Experimental Performance Evaluation of Multiuser Zero Forcing Relaying in Indoor Scenarios

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***Abstract*— We consider a wireless ad hoc network with single antenna nodes under a two-hop relay traffic pattern. All source-destination pairs communicate concurrently on the same physical channel with the assistance of relay nodes. The gains of the amplify-and-forward relays are assigned such that the interference between different source-destination links is nulled [1]. This essentially realizes a distributed spatial multiplexing gain with single antenna nodes. The main contribution of this paper is the performance evaluation of this approach on the basis of multihop/multinode channel measurements at 5.25 GHz. We provide comprehensive results on the sum rate supported by multiuser zero forcing (ZF) in relaying– and linear distributed antenna systems in an indoor propagation scenario.**
Keywords – cooperative relaying, linear distributed antenna system, ad-hoc networks, spatial multiplexing, multihop/multinode channel measurements

I. Introduction

Spatial multiplexing is mandatory to achieve the extreme bandwidth efficiency of future Gigabit/sec wireless local area networks (WLANs). Multiple Input Multiple Output (MIMO) systems achieve an unprecedented spectral efficiency in a rich scattering environment. As opposed to conventional MIMO systems, distributed antenna systems (DAS) employ multiple antennas, which are not colocated at one site [2]. Recently, cooperative relaying schemes have been proposed to improve wireless communication in multinode networks. To date cooperative relaying schemes have primarily been proposed to achieve diversity [3], [4]. In [5], [6] the authors propose distributed antenna systems and linear relaying to relax the rich scattering requirement of conventional MIMO signalling. Upper and lower bounds on the capacity of MIMO wireless networks are given in [7].

In [1] the authors have proposed a multiuser relaying scheme, which nulls the interference between different source-destination pairs by an appropriate gain allocation at amplify-and-forward relays. The relays retransmit an amplified version of their received signal without decoding it. When the relaying nodes are autonomous, i.e., they don't exchange data apart from channel state information, we refer to this scheme as *linear relaying* (LinRel). If the relays are connected via a backbone, we speak of a *linear distributed antenna system* (LDAS). In a companion submission [8] this scheme is analysed for noisy channel state information. The main focus of the present paper is to verify the multiuser zero forcing approach on the basis of measured multihop/multinode channel impulse responses.

The remainder of the paper is organised as follows: In Section II we describe the system model and summarise our assumptions. The concept of multiuser zero forcing is discussed in Section III. In Section IV we describe the channel measurements that were used to evaluate the relaying schemes. Finally, in Section V we give comprehensive performance results of multiuser zero forcing based on the measurements.

Notation: In this paper $(\cdot)^{\mathrm{T}}$, $(\cdot)^*$, $(\cdot)^{\mathrm{H}}$, $(\cdot)^+$, $\mathrm{tr}(\cdot)$ stand for the transpose, conjugate complex, conjugate complex transpose, Moore Penrose inverse and trace operation, respectively. '$\mathbf{I}$' denotes the identity matrix. 'diag($\overrightarrow{d}$)' is a diagonal matrix with the elements of $\overrightarrow{d}$ on its main diagonal and '$\mathrm{diag}(\mathbf{D})$' a vector containing the diagonal elements of $\mathbf{D}$.

II. System Model

We consider a wireless network where all nodes are within radio range of each other. N_{a} source-destination pairs communicate concurrently on the same physical channel with the assistance of N_{r} relay nodes. The communication follows a two-hop relay traffic pattern, i.e., each transmission cycle includes two channel uses: one for the uplink transmission from the sources to all relays and one for the downlink transmission from the relays to the destinations. **Figs. 1** and **2** show the system configuration and the compound signal model, respectively.

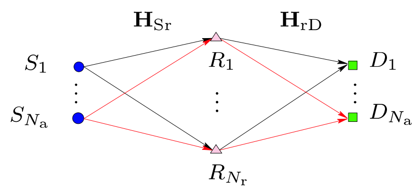

Fig. 1. Two hop relay system configuration

The scalar transmit symbols are stacked in the vector

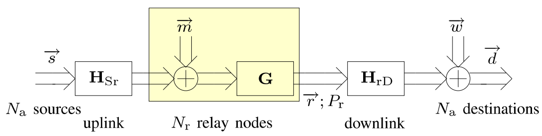

Fig. 2. Signal model

$\overrightarrow{s} \in \mathbb{C}^{N_{\mathrm{a}}}$. Each source is assumed to have the same transmit power $\sigma_{\mathrm{s}}^2 = \frac{P_{\mathrm{s}}}{N_{\mathrm{a}}}$, where P_{s} is the total transmit power. The source signal vector $\overrightarrow{s}$ is first transmitted over the uplink channel matrix $\mathbf{H}_{\mathrm{Sr}} \in \mathbb{C}^{N_{\mathrm{r}} \times N_{\mathrm{a}}}$ to the relays. The vector $\overrightarrow{m} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_{\mathrm{m}}^2 \mathbf{I}_{N_{\mathrm{r}}}\right)$ comprises the AWGN contributions at the relay nodes. After multiplication with the gain matrix $\mathbf{G}$, the signal $\vec{r}$ is passed through the downlink channel matrix $\mathbf{H}_{\mathrm{rD}} \in \mathbb{C}^{N_{\mathrm{a}} \times N_{\mathrm{r}}}$ to the N_{a} single antenna destination nodes. The vector $\vec{w} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_{\mathrm{w}}^2 \mathbf{I}_{N_{\mathrm{a}}}\right)$ comprises the AWGN contribution at the destinations. For all numerical results we let $\sigma_{\mathrm{w}}^2 = \sigma_{\mathrm{m}}^2 := \sigma_{\mathrm{wm}}^2$ and use the same sum transmit power at the sources and at the relays. The signals at the destinations are stacked in the vector

$$\vec{d} = \mathbf{H}_{\mathrm{rD}} \mathbf{G} \mathbf{H}_{\mathrm{Sr}} \cdot \vec{s} + \mathbf{H}_{\mathrm{rD}} \mathbf{G} \cdot \vec{m} + \vec{w} = \qquad (1)$$

$$= \mathbf{H}_{\mathrm{SD}} \vec{s} + \vec{n}_{\mathrm{wm}}, \qquad (2)$$

where $\mathbf{H}_{\mathrm{SD}}$ is called the *equivalent channel matrix* and $\vec{n}_{\mathrm{wm}}$ the *equivalent noise vector*. The components of $\vec{n}_{\mathrm{wm}}$ are spatially no longer white.

III. Multiuser Zero Forcing

The relays in the system configuration shown in **Fig. 1** shall assist the communication between the source-destination pairs such that the transmit data of source node i is received by destination i without interference from other sources. The relay nodes perform zero forcing in order to achieve this. To be able to calculate the average sum rate, we will in the following derive the SNR at each destination node. Then we can easily calculate the mutual information for the source-destination link i of channel realisation j. Accumulation of all source-destination pairs and averaging over all realisations delivers the average sum rate

$$C = \mathrm{E}_j \left[\frac{1}{2} \sum_{i=1}^{N_{\mathrm{a}}} \log_2 \left(1 + \mathrm{SNR}_i^{(j)} \right) \right]. \qquad (3)$$

The factor $\frac{1}{2}$ comes from the fact that we need two timeslots for the transmission.

A. Linear Relaying (LinRel)

For the linear relaying case, we assume perfect global channel knowledge at the relays, i.e., all relays know the instantaneous uplink channel $\mathbf{H}_{\mathrm{Sr}}$ as well as the instantaneous downlink channel $\mathbf{H}_{\mathrm{rD}}$ perfectly. However, they only have local signal knowledge, which means that they only know the signals they receive. They have no knowledge about the signals at the other relays. As a consequence the gain matrix $\mathbf{G}$ is diagonal. It comprises the N_{r} gain factors on its main diagonal: $\mathbf{G} := \mathbf{D}_{\mathrm{r}} = \mathrm{diag}\left(\vec{d}_{\mathrm{r}}^{*}\right)$. Let $\vec{h}_{\mathrm{Sr}}^{(q)} \equiv \mathbf{H}_{\mathrm{Sr}}[:, q]$ be the vector of channel coefficients from the source q to all relays and $\vec{h}_{\mathrm{rD}}^{(p)\,\mathrm{T}} \equiv \mathbf{H}_{\mathrm{rD}}[p, :]$ the vector of channel coefficients from all relays to destination p. We define a matrix with the columns

$$\mathbf{H}[:, k] \equiv \vec{h}_{\mathrm{rD}}^{(p)} \odot \vec{h}_{\mathrm{Sr}}^{(q)} \; \forall \, p, q \in \{1, \ldots, N_{\mathrm{a}}\} \text{ and } p \neq q, \qquad (4)$$

where $\odot$ denotes the Hadamard (element-wise) product. The interference between different source-destination links is nulled, if the relay gain vector $\vec{u} = \mathrm{diag}\left(\mathbf{D}_{\mathrm{r}}^{*}\right)$ satisfies [1]

$$\vec{u}^{\mathrm{H}} \cdot \mathbf{H} \equiv \mathbf{0}. \qquad (5)$$

In [1] the authors introduce a relay gain allocation based on a *zero forcing projection* of an asymptotically optimum gain vector $\vec{d_A} = \mathrm{diag}\left(\mathbf{H}_{\mathrm{Sr}} \mathbf{H}_{\mathrm{rD}}\right)$. Let $\mathbf{Z} = \mathrm{null}\left(\mathbf{H}^{\mathrm{H}}\right)$ be the null space of $\mathbf{H}$. In [1] the zero forcing gain vector is defined by the projection of $\vec{d_A}$ on the null space $\vec{u} \equiv \mathbf{Z}\mathbf{Z}^{\mathrm{H}} \vec{d_A}$. We refer to this class of gain vectors as *multiuser zero forcing relaying*. The approach is very efficient to achieve a distributed spatial multiplexing gain. At least $N_{\mathrm{a}}^2 - N_{\mathrm{a}} + 1$ relays are needed to be able to perform the projection. Otherwise the null space of the matrix $\mathbf{H}$ might be empty, if $\mathbf{H}$ has full rank. We refer to the case that $N_{\mathrm{r}} = N_{\mathrm{a}}^2 - N_{\mathrm{a}} + 1$ as *minimum relay configuration*.

The SNR at destination node p is in this case

$$\mathrm{SNR}_{\mathrm{D}_p} = \frac{\left|\mathbf{H}_{\mathrm{SD}}[p,p]\right|^2 \cdot \sigma_{\mathrm{s}}^2}{\sigma_{\mathrm{mw}}^2 \left(\mathbf{H}_{\mathrm{rD}}[p,:] \mathbf{G} \mathbf{G}^{\mathrm{H}} \mathbf{H}_{\mathrm{rD}}^{\mathrm{H}}[:,p] + 1 \right)}. \qquad (6)$$

B. Linear Distributed Antenna System (LDAS)

In a linear distributed antenna system the relays are connected by a backbone over which they can exchange data. As in the linear relaying case, they are assumed to have perfect global channel knowledge. However, because of the backbone, they also have global signal knowledge, i.e., they know the signals at all relays. As a consequence, the gain matrix $\mathbf{G}$ no longer has to be diagonal. We distinguish two cases:

1) The N_{a} sources as well as the destinations are connected among themselves and can process the received data jointly.
2) The system comprises N_{a} independent single antenna sources and destinations.

1) Joint signal processing at source and destination: Consider for example the case of colocated antennas at the source and destination, where the transmit and receive signals can be processed jointly. The system model in **Fig. 2** can then be diagonalized [1]. Let $\mathbf{H}_{\mathrm{Sr}} = \mathbf{U}_{\mathrm{Sr}} \mathbf{\Sigma}_{\mathrm{Sr}} \mathbf{V}_{\mathrm{Sr}}^{\mathrm{H}}$ and $\mathbf{H}_{\mathrm{rD}} = \mathbf{U}_{\mathrm{rD}} \mathbf{\Sigma}_{\mathrm{rD}} \mathbf{V}_{\mathrm{rD}}^{\mathrm{H}}$ be the singular value decomposition of the uplink and the downlink channel matrix, respectively. At the sources no power loading is done and we assume a gaussian codebook in order to achieve capacity. This means that the transmit samples are i.i.d. complex normal. Then the multiplication of $\vec{s}$ with the unitary matrix $\mathbf{V}_{\mathrm{Sr}}^{\mathrm{H}}$ does not change its statistics. For capacity considerations, $\mathbf{V}_{\mathrm{Sr}}^{\mathrm{H}}$ can thus be omitted. As the receiver has perfect channel state information and the noise vector $\vec{w}$ is white, $\mathbf{U}_{\mathrm{rD}}$ can be dropped for the same reason. The gain matrix $\mathbf{G}$ can be chosen such that

$$\mathbf{G} = \mathbf{U}_{\mathrm{Sr}}^{\mathrm{H}} \mathbf{D} \mathbf{V}_{\mathrm{rD}}. \qquad (7)$$

The resulting diagonal system model in **Fig. 3** is obtained with the fact that the statistics of white noise is not influenced by the multiplication with the unitary matrix $\mathbf{U}_{\mathrm{Sr}}^{\mathrm{H}}$. The following

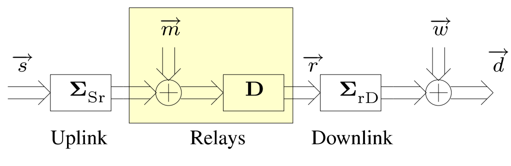

Fig. 3. Diagonal system model

constraints are imposed on the LDAS system in order to derive a lower bound for the mutual information of the system:

- The equivalent gain matrix $\mathbf{D}$ is diagonal. [1] refers to this case as *stream-LDAS*.
- The singular values are sorted in decreasing order
- Uniform allocation of the total support node transmit power P_r across the first $N = \min(N_\mathrm{a}, N_\mathrm{r})$ downlink eigenmodes.
- No transmit power allocation to the remaining eigenmodes.

With these constraints, the equivalent gain factors of the nonzero eigenmodes are

$$d_n = \sqrt{\frac{\sigma_\mathrm{s}^2}{\sigma_{\mathrm{Sr},\,n}^2 \cdot \sigma_\mathrm{s}^2 + \sigma_\mathrm{m}^2}} \quad \forall \quad i = 1, .., N_\mathrm{r}, \tag{8}$$

where $\sigma_{\mathrm{Sr},\,n}$ is the singular value of the nth uplink eigenmode. These gains assure that the sum power constraint at the relays is met. The uplink and downlink SNR on the n-th eigenmode are then [1]

$$\mathrm{SNR}_{\mathrm{U},\,n}^{(j)} = \frac{\sigma_\mathrm{s}^2 \cdot \sigma_\mathrm{Sr}^{(n,j)\,2}}{\sigma_\mathrm{m}^2}, \text{ and } \mathrm{SNR}_{\mathrm{D},\,n}^{(j)} = \frac{P_\mathrm{r} \cdot \sigma_\mathrm{rD}^{(n,j)\,2}}{N \cdot \sigma_\mathrm{w}^2} \tag{9}$$

for each realisation j. The concatenated SNR is calculated by

$$\mathrm{SNR}_n^{(j)} = \frac{\mathrm{SNR}_{\mathrm{U},\,n}^{(j)} \cdot \mathrm{SNR}_{\mathrm{D},\,n}^{(j)}}{\mathrm{SNR}_{\mathrm{U},\,n}^{(j)} + \mathrm{SNR}_{\mathrm{D},\,n}^{(j)} + 1}. \tag{10}$$

2) Separated sources and destinations: For this configuration the gain matrix $\mathbf{G}$ of the system model shown in **Fig. 2** has to be designed such that the concatenation of uplink channel $\mathbf{H}_\mathrm{rD}$, gain matrix $\mathbf{G}$, and downlink channel $\mathbf{H}_\mathrm{Sr}$ results in a diagonal matrix $\mathbf{D}$. The gain matrix is found to be

$$\mathbf{G} = \mathbf{H}_\mathrm{rD}^\mathrm{H} \left(\mathbf{H}_\mathrm{rD}\mathbf{H}_\mathrm{rD}^\mathrm{H}\right)^{-1} \mathbf{D} \left(\mathbf{H}_\mathrm{Sr}^\mathrm{H}\mathbf{H}_\mathrm{Sr}\right)^{-1} \mathbf{H}_\mathrm{Sr}.$$

In order to keep the sum power constraint at the relays, $\mathbf{D}$ has to be scaled accordingly. To ensure a fair transmission, the signal strength at all destination nodes shall be the same. This implies that $\mathbf{D} = c \cdot \mathbf{I}$, where $c \in \mathbb{R}$ is a scaling factor. The relay power constraint states that

$$P_\mathrm{r} = c^2 \cdot P_\mathrm{r}\Big|_{\mathbf{D}=\mathbf{I}} \stackrel{!}{=} P_\mathrm{s}. \tag{11}$$

Thus the gain matrix is chosen to be

$$\mathbf{G} = c \cdot \mathbf{H}_\mathrm{rD}^\mathrm{H} \left(\mathbf{H}_\mathrm{rD}\mathbf{H}_\mathrm{rD}^\mathrm{H}\right)^{-1} \left(\mathbf{H}_\mathrm{Sr}^\mathrm{H}\mathbf{H}_\mathrm{Sr}\right)^{-1} \mathbf{H}_\mathrm{Sr}, \tag{12}$$

with the scaling factor

$$c = \sqrt{\frac{P_\mathrm{s}}{\mathrm{tr}\left(\sigma_\mathrm{s}^2 \mathbf{G}_I \mathbf{H}_\mathrm{Sr}\mathbf{H}_\mathrm{Sr}^\mathrm{H}\mathbf{G}_I^\mathrm{H} + \sigma_\mathrm{m}^2 \mathbf{G}_I \mathbf{G}_I^\mathrm{H}\right)}}, \tag{13}$$

where $\mathbf{G_I}$ is the gain matrix for $c = 1$.

IV. Channel Measurements

In order to verify theory and simulation results of *multiuser zero forcing* for single antenna nodes [1], channel measurements with the RACooN Lab [9] have been performed. This is a system comprising 10 single antenna units which can receive and transmit in half duplex mode. We are able to employ user-defined transmit data that can after transmission be processed by a MATLAB process for each node. As the RACooN units are mobile, we can realise arbitrary system topologies. The goal of the measurements was to quantify the $N_\mathrm{a}^2 \cdot N_\mathrm{r}$ SISO transfer functions of a configuration as shown in **Fig. 1**. With this information the average sum rate of the shown *multiuser zero forcing* signal processing schemes can be calculated as shown in Section III.

A. Measurement Setup

Eight independent RACooN nodes are used to represent 2 sources, 2 destinations and 4 relaying nodes. In order to cope with the inherent phase noise, all uplink– and downlink channel coefficients are measured simultaneously. When performing consecutive measurements under the assumption of a quasi static environment, the resulting channels tend to look better than they actually are [10]. The arbitrary phase shift that is applied to the received data, misleadingly increases the rank of the channel matrix. To be able to measure all channels concurrently, each source and each destination transmits a version of an m-sequence of length 127 which is in frequency orthogonal to the other sequences. This is achieved by repetition in the time domain (which makes the spectrum discrete) and a frequency shift that is small compared to the measurement bandwidth. Correlation at the receiver then delivers the channel impulse response.

All measurement sets are classified into the scenarios *open office* and *meeting room*. In both cases, the relays are situated in the four corners of the room. For the *meeting room* scenario, the sources and destinations are located close together in the middle while they are further apart in the *open office* scenario (see **Fig. 4**). The positions of the RACooN units 5,6, and 8 are framed with the solid squares for the meeting room scenario, and with dashed squares for the open office scenario. The positions of the other units did not change. The room where

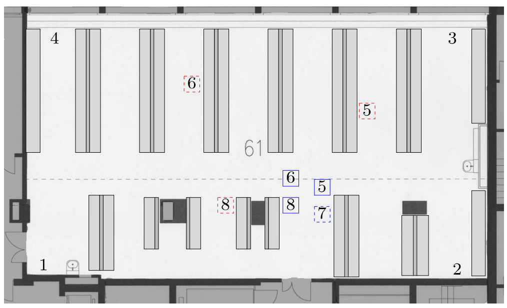

Fig. 4. *Meeting room* and *open office* scenario

the measurements were performed is an electronic laboratory with lots of metallic equipment on long tables (long, light grey rectangles), chairs and cupboards (dark rectangles) acting as scatterers. It has a size of 12.3 m×22.3 m. One side of the room has large windows, the other sides consist of concrete. The units 5 and 6 represented the sources, units 7 and 8 the destinations. All antennas are mounted at a height of about 1.50 m. In order to be able to get a large amount of transfer functions of one configuration, snapshots of the channels were taken about every second. During the whole measurement period of 1000 snapshots, the antennas of the units 5 to 8 were moved at a slow speed and in an arbitrary fashion within a square of size 60 cm×60 cm.

B. Measurement Execution

Due to channel reciprocity of the present scenarios, it suffices to measure the transfer functions from all sources and destinations to all relays in order to describe the configuration. The 16 transfer functions are measured at a center frequency of 5.25 GHz and a bandwidth of 80 MHz. One measurement action consists of the transmission of 128 repetitions of the m-sequence and takes 0.2 ms. The channel is assumed to be constant during this time.

V. Results

In this section, we present the measurement results as well as performance results of the signal processing schemes discussed in Section III. The results of the channel measurements will be used to determine the average sum rate and the performance gain of multiuser zero forcing. It has turned out that apart from the channel characteristics like *delay spread* and *mean excess delay*, the results are not sensitive to the chosen scenario. If not otherwise stated, we will use the measurement results of the *open office* scenario in the following.

A. Measurement Results

As an example, the absolute values of the uplink transfer functions from source unit 5 to all relays, measured in a *open office* scenario are shown in **Fig. 5**. In an OFDM transmission the plots show the absolute values of the entries of $\mathbf{H}_{\mathrm{Sr}}[:,p]$ for each frequency bin. The notch of the transfer functions at

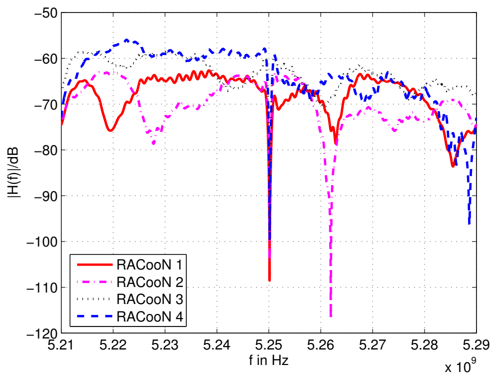

Fig. 5. Transfer functions from unit 6 to units 1-4 in an *open office* scenario

the carrier frequency is due to the spectral properties of the m-sequence.

The average delay spread of the measured channels reaches from 16.7 ns to 29.3 ns, the average mean excess delay from 28.7 ns to 60.2 ns.

B. Performance Results

We consider multiuser zero forcing in linear relaying (LinRel) networks as well as in linear distributed antenna systems (LDAS) [1], as discussed in Sections III-A and III-B. We did however not take the whole 80 MHz bandwidth into account. Instead we constrained ourselves to an OFDM subcarrier at 5.23 GHz. The fading is then frequency non-selective. In the following we will denote a configuration with N_{a} sources, N_{r} relays, and N_{a} destinations as $(N_{\mathrm{a}} \times N_{\mathrm{r}} \times N_{\mathrm{a}})$. The link from source q over relay l to destination p will be referred to as q-l-p link.

1) Average Sum Rate vs. SNR: In order to be able to look at the effects of small scale fading, we normalise the measured channel matrices in a way that shadowing effects are cancelled out. The uplink and downlink channel matrices $\mathbf{H}_{\mathrm{Sr}}^{(j)}$ and $\mathbf{H}_{\mathrm{rD}}^{(j)}$ of all realisations j are normalised such that the average SNR of each source i - relay l - destination i SISO link amounts to a defined value. The averaging is done over all 1000 measured realisations. In **Fig. 6** we give the $(1\times1\times1)$ reference configuration and its block diagram to motivate this kind of normalisation. Considering the reference configuration,

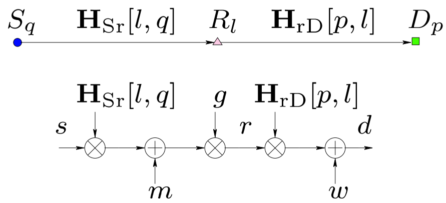

Fig. 6. Reference configuration (top) and appropriate block diagram (bottom)

we want to answer two questions:

1) How does the performance change if we add more relays?
2) How does a second source-destination pair affect the behaviour of the system if the relays perform zero forcing?

We apply a normalisation to the measured channel matrices as described above. It is important to be aware of the fact that the sum power constraint of the relays applies also to the $(1\times1\times1)$ reference configuration. Only that in this case, the gain of the single relay reduces to a scaling factor g. The normalised channel matrices are used to calculate the mutual information of each channel realisation. Averaging over all realisations then delivers the average sum rate.

In **Fig. 7** the average sum rate versus the average SNR is plotted for a multiuser zero forcing signaling scheme. We

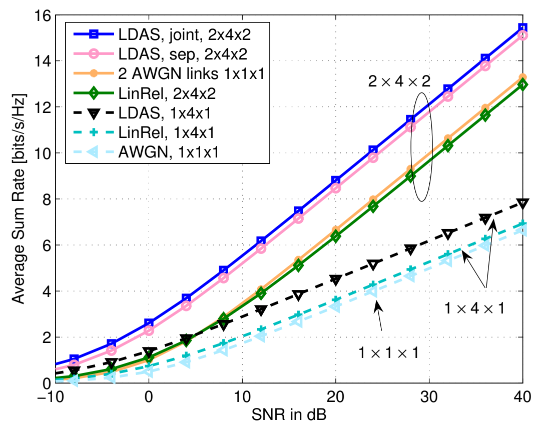

Fig. 7. Average sum rate versus the average SNR

compare the linear distributed antenna system (LDAS) with linear relaying (LinRel). As indicated in the figure, we consider three different source-relay-destination configurations: (1×1×1), (1×4×1) and (2×4×2). The LDAS systems with joint signal processing at the sources and the destinations (*LDAS, joint*) and with separate signal processing at the sources and destinations (*LDAS, sep*) are as described in the Sections III-B.1 and III-B.2. As a reference, the respective AWGN cases are also plotted. For the (1×4×1) as well as for the (2×4×2) case, the linear distributed antenna systems show a higher average sum rate than the AWGN links. This is because of the array gain the relays provide and maximum ratio combining they perform. As expected, the system where the source and the destination can process their data jointly, shows higher average sum rate than the case where there is no cooperation. The linear relaying (LinRel) system is slightly better than the AWGN reference case for 1 source-destination pair and slightly worse for 2 source-destination pairs. The reason is that for the (2×4×2) case, at least three degrees of freedom that are gained by the relays are used for zero forcing (minimum relay configuration). The additional degrees of freedom cannot provide very much extra gain. For the (1×4×1) case, all relays can together perform maximum ratio combining which results in an increase of the average sum rate compared to the AWGN case. Finally, we see that both LDAS and LinRel achieve full spatial multiplexing gain for two source-destination pairs.

For the plot in **Fig. 8**, where we show the CDFs (cumulative distribution function) of the average sum rate, we assume the SNR to be 20dB. The diversity gain of the LDAS system compared to LinRel can be seen by observing the higher slope. For the (2×4×2) configuration, the 1% outage rate of *LDAS, joint* and *LDAS, sep* is 3.5 bits/s/Hz and 4.3 bits/s/Hz higher than of *LinRel*, respectively.

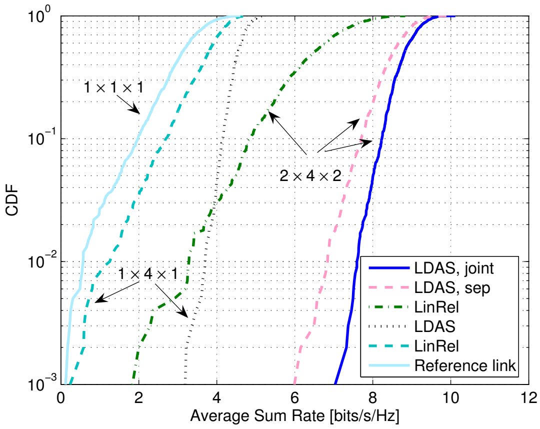

Fig. 8. CDF of the sum rate at an average receive SNR of 20dB

We now consider a communication system with a thermal noise power spectral density of $\frac{N_0}{2} = -174\text{dBm/Hz}$ and a noise figure of 10dB. How much transmit power per source node do we need to achieve a certain average sum rate? The abscissa of **Fig. 9** shows the transmit power σ_s^2 of a (1×4×1) and a (2×4×2) system, respectively. The curves imply that

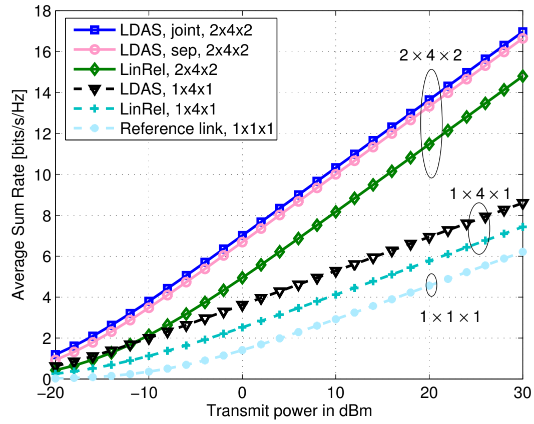

Fig. 9. Average sum rate versus the transmit power per source node

for linear relaying, about 7dB more transmit power is needed than for a linear distributed antenna system to achieve the same average SNR at the destinations. The curve for the (1×1×1) reference scenario shows the worst result of the plot. This is due to the fact that for this case, no spatial diversity and no maximum ratio combining can be exploited.

VI. Conclusions

In this paper we considered a wireless network with a two-hop relay traffic pattern. We presented comprehensive performance results of *multiuser zero forcing* based on indoor channel measurements at 5.25 GHz for one and two source-destination pairs. *Linear relaying* (LinRel) as well as *linear distributed antenna systems* (LDAS) were shown to achieve full spatial multiplexing gain. We also showed that LDAS achieves an additional diversity gain compared to LinRel and an AWGN reference scenario.

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