Distributed Antenna Arrays versus Cooperative Linear Relaying for Broadband Indoor MIMO Wireless

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Abstract **– We investigate distributed antenna systems and cooperative relaying to improve the throughput between a MIMO source and a MIMO destination node in a Line-of-Sight dominated indoor environment with poor scattering. We derive the capacity for different traffic patterns and give typical numerical results. The main conclusion is surprising: a simple amplify&forward linear relaying approach outperforms distributed antenna systems in many cases under the considered traffic patterns. On this basis it seem likely, that cooperative relaying will be key in future MIMO enhanced WLANs beyond 5 GHz due to the increasingly poor scattering of the channel.**

1 INTRODUCTION

It is well known, that multiple transmit and receive antennas improve the performance of wireless communication. These Multiple Input/Multiple Output (MIMO) systems achieve an unprecedented spectral efficiency in a rich scattering environment [7]. As opposed to most MIMO systems, distributed antenna systems (DAS) employ multiple antennas, which are not co-located at one site [5, 6]. Recently cooperative relaying schemes have been proposed to improve wireless communication in multi-node networks. They are based on the idea to have multiple idle nodes assist in the communication of active nodes. To date cooperative relaying schemes have primarily been proposed to achieve diversity [2,3,4]. In [8] bounds on the capacity of a Gaussian relay network with multiple relays and Single Input/Single Output (SISO) nodes have been derived. Our results may be considered an extension of the expressions in [8] to the MIMO case.

Due to the availability of spectrum future Wireless Local Area Networks (WLAN) will operate beyond 5 GHz. Link level throughput requirements will require a spectral efficiency beyond 10 bit/channel use. MIMO wireless may be the only feasible approach. A major problem however is the rich scattering requirement, as the propagation channel becomes increasingly Line-of-Sight (LoS) beyond 5 GHz.

In this paper we investigate distributed antenna systems and cooperative linear relaying to improve the throughput between a MIMO source and a MIMO destination node in a LoS dominated indoor environment. The main contributions are capacity expressions for different traffic patterns and typical numerical results. Our main conclusion is surprising: a simple amplify&forward linear relaying approach outperforms DAS in many cases under the considered traffic patterns. Both for DAS and for cooperative relaying the performance is quite insensitive to the scattering properties of the channel. The paper is organized as follows: in Section 2 we introduce the system model and the considered traffic patterns. In Section 3 we give expressions for the capacity under our traffic patterns. In Section 4 we compare DAS and cooperative relaying for MIMO on the basis of numerical results on the 10% outage capacity.

2 SYSTEM MODEL

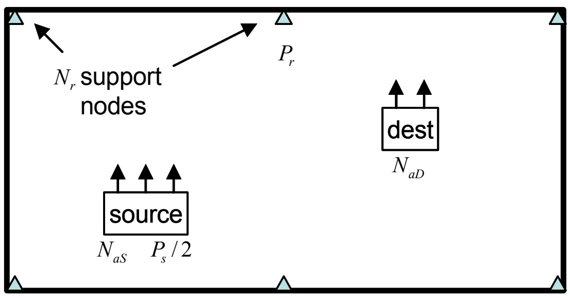

Fig. 1: Typical deployment in a room.

Fig. 1 shows a typical deployment of the MIMO wireless system under consideration in this paper. The source has N_{aS} antenna elements and transmits with average power $P_S/2$. We assume that the source has no channel state information (CSI) and thus can not apply power loading. The destination features N_{aD} antenna elements. The communication between source and destination is assisted by N_r support nodes. Each support node transmits with average power P_r. In this paper we are concerned with the throughput between source and destination. Due to the random positions of source and destination the throughput is a random variable. The purpose of the support nodes is to maximize a throughput related cost function (e. g. mean throughput).

We consider three traffic patterns. **Traffic pattern T0** is the reference case. The source and destination communicate directly. The support nodes are not engaged in the communication. T0 reflects a peer-to-peer communication mode. In **traffic pattern T1** the support nodes are the distributed antenna elements of a central access point (AP). They are linked through a wired backbone network. As a result all received signals of the distributed antenna system may be processed jointly in the access point. We consider two

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flavours of T1. Under T1a all support nodes transmit the same signal on the downlink (simulcast) so as to improve coverage. Under T1b the AP uses different codebooks for each support node so as to achieve capacity. T1 reflects an infrastructure mode. **Traffic pattern T2** relates to an infrastructureless wireless network. The support nodes are not linked by a wired infrastructure. Rather they act as cooperative relays to improve the communication between source and destination.

	T0		T1		T2	
slot	1	2	1	2	1	2
S	TX	TX	TX	-	TX	-
r	-	-	RX	TX	RX	TX
D	RX	RX	-	RX	RX	RX

Fig. 2: Transmit (TX)/Receive (RX) multiplexing for the different traffic patterns.

Fig. 2 illustrates the TX/RX multiplexing for the different traffic pattern. This multiplexing is required, because wireless nodes usually are not able to transmit and receive simultaneously. Under T1 the source transmits in every odd timeslot to the AP (uplink). The AP decodes the signal and transmits it to the destination in every even timeslot (downlink). Note that the destination receives only in even timeslots. It does not exploit the direct path, which may exist between source and destination. Under T2 the source transmits in every odd timeslot. The relays receive in odd timeslots and jointly transmit in even timeslots. Note that the destination receives in all timeslots. In contrast to T1 the destination may additionally exploit the signal, which is received directly from the source. The performance under T2 could be improved further by allowing the source to transmit in all timeslots. We do not consider this case herein, so as to achieve a fair comparison between T1 and T2. As a side benefit T1 and T2 are transparent to the source, i.e. the source signaling is not affected by the traffic pattern.

Notation: The subscript i denotes the timeslot index. The superscript (k) identifies variables associated with support node (k). The channel matrix H_{SD} refers to the direct link from source to destination. The uplink channel from source to support node (k) is $H_{Sr}^{(k)}$, the corresponding downlink channel to the destination is $H_{rD}^{(k)}$. In timeslot (channel use) i the source transmits the signal vector $\vec{s}_i$ and the destination receives the decision vector $\vec{d}_i$. The additive white Gaussian noise (AWGN) variables at the antenna elements of the destination have the variance σ_w^2 and comprise the vector $\vec{w}_i$.

Fig. 3 shows the receive part of the support node (k). The local AWGN contribution is $\vec{m}_i^{(k)}$. Each element has the variance σ_m^2. The local oscillator at the support node determines the local phase reference $\phi^{(k)}$ against which the channel matrix is measured. The diagonal matrix $D_\phi^{(k)} = I \cdot \exp\left(j \cdot \phi^{(k)}\right)$ - with I = identity matrix - considers the phase shift due to the local phase reference. If a global phase reference is available, $\phi^{(k)} = 0$ for all support nodes. Without global reference, $\phi^{(k)}$ is a uniform random variable across all support nodes. Under traffic pattern T2 we constrain our attention to linear relay nodes. These relays amplify the received signal vector and forward it in another timeslot. The gain matrix $G_r^{(k)}$ (Fig. 3) describes this operation.

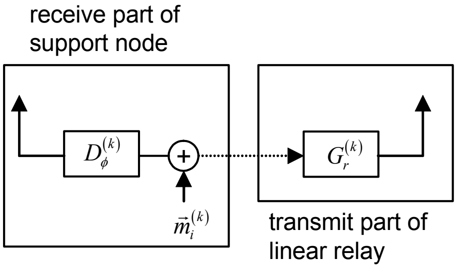

Fig. 3: Support node.

To emphasize the impact of the support nodes, we assume an i.i.d. Ricean fading channel with path loss exponent $\gamma = 2$. Variation of the Ricean k-factor k_{Rice} zooms between a free space propagation scenario ($k_{Rice} = \infty$) and a rich scattering situation ($k_{Rice} = 0$). Source and destination employ uniform linear array antennas with $\lambda/2$-spaced elements. Our results are based on a block fading channel model, i.e. the channel matrices are constant over 2 timeslots. Some further assumptions are (i) perfect channel estimation at any receiver, (ii) perfect frequency synchronization at support nodes.

3 CAPACITY

For the ease of notation we pile the N_r source-to-support node channel matrices $H_{Sr}^{(k)}$ in the compound matrix H_{Sr} and the corresponding support node-to-destination channel matrices $H_{rD}^{(k)}$ in the compound matrix H_{rD}. The support node noise vectors $\vec{m}_i^{(k)}$ are stacked in the compound noise vector $\vec{m}_i$. The gain matrices $G_r^{(k)}$ are arranged along the main diagonal of the compound gain matrix G_r and the phase matrices $D_\phi^{(k)}$ along the main diagonal of the compound phase matrix D_ϕ.

Traffic pattern T0: the destination receives the signal $\vec{d}_i = H_{SD} \cdot \vec{s}_i + \vec{w}_i$. This is the standard MIMO channel and the capacity/complex dimension/channel use follows readily [7]

$$C_0 = \sum_k \log_2\left(1 + \frac{\left(\sigma_k\right)^2 \cdot P_s}{2 \cdot N_{aS} \cdot \sigma_w^2}\right)$$

Here σ_k are the singular values of the source-to-destination channel matrix H_{SD} and $P_s/2$ is the average source transmit power per channel use.

Traffic pattern T1: the uplink and the downlink channel are standard MIMO channels each. The access point is able to decode the source signal, if the source rate is no larger than the uplink capacity C_{1u}. Conversely the downlink rate is constrained by the downlink capacity C_{1d}. The throughput/complex dimension/channel use from source to destination thus is given by $C_1 = 0.5 \cdot \min(C_{1u}, C_{1d})$. The factor 0.5 results, because the transmission from source to destination involves 2 channel uses under traffic pattern T1. C_{1u} is given by

$$C_{1u} = \sum_k \log_2 \left(1 + \frac{(\sigma_k)^2 \cdot P_s}{N_{aS} \cdot \sigma_m^2} \right)$$

Here σ_k are the singular values of the compound source-support node channel matrix H_{Sr}. The downlink capacity follows as (no power loading)

$$C_{1d} = \sum_k \log_2 \left(1 + \frac{(\sigma_k)^2 \cdot P_r}{\sigma_w^2} \right)$$

Under traffic pattern T1b $\{\sigma_k\}$ are the singular values of the compound support node-to-destination channel matrix H_{rD}. Under traffic pattern T1a all support nodes transmit the same signal (simulcast) and $\{\sigma_k\}$ are the singular values of the equivalent downlink channel matrix $H'_{rD} = H_{rD} \cdot \vec{1}$ - with $\vec{1} = [1 \;\; 1 \;\; \cdots]^T$. Note these differences to C_{1u}.: (i) each support node transmits with the power P_r whereas the source has to distribute the transmit power across all antennas and (ii) the noise variance σ_w^2 at the destination may differ from the noise variance σ_m^2 at the support nodes.

Traffic pattern T2: in timeslot 1 the destination receives a corrupted version $\vec{d}_1 = H_{SD} \cdot \vec{s}_1 + \vec{w}_1$ of the source transmit signal. In timeslot 2 the destination receives a corrupted version of the relay transmit signals (Fig. 3)

$$\vec{d}_2 = H_{rD} \cdot \left(G_r \cdot \left(D_\phi \cdot H_{Sr} \cdot \vec{s}_1 + \vec{m}_1 \right) \right) + \vec{w}_2$$

The noise component $\vec{n}_2$ of $\vec{d}_2$ consists of the local AWGN $\vec{w}_2$ and a linear transformation of the relay noise $\vec{m}_1$. Note that $\vec{n}_2$ is not necessarily white. This has to be considered in the capacity analysis. We define a joint channel matrix H for timeslots 1 and 2 and a joint destination receive vector $\vec{d}$:

$$H = \begin{bmatrix} H_{SD} \\ H_{rD} G_r D_\phi H_{Sr} \end{bmatrix} \qquad \vec{d} = \begin{bmatrix} \vec{d}_1 \\ \vec{d}_2 \end{bmatrix}$$

Let $\vec{n}$ be the noise component of $\vec{d}$. The normalized (σ_w^2) correlation matrix of $\vec{n}$ follows as

$$\Lambda'_{nn} = \left(I_{2N_{aD}} + \begin{bmatrix} 0 & 0 \\ 0 & H_{rD} G_r G_r^H H_{rD}^H \end{bmatrix} \cdot \frac{\sigma_m^2}{\sigma_w^2} \right)$$

The superscript ^{H} denotes conjugate transpose and $I_{2N_{aD}}$ is the $(2N_{aD} \times 2N_{aD})$ identity matrix. Premultiplication of $\vec{d}$ with $(\Lambda'_{nn})^{-1/2}$ whitenes the noise component and we obtain the equivalent channel matrix $H_e = (\Lambda'_{nn})^{-1/2} \cdot H$

The capacity/channel use/complex dimension follows immediately from the singular values $\{\sigma_{e,k}\}$ of H_e.

$$C_2 = 0.5 \cdot \sum_k \log_2 \left(1 + \frac{(\sigma_{e,k})^2 \cdot P_s}{N_{aS} \cdot \sigma_w^2} \right)$$

Again the factor 0.5 results because the transmission from source to destination involves 2 channel uses under this traffic pattern.

4 NUMERICAL RESULTS

In this section we present some typical simulation results for the 10% outage capacity under traffic pattern T0, T1a/b and T2a/b. Fig. 1 shows the simulation setup. We consider a $(100\lambda \times 100\lambda)$ square room. Source and destination have uniform random positions within the room. The support nodes are equi-spaced along the edges of the square. They have one antenna each. The gain allocation at the support nodes under traffic pattern T2 is crucial for the system performance. In this section we consider two different gain allocation algorithms. Under T2a support node (k) only knows the uplink path gain $a_{Sr}^{(k)} = |H_{Sr}[k,:]|^2 / N_{aS}$. Under T2b the support node in addition knows the downlink path gain $a_{rD}^{(k)} = |H_{rD}[:,k]|^2 / N_{aD}$. The gain $g^{(k)}$ of support node (k) is then given by

$$g_{T2a}^{(k)} = \left(P_r / \left(a_{Sr}^{(k)} \cdot P_s + \sigma_m^2 \right) \right)^{1/2}$$

$$g_{T2b}^{(k)} = A \cdot \sqrt{a_{Sr}^{(k)} \cdot a_{rD}^{(k)}} / \left(\left(a_{Sr}^{(k)} \cdot P_s + \sigma_m^2 \right) / N_r + \sigma_m^2 / \sigma_w^2 \cdot a_{rD}^{(k)} \right)$$

The constant A is chosen such, that the average power constraint across all support nodes is satisfied. A support node splits each transmit timeslot in 10 subslots and intentionally applies a different pseudo-random phase shift in each subslot. This introduces a kind of distributed transmit diversity on the downlink.

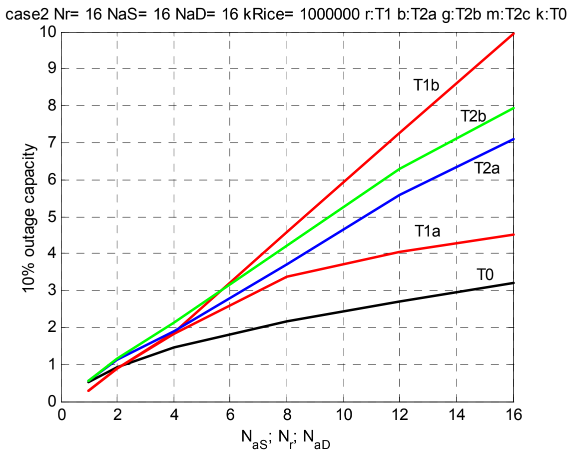

Fig. 4: 10% outage capacity versus the number of source/destination antenna elements.

In Fig. 4 we illustrate the 10% outage capacity of a system with the same number of source antennas N_{aS}, destination antennas N_{aD} and support nodes N_r. The channel has no scattering ($k_{Rice} = \infty$). For this reason H_{SD} has low rank and the capacity increase under T0 is primarily due to the array gain of the destination antenna. Traffic pattern T1 and T2 benefit from the large spatial separation of the support nodes, which increases the rank of H_{Sr} and H_{rD}. The outage capacity of T1b, T2a and T2b increases linearly with the number of antennas. The reduced slope of T2 is due to the AWGN at the support nodes, which is forwarded to the destination. Beyond 8 antennas the improvement of T1a diminishes due to a capacity bottleneck on the downlink (as a result of the simulcast operation the equivalent downlink channel matrix has rank 1). Note the limited benefit of downlink channel state information (T2b versus T2a) in this scenario.

In Fig. 5 we study the impact of the number of support nodes for a fixed number of source/destination antennas $N_{aS} = N_{aD} = 8$. Again the channel has no scattering ($k_{Rice} = \infty$). As long as the number of support nodes is smaller than the number of antennas, T2 outperforms T1. This is particularly important, as T2 requires much less complexity than T1. Only T1b is able to benefit from an excessive number of support nodes however. For a heuristic interpretation assume that source and destination are located in opposite corners of the room. T1a essentially uses the 8 antennas for uplink reception, which are closest to the source. Conversely it uses the corresponding cluster of antennas in the opposite side of the room for downlink transmission to the destination. Both hops span a small distance and the signal to noise ratio (i.e. the capacity) is accordingly high. Under T2 the effective uplink antenna cluster is the same as for T1; due to the lack of wired infrastructure however the same antennas essentially contribute to the destination receive signal. Thus the second hop has to span a longer distance and the receive signal to noise ratio (i.e. the capacity) drops accordingly. The performance of T1a is again essentially limited by the downlink whereas T1b reflects the uplink performance.

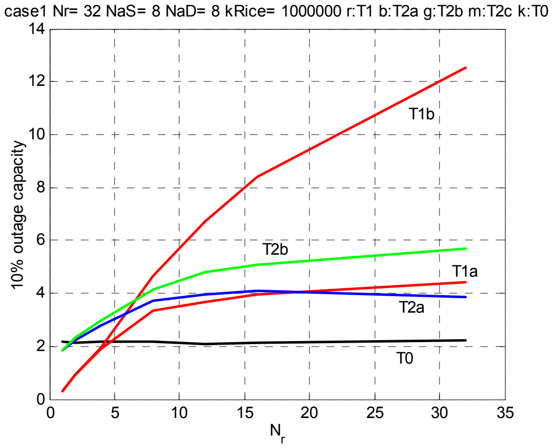

Fig. 5: 10% outage capacity versus the number of support nodes N_r. Source and destination have 8 antenna.

In Fig. 6 we investigate the impact of the Ricean k-factor for $N_{aS} = N_{aD} = N_r = 8$. For $k_{Rice} = 0$ T0 benefits from spatial multiplexing, because the channel has rich scattering. T1 is invariant to the channel characteristic, because the distributed antenna array results in a full rank channel matrix regardless of the scattering properties. T2 benefits from rich scattering, because it exploits the direct path from source to destination. For the same reasons as T1, T2 achieves a spatial multiplexing gain in a poor scattering environment.

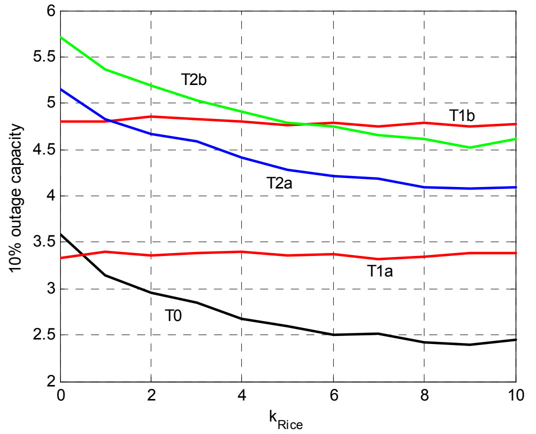

Fig. 6: 10% outage capacity versus the Ricean k-factor

5 CONCLUSIONS

Our main conclusion is that a simple amplify&forward linear relaying approach outperforms distributed antenna systems in many cases under the considered traffic patterns. This is particularly important, because the relaying schemes are much simpler to implement and require no wired infrastructure. Both for DAS and for cooperative relaying the performance is quite insensitive to the scattering properties of the channel. Although much further research is required, we believe that cooperative relaying will be key in MIMO enhanced WLANs beyond 5 GHz due to the increasingly poor scattering channels.

References

[1] D. Gesbert, M. Shafi, D. S. Shiu, P. Smith, and A. Naguib, “From theory to practice: An overview of MIMO space-time coded wireless systems,” *IEEE Journal on Selected Areas in Communications*, to appear, 2003.

[2] N. Laneman, D. Tse, and G. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behaviour,” submitted to *IEEE Trans. Inf. Theory*, Jan. 2002.

[3] A. Sendonaris, E. Erkip, B. Aazhang, „User Cooperation Diversity - Part I and II,” *IEEE Trans. on Communications*, submitted 2002.

[4] P. A. Anghel, G. Leus, M. Kaveh, “Multi-user space-time coding in cooperative networks,” *IEEE ICASP 2003*.

[5] M. V. Clark et al, “Distributed Versus Centralized Antenna Arrays in Broadband Wireless Networks,” *IEEE Vehicular Technology Conference VTC 2001*.

[6] W. Roh, A. Paulraj, “Outage performance of the distributed antenna systems in a composite fading channel,” *IEEE Vehicular Technology Conference, VTC Fall 2002*.

[7] G. Foschini, M. J. Gans, “On limits of wireless communication in a fading environment when using multiple antenna arrays,” *Wireless Personal Communication*, vol. 6, pp. 311-335, March 1998.

[8] M. Gastpar, M. Vetterli, “On the capacity of wireless networks: the relay case,” *IEEE Infocom 2002*.