna index over the route, if λ_c is fixed and if it is allowed to vary. Clearly $\lambda_c = 0.25$ is the value that is

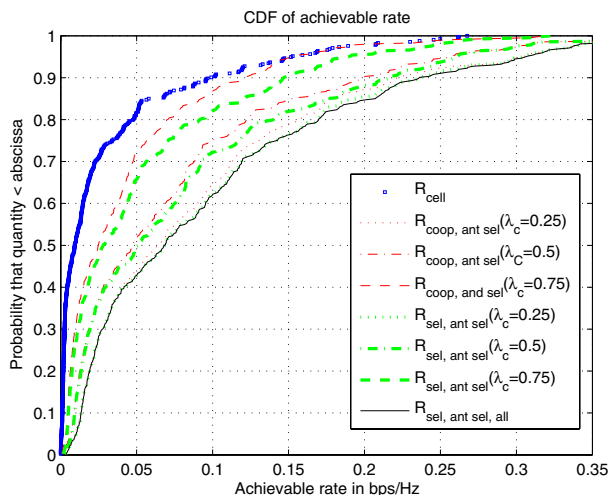


Fig. 7. Rate improvement with relaying and antenna selection

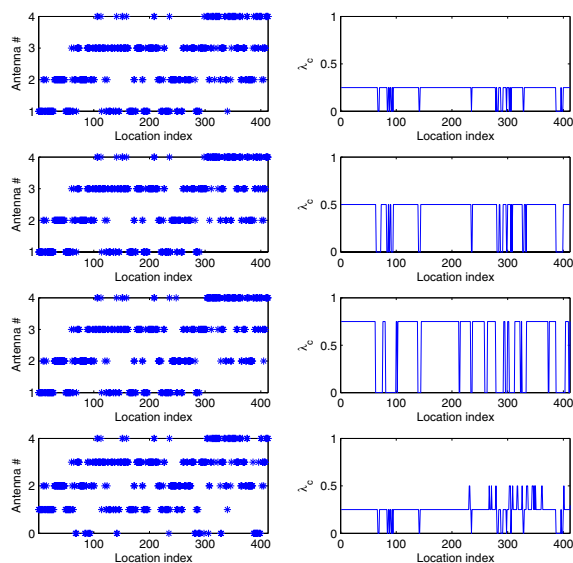


Fig. 8. Optimum λ_c

selected most frequently. However, even for fixed λ_c there are rapid variations in the selection of the optimal relay antenna. This means that in these settings, although λ_c need not be updated very frequently, the antenna index would have to. This increases the feedback overhead requirements of the system.

B. Statistics of rate improvement over the possible links

Let (i,k) denote a system that uses the i -th AP2 antenna as the origin and the k -th UE1 antenna as the destination D ($i, k \in \{1, 2, 3, 4\}$). For each (i,k) we can define the percentage of time that relaying is preferred to direct transmission if the relay node can also select the optimum antenna for the relaying. If we repeat these calculations for all pairs (i,k) ,

TABLE III
RATE IMPROVEMENT

% relay usage	$\lambda_c = 0.25$	min	Mean	MAX
	$\lambda_c = 0.5$	43%	67%	94%
	$\lambda_c = 0.75$	34%	58%	92%
	Optimum λ_c	22%	41%	75%
Rate improvement	$\lambda_c = 0.25$	44%	67%	95%
	$\lambda_c = 0.5$	38%	207%	648%
	$\lambda_c = 0.75$	39%	144%	451%
	Optimum λ_c	7%	69%	222%
		40%	208%	648%

we can investigate the statistics over the possible antenna combinations. Table III shows the minimum, mean and maximum percentage of relay use, as well as the corresponding improvement in rate.

VI. CONCLUSIONS

In this paper we investigated the performance of relaying schemes, based on actual channel measurements. The measurements involved two access points (APs) and two user terminals, each of which is equipped with 4 antennas. The data allowed for the simultaneous characterization of the links from the APs to the user terminals and between the user terminals. We showed that the links between user terminals are impaired by body shadowing and near field loading, and have therefore much lower gains than the direct links to the APs. This effect is very significant. Relaying is a viable option when one of the links (either AP to R or R to D) is significantly stronger than the others. In this case, an appropriate choice of relaying power and most importantly relay antenna (diversity) can significantly further increase the achievable rate. Specifically, the achievable rate increases on average by a factor of 4 without antenna diversity, and by a factor of more than 6 with diversity.

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