# Interference Mitigation and Spectrum Sharing for Heterogeneous Networks Based on CQI Feedbacks

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***Abstract*—In this paper, we address a cross-tier interference mitigation scheme for heterogeneous networks based on cognitive radio technology, where the femtocell equipments, functioning as the secondary user, share the same frequency resource with the macrocell in the underlay mode. Different from other work, we assume that the femtocell access point (FAP) is able to listen to the quantized cellular channel quality information from the macrocell user equipments (MUEs) in its vicinity, and judiciously selects its own transmission power such that the average femtocell throughput is maximized with tolerable rate loss to the macrocell. We demonstrate the efficacy of the proposed scheme through extensive simulations under three typical scenarios: FAP has macrocell's scheduling information, FAP does not have this scheduling information but protects MUEs in a statistical fashion and, finally, FAP conservatively utilizes the channel by assuming the activated MUE always exists in its vicinity.**

## I. Introduction

The explosive increase in demand for higher data rates and lower power consumptions is the fundamental momentum for the next generation mobile networks. While the capacity provided by the existing LTE macrocell is satisfactory, studies show most of the communication activities are initiated from indoors [1]. In order to offload the traffic from the macrocell and improve the coverage of the cellular network, recently a new class of user deployed base station (i.e. FAP) has received considerable attention [2]. The distinct advantage of femtocells is that they offer immense capacity improvement for the network due to the ability of reusing the frequency. However, unauthorized (to FAP) MUEs could only connect to the macrocell eNodeB (MeNB) even if a FAP exists in the proximity. These MUEs may suffer heavy cross-tier interference from the femtocell.

Existing literature has proposed some possible solutions for this issue [3]. In this paper, we borrow the idea from the cognitive radio and allow the femtocell UE (FUE) share the same subband with the MUE in the downlink session as suggested in [4]. In this scenario, the femtocell works as the secondary user (SU) which occupies the macrocell (as primary user, PU) spectrum with some protection mechanism. In [5], the Cognitive Femto Base Station (CFBS) is equipped with sensing capability and able to construct a radio environment map (REM). Al-Rubaye et al. [6] considers the QoS and cross-layer design at the femtocell gateway and allows the femto to utilize the macrocell spectrum in the interweave fashion. In [7], the authors suggest the femto user to share the same frequency band with the macro when the macro user is in the retransmission mode. Nishimori et al. [8] proposes an enhanced interference cancelation technique by introducing a helper that decodes and transfers the interference from the primary to the secondary node. Different from all the existing work, we apply the spectrum sharing scheme (as one of the important cognitive radio technologies) in [9] and allow the FAP to overhear the channel quality information/indicator (CQI) from the MUE by listening to the macrocell uplink control channel; thereafter the FAP adopts proper transmission power to keep the MUE rate loss within a certain threshold.

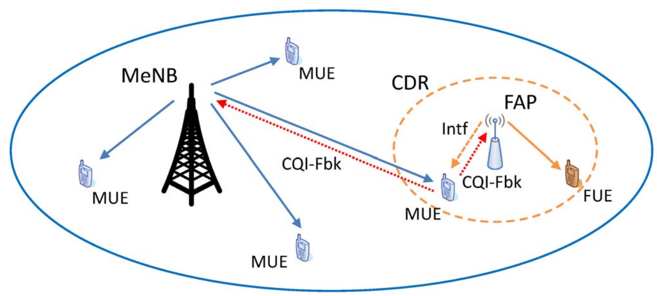


Fig. 1. Femtocell co-exists with macrocell and its interference to MUE

The contributions of this paper are listed as below:

- we investigate the spectrum sharing opportunities of the femtocell when co-existing with a multiple-user macrocell in a heterogenous network system;
- through listening to the CQI feedbacks from multiple MUEs in its vicinity, the FAP can judiciously select its transmission power and rate such that the effective femtocell throughput is maximized;
- in the meanwhile, the optimization problem is able to guarantee that the rate loss to the macrocell is limited by the preset threshold.

## II. System Model

We consider a typical downlink macrocell/femtocell co-existing problem, where the same subband is shared between two parties. The fundamental issue herein is how to cope with the interference from FAP to MUE as shown by the dashed arrow in Figure 1. The MeNB is responsible for serving $M$ connected users within the cell according to the channel quality indicator (CQI) fed back from the MUE side, as illustrated by the red dot arrow. The channel propagation gains from MeNB to multiple MUEs are represented by $g_m$ where $m = 1, 2, \ldots, M$. It is assumed that MeNB applies the max-C/I scheduler where the MUE with highest CQI index is selected as the active user. The MeNB adopts a constant transmission power $P_{\mathrm{M}}$ but applies the Adaptive Modulation and Coding (AMC) to match the channel with proper transmission rate. The codebook is designed such that the average cell throughput is maximized (the detail will be presented in Section III-A). Note that MU-MIMO is out of the scope of this paper, i.e. only one MUE can be served for each timeslot on this subband.

We assume that the CQI feedbacks from all the MUEs within the so-called CQI detectable region (CDR, the dashed circle around FAP) can be listen by the FAP. This may require the synchronization between the femto and the macrocell. In addition, the MUEs whose CQIs can not reach the FAP are believed to be out of the interfered area of the femtocell, according to channel reciprocity. Note that it requires to limit the maximum transmission power of the FAP. Without loss of generality, we assume that there are $N$ ($N \leq M$) MUEs within the CDR. We also denote the channel gains between FAP and MUE, FAP and FUE, MeNB and FUE as $h_n$, $g_{\mathrm{F}}$, $h_{\mathrm{F}}$, respectively. It is assumed that the instantaneous values for these channel gains are not available but their long-term statistics (mean $\bar{h}_{\mathrm{M}}$, $\bar{g}_{\mathrm{F}}$, $\bar{h}_{\mathrm{F}}$ and distribution) are known through monitoring reference signal and backhaul connection.

## III. Interference Mitigation Scheme of Femtocell

In this section, we will introduce the interference mitigation scheme in detail. At first, the codebook design for the macrocell AMC is elaborated. Then, we formulate an optimization problem by introducing the spectrum sharing technique in cognitive radio. Finally, Sequential Convex Programming (SCP) [10] is exploited to solve the non-convex problem.

### *A. Codebook Design for Macrocell Downlink AMC*

As mentioned in the system model, MeNB serves one active MUE at a time with max-C/I scheduler. It is s-traightforward to design the codebook according to the distribution of the largest Carrier to Interference plus Noise Ratio (CINR) at the MUE side. If defining a virtual index $\tilde{m} = \mathrm{argmax}_m \ \{g_1, g_2, \ldots, g_M\}$ (which may change in each transmission timeslot), the CQI quantize thresholds are derived from the distribution of $g_{\tilde{m}}$ instead of individual $g_m$. Therefore, we could assume the *cdf.* function of the Carrier to Noise Ratio (CNR) at MUE $\tilde{m}$ (i.e. $\gamma_{\tilde{m}} \triangleq \frac{g_{\tilde{m}}}{N_0}$ where $N_0$ is the background Gaussion noise with mean $\sigma^2$) to be $F_{\Gamma_{\tilde{m}}}(\gamma)$, and further divide the domain of the CNR into $L$ quantize regions i.e. $[T_0, T_1), [T_1, T_2), \ldots, [T_{L-1}, T_L)$ (where $T_0 = 0$ and $T_L = +\infty$). Here $T$'s denote the quantize thresholds, and each region is indicated by its CQI feedback index $l$ from 0 (Out of Range, OOR) to $L-1$. The total number of feedback bits for each MUE is $\lceil \log_2(L) \rceil$. It is assumed MeNB is with constant transmission power $P_{\mathrm{M}}$, except that if OOR's are received from all MUE's. By this it means if no MUE within the cell has ideal conditions for receiving message, the MeNB will restrict from transmitting in this slot. In summary, the rate maximization problem for macrocell is given as

$$\max_{\mathbf{T}} \ \bar{R}_{\mathrm{M}} = \sum_{l=1}^{L-1} \log\left(1 + T_l P_{\mathrm{M}}\right) F_{\Gamma_{\tilde{m}}}(T_l, T_{l+1}) \qquad (1)$$

where $0 = T_0 \leq \ldots T_l \leq T_{l+1} \ldots \leq T_L = +\infty$, $\bar{R}_{\mathrm{M}}$ is the expected average throughput for the macrocell, $F_{\Gamma_{\tilde{m}}}(a, b) \triangleq F_{\Gamma_{\tilde{m}}}(b) - F_{\Gamma_{\tilde{m}}}(a)$, and the summation is from quantize region 1 since no MUE contributes to the total throughput when $\gamma_{\tilde{m}}$ falls in region 0 (OOR). The solution of problem (1) can be easily found in [11] as a special case.

### *B. Femto Throughput Maximization with Rate Loss Concern*

As assumed in the system model, the FAP can monitor the CQI feedbacks from the MUEs within its CQI detectable region, and sneak into the same subband. The most obvious opportunities come when all the received CQIs are 0, i.e. OOR, or none is received at FAP. By this it means there will be no active MUE within CDR in the upcoming timeslot, and femtocell activities are not interfering with any macrocell user. Additionally, transmission opportunities for femtocell also exist when CQI $> 0$. The reason is that small amount of interference from the FAP could be tolerable to the MUE as long as the received CINR is greater than lower quantize threshold $T_l$ (assume Index $l$ is sent from the MUE side). In order to further quantify these two types of transmission opportunities, we formulate the optimization problem in the following 3 scenarios:

*1) Scheduling Information is Available at FAP:* In this case, FAP knows exactly which MUE has been selected by MeNB and whether this active MUE is within the CDR or not. In order to quantify the rate loss to the macrocell, we can initially calculate the probability of $\tilde{n} = \tilde{m}$ ($\tilde{n}$ denotes the MUE index which has the largest CQI within CDR), i.e. the MUE who has the highest CINR is located close to FAP. By assuming i.i.d. Rayleigh fading on each macrocell downlink channel ($\bar{g}_M$ indicates the average channel gain), this probability is simply given by $N/M$ through the symmetry assumption. Therefore, with probability $1 - N/M$, the transmission of FAP has no interference to MUEs since the active MUE is out of the CDR, but when $\tilde{n} = \tilde{m}$, FAP should carefully choose its transmission power such that the rate loss to the macrocell is under the predefined threshold $R_{\mathrm{lo}}$, i.e.

$$\frac{N}{M}\left(\sum_{l=1}^{L-1} \log(1 + T_l P_{\mathrm{M}}) \left(F_{\Gamma_{\tilde{n}},l} - F_{\tilde{\Gamma}_{\tilde{n}},l}\right)\right) \leq R_{\mathrm{lo}} \qquad (2)$$

where $F_{\Gamma_{\tilde{n}},l} = F_{\Gamma_{\tilde{n}}}(T_l, T_{l+1})$, $F_{\tilde{\Gamma}_{\tilde{n}},l} = F_{\tilde{\Gamma}_{\tilde{n}}}(T_l, T_{l+1})$, and the new random variable $\tilde{\Gamma}_{\tilde{n}}$ represents the CINR at MUE $\tilde{n}$ when the interference from FAP is included in the denominator

$$\tilde{\gamma}_{\tilde{n},l} = \frac{g_{\tilde{n}}}{N_0 + h_{\tilde{n}} P_{\mathrm{F},l}} = \frac{\gamma_{\tilde{n}}}{1 + \frac{h_{\tilde{n}} P_{\mathrm{F},l}}{N_0}}. \qquad (3)$$

The difference between $F_{\Gamma_{\tilde{n}},l}$ and $F_{\tilde{\Gamma}_{\tilde{n}},l}$ in (2) actually indicates the outage probability of MUE $\tilde{n}$ under the interference from FAP i.e. $\tilde{\gamma}_{\tilde{n}} < T_l$. The detailed derivation for this outage probability is given in Appendix A. Note that the corresponding long term power limitation for the FAP is

$$\left(1-\frac{N}{M}\right)P_{\mathrm{F},0}+\frac{N}{M}\sum_{l=0}^{L-1}F_{\Gamma_{\tilde{n}},l}P_{\mathrm{F},l}\leq P_{\mathrm{F,th}} \quad (4)$$

where the first item reflects the power consumption when no active MUE is within the CDR.

*2) FAP protects MUEs Statistically without Scheduling Information:* Due to lack of the reliable backhaul between MeNB and FAP, the scheduling information is not available at FAP in general. However, the i.i.d. distribution of the macro downlink channels causes the max-C/I scheduler fairly selecting the MUEs inside and outside the CDR. We, therefore, can estimate the average rate loss to the MUE $\tilde{n}$ in each fading block by assuming that the probability of the active MUE within the CDR is given by $N/M$, and the corresponding rate loss and power limitation constraint are revised as

$$\frac{N}{M}\left(\sum_{l=1}^{L-1}\log(1+T_lP_{\mathrm{M}})\left(F_{\Gamma_{\tilde{n}},l}-F_{\tilde{\Gamma}_{\tilde{n}},l}\right)\right)\leq R_{\mathrm{lo}} \quad (5)$$

$$\sum_{l=0}^{L-1}F_{\Gamma_{\tilde{n}},l}P_{\mathrm{F},l}\leq P_{\mathrm{F,th}} \quad (6)$$

where the second constraint on the average power limitation is different from (4) since the FAP does not know whether the active MUE is in the CDR or not. In the other words, it can not separate the first item in (4) from the summation when no scheduling information from the macrocell is available.

*3) FAP assumes active MUE within CDR of all time:* In order to protect MUEs even more, we can hypothetically identify that the active MUE is always within the CDR, which leads to the conservative usage of the subband. The overestimated rate loss to the macrocell is

$$\sum_{l=1}^{L-1}\log(1+T_lP_{\mathrm{M}})\left(F_{\Gamma_{\tilde{n}},l}-F_{\tilde{\Gamma}_{\tilde{n}},l}\right)\leq R_{\mathrm{lo}} \quad (7)$$

which does not consider the probability $N/M$ in (5), but the power limitation constraint keeps the same with Scenario 2.

*Remark*: Scenario 1 relies on high speed backhaul connection between MeNB and FAP, or the possibility that the FAP is able to somehow decode the macro downlink control channel before the transmission. Conservatively speaking, the result can serve as an upperbound for the other two cases. Scenario 2 and 3, which do not need to know exactly which MUE is scheduled, are more realistic, by protecting the victim MUE in a statistic fashion or allowing spectrum sharing only when there is no active MUE near FAP. Certainly, the expected throughput of the femtocell will decrease, but the interference to the MUE will be greatly mitigated than applying full power.

At the current stage, we could apply three sets of constraints, i.e. (2,4), (5,6), and (7,6) to the femtocell power allocation problem. The objective is to maximize the femtocell throughput by judicious power selection. In the slow block fading channel, it is better to apply outage rather than ergodic capacity (which requires long code to capture the ergocity of the channel [12]). When only partial channel state information (CSI) is not available at the FAP, a small outage probability threshold $\epsilon$ is introduced, such that we can derive the corresponding transmission rate to meet this outage threshold. In this manner, the average effective throughput can be written into two parts

$$\bar{R}_{\mathrm{F,S1}}=\bar{R}_{\mathrm{F},0}+\bar{R}_{\mathrm{F},>0} \quad (8)$$

where 'F' indicates femtocell, 'S1' means Scenario 1, $\bar{R}_{\mathrm{F},0}=\left(1-\frac{N}{M}\right)(1-\epsilon)\log(1+\gamma_{\mathrm{F},0})$ denotes the throughput when no active MUE in the CDR, and $\bar{R}_{\mathrm{F},>0}=\frac{N}{M}\sum_{l=0}^{L-1}(1-\epsilon)\log(1+\gamma_{\mathrm{F},l})F_{\Gamma_{\tilde{n}},l}$ summarizes the throughput when $\mathrm{CQI}_{\tilde{n}}>0$. In Scenarios 2 or 3, due to lack of scheduling information, FAP can not benefit from separating $\bar{R}_{\mathrm{F},0}$ from the equation and the corresponding average throughput is given as

$$\bar{R}_{\mathrm{F,S2/S3}}=\sum_{l=0}^{L-1}(1-\epsilon)\log(1+\gamma_{\mathrm{F},l})F_{\Gamma_{\tilde{n}},l}. \quad (9)$$

The pre-designed SINR $\gamma_{\mathrm{F},l}$ in the above equations satisfies

$$\Pr\left\{\frac{g_{\mathrm{F}}P_{\mathrm{F},l}}{h_{\mathrm{F}}P_{\mathrm{M}}+N_0}<\gamma_{\mathrm{F},l}\right\}\leq\epsilon. \quad (10)$$

In other words, if we regulate the transmission rate of the femto-link to be $\log(1+\gamma_{\mathrm{F},l})$, the corresponding outage probability should be less or equal to $\epsilon$ with transmission power $P_{\mathrm{F},l}$. Furthermore, it can be shown that the SINR threshold $\gamma_{\mathrm{F},l}$ in equation (8) and (9) can be approximated as $\gamma_{\mathrm{F},l}\approx\kappa P_{\mathrm{F},l}$ where tuning parameter $\kappa=\frac{\epsilon\bar{g}_{\mathrm{F}}}{(1-\epsilon)P_{\mathrm{M}}\bar{h}_{\mathrm{F}}-\epsilon\sigma^2/\log(1-\epsilon)}$ (see Appendix B for derivation). The approximation is accurate when outage probability $\epsilon$ is less than 20%.

At the current stage, the formulated problem is given as

$$\max_{P_{\mathrm{F}}}\ \bar{R}_{\mathrm{F}} \quad (11)$$

$$\text{s.t.}\quad (2)\ (4), (5)\ (6),\ \text{or}\ (7)\ (6).$$

The objective function follows equation (8) or (9), given that scheduling information is available at the FAP or not. The problem aims to maximize the expected throughput of the femtocell subject to one of the three sets of the rate loss and power limitation constraint as discussed early. Note that all the transmission power $P_{\mathrm{F}}$'s are non-negative.

### C. Solution

(11) is a non-linear and non-convex optimization problem, which is generally hard to solve in polynomial time. However, after simple variable substitution $Q_{\mathrm{F},l}\triangleq 1/P_{\mathrm{F},l}$, both the rate loss as shown in Appendix A and the power limitation constraint appear to be convex constraints, and the objective is convex in terms of the new variables. Therefore, the above rate maximization is a typical differential convex (or called *d.c.*) problem. We apply the sequential convex programming (SCP) in [10], which linearizes the objective whenever a new set of $Q_{\mathrm{F},l}$'s is available. The process will be repeated until the convergence is achieved. Note that there are two issues with SCP: 1) the final solution could be a local, not global, optimal;

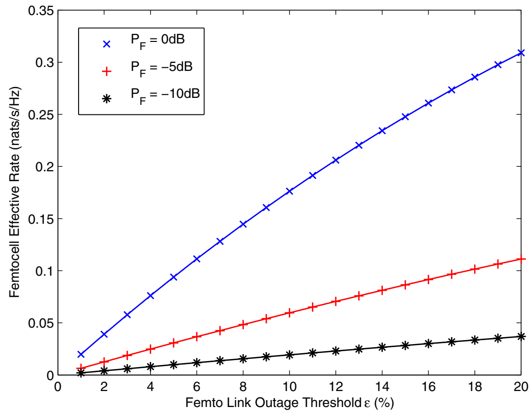


Fig. 2. Accuracy of approximation in (15)

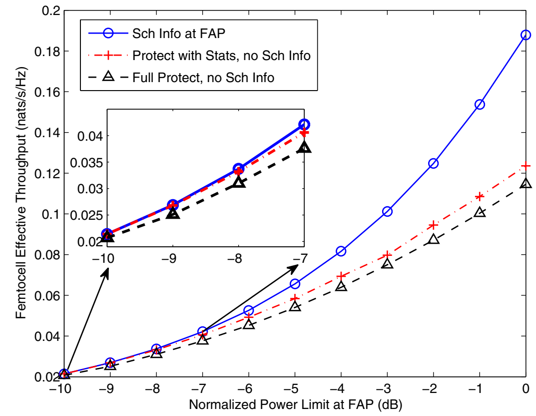


Fig. 3. Femtocell throughput with increased power limitation at FAP

2) sometimes, it is hard to find a feasible starting point. However, those issues do not exist in this problem. Initially, the 'time-sharing' condition in [13] can be substituted by fading instance sharing, due to the continuity of the channel gain distribution. Therefore, any local optimal which satisfies the Karush-Kuhn-Tucker (KKT) conditions is the global optimal. Secondly, we could find a starting point by just assuming the transmission power for the FAP is quite small such that the rate loss and the average power constraint are not violated.

## IV. Numerical Results

In this section, we will present some simulation results for the proposed interference mitigation scheme. It is assumed that all the channel links follow exponential distribution (Rayleigh fading) with mean values $\bar{g}_m = \bar{h}_{\mathrm{F}} = 1$ $(m = 1, \ldots, M)$ and $\bar{g}_{\mathrm{F}} = 4$. There are totally $M = 10$ MUEs within the whole macrocell, and 4 of them (unless notified otherwise) are in the CQI detectable region. We assume 4-bit CQI feedback from each MUE within the cell, which indicates by quantize region $l = 0$ to 15. In addition, the transmission power and the Gaussian noise at the receiver are equal to 1. The rate loss tolerance at the macrocell $(R_{\mathrm{lo}}/\bar{R}_{\mathrm{M}})$ is assumed to be 10%, same as the outage threshold for the femto link $\epsilon = 10\%$.

Figure 2 first demonstrates the accuracy of the throughput approximation in (15). The results denoted by the solid line are from the approximation, whereas the markers are derived from numerically solving equation (14) in Appendix B. It is observed that the approximation is applicable when the outage threshold is less than 20%. The transmission power of the FAP considered here is from 0, -5, to -10dB (normalized over $P_{\mathrm{M}}$).

Figure 3 assumes a weak interference scenario when the average channel gain from FAP to the MUE within CDR $\bar{h}_n = 0.4$ $(n = 1, \ldots, N)$. The average power limitation for the FAP is normalized over the macrocell peak power $P_{\mathrm{M}}$ and increases from -10dB to 0dB. Simulation results for the three Scenarios discussed in Section III-B are denoted, from top to bottom, by solid, dash-dot, and dashed line, respectively. It can be found that the scheduling information from the macrocell plays an important role in improving femtocell throughput. The gap with other scenarios is significant when FAP's power limitation approaches $P_{\mathrm{M}}$. In addition, it can be noticed that statistical protection (Scenario 2) can always achieve higher throughput and even approach the upperbound (provided by Scenario 1) when $P_{\mathrm{F,th}}$ is low. The reason is that the rate loss constraint is deactivated in this cases such that the expected throughput is only limited by the transmission power. However, Scenario 3 with full protection is competent on mitigating the interference and achieving comparable femtocell throughput, more importantly, requiring minimum information from the macrocell.

Finally, we consider the case when increasing $N$ - the total number of MUEs within CDR - from 1 to 10 and keeping $M = 10$ the same. In this simulation, it is assumed the strong interfering links from FAP to MUEs, i.e. $\bar{h}_n = 2$. It can be observed that increasing the connected MUEs in the femtocell reduces the effective throughput in that there are more victims with the CDR. Similar to Figure 3, full protection scheme (Scenario 3) denoted by the dashed line can achieve comparable results with statistical protection, except the case when only one or two MUEs are within CDR. In addition, all of the three schemes end up with the same result when all the 10 MUEs are in the CDR as shown in the graph.

## V. Conclusion

In this paper, we have proposed an interference mitigation scheme for the heterogenous network based on the cognitive radio technology. The novelty of the work is to allow the FAP to receive some feedback/control information from the MUEs within its detectable region. In this fashion, the femtocell can exploit the multiuser diversity between the MUE and the FUE by accessing the channel when the macrocell link is not optimistic, and restricting its transmission power when the active MUE is in its vinicity. The optimization problems in this paper are solved through successive convex programming, and the extensive simulation results shows the efficacy of the interference mitigation scheme with limited rate loss to the macrocell.

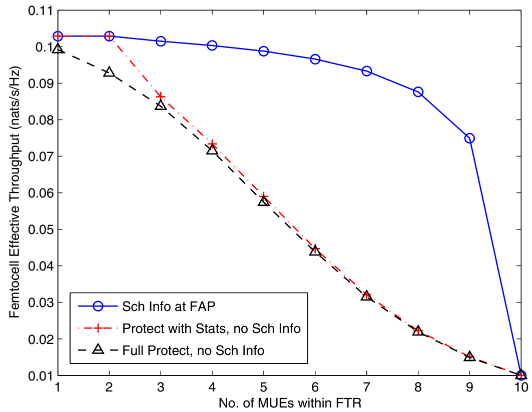


Fig. 4. Femtocell throughput versus total number of MUEs within CDR

## Appendix

### A. Derivation of Rate Loss for MUE

In this section, we are going to further derive the outage probability in equation (2), (5) and (7). The major cause of this outage is the undesirable interference from the FAP, i.e. the received CINR at the interested MUE is degraded from $\gamma_{\tilde{n}}$ to $\tilde{\gamma}_{\tilde{n}}$ as shown in (3) due to the femtocell transmission.

$$
\begin{aligned}
& F_{\Gamma_{\tilde{n}},l} - F_{\tilde{\Gamma}_{\tilde{n}},l} = F_{\Gamma_{\tilde{n}}}(T_l, T_{l+1}) - F_{\tilde{\Gamma}_{\tilde{n}}}(T_l, T_{l+1}) \\
&= F_{\Gamma_{\tilde{n}}}(T_l, T_{l+1}) - \Pr\left\{\tilde{\gamma}_{\tilde{n}} \geq T_l, T_l \leq \gamma_{\tilde{n}} < T_{l+1}\right\} \\
&= F_{\Gamma_{\tilde{n}}}(T_l, T_{l+1}) - \Pr\left\{h_{\tilde{n}} \leq \left(\frac{\gamma_{\tilde{n}}}{T_l} - 1\right)\frac{N_0}{P_{\mathrm{F},l}}, \gamma_{\tilde{n}} \in [T_l, T_{l+1})\right\} \\
&= F_{\Gamma_{\tilde{n}}}(T_l, T_{l+1}) - \int_{T_l}^{T_{l+1}} \left[1 - e^{-\left(\frac{\gamma}{T_l}-1\right)\frac{\sigma^2}{P_{\mathrm{F},l}h_{\tilde{n}}}}\right] f_{\Gamma_{\tilde{n}}}(\gamma)d\gamma \\
&= \int_{T_l}^{T_{l+1}} e^{-\left(\frac{\gamma}{T_l}-1\right)\frac{\sigma^2}{P_{\mathrm{F},l}h_{\tilde{n}}}} f_{\Gamma_{\tilde{n}}}(\gamma)d\gamma
\end{aligned}
$$

where the *cdf.* function of the maximal CINR within the femtocell CDR is given by

$$
F_{\Gamma_{\tilde{n}}}(\gamma) = \prod_{n=1}^{N} \Pr\left\{\frac{g_n}{N_0} \leq \gamma\right\} = \left(1 - e^{-\frac{\sigma^2\gamma}{\bar{g}_n}}\right)^N \tag{12}
$$

when i.i.d Rayleigh fading is assumed, and its *pdf.* function can be written as

$$
f_{\Gamma_{\tilde{n}}}(\gamma) = \frac{N\sigma^2}{\bar{g}_n} e^{-\frac{\sigma^2\gamma}{\bar{g}_n}} \left(1 - e^{-\frac{\sigma^2\gamma}{\bar{g}_n}}\right)^{N-1} \tag{13}
$$

by taking the first order derivative of equation (12). $F_{\Gamma_{\tilde{n}},l} - F_{\tilde{\Gamma}_{\tilde{n}},l}$ will be a convex function if taking the variable substitution $Q_{\mathrm{F},l} = 1/P_{\mathrm{F},l}$. Since the integral essentially does not change the convexity of the equation in terms of the new variable $Q_{\mathrm{F},l}$.

### B. Femtocell Throughput Approximation

In this paper, we assume that the wireless channels undergo Rayleigh fading with mean $\bar{g}_{\mathrm{F}}$ and $\bar{h}_{\mathrm{F}}$. Equation (10) can be further derived as

$$
\Pr\left\{\frac{g_{\mathrm{F}}P_{\mathrm{F},l}}{h_{\mathrm{F}}P_{\mathrm{M}} + N_0} < \gamma_{\mathrm{F},l}\right\} = 1 - \frac{e^{-\frac{\gamma_{\mathrm{F},l}\sigma^2}{\bar{g}_{\mathrm{F}}P_{\mathrm{F},l}}}}{\left(1 + \frac{\gamma_{\mathrm{F},l}\bar{h}_{\mathrm{F}}P_{\mathrm{M},l}}{\bar{g}_{\mathrm{F}}P_{\mathrm{F},l}}\right)} = \epsilon
$$

i.e. we choose a proper SINR threshold $\gamma_{\mathrm{F},l}$ such that the same outage probability constraint is met for any $l = 0, 1, \ldots, L-1$. The result can be derived by solving the following equation

$$
e^{-\frac{\gamma_{\mathrm{F},l}\sigma^2}{\bar{g}_{\mathrm{F}}P_{\mathrm{F},l}}} = (1-\epsilon)\left(1 + \frac{\gamma_{\mathrm{F},l}\bar{h}_{\mathrm{F}}P_{\mathrm{M},l}}{\bar{g}_{\mathrm{F}}P_{\mathrm{F},l}}\right) \tag{14}
$$

where the left hand side is a monotonically decreasing function and the right one is increasing in terms of $\gamma_{\mathrm{F},l}$. By this it means there is only one solution for this SINR threshold $\gamma_{\mathrm{F},l}$, which can be numerically derived. In this paper, we simplify the searching procedure by approximating the exponential function with a straight line between $(0, 1)$ and $\left(-\log(1-\epsilon)\bar{g}_{\mathrm{F}}P_{\mathrm{F}}/\sigma^2, 1-\epsilon\right)$. The intersection of these two straight lines on the left and right hand side of the equation is the solution for $\gamma_{\mathrm{F},l}$. After simple algebra, we have

$$
\gamma_{\mathrm{F},l} \approx \frac{\epsilon\bar{g}_{\mathrm{F}}P_{\mathrm{F},l}}{(1-\epsilon)\bar{h}_{\mathrm{F}}P_{\mathrm{M}} - \epsilon\sigma^2/\log(1-\epsilon)} = \kappa P_{\mathrm{F},l}. \tag{15}
$$

The corresponding rate threshold is given by $\log(1 + \gamma_{\mathrm{F},l})$, which can further provide the average throughput of the femtocell when the interference from the macrocell is considered.

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