QoS-Aware Autonomous Distributed Power Control in Co-Channel Femtocell Networks

Nessrine Chakchouk and Bechir Hamdaoui
School of EECS, Oregon State University
chakchon@eecs.oregonstate.edu, hamdaoui@eecs.oregonstate.edu

***Abstract*—Femtocells (FCs) are small-area cellular networks deployed over a macrocell (MC) network. Typically, FCs are independent of each other and of the underlying MC, thereby necessitating distributed non-cooperative resource allocation schemes. This paper develops a new distributed autonomous uplink (UL) power control (PC) scheme for femto users (FUs). Our work aims at maintaining the minimum required signal to interference plus noise ratio (SINR) for a maximum number of FUs via distributed QoS-aware stochastic power allocation to FUs. We evaluate the performance of our proposed solution and compare it with existing power allocation techniques. Results show that our scheme yields a significant performance improvement in terms of percentage of satisfied users when compared with these existing solutions.**

Index Terms—Distributed power control, resource allocation, ordinary differential equations, femtocells.

I. Introduction

Femtocell (FC) networks are small area cellular networks that have been recently introduced by the cellular operators in order to improve the capacity and coverage of existing macrocell (MC) network at a low cost. However, the deployment of these networks raises many new issues mainly due to the lack of a central network entity/agent to coordinate their operation. FCs are independent of each other and of the underlying MC. Therefore, new distributed mechanisms are needed to let the FCs optimize their resource utilization locally without exchanging any information with the external agents (i.e. other FCs and/or the MC). The problems that need to be solved for the FCs are common wireless problems such as mitigating interference, increasing network capacity, maintaining some required QoS, etc. Power control (PC) is considered to be an essential approach for achieving these key objectives in wireless networks.

Designing efficient PC schemes is very challenging in the case of FCs, mainly due to their autonomous nature. Therefore, it has been the focus of many recent works. Some of these works use game theoretical approaches to design PC schemes [1]–[4]. In [2]–[4], different utility functions are developed to achieve a balance between maximizing the total network utility and minimizing the power consumption. Some of these game-theoretic approaches are based on the well known distributed power update formula, proposed by Foschini-Miljanic (FM) [5]. For example, in [2], a joint power and admission control algorithm is proposed to support the macro users (MUs) with guaranteed QoS requirements, while letting the femto users (FUs) only exploit the remaining network capacity. The authors of [1] also use the FM power update along with a bargaining algorithm to maximize fairness in terms of achieved throughput among the autonomous nodes (i.e. FUs). Other works formulate the power allocation as an optimization problem [6]–[9], and solve it using different approaches. For instance, in [8], the authors present a centralized power allocation scheme that assigns power to FCs in order to maximize their capacities while ensuring that a minimum SINR value is maintained in the MC. In [6], Chandrasekhar et al. propose a distributed utility-based SINR adaptation at FCs for joint MC and FC capacity improvement. Although their scheme is distributed, it assumes cooperation and possibility of communication between FCs and the underlying MC. In [9], we design a distributed non-cooperative predictive FC power allocation scheme that aims at maximizing the throughput of FUs by adapting its transmission power to the surrounding interference, while considering fairness aspects as well.

In this paper, we consider the case where FUs have a QoS constraint expressed in terms of a minimum SINR requirement that needs to be maintained. In order to solve this problem, we use a reverse engineering approach: Starting from the desired solution, we develop a set of ordinary differential equations (ODEs) that help us design the power control scheme to be used by the FCs in order to meet their required QoS whenever possible. We evaluate the effectiveness of our proposed scheme by comparing its achievable performance with those achievable under the approach recently proposed by Chandrasekhar et al. [6] for the case where only one MU is assumed to be active per time slot (TS), as well as under the well known FM power control [5] for the case where multiple MUs are assumed to be active per TS.

The remainder of this paper is organized as follows. Section II describes the system model. Section III states and formulates the studied problem and presents the detailed design of the proposed allocation scheme. Section IV evaluates the performance of the proposed scheme via simulations, and compares it with the works proposed in [6] and [5]. Section V concludes the paper

II. Network Model

We consider a single-carrier two-tier cellular system consisting of FCs overlaid on one MC, where both of them operate over an identical carrier frequency f. The MUs and the FUs are spatially distributed in the two-dimensional plane according to two independent homogeneous Poisson point processes with intensities (i.e. spatial densities) λ_{MU} and λ_{FU} respectively. In this work, we consider the uplink (UL) communication stream; i.e., communication from the MUs to the macrocell base station (MBS) and from the FUs to their corresponding femtocell access points (FAPs). We assume that time is slotted and TDMA is used by the cellular users (CUs) (ie., MUs and/or FUs) to access the wireless channel, and that the UL communications at the FCs are synchronized with those at the MC [10][1], and consequently are mutually synchronized. We further assume that FUs residing in the same FC do not interfere with each other since they are scheduled in different TSs. However, we assume that it is possible to have multiple simultaneously active MUs in the MC per TS. Indeed, in our work the activity of the MUs is modeled by independent Bernoulli random variables with mean $\overline{\tau}$, representing the average activity rate per MU.

The wireless channel gain g_{ji} of user j to base station i is modeled in compliance with the ITU specifications [11], according to which at time slot t

$$g_{ji}(t) = d_{ji}^{-\alpha_j}(t)10^{-\frac{Y_{ji}(t)}{10}} \quad (1)$$

where $d_{ji}(t)$ represents the distance from user j to base station i at time t, α_j the path loss propagation factor related to the transmission environment (we distinguish between three environments cellular, indoor, and indoor-to-outdoor), and Y_{ji} represents the normal variable associated to the log-normal shadowing realization at time t, with a standard deviation of $8dB$ for MUs and $4dB$ for FUs. Hence, the SINR of the transmission from FU_i belonging to FC_i to its associated FAP_i at time slot t is

$$\gamma_i(t) = \frac{g_{ii}(t)P_i(t)}{I_i(t)} \quad (2)$$

where $P_i(t)$ denotes the transmission power of FU_i at time t, and $I_i(t)$, expressed in (3), is the interference experienced by FAP_i at time t due to the transmission of the simultaneously active neighboring FUs indexed with $(j \neq i)$ and the transmission of the simultaneously active MUs indexed with k.

$$I_i(t) = \sum_{FU_j;j\neq i} g_{ji}(t)P_j(t) + \sum_{MU_k} g_{ki}(t)P_k(t) + \sigma_i(t) \quad (3)$$

where $\sigma_i(t)$ denotes the additive white Gaussian noise at FAP_i at time t.

III. Problem Statement and Proposed Solution

Consider a set of N active FUs whose traffic requires a minimum data rate to guarantee a desired QoS. An example of such traffic is the voice traffic which requires a data rate of about 56 to 64 kbps in order to achieve an acceptable QoS. Recall that the data rate achievable by a wireless node i could be expressed as a function of its achievable SINR, γ_i (according to Shannon capacity formula). Hence, this data rate constraint could be mapped into the following minimum SINR constraint:

$$\gamma_i(t) \geq \gamma^{th}, \forall i = 1..N$$

[1]Once turned on and before initiating any communication, FCs get synchronized to the cellular core network using an asymmetric communication link such as xDSL thanks to an enhanced version of IEEE 1588 [10].

where γ^{th} is the minimum required SINR threshold. More specifically, in this work, we are interested in making sure that these FUs are able to achieve and maintain a SINR value $\gamma_i(t)$ that is close to the target γ^{th} as much as possible; i.e., $\gamma_i(t) \simeq \gamma^{th}$. Therefore, this objective can be formulated with the following equation:

$$\mid \gamma_i(t) - \gamma^{th} \mid = \frac{\mid \gamma_i(0) - \gamma^{th} \mid}{t+1} \quad (4)$$

The physical interpretation of this equation (4) is that the distance between the achieved SINR and the minimum required SINR decays geometrically with rate $1/t$ as $t \to \infty$ for any active FU_i. This represents the target we want to achieve via our distributed autonomous power control scheme developed hereafter. Notice that in our formulation of the problem, we use a backward/reverse engineering approach. That is, starting from the desired solution (4), we develop a power control scheme which aims at achieving our goal of sustaining the achieved SINR $\gamma_i(t)$ in the vicinity of/at the desired γ^{th} level.

In fact, starting from (4) the differential dynamic of our system can be derived as follows

$$\begin{aligned} \frac{\partial(\gamma_i(t) - \gamma^{th})}{\partial t} &= -sign(\gamma_i(t) - \gamma^{th}) \times \frac{\mid \gamma_i(0) - \gamma^{th} \mid}{(t+1)^2} \\ &= -(\gamma_i(t) - \gamma^{th}) \left| \frac{\gamma_i(t) - \gamma^{th}}{\gamma_i(0) - \gamma^{th}} \right| \end{aligned}$$

Thus, the differential dynamic of our system is described by the following set of ODEs:[2]

$$\dot{\gamma}_i(t) = -(\gamma_i(t) - \gamma^{th}) \left| \frac{\gamma_i(t) - \gamma^{th}}{\gamma_i(0) - \gamma^{th}} \right|, \forall i = 1..N \quad (5)$$

Moreover, we assume that the channel gain modeled via log-normal shadowing does not vary during the power update process, which is a reasonable assumption that has been adopted in several power control works [3]–[6], [8], [12]. Hence, by replacing $g_{ii}(t)$ by g_{ii} in (2) and deriving this expression with respect to time, we get:

$$\dot{\gamma}_i(t) = g_{ii} \frac{\dot{P}_i(t)I_i(t) - P_i(t)\dot{I}_i(t)}{I_i^2(t)} \quad (6)$$

Hence, by equating (5) and (6), we get:

$$\dot{P}_i(t) = P_i(t)\frac{\dot{I}_i(t)}{I_i(t)} - \frac{I_i(t)}{g_{ii}}(\gamma_i(t) - \gamma^{th}) \left| \frac{\gamma_i(t) - \gamma^{th}}{\gamma_i(0) - \gamma^{th}} \right|$$

Finally, using Taylor Series Expansion of order one we have:

$$\dot{P}_i(t) = \frac{\partial P_i(t)}{\partial t} \simeq P_i(t+1) - P_i(t)$$

and

$$\begin{aligned} \frac{\dot{I}_i(t)}{I_i(t)} &= \frac{\frac{\partial I_i(t)}{\partial t}}{I_i(t)} \\ &= \frac{\partial \ln(I_i(t))}{\partial t} \\ &\simeq \ln\left(\frac{I_i(t+1)}{I_i(t)}\right) \end{aligned}$$

[2]Here, we use the mathematical notation $\dot{x}(t) = \frac{\partial x(t)}{\partial t}$

Hence, we deduce our desired power control rule as:

$$\begin{aligned} P_i(t+1) &= P_i(t) \times \left(1 + \ln \frac{I_i(t+1)}{I_i(t)}\right) \\ &- \frac{I_i(t)}{g_{ii}}(\gamma_i(t) - \gamma^{th}) \left| \frac{\gamma_i(t) - \gamma^{th}}{\gamma_i(0) - \gamma^{th}} \right| \end{aligned} \quad (7)$$

Note that at time $(t+1)$, the value of the interference $I_i(t+1)$ is not known before running the power control algorithm, and hence, the exponential weighted moving average (EWMA) prediction technique is used as a means for getting an approximate value $\widehat{I}_i(t+1)$ of $I_i(t+1)$. Our proposed power control scheme given in (7) above can then be refined as:

1) *Power constraint:* When $P_i(t+1)$ obtained from (7) is negative, FU_i chooses not to transmit, and when $P_i(t+1)$ exceeds the maximum allowed per-FU power level, P^f_{max}, FU_i sets its transmission power to P^f_{max}. Formally, $P_i(t+1) = \min(\max(0, f_i(t)), P^f_{max})$.
2) *Safety margin:* The value of γ^{th} is multiplied with a safety factor $\delta \geq 1$ in order to provide a safety margin. The intuition here is that targeting an SINR slightly higher than the threshold γ^{th} provides more guarantees by increasing the chances of meeting the required γ^{th}.
3) *Smoothing factor:* A smoothing factor $0 \leq \beta < 1$ is introduced to reduce the fluctuations in FU_i's transmission power evolution during the power control process/period. This is shown in equation (9) below.

To sump up all the above, the final proposed power control rule can be written as

$$P_i(t+1) = \min(\max(0, f_i(t)), P^f_{max}) \quad (8)$$

with

$$f_i(t) = \beta h_i(t) + (1-\beta) P_i(t) \quad (9)$$

where $h_i(t)$ is the function defined by

$$\begin{aligned} h_i(t) &= P_i(t) \times \left(1 + \ln \frac{\widehat{I}_i(t+1)}{I_i(t)}\right) \\ &- \frac{I_i(t)}{g_{ii}}(\gamma_i(t) - \delta\gamma^{th}) \left| \frac{\gamma_i(t) - \delta\gamma^{th}}{\gamma_i(0) - \delta\gamma^{th}} \right| \end{aligned} \quad (10)$$

Now that we have defined our PC rule, we next give a brief description of our PC algorithm progress at each active FU_i. First, recall that in our system, FUs are scheduled according to TDMA so that only one FU is active per FC per TS. We further assume that each time slot, when a FU becomes active, it stays so for N_{TS} contiguous TSs, during which it uses the proposed PC algorithm (Algorithm 1) for determining/allocating its power.

Algorithm 1 Power Control Algorithm at FU_i

Initialize t=0, Select $P_i(t)$ randomly from $[0, P^f_{max}]$, Send data.
Set $\widehat{I}_i(0) = I_i(0)$
while $t \leq N_{TS}$ **do**
  Collect Previous Interference measurement from FAP_i
  Predict new Interference $\widehat{I}_i(t+1) = \alpha I_i(t) + (1-\alpha)\widehat{I}_i(t)$
  Compute Transmission power $P_i(t+1)$ using (8)
  Send data
  $t \leftarrow t+1$
end while

IV. Performance Evaluation and Analysis

In this section, we evaluate the performance of our proposed PC scheme (referred to as AD-PC for autonomous distributed PC) and compare it with two existing PC schemes: Utility-PC [6] and FM-PC [5]. We first start with a brief description of these two existing schemes, and then evaluate and analyze the performance gain AD-PC achieves in terms of the percentage of satisfied users when compared with Utility-PC and FM-PC.

A. Simulated Schemes and Performance Metric

1) Utility-PC Scheme [6]: Utility-based PC (hereafter referred to as Utility-PC for short) scheme, proposed by Chandrasekhar et al. [6], assumes that both the FUs and the MUs use TDMA as the multiple access method for sharing the wireless channel. Further, it also assumes that there is only one active FU per FC per TS and one active MU per TS in the underlying MC. Utility-PC's power control formula proposed to allow the active FU_i to achieve its desired SINR threshold γ^{th} is as follows.

$$P_i(t+1) = \min\left(\left(\frac{P_i(t)}{\gamma_i(t)}\left[\gamma^{th} + \frac{1}{a}\ln\left(\frac{ag_{ii}}{bg_{0i}}\right)\right]^+\right); P^f_{max}\right) \quad (11)$$

where $\left[\gamma^{th} + \frac{1}{a}\ln\left(\frac{ag_{ii}}{bg_{0i}}\right)\right]^+ = \max\left(0, \gamma^{th} + \frac{1}{a}\ln\left(\frac{ag_{ii}}{bg_{0i}}\right)\right)$, g_{0i} is the channel gain from the active MU to FAP_i, and a and b are two constants set respectively to 0.1 and 1 in order to maximize the FCs capacities. Although this scheme is distributed it still requires coordination between the FCs and the underlying MC.

2) FM-PC Scheme [5]: We also compare our PC scheme to the well known distributed PC scheme proposed by Foschini and Miljanic [5]. In what follows, this scheme is referred to as FM-PC. Its PC rule is summarized as follows.

$$P_i(t+1) = \frac{\gamma^{th}}{\gamma_i(t)} P_i(t) \quad (12)$$

Note that this power update requires only the knowledge of previous measures of some intrinsic parameters of the active FU_i, which is also the case in our proposed scheme.

3) Performance Metric: The goal of this work is to provide a distributed, non-cooperative power control scheme with the objective of maintaining the SINR achieved by each FU as close as possible to the desired level γ^{th}. Therefore, the outage percentage defined as the percentage of FUs whose QoS constraints are not met is used as the performance metric to evaluate the effectiveness of our proposed PC scheme.

B. Simulation Settings and Performance Evaluation

1) Simulation Settings: We consider a two-tier FC/MC network, in which the FAPs, the FUs and the MUs are scattered randomly over a $50m \times 50m$ area, with spatial densities λ_{FAP}, λ_{FU} and λ_{MU} respectively. In each FC, the FUs are scheduled

TABLE I
SUMMARY OF SIMULATION PARAMETERS

Maximum FU Power P^f_{max}	0.55 Watt
Maximum MU Power P^m_{max}	1 Watt
Femto SINR Threshold γ^{th}	1.8 dB
Number of Contiguous Time Slots per FU	100 Time Slots
Average number of FCs	75 FCs
Average number of FUs	375 FUs
Average number of MUs	50 MUs
EWMA Prediction Factor α	0.8
PC Smoothing Factor β	0.8

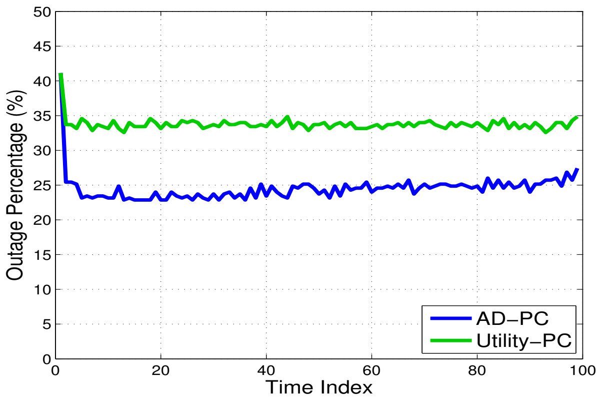

Fig. 1. Outage Percentage

in a round robbin fashion. Each active FU is allowed to transmit during N_{TS} contiguous time slots. On the other hand, the MUs activity is modeled with a Bernoulli random variable with mean $\overline{\tau} = \frac{1}{3}$. Main simulation parameters are summarized in Table I.

2) Performance Evaluation: In our performance evaluation we focus on two main aspects: First, and most importantly, we study the outage percentage since it allows us to measure how well the proposed PC scheme performs in terms of meeting FUs' QoS constraints. Second, we consider investigating the general behavior of the power and/or SINR obtained as a result of using our PC scheme, so as to assess the ability of our scheme vis-a-vis of stability and convergence.

Fig. 1 shows that our scheme, AD-PC, achieves a gain of 10% of satisfied FUs when compared to Utility-PC. Recall that AD-PC achieves such gain without needing any coordination among other FCs nor the underlying MC; i.e., it is fully decentralized. Moreover, Fig. 2 shows that AD-PC achieves such performance again with only half the FU power (on average) consumed by its counterpart Utility-PC scheme. In Fig. 3, we plot the power evolution of three randomly picked FUs during their assigned contiguous time slots. We clearly see that the power level consumed by these three FUs (which is determined by AD-PC) smoothly converges to a steady state. Moreover, the figure shows that the speed of convergence (or time required to converge to the steady state) varies from one FU to another and is upper bounded by about 50 TSs. Likewise, Fig. 4 also shows that the SINR of these randomly picked FUs smoothly converges to a steady state. This is an expected result since the SINR is nothing but a function of the controlled FU power variables which have been already shown to converge to a steady state from Fig. 3.

Not only does our proposed PC scheme outperform the recently proposed PC scheme [6], which assumes only one

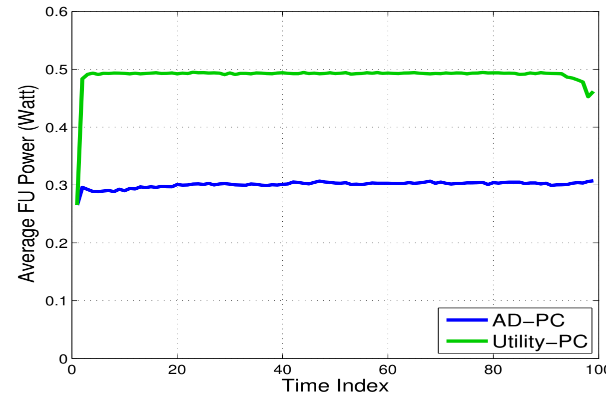

Fig. 2. Average FU Power

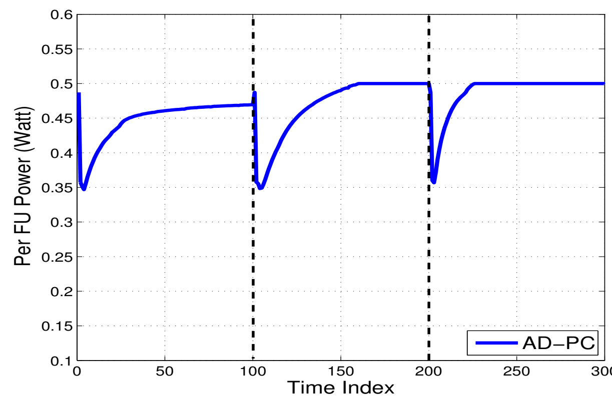

Fig. 3. Power Temporal Evolution for three randomly picked FUs

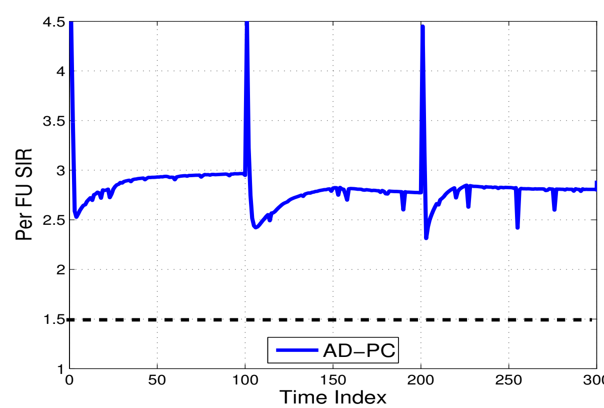

Fig. 4. SINR Temporal Evolution for three randomly picked FUs

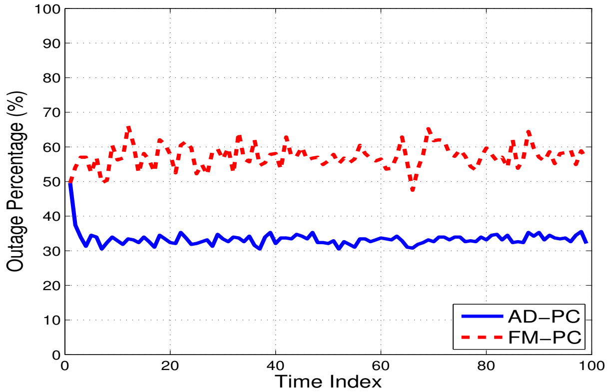

Fig. 5. Outage Percentage

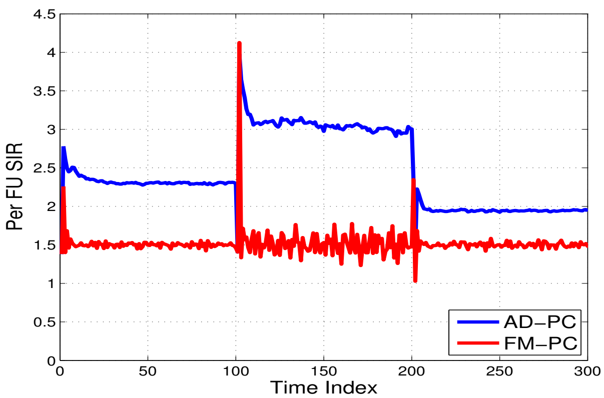

Fig. 6. SINR Temporal Evolution for three randomly picked FUs

active MU per TS in the underlying MC, but it also applies to a more general case where multiple MUs can be simultaneously active in the MC. Now in order to assess how well our scheme performs in the case where multiple MUs are active per TS and transmitting with random powers, we compare it against FM-PC scheme [5]. Here, we still maintain the assumption of orthogonally scheduled FUs inside a given FC (one active FU per FC per TS). Fig. 5 shows that the percentage of unsatisfied FUs (i.e., users whose SINR is below γ^{th}) is about 30% for our scheme compared to 60% for the FM-PC scheme. Hence, our scheme yields a significant gain (about 30%) in terms of the fraction of satisfied FUs when compared with FM-PC. On the other hand, Fig. 6 shows that for a three randomly picked FUs, the achieved SINR quickly converges to a steady state, but with higher/more frequent fluctuations for the FM-PC scheme. Thus, clearly our stochastic power control algorithm provides better SINR stability as well as better percentage of satisfied FUs.

V. Conclusion

In this paper, we propose a new distributed, non-cooperative uplink power control algorithm that enables FUs to autonomously meet their minimum required SINRs, whenever possible. Through simulations, we show that our scheme outperforms the Foschini-Miljanic scheme in terms of the number/rate of satisfied FUs. In addition to its distributiveness and simplicity/ease of computation, simulations show that our scheme is very stable and converges quite quickly to its steady state.

VI. Acknowledgment

This work was supported in part by National Science Foundation through NSF CAREER award CNS-0846044.

References

[1] V. Douros, G. Polyzos, and S. Toumpis, “Negotiation-based distributed power control in wireless networks with autonomous nodes,” in *Proc. IEEE 73rd Vehicular Technology Conference (VTC-Spring)*, May 2011.
[2] D. Ngo, L. Le, T. Le-Ngoc, E. Hossain, and D. Kim, “Distributed interference management in two-tier cdma femtocell networks,” *IEEE Transactions on Wireless Communications*, vol. 11, pp. 979–989, March 2012.
[3] E. Hong, S. Yun, and D. Cho, “Decentralized power control scheme in femtocell networks : A game theoretic approach,” in *Proc. IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2009.
[4] X. Kang, Y. Liang, and H. Garg, “Distributed power control for spectrum-sharing femtocell networks using stackelberg game,” in *Proc. IEEE International Conference on Communications (ICC)*, June 2011.
[5] G. Foschini and Z. Miljanic, “A simple distributed autonomous power control algorithm and its convergence,” *IEEE Transactions on Vehicular Technology*, vol. 42, pp. 641–646, Nov 1993.
[6] V. Chandrasekhar, J. G. Andrews, Z. Shen, T. Muharemovic, and A. Gatherer, “Distributed power control in femtocell-underlay cellular networks,” in *Proc. IEEE Global Telecommunications Conference (GLOBECOM)*, Dec 2009.
[7] Z. Huang, Z. Zeng, H. Xia, and J. Shi, “Power control in two-tier ofdma femtocell networks with particle swarm optimization,” in *Proc. IEEE 73rd Vehicular Technology Conference (VTC-Spring)*, May. 2011.
[8] K. Krishnan and H. Luss, “Power selection for maximizing sinr in femtocells for specified sinr in macrocell,” in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, March. 2011.
[9] N. Chakchouk and B. Hamdaoui, “Estimation-based non-cooperative power allocation in two-tier femtocell networks,” in *Proc. IEEE Global Communications Conference (GLOBECOM)*, Dec. 2011.
[10] S. Lee, “An enhanced IEEE 1588 time synchronization algorithm for asymmetric communication link using block burst transmission,” *IEEE Communications Letters*, vol. 12, pp. 687–689, Sep. 2008.
[11] *ITU-R Rec, M.1225, Guidelines for evaluation of radio transmission technologies for IMT-2000*, Feb.
[12] S. Ulukus and R. D. Yates, “Stochastic power control for cellular radio systems,” *IEEE Transactions on Communications*, vol. 46, pp. 784–798, Jun. 1998.