The Impact of Combined Physical Layer Cooperation and Scheduling for the Downlink of LTE-Advanced Networks

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***Abstract*— In this paper, five different locally restricted cooperation schemes for the downlink of 4G systems are compared. Interference among different sectors is mitigated and the downlink capacity is increased. The focus of our research is to investigate the potential of combined physical layer cooperation and scheduling by considering user-outage within the coordinated multipoint (CoMP) schemes to accomplish further power reduction of the eNodeBs, while maintaining a target data rate. Two methods to identify and discard users requiring large powers are proposed. One is based on a simple peak power constraint, whereas the second approach assumes a channel-aware scheduler which is able to defer data packets. Both outage criteria are implemented for all cooperation schemes and compared with each other. The power reduction achieved is determined by means of the CDF of the peak powers per sector for all considered cooperation schemes.**

I. Introduction

Affordability and easy access to mobile devices with third-generation (3G) radio modules such as notebooks, tablet computers, and smart phones have led to a notorious increase of mobile data traffic. 3G networks have so far been able to support the traffic growth. However, the ITU requirements for IMT-Advanced establish that 4G networks have to support rates of up to 100 Mbit/s for high mobility such as mobile access, and up to 1 Gbit/s for low mobility such as local access [1]. For LTE-Advanced even data rates up to 3 Gbit/s are discussed [2]. This implies that new development concepts and more efficient wireless technologies are going to be needed. Cell sizes will decrease at higher carrier frequencies and, even though higher bandwidths are contemplated for LTE-Advanced, transmission power will be limited due to regulatory restrictions. Data rates at cell edges are also limited using locally independent transmission schemes and the actual existing sites. It is already becoming more complicated for the operators, to find new sites to locate base stations.

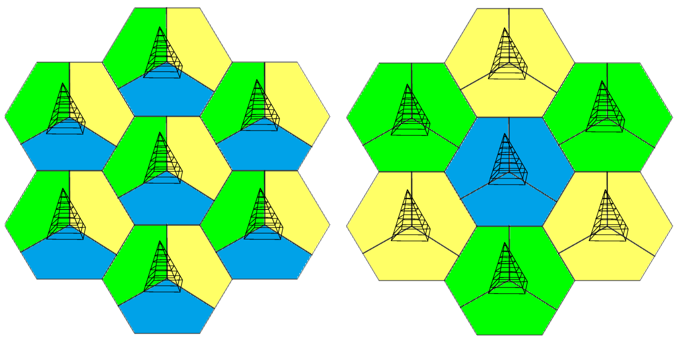
In [3], [4], [5] it has been shown that coordinated multipoint or cooperative multiple-input multiple-output (MIMO) techniques in the downlink of 4G networks are able to improve cell edge user data rates and spectral efficiency. These schemes exploit (or mitigate) interference among different sites or sectors. Cooperation can be given between different eNodeBs, between mobile user equipments, or between several sectors of one eNodeB to achieve a higher spectral density.

Although coordinated multipoint (CoMP) transmission and reception has been standardized for LTE-Advanced [2], in real networks the number of cells is too high to consider all eNodeBs in one cooperation scheme. To deal with the increased synchronization requirements, higher complexity, more channel estimation effort and delay specifications, cooperation in [6] and [7] has been limited to a subset of eNodeBs, while the other eNodeBs are to be considered as interference. In this paper, we aim to minimize the transmission power among different CoMP schemes by considering scheduling aspects. We distinguish between two different methods of scheduling which have been implemented for the five locally restricted cooperation schemes proposed in [7]. Furthermore, a minimum target data rate is kept while the transmission power of the schemes is reduced.

II. System Model and Cooperation Schemes

The setup of the non-cooperative reference scenario consists of hexagonal shaped cells regularly distributed throughout the entire area. The eNodeBs are located in the centre of the cells and have a distance of 700m. The base antenna transmissions are not coordinated. Frequency reuse factor of 3 is used to separate the different sectors of one cell by different carrier frequencies and avoid co-channel interference (see Fig. 1(a)). The eNodeBs are equipped with sectorized 120 degree directional antennas, and each eNodeB has 4 antennas per sector.

The scenario is then modified according to the characteristics

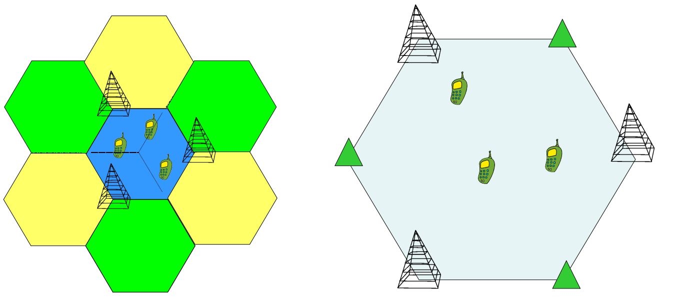


(a) Reference scenario (b) Sector cooperation

Fig. 1. Cell setup for different scenarios.

of each cooperation scheme. The schemes described in [7] include:

- *Sector Cooperation* where cooperation is given between different sectors of one eNodeB, allowing several UEs to be served by one eNodeB using multi-user MIMO broadcast techniques. All sectors of one eNodeB use the same frequency band, neighboring eNodeBs use different frequencies (see Fig. 1(b)).
- *Cell Cooperation* where the cooperation area is formed by $M = 3$ adjacent sectors of three eNodeBs. The antenna orientation of each eNodeB is rotated by 30 degree in reference to sector cooperation, changing the frequency allocation and making all three sectors of the adjacent eNodeBs share one frequency (see Fig. 2(a)).
- *Low-power Nodes* where the cell cooperation scheme is enhanced by adding $L = 3$ low-power nodes at the remaining edges of the cooperation area as shown in Fig. 2(b). These extra nodes will be assumed to have only two directional antennas and a limited transmission power of 6W.



(a) Cell cooperation

(b) Placement of additional nodes (green triangles)

Fig. 2. Cell cooperation and placement of additional low-power nodes.

We distinguish three different types of low-power nodes. These are:

- *Supporting Nodes* which can be seen as a distributed antenna system and include backhaul links with unlimited capacity,
- *Femto Cells* where no backhaul is available and data to be transmitted will be first sent by eNodeBs to the low-power nodes and in a second step the received and decoded data will be forwarded by the low-power nodes to the particular UE using a secondary frequency, and
- *Relay Nodes* which is similar to femto cells, however, the same frequency band as for the eNodeB-to-relay link is used for the link between relay and UE (inband relaying).

For a detailed description of these schemes see [7].

III. Cooperation Algorithm

A MIMO coherent cooperative cellular network is assumed, where the received signal and therefore the performance is corrupted not only by thermal noise, but also by co-channel interference. The system design for the coherent cooperation scheme of supporting nodes is described as M cooperating eNodeBs, each equipped with N_B antennas, and L supporting nodes, each using N_S antennas. $K = M$ user devices are assumed to be present in the cooperation area per resource block. The downlink signal received at user device k, with N_U antennas, is defined as

$$\mathbf{y}_k = \sum_{b=1}^{M} \mathbf{H}_{k,b}^{(\mathrm{B})} \cdot \mathbf{x}_b^{(\mathrm{B})} + \sum_{\ell=1}^{L} \mathbf{H}_{k,\ell}^{(\mathrm{S})} \cdot \mathbf{x}_\ell^{(\mathrm{S})} + \mathbf{n}_k, \tag{1}$$

where $\mathbf{H}_{k,b}^{(\mathrm{B})} \in \mathbb{C}^{N_U \times N_B}$ describes the block-fading MIMO channel between k-th user device and the b-th eNodeB ($b = 1, \ldots, M$), and $\mathbf{H}_{k,\ell}^{(\mathrm{S})} \in \mathbb{C}^{N_U \times N_S}$ defines in a similar way, the block-fading MIMO channel between k-th user device and the ℓ-th low-power node within the cooperation set. The vectors $\mathbf{x}_b^{(\mathrm{B})} \in \mathbb{C}^{N_B}$ and $\mathbf{x}_\ell^{(\mathrm{S})} \in \mathbb{C}^{N_S}$ are the transmitted signals from the M eNodeBs and the L supporting nodes of the cooperating M eNodeBs. The interference caused by the transmission nodes outside the cooperation set, and also the thermal noise induced at the receiver, are included in the term $\mathbf{n}_k$.
According to [7], the interference terms within the cooperation set are eliminated by decomposing the precoding matrices of the base stations into the product

$$\mathbf{G}_{k,b}^{(\mathrm{B})} = \mathbf{Z}_{k,b}^{(\mathrm{B})} \cdot \mathbf{Q}_{k,b}^{(\mathrm{B})} \tag{2}$$

where $\mathbf{Z}_{k,b}^{(\mathrm{B})} \in \mathbb{C}^{N_B \times N_D}$ is a block zero-forcing matrix and the power allocation for the different signal streams intended for the different UEs takes place on $\mathbf{Q}_{k,b}^{(\mathrm{B})} \in \mathbb{C}^{N_D \times N_D}$. The block zero-forcing matrices are chosen so that $\mathbf{H}_{i,b}^{(\mathrm{B})} \cdot \mathbf{Z}_{j,b}^{(\mathrm{B})} = \mathbf{0}$, $\forall i \neq j$ and $\mathbf{Z}_{j,b}^{(\mathrm{B})H} \cdot \mathbf{Z}_{j,b}^{(\mathrm{B})} = \mathbf{I}$. The precoding matrices of the supporting nodes are decomposed similarly. In order to fulfill these requirements, the block zero-forcing matrices $\mathbf{Z}_{k,b}^{(\mathrm{B})}$ and $\mathbf{Z}_{k,\ell}^{(\mathrm{S})}$ can be chosen as components of the $N_D = M \cdot N_B + L \cdot N_S - (K-1) \cdot N_U$ orthonormal basis vectors of the null space of $\left[\tilde{\mathbf{H}}_1^T, \ldots, \tilde{\mathbf{H}}_{k-1}^T, \tilde{\mathbf{H}}_{k+1}^T, \ldots, \tilde{\mathbf{H}}_K^T\right]^T$, where $\tilde{\mathbf{H}}_k = \left[\mathbf{H}_{k,1}^{(\mathrm{B})}, \mathbf{H}_{k,2}^{(\mathrm{B})}, \ldots, \mathbf{H}_{k,M}^{(\mathrm{B})}, \mathbf{H}_{k,1}^{(\mathrm{S})}, \ldots, \mathbf{H}_{k,L}^{(\mathrm{S})}\right]$ is the channel matrix from *all* transmitting nodes within the cooperation set to UE k. Hence, the I-O relation (1) can then be rewritten as

$$\begin{aligned}\mathbf{y}_k = &\sum_{b=1}^{M} \mathbf{H}_{k,b}^{(\mathrm{B})} \cdot \mathbf{Z}_{k,b}^{(\mathrm{B})} \cdot \mathbf{Q}_{k,b}^{(\mathrm{B})} \cdot \mathbf{s}_k \\ &+ \sum_{\ell=1}^{L} \mathbf{H}_{k,\ell}^{(\mathrm{S})} \cdot \mathbf{Z}_{k,\ell}^{(\mathrm{S})} \cdot \mathbf{Q}_{k,\ell}^{(\mathrm{S})} \cdot \mathbf{s}_k + \mathbf{n}_k.\end{aligned} \tag{3}$$

The main point of the optimization algorithm is to calculate the matrices $\mathbf{Q}_{k,b}$ allowing for the per-node constraints

$$\begin{aligned}&\mathrm{Tr}\left\{\mathbf{x}_b^{(\mathrm{B})} \cdot \mathbf{x}_b^{(\mathrm{B})H}\right\} = \\ &\mathrm{Tr}\left\{\sum_{j=1}^{K} \mathbf{Z}_{j,b}^{(\mathrm{B})} \cdot \mathbf{Q}_{j,b}^{(\mathrm{B})} \cdot \mathbf{Q}_{j,b}^{(\mathrm{B})H} \cdot \mathbf{Z}_{j,b}^{(\mathrm{B})H}\right\} \leq P_B,\end{aligned} \tag{4}$$

and

$$\mathrm{Tr}\left\{\mathbf{x}_\ell^{(\mathrm{S})}\cdot\mathbf{x}_\ell^{(\mathrm{S})H}\right\}= \mathrm{Tr}\left\{\sum_{j=1}^{K}\mathbf{Z}_{j,\ell}^{(\mathrm{S})}\cdot\mathbf{Q}_{j,\ell}^{(\mathrm{S})}\cdot\mathbf{Q}_{j,\ell}^{(\mathrm{S})H}\cdot\mathbf{Z}_{j,\ell}^{(\mathrm{S})H}\right\}\le P_S, \tag{5}$$

to be satisfied for $\forall b\in\{1,\dots,M\}$ and $\forall\ell\in\{1,\dots,L\}$. Fairness between the users is accomplished by defining a minimum target rate that all users within the cooperation set will have to achieve. Including the zero-forcing approach, the achievable data rate is defined as

$$R_k=\log\det\left\{\mathbf{K}_s^{(k)}+\mathbf{K}_i^{(k)}+\mathbf{K}_n^{(k)}\right\} - \log\det\left\{\mathbf{K}_i^{(k)}+\mathbf{K}_n^{(k)}\right\} \tag{6}$$

where $\mathbf{K}_s^{(k)}$, $\mathbf{K}_i^{(k)}$, and $\mathbf{K}_n^{(k)}$ are the covariance matrices of the signal, the interference, and the noise with respect to user k. Note that the out-of-cooperation interference is considered in $\mathbf{K}_n^{(k)}$ and $\mathbf{K}_i^{(k)}=0$ due to the zero-forcing approach.

IV. Scheduler

The optimization algorithm proposed in [7] minimizes the transmission power of the eNodeBs. However, there is no upper limit on Tx power as can be seen from the cumulative distribution functions (CDF) in Fig. 3. In real systems, the peak transmission power has to respect regulatory limits. This results in users which cannot achieve our target data rate and hence are in outage. We assume the Tx power to be limited to 80W (49 dBm). As can be seen from Fig. 3 in case of no cooperation, this power is not sufficient in 55% of all simulation runs to supply all scheduled users with a data rate of at least 1 bit/s/Hz.

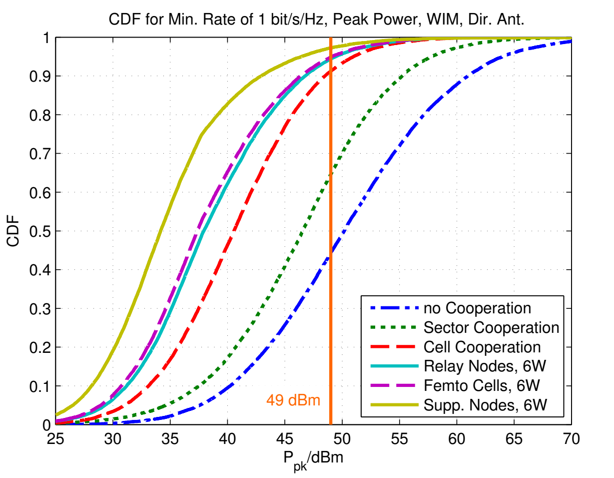


Fig. 3. CDF of peak power for all considered cooperation schemes to achieve min. rate of 1 bit/s/Hz. Setup and parameters of the simulations are described in Section V.

A. Scheduler with Simple Power Constraint

A simple criterion is that users are randomly picked from a set of users and scheduled at one point of time. The precoding matrices $\mathbf{G}_{k,b}^{(\mathrm{B})}$ and $\mathbf{G}_{k,\ell}^{(\mathrm{S})}$ are determined and the transmission powers P_B^* and P_S^* required to achieve the minimum data rate are calculated. If the calculated transmission power is higher than the pre-defined power constraint, users do not achieve the target data rate and hence are dropped by the scheduler which means they are in outage. Hence, if by leaving one user out of service, the transmission power is still higher than the predefined power constraint, a second user of the set can also be dropped. Finally, if it is not possible to serve the remaining user maintaining the transmission power lower than the constraint, the third users will be excluded and therefore no user within the set can be served. For the simulation of this method, the power constraint chosen is 80W (or 49 dBm).

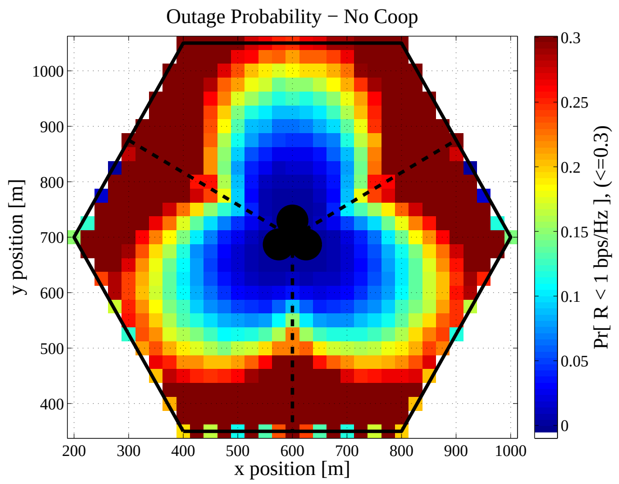
The outage probability for the peak power constraint is shown in Fig. 4(a) for the reference scenario and in Fig. 4(b) for cell cooperation over the cell. It is defined as the probability that the outage rate of 1 bit/s/Hz is not supported by the given random channel realizations. In case of the reference scenario, only next to the eNodeB outage probabilities are below 10%. At the cell border, the supported rates are significantly lower than the target of 1 bit/s/Hz. The cooperation of three cells, i.e. the cooperation of three adjacent sectors of three neighboring cells, leads to a significant improvement. Over almost the whole cooperation area, the outage probability is below 5%. Only at the edge of the cooperation area, exactly at three small areas, where the borderlines of the sectors meet the edge of the cooperation area, there is an outage probability between about 10% and 15%.

B. Channel-Aware Scheduler

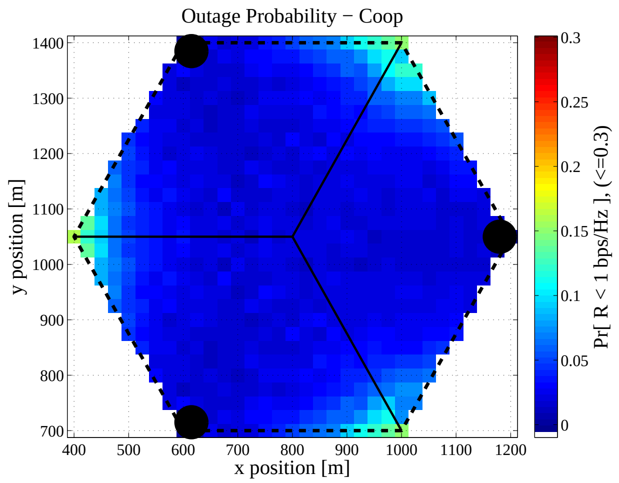
Cooperation schemes are able to reduce the outage probability as can be seen from Fig. 3. However, even when adding low power nodes to the network outage cannot be completely prevented. Therefore a countermeasure to reduce outage is to consider scheduling in our optimization. The scheduler could be changed in a way, that unfavorable combinations of users scheduled in the same timeslot (or resources in general) will be avoided. To implement this, the scheduler needs full channel knowledge. As channel state information at the transmitter (CSIT) is available at the eNodeBs to allow CoMP, transmit cooperation can be combined with scheduling in the same entity to further reduce transmit power. Furthermore it must be possible to swap timeslots without jeopardizing QoS constraints. With these assumptions, the scheduler can calculate best combinations (which means lowest peak power) how to distribute $N\cdot K$ users over N timeslots (resources) in case we have K users per timeslot (resource). This results in

$$\frac{(N\cdot K)!}{(K!)^N\cdot N!} \tag{7}$$

different combinations how to divide the users over the timeslots (resources). So we could assume that a scheduler percent and only one user in O_1 percent of all simulation runs.



(a) Reference scenario



(b) Cell cooperation

Fig. 4. Outage Probability for an outage rate of 1 bit/s/Hz in case of reference scenario and cell cooperation. Setup and simulation parameters are described in Section V.

will be able to help reducing the peak power by aggregating users properly. The resulting peak power for all combinations could be calculated based on estimated out-of-cooperation interference. However, considering all possible permutations results in a high computational complexity, especially for large values of N.

C. Simplified Channel-Aware Scheduler

The design of the scheduler will be simplified in case we assume that our system is not fully loaded. This means, scheduling only one or two users per resource block will be possible for a certain number of timeslots without loss. The task of the scheduler, however, is to find the combinations which achieve the largest peak power reduction in one timeslot. The potential of this kind of peak power reduction is investigated in this paper by means of simulations. Therefore we assume it is sufficient to schedule only two users in O_2 percent and only one user in O_1 percent of all simulation runs.

V. Numerical Results

The simulated cellular network consists of 12 cells (36 sectors), with a cooperation set of $M = 3$ sectors. In our computer simulations, we consider one subcarrier (frequency-flat fading) that is modeled by Rayleigh-fading with a distance dependent pathloss and shadowing that corresponds to scenario C2 Urban NLOS environment in the WINNER II channel model [8]. One user per sector is scheduled at one point of time. The total number of simulations per scheme simulated is 2000. It is assumed that the low-power nodes are located 5m above ground. The eNodeBs located in the adjacent cells are considered to transmit with a Tx power of 80W and the power of the low-power nodes is limited to 6W. The minimum target data rate of 1 bit/s/Hz has to be achieved by all users within the cooperation set. The simulation parameters are given in Table I.

TABLE I
Parameters of our Computer Simulations.

Parameter	Value
Channel model	Simplified WINNER C2 Urban NLOS
Distance of eNodeBs	700m
Number of simulated cells	12
Carrier frequency	2.6 GHz
Frequency reuse	3
Antennas at eNodeB	4
Antenna height eNodeB	20m
Antenna gain eNodeB	17dBi
Antennas at UE	2
Antenna height UE	1.5m
Antenna gain UE	0dBi
Noise power at UE	-85 dBm

For the investigation of the scheduler with simple power constraint, the power limit chosen is 49 dBm, which is also the maximum transmission power assumed for the eNodeBs outside the cooperation set. In case the calculated power is higher than this peak value, the combination with two users resulting in the lowest power is chosen. However, there are cases, where it is not sufficient to exclude one user. In this case only one user (resulting in lowest Tx power) is selected. Hence, in a certain number of simulation runs one or two users have to be dropped to meet both the target data rate and the power limitation constraints. However, with this approach it is assured, that 100% of the simulations of all schemes achieve a minimum target rate of 1 bit/s/Hz using a Tx power of 49 dBm. The outage per cooperation scheme needed is described in Table II. The outage probability of the cooperative schemes is significantly lower than the outage of the reference scenario (55%). As can be seen, in case of sector cooperation there are also cases where even scheduling only one user would exceed the maximum transmission power. For the simplified channel-aware scheduler method we define $O_1 = 5\%$ and $O_2 = 10\%$. This means in 5% of the cases the cooperation set consists only of 1 user and in 10% it consists of 2 users. First, each user's rate and each transmission power per sector are computed assuming that all users in the cooperation area

TABLE II

OUTAGE NEEDED TO ACHIEVE A MAXIMUM TRANSMISSION POWER OF 80W (49 DBM).

Scheme	1 user in outage	2 users in outage	3 users in outage
Sector Coop.	31.4%	3.25%	0.05%
Cell Coop.	8.65%	0.25%	0%
Supp. Nodes	2.45%	0.05%	0%
Femto Cells	4.75%	0.10%	0%
Relay Nodes	5.35%	0.10%	0%

are served. A search for the cooperation set that requires the highest transmission power is done. When found, the optimization algorithm is applied for all possible user-combinations dismissing one and two users of the set (new block zero-forcing matrices need to be chosen due to the fact that the null space changes to $N_D = M \cdot N_B + L \cdot N_S - (K-2) \cdot N_U$ or $N_D = M \cdot N_B + L \cdot N_S - (K-3) \cdot N_U$, respectively). Therefore, "new" radiated powers and user's rates are re-calculated. All possible results are compared and considered for given values of O_1 and O_2. The graphs in Fig. 5 show the distribution of the maximum transmission power from the three sectors, i.e $\max\{P^*_{B,\text{ Sector 1}}, P^*_{B,\text{ Sector 2}}, P^*_{B,\text{ Sector 3}}\}$. It can be pointed out that when a fraction of the users can be dropped, a higher percentage of the simulations achieve the target rate of 1 bit/s/Hz with lower transmission powers compared to the scheduler with simple power constraint (cf. Fig. 3). In all schemes except sector cooperation, 100% of our simulations achieve the target rate using a transmission power of less than 49 dBm (between 40 and 47 dBm). This means a significant reduction of the peak transmission power is observed.

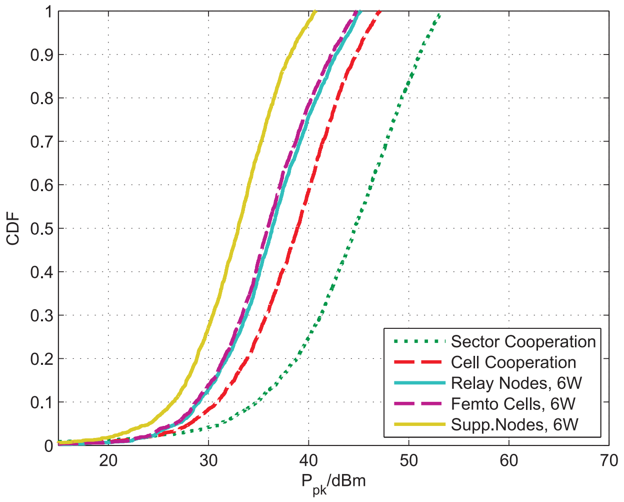


Fig. 5. CDF of peak power for all considered schemes with $O_1 = 5\%$ and $O_2 = 10\%$.

VI. SUMMARY AND CONCLUSIONS

The focus of this investigation has been on the reduction of transmission power within different cooperation schemes for the downlink of 4G networks by considering combined physical layer cooperation and scheduling. Using a scheduler which is able to effectively identify and delay transmission to users which suffer from bad channel conditions, it is possible to achieve a significant decrease in peak transmission powers. The results of our simulations show that among all five CoMP schemes, the sector cooperation scheme needs the highest transmission powers to achieve the same target data rate as the other schemes. This was expected due to the non-optimal antenna radiation pattern which partially separates large parts of the cooperation area. It can also be observed, that the performance of the relay nodes and femto cells schemes is very similar whereas the supporting nodes scheme is performing best. However, outage cannot be avoided completely. As it can be seen from the simulation results, outage-aware scheduling leads to a significant reduction of the maximum peak powers of every cooperation scheme. Higher transmission powers are cancelled out and hence protecting a mobile communication network from excessive transmission power values, while maintaining a minimum data rate for the users that will be served.

We can therefore conclude that using a channel-aware scheduler approach, which is able to defer transmissions to users and to concentrate the service of the network on the users with good channel conditions, the transmission power can be significantly decreased. Thus, interference between adjacent cells will be minimized, resulting in further reduction of transmission power. We also investigated the outage constraints for the scheduling algorithm when implementing a simple peak-power limit. This assures that a certain peak Tx power will not be exceeded, and only the users that lay under this power limitation will be served.

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