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System Performance Analysis of Single-Path and Cooperative MIMO Relaying

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*Abstract***— The demand for even higher data rates in future mobile communications systems calls for new techniques capable of improving the performance of cellular systems. One possibility are relay enhanced cells where additional radio access points without wired backhaul are mounted and served by a base station using in-band resources. Although relaying can significantly improve channel conditions in terms of pathloss and fading, it suffers from a limited link between base station and relay node as well as from the half-duplex operation in which relay nodes retransmit messages.**

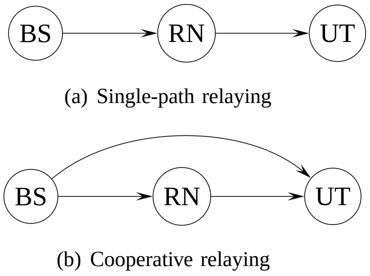
In this work we discuss and evaluate relaying strategies for multiple antenna based systems in terms of average user throughput. The performance of a conventional cellular system is compared with single-path relaying and cooperative relaying where base stations and relay nodes cooperatively serve user terminals.

I. INTRODUCTION

In recent years the global success of wireless communications systems, such as cellular networks, stimulated the research for more (cost) efficient ways of utilizing existing bandwidth. Currently, research activities focus on different topics to support ubiquitous high rate services in next-generation networks; among others, these are multiple antenna systems [1], [2] and multi-hop transmission [3].

A. Motivation of our work

In multi-hop based systems additional, intermediate radio access points (so called *relay nodes*) are used to reduce distances between individual nodes and simultaneously improve the channel conditions. In his seminal paper van der Meulen [3] introduced the three-terminal relay channel where a single intermediate node supports a single communication pair. Later, Cover and El Gamal [4] proposed different relaying protocols which still serve as a basis for many relaying strategies. Sendonaris *et al.* were the first who applied in [5], [6] the idea of relaying to *wireless fading channels*. Motivated by the usage of a CDMA based system their approach considered nodes operating in a full-duplex mode, i. e., the transmit and receive signal are perfectly separated. Due to practical restrictions, such as the coupling of the transmit signal into the receiver path in today’s transceiver frontends, it is more realistic to assume half-duplex relay nodes. Laneman *et al.* examined this problem in [7] in the context of wireless fading channels and proposed various protocols for half-duplex *cooperative relaying*. Throughout this work we will only consider relay nodes constrained by a half-duplex operation and show the impacts on the system level performance.



(a) Single-path relaying

(b) Cooperative relaying

Fig. 1. Single-path versus cooperative relaying involving base station (BS), relay node (RN) and user terminal (UT) in the downlink.

So far, most research activities concentrated on the link layer behavior, and only little work has been done to investigate the *system level performance* and integration of (cooperative) relaying in a wireless system. Furthermore, most work regards *single-path relaying* which is illustrated in Fig. 1(a) for the downlink of a wireless system involving a base station (BS), one relay node (RN) and the user terminal (UT). In this case, the protocol structure is divided into two phases: in the first phase the relay node receives the message sent by the base station and the user terminal ignores this transmission. In the second phase the relay node forwards the BS message to the user terminal. It exploits only the relay node transmission and does not benefit from the existing large scale spatial diversity.

Relaying based systems can be distinguished into those using mobile relay nodes and those where relay nodes are fixed in their position. In comparison to mobile relay nodes, the fixed relay node approach looses flexibility as the number of potential relay nodes might be smaller. On the other hand, mobile relay nodes increase the complexity to secure a relayed transmission and to award the relay service (billing problem). We will consider in this work only fixed relay nodes with a high quality link towards the BS. This concept also covers the idea of movable relays which are temporarily deployed at points of high traffic such as stadiums or in case of other events attended by a large number of potential users.

Additional flexibility in a relay based network is offered due to the cooperation of relay nodes and base stations

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which results in a *virtual antenna array* [8]. As shown in Fig. 1(b) the user terminal exploits both the base station *and* relay node transmission to gain on large scale spatial diversity. Since next generation wireless networks are likely to employ multiple-antenna (MIMO) based devices, there is consequentially an interest for the analysis of relaying in the context of systems utilizing MIMO devices. So far, a variety of advanced multiple-antenna algorithms for distributed MIMO systems (in most cases a coordinated transmission of multiple base stations) were published but not analyzed in the relaying context. An application of these algorithms to relaying based systems such that relay nodes and base stations coordinately transmit, combines the advantages of multiple-antenna algorithms and relaying, and thus promises higher data rates, less intra/inter-cell interference and more resource management flexibilities. To the authors' knowledge only [9] investigated so far the system level performance of MIMO relaying. Nevertheless, their work only considered channel state information at the receiving nodes. This work considers preprocessing algorithms based on channel state information at the transmitter which are applicable in case of high channel coherence time and frequency.

B. Outline and contribution of this work

Motivated by the possibilities in relaying based systems and of distributed MIMO algorithms exploiting channel state information at the transmitter, we aim at presenting a qualitative and quantitative analysis of MIMO relaying in a 4G cellular system. At first we define in Section II the assumed architecture and system parameters. Then we discuss single-path and cooperative relaying approaches for relay enhanced cells in Section III. In Section IV we discuss numerical results comparing a conventional cellular system with a system using solely single-path relaying and a system using both cooperative and single-path relaying. The performance is compared using the per-user throughput. Finally, we conclude the paper in Section V and give future directions for our work on the system level analysis of relaying.

II. SYSTEM MODEL

A. The system parameters

In our work we consider the downlink of a time-division duplex based OFDMA system where frames of 15 OFDM symbols for up- and downlink are alternating. Its basic parameters are taken from the WINNER project [10] and given in Table I. Let $\theta(c, k, x, y)$ be the instantaneous throughput on a specific subcarrier c, time instance k and position (x, y). In our analysis we use a snapshot based approach where users are uniformly distributed and no mobility is considered. Let $\mathcal{C}_p$ be a set of subcarriers assigned to a user p at location (x_p, y_p). Then, for a particular snapshot and user p the throughput is given by $\theta(k, x_p, y_p) = \sum_{c \in \mathcal{C}_p} \theta(c, k, x_p, y_p)$. For the performance evaluation in Section IV we use the expected throughput at a particular location which is defined by $\theta(x, y) = \mathbb{E}_k\left(\theta(k, x, y)\right)$ where $\mathbb{E}(\cdot)$ is the expectation operator. Furthermore, we assume full buffers at the BS so that the system is always fully loaded and each user receives data at the maximum possible rate.

User density	70 per km^2
Channel models	as defined in [11]
Number of antennas BS / RN / UT	4 / 2 / 1
BS transmit power	46 dBm
RN transmit power	37 dBm
UT noise figure	7 dB
Noise power spectral density	-174 dBm/Hz
FFT-Size	2048
Carrier frequency	3.95 GHz
FFT bandwidth	100 MHz
Symbol duration	20.48μs
Guard interval	2.00μs
Used subcarriers	$[-920; 920] \setminus \{0\}$
Channel state information	assumed perfect at transmitter and receiver

TABLE I
SYSTEM PARAMETERS OF THE ANALYZED OFDM SYSTEM.

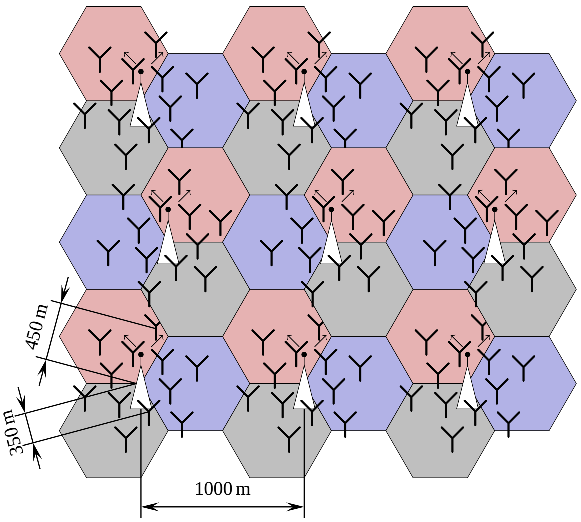


Fig. 2. Typical urban coverage scenario with 12 RNs per site, i. e., four RNs per cell. At each site 3 BSs with sectorized antennas are deployed. Both tiers of relay nodes are rotated to each other to offer a uniform coverage by RNs.

B. Reference scenario

In the following, we will compare the performance of a conventional cellular network with a relay enhanced cell (REC) using a typical urban area scenario. In this urban scenario, shown in Fig. 2, each site hosts three BSs which serve the three adjacent hexagonal cells. Additionally, in case of a REC we place two tiers of six RNs around each site with radius $r_1 = 350\,\mathrm{m}$ and $r_2 = 450\,\mathrm{m}$, respectively. To reduce interference from neighboring cells, partial frequency reuse (PFR) with equal power allocation as in [12] is applied. Obviously, each RN is able to form an own micro-cell. Hence the effective frequency reuse factor f_{reuse} (the degree how resources are reused, i. e., one resource group is used in $^1/_{f_{\text{reuse}}}$ of the overall area) can be decreased, as part of the total resources are reused in each micro-cell. Furthermore, we use the pathloss and channel models described in [11] for our evaluation.

III. RELAYING PROTOCOLS

A. The broadcast access

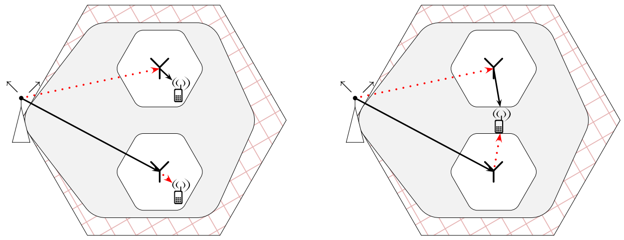
In our system we use multiple antenna devices to improve the system throughput. An important part of this system is the broadcast access, i. e., how BSs and RNs transmit multiple streams to multiple destinations. In [13] this problem was investigated for multiple antenna transmitters and single antenna receivers. It was shown that using a LQ precoding approach combined with dirty paper coding (called Zero-Forcing Dirty Paper Coding in [13]) achieves rates close to (sum-rate) capacity. Before explaining the multiple antenna cooperative relaying approach in more detail, we briefly repeat the LQ transmit precoding technique.

Consider a system with N receive antennas (not necessarily at a single terminal) and $M \geq N$ transmit antennas. The LQ precoding approach decomposes the compound channel matrix $\mathbf{H} \in \mathbb{C}^{N \times M}$ into a lower triangular matrix $\mathbf{L} \in \mathbb{C}^{N \times N}$ and a unitary matrix $\mathbf{Q} \in \mathbb{C}^{N \times M}$. Instead of directly transmitting the data vector $\mathbf{d} \in \mathbb{C}^{N \times 1}$, it is multiplied by the complex conjugate of $\mathbf{Q}$. This ensures that the signal received by user $i \in [1; N]$ is not interfered by the transmissions dedicated to users $j > i$. Furthermore, if a dirty paper coding technique is used [14], we obtain a single user channel for user i as it does not experience any interference from users $j < i$. Hence, the SINR for user i is given by $\left|\mathbf{L}_{ii}\right|^2 p_i / \sigma^2$, where $\mathbf{L}_{ii}$ is the i-th diagonal element of $\mathbf{L}$, $p_i = \mathbb{E}\left(\left|d_i^2\right|\right)$ and σ^2 models the sum of noise and interference power.

B. Recovering the half-duplex loss

Two-hop relaying protocols are divided into two phases: in the first phase the BS transmits data to the RN and in the second phase the RN forwards this data. The type of a RN can be distinguished by the way how received messages are forwarded; one group amplifies and forwards (analog relaying) whereas the other group decodes and forwards (digital relaying) the messages [7]. In this work we consider the latter group, where relay nodes decode BS transmissions and reencode them before they are retransmitted. We further use the adaptive re-transmission approach developed in [15], which proposes that the RN *and* BS remain silent in case of a decoding error at the relay terminal (detected through the use of reliability information, e. g., LLR-values).

The bottleneck of this protocol structure is the half-duplex constraint which implies that each node either transmits or receives on a particular time-frequency resource. One way to recover this loss are groups of RNs which are alternately transmitting and receiving as presented in [16], [17]. This is implemented in our system by defining an own micro-cell for each RN where in each micro-cell all RN-resources are reused. At a particular UT the ratio of the received signal power from the assigned RN to the noise and interference power must satisfy in our system $\gamma_{\text{micro}} = 13\,\mathrm{dB}$ such that this UT is served using the micro-cell resources of the assigned RN.



(a) Relay micro-cells (b) Alternately serving RNs

Fig. 3. Two possibilities for concurrently operating RNs. In both situations each RN manages its own micro-cell. Dotted and solid lines from BS to RNs and RNs to UTs indicate two different time-frequency resources. An edge-band (hashed area) is used at the global cell edges.

In our system we consider the following two possibilities to exploit the concurrency of RN to UT and BS to UT transmission. The first alternative is illustrated in Fig. 3(a) where one group of RNs is served by the assigned BS while the other group serves UTs on the same resource. This parallel transmission by multiple nodes within one cell significantly improves the frequency reuse though the intra-cell interference is increased. Hence, an intelligent deployment of fixed RNs is necessary to avoid that the performance benefit through serving multiple nodes in parallel is not outweighed by a worse SINR resulting from an increased intra-cell interference. Besides, this approach can be implemented using both a centralized and a decentralized resource management as each RN can manage its own resource pool given by the BS.

Fig. 3(b) illustrates the second alternative where two RNs are alternately serving the same UT. While one of both RNs is serving the UT the other one is served by the BS. With this protocol BS and RNs must coordinate each other and hence a fully decentralized resource management is not possible.

C. Multiple antenna cooperative relaying

A major benefit of relaying are the improved resource management flexibility and, even more important, the improved channel quality. Nonetheless, to achieve a more uniform service quality a high RN density is necessary since RNs are power limited due to practical limitations. One way to achieve a uniform service quality is to exploit a cooperative transmission of RNs and BS, as an alternative to single-path relaying. This is of high interest in those areas where the link SINR from RN to UT and BS to UT are of similar quality, i. e., the area between RNs and BS which is more likely to suffer from a performance drop than to the remaining cell area (since neither RNs nor BS have a sufficient connection to the UTs in this area). In our system the difference between both SINRs must not exceed $\gamma_{\text{coop}} = 20\,\mathrm{dB}$ such that a UT is cooperatively served.

To gain on large-scale spatial diversity, most cooperative relaying protocols exploit a combination of the first and second phase transmissions. In a multiple-antenna based system this implies that dedicated MIMO algorithms might be not applicable. Consider the BS-RN feeder link where the

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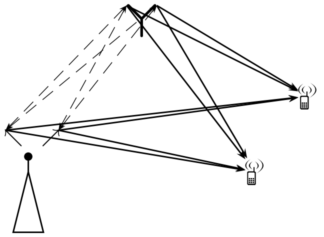

Fig. 4. MIMO cooperative relaying: In the first phase (dashed lines) the BS serves the RN and in the second phase (solid lines) both cooperatively serve the UTs.

position of a RN can be well chosen to obtain good channel conditions. Hence, the data rate on the feeder link is likely to exceed the data rate on the RN-UT link. Let us further apply beamforming or other SDMA algorithms such that all degrees of freedom are utilized. To combine the first and second phase transmission, user terminals must decode the BS-RN transmission. If the BS-RN transmission quality shall remain unaffected, the user terminal can most likely only decode parts of the transmission, e. g., through multi-level modulation. This would further complicate the detection at the user terminal as well as the signaling overhead, since a user terminal is only allowed to decode parts of the BS-RN transmission. Besides, if we try to optimize the BS-UT transmission, then the BS-RN data rate will most probably drop. This, of course, worsens the bottleneck problem on the BS-RN feeder link which becomes even more severe. Therefore, in our system we restrict the cooperation to the second phase. BS and RN build a virtual antenna array and jointly transmit towards the user terminal using distributed MIMO algorithms.

In this work we consider a cooperation between BS and RN similar to the proposal of [18], i. e., a coordinated LQ precoding of RN and BS. One could also think of a cooperation between multiple RNs building a virtual antenna array. Such an approach might increase the benefits due to cooperative relaying but also goes in hand with an increased complexity regarding synchronization, signaling, resource management and other related functions. Fig. 4 illustrates our approach which is divided in two phases. In the first phase the BS transmits all necessary user data as well as all channel coefficients for the BS-UTs links to the RN (in the numerical simulation we only consider the user payload). Furthermore, in the successive uplink frame the RN transmits all channel coefficients of the RN-UTs links to the BS. In the next downlink slot both RN and BS cooperatively serve the UTs. Both use the compound channel matrix from BS and RN to the respective UTs for a distributed LQ transmit precoding.

This approach has several advantages: first of all it is scalable regarding the granularity of exchanged channel information which highly depends on the channel quality between BS and RN, i. e., on the feeder link quality. Furthermore, we restrict the number of UTs for a cooperative transmission to the maximum number of UTs which can be served by a single BS. Hence, we are able to implement an adaptive protocol such that the BS solely serves the UTs in case the RN is either fully loaded or wrongly decoded the BS-RN transmission. Finally, we want to mention that this approach could be extended to a multi-hop approach to gain on multi-hop based RECs as investigated for single-antenna systems in [19].

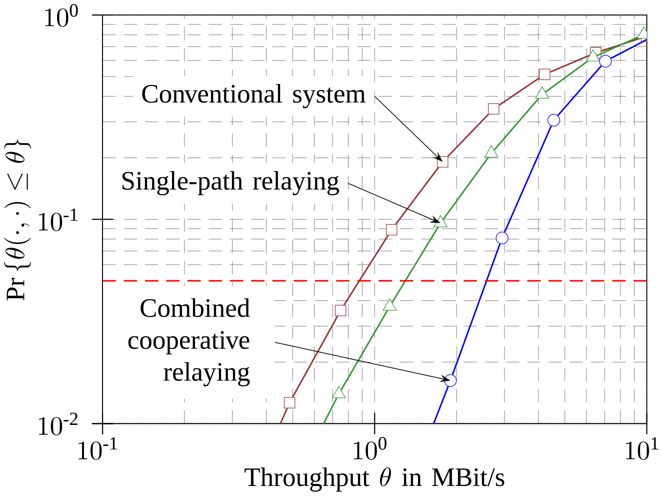

Fig. 5. Logarithmic CDF for the throughput in our considered system. Combined cooperative relaying includes single-path relaying and the use of RN-micro-cells (see Section III).

Protocol	$\theta_{5\%}$	$\overline{\theta}$	σ_θ
Conventional system	0.84	8.68	7.72
Single-Path relaying	1.29	6.87	5.58
Combined cooperative relaying	2.44	8.02	5.72

TABLE II

NUMERICAL RESULTS FOR LINK THROUGHPUT. ALL VALUES ARE GIVEN IN MBIT/S.

IV. NUMERICAL RESULTS

To evaluate the potential benefits of relay enhanced cells, we compare the cooperative relaying approach (using all techniques presented in section III) with a conventional cellular system and a system using only single-path relaying. For our analysis of the typical urban coverage scenario described in Section II-B, we use the numerical results shown in Fig. 5 obtained for one site surrounded by one tier of 6 sites. The results present the cumulative distribution function (CDF) of the expected user throughput $\theta(\cdot,\cdot)$. Besides, we use the following measures listed in Table II to evaluate the system performance:

- the minimal expected throughput value achieved by at least 95% of all users given by the 5%-ile $\theta_{5\%}$ and defined by $\Pr\{\theta(\cdot,\cdot) \leq \theta_{5\%}\} = 0.05$,
- the average throughput $\overline{\theta} = \mathbb{E}_{x,y}[\theta(x,y)]$,
- the standard deviation of the throughput is defined as

$$\sigma_\theta = \sqrt{\mathbb{E}_{x,y}\left[\left(\theta(x,y) - \overline{\theta}\right)^2\right]}.$$

A. Benefits of relay enhanced cells

The throughput CDF as well as the increased $\theta_{5\%}$ show that relaying reduces the number of users with low throughput.

Also the standard deviation of the throughput can be significantly improved in both relaying scenarios.

Throughout our simulations we observed a major throughput improvement nearby the BS. In a conventional deployment the BS has to distribute its resources among all UTs which includes those with poor performance (mainly at the cell edge). In a REC these UTs are served by RNs, hence the BS needs to serve only UTs with low pathloss and high throughput. Therefore, the deployment of RNs not only increases the performance at the cell edge (which is intuitively clear due to the lower pathloss) but also at the cell center. Not answered by the presented results is the question how the throughput changes if more RNs are deployed and therefore the pathloss is further decreased. Such a system surely requires more advanced schedulers to coordinate the RN-UT transmissions but it also has the potential to further increase the average throughput. On the other hand, an increased number of RNs might worsen the cost-benefit tradeoff.

B. Comparison of single-path and cooperative relaying

The simulation results show that the choice of the relaying protocol has a major influence on the performance in a REC. Using Cooperative relaying improves the throughput more significantly than applying only single-path relaying. The difference in terms of the 5%-ile throughput is slightly above 1 MBit/s which means that the throughput performance of the worst 5% is almost doubled in comparison to single-path relaying. Furthermore, the lower standard deviation σ_θ of both relaying approaches indicates that they are able to offer a more uniform service. These enhancements can be achieved without a large loss regarding the average throughput $\overline{\theta}$.
Since each RN is equipped with two antennas, it only serves up to two UTs concurrently on one resource in case of single-path relaying. If RNs and BSs are jointly serving UTs, they build a virtual antenna array with six transmit antennas, hence they can serve up to six UTs concurrently (in our setup only up to four UTs are scheduled together). The high choice of $\gamma_{\text{coop}} = 20\,\text{dB}$ further ensures that a large number of users (almost 60% of all UTs) is cooperatively served.

V. CONCLUSIONS AND FURTHER WORK

In this work we analyzed the relaying performance using system level results in a typical urban coverage scenario. Furthermore, we compared a conventional cellular system with a relay enhanced cell using either solely single-path relaying or a mixed approach of single-path and cooperative relaying. In both cases RNs have to fulfill the orthogonality constraint which implies that relays either transmit or receive on a particular time-frequency resource.

As shown in the previous sections, relaying is a useful alternative to improve the performance in MIMO based next generation mobile communications systems. These advantages are achieved through the improved channel conditions as well as coordinated BS-RN transmissions. Furthermore, relaying enables the usage of low cost, small and flexibly deployable radio access points which may potentially improve the user acceptance and might decrease deployment costs. Even if relays are constrained by a half-duplex operation, relaying is able to achieve higher throughput results though parts of the resources are used to feed and coordinate the RNs. This leads us to an important focal point of future work: the cost-benefit analysis of different RN densities and different RN devices. Obviously, less BSs are necessary to achieve the same performance as in a conventional system. Due to the fact that even low cost devices underlying the half-duplex constraint are able to achieve significant performance improvements, we can expect that the deployment costs are reduced. This is mainly due to lower fixed infrastructure costs, e. g., for the wired backhaul and the usually more expensive BS equipment.

REFERENCES

[1] E. Telatar, "Capacity of multi-antenna gaussian channels," *European Transaction Telecommunication*, vol. 10, pp. 585–595, 1999.

[2] G. Foschini and M. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications: An International Journal*, vol. 6, no. 3, pp. 311–335, March 1998.

[3] E. van der Meulen, "Transmission of information in a t-terminal discrete memoryless channel," Dept. of Statistics, Univ. of California, Berkeley (CA), Tech. Rep., 1968.

[4] T. Cover and A. E. Gamal, "Capacity theorems for the relay channel," *IEEE Transactions on Information Theory*, vol. 25, no. 5, pp. 572–584, September 1979.

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. part i. system description," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1927–1938, November 2003.

[6] ——, "User cooperation diversity. part ii. implementation aspects and performance analysis," *IEEE Transactions on Communications*, vol. 51, no. 11, pp. 1939–1948, November 2003.

[7] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, December 2004.

[8] M. Dohler, "Virtual antenna arrays," Ph.D. dissertation, King's College London, London, UK, 2003.

[9] O. Muñoz, A. Agustín, and J. Vidal, "Cellular capacity gains of cooperative MIMO transmission in the downlink," in *International Zurich Seminar on Communications (IZS)*, Zurich, Switzerland, February 2004, pp. 22–26.

[10] WINNER, "Ist-winner," http://www.ist-winner.org.

[11] IST-4-027756 WINNER II, "D1.1.1 WINNER II Interim channel models," November 2006.

[12] Y. Xiang, J. Luo, and C. Hartmann, "Inter-cell interference mitigation through flexible resource reuse in ofdma based communication networks," in *13th European Wireless Conference EW2007*, 2007.

[13] G. Caire and S. S. (Shitz), "On the achievable throughput of a multi-antenna gaussian broadcast channel," *IEEE Transactions on Information Theory*, vol. 49, no. 7, pp. 1691–1706, July 2003.

[14] M. Costa, "Writing on dirty paper," *IEEE Transactions on Information Theory*, vol. IT-29, no. 3, pp. 439–441, May 1983.

[15] P. Herhold, E. Zimmermann, and G. Fettweis, "A simple cooperative extension to wireless relaying," in *International Zurich Seminar on Communications (IZS)*, Zurich, Switzerland, February 2004.

[16] T. Oechtering and H. Boche, "Capacity of a gaussian FIR linear relay network," in *International Conference on Wireless Networks, Communications and Mobile Computing*, Maui (Hawaii), USA, June 2005.

[17] P. Rost and G. Fettweis, *Cognitive Wireless Networks: Concepts, Methodologies and Visions*. Springer, 2007, ch. Scalable Cooperation in Multi-Terminal Half-Duplex Relay Networks, pp. 179–197.

[18] K. Karakayali, G. Foschini, R. Valenzuela, and R. Yates, "On the maximum common rate achievable in a coordinated network," in *IEEE International Conference on Communications*, vol. 9, Istanbul, Turkey, June 2006, pp. 4333–4338.

[19] P. Herhold, E. Zimmermann, and G. Fettweis, "Cooperative multi-hop transmission in wireless networks," *Journal on Computer Networks*, vol. 49, no. 3, pp. 299–324, October 2005.