A NOVEL DECENTRALIZED MIMO-OFDM UPLINK DETECTION SCHEME

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ABSTRACT

Decentralized interference cancellation in MIMO-OFDM (orthogonal frequency division multiplexing) systems can be considered as a promising approach in next generation wireless systems. Considering the entirety of the antennas of all mobile terminals at one end and the antennas of the access points (APs) at the other end of the communication link, state of the art interference cancellation is based on a central signal processing unit, e. g. a central unit (CU), where joint detection can be applied in the uplink (UL) and joint transmission in the downlink (DL), respectively. Unfortunately such setups require cost-intensive optical fibers or point-to-point radio links in order to deliver all the required information to the CU. Therefore decentralized, cost-efficient solutions, which by-pass the CU, are of common interest. In this contribution a novel decentralized uplink detection scheme for MIMO-OFDM systems is presented and evaluated under real channel conditions.

1. INTRODUCTION

Multiple-Input Multiple-Output (MIMO) systems are capable of increasing the achievable capacity and integrity of wireless systems and hence, they may be expected to form an integral part of next generation wireless systems. Classic infrastructure-based wireless networks, such as cellular systems or wireless Local Area Networks (LANs) have attracted a lot of research and have reached a state of maturity. By contrast, despite decades of research, the family of networks operating without an infrastructure-based network, such as ad hoc wireless networks, require substantial further research. Cellular systems constitute a specific example of an infrastructure-based network, where APs distributed over a given geographic area, provide access for mobile terminals with the aid of a central signal processing unit. However such solutions are cost-intensive and solutions are of common interest that by-pass the central signal processing unit.

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MIMO-OFDM systems can be considered as a promising technique in Next-Generation Wireless Systems based on their ability to establish a reliable, cost-efficient data communication [1]. Different proposals for MIMO-OFDM systems are known in the literature, where state of the art interference cancellation is based on joint signal processing in the CU [2–5]. Unfortunately, such setups require cost-intensive optical fibers or point-to-point radio links in order to deliver all the required information to the CU. Therefore solutions which by-pass the CU are of common interest [6]. In this contribution a novel decentralized uplink detection scheme, based on a distributed signal processing at the APs, is proposed. A prerequisite for this kind of signal processing are efficient communication links between neighbouring APs.

The remaining parts of this contribution are organized as follows: Section 2 introduces the system model and state of the art interference cancellation schemes are briefly reviewed. The novel decentralized uplink detection scheme is introduced in section 3, whereas in section 4 the obtained results are presented and discussed. Finally, section 5 provides some concluding remarks.

2. SYSTEM MODEL AND STATE OF THE ART INTERFERENCE CANCELLATION

In the following, a multiuser MIMO-OFDM system is considered and the time-discrete equivalent low-pass representation of signals is chosen. Consequently, signals are represented by complex vectors and matrices, which are printed in bold face. In the investigated scenario K_{A} APs are at fixed locations and K_{M} MTs are simultaneously active. In general, the number of MTs, simultaneously supported on each subcarrier without interference from each other is limited by the number of antennas used at the APs when Zero-Forcing (ZF) detection is applied. This limitation can simply be abolished by using more antennas, at both, the transmitter and receiver sides in order to increase the available degrees of freedom [7]. Furthermore, the combination with other multiple access techniques, such as TDMA (time division multiple access) or FDMA (frequency division multiple access) is feasible.

Due to the application of OFDM a subcarrierwise modelling is feasible [2]. The data symbols of the MTs, which are transmitted simultaneously over the same subcarrier, can be stacked in a vector and result in

$$\underline{\mathbf{d}}_{\mathrm{u}} = \left(\underline{d}_{\mathrm{u}}^{(1)}, \underline{d}_{\mathrm{u}}^{(2)}, \cdots, \underline{d}_{\mathrm{u}}^{(K_{\mathrm{M}})}\right)^{\mathrm{T}} \quad . \tag{1}$$

Throughout this contribution, PSK (phase shift keying) modulation is assumed.

OFDM leads to a non-frequency selective channel per subcarrier, described by a complex channel coefficient. Extending these considerations to a multiuser MIMO-OFDM system, the following subcarrier specific system matrix can be obtained

$$\underline{\mathbf{H}}_{\mathrm{u}} = \begin{bmatrix} \underline{H}_{\mathrm{u}}^{(1,1)} & \cdots & \underline{H}_{\mathrm{u}}^{(1,K_{\mathrm{M}})} \\ \vdots & & \vdots \\ \underline{H}_{\mathrm{u}}^{(K_{\mathrm{A}},1)} & \cdots & \underline{H}_{\mathrm{u}}^{(K_{\mathrm{A}},K_{\mathrm{M}})} \end{bmatrix} \quad , \tag{2}$$

where the value $\underline{H}_{\mathrm{u}}^{(k_{\mathrm{A}},k_{\mathrm{M}})}$ denotes the subcarrier specific channel transfer function between the k_{A}-th AP and the k_{M}-th MT in case of a single antenna per AP [8]. The channel transfer functions are characterized by a path loss model with a path loss exponent of 4.0 and Rayleigh fast fading. In a centralized system, the signals are received by the APs and collected at the CU. Let the received vector $\underline{\mathbf{e}}_{\mathrm{u}}$ be expressed as

$$\underline{\mathbf{e}}_{\mathrm{u}} = \left(\underline{e}_{\mathrm{u}}^{(1)}, \underline{e}_{\mathrm{u}}^{(2)}, \cdots, \underline{e}_{\mathrm{u}}^{(K_{\mathrm{A}})}\right)^{\mathrm{T}} \quad . \tag{3}$$

Then, the subcarrierwise representation leads to

$$\underline{\mathbf{e}}_{\mathrm{u}} = \underline{\mathbf{H}}_{\mathrm{u}} \cdot \underline{\mathbf{d}}_{\mathrm{u}} + \underline{\mathbf{n}}_{\mathrm{u}} \quad , \tag{4}$$

where the noise vector $\underline{\mathbf{n}}_{\mathrm{u}}$ is defined as follows

$$\underline{\mathbf{n}}_{\mathrm{u}} = \left(\underline{n}_{\mathrm{u}}^{(1)}, \underline{n}_{\mathrm{u}}^{(2)}, \cdots, \underline{n}_{\mathrm{u}}^{(K_{\mathrm{A}})}\right)^{\mathrm{T}} \quad . \tag{5}$$

The noise $\underline{\mathbf{n}}_{\mathrm{u}}$ is assumed to be white with a variance of $\sigma^2/2$ for both the real and imaginary parts.

The interference between the different data streams, which is introduced by the non-diagonal channel matrix $\underline{\mathbf{H}}_{\mathrm{u}}$, requires appropriate data detection strategies. In a centralized system, interference cancellation is based on a central signal processing unit, e. g. a CU, where joint detection (JD) can be applied in the UL and joint transmission (JT) in the DL, respectively [9, 10]. Popular techniques are based on PIC or SIC (parallel or serial interference cancellation), which have attracted a lot of attention within the last years [2, 3, 11]. The general structure of a PIC scheme in the UL is shown in Fig. 1. The matched filter (MF) includes several correlators to match the corresponding channel coefficients and can be defined as follows

$$\underline{\mathbf{V}}_{\mathrm{u\,f}} = \left(\mathrm{diag}\left(\underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \cdot \underline{\mathbf{H}}_{\mathrm{u}}\right)\right)^{-1} \underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \quad . \tag{6}$$

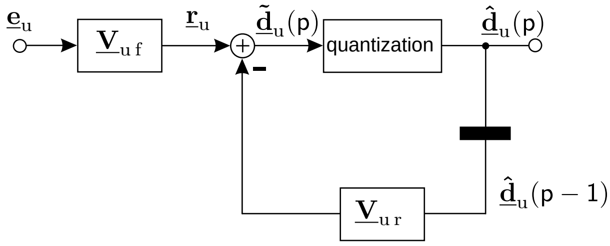

Fig. 1. UL interference cancellation

The expression $\mathrm{diag}\left(\underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \cdot \underline{\mathbf{H}}_{\mathrm{u}}\right)$ returns a diagonal matrix with the elements of the square matrix $\left(\underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \cdot \underline{\mathbf{H}}_{\mathrm{u}}\right)$ on its diagonal. The MF delivers a biased estimation vector

$$\underline{\mathbf{r}}_{\mathrm{u}} = \underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{e}}_{\mathrm{u}} = \underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{H}}_{\mathrm{u}} \cdot \underline{\mathbf{d}}_{\mathrm{u}} + \underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{n}}_{\mathrm{u}} \quad . \tag{7}$$

Rearranging equation (7) leads to

$$\underline{\mathbf{r}}_{\mathrm{u}} = \underline{\mathbf{d}}_{\mathrm{u}} + \left(\underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{H}}_{\mathrm{u}} - \mathbf{I}\right) \cdot \underline{\mathbf{d}}_{\mathrm{u}} + \underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{n}}_{\mathrm{u}} \quad , \tag{8}$$

with $\mathbf{I}$ describing the identity matrix. Analyzing (8) it is obvious that the remaining interferences can be removed by a matrix $\underline{\mathbf{V}}_{\mathrm{u\,r}}$, which has to be defined as follows

$$\underline{\mathbf{V}}_{\mathrm{u\,r}} = \underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{H}}_{\mathrm{u}} - \mathbf{I} \quad . \tag{9}$$

Finally, the vector $\tilde{\underline{\mathbf{d}}}_{\mathrm{u}}(p)$ is given by

$$\tilde{\underline{\mathbf{d}}}_{\mathrm{u}}(p) = \underline{\mathbf{r}}_{\mathrm{u}} - \underline{\mathbf{V}}_{\mathrm{u\,r}} \cdot \hat{\underline{\mathbf{d}}}_{\mathrm{u}}(p-1) \quad . \tag{10}$$

The hard or soft decision of $\tilde{\underline{\mathbf{d}}}_{\mathrm{u}}(p)$ results in $\hat{\underline{\mathbf{d}}}_{\mathrm{u}}(p)$ and can be used in the next stage to outperform the current detection. Nonetheless, it is worth mentioning that the proposed structure can also be applied without quantization. Assuming convergence and an infinite number of iterations p, i. e. asymptotically, equation (10) corresponds to the ZF solution and results in

$$\tilde{\underline{\mathbf{d}}}_{\mathrm{u}}(\infty) = \left(\underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \cdot \underline{\mathbf{H}}_{\mathrm{u}}\right)^{-1} \underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \underline{\mathbf{e}}_{\mathrm{u}} \quad . \tag{11}$$

3. NOVEL UPLINK DETECTION SCHEMES

3.1. State of the Art Interference Cancellation

Assuming PSK modulation, the normalization contained in (6) simplifies and the matrix $\underline{\mathbf{V}}_{\mathrm{u\,f}}$ results in

$$\underline{\mathbf{V}}_{\mathrm{u\,f}} = \underline{\mathbf{H}}_{\mathrm{u}}^{*\,\mathrm{T}} \quad . \tag{12}$$

For the matrix $\underline{\mathbf{V}}_{\mathrm{u\,r}}$ defined in (9) the following solution can be found

$$\underline{\mathbf{V}}_{\mathrm{u\,r}} = \underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{H}}_{\mathrm{u}} - \mathrm{diag}\left(\underline{\mathbf{V}}_{\mathrm{u\,f}} \cdot \underline{\mathbf{H}}_{\mathrm{u}}\right) \quad . \tag{13}$$

Using (12) and (13), the estimate of the k_M-th user signal in the p-th iteration, described by the k_M-th element of the data vector $\underline{\mathbf{d}}_\mathrm{u}$, results in

$$\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p) = \sum_{k_\mathrm{A}=1}^{K_\mathrm{A}} \underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}\left(\underline{e}_\mathrm{u}^{(k_\mathrm{A})} - \sum_{\substack{k=1\\ k\neq k_\mathrm{M}}}^{K_\mathrm{M}} \underline{H}_\mathrm{u}^{(k_\mathrm{A},k)}\cdot \hat{\underline{d}}_\mathrm{u}^{(k)}(p-1)\right) . \tag{14}$$

In the first detection stage, i. e., $p=1$, only a coarse estimate can be achieved due to $\hat{\underline{d}}_\mathrm{u}^{(k)}(0)=0$, i. e., no knowledge about the interferers is available. In this case, the detection of the k_M-th user signal takes the interferences from the other MTs into account. In the following stages, this influence can be approximately eliminated from the received signal $\underline{e}_\mathrm{u}^{(k_\mathrm{A})}$ at the k_A-th AP using detection results $\hat{\underline{d}}_\mathrm{u}^{(k)}(p-1)$ from the preceding stage. In general, each AP contributes to the detection of the k_M-th user signal. The complex conjugate multiplication by $\underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}$ in (14) allows a coherent summation of the detection results for the k_M-th user signal. The hard or soft decision of $\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p)$ results in $\hat{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p)$ and can be used in the next stage to outperform the current detection. In general the above described algorithms are performed at a central processing unit [2, 3].

3.2. Decentralized Interference Cancellation

The drawback of a centralized system, using a CU, can be avoided as a main feature of the proposed scheme. As shown in (14), at least theoretically, all APs contribute to the detection of the k_M-th user signal. In a decentralized system, the matched filter estimate

$$\underline{r}_\mathrm{u}^{(k_\mathrm{M})} = \sum_{k_\mathrm{A}=1}^{K_\mathrm{A}} \underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}\underline{e}_\mathrm{u}^{(k_\mathrm{A})} \ , \tag{15}$$

must be separated into its AP specific contributions and leads to

$$\underline{r}_\mathrm{u}^{(k_\mathrm{M})} = \sum_{k_\mathrm{A}=1}^{K_\mathrm{A}} \underline{r}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})} \ , \tag{16}$$

with

$$\underline{r}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})} = \underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}\,\underline{e}_\mathrm{u}^{(k_\mathrm{A})} \ . \tag{17}$$

The weighting using $\underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}$ has to be performed at each AP k_A for each user signal k_M. Separating $\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p)$ into its AP specific user contributions leads to

$$\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}(p) = \underline{r}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})} - \sum_{\substack{k=1\\ k\neq k_\mathrm{M}}}^{K_\mathrm{M}} \underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}\,\underline{H}_\mathrm{u}^{(k_\mathrm{A},k)}\,\hat{\underline{d}}_\mathrm{u}^{(k)}(p-1). \tag{18}$$

From the AP specific matched filter estimates for the k_M-th user signal $\underline{r}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}$ the interferences introduced by the other MTs have to be removed.

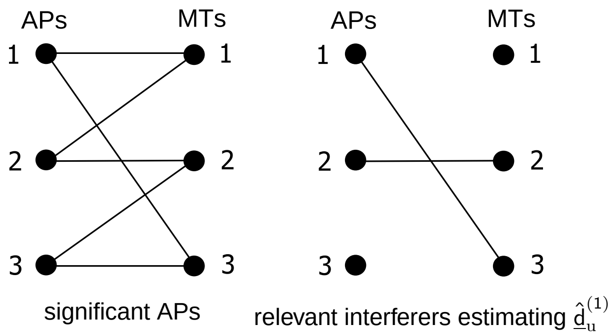

Fig. 2. Relationship between significant APs and relevant interferers in an exemplarily considered scenario

The novelty of the proposed decentralized UL detection scheme results from the point that only local channel state information is necessary to estimate the AP specific user contributions. As shown in (18), the processing of the AP specific data estimates $\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}(p)$ at the k_A-th AP requires only local channel state information, e. g., $\underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}$ for $k_\mathrm{M} = 1, 2, \ldots, K_\mathrm{M}$, which is available at the k_A-th AP. Taking the networking between the APs into account, an improved data estimate can be obtained based on an exchange of AP specific user results

$$\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p) = \sum_{k_\mathrm{A}=1}^{K_\mathrm{A}} \tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}(p) \ , \tag{19}$$

which describes the novelty of the proposed decentralized system concept. Based on (17) a coherent superposition of the different signal parts stemming from the same mobile is possible. From a practical point of view (18) can be simplified taking only dominant interferers into account as it is exemplarily highlighted in Fig. 2. In this case, equation (18) is simplified to

$$\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}(p) = \underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})*}\left(\underline{e}_\mathrm{u}^{(k_\mathrm{A})} - \sum_{\substack{\text{relevant}\\ \text{interferers } k}} \underline{H}_\mathrm{u}^{(k_\mathrm{A},k)}\,\hat{\underline{d}}_\mathrm{u}^{(k)}(p-1)\right) . \tag{20}$$

Furthermore only significant signal parts have to be taken into account (Fig. 2). This means that not all user signals have to be considered at each AP. Only few dominant neighboring APs need to be included when doing the matched filtering. Equation (19) results in

$$\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p) = \sum_{\substack{\text{significant}\\ \text{(neighbouring) APs } k_\mathrm{A}}} \tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})}(p) \ . \tag{21}$$

Equations (20) and (21) show the theoretical basis of the decentralized uplink detection scheme for multipoint-to-multipoint OFDM systems. The proposed scheme requires only local channel state information at the APs. In comparison to a centralized system, here no channel state information has to

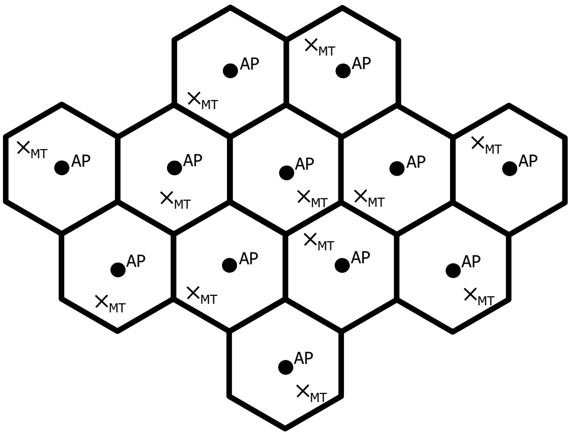

Fig. 3. Investigated scenario consisting of 12 cells, 12 APs and 12 MTs

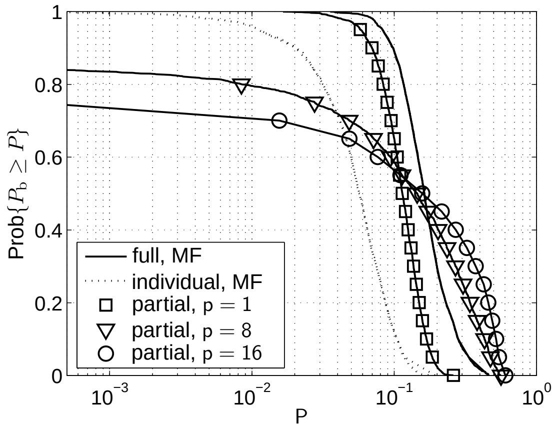

Fig. 4. UL CCDF of the BER distribution P_b without quantization and one antenna per AP

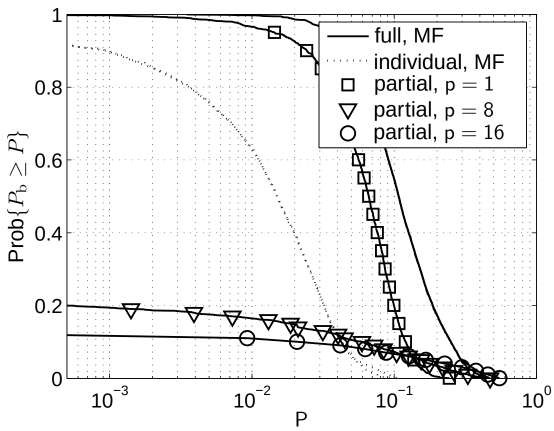

Fig. 5. UL CCDF of the BER distribution P_b without quantization and two antennas per AP

be exchanged between the APs. This will reduce the complexity of the proposed algorithm significantly. Only preliminary detection results have to be exchanged between (neighbouring) APs.

4. RESULTS

In order to assess the performance of the proposed distributed system architecture with partial cooperation, a scenario consisting of 12 cells, 12 APs and 12 MTs is considered as shown in Fig. 3. One MT is randomly located in each cell with uniform distribution. The channel transfer functions between the APs and MTs are characterized by a path loss model with a path loss exponent of 4.0 and Rayleigh fast fading [12]. Furthermore, QPSK modulation is chosen. In order to evaluate the BER characteristic properly, the CCDF (complementary cumulative distribution function) is used, whereby a purely interference limited system is considered, i. e., the thermal noise is ignored. The simulation results are shown in Fig. 4, 5 and 6, respectively.

Applying full cooperation, MF describes the first iteration of PIC. The k_M-th user signal, described by the k_M-th element of the data vector $\underline{\mathbf{d}}_\mathrm{u}$, results in

$$\tilde{\underline{d}}_\mathrm{u}^{(k_\mathrm{M})}(p) = \sum_{k_\mathrm{A}=1}^{K_\mathrm{A}} \underline{H}_\mathrm{u}^{(k_\mathrm{A},k_\mathrm{M})\,*}\, \underline{e}_\mathrm{u}^{(k_\mathrm{A})} \quad . \tag{22}$$

In comparison to full cooperation, individual MF describes the operation at the corresponding AP for the MT in the same cell, i.e., it corresponds to a conventional cellular system with no cooperation among cells. The BER CCDFs show a superiority of the individual MF compared to the full MF. The reason for this behavior can be justified by the unconsidered interferences from the other MTs.

Partial cooperation requires a cooperation between the APs in order to bypass the CU. Mostly, not all APs are involved in the MT specific data detection process [13]. Ignoring fast fading, the squares of the channel transfer function amplitudes between the APs and MTs decay with a power of 4.0 of the distances. This implies that the received energy at an AP is mainly contributed by the MTs close to the AP. Therefore we can conclude that only a few APs have to exchange preliminary MT specific data detection results and therefore partial cooperation requires only a cooperation between neighbouring APs with significant MT specific channels. The BER distributions with partial cooperation are depicted in Fig. 4, 5 and 6, whereby the number of considered APs per MT was limited to two.

From the theoretical point of view it can be concluded, that under certain circumstances, e. g., the received power at the AP stemming from different MTs is in the same range,

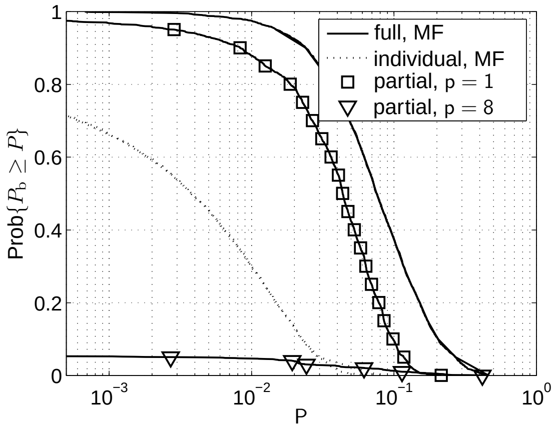

Fig. 6. UL CCDF of the BER distribution P_b without quantization and three antennas per AP

no reliable estimation can be performed. In order to overcome this limitation, the degrees of freedom should be further increased, e. g., the APs can be equipped with more than a single antenna or a more advanced multi-user detection is necessary [2, 14]. Therefore we have assumed that each AP is equipped with two or three antennas. The arising performance improvements can be seen in Fig. 5 and 6. For a high number of iterations partial cooperation is able to achieve a good compromise between performance and complexity.

5. CONCLUSIONS

A novel decentralized uplink detection scheme for multiuser MIMO-OFDM systems was presented and evaluated under real channel conditions. A prerequisite for the proposed distributed signal processing are efficient communication links between neighboring APs. These could be based on wires, optical fibers or point-to-point radio links.

Furthermore, our proposed architecture requires no central unit and only local communication and local channel state information are required. The results have shown that decentralized, cost-efficient solutions, which by-pass the CU, are possible and seem to be a promising approach in next generation wireless systems.

6. REFERENCES

[1] H. Sampath, S. Talwar, J. Tellado, V. Erceg, and A. Paulraj, "A Fourth-Generation MIMO-OFDM Broadband Wireless System: Design, Performance, and Field Trial Results," *IEEE Communications Magazine*, vol. 40, no. 9, pp. 143 – 149, September 2002.

[2] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-user Communications WLANs and Broadcasting*, Wiley, West Sussex, 2003.

[3] P. Vandenameele, L. Van Der Perre, and M. G. E. Engels, *Space Division Multiple Access for Wireless Local Area Networks*, Kluwer, Boston, 2001.

[4] T. Weber, A. Sklavos, Y. Liu, and M. Weckerle, "The Air Interface Concept JOINT for Beyond 3G Mobile Radio Networks," in *15th International Conference on Wireless Communications*, July 2003, vol. 1, pp. 25–33.

[5] P. Zhang, X. Tao, J. Zhang, Y. Wang, L. Li, and Y. Wang, "A Vision from the Future: Beyond 3G TDD," *IEEE Communications Magazine*, vol. 43, no. 1, pp. 38–44, January 2005.

[6] T. Weber, A. Ahrens, and S. Deng, "Decentralized Interference Cancellation in Mobile Radio Networks," in *IEEE Wireless Communications and Networking Conference (WCNC)*, Hong Kong, March 2007.

[7] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, University Press, Cambridge, 2005.

[8] M. Meurer, P. W. Baier, T. Weber, Y. Lu, and A. Papathanassiou, "Joint Transmission: An Advantageous Downlink Concept for CDMA Mobile Radio Systems using Time Division Duplexing," *Electronics Letters*, vol. 36, no. 10, pp. 900–901, May 2000.

[9] T. Weber, I. Maniatis, A. Sklavos, and Y. Liu, "Joint Transmission and Detection Integrated Network (JOINT), a Generic Proposal for Beyond 3G Systems," in *International Conference on Telecommunications*, Beijing, June 2002, vol. 3, pp. 479–483.

[10] T. Weber and M. Meurer, "Optimum Joint Transmission: Potentials and Dualities," in *International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Yokosuka, Oct. 2003, vol. 1, pp. 79–83.

[11] J. G. Andrews, "Interference Cancellation for Cellular Systems: A Contemporary Overview," *IEEE Wireless Communications*, vol. 12, no. 2, pp. 19–29, April 2005.

[12] B. Sklar, *Digital Communications – Fundamentals and Applications*, Prentice Hall, Upper Saddle River, New Jersey, 2 edition, 2001.

[13] S. Deng, T. Weber, and A. Ahrens, "Interference Statistics in the Downlink of Service Area based Mobile Radio Networks.," in *11th International OFDM-Workshop*, Hamburg, August 2006, pp. 31–35.

[14] S. Verdú, *Multiuser Detection*, University Press, Cambridge, 1998.