Per Cluster Based Opportunistic Power Control for Heterogeneous Networks

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***Abstract*—This paper proposes an opportunistic power control (PC) algorithm to mitigate the aggregate interference (AGGI) from active femtocells in uplink transmission. Macrocell base station (BS) decides the interference allowance per femtocell and femtocell users then allocate their transmit power within the allowance to suppress the cross-tier interference in heterogeneous networks. The PC algorithm should reflect the number of active femtocells per cluster to effectively control the AGGI, and we propose two sensing algorithms, such as centralized and distributed ones, to estimate the number of active femtocells. We compare the two sensing algorithms in terms of the outage and throughput performance. The algorithms exploit large-scale channel information and shadowing variation to guarantee the macrocell uplink channel quality. Consequently, the two sensing algorithms increase total cell throughput.**

***Index Terms*—Aggregate interference (AGGI), heterogeneous networks, cross-tier interference, opportunistic power control, centralized sensing, distributed sensing.**

I. Introduction

Recently, as demand for wireless applications with high data rate increases, femtocells have emerged as a solution to increase both the capacity and coverage while reducing operating expenses. Femtocells, which consist of low power base stations (BSs) and stationary or low-mobility femtocell users deployed in an indoor environment, are located within an existing macro cellular network; a macro-femto cochannel network is deployed. The new low power femtocells benefit the system average throughput because of the cell-split gain, while the macro user equipment (UE) may suffer from the interference caused by another cell layer. The main reason of the uplink edge coverage degradation in heterogeneous networks (Het-Nets) is the intensive interference aggression from another layer's UEs, which operate in the licensed spectrum owned by wireless operators and share this spectrum with macrocell networks. Thus, this makes the received signal-to-interference-plus-noise ratio (SINR) of the macro UE not sufficient and may lead to poor edge coverage performance [1], especially for a macro UE near the area where femtocells are densely deployed (e.g., shopping center and apartment area).

In literature, to mitigate the aggregate interference (AGGI), previous studies have developed cross-tier interference control methods by using transmit power control (PC) algorithm in [2] and [3], which have considered path loss (PL) for a two-tier Het-Net. An SIR based power control scheme is shown to improve uplink performance, but does not account for shadow fading [2], or is under the assumption that macro BS knows the instantaneous cross-channel state information of the underlaid users [3]. However, from the practical point of view, it is not easy to obtain the cross-channel state information and will increase the complexity and signaling overhead caused by the frequent measurement and update of the cross-channel state information. Therefore, this paper proposes the PC algorithm to obtain a feasible solution, which assumes that macro BS does not have the cross-channel state information of the underlaid users and considers the uncertainty caused by large-scale shadow fading for effective interference management, while minimizing the complexity and signaling overhead [4].

In this paper, the main objective of this PC algorithm is 1) ensuring that the service (data rate) provided to macro UE remain unaffected by femtocells underlaid which operate in the same spectrum, and 2) maximizing total cell throughput of the Het-Net system with little degradation to other layers by placing the uplink interference allowance per femtocell. The latter guarantees macro UE uplink channel quality by limiting the interference per femtocell [3]. We exploit large-scale channel information to predict the interference allowance, and also to ensure the proper functionality of a network, the shadowing variation is taken into account by an outage probability constraint.

In addition, this paper proposes an interference mitigation strategy in which macro BS adjusts the femtocell transmit power using a centralized sensing and a distributed sensing technique. The macrocell UE near the area where femtocells are densely deployed receives the AGGI from only those active femtocell UEs (FUEs) actually transmitting to their femtocell BSs (FeNBs)irrespective . The PC algorithm should reflect the number of active femtocells, not the number of entire femtocells. Consequently, the sensing algorithms are required to predict whether the femtocells are active. In the centralized sensing algorithm, macro BS considers all the femtocells within a single *cluster* and estimates the number of active femtocells from the received AGGI. On the other hand, in the distributed sensing algorithm, some of femtocells constitute *a new cluster* in less than cut-off distance and each femtocell senses whether the other femtocells are active in the same cluster. By using this, an opportunistic power control based on the effective interference level can increase cell throughput because more power can be allocated to active femtocells when more femtocells are in idle mode.

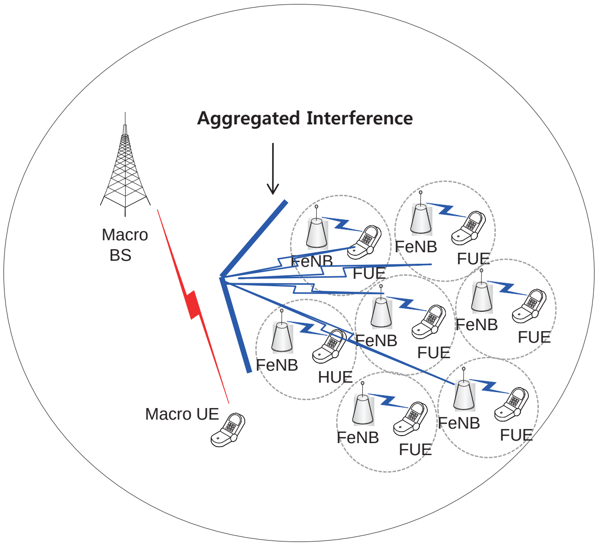

Fig. 1. Uplink interference scenario of macrocell and femtocells cochannel deployment.

The rest of the paper is organized as follows. We first describe the system model for opportunistic power control in Section II. In Section III, uplink interference allowance per femtocell is defined based on outage. Section IV is devoted to describing the proposed per cluster based opportunistic power control using the two sensing algorithms. Section V presents results and conclusions are drawn in Section VI.

II. System model

We consider a two-tier Het-Net where femtocells are densely deployed, and then the macrocell BS receives the AGGI as shown in Fig. 1.

The system consists of a single central macrocell B_0 with cell coverage radius R_c and femtocells, each of which consists of one FeNB and one FUE. The macrocell is underlaid with N cochannel femtocell BSs B_i, $i \geq 1$, which are randomly distributed in a building. A macrocell UE and FUEs are also randomly located in macrocell and femtocells. In other words, we assume that the channel information, such as path loss and user location is *a priori* known to macrocell, but shadowing remains an unknown variable. However, it is difficult for macrocell BS to fast and accurately track the instantaneous channel gains, and the resource allocation adaptive to fast variations in the channel gains will increase the complexity due to frequent measurements and updates. Therefore, in this paper, we exploit the large-scale channel information and shadowing variation for effective interference management, while reducing the complexity and signaling overhead. For analytical tractability, cochannel interference from neighboring macrocell transmissions is ignored.

For the uplink, let $i \in \{0, 1, ..., N\}$ denote the UE connected to its BS B_i, σ_n^2 be the variance of additive white Gaussian noise (AWGN). The received SINR γ_i of user i can be expressed as [5]

$$\gamma_i = \frac{p_i g_{i,i}}{\sum_{j\neq i} p_j g_{i,j} + {\sigma_n}^2} = \frac{p_i {r_{i,i}}^{-\alpha_i} 10^{\frac{\xi_i}{10}}}{\sum_{j\neq i} p_j {r_{i,j}}^{-\alpha_j} 10^{\frac{\xi_j}{10}} + {\sigma_n}^2} \quad (1)$$

where each p_i and p_j represent the power allocated to UE in i^{th} cell and j^{th} cell, $g_{i,i}$ is the channel gain from i^{th} UE to its corresponding BS in i^{th} cell, $g_{i,j}$ is the cross-channel gain from j^{th} UE to BS in i^{th} cell, ${r_{i,j}}^{-\alpha_j}$ is the path loss between j^{th} UE to i^{th} BS, and ${r_{i,i}}^{-\alpha_i}$ is similar. The terms α_j and α_i are the pass loss exponents (i.e., FUE to FeNB is α_{f1}, FUE to macro BS and macro UE to FeNB is α_{f2} and maro UE to macro BS is α_c). ξ_i and ξ_j are normal distributed random variables (RVs) with zero mean and standard deviation σ_i and σ_j. $10^{\frac{\xi_i}{10}}$ and $10^{\frac{\xi_j}{10}}$ are the shadowing effects and lognormal RVs characterizing the random variations of the received power around a mean value.

III. Outage based power control with interference allowance

In this section, an uplink power control for femtocell users is proposed that increases total cell throughout of the Het-Net system with little degradation to other layers by placing the uplink interference allowance per femtocell (P_r). It guarantees the uplink transmission quality from macro UE to its BS by limiting the interference per femtocell. When the interference allowance is predicted, large-scale channel information is exploited. To ensure the proper functionality of a network, the shadowing variation is controlled by an outage probability constraint. The maximum outage probability δ is allowed for large-scale shadow fading with the required SINR threshold (Γ_0), which is defined as

$$\Pr[\gamma_0 < \Gamma_0] < \delta. \quad (2)$$

To calculate the SINR distribution of macro UE, we take into account the shadowing modeled as an independent log-normal RV. So the received power from macro UE in (1) can be expressed as

$$p_i g_{i,i} = p_0 {r_0}^{-\alpha_c} 10^{\frac{\xi_i}{10}} \triangleq 10^{\frac{X}{10}} \quad (3)$$

where X is Gaussian RV with mean $\mu_x = \frac{1}{a}\ln(p_0 {r_0}^{-\alpha_c})$ for $a = \ln 10/10$ and variance σ_c^2 for shadowing ξ_0.

We attempt to control the transmit power of j^{th} FUE such that the received power at the macrocell is the same for all FUEs, i.e., $p_j {r_{i,j}}^{-\alpha_j} = P_r$. So the received power at macrocell BS from j^{th} FUE in (1) can be defined as

$$p_j g_{i,j} = p_j {r_{0,j}}^{-\alpha_j} 10^{\frac{\xi_j}{10}} = P_r 10^{\frac{\xi_j}{10}} \quad (4)$$

where ξ_j is Gaussian RV with mean zero and variance σ_f^2.

Therefore, if the AWGN is negligible, the received SINR γ_0 of macrocell UE at B_0 can be rewritten as $\gamma_0 \triangleq \frac{1}{Y}$

$$Y \simeq \sum_{j=1}^{N} \frac{P_r 10^{\frac{\xi_j}{10}}}{10^{\frac{X}{10}}} = \sum_{j=1}^{N} e^{a\xi_j^*} \quad (5)$$

where ξ_i^* is Gaussian RV with mean $\mu_{\xi_i^*} = \frac{1}{a}\ln P_r - \mu_x \triangleq \eta$ and variance $\sigma^2 = \sigma_c^2 + \sigma_f^2$, and N is the number of active femtocells. The lognormal sum Y can be well approximated by a new lognormal RV as

$$Y \cong \sum_{j=1}^{N} e^{a\xi_j^*} \triangleq e^{aZ}. \tag{6}$$

Then, combining (2) and (6), the outage probability can be evaluated as

$$1 - Q\left(\frac{\mu_z + \frac{1}{a}\ln\Gamma_0}{\sigma_z}\right) < \delta \tag{7}$$

where $Q(x) = 1/\sqrt{2\pi}\int_x^\infty e^{-y^2/2}\,dy$, μ_z and σ_z denote the mean and standard deviation of RV Z. We can compute μ_z and σ_z by exactly matching the first and second central moments of RV Y using the Fenton-Wilkinson method [6]. The first and second moments of RV Y in (5) can be expressed as

$$\mathbf{E}\{Y\} = \mathbf{E}\{\sum_{j=1}^{N} e^{a\xi_i^*}\} = Ne^{a\eta + a^2\sigma^2/2} \tag{8}$$

$$\begin{aligned}\mathbf{E}\{Y^2\} &= \sum_{j=1}^{N}\mathbf{E}\{e^{2a\xi_i^*}\} + \sum_{j=1}^{N}\sum_{j'>j}\mathbf{E}\{e^{a\xi_j^*}\}\mathbf{E}\{e^{a\xi_{j'}^*}\} \\ &= Ne^{2a\eta+2a^2\sigma^2} + (N^2 - N)e^{2a\eta + a^2\sigma^2}.\end{aligned} \tag{9}$$

Similarly, the first and second moments of RV Y in (6) can be expressed as

$$\mathbf{E}\{Y\} = \mathbf{E}\{e^{az}\} = e^{a\mu_z + \frac{1}{2}a^2\sigma_z^2} \tag{10}$$

$$\mathbf{E}\{Y^2\} = \mathbf{E}\{e^{2az}\} = e^{2a\mu_z + 2a^2\sigma_z^2}. \tag{11}$$

Now, combining (8), (9), (10) and (11), μ_z and σ_z can be derived as

$$\begin{aligned}\mu_z = &\frac{1}{a}\ln\left(Ne^{a\eta + a^2\sigma^2/2}\right) \\ &- \frac{1}{2a}\ln\left[\frac{1}{N}e^{a^2\sigma^2} + \left(1 - \frac{1}{N}\right)\right]\end{aligned} \tag{12}$$

$$\sigma_z = \frac{1}{a}\sqrt{\ln\left[\frac{1}{N}e^{a^2\sigma^2} + \left(1 - \frac{1}{N}\right)\right]}. \tag{13}$$

Hence, the outage probability can be evaluated as a function of P_r and N, namely $f(P_r, N)$ from (7), (12) and (13) as

$$1 - Q(f(P_r, N)) < \delta. \tag{14}$$

Therefore, if the number of active femtocells N is estimated, the interference allowance per femtocell P_r can be predicted. In the following section, the two sensing algorithms are described to estimate the number of active femtocells N.

IV. Per cluster based opportunistic power control

An opportunistic uplink power control scheme for femtocell UEs (FUEs) is proposed that adjusts the interference allowance per femtocell via the estimation of effective AGGI using centralized and distributed sensing algorithms.

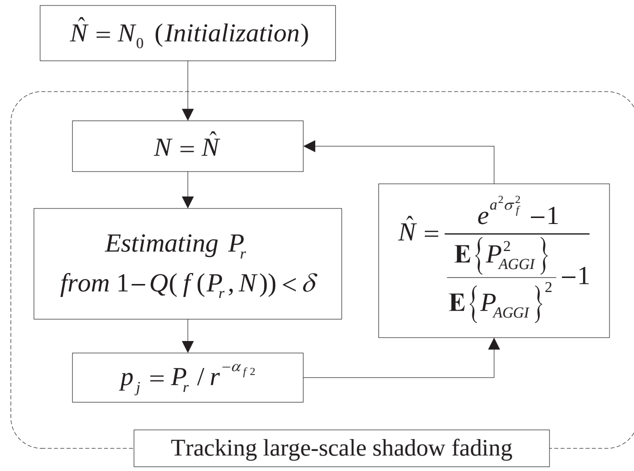

Fig. 2. A flow diagram for opportunistic power control with centralized sensing.

The macrocell BS receives the cross-tier interference from only those active FUEs transmitting to their own FeNBs. The PC algorithm should reflect the number of active FUEs, not the number of entire FUEs. The opportunistic power control based on the effective AGGI level can increase cell throughput because more power can be allocated to active FUEs when more FUEs are in idle mode.

A. Centralized sensing algorithm

In centralized sensing algorithm, macrocell BS estimates the number of active femtocells (N) from the received AGGI level. Assumed that AWGN is negligible, the received AGGI level is formulated as

$$\sum_{j=1}^{N} p_j g_{0,j} + \sigma_n^2 \cong \sum_{j=1}^{N} P_r 10^{\frac{\xi_j}{10}} = P_{AGGI}. \tag{15}$$

Interference from each femtocell has an independently and identically distributed (i.i.d) lognormal random characteristic via the interference allowance per femtocell (P_r). Thus, the *aggregate* interference (P_{AGGI}) from all active femtocells has also a lognormal random characteristic. By using these characteristics, the number of active femtocells can be estimated using the two terms of the first moment of AGGI and its second moment expressed as

$$\mathbf{E}\{P_{AGGI}\} = NP_r\, e^{\frac{1}{2}a^2\sigma_f^2} \tag{16}$$

$$\mathbf{E}\{P_{AGGI}^2\} = \left(N^2 - N\right)P_r^2\, e^{a^2\sigma_f^2} + NP_r^2\, e^{2a^2\sigma_f^2}. \tag{17}$$

Thus, combining (16) and (17), the number of all active femtocells $\hat{N}$ is estimated as

$$\hat{N} = \frac{e^{a^2\sigma_f^2} - 1}{\mathbf{E}\{P_{AGGI}^2\}/\mathbf{E}\{P_{AGGI}\}^2 - 1}. \tag{18}$$

Fig. 2 shows the opportunistic power control procedure with centralized sensing used to estimate the number of active femtocells N. After the number of active femtocells ($\hat{N}$) is estimated in (18), femtocell UE (FUE) uplink power (p_j) is allocated subject to the interference allowance per femtocell (P_r), being predicted by (14) with N replaced with $\hat{N}$, *entirely*.

B. Distributed sensing algorithm

In centralized sensing, macrocell BS estimates continuously the interference from all active femtocells and determines the number of active femtocells. For this reason, the message overhead of X2 interface at macrocell BS increases. In order to reduce the message overhead of X2 interface, we propose distributed sensing algorithm being conducted *locally*.

The whole distributed sensing scenario is depicted in Fig. 3. First, some of femtocells constitute *a new cluster* in less than cut-off distance (step1) and each femtocell senses whether the other femtocells are active in the same cluster. In other words, each femtocell makes a table about the *cell ID* and *activity* (ON/OFF) from directly connected one (1 hop) to the farthest one in order. The updating process keeps going until there is not a newly updated cell ID (step 2). Then, by using this information, an active femtocell ratio (k) is computed (step 3), while all femtocells in a cluster maintaining the same active femtocell ratio. Subsequently, each femtocell determines its effective interference allowance (P_r^*) by normalizing P_r with the active ratio k (step 4). Therefore, femtocells can opportunistically increase their uplink power (p_j) by sensing the number of non-active femtocells in the same cluster, locally (step 5).

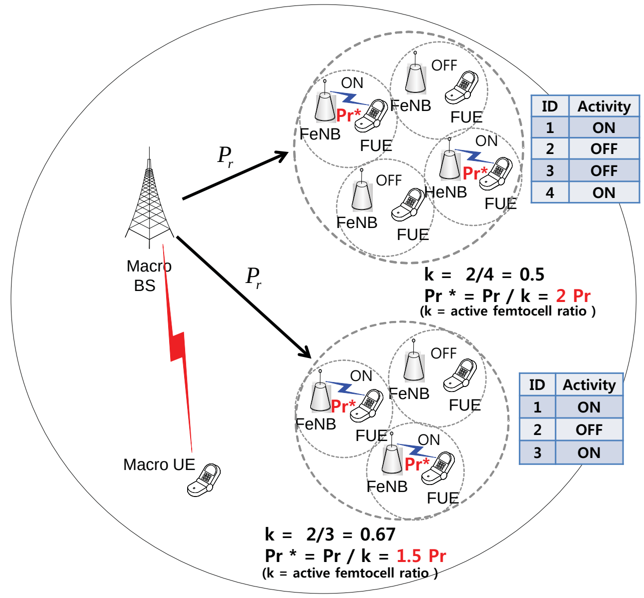

Fig. 3. Opportunistic power control with distributed sensing.

V. Results

We evaluate the performance of opportunistic power control with the proposed sensing algorithms. In our simulation, the Het-Net consists of a macrocell and femtocells. The simulated cell layout assumes 16 femtocells and one macro UE, which is located in the macrocell coverage R_c of 1000 meters. Each femtocell is assumed to have a circular coverage with radius 15 meters and one FUE 5 meters distant from itself. The femtocells whose activity and location are decided in the initialization phase and kept constant for the whole simulation time, are distributed in a building with radius 100 meters. In the following performance evaluations, we set the transmit power of the j^{th} femtocell p_j 15dB and a macrocell p_0 30dB. The AWGN σ_n^2 in (1) was set by assuming a cell-edge user obtains a cellular SNR equaling 20dB at B_0. The propagation model assumes the operation in urban environment and takes into consideration path loss and shadowing. The path loss exponents α_{f1} and α_c are set to be 3 while α_{f2} is set to be 4, and shadowing for each user is modeled as an independent lognormal RV with standard deviation 6dB (σ_f) and 8dB (σ_c). To check whether the opportunistic power control algorithms satisfy outage probability constraints, we generate sufficient number of different short-term fading events.

A. Outage probability performance

To see the outage performance of the proposed opportunistic power control using active femtocell sensing algorithms, we compare the measured outage probability obtained from the proposed centralized and distributed sensing algorithms to the one obtained from N known case for the fixed target SINR 10dB and 20dB. In Fig. 4, we first see that the outcome of centralized sensing algorithm is about the same as the N known case. However, in distributed sensing algorithm, the outage probability is kept to a lower level than the other two cases. This is because in distributed sensing macrocell BS computes P_r under the assumption that all femtocells are active. In other words, N is not estimated as proposed in centralized sensing algoritnm, but N is total number of femtocells. Therefore, each femtocell is initially allocated a lower transmit power than the centralized sensing. This results in lower aggregate interference in macrocell BS. In Fig. 5, we observe higher outage probability than its average in centralized sensing, and that distributed sensing is more stable than centralized sensing. However, every outcome of all trials does not always satisfy a target outage probability because of fluctuations due to unexpected short-term fading and added white Gaussian noise. Therefore, we replace Γ_0 with $\Gamma_0 + \alpha$ in (7) to set some margin in P_r, so as to satisfy the target outage probability with limited violation rate, say 25%.

B. Throughput performance

The total cell throughput is shown in Fig. 6. We see that the sum rate of distributed sensing algorithm incurs about 2.1% of loss when compared to that of N known case and about 1.9% of loss when compared to that of centralized sensing algorithm. As mentioned earlier, this is because in distributed sensing each femtocell is initially allocated a lower transmit power than the other two cases. Also, the resulting lower outage probability with distributed sensing was not accounted for. If we set the margin in the target SINR by αdB to meet a limited violation rate for a target outage probability, Fig. 7 then shows the total cell throughput with Γ_0 and $(\Gamma_0 + \alpha)$dB when Γ_0 is 10dB. We observe that the sum rate of the three

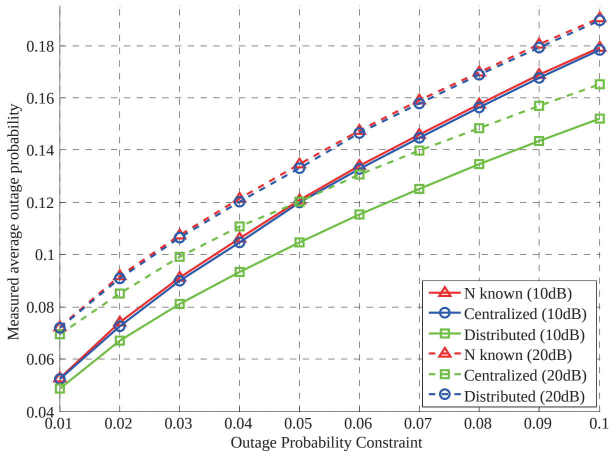

Fig. 4. The measured outage probability (averaged over channel fading) versus outage probability constraint δ with target SINRs 10dB and 20dB.

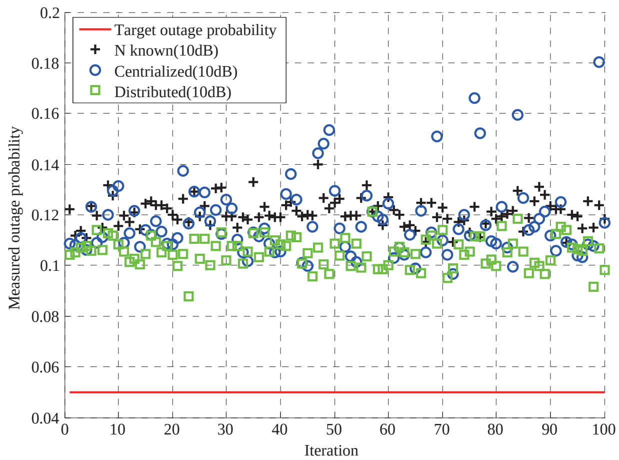

Fig. 5. The measured outage probability in each long-term channel realization (iteration) with target SINR 10dB.

cases is similar. Therefore, the proposed sensing algorithms are effective to increase the total cell throughput.

VI. Conclusion

We have proposed per cluster based opportunistic power control via activity sensing for a cochannel deployment with macrocell and femtocells. The power control scheme exploits large-scale channel information and shadowing variation to predict the interference allowance per femtocell based on the received aggregate interference. The power control scheme guarantees the macrocell UE uplink channel quality by placing the interference allowance per femtocell. The centralized and distributed sensing algorithms were shown to be effective in estimating the number of active femtocells to perform the opportunistic power control, either entirely or locally. Thus, total cell throughput can be increased.

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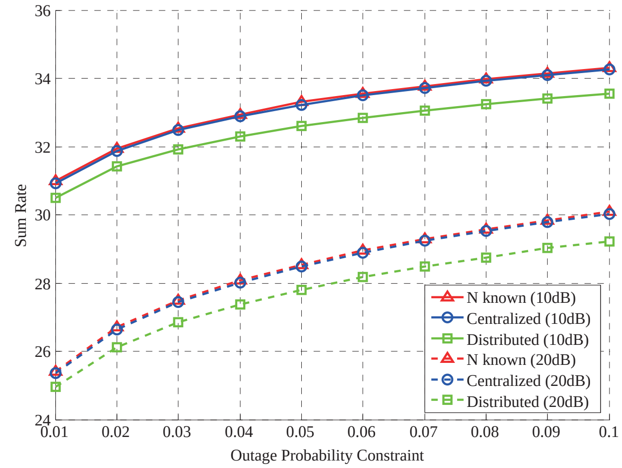

Fig. 6. Total cell throughput with target SINRs 10dB and 20dB.

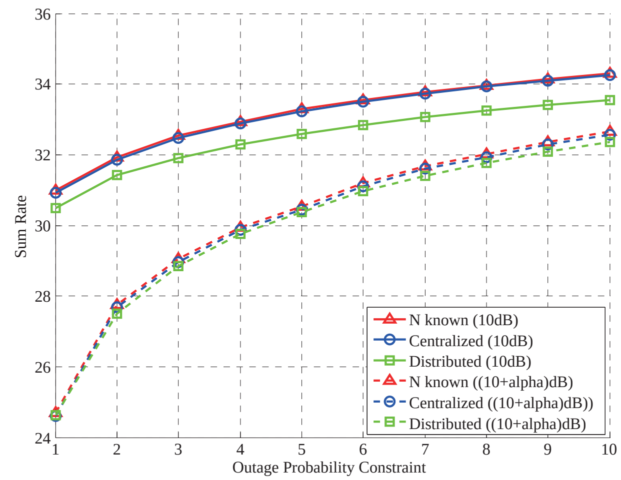

Fig. 7. Total cell throughput with target SINRs 10dB and $(10+\alpha)$dB when the margin αdB is set to meet a limited violation probability.

References

[1] 3GPP TSG RAN WG1 Meeting #61b R1-103499, CATT, “Uplink data channel interference mitigation via power control.”

[2] 3GPP TR 36.814, “Further advancements for E-UTRA physical layer aspects,” v9.0.0, Mar. 2010.

[3] V. Chandrasekhar, J. G. Anrews, T. Muharemovic, Z. Shen, and A. Gatherer, “Power control in two-tier femocell networks,” *IEEE Trans. Wireless Commun.*, vol. 8, pp. 4316-4328, Aug. 2009.

[4] D. I. Kim, L. Le, and E. Hossain, “Joint rate and power allocation for cognitive radios in dynamic spectrum access environment,” *IEEE Trans. Wireless Commun.*, vol. 7, pp. 5517-5527, Dec. 2008.

[5] Y. Bai, J. Zhou, and L. Chen, “Hybrid spectrum usage for overlaying LTE macrocell and femtocell,” *IEEE Proc. GLOBECOM ‘09*, pp. 1-6, Dec. 2009.

[6] J. Wu, N. B. Mehta, and J. Zhang, “A Flexible lognormal sum approximation method,” *IEEE Proc. GLOBECOM ‘05*, vol. 6, pp. 3413-3417, Dec. 2005.