Relaying and Base Station Cooperation: a Comparative Survey for Future Cellular Networks

Raphael Rolny, Marc Kuhn, Armin Wittneben
Communication Technology Laboratory, ETH Zurich, Switzerland
Email: {rolny,kuhn,wittneben}@nari.ee.ethz.ch

Thomas Zasowski
Swisscom (Switzerland) Ltd., Bern, Switzerland
Email: thomas.zasowski@swisscom.com

***Abstract*—We develop a unified framework to investigate the performance of future cellular networks with relays and/or coordinated multipoint (CoMP) transmission. Based on this framework, we study the benefits of CoMP and relaying in a realistic setup. We consider imperfect channel knowledge, different power levels, and simple (thus practically relevant) cooperation schemes with different complexity: non-cooperative reference, decode-and-forward relaying with relay selection, base station cooperation with block zero-forcing (coherent joint transmission), and a combination of relaying and CoMP. Based on computer simulations, we compare the different schemes with respect to performance, robustness, complexity, and required transmit power.**

I. Cooperation is the Future

Research suggests large benefits by cooperative communication, which is required to meet the ever growing demands in cellular networks [1]. Thus, substantial efforts are undertaken to develop cooperation schemes and to include them into the standardization of next generation networks such as 3GPP LTE-Advanced [2]. Also the use of relays and the development of heterogenous networks that include femto cells, remote radio heads (RRHs), or other types of nodes is widely discussed in literature, see e.g. [3]–[5] and references therein. These efforts thus indicate that future networks will consist of different types of infrastructure nodes which serve mobile users in a cooperative fashion. Here, cooperation can mean that multiple nodes jointly transmit/receive signals to/from multiple mobiles and/or that multiple nodes coordinate themselves e.g. for resource allocation or power control.

However, most academic research has focused either on strongly simplified networks such as Wyner type models (e.g. [6]), or only on individual aspects of cellular networks. Such individual aspects include relaying [3], [7], coordinated multipoint (CoMP) transmission in fixed or dynamic cooperation clusters [8], [9], impact of sectorization on certain schemes [10], or robustness of certain schemes against inaccuracies (e.g. imperfect channel state information (CSI)) [11].

As available scientific work differs in its models and assumptions, it is difficult to compare several techniques with each other. Moreover, the performance heavily depends on various parameters such as traffic load or effective signal-to-interference-and-noise ratio (SINR), which are hard to predict and model [12]. To this end, it is important to have a unified framework, which allows comparing different schemes in a fair and consistent fashion, and capture practical considerations in a realistic way. These include, among others, network topology, backhaul connection, accurate channel models, and imperfections. In this work, we develop such a framework and compare different communication schemes of high practical relevance for the downlink in future cellular networks: a non-cooperative reference, decode-and-forward (DF) relaying with selection combining, base station (BS) cooperation based on block zero-forcing and optimized power allocation. The framework also allows for combinations thereof.

As future networks are expected to be very heterogenous, i.e. they can contain eNodeBS, home NodeBs, RRHs, or other nodes, a comprehensive discussion of future cellular networks has also to take different types of infrastructure nodes into account. To this end, our developed framework can capture a variety of infrastructure nodes. These nodes are modeled in a way that they are distinguished only by parameters as transmit power, backhaul connection, and antenna configuration. Combined with a realistic channel and interference model, this approach allows to study and compare different scenarios in a realistic way.

After introducing our unified framework, we study the influence of the type of the infrastructure nodes and how the performance of a network depends on network topology and cooperation complexity. By means of computer simulations, we evaluate various relevant scenarios with respect to performance, robustness, and complexity. Important aspects that we address include the influence of the node type and their transmit power. Also the impact of the number of cooperating nodes as well as the required amount and quality of CSI that limits the cooperation level from relaying to CoMP is discussed. Furthermore, we also comment on the feedback and backhaul load required for the different schemes. All together, these contributions give a unified view on the most important aspects of future cooperative cellular networks.

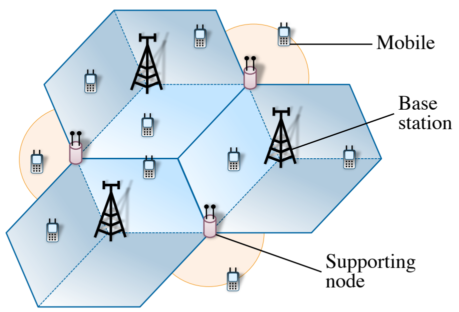

Fig. 1. A cooperative cellular network that is assisted by supporting nodes. These can correspond to relays, home NodeBs, or remote radio heads.

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II. Unified Framework

In order to capture networks with different types of nodes within a unified framework, the description of the nodes is simplified in a way that they are only distinguished by parameters such as transmit power, backhaul connectivity, and antenna configuration (including sectorization). This allows for considering and comparing different scenarios that include relaying and CoMP as well as combinations thereof. In our framework, we consider two types of infrastructure nodes, namely *base stations* (BSs) and *supporting nodes* (SNs). These SNs assist the communication of BSs with mobiles (MSs) and can represent relays, home NodeBs, or RRHs. Due to the abstraction of the infrastructure nodes, we can easily change SNs into BSs, or vice versa, by adjusting the corresponding parameters in our model. In the following, we focus on the downlink and describe the system in the equivalent baseband representation. For the sake of simplicity, we consider only a single subcarrier in our framework, but the model can easily be extended to multi carrier systems.

The set of all BSs and SNs is divided into *cooperation clusters* that can comprise multiple BSs and/or SNs. The infrastructure nodes of one cooperation cluster can then jointly serve one or multiple MSs. The cooperation clusters are described by the index sets $\mathcal{M}_1, \ldots, \mathcal{M}_C$, where C is the number of clusters within a network and the elements of these sets correspond to the indices of BSs and SNs that are associated to these clusters. The cooperation clusters are assumed to be fixed during a transmission period and a specific resource (time/frequency) block. Note that different clusters can contain a different number of infrastructure nodes; some can consist of only a single BS, while others can contain a plurality of BSs and SNs. Each element of a cooperation cluster $\mathcal{M}_c$, $c \in \{1, \ldots, C\}$, transmits signals to MSs described by the index set $\mathcal{K}_c$. Also these sets can contain multiple or only one active node, depending on the specific scenario.

Each infrastructure node within a cooperation cluster, say node $b \in \mathcal{M}_c$, transmits a sum of linearly precoded signals

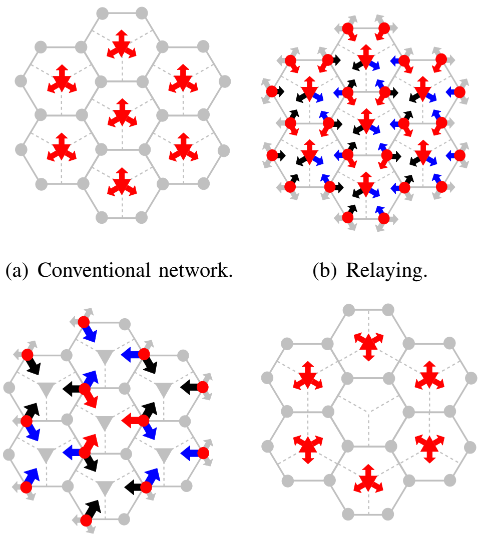
$$\mathbf{x}_b = \sum_{k \in \mathcal{K}_c} \mathbf{G}_k^{(b)} \cdot \mathbf{s}_k, \qquad (1)$$

where each summand corresponds to the signal intended for one of the associated MSs. The matrix $\mathbf{G}_k^{(b)}$ denotes the precoding matrix of the signal from infrastructure node b to MS k, and $\mathbf{s}_k$ is the corresponding data symbol vector. Note that $\mathbf{G}_k^{(b)} \in \mathbb{C}^{N_b^{(\mathrm{T})} \times N_k^{(\mathrm{D})}}$ and $\mathbf{s}_k \in \mathbb{C}^{N_k^{(\mathrm{D})}}$, with $N_b^{(\mathrm{T})}$ and $N_k^{(\mathrm{D})}$ the number of transmit antennas of node b and data streams for MS k, respectively.

The receive signal $\mathbf{y}_k \in \mathbb{C}^{N_k^{(\mathrm{R})}}$, with $N_k^{(\mathrm{R})}$ the number of receive antennas of an MS k from $\mathcal{K}_c$ served by the cooperation cluster $\mathcal{M}_c$, can then be written as

$$\mathbf{y}_k = \underbrace{\sum_{b \in \mathcal{M}_c} \mathbf{H}_{k,b} \mathbf{G}_k^{(b)} \mathbf{s}_k}_{\text{desired signal}} + \underbrace{\sum_{b \in \mathcal{M}_c} \sum_{j \neq k} \mathbf{H}_{k,b} \mathbf{G}_j^{(b)} \mathbf{s}_j}_{\text{intra-cluster interference}} + \underbrace{\sum_{i \notin \mathcal{M}_c} \mathbf{H}_{k,i} \mathbf{x}_i + \mathbf{n}_k}_{\text{inter-cluster interference and noise}}.$$

Therein, the first term captures all desired signals (transmitted by the nodes in $\mathcal{M}_c$ to MS $k \in \mathcal{K}_c$). The second term contains the signals transmitted by nodes within $\mathcal{M}_c$ but intended for other MSs of $\mathcal{K}_c$. The third and fourth term describe the interference caused by nodes outside cluster $\mathcal{M}_c$ and noise. The matrix $\mathbf{H}_{k,b} \in \mathbb{C}^{N_k^{(\mathrm{R})} \times N_b^{(\mathrm{T})}}$ describes the channel from the b-th transmitting node to MS k, where we assume that the channel is frequency flat and constant for one transmission period, i.e., we look at a single sub-carrier of an OFDM based system with a slow fading channel. The precoding matrices $\mathbf{G}_k^{(b)}$ can be chosen in different ways, depending on the particular transmission scheme as described in the next section.



(a) Conventional network. (b) Relaying. (c) 3-BS CoMP. (d) 6-BS "super cell."

Fig. 2. Example network configurations.

Depending on how the cooperation clusters are chosen and which infrastructure node is set to a BS or SN, different network configurations can be realized. A collection of example networks can be seen in Fig. 2. A conventional network that acts as a reference is shown in Fig. 2(a) where the red triangles with arrows correspond to BSs. There, each sector is served by a single BS[1] that operates independently of other BSs and with a transmit power of P_{B}. Consequently, the cooperation clusters contain only a single BS and no SNs (the nodes shown as gray circles are turned off). A network in which BSs are supported by relays is depicted in Fig. 2(b). In this case, a cooperation cluster consists of a BS (triangles) and two sectorized relays (circles) located on the cell corners. The relays assist the communication within a sector with a transmit power of P_S. By turning off the triangles and considering three circles as BSs that cooperate with each other, a 3-BS CoMP scenario can be formed (Fig. 2(c)). Three sectorized BS arrays form a cooperation cluster that serve three adjacent sectors. Fig. 2(d) shows a somewhat more exotic network configuration: six BSs placed on a ring around a center cell form a cooperation cluster. In this case, six BS antenna arrays can serve nine sectors, while the BS that would be located in the center cell of a conventional network is not in operation. Such a configuration can be used to save BSs and/or to compensate BS failures. These networks are discussed in more detail in Section IV.

[1]Multiple BS arrays located on the same site are considered as different BSs when they serve different independent sectors.

III. Transmission Schemes & Achievable Rates

The precoding matrices $\mathbf{G}_k^{(b)}$ introduced in (1) can be chosen in many ways which differ in complexity, required knowledge (such as CSI), performance, and robustness. In this work, we consider three different levels of transmission schemes with varying complexity: a) a simple non-cooperative reference scheme, b) a decode-and-forward (DF) relaying scheme with selection combining, and c) a multiuser MIMO CoMP scheme where multiple transmitting nodes (BSs and/or SNs) serve multiple MSs with optimized precoding and power allocation. With each of these categories, we present a scheme of high practical relevance that is easy to implement.

A. Non-Cooperative Reference

The non-cooperative reference scheme is of the lowest complexity. No SNs are present (or they are all shut off) and each BS independently serves a single user (per resource block) by a spatially white signal of transmit power P_{B} uniformly allocated across all antennas. The cooperation clusters thus only contain a single BS. Therefore, the precoding matrix of BS b is $\mathbf{G}_k^{(b)} = \sqrt{P_{\mathrm{B}}/N_b^{(\mathrm{T})}} \cdot \mathbf{I}$, with $\mathbf{I}$ the identity matrix of appropriate dimension, i.e. of size $N_b^{(\mathrm{T})}$. Note that this transmission strategy is optimal in the absence of CSI at the transmitter (CSIT) which is thus not required in this case. This scheme is of very low complexity as no CSI feedback and no complicated precoder calculation is required. The resulting achievable rate for a mobile k can be calculated as

$$R_k = \log_2 \left| \mathbf{I} + \mathbf{K}_{\mathrm{s}}^{(k)} \cdot \left(\mathbf{K}_{\mathrm{i}}^{(k)} + \mathbf{K}_{\mathrm{n}}^{(k)} \right)^{-1} \right| \quad \left[\frac{\text{bit}}{\text{channel use}} \right], \quad (2)$$

where $|\cdot|$ stands for the determinant and $\mathbf{K}_{\mathrm{s}}^{(k)}$, $\mathbf{K}_{\mathrm{i}}^{(k)}$, and $\mathbf{K}_{\mathrm{n}}^{(k)}$ are the covariance matrices of the desired signal, interference, and noise.

B. Relaying with Selection Combining

In the case of additional nodes hat support the communication of BSs as SNs, the following DF scheme with selection combining can be used. Here we assume again that in each sector a single MS is active per resource block. The cooperation cluster consists of one BS and multiple SNs (two per sector in the example of Fig. 2(b)) that can correspond e.g. to relays or RRHs. For each transmission block, an active MS associated to cluster $\mathcal{K}_c$ now chooses the link to the best infrastructure node from its serving set $\mathcal{M}_c$. When the best link is chosen, the corresponding infrastructure node (BS or SN) transmits again spatially white (with transmit power P_{B} if the BS is chosen or with power P_S in case a SN is chosen), while the other nodes within $\mathcal{M}_c$ are silent. The resulting achievable rate is then

$$R_k = \max \left\{ R_1^{(k)}, \ldots, R_{|\mathcal{M}_c|}^{(k)} \right\}, \quad (3)$$

where $R_i^{(k)}$ is the achievable rate between infrastructure node (BS or SN) $i \in \mathcal{M}_c$ and mobile k. In case the SNs are RRHs, home NodeBs or other nodes that are fed by a wired or wireless out-of-band backhaul connection of sufficient capacity and small delay, the rates $R_i^{(k)}$ can be calculated as in (2). To this end, the covariance matrices of the desired signal as well as interference have to be computed according to the nodes that are present in the network (now including the SNs).

If the SNs correspond to wireless in-band DF relays, the backhaul links from the BS to these relays use the same physical channel as the transmission to the MS. In this case, the resulting rates via the relays are calculated as follows. Denoting the rate of the link from the BS to relay i by $R_{i,1}^{(k)}$ and the one of the second hop (relay to MS) by $R_{i,2}^{(k)}$ and allowing for different time allocation on both links, we can optimize the time in which the two hops operate. In this way, less time can be assigned for the better and more time for the worse hop in order to balance the two rates. With t_1 and t_2 denoting the normalized durations of the first and second hop transmission, this can be formulated as the following optimization problem

$$R_i^{(k)} = \max_{t_1, t_2} \min \left\{ t_1 \cdot R_{i,1}^{(k)}, t_2 \cdot R_{i,2}^{(k)} \right\}, \quad \text{s.t. } t_1 + t_2 = 1,$$

which has the solution

$$R_i^{(k)} = \frac{R_{i,1}^{(k)} \cdot R_{i,2}^{(k)}}{R_{i,1}^{(k)} + R_{i,2}^{(k)}}. \quad (4)$$

The selection of the best link is based on a measurement of the link quality. Therefore, a rate feedback from the MS is required. However, as the precoding is again spatially white, no CSIT is required also in this case. Therefore, the increase of complexity as compared to the reference scheme is only small. Additionally, relaying seems to be well suited in case of (fast) moving mobile users.

C. Block Zero-Forcing with Optimized Power Allocation

A more sophisticated transmission scheme that increases the complexity in all involved nodes is a multiuser CoMP scheme that uses block zero-forcing and optimized power allocation across all transmitted data streams. All mobiles within a cooperation area, that can now comprise multiple sectors, are served jointly by the corresponding transmit nodes where the intra-cooperation interference is nulled and the power is allocated to each stream such that the minimum rate is maximized [13]. To this end, the precoding matrices are decomposed to $\mathbf{G}_k^{(b)} = \mathbf{Z}_k^{(b)} \cdot \mathbf{Q}_k^{(b)}$, where $\mathbf{Z}_k^{(b)}$ is a block zero-forcing matrix and the power allocation for the different streams is handled in $\mathbf{Q}_k^{(b)}$. The zero-forcing matrices are obtained by components of the null space of all undesired links within the cooperation set, i.e. of $\operatorname{null}\left\{ \left[\bar{\mathbf{H}}_{c,1}^T, \ldots, \bar{\mathbf{H}}_{c,k-1}^T, \bar{\mathbf{H}}_{c,k+1}^T, \ldots, \bar{\mathbf{H}}_{c,|\mathcal{K}_c|}^T \right]^T \right\}$, where $\bar{\mathbf{H}}_{c,i}$ is the collocated channel matrix from all transmitting nodes within a cooperation cluster $\mathcal{M}_c$ to MS $i \in \mathcal{K}_c$.

Once the zero-forcing matrices are calculated, the power loading matrices $\mathbf{Q}_k^{(b)}$ need to be found. As we assume the transmitting nodes only have CSI from links within the cooperation area, the inter-cluster interference is ignored for the calculation of $\mathbf{Q}_k^{(b)}$. This allows to formulate the optimization problem

$$\max_{\left\{\mathbf{Q}_k^{(j)}\right\}_{\substack{j \in \mathcal{M}_c \\ k \in \mathcal{K}_c}}} \min \left\{ \tilde{R}_k \right\}_{k \in \mathcal{K}_c}$$

$$\text{s.t. } \operatorname{tr} \left\{ \sum_{k \in \mathcal{K}_c} \mathbf{G}_k^{(b)} \mathbf{G}_k^{(b)H} \right\} \le P_x, \ \forall b \in \mathcal{M}_c,$$

where $\mathrm{tr}(\cdot)$ is the trace and $\tilde{R}_k$ is the achievable rate that would result without inter-cluster interference (the intra-cluster interference is already nulled by zero-forcing) and $P_x = P_{\mathrm{B}}$ or P_S being the per node power constraint depending on whether the corresponding node is a BS or SN. Note that as there is no interference present, this optimization is convex and can thus be efficiently solved by standard optimization tools. However, in the evaluation of the rates, the inter-cluster interference is taken into account. This form of cooperation requires accurate CSI for all links within the corresponding cooperation area. It is therefore of relatively high complexity.

In the following, the described transmission schemes are compared with each other in various network settings. We are particularly interested in the impact of the network topology on the performance of the different schemes, the robustness of the schemes with respect to CSI imperfections, and the overhead they introduce in a practical system.

IV. Simulative Survey

In order to evaluate the performance of relaying and CoMP, we use a basic network model that consists of 19 regularly arranged hexagonal cells, all divided into three sectors. We assume urban micro cells with a diameter of 700 meters. Three BSs (one for each sector) are placed in the center of their corresponding cell, each equipped with $N_b^{(\mathrm{T})} = 4$ antennas. Assuming a total bandwidth of $100\,\mathrm{MHz}$, the sum transmit power of each BS array is constrained to P_{B}. This basic model is extended by additional SNs placed on each cell corner. The sum transmit power of these nodes is denoted by P_S.

We use the WINNER II channel model [14] (scenario C2 urban non-line-of-sight environment) but simplify it in the sense that we are looking at only one resource (e.g. OFDM sub-carrier) over which the channel is assumed to be constant. Consequently, we consider one active MS per sector. The MSs are equipped with $N_k^{(\mathrm{R})} = 2$ omnidirectional antennas.

Different cooperation strategies are compared in Fig. 3 in the form of empirical cumulative distribution functions (CDFs). The non-cooperative reference corresponding to the network of Fig. 2(a) is compared with the relaying as well as the CoMP scheme. Here, we assume a transmit power of $P_{\mathrm{B}} = 80\,\mathrm{W}$ at all BSs, and one of $P_S = 6\,\mathrm{W}$ at the SNs. The SNs are equipped with 2 sectorized antennas. Two cases for the relaying scheme are considered, one assuming in-band relays where the resulting rates are calculated according to (4), and the other where the first hop has been dropped, i.e. assuming a wired backhaul of sufficiently high capacity. These two curves show almost no difference, since when dedicated relays are used, the first hop is usually much better than the second one (LOS connection between BS and SNs are assumed in the simulations). Therefore, much more of the available time can be allocated for the (weaker) second hop and consequently the loss that results from the in-band link to the relay is very small. It will therefore be ignored for the rest of the paper. The figure also shows the performance of the 3-BS CoMP scenario from Fig. 2(c), once with a reuse 1 frequency allocation across the entire network and once with an FDMA frequency allocation with reuse factor 3 where adjacent cooperation areas

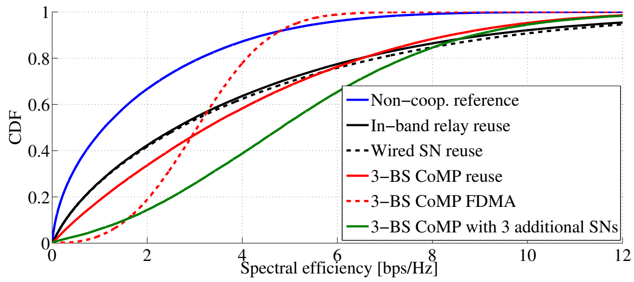


Fig. 3. CDFs of spectral efficiency for different schemes.

use orthogonal frequencies. In the latter case, a prelog factor of $1/3$ has been included in the rates. These curves show a higher gain as with relaying, but this is not surprising, as the CoMP scheme is of much higher complexity. An even higher gain can be achieved when the 3-BS CoMP scenario is combined with additional SNs located at the three other corners of the cooperation area and used as RRHs.

We now want to study the influence of transmit power and robustness against CSI inaccuracies of the different schemes. To this end, CSI imperfections are modeled as follows. Instead of the true channel matrix $\mathbf{H}_{k,b}$, the transmitting nodes use an estimate $\hat{\mathbf{H}}_{k,b} = L_{\mathrm{Path}} \cdot \left(\sqrt{1-\vartheta^2} \cdot \mathbf{H}_{k,b} + \vartheta \cdot \mathbf{W}\right)$, where the elements of $\mathbf{W}$ are i.i.d. $\mathcal{CN}(0,1)$ and $\vartheta^2 \in [0,1]$ is the CSI noise scaling factor. This model captures effects as outdated CSI (if MSs are moving) as well as quantization and estimation errors. Note that the pathloss L_{Path} is not affected by CSI noise, as we assume its estimation is much easier in practice than that of the actual fading coefficients.

In Fig. 4, we show the CDF plots of the achievable rates of a network where three BS arrays in the center of the same cell form a cooperation cluster together with six SNs located on the cell corners whose transmit power is gradually increased. A reuse factor of 1 is used here. Fig. 4(a) compares the non-cooperative case (the three BS arrays are independent and the SNs are turned off) with the selection combining scheme as well as the CoMP scheme for varying SN power P_S and perfect

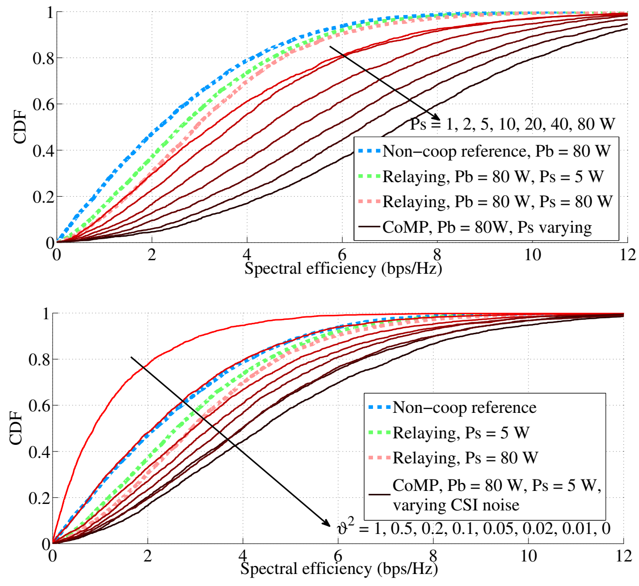


Fig. 4. CDFs of spectral efficiency for CoMP and relaying with varying transmit power and CSI noise scaling.

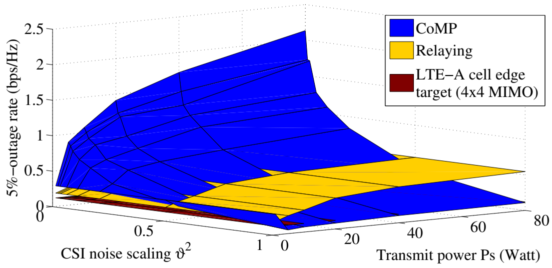


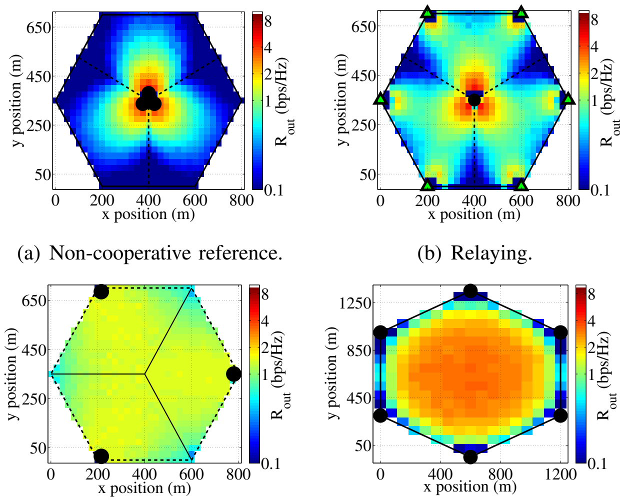
Fig. 5. CoMP vs. relaying with varying power and varying CSI noise.

CSI. CoMP gains more from increasing P_S than relaying. Fig. 4(b) shows the behavior of the same setup for fixed transmit powers but a varying CSI noise scaling parameter ϑ^2. The curves show that for reasonable choices of ϑ^2, the CoMP scheme is quite robust and outperforms relaying. For higher CSI inaccuracies, however, the performance of CoMP decreases but relaying does (almost) not vary with ϑ^2. The reason for this is that the link selection requires only knowledge of the link quality which is essentially given by the second order statistics of the channel, which corresponds to L_{Path}. This estimation, in turn, is very robust due to the diversity offered by the MIMO channels. Even though CoMP achieves higher gains than relaying, at least for accurate CSI, relaying has still some advantages. Fig. 5 shows the 5%-outage rates that are achieved for the different schemes. The 5%-outage rate is a good measure to capture the performance that can be guaranteed in the entire network, particularly on the cell-edge. It can be seen, that relaying proves to be a better choice than CoMP when the CSI imperfections are too large.

The spatial distribution of the 5%-outage rates of the network configurations from Fig. 2 with reuse 3 are shown in Fig. 6. There, the gain of the relaying scheme as compared to the reference can nicely be seen. Relaying seems thus to be an attractive, since simple and very robust, way to increase the coverage of a BS, particularly when certain spots of poor performance should be covered, or when CSI is not accurate enough. Also interesting is that the distribution of the 5%-outage rates of the CoMP scheme is very homogenous. Moreover, the 6-BS "super cell" layout shows even higher rates although the BS density is much lower here – only six BSs for nine sectors.

V. Discussion & Conclusion

We evaluated and compared different aspects of cooperative transmission schemes for future cellular networks in a unified and realistic way. It was shown that relaying and especially CoMP can offer significant gains when sufficiently accurate CSI is available. Simulations show that only a small rate loss has to be accepted if the CSI noise scaling factor ϑ^2 is not higher than 0.02 or 0.01, which corresponds to the same performance as when the errorless CSI is quantized with a simple scalar uniform quantizer with 3 and 4 bits per dimension, respectively. For a frequency selective 2×4 MIMO channel of $100\,\text{MHz}$ bandwidth with 20 relevant taps between infrastructure nodes and MSs, and assuming that the CSI is updated by the MS every $10\,\text{ms}$, the resulting feedback rate required for the CSI dissemination does not exceed 288 or $384\,\text{kbit/s}$, respectively. In either case, the LTE-Advanced uplink rates will certainly be able to support these rates. Compared to the dissemination of user data, also the backhaul rates are not affected too much when CSI is exchanged between different BSs. The considered schemes with the shown gains thus seem possible for implementation in cellular networks of the upcoming generation.



(a) Non-cooperative reference. (b) Relaying.

(c) CoMP with cluster size 3. (d) "Super cell" with 6-BS CoMP.

Fig. 6. 5%-outage rate maps of networks that correspond to Fig. 2.

References

[1] D. Gesbert *et al.*, "Multi-cell MIMO cooperative networks: a new look at interference," *IEEE JSAC*, vol. 28, No. 9, Dec. 2010.

[2] J. Lee *et al.*, "Coordinated multipoint transmission and reception in LTE-advanced systems," *Communications Magazine, IEEE*, vol. 50, no. 11, pp. 44 –50, Nov. 2012.

[3] H. Viswanathan and S. Mukherjee, "Performance of cellular networks with relays and centralized scheduling," *Wireless Communications, IEEE Transactions on*, vol. 4, no. 5, pp. 2318 – 2328, Sep. 2005.

[4] A. Ghosh *et al.*, "Heterogeneous cellular networks: From theory to practice," *IEEE CommMag*, vol. 50, no. 6, pp. 54 –64, June 2012.

[5] W. Choi and J. Andrews, "Downlink performance and capacity of distributed antenna systems in a multicell environment," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 1, pp. 69 –73, Jan. 2007.

[6] O. Somekh and S. Shamai, "Shannon-theoretic approach to a gaussian cellular multiple-access channel with fading," *IEEE Trans. Inform. Theory*, vol. 46, no. 4, pp. 1401 –1425, Jul. 2000.

[7] T. Balercia, T. Kuerner, and M. Mueck, "(m,n)-relaying as an alternative to base station cooperation for cellular OFDMA networks," in *IEEE International Conference on Communications (ICC)*, Jun. 2011.

[8] P. Marsch and G. Fettweis, "Static clustering for cooperative multi-point (CoMP) in mobile communications," in *IEEE International Conference on Communications (ICC)*, Jun. 2011.

[9] I. Garcia, N. Kusashima, K. Sakaguchi, and K. Araki, "Dynamic cooperation set clustering on base station cooperation cellular networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, Sep. 2010, pp. 2127 –2132.

[10] I. Riedel, P. Rost, P. Marsch, and G. Fettweis, "Creating desirable interference by optimized sectorization in cellular systems," in *IEEE GLOBECOM 2010*, Dec. 2010.

[11] E. Bjornson, M. Bengtsson, G. Zheng, and B. Ottersten, "Computational framework for optimal robust beamforming in coordinated multicell systems," in *Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP), 2011 4th IEEE International Workshop on*, Dec. 2011.

[12] P. Bhat *et al.*, "LTE-advanced: an operator perspective," *IEEE Commun. Magazine*, vol. 50, no. 2, pp. 104 –114, Feb. 2012.

[13] M. Kuhn, R. Rolny, A. Wittneben, M. Kuhn, and T. Zasowski, "The potential of restricted PHY cooperation for the downlink of LTE-advanced," in *IEEE Vehicular Technology Conference*, Sep. 2011.

[14] P. Kyösti *et al.*, "WINNER II channel models," Tech. Rep. IST-4-027756 WINNER II D1.1.2 V1.2 Part I Channel Models, Sep. 2007.