Performance Comparison of Relaying and User Cooperation in Multi-Cell Scenarios

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***Abstract*—This work focuses on the signal to interference plus noise ratio (SINR) comparison of a relaying and a user cooperation strategy. For the relaying strategy we consider operator placed relays in each cell and power control is utilized in the source nodes to achieve a target SINR. For the cooperative strategy, user cooperation with coherent combining is utilized in order to meet a given target SINR at the receiver. Both cases are analyzed in a multi-cell scenario with a soft frequency reuse factor of 3. With 16QAM modulation and no cooperation only 80% of the users achieve the target SINR. We can show that with user cooperation 82% of all users achieve the target SINR and with relaying 98%.**

***Index Terms*—Relay, user cooperation, cellular networks.**

I. Introduction

In cellular networks the base station, or enhanced Node B (eNB) in LTE advanced networks [1], coordinates the operation of the network, using orthogonal resource allocation, however, there is no coordination between neighboring eNBs. This lack of coordination between neighboring cells cause undesired interference to be present in the cellular network. That is, the resource allocation is orthogonal within one cell, but it is not necessarily orthogonal with respect to neighboring cells. This leads to undesired interference towards the eNB in the uplink, which is caused by the user equipments (UEs) that are in the neighboring cells.

The work presented in [2] deals with uplink cooperative relaying strategies, but just a single cell scenario is considered. The work in [3] considers a multi-cell scenario exploiting interference mitigation by inter-cell interference coordination in the uplink, but does not deal with relaying or user equipment cooperation schemes. The work in [4] studies a relaying methodology with a topology similar to the one studied in this paper, however the relay placement is fixed and not optimized. Besides that, just a single cell scenario is analyzed. [5] proposes a power control algorithm to mitigate inter-cell interference in the uplink, but neither relaying nor user cooperation strategies are analyzed. Generally in recent works it has been shown that relays or user cooperation can bring benefits in wireless networks, however in those studies usually the interference from neighboring cells is neglected. Thus, the main question that motivates the present work is: are higher the benefits from relaying and user cooperation than the impairments caused by the interference generated to neighboring cells? Hence, one of our goals is to quantify the SINR in a network scenario in which relaying or user cooperation is implemented.

We compare the performance of a relaying and a user cooperation strategies, taking into account the interference between cells. The results show that in a network scenario, the relaying strategy and the user cooperation strategy bring improvements that are not overshadowed by the increase of interference toward neighboring cells.

Scientific Contribution:

- For the relaying strategy we propose a novel optimal relay placement by using convex optimization.
- We assume that there is a user cooperation strategy in which two UEs can join efforts in order to increase the received SNR at the eNB by coherent combining. In this case, the cooperation with another user allows an improvement in the received SNR at the eNB. The performance of this strategy, under interference, is characterized.
- In the relaying strategy and in the user cooperation strategy, to control the amount of interference, we consider a frequency reuse scheme and a power control strategy.

II. System model

We consider a network model similar to the one described in [6] to model intercell interference. The network is modeled as a central hexagonal cell surrounded by two rings of cells, as shown in Figure 1. Hence, we consider 19 cells in total. The eNB is placed in the center of each hexagonal cell, while the UEs are uniformly distributed in each cell. The distance between adjacent eNBs is denoted by γ and the UEs per cell by η respectively. Besides that, α counts the UEs that are active and communicating in the uplink.

A. Channel model and outage definition

We consider only indoor to outdoor links, which is the worst case scenario in cellular networks regarding the path loss between the UEs and the eNB. The UEs are assumed to be uniformly distributed in a room with length 15m. The incidence of the radio wave is assumed to be perpendicular to the wall of the room. The base station is in an outdoor

This work was partially supported by the European Commission in the framework of the FP7 Network of Excellence in Wireless COMmunications NEWCOM++, and by the Vienna Science and Technology Fund in the FTW project PUCCO. The FTW Telecommunications Research Center Vienna is supported by the Austrian Government and the City of Vienna within the competence center program COMET.

978-1-4673-0990-5/12/$31.00 ©2012 IEEE

microcell environment. The indoor to outdoor propagation is modeled by the scenario A2 NLOS of the WINNER II model [7]. The outdoor propagation, that is, from the wall to the eNB, is modeled by equations (4) and (24) in [8]. The path loss and the shadowing depend on: (i) the distance d_0, from the wall of the room in which the UE is located to the eNB, and (ii) the distance d_i from the UE to the wall. Thus, d_i is a uniformly distributed random variable between 0 and 15m. The overall pathloss and shadowing model is described by

$$L = L_0 + L_{\mathrm{W}} + L_{\mathrm{I}}, \tag{1}$$

where ([7], [8])

$$L_0 = 135.78 + 38.86 \log_{10}(d_0) + 7.96x \tag{2}$$

$$L_{\mathrm{W}} = 14dB \tag{3}$$

$$L_{\mathrm{I}} = 0.5d_{\mathrm{i}} + 7y \tag{4}$$

with x, y Gaussian variables with zero mean and variance one.

The i-th UE, denoted by UE$_i$, is said to be in an outage when its SNR at the eNB, γ_i, is smaller than a given threshold γ_{thr}. The noise is considered to be thermal noise at standard temperature (T = 17°C), while having a system bandwidth of B = 7.68MHz. Thus, assuming antenna gains equal to one, the SNR for UE$_i$, at the eNB, can be calculated by

$$\gamma_i[dB] = P_{\mathrm{Tx,i}}[dBW] - L_{\mathrm{i}}[dB] - 10\log_{10}(KTB), \tag{5}$$

where: $P_{\mathrm{Tx,i}}$ represents the power transmitted by UE$_i$, in logarithmic scale, L_{i} denotes the overall path loss and shadowing, in dB, from UE$_i$ towards the eNB in its cell as given by (1), and $K = 1.380 \times 10^{-23} J/K$ is the Boltzmann constant. For a given UE transmit power, and since the noise power is constant, there is a maximum path loss and shadowing, such that γ_i is not below the threshold that determines if UE$_i$ is in an outage.

An exemplary network setup is shown in Figure 1. The eNBs are the red circles in the center of each cell. The UEs are indicated by the red exes. Note that the UEs in outage, indicated by a black circle, are mostly at the cell edge.

To avoid outage, the UEs implement one of the following strategies: (i) use *operator placed relays* or (ii) join with another user equipment using cooperative communications assuming coherent combining at the eNB. The last strategy is called *user cooperation*.

B. Relaying Strategy: Operator Placed Relays

In this relaying strategy, we assume that the link between the relays and the eNB has constantly high SNR by network design and operates in frequency block that does not cause interference. Therefore we neglect the link between relay and eNB and just consider the communication from the UEs towards the relays or to the eNB, whichever is closer. When the UE communicates with a relay, the effective received power for the uplink is thus given only by the link between the UE and the relay.

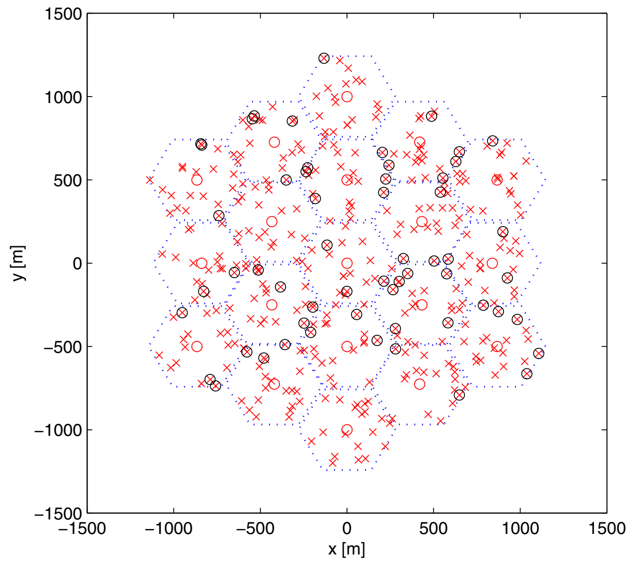

Fig. 1. Network setup: 19 cells with the eNBs (○), α = 20 active user equipments per cell (×) and the UEs that are in an outage (⊗).

It is assumed that the network operator places a set of relays in a ring around the eNB in each cell. In this way the UEs can save power and the load in the cell is distributed among the eNB and the relays.

Thus, a group of relays is uniformly distributed in a ring centered around the eNB. The UE is communicating to whoever is closer, in terms of pathloss and shadowing: a relay or the eNB. The angular position of the relays is fixed for all cells, by putting one relay on a line connecting the center of the hexagon and one of its vertices. The radius of the ring, $d_{\mathrm{R,eNB}}$, is a discrete variable defined by

$$d_{\mathrm{R,eNB}} = \frac{D}{M} n, n = \{1, 2, ..., M\} \tag{6}$$

where D is the distance from the center of the hexagonal cell to one of its vertices and M is a positive integer number. Note that the granularity of the discrete variable $d_{\mathrm{R,eNB}}$ can be chosen arbitrarily according to M.

$d_{\mathrm{R,eNB}}$ is optimally chosen to solve the following problem

$$\min_{d_{\mathrm{R,eNB}}} \max_{(x,y)} \min_{j} (d_{\mathrm{UE,R}_j}, d_{\mathrm{UE,eNB}}), \tag{7}$$

where (x, y) represents all the possible locations of a UE in the cell, that is, (x, y) is a coordinate that lies inside the hexagon that defines the cell area. j indexes all the relays in the cell, $d_{\mathrm{UE,R}_j}$ denotes the distance between the coordinate (x, y) and the relay R$_j$ and $d_{\mathrm{UE,eNB}}$ stands for the distance between the coordinate (x, y) and the eNB. Hence, the optimization problem minimizes, over all the possible positions of a UE in the cell, the maximum distance from a UE towards a receiver, either the eNB or a relay. This is equal to minimizing the maximum possible path loss of the UEs.

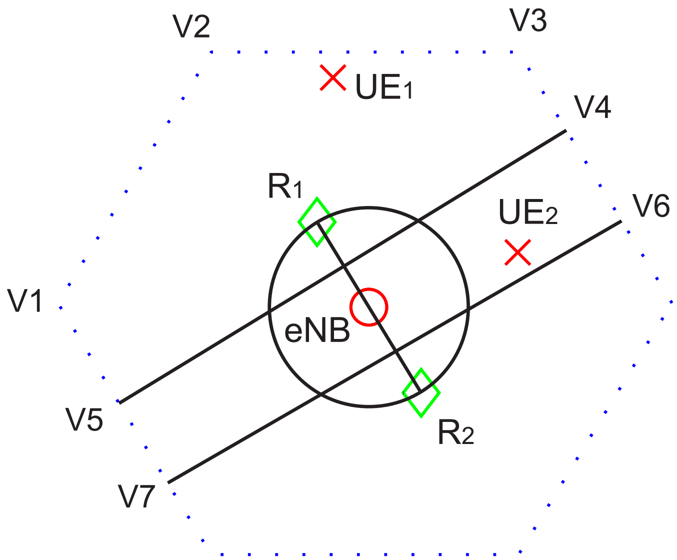

Fig. 2. The relays are placed in a circumference centered in the eNB.

Figure 2 presents a sample case with 2 relays (diamonds) to illustrate how the previous optimization problem can be simplified. The figure shows a cell with an eNB (circle in the center of the cell) and two sample UEs (crosses). Let us analyze by parts the optimization problem in (7). The inner minimization stands for the minimum distance between the UE_i and each relay or the eNB. In our sample case in Figure 2, UE_1 is nearer to R_1 than to the eNB or to other relay. Similarly, UE_2 is nearer to the eNB than to any relay. The set of points in which a UE is closer to the eNB or to a relay can be found by Voronoi partitions: Trace a line between the location of the eNB and a relay (e.g. line between R_1 and the eNB in Figure 2). Then, trace a perpendicular line that bisects, in equal parts, the previous one (e.g. line between V_4 and V_5 in Figure 2). The last line corresponds to the set of points that are equidistant to the considered relay (R_1) and the eNB. That is, the line is defining also the set of points in which an UE will be nearer to the relay or to the eNB. Since the hexagon is a convex set, the sets obtained by the previous procedure are also convex sets (e.g. the set defined by the vertices V_1, V_2, V_3, V_4, and V_5 and the set defined by the vertices V_4, V_5, V_7 and V_6). This follows since a line that cuts a convex set, defines 2 new convex sets, because a line defines convex half spaces and the intersection of convex sets is convex [9]. In general, the Voronoi partitions should be found between the eNB and each relay and between adjacent relays. In each of the convex sets found, the distance to the receiver node (i.e. either a relay or the eNB) can be represented by the boundary of a cone with the apex in the position of the receiver node. However, on the boundary of each convex set, the cone intersects a plane that is parallel to the axis of the cone. The intersection of the boundary of a cone with a plane parallel to the axis of the cone is a convex curve, as shown in the appendix, therefore its maximum is necessarily on one of the vertices of the convex set. That is, the maximization in (7) can be restricted to the vertices, over all the convex sets. This observation simplifies enormously the complexity of the optimization problem, because it is known that the maximum over all the UE in (7) lies in one of the vertices of the convex regions defined by the Voronoi partitions. Hence, the external minimization in (7) can be solved by a low complexity exhaustive search, considering the simplified problem in which just the vertices of all the convex sets must be checked. Following the previous procedure, it was found that the optimum radius for the case of 2 relays is 0.66 of the cell radius and 0.51 for the case with 6 relays.

C. *Cooperation Strategy: User Cooperation*

In this strategy, a UE in outage cooperates with another peer UE, in order to increase the received SNR at the eNB. The cooperation is carried out with a peer UE in the neighborhood of the UE in outage. The neighborhood of a UE is defined as a circle, with a radius of 30 m, centered at the UE in outage. Two kind of cooperating UEs are available: i) UEs that are also in an outage and ii) UEs that are in the neighborhood but they are not in an outage. We consider a general cooperation strategy with coherent combining at the eNB, therefore in this strategy we assume that the signal power from the UE that is in outage and the signal power from its cooperative partner in the neighborhood add up at the eNB. Therefore the effective received power of the link is the total amount of power received from both UEs. Note that the cooperation will therefore increase the received signal power, but it also will increase the interference towards neighboring cells.

Note that in the *cooperation strategy* the cooperative partner is a peer UE. But in the *relaying strategy* the cooperating partner is a relay which is able to receive the information from the UE and forward it directly to the eNB employing a high SNR link with high reliability.

III. Frequency Reuse and Power Control Mechanisms

A. *Frequency Reuse Mechanism*

Frequency division multiplexing is employed to assign different frequencies to neighboring cells. The whole frequency band is divided in 3 frequency subbands, i.e. soft frequency reuse is assumed. The frequency subbands are assigned to neighboring cells, such that never there are two neighboring cells using the same frequency band. That is, we implement a frequency reuse scheme with a frequency reuse factor equal to three.

B. *Power Control Mechanism*

A power control mechanism is implemented, trying to save power but still matching the target SINR. The power control mechanism is described by **Algorithm 1**, where $\tilde{L}$ stands for the path loss and shadowing in linear scale and KTB represents the thermal noise. $P_{\text{Tx-MAX}}$ represents the maximum UE transmitt power. The interference, I, is calculated from the UEs transmit powers and the path loss and shadowing model described in Section II. Following the ideas in [10] and assuming that the interference can be modeled as noise, we iteratively set the transmitted power, in order to match the target SINR, while taking into account that the UE maximum transmit power is 23dBm.

Algorithm 1

procedure POWER CONTROL ALGORITHM
    Set P_{Tx} according to: $P_{\text{Tx}} = \gamma_{\text{thr}}\,(\text{KTB})\,\tilde{L}$
    if $P_{\text{Tx}} > P_{\text{Tx-MAX}}$ **then**
        $P_{\text{Tx}} = P_{\text{Tx-MAX}}$
    end if
    Calculate the overall interference (I)
    $j = 0$
    while $j \neq$Max. Num. Iterations **do**
        Set P_{Tx} according to: $P_{\text{Tx}} = \gamma_{\text{thr}}\,(I + \text{KTB})\,\tilde{L}$
        if $P_{\text{Tx}} > P_{\text{Tx-MAX}}$ **then**
            $P_{\text{Tx}} = P_{\text{Tx-MAX}}$
        end if
        Calculate the overall interference (I)
        $j = j + 1$
    end while
end procedure

IV. SIMULATION RESULTS

In order to analyze the performance of the different strategies, initially we simulate them neglecting the inter-cell interference (Figure 3, summarized in Table I), then we present the simulation results including the effect of interference (Table II). For the case without interference and for the case with it, we present the performance of the operator placed strategy and the user cooperation strategy. In Table I) and Table II the minimum Monte Carlo simulation resolution is 1e-3 and 1e-2 respectively. In each simulation run we consider 100 network realizations.

The inter eNB distance, $\rho = 500$m, and the number of UEs per cell, $\eta = 865$, were chosen trying to match the population density in Vienna, Austria. We assume that out of the 865 UEs per cell, α = 20 are active and communicating in the uplink.

A. No interference

As a benchmark, all the strategies considered were evaluated neglecting the inter-cell interference.

TABLE I
OUTAGE PROBABILITIES WITHOUT INTERFERENCE

	Outage probabilities: P $(\gamma_i < \gamma_{\text{thr}})$		
	$\gamma_{\text{thr}} = 0$dB	$\gamma_{\text{thr}} = 10$dB	$\gamma_{\text{thr}} = 23$dB
Without coop. or rel.	1.711e-3	16.39e-3	153.4e-3
Coop. with best rel. in outage	1.184e-3	13.05e-3	91.71e-3
Operator placed relays	<1e-3	<1e-3	9.211e-3
Coop. with best rel.	<1e-3	<1e-3	<1e-3

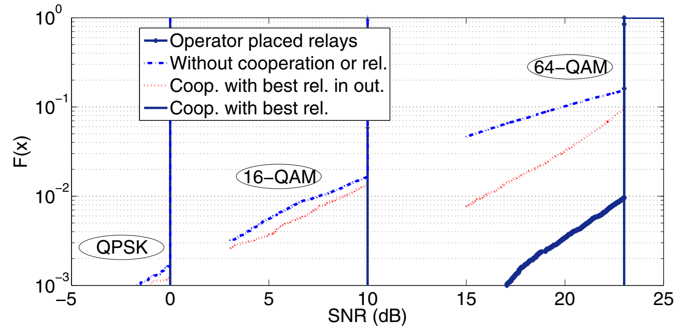

Fig. 3. Performance of the different schemes, without interference. F(x) represents the cumulative distribution function of the SNR.

1) Operator placed relays: We consider a simulation scenario with two relays per cell. In the power control mechanism 20 power iterations are utilized. The desired SNR threshold, γ_{thr}, is chosen to match the minimum SNR to employ the modulation alphabet QPSK, 16-QAM and 64-QAM [11]. Thus, γ_{thr} = 0dB for QPSK, γ_{thr} = 10dB for 16-QAM and γ_{thr} = 23dB for 64-QAM.

The results in Table I show that for QPSK or 16-QAM, 99.9% of the users achieve the desired value for γ_{thr}. In the case of 64-QAM, 99% of the users achieve γ_{thr}=23dB.

2) User cooperation: In this strategy, using 64-QAM and the best relay in outage as cooperation partner, allows 91% of the UEs to achieve the desired SINR. 95% of the UEs achieve the desired threshold for 16-QAM and 99.8% for QPSK.

Using the strategy user cooperation with the best relay as cooperation partner, there is a higher percentage of UEs that achieve the desired SNR threshold. This percentage is smaller than 99.9% for all the 3 modulation alphabets analyzed. However this percentage is not so high in the case in which inter-cell interference is taken into account as will be seen in the following subsections.

It is interesting to note that 99.9% of the users are connected not just in the operator placed relays, but also in the strategy user cooperation using the best relay.

B. Interference from other cells

TABLE II
OUTAGE PROBABILITIES WITH INTERFERENCE

	Outage probabilities: P $(\gamma_i < \gamma_{\text{thr}})$		
	$\gamma_{\text{thr}} = 0$dB	$\gamma_{\text{thr}} = 10$dB	$\gamma_{\text{thr}} = 23$dB
Without coop. or rel.	3.703e-2	21.89e-2	65.8e-2
Coop. with best rel. in outage	3.703e-2	21.89e-2	63.33e-2
Coop. with best rel.	3.703e-2	16.22e-2	52.78e-2
Operator placed relays	<1e-2	1.487e-2	26.41e-2

1) Operator placed relays: Table II shows the outage probability for different threshold SINR. The worst performance is obtained without the relaying or cooperation strategies. Without cooperation or relaying, just 34% of the UEs are able to achieve the desired SINR (γ_{thr}) with 64-QAM, 77% with 16-QAM and 95% with QPSK. Taking the performance without coopreration or relaying as reference, it can be seen that an improvement is obtained for the operator placed relays strategy. For the 64-QAM case, 40.6% more user equipments are able to achieve the desired threshold, for 16-QAM 21.5% and for QPSK 4.6%.

In our simulations it was found that the percentage of cases in which the UEs communicate with a relay and not with the eNB oscillates between 63% and 74%, that is, around one third of the users communicate directly with the eNB.

Finally, an interesting result is that all the UEs that were in an SNIR outage ($\gamma_{\text{i}} < \gamma_{\text{thr}}$) before the placement of the relays are able to connect either to the eNB or to a relay. But unfortunately, due to the interference generated, there are still some UEs that can not achieve the threshold SINR.

2) User cooperation: Table II presents the outage probabilities for the cases with cooperation and without cooperation. As for the case without interference, there are two possible kinds of partner UEs to implement the strategy user equipments as relays: (i) the cooperating partner is a UE that is as well in an outage or (ii) the cooperating partner is not necessarily in an outage.

As can be seen, the improvement in the performance is almost negligible when the cooperation is carried out with the best relay in outage. However, when the user cooperation strategy is implemented with the best relay, the improvements in the performance are significant. Thus, 11.4% more users are connected with 64-QAM, 5.82% with 16-QAM and no improvement is seen for QPSK, although 97% of the users are already connected.

V. Conclusions

In this paper we compare the signal to interference and noise ratio (SINR) of a relaying and a user cooperation strategy for the uplink of a cellular communication system in a multi-cell scenario. We use a soft frequency reuse of three.

For the relaying strategy, we optimally place the relays in a ring around the eNB using convex optimization. For the user cooperation strategy we assume that the signal of both cooperating UEs can be coherently combined at the eNB. The joint effects of relaying, soft frequency reuse and the power control mechanism, are included in the target SINR calculation of each UE.

We analyzed three different symbol alphabets: QPSK, 16QAM and 64AQM. With 16QAM (64QAM) and no cooperation 80% (35%) of the users achieve the target SINR. We could show that with user cooperation 82% (50%) of all users achieve the target SINR and with relaying 98% (77%). Additionally, our analysis showed that cooperation in a multi-cell environment provided the largest gain if soft frequency reuse is applied together with a power control policy.

Appendix

The boundary of a cone with the apex in (X_0, Y_0) is described by:

$$C(x,y) = \sqrt{(x - X_0)^2 + (y - Y_0)^2}, \tag{8}$$

therefore its intersection with the plane $y = 0$ is given by:

$$Z(x) = \sqrt{(x - X_0)^2 + Y_0^2}. \tag{9}$$

Note that although the plane is fixed, the apex of the cone is arbitrarily chosen, therefore, due to the symmetry of the cone, the intersection obtained is equivalent as if the apex would be fixed and the plane would be arbitrarily chosen.

To prove that $Z(x)$ is a convex curve we use the fact that a function $Z(x)$:**R**→**R** is convex if and only if its domain is a convex set and its second derivative is non-negative [9]. $Z(x)$ is defined over the real numbers, therefore we just need to prove that its second derivative is non-negative. Hence,

$$\begin{aligned} Z''(x) &= \left[(x - X_0)^2 + Y_0^2\right]^{-1/2} && (10) \\ &\quad - \left[(x - X_0)^2 + Y_0^2\right]^{-3/2} (x - X_0)^2, && (11) \end{aligned}$$

which is greater or equal than 0 when $Y_0^2 \geq 0$.

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