Distributed Interference Management in Femtocell Networks

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***Abstract*—This paper considers a two-tier cellular network wherein femtocell users, who communicate with their home-owner-deployed base stations, share the same frequency band with macrocell users by code-division multiple access (CDMA) technology. Since macrocell users have strictly higher priority in accessing the available radio spectrum, their quality-of-service (QoS) performance expressed in terms of the minimum required signal-to-interference-plus-noise ratio (SINR) should be maintained at all times. Femtocell users, on the other hand, are allowed to exploit residual network capacity for their own communications. In this work, we develop a joint power- and admission-control algorithm for interference management in such two-tier networks. Specifically, throughput-power tradeoff optimization is achieved for femtocell users while all macrocell users being supported with guaranteed QoS requirements whenever feasible. Importantly, the proposed algorithm makes power and admission control decisions in an autonomous and distributive manner with minimal coordination signaling, a desirable feature in two-tier networks where only limited exchange of signaling information can be afforded on backhaul links. Under certain practical conditions, the developed scheme is shown to converge to a stable solution. An effective technique is also proposed to improve the efficiency of such equilibrium in lightly-loaded networks. The performance of our proposed algorithm is demonstrated by numerical results.**

I. Introduction

Femtocells have emerged as an important technology to provide broadband access in wireless cellular networks [1]. By deploying low-cost femtocell base-stations (BSs), indoor users can enjoy high-speed wireless communications due to the close proximity between themselves and their own BSs. Femtocell solution offers significant economic benefits compared to the traditional cell-partitioning approach for which a large number of more expensive BSs are typically required. One of the central research issues for femtocells is how to develop autonomous interference management schemes such that the quality-of-service (QoS) requirements of all macrocell users are maintained while the residual network capacity can be effectively exploited by femtocell users [2], [3]. Given that the wired network infrastructure may only provide limited capacity for the exchange of signaling information, it is challenging to coordinate femtocell and macrocell BSs in a centralized manner to allocate radio resources and manage interference in such networks. Moreover, because of the different access tariffs applicable for these two types of users, macrocell users typically have strictly higher priority than femtocell users in accessing the underlying radio spectrum.

In traditional CDMA wireless network settings, one of the most popular power-control schemes is the one presented in [4], which converges to a Pareto-optimal solution whenever it is feasible to support all users' minimum SINRs. If the required QoS cannot be supported, admission-control algorithms are also executed [5]. The works in [6], [7] investigate several other power control algorithms from a game-theoretical point of view. In most cases, distributed solutions are devised that converge to the Nash equilibrium of the corresponding power control games. Various pricing schemes are also developed to achieve a balance between maximizing total network utility and minimizing power consumption and/or to improve the efficiency of equilibrium solutions [6], [7], [8].

In this paper, we develop a joint power- and admission-control solution for distributed interference management in two-tier CDMA-based networks. The fundamental difference between the setting considered here and that in traditional CDMA wireless networks is that the QoS requirements of macrocell users should always be maintained while femtocell users are only permitted to exploit the remaining available capacity. To the best of our knowledge, our present work is closest in spirit with that in [9]. However, it is important to point out that the methods proposed in [9] are neither able to guarantee minimum required SINRs for macrocell users, nor do they investigate mechanisms to effectively utilize network capacity in the low-load regime. On the contrary, the joint power- and admission-control algorithm devised here is able to protect the macrocell users at all times. As for femtocell users, we explicitly consider a practical scenario in which such users desire to balance between maximizing throughput and minimizing power consumption. Due to the different spectrum access priorities and performance goals, macrocell and femtocell users in this setting employ different utility and (possibly) cost functions. Accordingly, analysis of the convergence of the devised scheme is distinct from and, indeed, more difficult than that of other power and admission control algorithms available in the literature. For networks in low-loaded condition, we also propose a technique to improve the performance of macrocell users at equilibrium.

II. System Model and Assumptions

Consider a two-tier wireless network with power-controlled users. Specifically, we investigate the scenario where a macrocell serving M macrocell users is underlaid with K femtocells using CDMA technology. While we mainly focus on the downlink transmission, the results obtained in this paper can as well be adapted to the uplink case with only minor modifications. Assume that femtocell j has N_j users and define $N = \sum_{j=1}^{K} N_i$. It is further assumed that the association of femtocell users with their closest femtocell BSs is fixed during the runtime of the underlying power- and admission-control algorithm. Denote the set of all users by $\mathcal{L}$, and the set

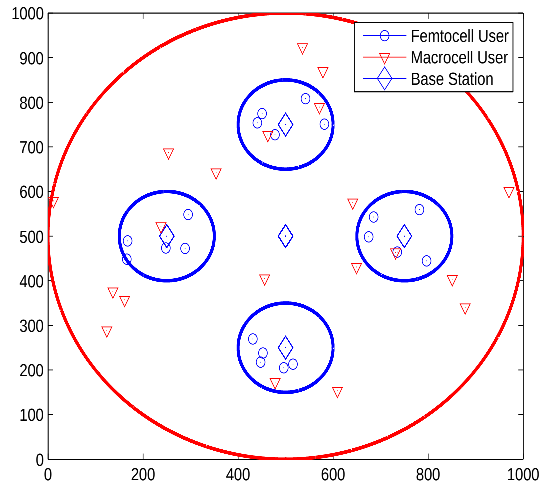


Fig. 1. Network topology and user placement in a two-tier wireless network.

of macrocell and femtocell users by $\mathcal{L}_m$ and $\mathcal{L}_f$, respectively. The network topology is illustrated in Fig. 1.

Let p_i be the transmit power of user $i \in \mathcal{L}$ and σ_i the power of additive Gaussian white noise measured in the spectrum bandwidth at the receiver of that user. Also, denote the channel gain from the transmitter of user $j \in \mathcal{L}$ to the receiver of user $i \neq j$ by g_{ij} and to the receiver of user j by g'_{jj}. Then, the SINR of user $i \in \mathcal{L}$ can be written as

$$\gamma_i = G g'_{ii} p_i \Big/ \left(\sum_{j \in \mathcal{L}, j \neq i} g_{ij} p_j + \sigma_i \right), \tag{1}$$

where G is the processing gain of the system. It is noteworthy that for the first term in the denominator of (1) we include both in-cell and cross-tier interferences, i.e., *aggregated* interference from all macrocell and femtocell users except the considered user i (which can be either a macrocell or a femtocell user). Here, channel gain g_{ij} simply reduces to g'_{ii} for the in-cell interference, while g_{ij} is termed *cross-channel* gain for the cross-tier interference. For notational convenience, let $g_{ii} \triangleq G g'_{ii}$ where the processing gain G is absorbed into the channel gain g'_{ii}. The SINR of user $i \in \mathcal{L}$ is simplified to

$$\gamma_i = g_{ii} p_i \Big/ \left(\sum_{j \in \mathcal{L}, j \neq i} g_{ij} p_j + \sigma_i \right). \tag{2}$$

We consider a "snapshot" model where the channel gains are assumed to remain unchanged during the entire power- and admission-control period. Further assume that macrocell user $i \in \mathcal{L}_m$ requires his/her SINR to be at least equal to a desired threshold Γ_i for QoS guarantee, i.e.,

$$\gamma_i \geq \Gamma_i, \quad \forall i \in \mathcal{L}_m. \tag{3}$$

Each femtocell user $j \in \mathcal{L}_f$ is assumed to have an SINR threshold below which he/she does not transmit. These constraints are very natural since, in practice, femtocell users should not transmit at very low power levels which only enable them to achieve negligible SINR. As such, we require that

$$\gamma_j \geq \underline{\gamma}_j^{(f)}, \quad \forall j \in \mathcal{L}_f. \tag{4}$$

It is worth noticing that an efficient interference management solution for femtocell networks should balance between two conflicting design objectives. On one hand, the owners who deploy femtocell networks may only be concerned with the optimization of their own network performance. On the other hand, femtocell users should be appropriately configured such that the normal operation of macrocell users is not harmed by exceeding interference. Further, macrocell users are particularly interested in achieving their prescribed SINRs with minimal power. To meet all these objectives, it is user i's interest to maximize the following performance objective:

$$\max_{\gamma_i, p_i \in [0,\infty)} \left\{ U_i(\gamma_i) - C_i(p_i) \right\}, \ i \in \mathcal{L}. \tag{5}$$

In (5), $U_i(\gamma)$ and $C_i(p_i)$ denote, respectively, the utility and cost of user i. It is indeed possible to design an efficient joint power and admission control algorithm by appropriately selecting different functions with corresponding parameters for $U_i(\gamma_i)$ and $C_i(p_i)$. The key aspect that makes existing algorithms (such as that in [5]) unsuitable for our current purpose is that the minimum SINRs of macrocell users should be maintained at all times. Accordingly, femtocell users should properly control their transmit powers or, if needed, may even be removed in order to protect macrocell users.

III. Distributed Joint Power and Admission Control for Two-tier Wireless Networks

We allow each user to maximize its instantaneous performance objective in (5), given the transmit powers of other users. Specifically, the total payoff for user i is defined as

$$U_{\text{tot},i} \triangleq U_i(\gamma_i) - C_i(p_i), \ \forall i \in \mathcal{L}. \tag{6}$$

Assume that $U_i(\gamma)$ is a strictly concave function. A necessary condition for the optimization problem (5) can be derived as

$$U'_i(\gamma_i) = (p_i/\gamma_i) C'_i(p_i) = (I_i/g_{ii}) C'_i(p_i), \tag{7}$$

with $I_i \triangleq \sum_{j \in \mathcal{L}, j \neq i} g_{ij} p_j + \sigma_i$ being the total noise and interference power at the receiving side of user $i \in \mathcal{L}$. From (7), it can be shown that

$$\widehat{\gamma}_i = f_i^{-1} \Big((I_i/g_{ii}) C'_i(p_i) \Big), \tag{8}$$

where $f_i(\gamma_i) = U'_i(\gamma_i)$. Based on $\widehat{\gamma}_i$ in (8), the following iterative power update rule can be applied [8]:

$$p_i(t+1) = \widehat{\gamma}_i(t) I_i(t)/g_{ii}(t) = \big[\widehat{\gamma}_i(t)/\gamma_i(t)\big] p_i(t), \tag{9}$$

where t denotes the iteration index. This represents a more general power-control rule compared to the well-known power update $p_i(t+1) = [\Gamma_i/\gamma_i(t)]p_i(t)$, which has been studied extensively in the literature [4]. In what follows, we will show how to choose appropriate functions $U_i(\gamma_i)$ and $C_i(p_i)$ for the macrocell and femtocell users, which enables us to design an efficient distributed power- and admission-control algorithm.

A. QoS Guarantees for Macrocell Users

In the design of their power control scheme, [8] recommends the use of a sigmoid utility function and a linear cost function. For our problem at hand, by using similar utility and cost functions (with appropriate parameters) for macrocell users, we can develop an efficient and robust power control algorithm that is capable of maintaining the minimum

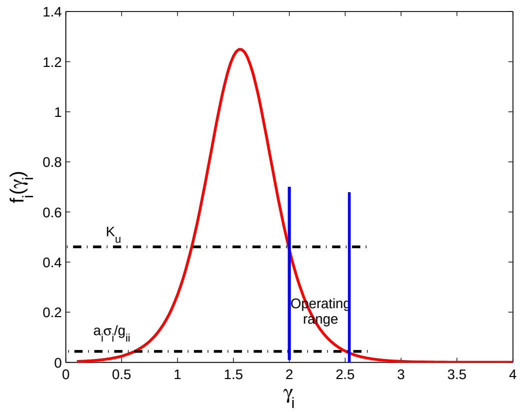


Fig. 2. Illustration of equilibrium solution for $\Gamma_i = 2$ and $b_i = 5$.

SINR requirements for these users. Specifically, we choose the following cost and utility functions for macrocell user $i \in \mathcal{L}_m$:

$$C_i(p_i) = a_i^{(m)} p_i, \tag{10}$$
$$U_i(\gamma_i) = 1/[1 + e^{-b_i(\gamma_i - c_i)}], \tag{11}$$

where $a_i^{(m)}$ is the "pricing" coefficient for user i, and b_i and c_i control the center and the steepness of sigmoid utility function, respectively. Since the cost function can be rewritten as $C_i(p_i) = a_i^{(m)} \gamma_i I_i/g_{ii}$, $a_i^{(m)} I_i/g_{ii} \leq K_{i,u}$ is required to achieve nonnegative total utility with $K_{i,u}$ being the derivative of $U_i(\gamma)$ at the point where the line $K_{i,u}\gamma_i$ is tangent to $U_i(\gamma)$. This implies that $K_{i,u} = U_i^{'}(\gamma_{i,u})$, where $\gamma_{i,u}$ satisfies

$$U_i^{'}(\gamma_{i,u})\gamma_{i,u} = U_i(\gamma_{i,u}). \tag{12}$$

Given the choice of utility and cost functions in (10) and (11), equation (7) can then be expressed as:

$$U_i^{'}(\gamma_i) = f_i(\gamma_i) = a_i^{(m)} I_i/g_{ii}. \tag{13}$$

From this relationship, it is straightforward to see that

$$\widehat{\gamma}_i = f_i^{-1}\left(a_i^{(m)} I_i/g_{ii}\right). \tag{14}$$

With (11), an analytical form of (14) can be obtained as [8]:

$$\widehat{\gamma}_i = c_i - \frac{1}{b_i}\ln\left[\frac{b_i g_{ii}}{2a_i^{(m)} I_i} - 1 - \sqrt{\left(1 - \frac{b_i g_{ii}}{2a_i^{(m)} I_i}\right)^2 - 1}\right]. \tag{15}$$

Note that the solution γ_i in (13) achieves non-negative total payoff only if $\gamma_i \geq \gamma_{i,u}$; otherwise, macrocell user i should not transmit, achieving zero total payoff. Therefore, by setting

$$\gamma_{i,u} = \Gamma_i, \tag{16}$$

we can ensure that any active macrocell user (i.e., whose transmit power is strictly positive) will attain its minimum SINR target. It is so because under this design an active macrocell user i will have the solution γ_i of (13) satisfying

$$\gamma_i \geq \gamma_{i,u} = \Gamma_i. \tag{17}$$

Some manipulations of (12) and (16) result in [8]

$$c_i = \Gamma_i - (1/b_i)\ln(b_i\Gamma_i - 1). \tag{18}$$

Fig. 2 shows the operating range for an active macrocell user $i \in \mathcal{L}_m$. With a sufficiently large b_i, the function $U_i^{'}(\cdot)$ becomes very steep; therefore, the resulting γ_i of an active user i will be very close to its SINR threshold Γ_i. As can also be observed, if it is feasible to support all macrocell users with their minimum required SINRs, we can make them all active by setting $a_i^{(m)}$ sufficiently small. Specifically, given the total received interference and noise power I_i, macrocell user $i \in \mathcal{L}_m$ is active if $a_i^{(m)} I_i/g_{ii} < K_{i,u} = U_i^{'}(\Gamma_i)$.

With macrocell users' QoS supported, the specific choice of utility and cost functions for femtocell users allows us to achieve some target design objectives. Notice that if these users also wish to maintain their respective QoS requirements, they may cause network congestion and hence badly affect the performance of macrocell users. In such cases, they should be penalized by appropriately tuning their operating parameters.

B. Balancing Throughput and Power for Femtocell Users

To balance the two often conflicting design goals, namely, maximizing system throughput and minimizing transmit power, we choose a utility function to capture the Shannon capacity for femtocell users, and a linear cost function, i.e.,

$$U_{\mathsf{tot},j} = W\ln(1+\gamma_j) - a_j^{(f)} p_j, \quad \forall j \in \mathcal{L}_f \tag{19}$$

where W denotes the system bandwidth, and $a_j^{(f)}$ denotes the pricing coefficient for user j. Again, suppose that each femtocell user $j \in \mathcal{L}_f$ sets its transmit power so that she can maximize her instantaneous total payoff. Applying the result in (7) to this particular choice of utility and cost functions gives $W/(1+\gamma_j) = a_j^{(f)} I_j/g_{jj}$. As $U_{\mathsf{tot},j}$ is strictly concave with respect to p_j, the global maximizer of $U_{\mathsf{tot},j}$ is indeed

$$p_j^* = \max\left(W/a_j^{(f)} - I_j/g_{jj}, 0\right). \tag{20}$$

Algorithm 1 presents a joint power and admission control scheme for both macrocell and femtocell users. This algorithm lends itself to a distributed implementation since each user $i \in \mathcal{L}$ (i.e., either macrocell or femtocell) only needs to estimate (i) its received interference power $I_i(t)$ and (ii) its own channel gain $g_{ii}(t)$ in order to update its transmit power in each iteration. Without loss of generality, we assume that the values of Γ_i's are given such that all macrocell users can be supported with their respective QoS requirements. Hence, admission control is not necessary for the macro-cell.

It is apparent from (20) that by increasing the pricing coefficient $a_j^{(f)}$, one can decrease the transmit power of femtocell user $j \in \mathcal{L}_f$, i.e., can penalize the user who creates undue cross-tier interference. Therefore, in step 7 of **Algorithm 1**, we gradually increase the pricing coefficients $a_j^{(f)}$ of all active femtocell users $j \in \mathcal{A}_f$ when there exists an active macrocell user $i \in \mathcal{A}_m$ with "soft" SINR target $\widehat{\gamma}_i(t)$ below the required SINR target (i.e., $\widehat{\gamma}_i(t) < \Gamma_i$). This pricing mechanism can be realized without acquiring the cross-channel gain information, unlike the one in [9] which may not be affordable in two-tier networks due to limited backhaul capacity. In step 12 of **Algorithm 1**, if a particular active femtocell user $j \in \mathcal{A}_f$ has her SINR falling below the minimum required threshold $\underline{\gamma}_j^{(f)}$, she will be removed with a small probability α at most

Algorithm 1 PROPOSED POWER AND ADMISSION CONTROL FOR TWO-TIER WIRELESS NETWORKS

1: Set $P_i := 0, \forall i \in \mathcal{L}$, initialize sets of active macrocell and femtocell users as $\mathcal{A}_m := \mathcal{L}_m$, $\mathcal{A}_f := \mathcal{L}_f$, and set $t := 1$.
2: Each macrocell user $i \in \mathcal{A}_m$ measures $g_{ii}(t)$ and $I_i(t)$, then calculate $\widehat{\gamma}_i(t)$ from (14).
3: **if** $\widehat{\gamma}_i(t) \geq \Gamma_i$ **then**
4: Update power: $p_i(t+1) := I_i(t)\widehat{\gamma}_i(t)/g_{ii}(t)$.
5: **else if** $\widehat{\gamma}_i(t) < \Gamma_i$ and $|\mathcal{A}_f| > 0$ **then**
6: Update power: $p_i(t+1) := I_i(t)\Gamma_i/g_{ii}(t)$.
7: Each femtocell user $j \in \mathcal{A}_f$ updates its pricing coefficient: $a_j^{(f)} := k_j^{(f)} a_j^{(f)}$ where $k_j^{(f)} > 1$ are predetermined scaling factors.
8: **end if**
9: Each femtocell user $j \in \mathcal{A}_f$ measures $g_{jj}(t)$ and $I_j(t)$, then calculates $\widehat{p}_j$ as $\widehat{p}_j := W/a_j^{(f)} - I_j(t)/g_{jj}(t)$.
10: Update power: $p_j(t+1) := \widehat{p}_j$.
11: **if** $\widehat{p}_j g_{jj}(t)/I_j(t) < \underline{\gamma}_j^{(f)}$ **then**
12: If $t = nT^{(f)}$ then with a small probability α, user j sets $p_j(t+1) := 0$ and removes himself from the set of active femtocell users: $\mathcal{A}_f := \mathcal{A}_f - \{j\}$.
13: **end if**
14: Femtocell BS with no active user informs macrocell.
15: Set $t := t+1$ and go to step 2 until convergence.

once in every $T^{(f)}$ iterations. This *conservative* user-removal scheme is employed to avoid eliminating too many femtocell users unnecessarily.

Theorem 1 (Convergence of Algorithm 1): **Algorithm 1** converges to an equilibrium if $f_i^{-1}(x)x$ is an increasing function for all $i \in \mathcal{L}_m$ and the following condition holds:

$$R_{\mathsf{max}}\,(N_f + M_m - 1) < 1, \qquad (21)$$

where $f_i(\cdot) = U_i^{'}(\cdot)$; $M_m = |\mathcal{A}_m| \leq M$ and $N_f = |\mathcal{A}_f| \leq N$ denote, respectively, the number of users in the active macrocell and femtocell user sets; and

$$R_{\mathsf{max}} \triangleq \max_{\left\{i\in\mathcal{L}_f, j\in\mathcal{L}-\{i\}\right\}} \frac{g_{ij}}{g_{ii}} = \max_{\left\{i\in\mathcal{L}_f, j\in\mathcal{L}-\{i\}\right\}} \frac{g_{ij}}{G g_{ii}^{'}}. \qquad (22)$$

Proof: First, the power control updates for macro and femtocell users in **Algorithm 1** can be summarized as follows:

$$\mathbf{P}(t+1) = \left[A_i\left(\mathbf{P}(t)\right)\right],\ i \in \mathcal{L}, \qquad (23)$$

$$A_i\big(\mathbf{P}(t)\big) = \frac{I_i(t)}{g_{ii}(t)} \max\left\{\Gamma_i, f_i^{-1}\left(\frac{a_i^{(m)} I_i(t)}{g_{ii}(t)}\right)\right\}, i \in \mathcal{L}_m, \qquad (24)$$

$$A_i\big(\mathbf{P}(t)\big) = \max\left\{W/a_i^{(f)} - I_i(t)/g_{ii}(t), 0\right\}, i \in \mathcal{L}_f. \qquad (25)$$

For users who achieve nonzero powers at the equilibrium, it is true that

$$p_i^* = \big(I_i^*/g_{ii}\big) f_i^{-1}\big(a_i^{(m)} I_i^*/g_{ii}\big),\ i \in \mathcal{A}_m, \qquad (26)$$

$$p_i^* = W/a_i^{(f)} - I_i^*/g_{ii},\ i \in \mathcal{A}_f, \qquad (27)$$

where $I_i^* = \sum_{j\neq i} g_{ij} p_j^* + \sigma_i$.

Let us define $\Delta p_i(t) \triangleq p_i(t) - p_i^*$ with p_i^* being the transmit power of user $i \in \mathcal{A}_m \cup \mathcal{A}_f$ at equilibrium [see (26) and (27)]. Also, denote by $\|\Delta p\|_{\mathcal{A}}$ the l_∞-norm of vector Δp over some set $\mathcal{A}$, i.e., $\|\Delta p\|_{\mathcal{A}} \triangleq \max_{i\in\mathcal{A}} |\Delta p_i|$. Then, by applying (25) and (27) to a particular femtocell user $i \in \mathcal{A}_f$, we have

$$\begin{aligned} |\Delta p_i(t+1)| &= \left|\frac{I_i^* - I_i(t)}{g_{ii}}\right| \leq \frac{1}{G}\left|\sum_{j\neq i}\frac{g_{ij}}{g_{ii}^{'}}\Delta p_j(t)\right| \\ &\leq \frac{1}{G}\sum_{j\neq i}\left|\frac{g_{ij}}{g_{ii}^{'}}\Delta p_j(t)\right| \leq R_{\mathsf{max}}\sum_{j\neq i}|\Delta p_j(t)| \\ &\leq R_{\mathsf{max}}(M_m + N_f - 1)\,\|\Delta p(t)\|, \end{aligned} \qquad (28)$$

where $\|\Delta p(t)\|$ denotes the l_∞-norm of vector Δp over the set of all active users, i.e., $\mathcal{A}_m \cup \mathcal{A}_f$. From this,

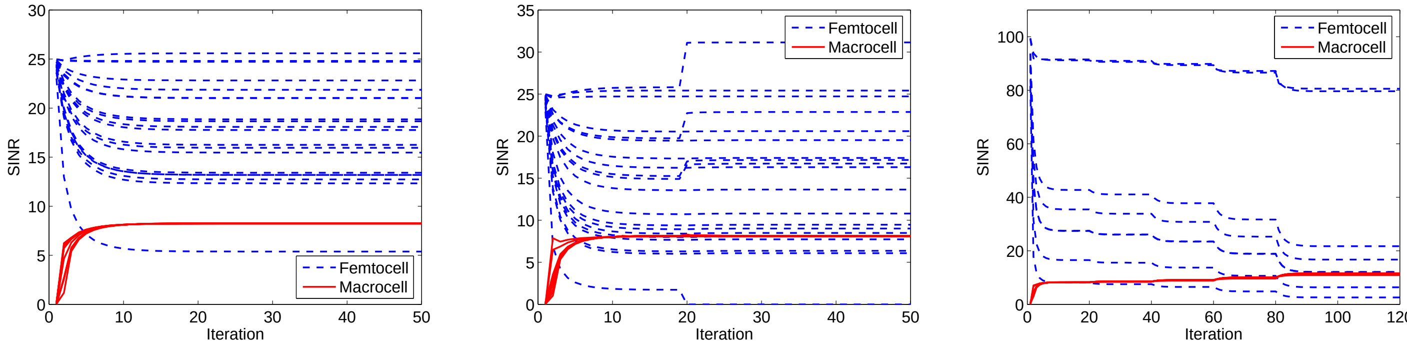
$$\|\Delta p(t)\|_{\mathcal{A}_f} \leq R_{\mathsf{max}}(M_m + N_f - 1)\,\|\Delta p(t)\|. \qquad (29)$$

Hence, $\|\Delta p(t)\|_{\mathcal{A}_f}$ will shrink over time if the condition in (21) is satisfied and also if $\|\Delta p(t)\|_{\mathcal{A}_m}$ shrinks over time.

Condition (21) is met if the network is not very congested. Specifically, R_{max} is quite small since it is inversely proportional to the processing gain G, which is typically a large number. As well, the integrated admission-control mechanism in **Algorithm 1** will autonomously remove "bad" femtocell users if the network becomes congested, making (21) feasible. On the other hand, it has been shown in [8] that $A_i\left(\mathbf{P}(t)\right),\ i \in \mathcal{L}_m$ in (24) is a standard function (i.e., it satisfies the positivity, monotonicity, and scalability attributes [10]) if $f_i^{-1}(x)x$ is an increasing function. Moreover, [10] has also established that a power control algorithm will converge if such a standard function property is satisfied. It can be verified that $f_i^{-1}(x)x$ is an increasing function if b_i is sufficiently large. As discussed earlier, this can certainly be achieved by our design. Since $\|\Delta p(t)\|_{\mathcal{A}_m}$ shrinks over time, so does $\|\Delta p(t)\|_{\mathcal{A}_f}$. Consequently, **Algorithm 1** converges to an equilibrium. ■

C. Improving Efficiency of the Equilibrium Solution

Efficiency of the equilibrium solution can be improved by making the SINRs of active macrocell users larger than the required thresholds. From (13), an active macrocell user $i \in \mathcal{A}_m$ at equilibrium has $f_i(\gamma_i^*) = a_i^{(m)} I_i^*/g_{ii}$, where the typical shape of function $f_i(\cdot)$ is illustrated in Fig. 2. As can be observed, for a given $a_i^{(m)} I_i^*/g_{ii}$ a higher SINR γ_i^* can be realized if $f_i(\cdot)$ becomes flatter. This corresponds to choosing smaller values of b_i, where recall that b_i is a control parameter of $U_i(\gamma_i)$. Ultimately, it is possible that the SINRs of macrocell users can be enhanced through reducing b_i whenever possible. Nevertheless, the values of b_i should be updated less frequently in comparison to the updates of power themselves. Toward this end, the following procedure can be employed. A particular interval T_b is chosen in advance to periodically update $b_i,\ i \in \mathcal{L}_m$. At the beginning of each interval of length T_b, macrocell users $i \in \mathcal{L}_m$ multiply their b_i by a factor of $k_b < 1$ if the corresponding macrocell BS has not been informed about any empty femtocell (e.g., through the signaling channel) during the previous interval. This occurs if the network is in low load, implying that almost all femtocell users converge to the desired equilibrium without being removed.



(a) Without femtocell-user removal

(b) With femtocell-user removal

(c) Improving SINRs of macrocell users

Fig. 3. Performance of Algorithm 1 for $k_j^{(f)} = 1.1$, $\Gamma_i^{(m)} = 8$, and $a_i^{(f)} = 10^9$.

IV. Numerical Results

The network setting and user placement in our numerical examples are shown in Fig. 1, where macrocell and femtocell users are randomly deployed inside circles of radii of 500m and 100m, respectively. Also, we assume that the number of users serviced by individual femtocell BSs is identical. For each network realization, channel gains from the transmitter $j \in \mathcal{L}$ to its receiver $i \in \mathcal{L}$ are calculated as d_{ij}^{-3} with d_{ij} being their corresponding geographical distance. The other system parameters are chosen as follows: $W = 10$ MHz, $G = 100$, $\sigma_i = 10^{-10}$, and $b_i = 10$, $\forall i \in \mathcal{L}_m$. The minimum SINR threshold used for the removal of femtocell users $j \in \mathcal{L}_f$ is taken to be $\underline{\gamma}_j^{(f)} = 3\text{dB} \approx 2$, a typical value in cellular WCDMA downlink. Additionally, the pricing coefficients of all macrocell users are set equal to $a_i^{(m)} = 1$, $\forall i \in \mathcal{L}_m$ in all simulation results. In step 12 of our proposed algorithm, the removal probability is specified as $\alpha = 0.1$. We designate the parameters for update interval as $T_b = 20$ and $T^{(f)} = 10$. Moreover, the same initial pricing coefficients $a_j^{(f)}$ and scaling parameters $k_j^{(f)}$ are selected for all femtocell users $j \in \mathcal{L}_f$.

Fig. 3(a) depicts the evolution of SINRs under **Algorithm 1** for $M = 10$ and $N = 20$. As can be seen, **Algorithm 1** converges to an equilibrium with the target SINRs achieved for all macrocell users. It is also clear that the convergence time is relatively small, slightly larger than 10 iterations. In particular, Fig. 3(b) illustrates the operation of **Algorithm 1** when the network becomes congested. Initially, the proposed algorithm converges to an equilibrium in which the SINR requirement of one femtocell user cannot be satisfied, i.e., its achieved SINR falls below $\underline{\gamma}_j^{(f)} = 3\text{dB}$. The admission-control mechanism in **Algorithm 1** then effectively removes this user, resulting in a noticeable growth in SINRs of the remaining femtocell users. Importantly, it is also evident here that the removal of femtocell users does not significantly affect the transmit powers and SINRs of macrocell users. This verifies the efficiency and robustness of the proposed algorithm in protecting macrocell users' performances.

Demonstrated in Fig. 3(c) is how the technique presented in Sec. III-C helps improve the SINRs of macrocell users $i \in \mathcal{L}_m$ for $M = N = 8$. Specifically, we have decremented all b_i's by a factor of $k_b = 0.5$ once in every $T_b = 20$ iterations. These updates are performed until one femtocell user has her SINR falling below a predetermined SINR threshold, chosen to be 3 in this case. Note also that T_b should be set sufficiently large so that the algorithm converges to a new equilibrium, preventing it from divergence. It is clear that by scaling down b_i, we can effectively increase the SINRs of all macrocell users at the cost of reducing the SINRs of femtocell users.

V. Conclusion

This paper proposes a joint power- and admission-control algorithm for autonomous interference management in two-tier femtocell networks. Specifically, femtocell users achieve an optimized balance between throughput and power, while performance of the macrocell users being robustly protected with their required SINRs maintained. Convergence of the developed solution has been proven analytically and confirmed through numerical examples.

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