Power Control for Cellular Networks with Large Antenna Arrays and Ubiquitous Relaying

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***Abstract*—We consider a cellular network in which the base stations (BSs) are supported by a large amount of very low-complexity relays that are spread over the entire area, like a carpet. This carpet of relays enables massive antenna arrays and sophisticated multi-user MIMO transmission at the BSs, as they see only the static relays as the nodes they communicate with. On the other hand, the communication via the small relay cells allows to improve coverage and data rates by distributed signal processing. In order to control the residual interference caused by the massively deployed relay nodes, we apply power control to either minimize the transmit power at the BSs and relays required to achieve desired user rates, to maximize the minimum rate, or to minimize the outage probability. The proposed schemes are all of low complexity and show that the relay carpet is a promising concept for communication in future cellular networks.**

I. Introduction

Future cellular networks should not only provide data rates that are higher by orders of magnitude than today's systems, but also have to guarantee high coverage and reliability. As such networks are mainly interference limited, interference management is inevitable. The classical approach for this is to introduce a spatial reuse that ensures a certain separation between base stations (BSs) that use the same physical channel [1]. This has the fundamental advantage that the adaptation to the user position is achieved by handovers between cells or sectors, which is easy to implement and requires little overhead. In order to cope with higher user densities, the number of BSs can be increased and cell sizes reduced such that the network consists of pico- or femto-cells [2]. In practice, however, this approach is, among others, limited by the difficulty to identify new BS sites e.g. due to social acceptance, availability of backbone access etc. and by the cost of deployment.

An alternative is to employ a large number of antennas at the BSs, eventually leading to massive MIMO [3], and to separate interfering users by beamforming. In this case, more users imply more antennas rather than more BS sites. Large antenna arrays can also be formed virtually by BS cooperation/coordinated multipoint (CoMP) transmission [4]. With sophisticated beamforming, interference can be mitigated and many users can be served in parallel. This, however, requires to track the instantaneous channels to each mobile station (MS). An increasing number of antennas leads therefore to a rapidly growing overhead, as more pilots have to be included in the signals, and achievable performance gains might stagnate or even decrease [5]. Moreover, BSs that cooperate to perform joint beamforming also require very high backhaul rates, not only to support the data rates of their users, but also to exchange user data and channel state information (CSI) with their cooperation partners. Even when the growing overhead and the backhaul limitations can be overcome, the performance of CoMP remains limited by residual interference [6].

An attempt to combine the aforementioned approaches is presented in [7], where a layer of small cells operates in parallel to a macro-cell tier with a large array BS. The small cells, however, need fully equipped small BSs connected to the wired backbone; their massive deployment might therefore be difficult and expensive. As an alternative, we apply a large amount of relays without connection to the backbone to support the BSs. If the relays are of low cost and low power, they can be installed in massive numbers across the entire area of the network, similar to a carpet. This "relay carpet" is thus an efficient concept to balance node density and complexity.

As a result, the network is turned into a two-hop network. If dedicated relays are mounted at fixed positions, the BSs see static relays as their communication partners; fast fading between them is eliminated. For the transmit CSI, the BSs thus only have to track quasi-static channels. This simplifies channel estimation and enables massive MIMO with sophisticated beamforming. The MSs, on the other hand, see a much simpler network of relays with only few antennas, while the relays can shape the (effective) channel in a beneficial way. Accordingly, network operators do not have to rely on random propagation channels which can result in deep fades or shadowed users, but can achieve much more homogeneous coverage. To this end, the relays can perform simple signal processing tasks that allow for signal amplification or distributed interference management. Moreover, allocating multiple relays to one MS can increase the angular spread of the effective channel (active scattering [8]) and the MSs can be equipped with more antennas in a compact space.

Such an approach is motivated by [9], where the bidirectional communication between BS and MSs is assisted by two-way relays that operate in time-division duplex (TDD) mode. Different relaying strategies are compared, some of which require sophisticated functionalities, e.g. CSI estimation or decoding of the signals, that do not differ much from other access points. Moreover, TDD relays introduce delays that at least double the round trip time and all nodes are enforced to transmit with full power. Practical networks, on the other hand, should reduce delays and require high coverage and good quality of service (QoS). Additionally, an economic usage of power has also gained much interest in order to limit the ever growing energy consumption of communication networks [10].

In this paper, we focus on the downlink and describe how the idea of the relay carpet can be realized with very low-complexity relays that do not introduce additional delays. To this end, we propose to use amplify-and-forward (AF) relays that operate in frequency-division duplex (FDD) mode. The relays thus apply a simple frequency conversion and amplification of their receive signals. We show that the use of many such relays not only simplifies the signal processing at the BSs, but also offers significant performance gains, even though the relays can be implemented in a very low-complexity and inexpensive fashion. Additionally, we apply power control to manage the residual interference and the energy consumption. Thereby, the relays also lead to considerable power savings as compared to conventional networks. To this end, existing power control schemes designed for conventional cellular networks (see [11] for an overview) or for pure relay channels (e.g. [12]) have to be adjusted such that they are feasible for the relay carpet network.

II. System Model

The organization of the network is similar to a conventional one. The area is divided into C cells, each with one BS that serves multiple MSs. For notational simplicity, we assume that all cells have M active MSs and that all nodes of the same kind have the same number of antennas, although a generalization is straightforward. The number of antennas at the BSs is denoted by N_B, the one of the MSs by N_M. We consider the downlink, i.e. BS c, with $c \in \{1, \dots, C\}$, wants to transmit $d_\mathrm{s} \leq N_\mathrm{M}$ data streams to MS (c, j) (the jth MS in cell c). The communication is assisted by $K \geq M$ relays, such that each relay serves one MS but a MS can be served by multiple relays, e.g. to avoid many hand-overs when users are moving. The relays are equipped with N_R antennas, where $N_\mathrm{M} \leq N_\mathrm{R} \leq N_\mathrm{B}$. The channel between BS b and relay (c, k) is denoted by $\mathbf{H}_k^{(c,b)} \in \mathbb{C}^{N_\mathrm{R} \times N_\mathrm{B}}$, the one between relay (c, k) and MS (b, j), possibly in a different frequency band, by $\mathbf{F}_{j,k}^{(b,c)} \in \mathbb{C}^{N_\mathrm{M} \times N_\mathrm{R}}$. Direct links between BSs and MSs are not considered.

The transmit symbol vector from BS c intended for MS (c, j), denoted by $\mathbf{s}_{c,j} \in \mathbb{C}^{d_\mathrm{s}}$, is premultiplied by the corresponding beamforming matrix $\mathbf{Q}_{c,j} \in \mathbb{C}^{N_\mathrm{B} \times d_\mathrm{s}}$. The receive signal of relay (c, k) can thus be written as

$$\mathbf{r}_{c,k} = \sum_{b=1}^{C} \mathbf{H}_k^{(c,b)} \sum_{j=1}^{M} \mathbf{Q}_{b,j} \mathbf{s}_{b,j} + \mathbf{n}_{c,k}, \tag{1}$$

where $\mathbf{n}_{c,k}$ is the relay noise. The relays multiply their receive signal (1) with a gain matrix $\mathbf{G}_{c,k} \in \mathbb{C}^{N_\mathrm{R} \times N_\mathrm{R}}$ and, after a frequency conversion, retransmit $\mathbf{t}_{c,k} = \mathbf{G}_{c,k} \cdot \mathbf{r}_{c,k}$. With $\mathbf{w}_{c,k}$ being the noise induced in MS (c, k), its receive signal is

$$\mathbf{y}_{c,k} = \sum_{b=1}^{C} \sum_{j=1}^{K} \mathbf{F}_{k,j}^{(c,b)} \cdot \mathbf{G}_{b,j} \cdot \mathbf{r}_{b,j} + \mathbf{w}_{c,k}. \tag{2}$$

A. Relay Architecture

Depending on their functionalities, the relays can fulfill different signal processing tasks. For a massive deployment, however, the relay nodes should be of very low complexity such that they can be implemented in an inexpensive way. In their simplest form, these relays apply a frequency conversion

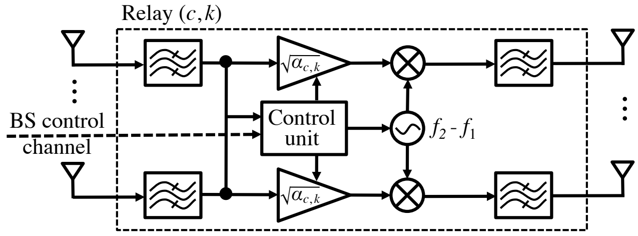

Fig. 1. Conceptual schematic of FDD AF relays.

from the input frequency band around f_1 to a band around f_2 and amplify the input signals with a scaled identity matrix

$$\mathbf{G}_{c,k} = \sqrt{\alpha_{c,k}} \cdot \mathbf{I}_{N_\mathrm{R}}. \tag{3}$$

As a result, no additional delays are introduced. If the relays convert their BS signals to frequency bands that are currently not used (cf. cognitive radio [13]) or lie in an ISM band, the spectrum of the second hop does not have to be included into the spectral efficiency as additional costs. The use of secondary links is especially motivated by the small transmit power of the relays that do not disturb other systems significantly.

A conceptual schematic of such a relay is sketched in Fig. 1. Apart from the frequency conversion and amplification, it contains an input and an output filter as well as a simple control unit that can adjust the relay gains or the local oscillator. A control channel from the corresponding BS is also included. This channel can be of very low rate and can be used for synchronization, to control the timing of the relays, or to transmit wake up patterns to activate the relays appropriately. We refer to these simple relays as *type A* relays.

More sophisticated relays that have access to local CSI can additionally apply a linear processing to reduce the interference present in the network. To this end, the gain matrix of relay (c, k) can be factorized to

$$\mathbf{G}_{c,k} = \sqrt{\alpha_{c,k}} \cdot \mathbf{G}_{c,k}^{(\mathrm{Tx})} \cdot \mathbf{G}_{c,k}^{(\mathrm{Rx})\mathsf{H}}. \tag{4}$$

As an example, the receive filter $\mathbf{G}_{c,k}^{(\mathrm{Rx})}$ can be chosen to suppress the interference coming from the BSs of adjacent cells. Assuming $N_\mathrm{R} > d_\mathrm{s}$, this filter can be obtained by $\mathbf{G}_{c,k}^{(\mathrm{Rx})} = [\mathbf{v}_1^{(c,k)}, \dots, \mathbf{v}_{d_\mathrm{s}}^{(c,k)}]$. Therein, $\mathbf{v}_i^{(c,k)}$ is the eigenvector corresponding to the ith smallest eigenvalue of

$$\mathbf{\Gamma}_{c,k} = \sum_{b \neq c} \mathbf{H}_k^{(c,b)} \cdot \mathbf{H}_k^{(c,b)\mathsf{H}}. \tag{5}$$

With this, the receive signal is projected into the subspace that contains the least BS interference under the assumption of spatially white signaling. Accordingly, $\mathbf{G}_{c,k}^{(\mathrm{Rx})}$ is independent of the actual BS signals and has thus not to be updated when a BS changes its beamforming. Moreover, when the relay position is fixed, the covariance matrix (5) is mainly static and simple to estimate.

The transmit filter of the relay is chosen as a transmit matched filter $\mathbf{G}_{c,k}^{(\mathrm{Tx})} = \mathbf{F}_{k,k}^{(c,c)\mathsf{H}}$ with respect to the channel to the corresponding MS, which is also simple to estimate, as the dimensions are small. We refer to these relays as *type B* relays. In this case, the functionality of the relays needs to be extended such that the gain matrix can be applied and allows the relays to obtain the required CSI. Nevertheless, the relay gain matrices can be calculated based on local CSI only and no cooperation with other nodes is required.

B. Base Station Signaling

If the relays are static, the BSs can perform sophisticated beamforming to separate the different relays within their cells. As an example, the BSs can apply block zero-forcing (ZF) with waterfilling as in [9], but also other techniques are possible. With this specific choice, the BSs only have to track quasi-static channels and can cancel the interference at all relays within their cell. The static relays thus enable such a precoding with large antenna arrays. For the acquisition of the required transmit CSI, the relays have to enable channel estimation at their BS. To this end, the relays can transmit training sequences triggered by a request on the control channel. This can e.g. be realized by varying the relay gains in a predefined manner and to transmit this signal on the reverse link to the BS. For this, the simple architecture shown in Fig. 1 would be sufficient. When the channel to the BS is quasi-static, this is required only on a slow time scale.

Note that with block ZF, only the interference between the BSs and their in-cell relays is cancelled. The remaining interference is further reduced by the relay filters if the type B architecture is used and/or when power control is applied.

C. Achievable Rate

For given BS precoding and relay gain matrices, the achievable rate for MS (c, k) can be calculated by

$$R_{c,k} = \log_2 \det \left\{ \mathbf{I}_{N_\mathrm{M}} + \left(\mathbf{K}_{c,k}^{(\mathrm{i+n})} \right)^{-1} \cdot \mathbf{K}_{c,k}^{(\mathrm{sig})} \right\}, \quad (6)$$

with the covariance matrix of the desired signal

$$\mathbf{K}_{c,k}^{(\mathrm{sig})} = \sum_{b,j} \sum_{b',j'} \mathbf{F}_{k,j}^{(c,b)} \mathbf{G}_{b,j} \mathbf{H}_{j}^{(b,c)} \mathbf{Q}_{c,k} \mathbf{Q}_{c,k}^{\mathsf{H}} \mathbf{H}_{j'}^{(b',c)\mathsf{H}} \mathbf{G}_{b',j'}^{\mathsf{H}} \mathbf{F}_{k,j'}^{(c,b')\mathsf{H}}$$

and of the interference and noise

$$\mathbf{K}_{c,k}^{(\mathrm{i+n})} = \mathsf{E}\left[\mathbf{y}_{c,k} \cdot \mathbf{y}_{c,k}^{\mathsf{H}} \right] - \mathbf{K}_{c,k}^{(\mathrm{sig})}.$$

Note that we excluded the prelog factor $1/2$ in (6), as it would occur with half-duplex relays, because we intentionally consider a second hop in a frequency band that is unlicensed or unused at the moment.

In Fig. 2, achievable sum rates of the aforementioned transmission with relays are compared with the rates of a network in which the BSs serve the MSs directly by block ZF. The BSs and relays transmit with a fixed transmit power of $P_\mathrm{B} = 40\,\mathrm{W}$ and $P_\mathrm{R} = 6\,\mathrm{W}$, respectively. Details on the simulation parameters are given in Section IV. Significant gains can be observed, even with the simple type A relays. Thereby, the gains are mainly due to the small relay cells that distribute the signal more evenly. But also CSI estimation at the BSs is simplified, which is not reflected in the achievable rate. Type B relays with the distributed signal processing of BS/relay precoding lead to further gains. The interference is reduced considerably, even though no cooperation is required and each node can calculate its precoding based on local CSI.

III. Power Control

Without power control, all nodes are enforced to transmit with full power. Even with the interference reduction of the BS/relay processing, the relays forward residual interference

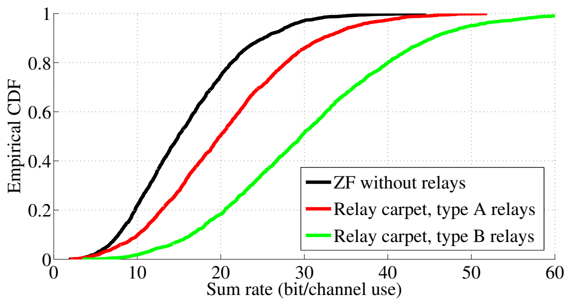

Fig. 2. Achievable sum rates of the relay carpet compared to a conventional network without relays.

to other users. Optimization of the power allocation can thus offer further improvements as the remaining interference can be controlled. Additionally, it can lead to savings regarding energy consumption and gains in terms of QoS or outage probability. Such power control schemes are studied e.g. in [12] for pure relay channels or in [11], [14] for traditional cellular networks without relays. However, these schemes cannot directly be applied to the network considered here, as the BS and relay powers of multiple links are coupled across different cells. This schemes would result in situations in which the BS and relay power optimization block each other and do not converge. In the following, we outline low-complexity power control algorithms for different objectives that guarantee convergence and show that the low-complexity relays offer large gains regarding power savings and coverage.

A. Minimize Power

The first goal is to minimize the required transmit power to achieve a target rate $R^\star$ at each of the MSs. To this end, the scaling factor $\alpha_{c,k}$ from (3) at relay (c, k) can be adjusted. On the BS side, we assign a scaling factor $\beta_{c,k} > 0$ for the signal to each MS in the corresponding cell, i.e. the beamforming matrix of the signal from BS c to MS (c, k) is $\mathbf{M}_{c,k} = \sqrt{\beta_{c,k}} \cdot \mathbf{Q}_{c,k}$. As in other power minimization problems, there are situations in which no feasible power allocation exists due to the stringent rate constraints [14]. Additionally, feasible scenarios can lead to transmit powers that are too high for practical systems with regulatory restrictions. We thus introduce a maximal power at each node that must not be exceeded: a maximal power $P_{\mathrm{B,max}}$ and $P_{\mathrm{R,max}}$ is assigned to the BSs and relays. These powers are then minimized in an alternating fashion.

1) Relay Power Minimization: Assuming that the beamforming matrices of the BSs as well as the relay gain matrices of all surrounding cells are fixed, the factors $\alpha_{c,k}$ for the relays in cell c can iteratively be optimized. To this end, the scaling factors are initialized according to $P_{\mathrm{R,max}}$ by setting

$$\alpha_{c,k}^{(0)} = P_{\mathrm{R,max}} / \mathrm{trace}\left\{ \mathsf{E}\left[\mathbf{G}_{c,k} \mathbf{r}_{c,k} \cdot \mathbf{r}_{c,k}^{\mathsf{H}} \mathbf{G}_{c,k}^{\mathsf{H}} \right] \right\} \quad \forall k.$$

Then, in iteration step $n = 0, 1, \ldots$, the relay with the highest rate $R_{c,l}^{(n)}$ at the corresponding MS is identified and the power of this relay is updated according to

$$P_{\mathrm{R},c,l}^{(n+1)} = P_{\mathrm{R},c,l}^{(n)} - \mu P_{\mathrm{R},c,l}^{(n)} \left(1 - \frac{R^\star}{R_{c,l}^{(n)}} \right), \quad (7)$$

where μ is a step size parameter that has to be small enough that the resulting rate cannot fall below $R^\star$. This can be realized by a backtracking line search. The update equation (7) reduces the power based on the ratio of the desired and the actual rate and guarantees that there is no change as soon as the target rate is achieved. The relay gain matrix is then scaled by

$$\alpha_{c,l}^{(n+1)} = P_{\mathrm{R},c,l}^{(n+1)} / \mathrm{trace}\left\{ \mathsf{E}\left[\mathbf{G}_{c,l}\mathbf{r}_{c,l} \cdot \mathbf{r}_{c,l}^{\mathsf{H}} \mathbf{G}_{c,l}^{\mathsf{H}} \right] \right\}. \quad (8)$$

These steps are repeated as long as there are rates that exceed $R^\star$ by more than some tolerance ε. In each step, the relay transmit power is reduced and the interference for all other MSs is strictly decreased and their rates improved. Therefore, the algorithm converges and any further change in the scaling factors $\alpha_{c,k}$ cannot reduce the transmit power without letting a rate fall below $R^\star$. The solution is thus a local optimum. The algorithm, however, does not necessarily lead to a solution in which all rates are higher than $R^\star$ (e.g. for too high $R^\star$).

2) BS Power Minimization: Similar to the optimization of the relay powers, the transmit power of BS c can also be minimized. To this end, the power allocated to each beamforming matrix $\mathbf{Q}_{c,k}$ is controlled while the relay gain matrices are fixed. Starting with equally allocated power, i.e.

$$\beta_{c,k}^{(0)} = \frac{P_{\mathrm{B,max}}}{M \cdot \mathrm{trace}\left\{ \sum_{i=1}^{M} \mathbf{Q}_{c,i} \cdot \mathbf{Q}_{c,i}^{\mathsf{H}} \right\}} \quad \forall k, \quad (9)$$

the highest rate $R_{c,l}$ in the selected cell c is identified and the corresponding power is reduced according to

$$\beta_{c,l}^{(n+1)} = \beta_{c,l}^{(n)} - \frac{R_{c,l}^{(n)} - R^\star}{m}. \quad (10)$$

Here, the step size can be chosen as

$$m = \frac{1}{\ln(2)} \cdot \mathrm{trace}\left\{ \left(\mathbf{K}_{c,l}^{(\mathrm{i+n})} \right)^{-1} \mathbf{K}_{c,l}^{(\mathrm{sig})} \right\}, \quad (11)$$

which corresponds to the derivative of $R_{c,l}$ evaluated at $\alpha_{c,l} = 0$. This step size is thus an upper bound on the slope of $R_{c,l}$ with respect to $\alpha_{c,l} > 0$ and guarantees that the resulting rate after the update cannot fall below $R^\star$.

3) Alternating Optimization: We can now combine both schemes such that the BS and the relay powers are minimized and the algorithm can be extended to the whole network. When the BS power is optimized in one cell, lowering the relay powers within this same cell cannot lead to further improvements, as MSs that already achieve $R^\star$ could fall below that value. In order to guarantee convergence, the algorithm is extended to all (or a cluster of) cells. Running the BS optimization once in each cell offers a potential to optimize the relays in a second turn, as the rates are further increased by the lower interference of the neighboring cells. The relay powers can thus be further reduced and we can again iterate over the relay and BS optimization until all MSs achieve $R^\star$ within the tolerance ε or are in outage as no further improvement is possible. The alternating procedure is summarized in Algorithm 1. The order of the BS and relay power optimization can also be swapped.

The optimization can be realized in a distributed way, where each node updates its scaling factor itself, or centralized at the BSs. In the latter case, only signal covariance matrices need to be fed back to the BSs. After computation, the relays can then be informed about their scaling factors via a control channel. This does not increase the signaling overhead significantly, as similar feedback and control signals are already included in current systems. If the optimization is distributed among different nodes, communication to exchange the necessary information between them would be required, which might introduce additional overhead.

Algorithm 1 Minimize power

Initialization: $P_{\mathrm{B},c,i} = P_{\mathrm{B,max}}$, $P_{\mathrm{R},c,i} = P_{\mathrm{R,max}}$, $\forall c, i$
while some $R_{c,i} > R^\star + \epsilon$ **do**
  for $c = 1 : C$ **do**
    while $\exists l : R_{c,l} > R^\star + \epsilon$ **do**
      update $\beta_{c,l}$ according to (10), calculate $R_{c,i}$, $\forall i$
    end while
  end for
  for $c = 1 : C$ **do**
    while $\exists l : R_{c,l} > R^\star + \epsilon$ **do**
      update $\alpha_{c,l}$ according to (8), calculate $R_{c,i}$, $\forall i$
    end while
  end for
end while

B. Maximize Minimum Rate

In order to achieve fairness across the users, power control can also be applied to maximize the minimum rate under a sum power constraint. To this end, Algorithm 1 is adapted such that the transmit power for the strongest MS is not only reduced, but transferred to the weakest user in the cell. For the derivation of this scheme, we focus on BS power control.

As before, the transmit power at BS c is equally distributed among all users of this cell. Then, in iteration step n, the MS (c, j) that achieves the lowest rate $R_{c,j}^{(n)} = R_{\min}^{(n)}$ and the one that achieves the highest rate $R_{c,l}^{(n)}$ are identified. The power allocated to MS (c, l) is then reduced by updating

$$\beta_{c,l}^{(n+1)} = \beta_{c,l}^{(n)} - \frac{R_{c,l}^{(n)} - R_{\min}^{(n)}}{m}, \quad (12)$$

in which m as in (11) guarantees $R_{\min}^{(n+1)} \geq R_{\min}^{(n)}$. The updated BS power is

$$P_{\mathrm{B},c,l}^{(n+1)} = \beta_{c,l}^{(n+1)} \cdot \frac{P_{\mathrm{B,max}}}{M} \quad (13)$$

and the saved power $\Delta P = P_{\mathrm{B},c,l}^{(n)} - P_{\mathrm{B},c,l}^{(n+1)}$ can be allocated to the weakest user (c, j) according to

$$\beta_{c,j}^{(n+1)} = \left(P_{\mathrm{B},c,j}^{(n)} + \Delta P \right) \cdot \frac{M}{P_{\mathrm{B,max}}} \quad (14)$$

in order to scale the corresponding beamforming matrix. These steps can be repeated until all rates in the cell are equal within a tolerance ε. The same scheme can also be applied to the relays when a sum transmit power constraint among all relays of the same cell is imposed.

C. Outage Reduction

While the max-min algorithm attempts to make the rates equal, resulting in maximal fairness, it can happen that a single user with very poor conditions can lower all other (possibly much higher) rates to a value that is not useful anymore. To avoid this, the scheme can be slightly modified such that the probability that a MS is in outage is reduced. To this end, the saved power of the strongest user, $\Delta P = P_{\mathrm{B},c,l}^{(n)} - P_{\mathrm{B},c,l}^{(n+1)}$, is allocated to MS (c, j) with $j = \arg\min_j \left(R^\star - R_{c,j} \right)^+$, where $(\cdot)^+ = \max\{0, \cdot\}$, i.e. the MS which is *closest below* $R^\star$.

IV. Simulation Results & Discussion

The performance of the described algorithms is assessed by means of computer simulations in a realistic setup. The network consists of $C = 7$ regularly arranged hexagonal cells. The BSs are located in the center of each cell and the distance between adjacent BSs is $1000\,\mathrm{m}$. The number of MSs and relays in each cell is $M = K = 6$, where the relays are regularly placed and the MSs randomly. Each MS, relay, and BS is equipped with $N_{\mathrm{M}} = 2$, $N_{\mathrm{R}} = 4$, and $N_{\mathrm{B}} = 24$ antennas. All antennas are omnidirectional and we apply a channel model with Rayleigh fading, pathloss, and shadowing according to the WINNER II model as in [9]. Assuming a system bandwidth of $100\,\mathrm{MHz}$ and a noise figure of $5\,\mathrm{dB}$, the noise variance is $\sigma_n^2 = \sigma_w^2 = 5 \cdot 10^{-12}\,\mathrm{W}$ and, if not stated otherwise, the maximal allowed transmit powers are $P_{\mathrm{B,max}} = 40\,\mathrm{W}$ and $P_{\mathrm{R,max}} = 6\,\mathrm{W}$. The target rate is $R^{\star} = 1$ bit/channel use.

Fig. 3 shows the empirical cumulative distribution functions (CDFs) of achievable user rates in the center cell and the required sum transmit power (BS plus relay power) allocated for one user when Algorithm 1 is applied. The performance of the relay carpet is also compared with a network without relays where the same power control scheme is applied, once with $P_{\mathrm{B,max}} = 40\,\mathrm{W}$ and once with $P_{\mathrm{B,max}} = 76\,\mathrm{W}$ (same sum power as BS and relays together). The BSs perform block ZF on the direct channels to the mobiles within their cell. It can be observed that the relays lower the outage probability significantly, especially when type B relays are used. Also the required transmit power is reduced to a large extent.

The algorithm that attempts to maximize the minimum rate is considered in Fig. 4, which shows the empirical CDF of the minimal rate within the cell of interest. Also here, the relay carpet shows a significantly better behavior than the conventional network without relays, even for type A relays. With type B relays, the minimal rates are even more increased. The performance of the outage minimization is shown in Fig. 5. Again, we observe that a much lower outage probability can be achieved by the help of the relays.

The relay carpet with its simple transmission and power control schemes presented in this paper shows a significant performance gain as compared to a conventional multi-user MIMO approach. By using frequency conversion relays, the

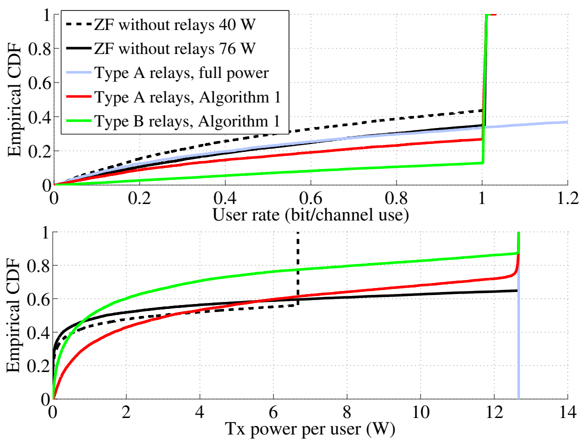

Fig. 3. Empirical CDF of user rates and the required transmit power (BS plus relay power) allocated to the transmission for one user.

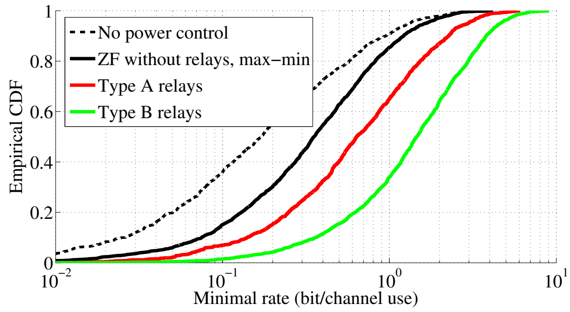

Fig. 4. Empirical CDF of the minimal rates after max-min optimization.

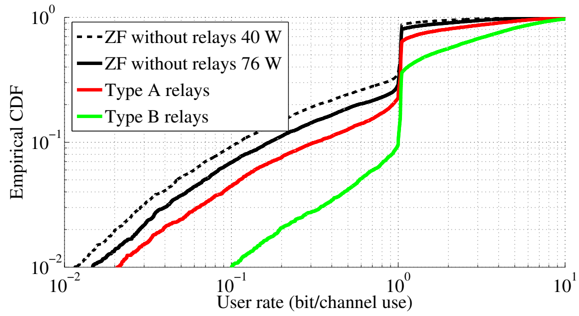

Fig. 5. Empirical CDF of the user rates after outage minimization.

two-hop concept for cellular networks does not lead to additional delays and the relays can be implemented in a low-complexity and inexpensive fashion. The relay carpet is thus not only a promising concept for future cellular networks but can also act as an enabler for massive MIMO at the BSs and a combination of sophisticated multi-user MIMO and small cells without the requirement of deploying additional BS sites with access to the wired backbone.

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