Multiuser Zero Forcing Relaying with Noisy Channel State Information

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***Abstract*— We consider a wireless ad hoc network with single antenna nodes under a two-hop relay traffic pattern. Some of the nodes in the network form source/destination pairs, while the other nodes serve as amplify and forward relays. The relay gains are assigned such, that the interference between different source/destination links is nulled (multiuser zero forcing relaying). This essentially realizes a spatial multiplexing gain with distributed single antenna nodes. We introduce a specific zero forcing gain allocation and give comprehensive performance results, which include the impact of noisy channel state information and time variant channel coefficients. One of our most intriguing results shows, that in a typical indoor scenario (delay spread < 500ns) multiuser zero forcing relaying at 5GHz and pedestrian speed achieves a six fold increase in the sum rate of the network, even if we take the overhead for the measurement and the dissemination of the channel matrices into account.**

I. Introduction

Pervasive wireless access networks (PWAN) provide ubiquitous short range wireless connectivity for a variety of heterogeneous nodes. They encompass applications ranging from RF identification, Wireless Sensor Networks, Wireless Personal Area Networks to Wireless Local Area Networks. Pervasive wireless networks introduce fundamental new characteristic and requirements: (i) seamless integration of heterogeneous nodes, (ii) heterogeneous quality of service (QoS) requirements, (iii) extreme scalability and adaptivity, (iv) high node density, (v) extremely low cost per node required for ubiquity (vi) low EM exposure required for user acceptance and (vii) extremely nonuniform data traffic with Gbps local hot spots around access points. For a variety of technical and political reasons it is unlikely that the community will agree on a generic pervasive wireless access air interface. To meet the PWAN challenges however we have to design the constituent systems for *cooperation* rather than for *coexistence* only.

To this end in this paper we consider *cooperative relaying* to utilize spatial multiplexing in a dense wireless ad hoc network with *single antenna nodes*. In order to facilitate link adaptation we focus on linear relaying schemes, which are transparent to the modulation and coding schemes used by the sources. In [11] we have proposed a multiuser relaying scheme, which nulls the interference between different source/destination pairs by distributed beamforming. We refer to this scheme as multiuser zero forcing (ZF) relaying. The main contribution of this paper are comprehensive performance results of multiuser ZF relaying, which take both noisy channel state information and time variant channel matrices into account. We show that under very realistic conditions, which include the overhead for channel estimation, multiuser ZF relaying is able to realize a six fold increase in the average sum rate.

Spatial multiplexing is mandatory to achieve the extreme bandwidth efficiency of future Gigabit/sec WLANs [1]. These Multiple Input/Multiple Output (MIMO) systems achieve an unprecedented spectral efficiency in a rich scattering environment. To date the bulk of the work on MIMO wireless has been concerned with co-located antennas at transmitter and/or receiver. Multiuser ZF relaying to the other hand essentially realizes a spatial multiplexing gain with distributed single antenna nodes. In contrast to this relaying approach distributed antenna systems (DAS) employ multiple antennas, which are also not co-located at one site [4,5] but which are connected to a central processor. 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]. In [6,7] we propose distributed antenna systems and linear relaying to relax the rich scattering requirement of conventional MIMO signaling. Upper and lower bounds on the capacity of wireless networks with a relay traffic pattern have been determined in [8]. The system model consists of one source/destination pair, while all other nodes operate as relays in order to assist this transmission. In [9] the analysis of [8] is extended and upper and lower bounds on the capacity of MIMO wireless networks are given.

The remainder of the paper is organized as follows: in Section II we describe the signal model and summarize assumptions and notation. In Section III we introduce multiuser ZF relaying [11]. In Section IV we describe the channel measurement and prediction approach used for our performance results. In Section V we give comprehensive performance results of multiuser ZF relaying and derive approximate expressions for the average sum rate with noisy channel state information.

II. Signal Model

In Fig. 1 we consider a wireless network with N_{node} single antenna nodes. All nodes are within radio range of each other.

The communication follows a two-hop relay traffic pattern. The transmission from the source S_q to its associated destination D_q thus includes two channel uses: one for the uplink transmission from the source to all relays and one for the downlink transmission from the relays to the destination. The relays multiply the received signal with a complex gain prior to retransmission (amplify&forward). They do not perform further signal processing. As a result the relaying operation is transparent to the symbol alphabet used by the source. This greatly facilitates link adaptation, adaptive modulation and deployment in heterogeneous networks. To make coherent combining at the destination possible, all nodes are phase synchronous (i.e. a global phase reference for all local oscillators is established by a suitable protocol). Each node is either in receive or transmit mode (half duplex). We consider a scenario, where N_a source/destination pairs S_q / D_q communicate concurrently on the same physical channel and the remaining $N_r = N_{node} - 2N_a$ nodes serve as amplify&forward relays for all links. We use the notation $(N_a \times N_r \times N_a)$ to denote a configuration with N_a sources, N_r relays and N_a destinations. In this application we utilize the relays to achieve diversity and to orthogonalize the individual source/destination links. We refer to this scenario as *multiuser ZF relaying* scenario. In this paper we constrain our attention to single user detectors; thus destination node D_q attempts to decode the data stream from source S_q while regarding all other signals as interference. Fig. 2 shows the compound signal model. The transmit symbols of the N_a sources are stacked in the transmit symbol vector $\vec{s}$. This vector is transmitted through the uplink channel matrix H_{Sr} to the relay nodes. $H_{Sr}[k,q]$ denotes the channel gain between the source q and the relay k. $\vec{m}$ comprises the AWGN contributions at the relay nodes. It has i.i.d. elements with variance σ_m^2. The received signal at the relay nodes is multiplied with the diagonal gain matrix D_r^H , i.e. each relay performs an amplify&forward operation. The relay node transmit signal $\vec{r}$ is passed through the downlink channel matrix H_{rD} to the N_a single antenna destinations. The received signal at destination p is given by the p-th element of the received vector $\vec{y}$. The vector $\vec{w}$ comprises the AWGN contribution at the destinations. It has i.i.d. elements with variance σ_w^2.

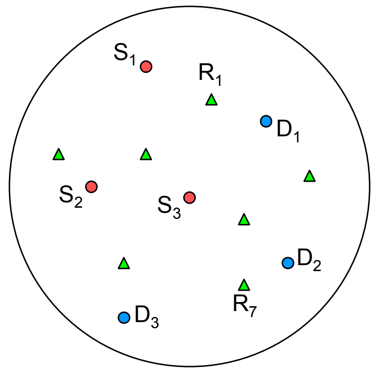

Fig. 1 Multiuser relay traffic pattern in a (3x7x3) configuration

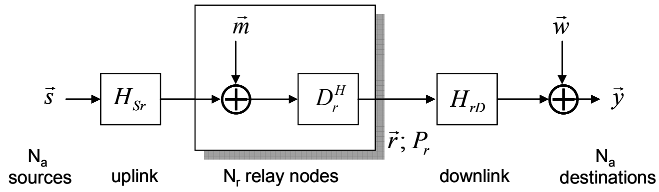

Fig. 2 System model

A. *Notation and Assumptions*

Column vectors are denoted as $\vec{h}$, matrices as H , the p-th column of a matrix is $H[:,p]$, the element *(p,q)* is denoted as $H[p,q]$ and H^H indicates hermitean transpose. $P_s = E\left[\vec{s}^H \cdot \vec{s}\right]$ is the total source transmit power and $P_r = E\left[\vec{r}^H \cdot \vec{r}\right]$ the total relay transmit power. Each source/destination pair has perfect *local* link state information: the source knows the instantaneous SINR at its destination and the destination knows the equivalent complex channel gain of the two-hop link. The source symbol vector $\vec{s}$ has i.i.d. complex normal elements with variance σ_s^2 (no power loading).

III. ZERO FORCING MULTIUSER RELAYING

In this section we summarize some of our results from [11], which are of relevance to this paper. Fig. 3 depicts a $\left(N_a \times N_a\right)$ system model, which is equivalent to Fig. 2.

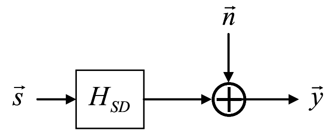

Fig. 3: Equivalent system model

Let $\vec{h}_{rD}^{(p)} = H_{rD}\left[p,:\right]^T$ be the p-th row of the downlink channel matrix and $\vec{h}_{Sr}^{(q)} = H_{Sr}\left[:,q\right]$ the q-th column of the uplink channel matrix. Then the element $H_{SD}\left[p,q\right]$ of the equivalent channel matrix H_{SD} is the projection of the gain vector $\vec{d}_r = \mathrm{diag}\left(D_r\right)$ on the Hadamard product (element-wise multiplication) of the respective channel vectors

$$H_{SD}\left[p,q\right] = \vec{d}_r^{\,H} \cdot \left(\vec{h}_{rD}^{(p)} \odot \vec{h}_{Sr}^{(q)}\right) \tag{1}$$

The equivalent noise vector $\vec{n}$ comprises the relay and the destination noise. The goal of multiuser zero forcing relaying is to determine the vector $\vec{d}_r$ such that the individual source/destination links are orthogonalized.

A. *Zero Forcing Projection*

If the matrix H_{SD} is diagonal, there is no interlink interference between the N_a source/destination links. For any gain vector $\vec{d}_{r,0}$ a corresponding zero forcing gain vector $\vec{d}_{r,ZF}$ is obtained by a projection of $\vec{d}_{r,0}$ onto the nullspace of the set of the $N_a \cdot (N_a - 1)$ vectors defined by

$$\left\{ \left(\vec{h}_{rD}^{(p)} \odot \vec{h}_{Sr}^{(q)} \right) \middle| p, q \in [1, N_a] \text{ and } p \neq q \right\} \quad (2)$$

Note that a sufficient condition for a nonempty nullspace is

$$N_r > (N_a - 1) \cdot N_a \quad (3)$$

because otherwise the set of vectors may have full rank.

A particularly suitable basis $\vec{d}_{r,0}$ for the calculation of the zero forcing gain vector $\vec{d}_{r,ZF}$ is given by

$$\vec{d}_{r,0}[k] = H_{Sr}[k,:] \cdot H_{rD}[:,k] \quad (4)$$

In [11] we show that this gain vector is asymptotical optimal in the large system limit (i.e., large number of relays). We refer to this gain allocation as *asymptotic zero forcing* gain allocation. Our performance results in Section V are based on this choice.

IV. Channel Estimation and Prediction

Asymptotic zero forcing requires only local channel state information at the relay. However, it suppressed multiuser interference efficiently only, if the number of relays N_r is much larger than the square of the number N_a of source/destination pairs (excess relay case). The zero forcing projection according to Section III.A in turn requires only $N_r > N_a \cdot (N_a - 1)$. Conversely each relay needs to have knowledge of the complete uplink and downlink channel matrix in order to calculate its complex gain locally. A channel measurement cycle thus consists of a *measurement phase*, where the relays determine their local channel coefficients, and of a *dissemination phase*, where each relay broadcasts its local channel state information (CSI) to the other relays.

The local CSI of each relay consists of N_a uplink and N_a downlink channel coefficients. One approach to measure the local CSI has each source and each destination transmit an orthogonal pilot symbol sequence. As we need $2N_a$ orthogonal sequences, this involves at least $2N_a$ channel uses. The relays determine the local channel coefficients by correlation with the pilot sequences. Thus each channel coefficient estimate is perturbed by i.i.d. Gaussian noise. The average signal to noise ratio SNR_{est} of this estimate is proportional to the energy P_{pilot} of the pilot symbol sequence. Let P_s be the source transmit energy per channel use and SNR the average signal to noise ratio at the relay in a $(1\times1\times1)$ configuration (as obtained by a source with transmit power P_s). Then SNR_{est} follows directly as is

$$SNR_{est} = P_{pilot} / P_s \cdot SNR \equiv SNR_{CSI} \cdot SNR \quad (5)$$

We refer to SNR_{CSI} as the *excess* channel estimation signal to noise ratio. In the dissemination phase N_r relays need to broadcast $2N_a$ channel coefficients each. We will assume in the sequel, that the dissemination of each channel coefficient requires one channel use. Thus the dissemination phase consists of $2N_a \cdot N_r$ channel uses.

If the channel is time variant, the relays have to predict the current channel matrices from past channel measurements. The numerical results in the next section are based on Jakes Doppler spectrum (uniform scatterer distribution). The relays know the autocorrelation function of the fading process perfectly and we employ a MMSE channel coefficient predictor.

V. Performance Results

We assume that both the uplink channel matrix H_{Sr} and downlink channel matrix H_{rD} have i.i.d. complex normal elements with unit variance and zero mean. According to (3) the minimum number of relays required for zero forcing is $N_{r,\min} = N_a(N_a - 1) + 1$. We will refer to a $(N_a \times N_{r,\min} \times N_a)$ configuration as *minimum relay* N_a*-configuration*, as it uses the minimum number of relays required for zero forcing with N_a links. The SNR is defined as the average signal to noise ratio at the relay in a $(1\times1\times1)$ configuration. We assume the same AWGN variance at the relays and at the destination, i.e. $\sigma_m^2 = \sigma_w^2$.

We consider two different power constraints: (i) *a total power constraint*, where the total transmit power of all sources and all relays is constant, i.e. $\sigma_s^2 = 1/N_a$ and $P_r = 1$ as well as (ii) a *link power constraint*, where each source transmits with power $\sigma_s^2 = 1$ and the total relay transmit power is proportional to the number of source/destination pairs $P_r = N_a$. The link power constraint seems more natural in real multiuser system. On the other hand the total power constraint facilitates the comparison with the single user MIMO case with N_a co-located antennas.

A. Perfect Channel State Information

In Fig. 4 we show the cumulative density function (CDF) of the sum rate (sum of the instantaneous rate supported by each source/destination link) for different numbers of source/destination pairs N_a. The signal to noise ratio is $SNR = 20dB$, we employ $N_r = 31$ relays, impose the total power constraint and assume perfect CSI. Due to (3) this system is not able to equalize more than 6 concurrent source/destination pairs. The slope of the CDF for $N_a = 1$ indicates the diversity gain due to the coherent relaying. The diversity gain diminishes as N_a increases, because the gain allocation is more and more dominated by the ZF condition. The circles indicate the average sum rate. The maximal average sum rate is obtained with $N_a = 4$ source/destination pairs. This is a result of the total power constraint. For larger N_a the increasing spatial multiplexing gain is over-compensated by the detrimental shift towards the low SNR regime. The choice $N_a = 4$ maintains some of the diversity gain of the $N_a = 1$ case.

In Fig. 5 we consider the CDF of the rate supported by any one link (out of the N_a links). The parameters are the same as in

Fig. 4 except that the link power constraint is imposed. For reference the dashed line gives the performance of a $(1\times1\times1)$ configuration (conventional single node forwarding). A comparison of the reference curve and the $N_a = 1$ curve indicates the diversity gain and the array gain obtained by using multiple relays. Note that the total relay transmit power is the same in both cases. Increasing the number of links reduces both diversity gain and array gain, as more and more relays are "occupied" by zero forcing.

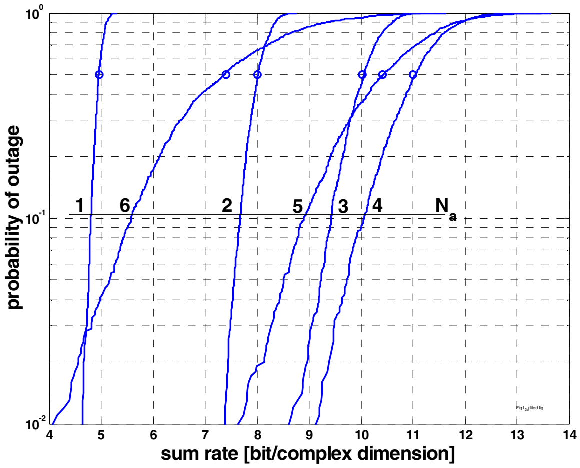

Fig. 4: Cumulative density function (CDF) of the sum rate of a $(N_a \times 31\times N_a)$ system with total power constraint. Parameter is the number of source/destination pairs.

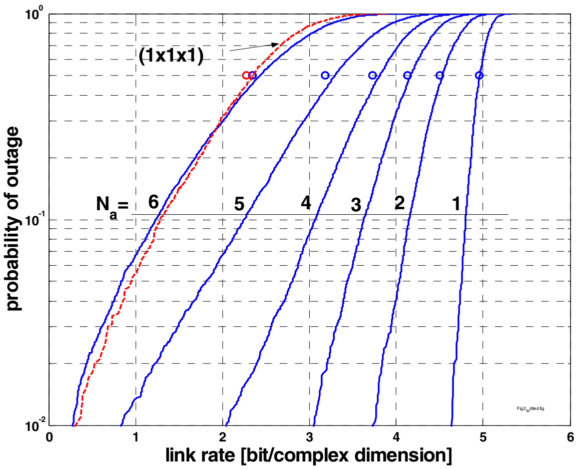

Fig. 5: CDF of the link rate of a $(N_a \times 31\times N_a)$ system with link power constraint.

An alternate viewpoint for Fig. 5 is as follows: starting from a $(1\times1\times1)$ configuration we obtain a six fold increase in the average sum rate (N_a-times the average link rate) without perceivable link level performance degradation by moving to a $(6\times31\times6)$ configuration. Note that this conclusion holds in general; under the link power constraint a *minimum relay* N_a*-configuration* achieves an N_a-fold sum rate improvement over a $(1\times1\times1)$ configuration without compromising the link level QoS.

To this end in Fig. 6 we show the average sum rate of the *minimum relay* N_a*-configuration* versus the number of source/destination pairs. Parameter of the curves is the SNR and we impose the link power constraint. The dashed lines show an empirical approximation of the average sum rate $\bar{C}_{sum}$ given by

$$\bar{C}_{sum} \approx N_a \cdot 0.5\cdot \log_2\left(1+0.22\cdot SNR\right) \qquad (6)$$

Equation (6) shows, that the *minimum relay* N_a*-configuration* achieves the spatial multiplexing gain N_a. Note, that the slope of the lines in Fig. 6 is determined by the SNR. We will use this observation to quantify the SNR-loss due to noisy channel state information.

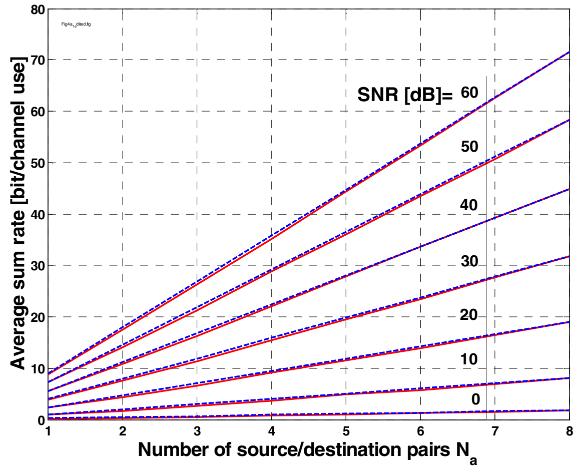

Fig. 6: Average sum rate of a *minimum relay* N_a*-configuration* versus the number N_a of source/destination pairs. Parameter is the SNR.

As we have seen in Fig. 4, the *minimum relay* N_a*-configuration* does not necessarily achieve the optimum average sum rate for a given SNR. In Fig. 7 we consider a network with N_{node} nodes. For each value of N_{node} and SNR the number of source/destination pairs N_a is chosen such, that the average sum rate is maximized ($N_a = N_{a,opt}$). For reference the dashed lines ($N_a = 1$) indicate the average sum rate, which is obtained, if only one source/destination pair is active and all other nodes in the network serve as relays. For a sensible comparison of the two configurations we impose the total power constraint; i.e. the average transmit power per link is inversely proportional to the number of links (or conversely the total transmit energy per channel use is independent of the number of source/destination pairs). For this reason each link drops deeper into the power limited regime as the number of nodes in the network increases. As a result the $N_a = N_{a,opt}$ curves flatten out for increasing N_{node}. For the $N_a = 1$ reference system the sum rate increases with N_{node} primarily due to the array gain inherent in the coherent relaying operation. The performance gain of multiuser zero forcing relaying in comparison to the single user $N_a = 1$ reference is impressive: for $N_{node} = 100$ and SNR=20dB the sum rate is tripled, for SNR=40dB we even observe a fivefold increase.

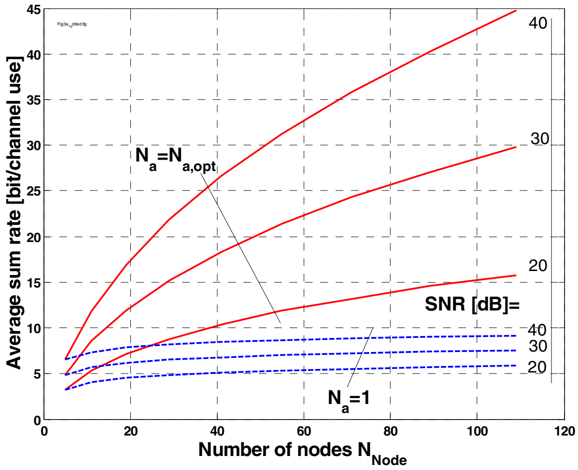

Fig. 7: Maximum average sum rate versus the total number N_{node} of nodes in the network. Parameter is the SNR. For reference the dashed curves give the performance of a $(1\times N_{node} - 2\times 1)$ configuration.

B. Noisy Channel State Information

Up to now our performance results have assumed perfect CSI. In Fig. 8 we study the impact of a noisy CSI at the relays on the average sum rate of the minimum relay configuration. The signal to noise ratio is SNR=30dB. Parameter of the curves is the excess signal to noise ratio SNR_{CSI} of the channel estimation (5). For $N_a = 1$ the minimum relay configuration is $(1\times 1\times 1)$. Clearly the performance of this two-hop channel with one relay is independent of the relay gain, as long as the relay transmit power is unaffected. For this reason all lines in Fig. 8 have the same origin.

It is evident from Fig. 8 that a noisy CSI at the relays translates into a reduced slope of the average sum rate curves. It essentially has the same impact as a reduced SNR. For this reason we define the slope of the sum rate curves in Fig. 8 as the (asymptotic) SNR-loss due to a noisy CSI. Experience has shown, that the SNR-loss is essentially independent of the considered SNR, if $SNR > 10dB$. In Fig. 9 we state the SNR-loss for SNR=30dB (solid line). The dashed line gives the heuristic approximation

$$SNR_{loss} \approx \frac{1}{1 + 5.5 \cdot SNR_{CSI}} \tag{7}$$

It is quite tight for $SNR_{CSI} \geq 0dB$. For very poor CSI the predicted loss is somewhat optimistic. With (6) and (7) we thus obtain an empirical approximation of the average sum rate for the *minimum relay configuration* with noisy channel state information and i.i.d. Rayleigh fading:

$$\bar{C}_{sum} \approx \frac{(N_a - 1)\cdot \log_2\left(1 + 0.22 \cdot \frac{SNR}{1 + 5.5 \cdot SNR_{CSI}}\right) + \log_2(1 + 0.22 \cdot SNR)}{2} \tag{8}$$

This approximation is tight for $SNR_{CSI} \geq 0dB$.

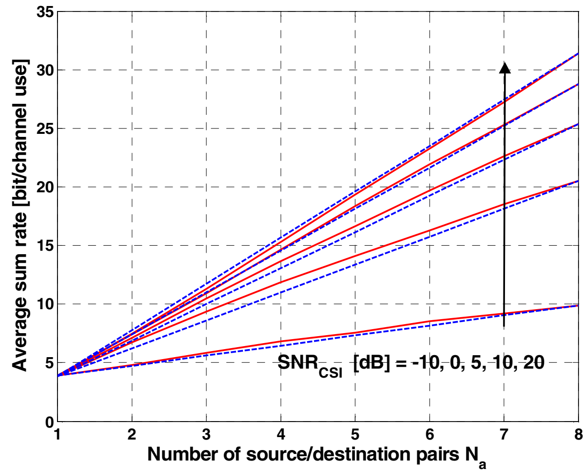

Fig. 8: Impact of noisy channel state information (CSI). We show the average sum rate of the *minimum relay* N_a *-configuration* versus the number of source/destination pairs. Parameter of the curves is the excess SNR of the CSI.

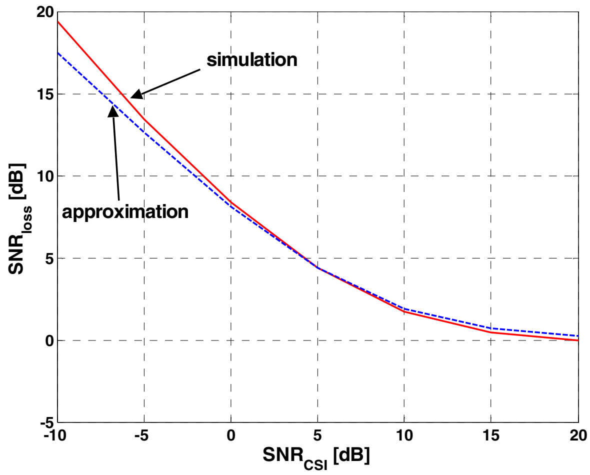

Fig. 9: Comparison of the approximated and the simulated SNR-loss of the *minimum relay* N_a *configuration* versus the excess SNR of the CSI.

A realistic mobile communication channel varies continuously over time. Thus periodic channel measurements are required to update the relay gains. According to Section IV a channel measurement cycle includes $2N_a$ channel uses to measure all uplink and downlink channel coefficients and $2N_a \cdot N_r$ channel uses to disseminate the local CSI among all relays. For a large Doppler spread and/or a large number of source/destination pairs this overhead may become prohibitive. For the performance results in Fig. 10 we let each relay utilize the last ten channel measurements to predict the current uplink and downlink channel matrices. We assume a Doppler bandwidth of 40Hz, which roughly corresponds to pedestrian speed at a carrier frequency of 5GHz. The signal to noise ratio is SNR=30dB and we impose the link power constraint. The source symbol rate is $f_s = 1MSps$. Note, that the results are immediately applicable to broadband indoor wireless (delay spread less than 500ns) by employing subcarrier modulation to diagonalize the frequency selective channel.

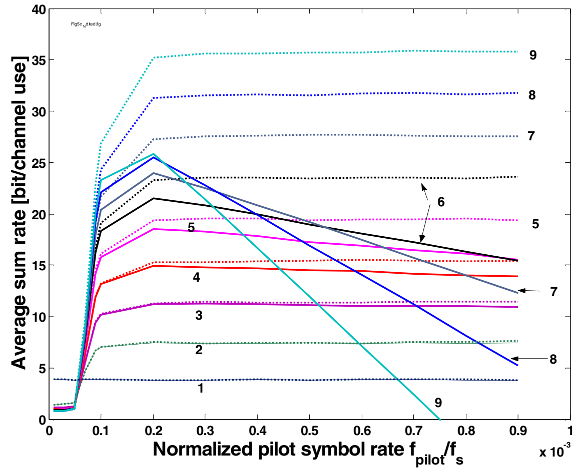

Fig. 10: Impact of a time-variant channel matrix on the average sum rate of the *minimum relay* N_a *configuration*. The x-axis gives the normalized pilot symbol rate, parameter of the curves is the number of source/destination pairs. The dashed lines take into account one channel use to measure and disseminate both channel matrices, the solid lines take into account $2N_a$ channel uses to measure and $2N_aN_r$ channel uses to disseminate both channel matrices.

The channel measurement cycles are performed periodically with the rate f_{pilot}. Let f_s be the source symbol rate. Then a channel measurement cycle is performed every f_s / f_{pilot} -th symbol interval (channel use). The quality of the channel prediction drops with the lag-time between measurements and prediction. For a worst case consideration we evaluate the average sum rate for the last channel use prior to a new measurement cycle. In Fig. 11 the sum rate is plotted versus the normalized pilot symbol rate (channel measurement cycle rate). We distinguish two cases:

(a) the dashed lines take into account one channel use to measure and disseminate both channel matrices,

(b) the solid lines take into account $2N_a$ channel uses to measure and $2N_aN_r$ channel uses to disseminate both channel matrices.

As the normalized pilot symbol rate increases, the maximum lag-time for the channel prediction is reduced and the CSI becomes more accurate. In Fig. 11 the pilot symbol rate $f_{pilot} / f_s \leq 10^{-3}$. In this range the overhead for case (a) is negligible and the dashed curves saturate for $f_{pilot} / f_s \geq 2 \cdot 10^{-4}$. For case (b) the channel measurement overhead is $O\left(N_a^3\right)$ for the minimum relay configuration. As a result the sum rate for $N_a = 9$ drops to zero as $f_{pilot} / f_s \geq 7 \cdot 10^{-4}$. At this pilot symbol rate all channel uses are allocated to the channel measurements and the dissemination of measurement results. As a reference, the minimum relay $N_a = 1$ configuration achieves an average rate of 4bit/channel use. For the given parameters it is not beneficial to employ more than $N_a = 8$ source/destination pairs (i.e. $N_r = 57$ relays, which amounts to $N_{node} = 73$ nodes totally).

Despite the pessimistic assumptions for case (b), the multiuser ZF relaying still achieves a maximum average sum rate of 25bit/channel use. This is roughly a six fold increase over the conventional approach with $N_a = 1$.

VI. Conclusions

We have introduced the notion of asymptotic zero forcing and zero forcing projection based gain allocation in cooperative multiuser relaying networks. We presented comprehensive performance results of multiuser zero forcing relaying. Particular emphasis was placed on practical impairments such as noisy channel state information and time-variant channel matrix. One of our most intriguing results shows, that multiuser zero forcing relaying at 5GHz and pedestrian speed achieves a six fold increase in the sum rate of the network, even if we take the overhead for the measurement and the dissemination of the channel matrices into account. We conclude that multiuser ZF relaying is an interesting and *realistic* approach for cooperative signaling in future pervasive wireless access networks. Our current work on this topic is specifically concerned with efficient protocols to establish a global phase reference under consideration of the local phase noise at all nodes in the network. The next step will be a verification of this approach in our RACooN testbed [12].

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[12] for information on the RACooN testbed of the Swiss Federal Institute of Technology refer to: www.nari.ee.ethz.ch/wireless/research/projects/racoon/introduction.html