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Multiuser MIMO: Principle, Performance in Measured Channels and Applicable Service

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***Abstract*—The exploitation of multiuser diversity and the application of multiple antennas at transmitter and receiver are considered to be key technologies for future highly bandwidth-efficient wireless systems. We combine both ideas in a downlink multicarrier transmission scheme where multiple users compete for the available resources in time, frequency and space. The instantaneous channel impulse responses for all users are assumed to be perfectly known at the transmitter. Our proposed algorithm allocates each spatial dimension on a subcarrier to the user which has the highest channel tap gain on the respective spatial dimension. The scheduling strategy is optimized for sum capacity maximization. In this paper, we restrict ourselves to a more illustrative description of the idea rather then providing mathematical details. We demonstrate the potential of the proposed scheme by capacity results for measured real world channels in a large office environment. Finally, video streaming is used as a potential application with high data rate and low latency demands. It is shown that the proposed method has the potential to exploit multiuser diversity while still providing stable video streams even though QoS constraints are not explicitly taken into account by the scheduler.**

Keywords: Multiuser MIMO, OFDMA, multiuser diversity.

I. INTRODUCTION

Future wireless systems are required to yield significantly higher spectral efficiency compared to today's systems. Two promising techniques in order to provide those high spectral efficiencies are the exploitation of multiuser diversity and the application of multiple antennas at transmitter and receiver (multiple-input multiple-output, MIMO). In this paper, we combine the ideas of multiuser diversity and MIMO, i.e. we include the spatial domain in the scheduling process.

The idea of multiuser diversity is to assign a resource unit in time, frequency and space to the user with the highest capacity on this resource. Particularly in case of a large number of users who compete for the available resources, this can significantly improve the cell throughput. The disadvantage of this scheduling strategy is that users which are in a bad channel state may not be scheduled at all for a significant period. Consequently, the idea of multiuser diversity is somehow in contradiction to the requirements of delay-sensitive applications such as video streaming.

Using MIMO technologies allows to increase the link capacity compared to single antenna systems particularly in environments with large scattering. We assume that the transmitter has perfect knowledge of the instantaneous channel transfer function to all users. Channel knowledge at the transmitter can be achieved through a feedback of channel estimates from the receiver or by channel estimation from the uplink signal in a time division duplex (TDD) system. The receivers are assumed to have perfect knowledge of the channel from the transmitter to themselves due to channel estimation.

In a single user MIMO system with perfect channel knowledge at transmitter and receiver, the best thing to do is diagonalization of the channel using a singular value decomposition (SVD) as indicated in Figure 1: The transmitter multiplies the transmit signal with the right singular vectors of the channel matrix **H**, the receiver multiplies with the left singular vectors. With n_T transmit and n_R receive antennas, this yields $\min\{n_T,n_R\}$ decoupled channels which we refer to as spatial dimensions. For reasons of cost and size, the number of antennas at the terminal will be smaller than the number of antennas which can be implemented at the base station. Consequently, the number of spatial dimensions which can be exploited is limited by the terminal. It is in general smaller than the number of spatial dimensions which could be supported by the base station.

A possibility to exploit all spatial dimensions which are supported by the base station is multiuser MIMO. I.e. the base station serves multiple users at the same time on the same subcarrier by spatial separation. However, since the receive antennas belong to different users, a singular value decomposition of the total multiuser channel cannot be computed. I.e., the channel cannot be decoupled and inter-user interference occurs. Our proposed algorithm CZF-SESAM (cooperative zero forcing - successive encoding successive allocation method), which will be described in the next section, avoids inter-user interference by means of signal processing at the transmitter.

In this paper, we consider a downlink scenario as depicted in Figure 1 where a large number of users compete for the available resources. Three basic options for allocation of the resources in time, frequency and space are indicated in Figure 2: Static OFDMA is a fair scheme in the sense that the same amount of resources is allocated to all users. Each user exploits MIMO, but all spatial dimensions on a subcarrier are allocated to the same user. Dynamic OFDMA increases the cell

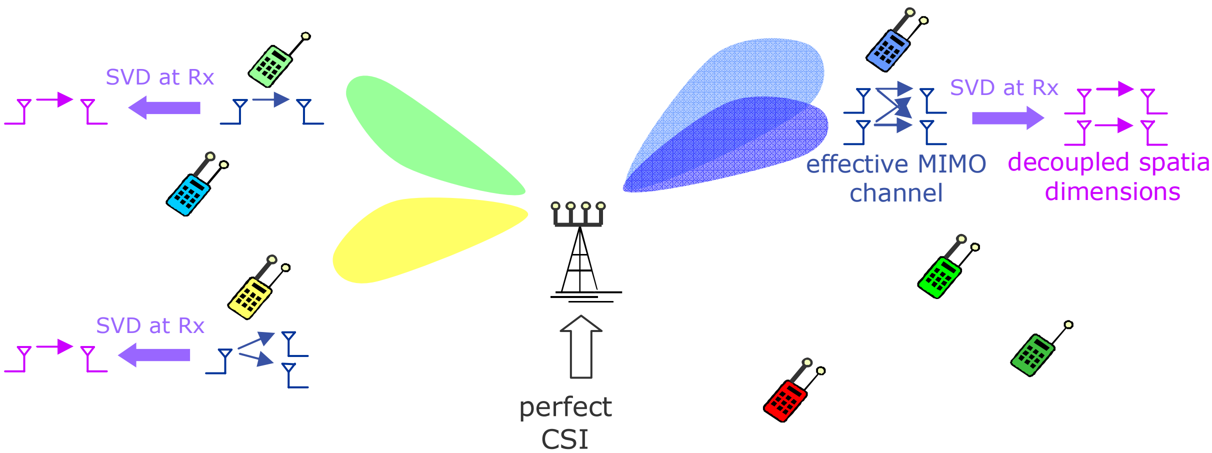

Fig. 1. Principle of multiuser MIMO.

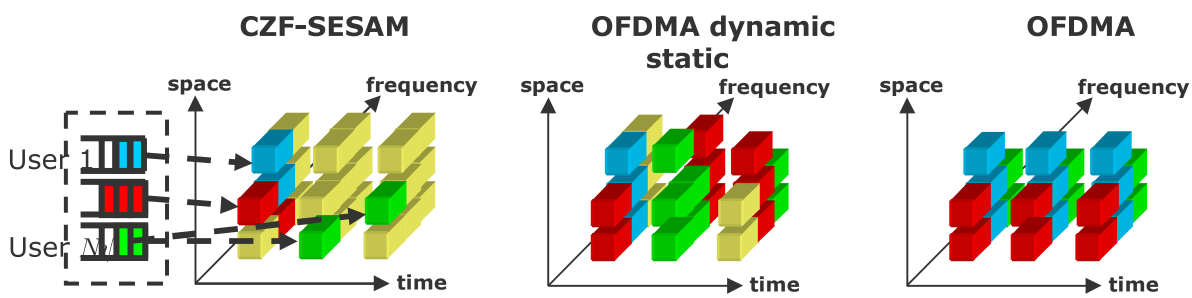

Fig. 2. Considered multiuser MIMO scheduling options.

throughput or sum capacity, respectively, by exploiting multiuser diversity. I.e. a subcarrier is allocated to the user which has the highest SNR, but still all spatial dimensions on a subcarrier are allocated to the same user. Our proposed algorithm CZF-SESAM additionally includes the spatial dimension in the scheduling, i.e. different spatial dimensions on the same subcarrier can be allocated to different users.

II. Principle of CZF-SESAM

In order to avoid interference between the spatial dimensions of different users, CZF-SESAM applies successive encoding where each beam (spatial dimension) lies in the null space of previously allocated beams and interference of previously allocated beams is cancelled at the transmitter by means of dirty paper coding which can be implemented as Tomlinson-Harashima precoding.

Here, we describe the principle idea of the algorithm. For mathematical details, we refer to [1]-[4]. We illustrate the successive steps in Figure 3. For simplicity, we restrict ourselves to two users for the explanation. The base station is equipped with $n_T=4$ transmit antennas, i.e. it can support 4 spatial dimensions. Each user has $n_R=2$ receive antennas, i.e. it can resolve 2 spatial dimensions. The broken lines in Figure 3 indicate the transmission paths.

The algorithm allocates spatial dimensions successively to users such that in each step the user with the highest SNR is served. In order to determine, to which user the first spatial dimension should be allocated, the SNR for both candidates is computed as indicated in the top figure of Figure 3. If the first spatial dimension was allocated to user *i*, the base station would form a beam using the right singular vector corresponding to the largest singular value of the channel to user *i*. The receiver would apply beamforming using the left singular vector corresponding to the largest singular value of the channel to user *i*. The tap gain of the effective spatial dimension is given by the respective singular value. In the example of Figure 3, the singular value of user 2 is higher than that of user 1. Consequently, the first spatial dimension is allocated to user 2. For the next spatial dimension, it has to be guaranteed that no interference to the already allocated spatial dimension occurs. This is achieved by zero forcing. I.e. we project the channel matrix to a new channel matrix which lies in the null space of the previously allocated spatial dimension. Then, the algorithm tests to which user the second spatial dimension should be allocated in the same way as described before. The algorithm proceeds accordingly until all n_T spatial dimensions which can be suppported by the base station have been allocated.

By doing so, we make sure that successive spatial dimensions do not interfere to previously allocated spatial dimensions. However, there is interference from previously allocated spatial dimensions to later allocated spatial dimensions. This interference is cancelled at the transmitter by

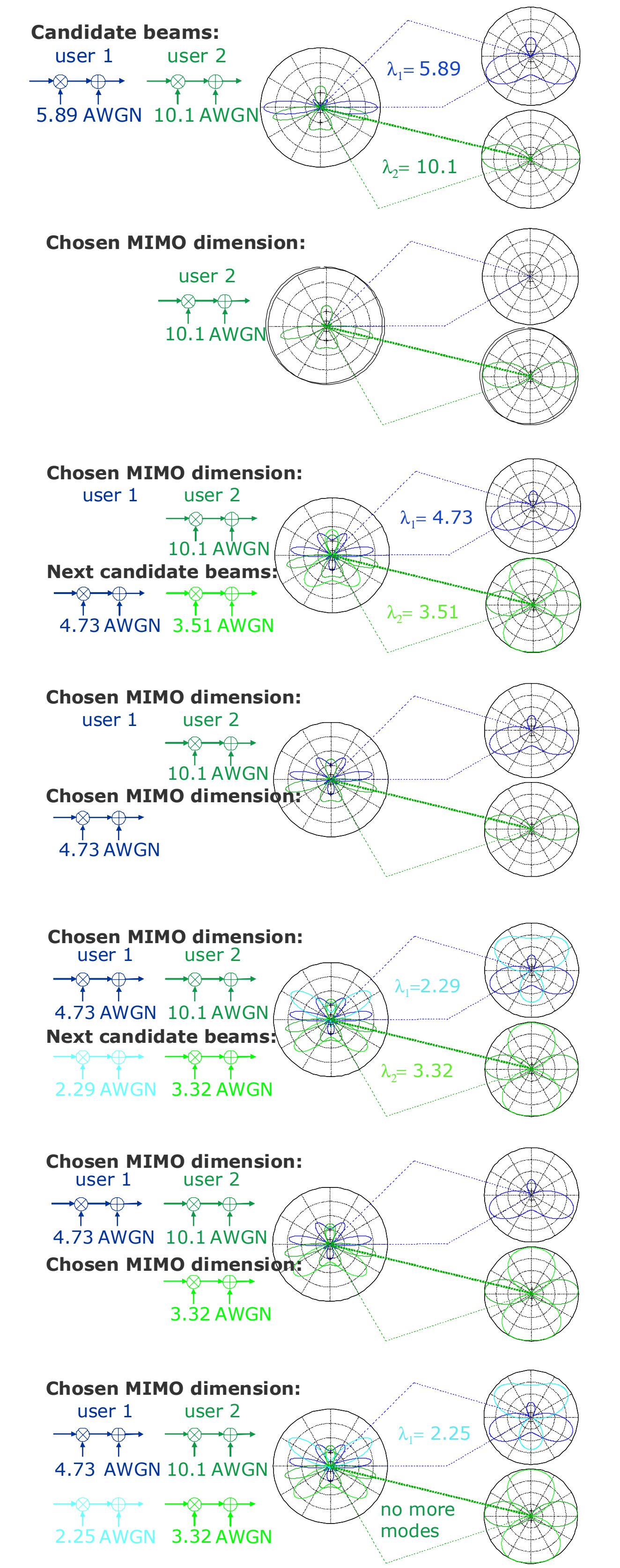

Fig. 3. Successive allocation of spatial dimensions by CZF-SESAM.

means of dirty paper coding, e.g. by Tomlinson-Harashima precoding.

In case of OFDM, the algorithm can be run on each subcarrier or resource block. It essentially performs resource allocation in space, time and frequency where the scheduling is done according to the criterion of cell throughput/sum capacity maximization.

III. Sum Capacity and Rate Distribution

For evaluation of the CZF-SESAM algorithm, we computed the achievable sum capacity for an indoor large office environment with measured channels. The measurements have been carried out at Aalborg University, Denmark [5]. The floor plan is depicted in Figure 4.

We used the access point AP1 in the middle of the room as base station with a uniform linear array (ULA) with 4 antennas.

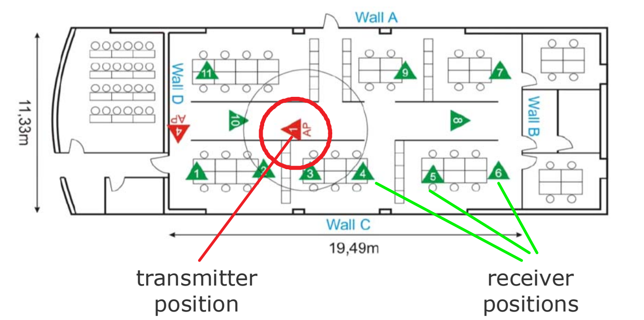

Fig. 4. Floor plan for channel measurements.

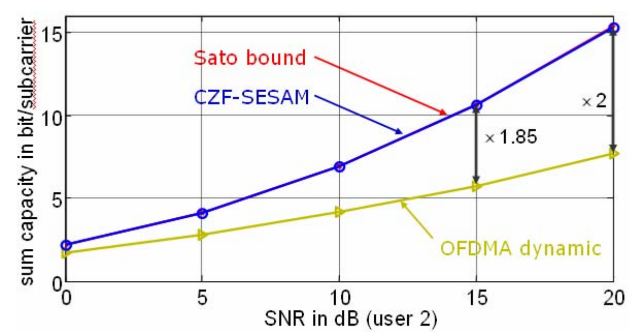

Fig. 5. Sum capacity for large office room environment.

Eleven users with 2-element ULAs whos antenna orientation is indicated by the green arrows compete for the resources. We used OFDM with 1024 subcarriers within a bandwidth of 65 MHz. Results on the achievable sum capacity are depicted in Figure 5. It is interesting to see that even though CZF-SESAM includes in general suboptimum parts such as zero forcing, the theoretical bound for the sum capacity, the Sato bound [6], can be reached. This is not true for all scenarios, but in all simulated scenarios we observed results very close to the Sato bound.

For comparison, we included the sum capacity of dynamic OFDMA according to the middle of Figure 2. CZF-SESAM achieves a gain of a factor 1.8-2 in terms of sum capacity over dynamic OFDMA. This is due to the fact that the maximum number of spatial dimensions can be exploited.

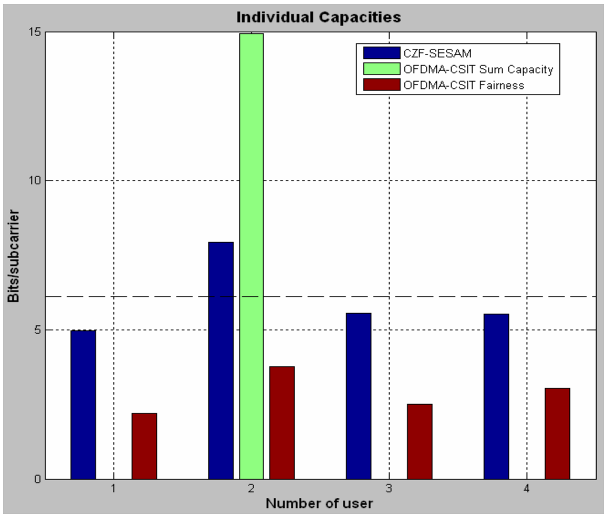

Fig. 6. Rate distribution for indoor scenario. SNR = 20 dB for reference user 2.

Multiuser diversity aims at maximization of the sum capacity, i.e. the cell throughput. However, it does not include fairness aspects. It can happen that a certain user is not served at all whereas another user gets almost all of the available capacity. It is a nice feature of CZF-SESAM, that including the spatial dimension in the scheduling process inherently brings some fairness. This can be seen in Figure 6 where we compare the rate distribution of the options given in Figure 2 for an indoor scenario with four users. OFDMA static allocates the same amount of resources to each subcarrier. All users are served but the sum rate is rather poor. On the other hand, dynamic OFDMA is rather unfair since one user gets almost all of the available capacity. CZF-SESAM achieves the highest sum capacity and serves all users with significantly higher rate than static OFDMA. Since fairness is not explicitly taken into account by the scheduler, this fairness cannot be guaranteed. However, it can be observed in most relevant scenarios. An extension of the algorithm could be a useful preselection of users who compete for the resources using CZF-SESAM such that fairness is achieved with high probability.

IV. Applicable Service: Video Streaming

Video streaming is a data rate demanding service which requires a stable data stream. Hence, application of multiuser diversity, where it can happen that a certain user is not served for some time, seems to be in contradiction to the requirements of video streaming. However, the inherent fairness aspect of CZF-SESAM which was described in the previous section may allow to benefit from the increased sum capacity and at the same time provide a stable video stream to the users. We consider an indoor scenario as depicted in Figure 7. The access point is equipped with 4 transmit antennas. The channel model is taken from the IST project WINNER [7]. Six users each with 2 receive antennas need to perform video streaming with different video sequences. We make the simplifying assumption that the source coding rate can be adapted independently from one frame to the next according to the allocated resources and there is no inter frame coding (INTRA frame mode of H.264motion JPEG). The buffers of the users are never empty. All users have the same average received SNR of 10 dB.

As video quality measure, we use the peak signal to noise ratio

$$\mathrm{PSNR} = 10\log_{10}\frac{255^2}{\mathrm{MSE}}$$

which gives the relation of the actual mean squared error (MSE) in the luminance component and its maximum error with 255 quantization levels. As a rule of thumb, we can say that a gain of 3 dB in terms of PSNR requires roughly doubling of the transmitted data rate.

As an example, we show in Figure 8 the PSNR versus the frame index for the three scheduling options given in Figure 2 for user 1 who transmits the ITU test sequence “foreman.” It can be observed that static OFDMA has the most stable performance since it allocates the same amount of resources to all users at any time. Dynamic OFDMA has sometimes significantly higher PSNR but on the other hand also often severe fades when the user is not scheduled. With CZF-SESAM, the PSNR is almost always higher than with static OFDMA. This indicates that the inherent fairness of CZF-SESAM allows stable video transmission even though fairness is not explicitly taken into account by the scheduler. The sudden degradation around frame index 220 in all scheduling options is due to a rapid move in the video sequence. Similar results are obtained for the other users.

user	test sequence	OFDMA static	OFDMA dynamic	CZF-SESAM
1	foreman	31.29	27.77	33.09
2	silent	30.30	27.82	32.56
3	mother & daughter	37.52	32.71	38.76
4	container	31.87	30.80	36.22
5	news	33.62	28.38	38.76
6	akiyo	39.28	36.49	43.87

Table 1: Average PSNR in dB for video streaming.

The achieved average PSNR for the six users is summarized in Table 1 for the three scheduling options given in Figure 2. CZF-SESAM achieves the highest average PSNR in all cases. Given the aforementioned rule of thumb that an PSNR gain of 3 dB requires about twice the data rate, the quality gains over static OFDMA are substantial and in the relevant range of PSNR. On the other hand, the average PSNR of dynamic OFDMA degrades significantly compared to static OFDMA. This is due to higher variance of the data rate which results from scheduling always the user with the highest SNR. The video quality is sometimes better but sometimes significantly worse than with static OFDMA. Again, we can conclude that including the spatial domain in the scheduling process achieves an averaging effect and allows to exploit

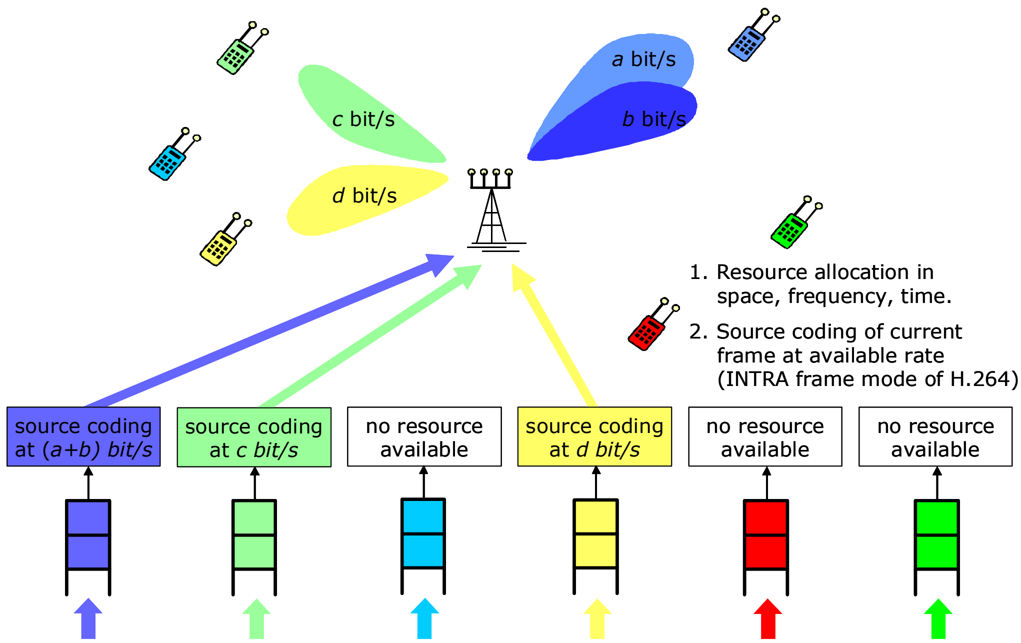

Fig. 7. Scenario for video streaming. (Snapshot of a resource allocation).

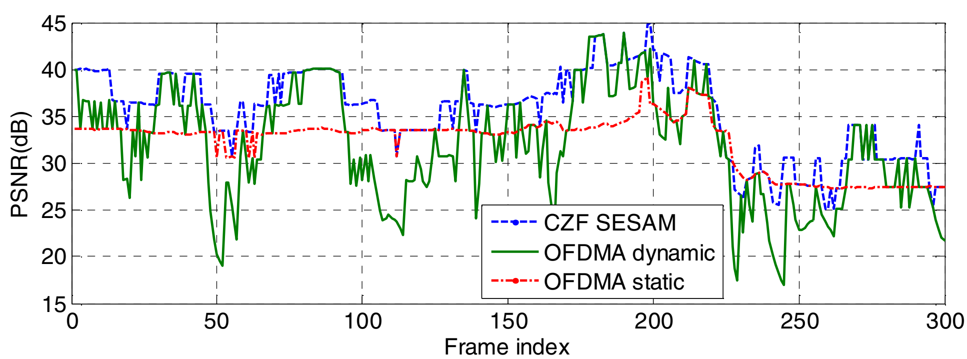

Fig. 8. PSNR for user 1.

multiuser diversity even in delay-sensitive applications as long as the average SNR of the users does not differ too much.

V. Conclusion

We have described a multicarrier downlink transmission scheme which combines the ideas of multiuser diversity and MIMO for cell throughput maximization. The proposed multiuser MIMO scheme uses perfect knowledge of the instantaneous channel for zero forcing and interference cancellation at the transmitter. The scheme has been evaluated based on measured channels for an indoor office environment. The theoretical limit for the sum capacity can be reached in most cases. Furthermore, we showed that including the spatial domain in the scheduling using the proposed scheme includes some inherent fairness even though QoS is not explicitly taken into account by the scheduler. This allows to benefit from multiuser diversity even for delay-sensitive applications such as video streaming.

References

[1] P. Tejera, W. Utschick, G. Bauch, J.A. Nossek: Subchannel allocation in multiuser multiple input multiple output systems. IEEE Transactions on Information Theory, Vol. 52, No. 10, October 2006.

[2] P. Tejera, W. Utschick, G. Bauch, J.A. Nossek: Efficient implementation of successive encoding schemes for the MIMO OFDM broadcast channel. IEEE International Conference on Communications (ICC), Istanbul, Turkey, June 11-15, 2006.

[3] P. Tejera, W. Utschick, G. Bauch, J.A. Nossek: Sum-rate maximizing decomposition approaches for multiuser MIMO-OFDM. IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Berlin, Germany, September 11-14, 2005.

[4] P. Tejera, W. Utschick, G. Bauch, J.A. Nossek: A novel decomposition technique for multiuser MIMO. International ITG/IEEE Workshop on Smart Antennas, Duisburg, Germany, April 4-5, 2005.

[5] J. Bach Andersen, J. Ø. Nielsen, G. Bauch, M. Herdin: The large office environment- measurement and modeling of the wideband radio channel. IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), Helsinki, Finland, September 11-14, 2006.

[6] H. Sato: An Outer Bound to the Capacity Region of Broadcast Channels. IEEE Transactions on Information Theory, Vol. 24, May 1978.

[7] IST project WINNER, www.ist-winner.org.