Experimental Performance Evaluation of Joint Cooperative Diversity and Scheduling

Ingmar Hammerstroem, Jian Zhao, Stefan Berger and Armin Wittneben
Swiss Federal Institute of Technology (ETH) Zurich, Communication Technology Laboratory, CH-8092 Zurich, Switzerland
Email: hammerstroem@nari.ee.ethz.ch

***Abstract*— We investigate the performance of adaptive scheduling schemes in a cooperative network based on a channel measurement campaign at 5.25 GHz in an usual indoor office scenario. We compare the performance of different scheduling algorithms. Furthermore, we show that the performance results based on the measurements match quite well with our results evaluated by means of computer simulations.**

I. Introduction

Space-time diversity techniques (e.g. space-time coding) have been widely used to increase the reliability of radio links in wireless networks with co-located antennas. Recently *cooperative diversity* has been proposed to realize spatial diversity in distributed antenna systems [1], [2]. The main idea is to use multiple nodes as a virtual macro antenna array, and realize spatial diversity in a distributed manner. In [3], a simple scheme to achieve cooperative diversity in a quasi-static fading environment with *amplify-and-forward* (AF) relays has been proposed. In such a scheme, the block-fading time-invariant channel is converted into a time-variant channel by introducing time-variant and relay specific phase offsets at the relays. The diversity in spatial dimension is therefore transformed into temporal dimension. In [4], [5], we proposed to exploit such time-variance to achieve multiuser diversity gain by jointly considering several source/destination pairs for scheduling purpose. Such scheme is referred to as *joint cooperative diversity and scheduling* (JCDS).

Up to now, the performance of joint cooperative diversity and scheduling has been evaluated by means of computer simulations with idealized assumptions about the fading channel environment. The purpose of this paper is to verify the joint cooperative diversity and scheduling scheme, which has been proposed in [4], in a real multiuser network scenario with measured channel transfer functions and compare the performance of different scheduling algorithms. For this we arranged channel measurements with the RACooN Lab [6] at 5.25 GHz with a bandwidth of 80 MHz. The channel impulse responses were measured simultaneously between 8 distributed RACooN units in two different indoor scenarios.

II. System Model

Fig. 1 exemplarily depicts the considered cooperative relay network with $N_{\mathrm{a}} = 2$ source/destination pairs and $N_{\mathrm{r}} = 4$ AF relays. We assume that communication takes place only over two-hop links, i.e. there is no direct connection between source and destination. All nodes are assumed to be frame synchronous, i.e., all nodes know the slot timing.

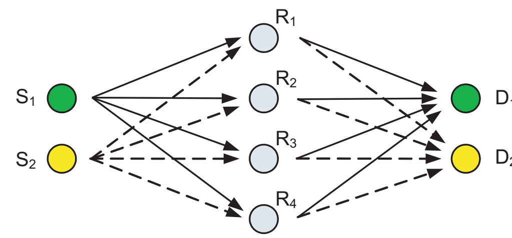

Fig. 1. Joint cooperative diversity and scheduling network scenario as considered for the measurements

In our scenario mobility of all nodes is low and the channel coefficients are constant over the latency time scale of interest. We assume that the channel is time-invariant over at least one *transmission cycle* (block fading).

To derive an expression for the SNR at the destination the channel coefficients between source and relays (*uplink*) for link n are stacked in the vector $\mathbf{h}_{1,n}$, whereas the channel coefficients between relays and destination (*downlink*) are stacked in $\mathbf{h}_{2,n}$. We consider frequency-flat fading (e.g., within one subcarrier of an OFDM system), which usually includes path loss, shadowing and small-scale fading. In this paper all channel coefficients are extracted from an indoor channel measurement campaign as described in section IV. The AWGN contribution at the AF relays and the destination is assumed to be $\mathcal{CN}(0, \sigma_{\mathrm{R}}^2)$ and $\mathcal{CN}(0, \sigma_{\mathrm{D}}^2)$, respectively. We define the gain matrix $\mathbf{G}_k = \mathrm{diag}\left[g_1^{(k)}, \ldots, g_{N_{\mathrm{r}}}^{(k)}\right]$, whereby $g_l^{(k)}$ is the relay amplification factor at time instance k. The transmit power of the source is P.

Neglecting the link index n, the SNR of the received signal at the destination is

$$\mathrm{SNR}^{(k)} = \frac{P\left|\mathbf{h}_2^T \mathbf{G}_k \mathbf{h}_1\right|^2}{\sigma_{\mathrm{D}}^2 + \sigma_{\mathrm{R}}^2 \mathbf{h}_2^T \mathbf{G}_k \mathbf{G}_k^{\dagger} \mathbf{h}_2^*}, \tag{1}$$

whereas the mutual information of such a link is

$$I^{(k)} = \frac{1}{2}\log_2\left(1 + \mathrm{SNR}^{(k)}\right). \tag{2}$$

A detailed derivation of the mutual information (2) can be found in [3]. Note that the factor $1/2$ accounts for the two channel uses required by the relay traffic pattern.

III. Joint Cooperative Diversity and Scheduling

Our starting point is the simple cooperative diversity scheme proposed in [3]. Simply speaking, we introduced time-variant and relay-specific phase offsets (phase signature sequence) at the relays. This scheme makes the equivalent source/destination channel coefficients time-variant (i.e. time-variant SNRs at the destinations), although the physical channel is time-invariant. It requires only very limited uplink channel state information (CSI) and no downlink CSI. Thus, the amplification gain of relay l at time instance k is, e.g., given as

$$g_l^{(k)} = \underbrace{\sqrt{\frac{P_{\mathrm{R}}}{P\left|h_{1,l}\right|^2 + \sigma_{\mathrm{R}}^2}}}_{\text{time-invariant}} \cdot \underbrace{\exp(j\varphi_l^{(k)})}_{\text{time-variant}}, \tag{3}$$

where $\varphi_l^{(k)}$ denotes the relay-specific and time-dependent phase offset. Each relay transmits with power P_{R}. We impose a total power constraint P on all relays, i.e., $P_{\mathrm{R}} = P/N_{\mathrm{r}}$. Due to the time-variant phase-shifts at the relays the spatial diversity offered by the N_{r} relays is translated into the temporal domain. The number of relays limits the maximum achievable diversity order to N_{r}, because there are only N_{r} independent downlink channel realizations. To exploit this temporal diversity the input signal sequence is precoded by a linear block code (matrix multiplication) as, e.g., in [7], [8].

Note, that the phases do not necessarily change with every transmitted symbol. They rather change every data packet which consists of several symbols. We assume that one *transmission cycle* is divided into two time-slots (uplink and downlink) each divided into N_{b} *segments*; N_{b} corresponds to the length of the phase sequences of the relays in the downlink. In this work, the phase sequences are chosen at random with an uniform distribution. But also N_{r} columns out of an IFFT matrix are appropriate.

The key idea of the work presented in [4] is to exploit the artificially introduced time-variance by joint consideration of several source/destination pairs to achieve multi-user diversity. On basis of a given metric the scheduler decides to which source/destination pair the channel resources are granted. In general there are two extreme optimization criteria. On one hand the scheduling entity wants to maximize the utilization of the physical resources which is usually measured in terms of *system throughput* or *aggregate throughput*. On the other hand the fairness among all competing source/destination pairs should be guaranteed which can be measured in terms of *link throughput*. The scheduling metric which maximizes the system throughput would allocate all resources to the best link (*greedy* scheduling) and therefore sacrifice the link throughput performance of the weak links.
The fairness issue in scheduling again can be divided into two cases: throughput fairness and temporal fairness. In both cases the scheduler gives a certain share of the entire resource to the users. In the first case the shared resource is the whole system throughput. In the latter case the shared resource is time. One scheduling scheme which assures the highest temporal fairness is the static scheduling scheme round robin (RR). The disadvantage of RR scheduling is that it does not incorporate the actual channel conditions into its decisions. Therefore, it is not possible to achieve multi-user diversity gains.

In this paper, we compare the performance of the following scheduling algorithms:

- **Round Robin Scheduling**: In this scheme, fixed amount of time slots are allocated for each link. This is an ideal case of fairness for each source/destination link.
- **Greedy (Maximum Rate) Scheduling** [5]: The scheduler only picks the link with the highest throughput at each segment .
- **Proportional Fair Scheduling** [9]: In each segment, the scheduler picks the user i with the highest ratio $R_i(t)/\overline{R}_i(t)$. $R_i(t)$ and $\overline{R}_i(t)$ represent the instantaneous throughput and the *average* throughput of user i at time t, respectively.
- **Temporal Fairness Enhanced Scheduling** [10], [11]: This scheme divides the whole time sequence into fairness windows of a certain size (e.g., one transmission cycle). Every source/destination link will be scheduled for the same maximum amount of times in each window. If a certain link has reached its maximum number, it will drop out of competition and remain inactive until the next window. In each segment, the scheduler only chooses the link with highest throughput within the remaining group of *active* links.

Note that, although fairness of *Greedy* and *Proportional Fair Scheduling* based JCDS explicitly benefits from the artificial introduced time-variance it does not assure that each source/destination link is scheduled within one transmission cycle. *Proportional Fair Scheduling* based JCDS only assures temporal fairness over a infinitely large horizon.

For a more detailed discussion of the used scheduling metrics the reader is referred to [11].

IV. Channel Measurements

We performed channel measurements in order to be able to provide some aspects of real world conditions to our simulations. The RACooN Lab [6] is an equipment at our institute which we used to collect the channel data. It consists of 10 mobile single antenna half-duplex nodes which can either transmit user-defined data or receive. Each node is placed on a cart which can be moved around. In this way we are able to realize colocated as well as distributed system topologies. We can measure the SISO channel transfer function between each of the units as well as the (distributed) MIMO channel between any combination of them. For the present measurements, we used short dipole antennas, which were mounted at a height of about 1.50 m.

In the following sections we will give a description of the measurement setup as well as details about how the measurements were performed and show an example of the measured transfer functions.

A. Measurement Setup

For the present work, 8 independent RACooN nodes were used to represent sources, destinations and relaying nodes. The measurements were performed in a students' laboratory as shown in Fig. 2. The room contains lots of electronic equipment on long tables (long, light grey rectangles), chairs and cupboards (dark rectangles) acting as scatterers. It has

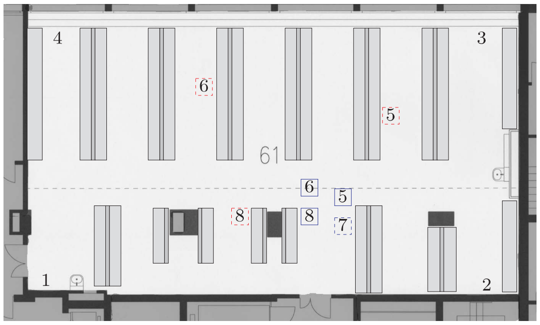

Fig. 2. *Meeting room* and *open office* scenario

a size of 12.3m×22.3m. One side of the room has large windows, the other sides consist of concrete. The RACooN nodes, which are numbered 1–8 are situated in the room as follows: Units 1–4 are placed in the corners of the laboratory. They were fixed during all measurements. We arranged the remaining units 5–8 in two different topologies in order to represent two scenarios: The *meeting room* scenario and the *open office* scenario. For the *meeting room* scenario, units 5–8 are located close together while they are further apart in the *open office* scenario (see Fig. 2). 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. Note that the position of unit number 7 is identical for both scenarios.

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 $N_\mathrm{s} = 1000$ snapshots, the antennas of the units 5–8 were moved at a slow speed and in an arbitrary fashion within a square of size 60 cm×60 cm. This corresponds to 10 times the wavelengths at 5 GHz.

B. Measurement Execution

When measuring MIMO channels, phase noise is always a critical issue [12]. It introduces an arbitrary phase shift to the measured channel coefficients. In order to cope with this problem, we measure all uplink and downlink channel coefficients simultaneously. Each of the units 5–8 broadcasts a m-sequence of length 127 which is in frequency orthogonal to the other three m-sequences. This is achieved by repetition in the time domain (which makes the spectrum of the sequence discrete) and a frequency shift that is small compared to the measurement bandwidth. Units 1–4 receive the superposition of all four signals. They can, due to the orthogonality of the sequences, identify the impulse response from each of the transmitting units via correlation. Due to channel reciprocity of the present scenarios, it suffices to measure the channels from units 5–8 to units 1–4 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.

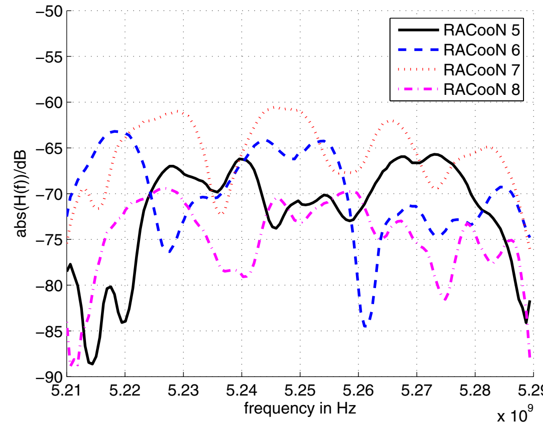

Fig. 3. Exemplary transfer functions from units 5–8 to unit 2 in *open office* scenario

TABLE I

AVERAGE ATTENUATION [dB]; MEETING ROOM (LEFT CELL) AND OPEN OFFICE (RIGHT CELL) SCENARIO

Node	5		6		7		8	
1	74.1	72.2	73.9	64.8	68.1	67.7	73.7	72.4
2	62.2	65.2	62.8	68.9	64.0	63.9	63.2	72.4
3	61.6	60.9	62.6	63.8	63.1	64.2	64.4	64.7
4	65.3	65.0	64.9	61.6	71.8	71.5	65.8	64.4

C. Measurement Results

To give an example of the measured channels, we show the absolute value of the transfer functions from RACooN units 5–8 to unit 2 in Fig. 3. The depicted channel snapshot was taken in the *open office* scenario.

1) Extraction of Frequency Flat Fading Channels: For the comparison of the different scheduling metrics for the joint cooperative diversity and scheduling scheme we assume frequency flat fading, as for example one subcarrier in an OFDM system experiences. To give an average performance of such a system within the considered bandwidth we sample each channel transfer function at $N_\mathrm{f} = 96$ frequencies. Due to filter effects of the measurement equipment, which occur at the borders of the spectrum, we consider only the frequency range from 5.22 GHz to 5.28 GHz for our simulations. As a consequence of this extraction we obtain for each channel coefficient within the meeting room or the open office scenario a sample set of length $N_\mathrm{f} \cdot N_\mathrm{s} = 96 \cdot 10^3$.

2) Average Attenuation: Let $h_{i,j}[n]$ denote the nth sample of the sample set for the channel coefficient between RACooN unit $i \in \{1, 2, 3, 4\}$ and unit $j \in \{5, 6, 7, 8\}$. Then the average attenuation of the signal due to the channel is the inverse of the average power of the channel coefficient given by

$$\sigma_{i,j}^2 = \frac{1}{N_\mathrm{f} \cdot N_\mathrm{s}} \sum_{n=1}^{N_\mathrm{f} \cdot N_\mathrm{s}} |h_{i,j}[n]|^2 .$$

In Table I the average attenuations between two RACooN units are summarized.

3) K-Factor of Ricean Fading Distribution: Due to the measured indoor scenarios it is likely that the channel be-

TABLE II

ESTIMATED K-FACTOR OF RICEAN FADING DISTRIBUTION; MEETING ROOM (LEFT CELL) AND OPEN OFFICE (RIGHT CELL) SCENARIO

Node	5		6		7		8	
1	0	0	0.3	0	0	0	0	0
2	0.5	0	1.4	1.0	1.0	1.3	1.1	0.2
3	0.7	0.6	0	0.3	0.4	0.3	0.8	0.9
4	0.2	0.4	1.9	1.4	0.9	0.9	0	0.9

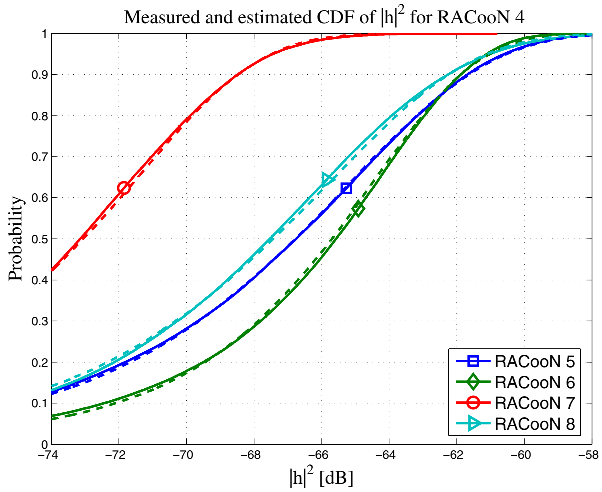

Fig. 4. Measured (solid lines) vs estimated (dashed lines) CDF of $|h|^2$ for RACooN 4 in the *meeting room* scenario; markers represent mean values of $|h|^2$

tween two RACooN units shows a considerable line-of-sight (LOS) component additionally to the multipath components. In Table II the estimated K-factors for the measured scenarios are given. For the estimation of these values we used the in [13] presented estimator.

To show that on basis of this parameter extraction we obtain a good estimation of the underlying fading distribution we compare the cumulative distribution function (CDF) of the squared magnitude of the measured channel coefficient with the corresponding ricean fading distribution. This is depicted in Fig. 4, where the CDF of the squared magnitude of the channel coefficients between RACooN units 5–8 and RACooN unit 4 are depicted. The solid lines are the CDFs which are calculated from the measurement data. The dashed lines are the corresponding estimated CDFs based on the parameters of Table I and Table II. It can be seen that the measured and estimated CDFs match quite well.

V. PERFORMANCE RESULTS

In this section we will present the performance results of the joint cooperative diversity and scheduling scheme on the basis of the measured channel impulse responses. We consider two concurrent source-destination pairs, RACooN unit 5 to unit 7 and RACooN unit 8 to unit 6, respectively. RACooN units 1–4 are the possible relays. Furthermore, we assume that the noise variance of the relays is equal to the noise variance of each destination, i.e, $\sigma_{\mathrm{R}}^2 = \sigma_{\mathrm{D}}^2 = \sigma^2$.

Simulation Setup: For the simulation,the parameter $\rho = P/\sigma^2 \cdot \sigma_{\mathrm{h}}^2$ denotes the average SNR over all nodes of the net-

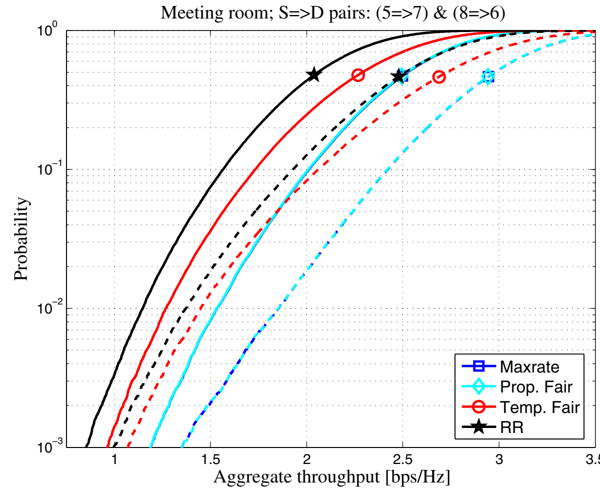

Fig. 5. CDF of aggregate throughput; *meeting room* scenario; source-destination pairs: $5 \rightarrow 7$ and $8 \rightarrow 6$; RACooN units 1-4 operate as relays (solid lines); units 2 and 3 operate as relays (dashed lines)

work. The parameter σ_{h}^2 is the average power of all measured channel coefficients, defined as

$$\sigma_{\mathrm{h}}^2 = \frac{1}{16 \cdot N_{\mathrm{f}} \cdot N_{\mathrm{s}}} \sum_{i=1}^{4} \sum_{j=5}^{8} \sum_{n=1}^{N_{\mathrm{f}} \cdot N_{\mathrm{s}}} |h_{i,j}[n]|^2 . \quad (4)$$

In the open office scenario σ_{h}^2 is equal to -65.13 dB, whereas it is -64.8 dB in the meeting room scenario. If not stated otherwise, we choose $\rho = 20$ dB. We assume that the channel is at least constant over one transmission cycle corresponding to two times the number of phase segments N_{b}, which is set to $N_{\mathrm{b}} = 200$ in the simulations.

A. Which nodes should act as relay?

From Table I it can be seen that some nodes have an attenuation which is larger than 70 dB, e.g., between unit 8 and 1 in both scenarios. The channel between other units exhibits only an attenuation of around 63 dB as, e.g, between unit 6 and 3. From this observation, one can ask the question if really all relay nodes should retransmit the signals.

In Fig. 5 the CDFs of the aggregate throughput of the considered scheduling schemes for two different cases in the meeting room scenario are depicted. In case one, all four RACooN units operate as relays (solid lines), in case two, only RACooN units 2 and 3 operate as relays (dashed lines). In case one the transmit power of each relay is equal to $P_{\mathrm{R}} = P/4$, whereas in case two it is equal to $P_{\mathrm{R}} = P/2$. It is clearly visible, that it is favorable not to spend transmit power at relays, which have an high attenuated uplink and/or downlink channels, respectively. They either mainly retransmit noise (bad uplink channel) and therefore degrade the received SNR at the destinations or their transmit signal is highly attenuated (bad downlink channel).

Furthermore, it can be seen that using only two relays causes a decrease in the slopes of the CDFs compared to the case of using all four relays. This can be interpreted as loss in diversity.

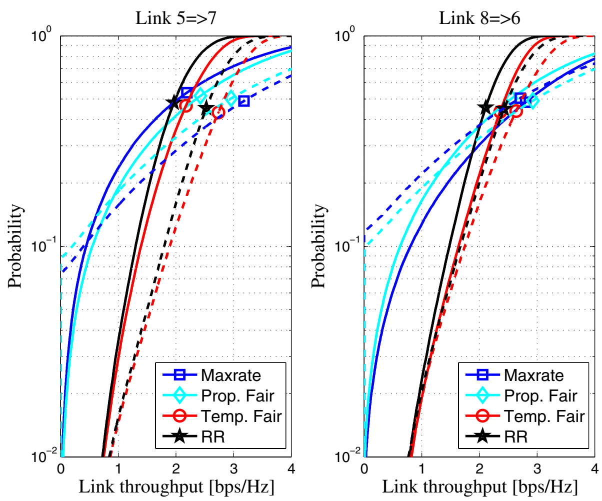

Fig. 6. CDF of link throughput; *meeting room* scenario; source-destination pairs: $5 \longrightarrow 7$ and $8 \longrightarrow 6$; RACooN units 1-4 operate as relays (solid lines); units 2 and 3 operate as relays (dashed lines)

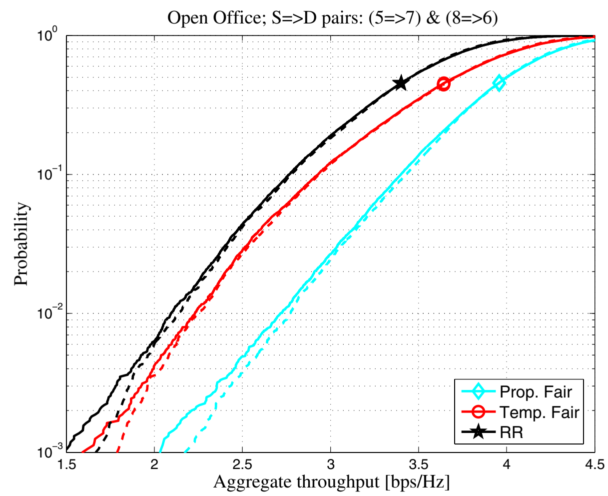

Fig. 7. CDF of aggregate throughput; *open office* scenario; source-destination pairs: $5 \longrightarrow 7$ and $8 \longrightarrow 6$; RACooN units 1-4 operate as relays; measured (solid lines) vs estimated (dashed lines) CDF; $\rho = 30$ dB

The shift to the right of the CDFs of the maximum rate and proportional fair scheduling scheme (note, that the CDFs of both schemes match in this simulation) compared to the static round robin scheme indicates the performance increase and therefore the advantage of adaptive scheduling.

In Fig. 6 the CDFs of the link throughput of both links are depicted for both cases which are described above. It can be seen that maximum rate and the proportional fair scheduler is not able to guarantee that each link is scheduled within each transmission cycle, which follows from the nonzero probability of zero link throughput. Only temporal fair scheduling [10], [11] and round robin guarantee that each link is scheduled at equal share. The decreased slope of the link throughput CDF using only two relays indicates the lower diversity the links would experience.

B. Scheduling performance with measured channels vs. estimated channel statistics

In Fig. 7 we verify the estimated fading distribution parameters of section IV on basis of the performance of the scheduling schemes. The CDFs of the aggregate throughput in the open office scenario is depicted. The solid line CDFs are simulated with the measured channels, whereas the dashed lines are simulated on basis of the estimated parameters. It can be seen that the CDFs are nearly the same. Only in area of probability smaller than 10^{-2} small differences between the CDFs can be observed.

VI. Conclusion

We investigated the performance of adaptive scheduling schemes in a cooperative network based on a channel measurement campaign at 5.25 GHz in an usual indoor office scenario. Using these measurement results we showed that channel adaptive scheduling compared to static scheduling is an efficient means to improve the use of the given network resources, i.e, bandwidth. Furthermore, we showed that it is not favorable to use every possible node in such a network as relay node. Therefore, relay selection is important an issue in cooperative relaying networks.

References

[1] N. J. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, pp. 3062–3080, Dec. 2004.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part I: System description," *IEEE Trans. Commun.*, vol. 51, pp. 1927–1938, Nov. 2003.

[3] I. Hammerstroem, M. Kuhn, and A. Wittneben, "Cooperative diversity by relay phase rotations in block fading environments," in *Proc. SPAWC*, (Lisbon, Portugal), Jul. 11–14, 2004.

[4] A. Wittneben, I. Hammerstroem, and M. Kuhn, "Joint cooperative diversity and scheduling in low mobility wireless networks," in *Proc. GLOBECOM*, (Dallas, TX), Nov. 29 – Dec. 3, 2004.

[5] I. Hammerstroem, M. Kuhn, and A. Wittneben, "Channel adaptive scheduling for cooperative relay networks," in *Proc. 60th IEEE Veh. Tech. Conf.*, (Los Angeles, CA), Sep. 26–29, 2004.

[6] "RACooN Laboratory of the Swiss Federal Institute of Technology." `www.nari.ee.ethz.ch/wireless/research/projects/racoon/introduction.html`.

[7] Y. Xin, Z. Wang, and G. B. Giannakis, "Space-time diversity systems based on linear constellation precoding," *IEEE Trans. Wirel. Comm.*, vol. 2, pp. 294–309, Mar. 2003.

[8] A. Wittneben and M. Kuhn, "A new concatenated linear high rate space-time block code," in *Proc. 55th IEEE Veh. Tech. Conf.*, vol. 1, (Birmingham, Al), pp. 289–293, May 6–9, 2002.

[9] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inform. Theory*, vol. 48, pp. 1277–1294, June 2002.

[10] S. S. Kulkarni and C. Rosenberg, "Opportunistic scheduling policies for wireless systems with short term fairness constraints," in *Proc. GLOBECOM*, vol. 1, (San Francisco, CA), pp. 533–537, Dec. 1–5, 2003.

[11] I. Hammerstroem, J. Zhao, and A. Wittneben, "Temporal fairness enhanced scheduling for cooperative relaying networks in low mobility fading environments," in *Proc. SPAWC*, (New York City, NY), Jun. 5–8, 2005.

[12] D. S. Baum and H. Bölcskei, "Impact of phase noise on MIMO channel measurement accuracy," in *Proc. 60th IEEE Veh. Tech. Conf.*, (Los Angeles, CA), Sep. 26–29, 2004.

[13] F. van der Wijk, A. Kegel, and R. Prasad, "Assessment of a pico-cellular system using propagation measurements at 1.9 ghz for indoor wireless communications," *IEEE Trans. Veh. Technol.*, vol. 44, pp. 155–162, Feb. 1995.