Power Control for Interference Management and QoS Guarantee in Heterogeneous Networks

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***Abstract*—We consider the sum-rate optimization problem with power control for uplink transmission in a heterogeneous network (HetNet) consisting of a macrocell and multiple femtocells. The considered problem includes the HetNet's crucial constraints of both cross-tier interference protection and user QoS in terms of outage probability and average delay. We transform the original non-convex problem into a convex problem and develop a distributed algorithm that can attain the global optimal transmit power values. This algorithm, however, has heavy network overheads, which may lead to increased energy consumption for femtocell user equipment. We propose a new practical near-optimal distributed algorithm that eliminates these network overheads. Numerical results show that the schemes have nearly identical performance.**

***Index Terms*—Power control, femtocell networks, interference management, optimization theory.**

I. Introduction

SPECTRUM-SHARING between a macrocell and femtocells in heterogeneous networks (HetNets) can significantly reduce the network QoS due to cross-tier and co-tier interference [1]. Consequently, the interference management (IM) in HetNets has become a popular research area. IM using power control (PC) to guarantee QoS for HetNets has been extensively investigated in the literature [2]–[4].

In [2], PC schemes for two-tier femtocell networks have been proposed. However, under the densely deployed scenario, the co-tier interference between femtocells cannot be neglected; and there is *no global optimal* PC strategy for the proposed schemes. In addition, that paper only considers the macro base station (MBS) protection but does not guarantee *the QoS for FUEs*. The authors in [3] developed a hybrid PC scheme to support different kinds of users with differentiated QoS targets. However, the authors do not explicitly mention *the MBS protection mechanism* in the case of high effective interference. The authors in [4] demonstrate increased performance by proposing an IM scheme that reduces the computation and overhead; however, the solution is *sub-optimal* and the network QoS guarantee is not considered.

In order to fill these gaps of previous works, we propose two distributed algorithms that can achieve: i) global optimal transmit powers; ii) MBS interference protection; and iii) QoS guarantee for all FUEs. Our main contributions can be summarized as follows

- The first proposed algorithm can attain the global optimal transmit powers using a dual-based algorithm. However, in order to update the dual variables and transmit powers, this scheme requires a large message exchange, which increases the network overhead and convergence time, resulting in additional energy consumption of FUEs.
- To alleviate the first algorithm's overhead-induced drawbacks, we propose a second algorithm that achieves global optimal transmit powers of the approximation problem and is near-optimal but practically implementable.
- Simulation results show that the two algorithms have nearly identical performance and outperform the conventional works.

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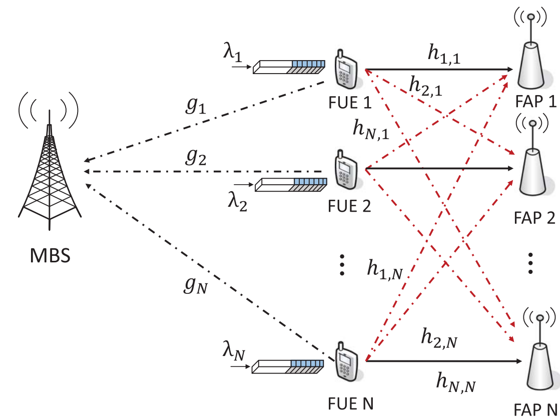

Fig. 1. System model.

II. System Model

A. Network Model

We consider a two-tier HetNet consisting a single central MBS and a set of N femtocells implementing spectrum sharing. There is one femtocell access point (FAP) providing service for several FUEs in each femtocell. However, for analytical tractability, we assume that at any given frequency band and time period, there is only one active FUE in each femtocell. Even though we only consider complete channel sharing model, the partial channel sharing mode can be an interesting extension in future.

We model the uplink transmission for a given time slot as shown in Fig. 1, where $h_{n,n}$ and $h_{m,n}$ are the channel power gains of the links between FUE n and FAP n and between FUE n and FAP m, respectively, and g_n is the channel power gain between FUE n and the MBS. $\mathbf{P} = [P_1, P_2, \ldots, P_N]$ is the vector of power levels for FUEs, and $P_n^{min} \le P_n \le P_n^{max}, \ \forall n$.

B. Problem Formulation

FUE Transmission Rate: The instantaneous signal-to-interference-noise-ratio (SINR) of FUE n at FAP n is

$$\gamma_n(\mathbf{P}) = \frac{P_n h_{n,n} F_{n,n}}{\sum_{m \ne n} P_m h_{n,m} F_{n,m} + \sigma_n^2}, \qquad (1)$$

where $F_{n,m}$ models the fast-fading channel from the FUE m to FAP n, and σ_n^2 is the background noise at FAP n. The additional interference from the macrocell users can be absorbed into the background noise. Employing a Rayleigh fading model, we assume $F_{n,m}$ is i.i.d. exponentially distributed with unit mean. Over the considered time slot, $h_{n,n}$ and $h_{m,n}$ are assumed constant [2]–[4]. The *certainty-equivalent* SINR [5] defined as follows:

$$\bar{\gamma}_n(\mathbf{P}) = \frac{\mathbf{E}[P_n h_{n,n} F_{n,n}]}{\mathbf{E}\left[\sum_{m\neq n} P_m h_{n,m} F_{n,m} + \sigma^2\right]} = \frac{P_n h_{n,n}}{\sum_{m\neq n} P_m h_{n,m} + \sigma^2}. \quad (2)$$

The transmission rate R_n of FUE n can be modeled as $R_n(\mathbf{P}) = W \log(1 + K\bar{\gamma}_n(\mathbf{P}))$, where W is the baseband bandwidth and K is a constant depending on modulation, coding scheme and bit-error rate (BER). Unless otherwise stated, we assume $W = K = 1$ without loss of generality.

The objective of the femtocell network is to maximize a system-wide efficiency metric, e.g., the total system throughput. Here, we assume that system operates in a high SINR regime, i.e., SINR is much larger than 1; thus, the data rate can be approximated as $R_n = \log(\bar{\gamma}_n(\mathbf{P}))$. This approximation is reasonable when the signal level is much higher than the interference level. Therefore, in the high SINR regime, the aggregate data rate for the femtocell networks can be written as follows:

$$R_{sum}(\mathbf{P}) = \sum_n R_n(\mathbf{P}) = \log\left[\prod_n (\bar{\gamma}_n(\mathbf{P}))\right]. \quad (3)$$

FUE QoS: In wireless networks, one of the most important QoS parameter for reliable communication is *outage probability*. A channel outage is declared (e.g., packets lost) when the received SINR falls below a given threshold SINR γ^{th}, often computed from the BER requirement. In this letter, we choose Rayleigh fading channel [5], [6] which can give a close-form of outage probability constraints to our problem as follows

$$\mathbf{Pr}\left[\bar{\gamma}_n \le \gamma_n^{th}\right] = 1 - \exp\left(-\frac{\sigma_n^2 \gamma_n^{th}}{P_n h_{n,n}}\right) \prod_{m\neq n}\left(1 + \gamma_n^{th} \frac{P_m h_{n,m}}{P_n h_{n,n}}\right)^{-1}. \quad (4)$$

Another important QoS design consideration for wireless communication is *average delay*. At the FUE n, the received packets are first buffered in a queue and then transmitted at a rate R_n. A FIFO queuing discipline is used here for simplicity. The packet arrival process of FUE n is assumed to be Poisson with parameter λ_n and have an exponentially distributed length with parameter π_n. Using the model of an M/M/1 queue [7], the probability of FUE n having a backlog of $N_n = k$ packets to transmit is well-known to be $\mathbf{Pr}[N_n = k] = (1 - \rho)\rho^k$, where $\rho = \lambda_n / \pi_n R_n(\mathbf{P})$, and the expected delay at FUE n is $\bar{D}_n(\mathbf{P}) = 1/(\pi_n R_n(\mathbf{P})) - \lambda_n$.

MBS Interference Protection: We assume that the maximum tolerable interference at MBS is I, i.e., the interference constraint is used to assure that the aggregate interference from all FUEs to the MBS is less than I. Mathematically, this constraint can be written as $\sum_n g_n P_n \le I$.

We next consider the following sum-rate optimization problem, taking into account constraints on maximum tolerable interference, outage probability, and expected delay:

$$\begin{aligned}
\underset{\mathbf{P}\in\mathcal{P}}{\text{maximize}} \quad & R_{sum}(\mathbf{P}) \\
\text{subject to} \quad & \sum_{n=1}^{N} g_n P_n \le I, \\
& \bar{D}_n(\mathbf{P}) \le \bar{D}_n^{max}, \quad \forall n, \\
& \mathbf{Pr}\left[\bar{\gamma}_n \le \gamma_n^{th}\right] \le \xi_n, \quad \forall n, \\
& \mathcal{P} = \left\{P_n, n \in \mathcal{F} | P_n^{min} \le P_n \le P_n^{max}\right\}, \quad (5)
\end{aligned}$$

where $\bar{D}_n^{max}$ and $\xi_n \in (0, 1)$ are the upper bound of expected delay and the outage probability threshold of FUE n, respectively. Problem (5) is generally a nonconvex problem. In the next section, we first transform (5) into an equivalent convex problem and then propose a distributed algorithm to achieve the global optimal transmit powers.

III. Optimal Algorithm

A. Equivalent Convex Formulation

We define a new variable $y_n = \log P_n$ and a new set $\hat{\mathcal{P}} = \{y_n, n \in \mathcal{F} | \log P_n^{min} \le y_n \le \log P_n^{max}\}$; thus, $P_n = e^{y_n}$. We also introduce an auxiliary variable $\{Z_n\}$ to show that every FUE n has the capability to estimate the interference $e^{Z_n} = \sum_{m\neq n} P_m h_{n,m}$. We transform problem (5) into the following equivalent non-linear programming problem

$$\begin{aligned}
\underset{\mathbf{y}\in\hat{\mathcal{P}},\mathbf{Z_n}}{\text{minimize}} \quad & \sum_{n=1}^{N} \log\left(\frac{e^{-y_n}}{h_{n,n}}\left(e^{Z_n} + \sigma_n^2\right)\right) \\
\text{s.t.} \quad & \sum_{n=1}^{N} g_n e^{y_n} - I \le 0, \\
& \log\left(\frac{e^{-y_n}}{h_{n,n}}\left(e^{Z_n} + \sigma_n^2\right)\right) - \Phi_n \le 0, \quad \forall n, \\
& \sum_{m\neq n} \log\left(1 + e^{y_m - y_n} \frac{\gamma_n^{th} h_{n,m}}{h_{n,n}}\right) \le \log \Gamma_n(e^{y_n}), \quad \forall n, \\
& \log\left(\sum_{m\neq n} h_{n,m} e^{y_m}\right) - Z_n \le 0, \quad \forall n, \quad (6)
\end{aligned}$$

where $\Phi_n = \frac{-1}{\pi_n}\left(\frac{1}{\bar{D}_n^{max}} + \lambda_n\right)$, and $\Gamma_n(P_n) = \frac{\exp(-\sigma_n^2 \gamma_n^{th} / P_n h_{n,n})}{1 - \xi_n}$. We further assume that γ_n^{th} and ξ_n are chosen such that there exist feasible points in problem (6). By employing admission control or relaxing QoS constraints, we can cope with the issue of non-existent feasible points, which is reserved for future work. Problem (6) is a convex problem and at the optimal solution, the last constraint is active, i.e., $\log\left(\sum_{m\neq n} h_{n,m} e^{y_m}\right) = Z_n$. The Lagrangian form of (6) can be decomposed into N subproblems as follows:

$$L(\{y_n\}, \{Z_n\}, \lambda, \mu, \nu, \zeta) = \sum_{n=1}^{N} L_n(y_n, Z_n, \lambda, \mu_n, \nu_n, \zeta_n), \quad (7)$$

where λ, μ_n, ν_n and ζ_n are Lagrange multipliers that represent *interference price*, *delay price*, *outage price*, and *consistency price*, respectively, and

$$\begin{aligned}
L_n(y_n, Z_n, \lambda, \mu_n, \nu_n, \zeta_n) &= \log\left(\frac{e^{-y_n}}{h_{n,n}}\left(e^{Z_n} + \sigma_n^2\right)\right) + \lambda g_n e^{y_n} \\
&+ \zeta_n \log\left(\sum_{m\neq n} h_{n,m} e^{y_m}\right) - \zeta_n Z_n + \mu_n \log\left(\frac{e^{-y_n}}{h_{n,n}}\left(e^{Z_n} + \sigma_n^2\right)\right) \\
&+ \sum_{m\neq n} \nu_m \log\left(1 + e^{y_n - y_m} \frac{\gamma_m^{th} h_{m,n}}{h_{m,m}}\right) - \nu_n \log \Gamma_n(e^{y_n}). \quad (8)
\end{aligned}$$

The dual problem is then given as

$$\begin{aligned}
\max \quad & D(\lambda, \mu, \nu, \zeta) \\
\text{s.t.} \quad & \lambda, \mu, \nu, \zeta \ge 0, \quad (9)
\end{aligned}$$

where $D(\lambda, \mu, \nu, \zeta) = \min_{y_n, Z_n} L(\{y_n\}, \{Z_n\}, \lambda, \mu, \nu, \zeta)$ is the dual function. Problem (6) is convex; hence, there exists a strictly feasible point so Slater's condition holds, leading to strong duality [8]. This allows us to solve the primal (6) via the dual (9). The dual problem (9) can be solved using the sub-gradient method, which updates the Lagrange multipliers as follows:

$$\lambda^{(t+1)} = \left[\lambda^{(t)} + \kappa_\lambda^{(t)}\left(\sum_{n=1}^{N} g_n P_n^{(t)} - I\right)\right]^+, \quad (10)$$

$$\mu_n^{(t+1)} = \left[\mu_n^{(t)} + \kappa_\mu^{(t)}\left(\log\left(\frac{e^{Z_n^{(t)}} + \sigma_n^2}{P_n^{(t)} h_{n,n}}\right) - \Phi_n\right)\right]^+, \quad (11)$$

$$\nu_n^{(t+1)} = \left[\nu_n^{(t)} + \kappa_\nu^{(t)}\left(\sum_{m\neq n}\log\left(1+\gamma_n^{th}\frac{P_m^{(t)} h_{n,m}}{P_n^{(t)} h_{n,n}}\right) - \log\Gamma_n\left(P_n^{(t)}\right)\right)\right]^+, \quad (12)$$

$$\zeta_n^{(t+1)} = \left[\zeta_n^{(t)} + \kappa_\zeta^{(t)}\left(\log\left(\sum_{m\neq n} P_m^{(t)} h_{n,m}\right) - Z_n^{(t)}\right)\right]^+, \quad (13)$$

where $\kappa_\lambda^{(t)}$, $\kappa_\mu^{(t)}$, $\kappa_\nu^{(t)}$, and $\kappa_\zeta^{(t)}$ are positive step sizes, and $[X]^+ = \max\{X, 0\}$. Based on the KKT condition [8], the optimal transmit power $\{P_n\}$ of each FUE n can be obtained through $\frac{\partial L_n(y_n, Z_n, \lambda, \mu_n, \nu_n, \zeta_n)}{\partial y_n} = 0$ as follows:

$$P_n^{(t+1)} = e^{y_n^{(t+1)}} = \left[\frac{1+\mu_n^{(t)}+\nu_n^{(t)}\Lambda_n^{(t)}\frac{\sigma_n^2}{\log(1-\xi_n)}}{\lambda^{(t)} g_n + \sum_{m\neq n}\nu_m^{(t)}\frac{\Lambda_m^{(t)} h_{m,n}}{1+P_n^{(t)} h_{m,n}\Lambda_m^{(t)}}}\right]_{P_n^{min}}^{P_n^{max}}, \quad (14)$$

where $\Lambda_n^{(t)} = \gamma_n^{th}/(P_n^{(t)} h_{n,n})$. The auxiliary variable Z_n can be achieved according to the KKT condition

$$e^{Z_n^{(t+1)}} = \left[\frac{\zeta_n^{(t)}\sigma_n^2}{1+\mu_n^{(t)} - \zeta_n^{(t)}}\right]^+. \quad (15)$$

B. Optimal Distributed Algorithm

Based on above optimization analysis, we present the optimal distributed power control algorithm

Algorithm 1 Optimal Distributed Power Control

Initialization

- Set $t = 0$, $P_n^{(0)}$ be any feasible point in feasible set $P_n^{min} \leq P_n^{(0)} \leq P_n^{max}$;
- Set $\lambda^{(0)} \geq 0$, $\mu^{(0)} \geq 0$, $\nu^{(0)} \geq 0$, $\zeta^{(0)} \geq 0$;
- Set step size $\kappa_\lambda^{(t)}, \kappa_\mu^{(t)}, \kappa_\nu^{(t)}, \kappa_\zeta^{(t)} > 0$;

Algorithm at FAP n

1) Measure the interference $\sum_{m\neq n} P_m^{(t)} h_{n,m}$ generated by all other FUEs and the noise power level σ_n^2;
2) Calculate $e^{Z_n^{(t+1)}}$ according to (15);
3) Update the *delay price* $\mu_n^{(t+1)}$ and *consistency price* $\zeta_n^{(t+1)}$ according to (11) and (13), respectively;
4) Transmit $\mu_n^{(t+1)}$, $h_{n,n}$ to FUE n;

Algorithm at FUE n

1) Estimate the channel gain g_n and receive $\{g_m, P_m\}_{m\neq n}$ to calculate the total interference at the MBS; Receive $\mu_n^{(t+1)}$ and $\zeta_n^{(t+1)}$, and estimate $\{h_{m,n}\}_{m\neq n}$;
2) Update the *interference price* $\lambda^{(t+1)}$ and the *outage price* $\nu_n^{(t+1)}$ according to (10) and (12), respectively;
3) Receive $\{\nu_m^{(t+1)}, \Lambda_m^{(t+1)}\}_{m\neq n}$, and then calculate the power value according to (14);
4) Broadcast g_n, $P_n^{(t+1)}$, $\nu_n^{(t+1)}$, and $\Lambda_n^{(t+1)}$;

Remark 1:

1) The convergence of Algorithm 1 can be proved using a gradient-based standard technique [8].
2) To update transmit power, each FUE n receives control messages from other FUEs and estimates the channel gain between itself and other FAPs m, i.e., $h_{m,n}$, using a training sequence. In practical mobile wireless networks, $h_{m,n}$ are stochastic rather than deterministic, and path loss estimations can be inaccurate.
3) The delay price update (11) needs only local information. The outage price update (12) requires the FAP n to measure interference separately from others FUEs $P_m^{(t)} h_{n,m}$ or the channel gain $h_{n,m}$, in general, $h_{n,m} \neq h_{m,n}$.
4) In Algorithm 1, the messages broadcast by FAPs and FUEs contain much individual information, causing incremental overhead and large convergence time.

IV. Near-Optimal Algorithm

In this section, we eliminate the impractical issues of interference estimation and message passing in Algorithm 1 by proposing a near-optimal scheme.

In order to do that, we first relax the outage constraints of (6). We apply the upper and lower bounds on the outage probability derived in [5] to the outage constraint as $\mathbf{Pr}\left[\gamma_n \leq \gamma_n^{th}\right] \leq 1 - \exp\left(-\frac{\gamma_n^{th}}{\bar{\gamma}_n}\right) \leq \xi_n$ and $\frac{\gamma_n^{th}}{\bar{\gamma}_n + \gamma_n^{th}} \leq \mathbf{Pr}\left[\gamma_n \leq \gamma_n^{th}\right] \leq \xi_n$, which correspond to the SINR constraints $\bar{\gamma}_n \geq -\frac{\gamma_n^{th}}{\log(1-\xi_n)}$ (upper bound) and $\bar{\gamma}_n \geq \gamma_n^{th}\left(\frac{1}{\xi_n} - 1\right)$ (lower bound), respectively. Hence, the outage constraints of problem (6) can be approximately replaced by $\bar{\gamma}_n \leq \eta_n$, where η_n is either of those two constants.

Next, we relax the interference constraints of (6). In Algorithm 1, to achieve the interference information at MBS, each FUE has to broadcast the channel gain between itself and MBS with a transmit power value to all other FUEs. The broadcast information increases the message exchange burden. To overcome this drawback, we divide the maximum interference level I into N equal parts. Each FUE assures that its interference to MBS does not exceed I/N.

Then, we have a new optimization problem

$$\begin{aligned}
\underset{\mathbf{y}\in\hat{\mathcal{P}}, \mathbf{Z_n}}{\text{minimize}} \quad & \sum_{n=1}^{N} \log\left(\frac{e^{-y_n}}{h_{n,n}}\left(e^{Z_n} + \sigma_n^2\right)\right) \\
\text{s.t.} \quad & g_n e^{y_n} \leq I/N, \quad \forall n, \\
& \log\left(\frac{e^{-y_n}}{h_{n,n}}\left(e^{Z_n} + \sigma_n^2\right)\right) - \Phi_n \leq 0, \quad \forall n, \\
& -\log\bar{\gamma}_n \leq -\log\eta_n, \quad \forall n, \\
& \log\left(\sum_{m\neq n} h_{n,m} e^{y_m}\right) - Z_n \leq 0, \quad \forall n. \quad (16)
\end{aligned}$$

This problem is also a convex problem. Using the same approach as in Section III, Lagrange multipliers are updated as follows

$$\lambda_n^{(t+1)} = \left[\lambda_n^{(t)} + \kappa_\lambda^{(t)}\left(g_n P_n^{(t)} - I/N\right)\right]^+, \quad (17)$$

$$\nu_n^{(t+1)} = \left[\nu_n^{(t)} + \kappa_\nu^{(t)}\left(\log\left(\frac{e^{Z_n^{(t)}} + \sigma_n^2}{P_n^{(t)} h_{n,n}}\right) + \log\eta_n\right)\right]^+. \quad (18)$$

Similarly, based on above approximation, we propose Algorithm 2 to obtain the global optimal solution for (16).

Algorithm 2 Near-Optimal Distributed Power Control

Initialization

Algorithm at FAP n

1) Measure the interference $\sum_{m\neq n} P_m^{(t)} h_{n,m}$;
2) Calculate

$$e^{Z_n^{(t+1)}} = \left[\frac{\zeta_n^{(t)}\sigma_n^2}{1+\mu_n^{(t)}+\nu_n^{(t)}-\zeta_n^{(t)}}\right]^+; \qquad (19)$$

3) Update $\mu_n^{(t+1)}$, $\nu_n^{(t+1)}$, and $\zeta_n^{(t+1)}$ according to (11), (18), and (13), respectively;

Algorithm at FUE n

1) Estimate g_n and update $\lambda_n^{(t+1)}$ according to (17);
2) Receive $\mu_n^{(t+1)}$, $\nu_n^{(t+1)}$, calculate the power value

$$P_n^{(t+1)} = \left[\frac{1+\mu_n^{(t)}+\nu_n^{(t)}}{\lambda_n^{(t)} g_n}\right]_{P_n^{min}}^{P_n^{max}}; \qquad (20)$$

Remark 2:

1) In Algorithm 2, each FAP n only needs to broadcast the consistency price, and FUE does not need to broadcast any individual information.
2) The interference price (17) and outage price update (18) require only local information. The power update (20) only requires the consistency price from other FAPs but no individual information from other FUEs.
3) Algorithm 2 converges to the global optimal point of (16), which is an approximated problem of (6). Hence, the optimal solution of (16) is considered as a near-optimal solution to (6) (due to the tightness of the bounds).

V. Numerical Results

We consider a cellular network with one MBS with a coverage radius of $r_1 = 500$ m and three femtocells distributed randomly inside. The distances between the three FUEs and the MBS are 50 m, 100 m, and 500 m, respectively. The baseband bandwidth W is set to 32 kHz, and we use $K = -1.5/\log(5\text{BER})$ with $\text{BER} = 10^{-3}$ for MQAM modulation. P_{max} and P_{min} are set to 1 mW and 0 mW, respectively. Background noise is assumed to be 0.005 dB. The slow-fading channel gain is assumed to be $h(d) = h_0(\frac{d}{100})^{-4}$, where h_0 is a reference channel gain at a distance of 100 m. Packet traffic at each FUE has intensity $\lambda_n = 200$ packets/s, and packet length is 100 bits [6]. The respective outage probability thresholds ξ_n of the three FUEs are [0.2, 0.1, 0.1]. The SINR thresholds γ_n^{th} are [30, 20, 10] dB. We set the delay bounds as [0.01, 0.01, 0.01] seconds. The maximum interference level $I = 0.05$ dB.

Fig. 2 illustrates the FUE power convergence of two algorithms. The numerical results show that the near-optimal scheme converges faster than the optimal scheme. We observe that the near-optimal algorithm converges close to optimal values. Moreover, FUE_3 is the farthest from MBS; hence, it can transmit with the highest power.

Fig. 3 shows the FUE throughput for different algorithms: target-SINR-tracking power control (TPC) or Foschini-Miljanic algorithm [9], and opportunistic power control (OPC) [10]. Our proposals outperform the TPC and OPC schemes and can achieve 14.7% and 2% higher throughput than that of TPC and OPC, respectively. This is due to the fact that in the TPC scheme, all users reach their target SINRs without optimizing transmission power. In contrast, the OPC scheme results in a very different SINRs at the equilibrium where the strongest user (low interference) attains high SINR while the weak ones (high

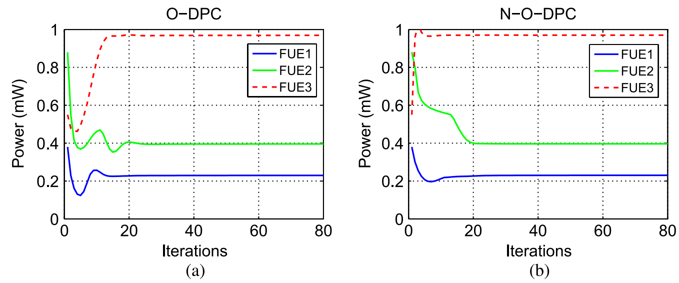

Fig. 2. Power convergence: (a) O-DPC, (b) N-O-DPC.

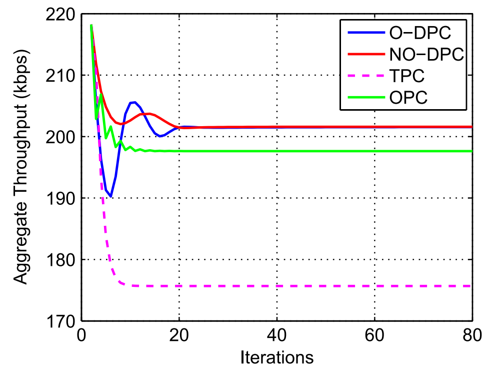

Fig. 3. Aggregate throughput in comparison with other algorithms.

interference) achieve low SINRs. Therefore, the OPC scheme tends to allocate more power to strong users to achieve high overall throughput.

VI. Conclusion

We have designed two distributed algorithms to solve the power control problem for interference management and network QoS guarantee in two-tier heterogeneous networks. The first algorithm is the optimal scheme but is impractical. The second design with a small-size control message is a near-optimal scheme based on a tight bound approximation on outage probability and partitioning of the maximum interference level. Numerical experiments show that the schemes' performances are almost indistinguishable and outperform the conventional works.

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