A performance analysis of power control for cellular systems with femtocells using fixed-switched beams

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***Abstract*— The utilization of femtocells integrated into cellular networks constitutes a way of increasing the capacity of the system creating the benefits of higher quality links, by getting the transmitter closer to the receiver, along with the benefits of an improved resource usage, by reusing them between macro- and femtocells. However, macro- and femtocells operating on the same frequency band build an obviously more challenging scenario due to the resulting mutual interference between them. In order to combat interference, antenna arrays to steer narrow beams towards the users of interest and distributed power control algorithms can be applied. In this work, the performance of distributed and soft drop power control algorithms into a two-tier cellular system composed of macro- and femtocells using fixed-switched beams is investigated. The obtained results show that the use of power control can provide considerable gains in terms of power economy and system capacity especially for the low-power femtocells.**

***Keywords*— Power control, fixed-switched beams, femtocells.**

I. Introduction

The utilization of femtocells, which are data access points installed by home users, integrated into cellular networks constitutes a way of increasing the capacity of the system creating the benefits of higher quality links, by getting the transmitter closer to the receiver, along with the benefits of an improved resource usage, by reusing them between macro- and femtocells [1].

Thus, heterogeneous networks consisting of macro- and femtocells represent a promising alternative for future wireless networks in which subscribers take the advantage of highly reliable individual connections to femtocells while the network profits of offloading traffic to the femtocells [1], [2].

However, macro- and femtocells operating on the same frequency band build an obviously more challenging scenario due to the resulting mutual interference between them [1], [2]. In order to combat co-channel interference, efficient radio resource management techniques, such as adaptive power control [3], [4], and multi-antenna techniques, such as the use of fixed or random switched beams [5], can be employed.

Indeed, the use of antenna arrays to direct narrow beams inside femtocells offer interference avoidance by restricting radio interference within a small angular range [6], which has been shown to achieve considerable improvement in terms of spectral efficiency [7], [8]. Similarly, the authors in [9] and [10] demonstrate that power control can be used to provide quality-of-service to both the macrocell and femtocell users.

In this work the performance aspects of distributed and soft drop power control algorithms into a two-tier cellular system composed of macro- and femtocells using fixed-switched beams are focused. The remainder of this paper is organized as follows: Section II presents the description of the system model, Section III discusses the results achieved by means the system-level simulations and, finally, Section IV draws the main conclusions of this work.

II. System modeling

We consider the downlink of a heterogeneous wireless network composed of one macrocell station, termed the Base Station (BS), and four femtocell stations, termed Femto Stations (FSs). The BS and the FS are disposed in a Manhattan-like grid as illustrated in Figure 1, where blue squares and red diamonds markers illustrate the positions of stations and User Equipments (UEs), respectively. For the BS and each FS, one single-antenna UE is randomly placed within their specified coverage area (illustrated by the dashed circles in Figure 1) according to a uniform distribution. The BS and the FSs are organized in a station set $\mathcal{S} = \{1, 2, \ldots, S\}$ and the UEs in user set $\mathcal{U} = \{1, 2, \ldots, U\}$. Moreover, the BS and the FS are assumed to be equipped with M-element antenna arrays. Despite of considering a small network, the model described here can be straightforwardly extended to a larger network.

The system employs Orthogonal Frequency Division Multiple Acesss (OFDMA) as part of its multiple access scheme and has a number of subcarriers organized in blocks of adjacent subcarriers which represent the system resources, which are considered to be organized in a Resource Block (RB) set $\mathcal{N} = \{1, 2, \ldots, N\}$. Dynamic resource allocation is assumed to work on a Transmission Time Interval (TTI) basis. In this work, we assume that resources are processed individually, thus leaving scheduling problems for future studies and allowing us to omit the resource index n in the following developments. The channel coherence bandwidth is assumed larger than the resource block bandwidth, so that we have flat fading on each resource. The complex channel coefficients $h_{i,j,m}$ between the transmit antenna m of the station $j \in \mathcal{S}$ and the receive antenna of the user equipment $i \in \mathcal{U}$ on a resource n are organized in the Downlink (DL) channel vector.

$$\mathbf{h}_{i,j} = \begin{bmatrix} h_{i,1} & h_{i,2} & \ldots & h_{i,M} \end{bmatrix} \in \mathbb{C}^{1\times M}, \quad (1)$$

where the index n is omitted for simplicity of notation.

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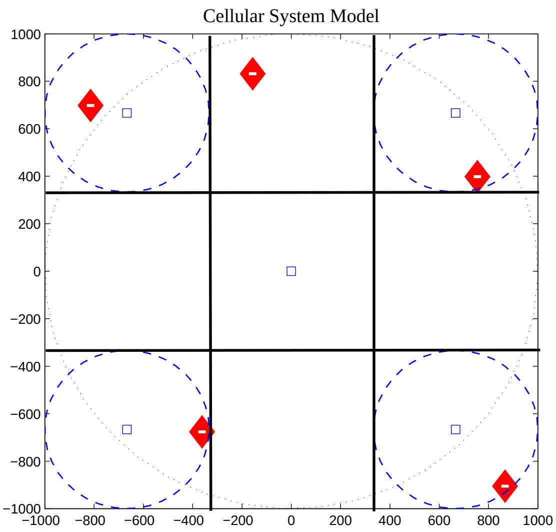


Fig. 1. Cellular system model.

For each resource n, each station can select a beam b out of a set $\mathcal{B}_j = \{1, 2, \ldots, B_j\}$ of beams steering towards predefined directions of interest, i.e., each station is equipped with a fixed-switched beam antenna array. The complex antenna weights $w_{j,b,m}$ used by station $j \in \mathcal{S}$ to steer beam $b \in \mathcal{B}_j$ on a given resource are organized in the beamforming vector

$$\mathbf{w}_{j,b} = \begin{bmatrix} w_{j,1} & w_{j,2} & \ldots & w_{j,M} \end{bmatrix} \in \mathbb{C}^{M \times 1}, \qquad (2)$$

which is assumed to have unitary norm.

The total transmit power of station j is divided among the resources with the transmit power allocated for use on resource n is denoted by $p_{j,n}$, or simply by p_j omitting the index n. The Signal-Interference plus Noise Ratio (SINR) γ perceived by the UE i for beam b of the station j on resource n is denoted by

$$\gamma_{i,j,b} = \frac{p_j \left|\mathbf{h}_{i,j}\mathbf{w}_{j,b}\right|^2}{\sigma^2 + \sum\limits_{k=1,k\neq j}^{S} p_k \left|\mathbf{h}_{i,k}\mathbf{w}_{k,b_k}\right|^2} \qquad (3)$$

where σ^2 denotes the average noise power on each resource and $\mathbf{w}_{k,b_k}$ is the beam used by the interfering station k.

A. Beam selection

For the communication from the BS and FSs to the UEs take place, each station sends reference signals using one of B_s fixed beams. The UE i associated with a given station j then estimates the Signal-to-Noise Ratio (SNR) $\varphi_{i,j,b}$ perceived for the beam b on resource n as

$$\varphi_{i,j,b} = \frac{p_j \left|\mathbf{h}_{i,j}\mathbf{w}_{j,b}\right|^2}{\sigma^2}, \qquad (4)$$

and reports it back to its serving station. We consider that this process is repeated by each station for each beam following a random beam order (as to average interference). After that, each station selects the beam $b \in \mathcal{B}_j$ with the best perceived SNR $\varphi_{i,j,b}$ for communicating with the UE i, i.e.,

$$b^{\star} = \arg\max_{b} \{\varphi_{i,j,b}\}, \qquad (5)$$

for each station. It is worth mentioning that, for the case with multiple UEs per cell, the same sort of measurements can be used straightforwardly to schedule the UE with the highest SNR on any beam.

B. Power control

The capacity of cellular mobile radio systems with macro- and femtocells can be increased by controlling their transmit powers so as reduce interference between them and balance the signal to interference ratios at the receivers to suitable levels [3], [11].

In this work, we study two power control schemes, namely the Distributed Power Control (DPC) [3] and the Soft Dropping Power Control (SDPC) [4].

The DPC guides the evolution of the power level of each base and femto station using only local measurements. Considering the DPC and starting from initial power level $p_i^{(0)}, i \in \mathcal{S}$, each station adapts its transmit power at discrete time steps t according to the dynamics [3]

$$p_i^{(t)} = p_i^{(t-1)} + \beta(\bar{\gamma} - \gamma^{(t-1)}), \qquad (6)$$

where $\bar{\gamma}$ is the target SINR value and $\gamma^{(t)}$ is the actual SINR at the time step t, which is computed according to (3), and β is a control parameter. Thus, if the achieved SINR $\gamma^{(t-1)}$ is lower than the target SINR $\bar{\gamma}$, the transmit power power $p^{(t)}$ will be increased, and vice-versa. If the target SINR value is attainable for each link, which depends on the channel condition, the dynamic of (6) will carry all the quality of all co-channel links to the fixed target SINR $\bar{\gamma}$.

However, it might be not possible for every link to attain its target SINR $\bar{\gamma}$. In this case, the power control is said to be unfeasible and one or more links will transmit at full power, even though attain unacceptable SINR levels [4]. In order to deal with such infeasibility problem, we analize SDPC in which the target SINR $\bar{\gamma}$ of each link i is variable and a decreasing function of the power demanded by the link [4]. The dynamic of the SDPC is expressed as

$$p_i^{(t)} = p_i^{(t-1)} + \beta(\bar{\gamma}^{(t)} - \gamma^{(t-1)}), \qquad (7)$$

where the target SINR $\bar{\gamma^{(t)}}$ is given by

$$\bar{\gamma}^{(t)} = \max\left\{\bar{\gamma}_m, \min\left\{\bar{\gamma}_M, \gamma_m \left(\frac{p^{(t-1)}}{p_M}\right)^{\rho}\right\}\right\}, \text{with} \quad \rho = \frac{\log_{10}(\gamma_M/\gamma_m)}{\log_{10}(p_m/p_M)} \qquad (8)$$

where $\bar{\gamma}_m$ and $\bar{\gamma}_M$ are respectively the minimum and maximum target SINR and p_m and p_M are respectively the minimum and maximum transmit power allowed for a station [4]. Notice that maximum target SINR values avoid wasting power since real modulation schemes reach near-zero error rates close for any SINR value higher than certain thresholds.

Thus, the SDPC decreases the target SINR of the links with critical propagation conditions and which demand more power while better links would improve their target SINR values which can be attained with less power. In this way, the target SINR values are automatically adjusted and the probability of configuring a feasible power control problem is increased.

Considering the exposed formulations, the resource allocation strategy applied in this work can be formulated as shown in the Algorithm 1.

Algorithm 1 Resource allocation strategy.

```
for all s ∈ S do
    for all b ∈ B do
        Estimate φ_{i,j,b}(t) according to (4).
        Select the optimal beam according to (5).
    end for
    for all t ∈ T do
        Apply power control either using the DPC, cf. (6),
        or the SDPC, cf. (7).
    end for
end for
```

Notice that this algorithm be applied on a resource-basis and periodically after a number of TTIs in order to schedule new UEs for reception. In this way, the signaling load associated with the beam selection can be reduced.

III. SIMULATION RESULTS

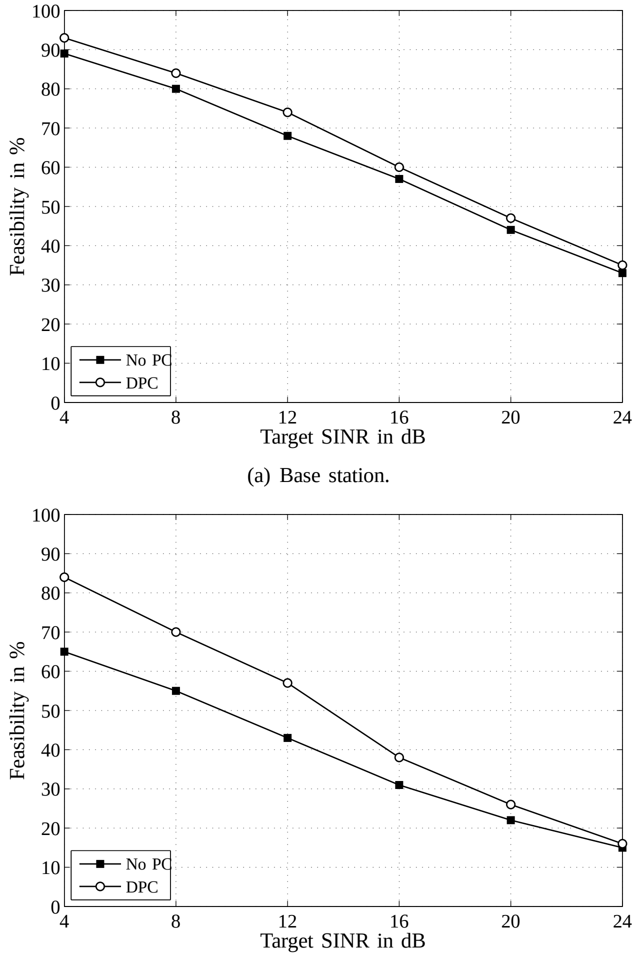
In this section, the impact of DPC and SDPC algorithms will be analyzed considering the setup presented in Section II, which employs fixed-beams antenna arrays at BS and FSs as to reduce interference. Several fixed target SINR values have been considered for the DPC algorithm and its performance has been compared with that of the SDPCs algorithm. Moreover, the case without power control is also considered for comparison purposes. At each of the five stations, a uniform linear array with $M = 4$ antennas separated by half wavelength is considered. As stated before, UEs have a single receive antenna each. Pedestrian mobility with an average UE speed of 3 km/h is considered. Moreover, for power control a dynamic range of 30 dB is considered between minimum and maximum transmission powers of the stations. Our analyses are based on a Monte Carlo simulation approach in which independent and identically distributed snapshots are simulated; at the end of each performance metrics are collected. The most relevant simulation parameters are listed in Table I.

Figure 2 presents the feasibility of the DPC algorithm as a function of the target SINR values. The feasibility corresponds to the percentage of cases in which the DPC algorithm is able to achieve the target SINR requirement and it is derived from the empirical Cumulative Distribution Function (CDF) of the SINR of our simulations. To avoid numerical problems, we relax the target SINR values by 1 dB. For example, for a target SINR values of 8 dB, SINR values of at least 7 dB are sufficient to consider the power control problem as feasible.

Based on the feasibility it is possible to get insight on the capacity of the DPC algorithm to attain a given Quality

TABELA I
SIMULATION PARAMETERS.

Parameter	Value	Unit
BS radius	1000	m
FS radius	333.3	m
Min. BS/FS - UE distance	35	m
System frequency	2	GHz
Number of subcarriers	512	-
Subcarrier bandwidth	15	kHz
Number of subcarriers/RB	12	-
Number of RB	1	-
Number of snapshots	300	
Snapshot duration	100	ms
TTI duration	1	ms
Path loss	$128.1 + 36.7 \log_{10}(d)$, d in km	-
Shadowing std. deviation	8	dB
Channel model	SCM urban micro [12], [13]	-
Noise power per RB	-112.4	dBm
Power control	None, DCP, SPDC	-
Target SINR for DPC	4, 8, 12, 16, 20, 24	dB
β parameter of DPC	0.9	-
SDPC SINR boundaries	4 to 24	dB
BS minimum power	13	dBm
BS maximum power	43	dBm
FS minimum power	24	dBm
FS maximum power	-6	dBm
Power allocation per RB	Equal power allocation	-

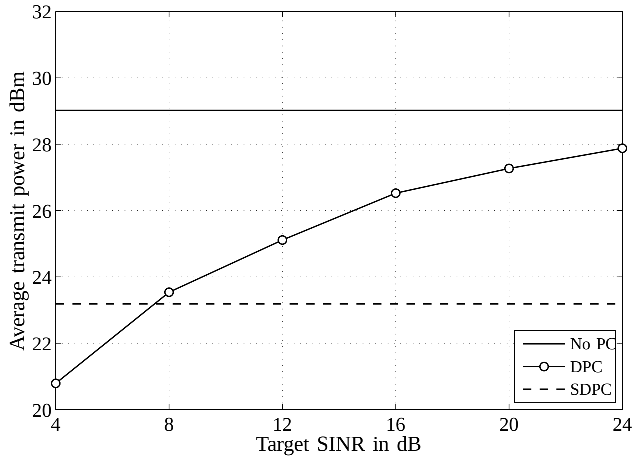


(a) Base station.

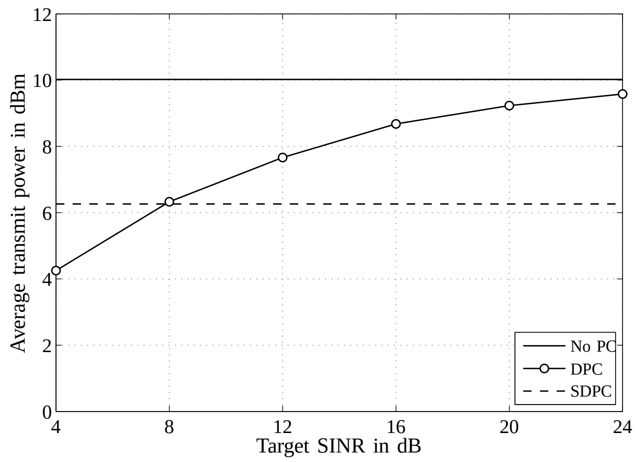
(b) Femto station.

Fig. 2. Power control problem feasibility.

of Service (QoS) requirement. For the case without power control, which is presented for comparisons, feasibility is derived in the same way. Figure 2(a) and Figure 2(b) show the feasibility for the DPC algorithm at the central BS and one FS compared to that cases without power control. Since the BS disposes of more power, the feasibility with and without power control are relatively similar in Figure 2(a). However, the DPC still achieves better results. For the FSs, which dispose of less power and are therefore more sensitive to interference, one can verify in Figure 2(b) that the DPC provides a considerable performance improvement for the system, making possible to attain higher QoS levels (target SINR) in many more situations (higher feasibility) compared to case without power control.



(a) Base station.



(b) Femto station.

Fig. 3. Average transmit powers of the stations.

As it can be seen in Figure 2, the more the target SINR raises, the more difficult attaining it becomes. As a consequence, the used transmit power levels tend to increase generating additional interference and compromising the efficiency of the system. Determining the ideal target SINR levels is a non-trivial problem, since it depends on channel state information that is usually not available at a central node. A variable target SINR, as used by the SDPC, allows to circumvent this problem and to lower the average transmit power levels considerably while keeping feasibility at relatively high values. Figure 3 presents average transmit power used by BS and FSs as a function of the SINR target for the cases without power control and using either the DPC or SDPC algorithm. Thus, one can compare the different usage of power made by the algorithms.

For lower target SINR values, the DPC presents lower average transmit powers than SDPC. This is explained by the fact that SDPC will allow itself to use more power than that necessary to attain a given (low) target SINR whenever channel conditions allow to exploit it and to achieve higher rates. The opposite is also true and lower target SINR might be aimed depending on the channel conditions. As a result, the average transmit power used by SDPC is lower than that of the DPC for most of the adopted target SINR values, as shown in Figure 3(a) and Figure 3(b) for the BS and for the FSs, respectively. In both cases, we can see that the use of power control reduces considerably the average transmit power compared to the cases without power control.

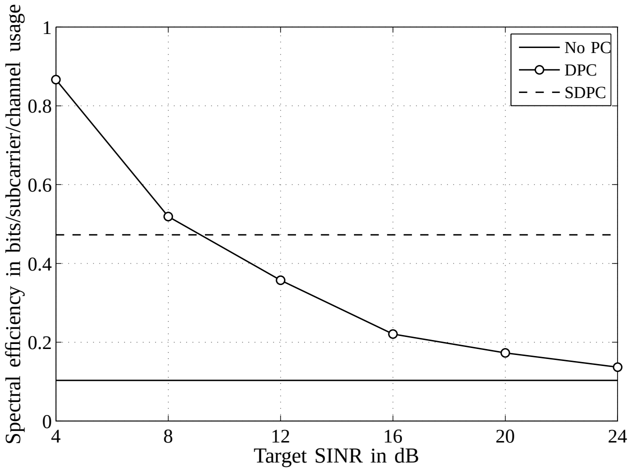
In fact, we have found in our experiments that only about 10% of the achieved SINR levels were below the minimum target SINR value of 4 dB for the BS while for the FSs, which are more sensitive to interference, this value was about 20%. For both BS and FSs, less that 1% of the SINR values with SDPC were above the maximum target SINR.

In order to illustrate the potential gains achievable by applying power control to our system with macro and femtocells equipped with fixed-switched beams, the 10^{th}, 50^{th} and 90^{th} percentiles of the capacity of the femtocells are presented in Figure 4. Because femtocells are assumed to dispose of less power and since similar capacity trends have been verified for both macro and femtocells, only the results of those last are presented.

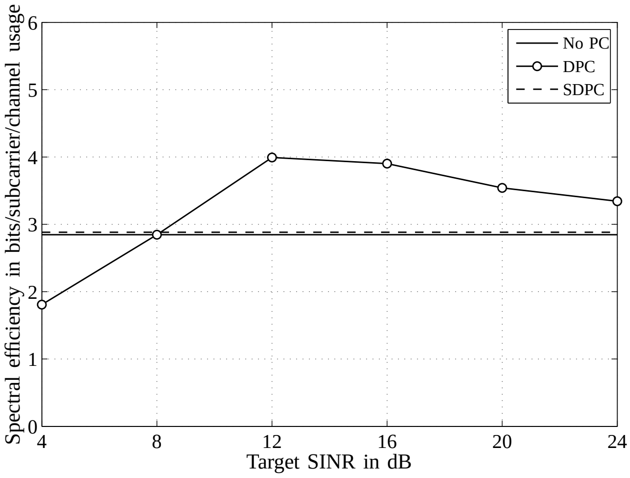
As it can be seen in Figure 4(a), if QoS is enforced the use of power control is able to increase considerably the capacity that can be achieved by 90% of the UEs. In this figure, we can observe that for low target SINR values, the DPC algorithm presents the highest capacity and which is many times larger than that of the case without power control. We can also observe that the SDPC can also considerably increase the capacity perceived by 90% of the UEs.

At the 50^{th} percentile of the capacity shown in Figure 4(b), we can see that the SDPC provides 50% of the UEs with approximately the same capacity than the case without power control. However, referring to Figure 3(b), we can see that such capacity values achieved using a much lower average power level. Consequently, using SDPC the system becomes much more energy efficient. Moreover, when considering the DPC, which according to Figure 3(b) uses a bit more power than SDPC but less power than the case without power control, we can see that the capacity perceived by 50% of the UEs is still increased for a large fraction of the target SINR values. Thus, power control can increase both the capacity and energy efficiency of the system.

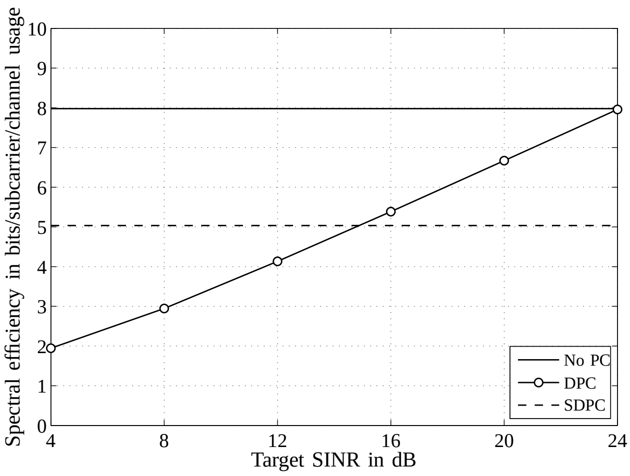
Finally, considering Figure 4(c), we observe that the 10% best UEs in the system would perceive better capacity if no power control be applied. However, this would come at the expenses of the other 90% of the UEs which would have their capacity reduced due to interference. Moreover, comparing the SDPC and DPC we can observe that for lower target SINR



(a) 10th percentile.



(b) 50th percentile.



(c) 90th percentile.

Fig. 4. Femtocell capacity values at different percentiles.

values, the DPC provides lower capacity to the best UEs while the opposite occurs to higher target SINR values. In fact, for very high target SINR values, only a few UEs are expected to be able to achieve the QoS requirement. Since SDPC trades the lowering of QoS by the increase of feasibility, this behavior is as expected.

IV. CONCLUSIONS

In this work, we analyzed the application of two power control algorithms, namely the DPC and the SDPC algorithms, in a system composed of one macrocell and several femtocells which employ fixed-switched beams antenna arrays. The application of power control in this system is shown to be able to improve the QoS levels that can be effectively provided to the UEs in the system. While the DPC works with fixed target SINR values and can suffer power control infeasibility, the SDPC considered varying target SINR values as to trade capacity by power efficiency. Indeed, our analyses show that the transmit powers employed by the macro- and femtocells can be significantly reduced using power control while the capacity achieved by a considerable fraction of the UEs is in fact increased. Thus, the use of power control has been shown to be able to increase both the capacity and the energy efficiency of the system.

Further investigations may consider the beamforming coordination among macro- and femtocells as well as the use of other beamforming techniques, such as orthogonal random beamforming, and consider the scheduling of multiple receiving UEs at each cell.

REFERÊNCIAS

[1] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks:a survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59–67, September 2008.
[2] D. Calin, H. Claussen, and H. Uzunalioglu, "On femto deployment architectures and macrocell offloading benefits in joint macro-femto deployments," *Communications Magazine, IEEE*, vol. 1, no. 1, pp. 26 –32, 2010.
[3] G. J. Foschini and Z. Miljanic, "A simple distributed autonomous power control algorithm and its convergence," *Vehicular Technology, IEEE Transactions on*, vol. 42, no. 4, pp. 641 – 646, november 1993.
[4] S. Gupta, R. D.Yates, and C. Rose, "Soft dropping power control-a power control backoff strategy," in *Personal Wireless Communications, 1997 IEEE International Conference on*, december 1997, pp. 210 – 214.
[5] J. C. Liberti, Jr. and T. S. Rappaport, *Smart antennas for wireless communications: IS-95 and third generation CDMA applications*, 1st ed., T. S. Rappaport, Ed. Prentice Hall, 1999.
[6] H. L. V. Trees, *Optimum array processing*, 1st ed. Wiley & Sons, 2002.
[7] J. Zhu and H.-C. Yang, "Interference control with beamforming coordination for two-tier femtocell networks and its performance analysis," in *Communications (ICC), 2011 IEEE International Conference on*, 2011.
[8] S. Ryoo, C. Joo, and S. Bahk, "Spectrum allocation with beamforming antenna in heterogeneous overlaying networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on*, 2010.
[9] X. Li, L. Qian, and D. Kataria, "Downlink power control in co-channel macrocell femtocell overlay," in *Information Sciences and Systems, 2009. CISS 2009. 43rd Annual Conference on*, 2009.
[10] G. Cao, D. Yang, X. Ye, and X. Zhang, "A downlink joint power control and resource allocation scheme for co-channel macrocell-femtocell networks," in *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, march 2011, pp. 281 –286.
[11] S. A. Grandhi, R. Vijayan, and D. J. Goodman, "Distributed power control in cellular radio systems," *Communications, IEEE Transactions on*, vol. 42, no. 234, pp. 226 –228, february 1994.
[12] 3GPP, "Spatial channel model for Multiple Input Multiple Output (MIMO) simulations," 3rd. Generation Partnership Project, Tech. Rep. TR 25.996 V7.0.0, Jun. 2007.
[13] D. S. Baum, J. Salo, M. Milojevic, P. Kyösti, and J. Hansen, "Matlab implementation of the interim channel model for beyond-3G systems (SCME)," IST WINNER Project, Tech. Rep., May 2005. [Online]. Available: http://www.tkk.fi/Units/Radio/scm/