Analytic Quantification of Outage Probability and Radiated Power of Cooperative Base Stations

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***Abstract*—Cooperative transmissions allow fast and reliable communication between user equipment (UE) and base stations (BSs) in radio access networks. Selecting which base stations cooperate is important to keep both effective radiated power (ERP) and outage probability low.**

In this paper, we quantify how knowledge about the instantaneous channel conditions can be used to select which BSs cooperate. We analytically derive the outage probability and ERP when instantaneous channel knowledge is used for BS selection, power control, both, or not at all. In particular, we quantify the added benefit of instantaneous over average channel knowledge, depending on the differences in average channel gains of the BSs.

We determine that the greatest reduction (both in terms of outage probability and ERP) from using instantaneous channel knowledge is achieved when the average channel gains of all possibly cooperating BSs are the same. Additionally, we show that when using instantaneous channel knowledge to select the cooperating BSs, adding power control only makes a difference at a single BS.

I. Introduction

Users of radio access networks expect their data transmissions to be reliable and fast. Cooperative transmissions from several base stations (BSs) are able to provide both in an environment with limited channel capacity.

An important decision in cooperative networks is to select the cooperating BSs from all possible BSs. In this paper we will compare different strategies to select the cooperating BSs.

Selecting the cooperating BSs can be based on average or instantaneous channel quality. Obviously, basing this decision on instantaneous knowledge provides better results, but collecting the channel state information for instantaneous knowledge adds overhead. This overhead will reduce the gain of instantaneous channel knowledge. To better understand the fundamental interactions we will analytically quantify the reduction of outage probability with instantaneous channel knowledge in this paper.

In addition to outage probability we also consider radiated power as a metric. BSs not only radiate power to the intended user equipment (UE), but also to other UEs in the surrounding area. This radiated power will be received by the other UEs, become interference, and increase their outage probability. Therefore, it is important to also keep the radiated power low.

Using cooperative transmissions from several BSs naively will radiate more power than a transmission from a single BS. Therefore, it is especially important to consider the effects of cooperation on the radiated power. As reducing outage probability and radiated power are both important goals, we will determine how different BS selection strategies trade-off the two goals.

In this paper we determine how much instantaneous channel knowledge reduces both outage probability and radiated power. We differentiate between two uses of instantaneous channel knowledge: (1) instantaneously changing the effective radiated power (ERP) of BSs and (2) selecting the BSs that cooperate to transmit the signal to the UE. We ignore the technical requirements and overheads of their implementation (e.g., obtaining channel state information). Instead we focus on determining the outage probability and the average ERP analytically. The only assumption we make is that BSs which use instantaneous channel knowledge need to be able to determine the channel state as fast as it changes. While related work has done this using simulations, we do this analytically to learn more about the underlying basics.

The contribution of this paper is the analytic description of outage probability and ERP for cooperating BSs in a radio access network with and without instantaneous channel knowledge. This allows to determine the expected gain from giving a radio access network access to instantaneous channel knowledge. Additionally, we show that the highest gain from instantaneous channel knowledge can be achieved when the possibly cooperating BSs have the same average channel gains. Therefore, we conclude that users at the cell edges will benefit the most from instantaneous channel knowledge.

We show that instantaneous selection of cooperating BSs can reduce the ERP, while keeping the outage probability low. As our only assumption about cooperation is the additivity of combined signals, our results apply to both coherent combining [1] and maximum-ratio combining [2].

II. Related work

Tse and Viswanath [3] describe waterfilling, which maximizes the *ergodic* capacity of a cooperative transmission with instantaneous channel knowledge and limited ERP. In contrast to this, we measure the *outage* probability and compare it under instantaneous and average channel knowledge.

Hoydis et al. [4] analyze the optimal fraction of coherence time of a channel to be used to determine the instantaneous channel quality. We ignore this overhead and analyze how ERP and outage probability can be traded off when using different cooperative schemes and instantaneous channel knowledge is known.

Park et al. [5] describe how an adaptive use of cooperative and non-cooperative schemes can maximize the network's

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capacity. Zakhour and Hanly [6] maximize the minimum data rate of any UE. Instead of data rate we use the outage probability as a metric for the quality of the resulting transmission.

Other work considers scenarios such as relaying [7], [8], [9] or multi-hop [10]. Biermann et al. [11] compare how well different back-haul topologies are suited for cooperative transmissions. We assume to have a list of all possibly cooperating BSs and select from these. Maaref and Aïssa [12] describe the outage and ergodic capacity of MIMO Systems. We determine the outage probability and the ERP of cooperating BSs and determine how to select which BSs cooperate.

While we assume the channel state to be determined without overhead, Ramprashad and Caire [13] consider the overhead of collecting this information in a MIMO System. Similarly, Goldenbaum et al. [14] consider the effect of delayed channel state information. Another group of work [15], [16] focuses on the practical aspects of cooperative transmissions while we provide analytical results.

III. Model

We consider only the connection of a single UE to the radio access network and only downlink transmissions from the BSs to the UE. We denote the instantaneous channel gain from BS i to the UE as γ_i and its probability density function as f_i with mean Γ_i. Note that we do not make any assumption about the distribution of the instantaneous channel gain and, hence, the results are valid for all block-fading fading environments. For simplicity, we assume the BSs to be ordered by decreasing average channel gain.

We define the ERP p_i to be the power that is transmitted from the sender's antenna including all gains and losses of the sender and its antenna. For simplicity, we normalize the ERP to be between 0 and 1. Here 0 means not transmitting any power and 1 means a BS transmitting at full power. *Power control* is the ability of a BS to change the ERP in the interval $[0, 1]$ for each fading block, while a BS without power control is limited to the values 0 and 1. Note that average ERP can – in addition to being a metric (when the BS adapts the ERP based on the channel quality) – also be a parameter (when setting ERP to a constant value). When not further specified we assume all BSs transmit at full power.

By *cooperating BSs* we understand multiple BSs that use the back-haul network to coordinate and transmit data to the same UE. We assume the combined signal is equivalent to a signal with a Signal-to-Noise-ratio (SNR) equal to the sum of the SNRs of the individual signals. One way to achieve this is to synchronously transmit from the senders so that the signals constructively interfere at the receiver. This is called coherent combining (CC). Another possibility is to transmit both signals at different times, record them in the receiver, and combine them inside the receiver. This is realized for example by maximum ratio combining (MRC). Both CC and MRC fulfill our assumption of additive SNRs [1], [2].

We do not explicitly consider the number of transmit and receive antennas at each BS, but as long as the signals of different BSs can be additively combined our results also hold for MIMO transmissions. As BS clustering and the back-haul network constrain the free selection of BSs, we assume to have a list of possibly cooperating BSs from which we select the actually cooperating BSs.

We compare two different types of cooperative schemes: static and dynamic. Using *static association*, the UE is associated to the c BSs with the highest *average* channel gain. Using *dynamic association*, the UE is associated to the c BSs with the highest *instantaneous* channel gain. We use n to denote the total number of available BSs while c denotes the number of BSs that can actively cooperate; both n and c will be used as parameters in the performance evaluation in Section VII.

We assume users require a fixed minimum data rate. We model this as a threshold T_R of SNR above which the transmission succeeds and under which it fails. The probability that this threshold is met is called *outage probability* O [1]:

$$\mathrm{P}(\mathrm{Outage}) = \mathrm{P}\left(\frac{p_i\gamma_i}{N} < T_\mathrm{R}\right) = \mathrm{P}\left(p_i\gamma_i < T\right), \qquad (1)$$

where N is noise. For simplicity we define the power threshold $T = T_\mathrm{R}N$ as the threshold of ERP p_i and channel gain γ_i for a successful transmission. This threshold T is system-dependent, but a constant for the purpose of our analysis. We denote the sum of the ERP of all BSs averaged over time by R.

IV. Outage probability

In this section we describe the outage probability for static and dynamic association when all cooperating BSs transmit at maximum power. While this minimizes the outage probability it will also radiate more power than necessary. These calculations provide a lower bound for the possible outage probability when the ERP is reduced. The calculation of outage probability using static association is not new [1], but we included it in this paper, using the notation of the rest of the paper, as a reference for dynamic association.

A. Static association

When a UE is statically associated to c BSs, it is best to select the c BSs with the highest average channel gain (note that this is only true as long as the distributions are the same). As we number the BSs in decreasing order of average channel gain, these are BSs 1 to c. The resulting outage probability with static selection of c BSs is:

$$\mathrm{O_S}(c) = \mathrm{P}\left(\sum_{i=1}^{c}\gamma_i < T\right) = s_c(T), \qquad (2)$$

where $s_i(t)$ is the probability that the sum of the channel gains of BSs 1 to i is lower than t (i.e., the convolution of all c involved instantaneous channel gains γ_i):

$$s_i(t) = \begin{cases} \int_0^t f_i(x_i)s_{i-1}(t-x_i)\mathrm{d}x_i & \text{if } i > 0, \\ 1 & \text{else.} \end{cases} \qquad (3)$$

[1]We denote the outage probability using static association with $\mathrm{O_S}$ and with dynamic association with $\mathrm{O_D}$ and power control with a "p" in the index.

B. Dynamic association

With dynamic association, we select the best c BSs out of n possible BSs based on their instantaneous channel gain. This results in an outage probability of:

$$\mathrm{O_D}(n,c) = \mathrm{P}\left(\max_{\pi \in \mathrm{S}_n} \sum_{i=1}^{c} \gamma_{\pi(i)} < T\right) = \sum_{\pi \in \mathrm{S}_n} h_\pi(n,c) = \sum_{\pi \in \mathrm{S}_n} \mathrm{P}\left(\sum_{i=1}^{c} \gamma_{\pi(i)} < T \wedge \forall i \in \{2,...,n\} : \gamma_{\pi(i-1)} > \gamma_{\pi(i)}\right), \tag{4}$$

where S_n is the symmetric group, that is, the set of all possible permutations of $(1,\ldots,n)$ and $\pi(i)$ is the ith Element of π. We use π to describe the order of instantaneous channel gains. We derive a formula for $\mathrm{O_D}(n,c)$ by applying the law of total probability over all possible permutations π of channel gains using the function h.

The function h calculates the probability that the threshold is not met when the best c BSs cooperate and the order of the instantaneous channel gains is π. We calculate it from the probability that the sum of the c largest instantaneous channel gains is smaller than T and they are in the order π (with the function r) and that the $n-c$ other channel gains are in the order π (with the function q):

$$h_\pi(n,c) = \int_0^{T/c} f_{\pi(c)}(x_c) r_\pi(c-1, T-x_c, x_c) q_\pi(n, c+1, x_c) \mathrm{d}x_c. \tag{5}$$

The function q calculates the probability that the channel gains from BSs i to n (which do not contribute to the combined signal) are in the order π:

$$q_\pi(n,i,x) = \begin{cases} \int_0^x f_{\pi(i)}(x_i) q_\pi(n, i+1, x_i) \mathrm{d}x_i & \text{if } i \leq n, \\ 1 & \text{else.} \end{cases} \tag{6}$$

The function r calculates the probability that the channel gains of BSs 1 to i are in order π and their sum is lower than T. The parameter x is the channel gain of the BS $i+1$ and is a lower bound for the channel gain of BS i. The parameter $t = T - \sum_{k=i+1}^{c} x_k$ is the channel gain that is left for the BSs 1 to i to not go over threshold T:

$$r_\pi(i,t,x) = \begin{cases} \int_x^{t/i} f_{\pi(i)}(x_i) r_\pi(i-1, t-x_i, x_i) \mathrm{d}x_i & \text{if } i > 0, \\ 1 & \text{else.} \end{cases} \tag{7}$$

V. Effective radiated power

In this section we calculate the total ERP (i.e., from all BSs) averaged over time for static and dynamic cooperation schemes with and without power control.

A. Static association

Without instantaneous channel knowledge, no inputs according to which to adapt the ERP to the situation are available. Hence, reducing the ERP can only be done by reducing the ERP in all channel situations.

Note that the outage probability with reduced ERP is the same as with reduced average channel gain: The channel gain with reduced ERP is equal to the channel gain multiplied by the ERP p. This holds both for average and instantaneous values. Therefore, the same calculations can be applied to determine the outage probability as we described in the previous section.

The total ERP of all BSs is $\mathrm{R_{S,p}}(c) = \sum_{i=1}^{c} p_i$ when BS i always transmits with ERP p_i. In the special case of full power transmission this becomes: $\mathrm{R_S}(c) = c$. We will use these as reference values to compare with dynamic association and instantaneous power control.

Allocating radiated power to BSs to minimize outage probability is not trivial when only the average channel gains are known. In contrast to this the distribution of power is easy with instantaneous channel knowledge (see Section V-B). In the next paragraph we explain why determining the optimal allocation of power with only average channel knowledge not trivial.

The calculation of $\mathrm{R_{S,p}}(c)$ and $\mathrm{O_{S,p}}(n,c)$ allows to calculate the outage probability for given ERPs, but does not provide a closed formula for the optimal distribution of total ERP to the BSs to minimize the outage probability. Using Newton's method to find a local minimum in the distribution of total ERP is possible, but one drawback of this method is that the found local minimum is not always the global minimum: For example, using 2 BSs with $\Gamma_1 = 15T$ and $\Gamma_2 = 0.995T$, a local minimum is at about 0.14 of the power allocated to BS 2, while the global minimum is at 0. While the actual difference in outage probability is small (at least in this example), the problem has to be considered when applying Newton's method. For the remainder of this paper we assume all transmitting BSs using static association transmit at full power. Hence, the power does not need to be distributed.

B. Dynamic association

At first we calculate the ERP with dynamic association without power control. That is, the BSs do not transmit at all when the sum of the channel gains will be lower than the necessary threshold and else only those BSs transmit which are needed to reach the threshold. With $\mathrm{O_D}(n,0) = 1$, the expected ERP without power control can be written as:

$$\mathrm{R_D}(n,c) = \sum_{i=1}^{c} i\, \mathrm{E_D}(n,i), \tag{8}$$

where $\mathrm{E_D}(n,c) = \mathrm{O_D}(n,c-1) - \mathrm{O_D}(n,c)$ is the probability that exactly c BSs have to cooperate.

With power control, it is possible to transmit only with the ERP necessary to reach the threshold T. The following definition and its use describe how much total ERP is necessary to reach the threshold T and how to distribute it.

We define an allocation of power to be an *on-off allocation* when the following condition is met:

$$\exists j \in \{1,\ldots,n\} : \forall i < j : p_i = 1 \wedge \forall i > j : p_i = 0. \tag{9}$$

Figure 1 illustrates the on-off power allocation: a BS j exists that transmits at some ERP, all BSs with a higher channel gain transmit at full ERP, and all BSs with a lower channel gain do not transmit. Note that the on-off allocation is uniquely

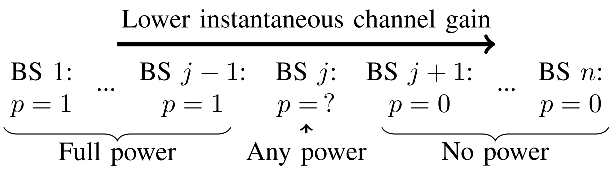

Fig. 1. The on-off allocation maximizes the ERP on the channels with the highest instantaneous channel gain.

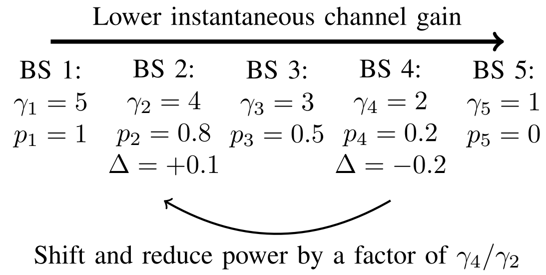

Fig. 2. This illustrates an example that only on-off allocations are using minimal ERP. Allocating ERP from BS 4 to BS 2 reduces the total ERP as the increase at BS 2 is lower than the decrease at BS 4, while the signal strength at the receiver does not change.

defined for a given total ERP, when all average channel gains Γ_i are different. Else they are unique except for permutation.

Claim: When the instantaneous channel gains γ_i are known, the threshold T is reachable with minimum radiated power when the ERP is distributed according to the on-off allocation sorted by instantaneous channel gains.

Proof: Assume an allocation A which is not an on-off allocation radiates the least total power and reaches the threshold T at the UE. Select j to be the index of the BS with the lowest channel gain with ERP $p_j > 0$. As all BSs i with smaller channel gain have $p_i = 0$ the statement $\forall i > j : p_i = 0$ is fulfilled. Hence, there must be a BS k with $k < j$ and $p_k < 1$ (else it would be an on-off allocation).

Select k such that BS k that violates $p_k = 1$. Now construct a power allocation that reaches the threshold and radiates less power than allocation A and, thus, prove it cannot have been the one that radiates least power. As we only change the ERP of BS i and k we will ignore all others. In allocation A the BS i and k generate a total received channel gain of $p_i\gamma_i + p_k\gamma_k$ at the receiver. Note that $\gamma_k > \gamma_i$ by the way k and j were selected. Select the new values $p_i^* = p_i - \gamma_i/\gamma_k\epsilon$ and $p_k^* = p_k + \epsilon$, with $\varepsilon < \min(p_i, 1 - p_k)$. This results in the same received channel gain $p_i^*\gamma_i + p_k^*\gamma_k$ as the allocation A: $p_i\gamma_i + p_k\gamma_k$. But as $\gamma_i < \gamma_k$ the total ERP is lower. ■

Figure 2 illustrates how shifting ERP to a BS with higher instantaneous channel gain reduces total ERP, but still reaches the same threshold of channel quality. Note that this is different from waterfilling power allocation [3], which maximizes ergodic capacity instead of minimizing ERP.

An implication from the optimality of the on-off allocation is the following: In a set of cooperating BSs with instantaneous power control, all BSs that transmit will transmit at full power, with the single exception of the BS with the lowest instantaneous channel gain. Hence, adapting the ERP will only make a difference at one BS, namely the BS that is actively transmitting and has the lowest instantaneous channel gain.

The on-off allocation describes how radiated power is distributed optimally. It is not only unique (when all channel gains are different), but also easy to calculate by assigning as much power to the BS with the highest instantaneous channel gain as possible and assigning left over power to the next-best BS in the same way. Note that while this results seems trivial it only holds for instantaneous channel gains, but not for average channel gains (see Section V).

The average ERP when selecting 1 out of n BSs with power control is:

$$\mathrm{R_{D,p}}(n,1) = \sum_{\pi \in \mathrm{S}_n} \int_T^\infty f_{\pi(1)}(x_1) \frac{T}{x_1} q_\pi(n,2,x_1)\mathrm{d}x_1, \quad (10)$$

where the function q_π is from Section IV. For $c > 1$ BSs the following formula describes the average total ERP:

$$\mathrm{R_{D,p}}(n,c) = \mathrm{R_{D,p}}(n,c-1) + \sum_{\pi \in \mathrm{S}_n} u_\pi(n,c,1,T,T), \quad (11)$$

where the function u describes the ERP when c of n BSs are necessary and sufficient to not be in outage and instantaneous channel gains are in order π:

$$u_\pi(n,c,i,t,x) = \begin{cases} \int_{t/(c-i+1)}^{\min(t,x)} f_{\pi(i)}(x_i) u(n,c,i+1,t-x_i,x_i)\mathrm{d}x_i & \text{if } i < c, \\ \int_t^x f_{\pi(i)}(x_i)(c-1+t/x_i) q_\pi(n,c+1,x_i)\mathrm{d}x_i & \text{else,} \end{cases} \quad (12)$$

where t is the received power that the BSs i to c have to provide. The channel gain of BS i must be smaller than the channel gain of BS $i-1$, which is represented as parameter x. The formula includes the calculation of a minimum in the boundaries of the integral, which must be replaced with a case distinction to evaluate it. This makes evaluation more complex, but we were unable to find a solution without.

Bounds for $\mathrm{R_{D,p}}(n,c)$, which are easier to evaluate than the exact formula, can be expressed with the help of the on-off allocation:

$$(c-1)\,\mathrm{E_D}(n,c) \le \sum_{\pi \in \mathrm{S}_n} u_\pi(n,c,T,1,T) \le c\,\mathrm{E_D}(n,c). \quad (13)$$

The lower bound ignores the power radiated from the BS that is not transmitting at full power. The upper bound considers it to transmit at full power. Note that it is only necessary to replace the exact terms of u_π in Equation 11 by the boundaries when three or more BSs cooperate as the exact terms for one and two BSs are easy to evaluate.

VI. Probability for correct selection of BSs

In this section we determine the probability that static association does not select the optimal BSs for cooperation (as determined by dynamic association). This describes a necessary condition to make a difference between static and dynamic association. The result will provide an intuition when dynamic association has the greatest benefit over static association. We

When the order of the average and the instantaneous channel gains of all BSs is the same, both will select the same BSs. More precisely, if and only if the c BSs with highest *average* channel gains also are the c BSs with the highest *instantaneous* channel gains, both schemes will pick the same BSs.

The probability that static association selects the best BSs is:

$$\mathrm{P}(\text{Correct selection}) = \mathrm{P}\left(\bigwedge_{c<j\le n}\left(\min_{1\le i\le c}\gamma_i\right) \ge \gamma_j\right)$$
$$= \int_0^\infty f_\Sigma(y) \prod_{j=c+1}^{n} \int_0^y f_j(x)\mathrm{d}x\mathrm{d}y, \tag{14}$$

where $f_\Sigma(y)$ is the probability density function of $\min_{1\le i\le c}\gamma_i$, which is exponentially distributed with a mean of $\Gamma_\Sigma = 1/\left(\sum_{i=1}^{c}\frac{1}{\Gamma_i}\right)$.

While dynamic association will always select the best BSs it will not guarantee a successful transmission, but when static and dynamic association select the same BSs their outage state will be the same. When they select different BSs there are two possibilities: (1) when the dynamic association is in outage, the static association must also be in outage, as it cannot select better channels and (2) when the dynamic association is not in outage, the static association may or may not be in outage, depending on the selection of BSs. Hence, when the static association selects non-optimal BSs it does not mean that it performs worse than the dynamic association, but it is a necessary condition to do so. We present an evaluation that quantifies which effects a wrong selection of BSs has on the outage probability and the radiated power in the next section.

For the special case of the exponential distribution this result has an intuitive interpretation: The probability that one exponentially distributed random variable X is smaller than another Y is $\mathrm{P}(X < Y) = \frac{\lambda_X}{\lambda_X+\lambda_Y}$ [17]. Hence, the probability that the order of two channel gains is different for the average and instantaneous values is smaller when their expected values are further apart.

We conclude that the gain from using instantaneous knowledge to associate UEs to BSs is greatest when the average channel gains are similar. Or described alternatively: using instantaneous knowledge for association is unnecessary when the average channel gains are very different.

VII. Evaluations

In this section, we discuss examples of the results of the previous section. Here, we assume the instantaneous conditions of the channel to be described by Rayleigh fading. Hence, the instantaneous channel gains are exponentially distributed [3]. The results shown in this section are analytical results derived with the help of the computer algebra system Maxima 5.27.0 (and not results of simulations).

Next, we illustrate that the benefit of dynamic association is greater the more similar the average channel gains are. Dynamic association will always select the BSs with the highest instantaneous channel gain to cooperate and, hence, will always use the best BSs. On the other hand, static association selects the BSs based on average channel knowledge

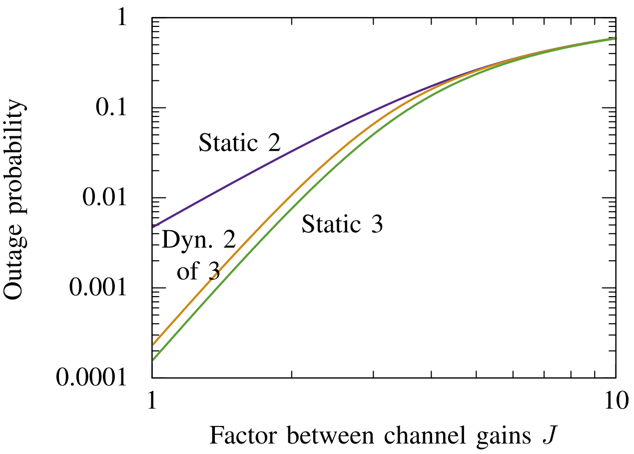

Fig. 3. The outage probability of different cooperation schemes for different factors between individual average channel gains. The average channel gain of BS i is $10T/J^i$.

and, hence, can make (for a concrete situation) non-optimal selections of BSs.

Figure 3 illustrates this effect. Additionally, it shows that dynamically selecting 2 out of 3 BSs is nearly as good as always using 3 BSs in terms of outage probability. Figure 3 shows it is important to determine which factors between successive BS channels are encountered in a radio access network. Next we will analytically determine this factor for a small example of cell edge users.

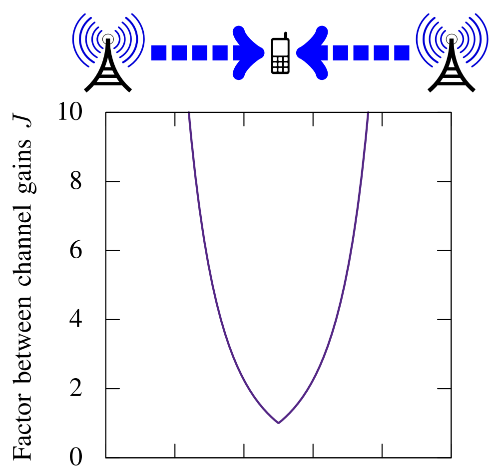

Fig. 4. The factor between channel gains is lowest (best for cooperation) when the distance to BSs is the same. Shown here for a path-loss exponent $\alpha = 2$.

In radio access networks the users with the worst data rates are on the edge cell. That is, they are close to the border between two cells and thus approximately equally far from two BSs. Therefore, the UEs which have the worst data rate benefit the most from cooperation because they usually have several BSs with similar average channel gain in range. The factor between channel gains for different locations is illustrated in

Figure 4.

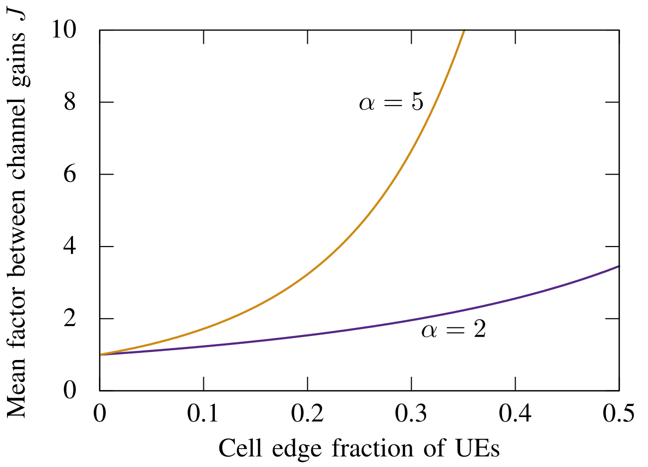

Fig. 5. The average factor between channel gains for UEs at the cell edge is close to 1. When the fraction of UEs considered as belonging to the edge increases the factor between channel gains J increases.

To get an understanding of the relevant sizes of the factor between the average channel gains J consider UEs on a line between two BSs. Figure 5 shows J depending on the fraction of UEs considered to belong to the cell edge. For example, when 30% of the area is considered to be part of the cell edge and the path-loss exponent α is 2, the average factor between channel gains for users belonging to the cell edge is about 2. It shows that even for relatively large fractions of considered locations of UEs the average factor between channel gains is low. It also shows that for higher path-loss exponents α, the factor J is higher for the same fraction of the edge UEs.

Figure 6 summarizes both ERP and outage probability for a scenario with 10 BSs in the range of the UE. The static association with power adaption achieves the lowest ERP as it only transmits when the channel is not in outage; but as its outage probability is about 63% in case $c = 1$ it does not transmit most of the time. The static association with power adaption and the dynamic association become more similar the higher the allowed number of cooperating BSs gets and becomes the same at $c = 10$ as both select all 10 BSs to cooperate and determine the necessary ERP using the on-off allocation.

We conclude that both the use of instantaneous channel knowledge to select the cooperating BSs and power control provide a large reduction in ERP. Additionally combining both reduces the ERP even further. Figure 6 also shows that a higher number of cooperating BSs does not radiate much more power than non-cooperative transmission when instantaneous channel knowledge can be used to control the ERP. Therefore it is important for an association strategy to be both flexible and able to quickly change associations and radiated power.

VIII. Conclusion

We provided the means to calculate the outage probability and effective radiated power (ERP) for cooperative schemes

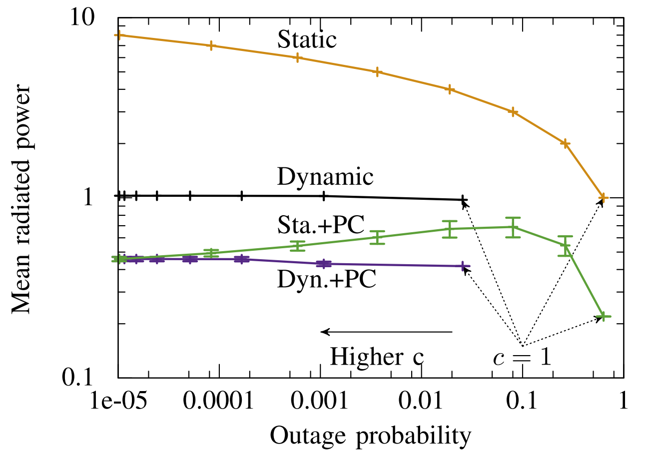

Fig. 6. The different schemes for static and dynamic association. In this scenario 10 BSs are available, which all have an average channel gain of $1T$. The intervals mark upper and lower bounds. The lines connect the different cooperative degrees of the same scheme: static and dynamic association with and without power control (PC). The cooperative degree starts at $c = 1$ on the right and increases to the left by 1 for each drawn point.

with and without instantaneous channel knowledge. The results allow us to quantify how much can be gained by providing cooperative base stations (BSs) with instantaneous channel knowledge. The formulas we provide can be used to quantify the different trade-offs between ERP, outage probability, and number of cooperating BSs.

The on-off allocation and the evaluations show that using instantaneous channel knowledge to select the cooperating BSs is similar to using it for power control as it only makes a difference at one BS. We also showed that instantaneous channel knowledge provides the greatest gain when the average channel gains of possibly cooperating BSs are the same.

Possible future work includes extending the two extreme cases (average channel knowledge and instantaneous channel knowledge) to a continuum of cases, that is, quantifying the effect of non-perfect and delayed channel knowledge. Also it is important to analyze real radio access networks to determine which factors between successive channels gains occur in reality. More over it is necessary to determine the costs for measuring the channel state and changing the set of cooperating BSs. Additionally the effects on energy efficiency of both radio access networks and user equipment can be analyzed.

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