Interference Tolerable Threshold Analysis in Cognitive Femtocells

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***Abstract*— In this paper interference management in co-channel deployment of macrocell and cognitive femtocells is investigated. For the purpose of the aggregate interference mitigation from all femtocell access points (FAP) to macrocell user equipment (MUE) and the purpose to increase the radio link quality of femtocell system, a parameter named *interference tolerable threshold* (I_{th}) is introduced, the aim is to reduce the interference an individual FAP causes to MUE to a level lower than I_{th}. A dynamic I_{th} control scheme is proposed to determine the appropriate value of this threshold. The simulation results show that the highest available I_{th} depends on the total number of FAPs, a larger number of FAPs does affect aggregate interference even if the individual interference is in acceptable range. The proposed method, however, achieves the adaptation of the highest available I_{th} without needing knowledge about the number of FAPs in the vicinity of MUEs.**

Keywords-component; Femtocell network, interference mitigation, co-channel deployment and cognitive radio network

I. INTRODUCTION

Cognitive Radio (CR) [1] research has attracted much attention all over the world because of its potential to resolve some of the radio resource shortage and spectrum underutilization problems. The key functionalities of a CR are spectrum sensing, spectrum reuse planning, opportunistic spectrum allocation and learning from the situation in the radio environment. On the other hand, Femtocell, promoted by FemtoForum [2], is defined as "*a low power wireless access point that operates in licensed spectrum to connect standard mobile devices to mobile operator's network using residential DSL or cable broadband connections.*" It can be one of the practical radio entities utilizing some of the above CR functions, such as radio environment measurement, dynamic spectrum allocation in femtocells to reuse the frequency used by the macrocell, interference management of co-channel deployment in macrocell and femtocell networks and self organization of such networks without need for coordinated deployment in the macrocell.

Interference analysis and spectrum allocation in co-channel deployments in macrocell and femtocell networks is often investigated [3]-[7]. The power scaling in such deployment is also investigated [8] [9]. In existing literature, mainly the sub-channel allocation mechanisms to avoid using interfered channels by the static power limit are addressed. Especially in [3], the proposed mechanism allocates only one channel resource per femtocell at the co-channel deployment of the macrocell. A solution to select an appropriate channel resource in a femtocell is investigated aiming to minimize the aggregate interference caused by the femtocells to the macrocell users. On the other hand, one of the femtocell advantages is that the femtocell user can use all channel resources of the femtocell exclusively, which results into the attractive improvement of the user throughput [2]. Then, each femtocell should be able to use as much channel resources as possible to a femtocell user for the improvement of user experience. In this scenario, it is expected that the femtocells adjust Transmission (Tx) power control mechanism which makes the Tx power less than a level to mitigate the interference to both macrocell and femtocell users. This interference mitigation should be calculated in each femtocell using the pre-defined interference threshold. However, the relation between the interference threshold level and the number of femtocells is important to be addressed.

In this paper, we use a parameter named *Interference tolerable threshold* (I_{th}) as a metric to optimize Tx power control and interference mitigation algorithms with a constraint that the all channel resources are used in every femtocell. The typical problem in this scenario is that individual interference to the macrocell users caused by one femtocell to macrocell users may be in an acceptable range but the aggregate interference from a large number of femtocells might exceed the acceptable range. Hence, the two objectives of this paper are

1. Mitigation of the aggregate interference from femtocell base stations to the macrocell user
2. Maximizing of signal to interference plus noise ratio (SINR) of femtocell systems for the higher throughput of femtocell systems. In this paper, this can be reworded as maximizing the Tx power of femtocell base stations when the inter-femtocell interference is low.

To achieve these two objectives, appropriate value of I_{th} is analyzed in this paper. This parameter limits the femtocell Tx power to mitigate the interference at macrocell users at the cost of received SINR of the femtocell users. This behavior results into the lower data rate in the femtocell. From the both femtocells and macrocell systems point of view, highest value of I_{th} is required with satisfying mitigated interference from femtocells to the macrocell users.

The paper is organized as follows. Section II describes the system model of our femtocell deployment scenario. In section III, the appropriate value of I_{th} is analyzed. In Section IV, the proposed dynamic I_{th} control scheme is described. The simulation results are shown and discussed in Section V, concluding remarks are given in Section VI.

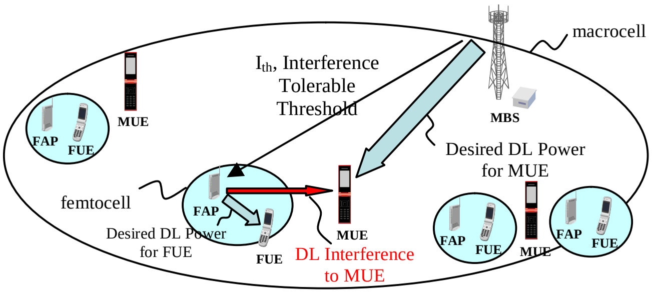


Fig. 1. System model for co-channel deployment of macrocell and femtocells.

II. System Model

Our system model for co-channel deployment of macrocell and femtocells is shown in Fig.1. We consider one macrocell having a base station (MBS) where a number of macrocell user equipments (MUE) exist. In the macrocell, there are many femtocell access points (FAP). Each FAP has a femtocell where femtocell user equipments (FUE) exist. To simplify the model, only one FUE is considered in each femtocell. In case of multiple FUEs in a femtocell, the analysis can be extended. With regards to the channel resources shared by macrocell and femtocell systems, MBS divides them by the number of active MUEs, and allocates one channel resource to each active MUE in the macrocell, whereas each FAP allocates all channel resources to an active FUE in the femtocell.

In this paper, the individual and aggregate downlink interference from FAP to MUE is considered. Each FAP will calculate the estimated individual interference received at each MUE from the own FAP. And then, FAP controls the Tx power to make the estimated individual interference lower than the parameter, I_{th}. MBS transmits the value of I_{th} to all FAPs in the macrocell. We do not assume any interactive communication between MBS and FAP in this paper. It can be a broadcast channel which is unidirectional interface. I_{th} is used by the macrocell system to mitigate the aggregate interference from all FUEs to each MUE and to make the radio link quality of each MUE stable. Hence, the first problem is to find out the appropriate value of I_{th}. In this scenario, it is assumed that FAPs are aware of MUE locations around the FAPs by any mechanisms, such as the estimation of the propagation loss of uplink radio from MUE to FAP.

III. Static Interference Tolerable Threshold

We define N as the number of active MUEs and the downlink Tx power vector of MBS is denoted as $\mathrm{P}^m = \left[P_1^m, P_2^m, \ldots, P_N^m\right]^{\mathrm{T}}$, where the channel resources in macrocell are divided to the number of MUEs, N, and nth channel is allocated to nth MUE. The P_n^m represents the MBS downlink Tx power for the nth MUE in nth channel. The superscript m represents macrocell, f represents femtocell, fm represents from femtocell to macrocell and mf represents from macrocell to femtocell. We define K as the number of FAPs and the downlink Tx power matrix of FAPs is denoted as

$$\mathrm{P}^f = \begin{bmatrix} P_{11}^f, P_{12}^f, \ldots, P_{1N}^f \\ P_{21}^f, P_{22}^f, \ldots, P_{2N}^f \\ \vdots \quad \vdots \quad \ddots \quad \vdots \\ P_{K1}^f, P_{K2}^f, \ldots, P_{KN}^f \end{bmatrix}^{\mathrm{T}} \tag{1}$$

where P_{kn}^f represents the downlink Tx power of the kth FAP in nth channel. The aggregate interference from all FAPs to nth MUE can be expressed as

$$I_n^{fm} = \sum_k^K \frac{P_{kn}^f}{L_{kn}^{fm}} \tag{2}$$

where L_{kn}^{fm} represents the propagation loss from kth FAP to nth MUE. The interference from MBS to kth FUE in nth channel and the aggregate interference from all FAPs to kth FUE in nth channel can be expressed as

$$I_{kn}^{mf} = \frac{P_n^m}{L_k^{mf}} \tag{3}$$

$$I_{kn}^{ff} = \sum_{i=1, i\neq k}^{K} \frac{P_{in}^f}{L_{ik}^{ff}} \tag{4}$$

In the practical radio system, the target SINR is pre-defined to guarantee the radio link quality required by the user's QoS (quality of service). It is often used to decide the Tx power per each user. The target SINR of the macrocell system can be expressed as

$$S_n^m = \frac{P_n^m}{L_n^{mm}(I_n^{fm} + P_N)} \tag{5}$$

where P_N represents the noise power. The macrocell system controls the aggregate interference with the interference constraint of MUE suffered by FAPs which is expressed as

$$I_n^{fm} \leq \gamma_1 P_N \tag{6}$$

where γ_1 is the MUE aggregate interference coefficient [3]. Then the Tx power of the MBS in nth channel can be calculated from (5) and (6) as,

$$P_n^m = S_n^m L_n^{mm} P_N (1+\gamma_1) \tag{7}$$

In the same way, the target SINR of the femtocell system and the aggregate interference constraint of FUE are

$$S_{kn}^f = \frac{P_{kn}^f}{L_{kk}^{ff}(I_{kn}^{ff} + I_{kn}^{mf} + P_N)} \tag{8}$$

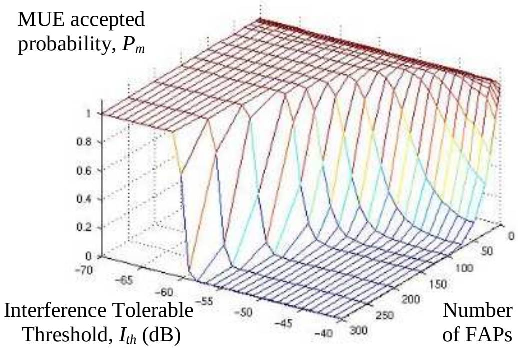
$$I_{kn}^{ff} + I_{kn}^{mf} \leq \gamma_2 P_N \tag{9}$$

Generally the inter-femtocell interference I_{kn}^{ff} is much smaller than the macro-femto interference I_{kn}^{mf}, hence the inter-femtocell interference I_{kn}^{ff} in equation (8) can be ignored [3].

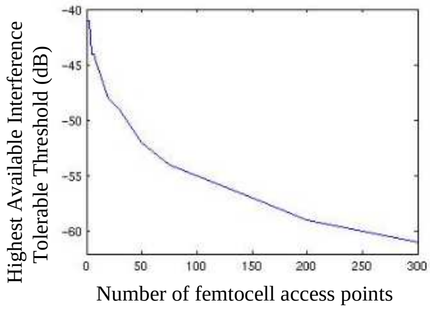
In this paper, each FAP estimates the interference from kth FAP to nth MUE in nth channel and controls the FAP Tx power per channel to make the interference lower than I_{th} signaled from the MBS.

TABLE 1 SIMULATION PARAMETERS

Parameter Name	Value	Description
Number of MUEs, N	8	MUEs are uniformly distributed in a macrocell.
Number of channels, N	8	All channels are shared by macrocell and femtocell systems.
Macrocell radius	500 [m]	MBS is located at the center of the macrocell.
Femtocell radius	10[m]	The femtocell coverage is not overlapped each other.
Target SINR of macrocell system, S_n^m	10 [dB]	-
Target SINR of femtocell system, S_{kn}^f	10 [dB]	This value may decrease due to the FAP Tx Power limited by I_{th}.
MUE aggregate interference coefficient, γ_1	10^{-4}	-
FUE aggregate interference coefficient, γ_2	10	-
Propagation Loss Model, L	$15.3 + 37.6 \log 10\, d + \alpha\, L_{wall}$, L_{wall} : 15 [dB], α: number of walls	



(a) MUE accepted probability, P_m to interference tolerable threshold and number of FAPs



(b) Highest interference tolerable threshold to Number of FAPs to guarantee $P_m = 1$

Fig. 2. Interference tolerable threshold analysis

$$I_{kn}^{fm} = \frac{P_{kn}^f}{L_{kn}^{fm}} < I_{th} \tag{10}$$

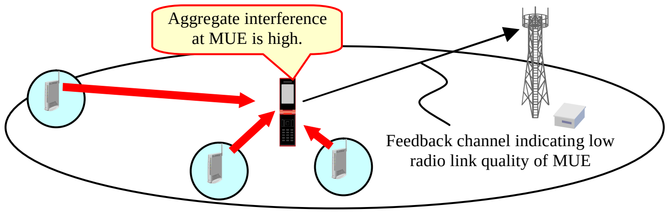
Then the Tx power of kth FAP in nth channel can be calculated from (8), (9) and (10)

$$P_{kn}^f = \min(S_{kn}^f L_{kk}^{ff} P_N (1+\gamma_2), L_{kn}^{fm} I_{th}) \tag{11}$$

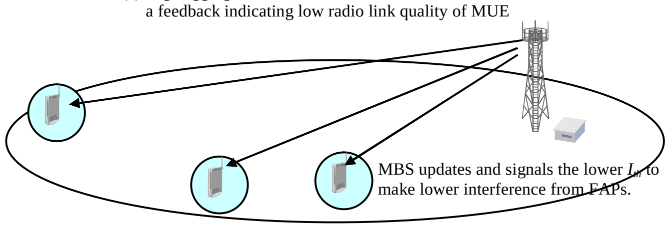
In case the Tx power is limited by (10), the target SINR of kth FUE of nth channel is considerably decreased, so that the data rate in the kth FUE of nth channel becomes lower. The parameters used in simulations are shown in Table 1. In the propagation model, the penetration loss of wall L_{wall} is used with the number of walls, α, which value is 0 for the space between MBS and MUE or FAP and FUE in same FAP, 1 for the space between FAP and MUE or MBS and FUE, 2 for the space between FAP and FUE in other FAP.

In Fig.2-(a), the MUE accepted probability 'P_m' is indicated from 2 input elements, I_{th} and the number of FAPs, which are uniformly distributed in a macrocell. The condition $P_m = 1$ guarantees that all MUEs are accepted at the value of I_{th} and the number of FUEs. The condition $P_m = 0$ means that at least one MUE is not accepted. From the objectives mentioned in section I, the required I_{th} is the highest value guaranteeing the condition $P_m = 1$ shown in Fig.2-(b). It is observed that the highest available interference tolerable threshold is -55 *dB* when the number of FAPs is 100. Generally, the highest available interference tolerable threshold depends on the number of FAPs which affects the aggregate interference to MUE. This means that the aggregate interference from FAPs becomes high at the large number of FAPs even if the individual interference from a FAP is small enough to be limited by the I_{th}.

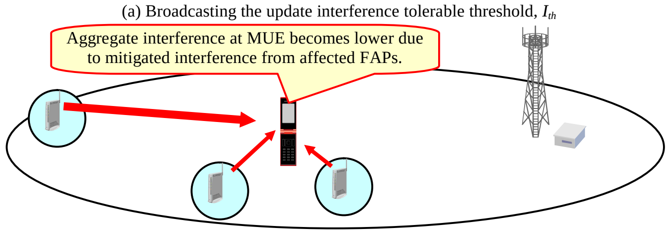
The result of Fig. 2-(b) is very useful for the macrocell system configuration that can make the aggregate interference at MUE in acceptable range. But it is available only when the macrocell system is aware of the number of FAPs in the macrocell. Some of FAPs may be turned off by the end users to save energy and additional FAPs may be installed after the configuration. Therefore, the awareness of the exact number of active FAPs is difficult practically. To resolve this second problem, a dynamic I_{th} control mechanism is proposed in next section.



(a) High aggregate interference from all FAPs to MUE and a feedback indicating low radio link quality of MUE



(a) Broadcasting the update interference tolerable threshold, I_{th}



(c) Aggregate interference at MUE is mitigated.

Fig. 3. Illustration of proposed scheme

IV. PROPOSED SCHEME

Fig. 3 shows the example scenario for the proposed scheme. In Fig. 3-(a), one MUE suffers from the high interference from all FAPs in aggregate which causes low radio link quality of the MUE. Then it is informed to MBS by the uplink feedback channel to trigger interference mitigation algorithm. In Fig. 3-(b), the parameter I_{th} is updated and signaled to all FAPs. In the case of low radio link quality, lower value is set to make the aggregate interference lower. 3-(c) shows that some of FAPs which are closed to the MUE control the Tx power downward which is limited by the updated I_{th} in equation (10), whereas the other FAPs which are far from the MUE don't change the Tx Power which is not affected to the updated I_{th}. At the result the aggregate interference at MUE from all FAPs becomes lower by this algorithm. If the MUE still suffers from the high interference from all FAPs, the same procedure is repeated until the aggregate interference at MUE from all FAPs becomes low enough to fulfill the equation (6).

The above mentioned algorithm updates the parameter I_{th} as expressed in (12). Please note that Fig.3 explains only second part of (12).

$$\begin{aligned} &I_{th}(t) = I_{th}(t-1) + \Delta I_{th} \\ &\qquad \text{if } I_n^{fm} \le \gamma_1 P_N \text{ for all N MUEs} \\ &I_{th}(t) = I_{th}(t-1) - \Delta I_{th} \\ &\qquad \text{if } I_n^{fm} > \gamma_1 P_N \text{ for at least one MUE} \end{aligned} \tag{12}$$

$$\underset{\text{for all N MUEs}}{I_n^{fm}(t) \le \gamma_1 P_N} \cap \underset{\text{for at least one MUE}}{I_n^{fm}(t-1) > \gamma_1 P_N} \tag{13}$$

where ΔI_{th} represents the control bit of the interference tolerable threshold, e.g. 1 *dB*. The highest available value of I_{th} is calculated from (12) at the condition in (13). The condition of $I_n^{fm} > \gamma_1 P_N$ for at least one MUE means harmful interference for the MUE. To avoid such interference, γ_1 shall have an appropriate offset internally.

While the proposed algorithm is executed, there are 4 states shown in Table 2. In the state 1, at least one MUE suffers from the Interference caused by FAP whereas FAP Tx power is not limited by I_{th}. The value of I_{th} has to be controlled lower by 2nd part of (12) and the state 1 will switch to the state 2 or 3 by this algorithm. In the state 2, some MUEs still suffer from the Interference caused by FAP the even though Tx power of some FAPs is limited by the proposed algorithm. The value of I_{th} has to be controlled lower again until the state 2 switches to the state 3. In the state 3, the aggregate interference at any MUE is low enough and Tx power of some FAPs is limited. To avoid over limitation of FAP Tx Power, the value of I_{th} is controlled higher by 1st part of (12). If state 3 is switched to state 1 or 2, then the highest value of I_{th} is given from (13). Depending on the initial setting of I_{th}, state 3 may be switched to state 4. In the state 4, all MUEs are accepted. At the same time, any FAP doesn't limit the Tx power by I_{th}. Since both MUEs and FUEs can achieve the target SINR in (5) and (8) respectively, any interference that is low enough is not affected by the I_{th} mechanism. This state 4 is observed only when the number of FAPs is small enough, especially less than 50 FAPs in one macro cell. For the proposed algorithm, the dynamic I_{th} control scheme should not be activated in the state 4. Then, (12) can be modified in order to deactivate the algorithm in state 4 as

$$\begin{aligned} &I_{th}(t) = I_{th}(t-1) + \Delta I_{th} \\ &\qquad \text{if } I_n^{fm} \le \gamma_1 P_N \text{ for all N MUEs and} \\ &\quad I_{kn}^{fm} = I_{th} \text{ for at least one } n\text{th channel in one FUE} \\ &I_{th}(t) = I_{th}(t-1) - \Delta I_{th} \\ &\qquad \text{if } I_n^{fm} > \gamma_1 P_N \text{ for at least one MUE} \end{aligned} \tag{14}$$

The highest available value of I_{th} can be calculated from (13) and (14) without depending on the initial setting of I_{th} value. The awareness of the number of deployed FAPs in macrocell is not necessary. The difference between (12) and (14) is third line of (14), the information of FAPs affected in the proposed algorithm. That means a feedback channel from FAP to MBS can deactivate this algorithm in the state 4. As the alternative simple solution, the range definition of I_{th} can avoid introducing this feedback channel in the proposed algorithm. In this case, I_{th} of state 4 may be controlled to the max value within the range when the number of FAPs is small enough. In this simulation, the activation of the algorithm in state 4 is excluded to observe the convergence of the highest available value of I_{th} by the proposed algorithm even when the number of FAPs is small enough.

TABLE 2 STATE ANALYSIS

State	Aggregate interference at MUE	Estimated interference from one FAP to MUE
1	$I_n^{fm} > \gamma_1 P_N$ for at least one MUE	$I_{kn}^{fm} = P_{kn}^f / L_{kn}^{fm} < I_{th}$ for all K FUEs and all N channels
2	$I_n^{fm} > \gamma_1 P_N$ for at least one MUE	$I_{kn}^{fm} = I_{th}$ for at least one channel in one FUE
3	$I_n^{fm} \le \gamma_1 P_N$ for all N MUEs	$I_{kn}^{fm} = I_{th}$ for at least one channel in one FUE
4	$I_n^{fm} \le \gamma_1 P_N$ for all N MUEs	$I_{kn}^{fm} = P_{kn}^f / L_{kn}^{fm} < I_{th}$ for all K FUEs and all N channels

V. SIMULATION RESULT

Fig. 4 shows the average of the interference tolerable threshold controlled by the proposed scheme and the highest available interference tolerable threshold in the static analysis from Fig. 2-(b). Here, the highest available value of I_{th} by the dynamic I_{th} control scheme is converged without depending on the initial setting of I_{th} value and it depends on the number of FAPs which affects the aggregate interference to MUE. At first, the result of the I_{th} from the dynamic I_{th} control scheme is similar to that of static analysis. That means that the dynamic I_{th} control scheme has a good benefit because the static I_{th} analysis needs the aware of number of FAPs but the dynamic I_{th} control scheme doesn't. Even if the number of active FAPs changes dynamically, the proposed scheme can adapt I_{th} to the appropriate value at the number of active FAPs at that time. For example, if the number of active FAPs is 250 in the daytime, I_{th} is controlled to -60dB and if it becomes 100 at night, it is controlled to -50dB automatically. This benefit is one of the self optimization network (SON) functions. Second, the value of I_{th} from the dynamic I_{th} control scheme is slightly higher than that from the static analysis, especially in case the number of FAPs is less than 100 in the macrocell. This means each FAP is able to use higher target SINR which results into the availability of higher data rate in that FAP. Finally, the slight difference between dynamic I_{th} control and static I_{th} analysis is investigated with considering Fig. 2-(a). In case the number of FAPs is 50, P_m degrades gradually between I_{th} = -50 *dB* and higher. This means that there are some cases that all MUEs can be accepted at higher value of I_{th} than -50 *dB*. These cases depend on the location of FUEs and MUEs. However, the dynamic I_{th} control scheme can adapt I_{th} to such location dependent element, and can achieve the higher value than the result of static analysis. On the other hand, in the case that the number of FAPs is 250, P_m degrades rapidly around I_{th} = -60 *dB*. This means there are quite few cases all MUEs can be accepted at higher value of I_{th} than -60 *dB* because the location dependence becomes lower by the larger number of FAPs.

VI. CONCLUDING REMARKS

We analyzed the co-channel deployment of macrocell and femtocells with a new parameter interference tolerable threshold for the interference estimation at femtocell access points, aiming to mitigate the aggregate interference at macrocell users. It was observed that the highest available interference tolerable threshold depends on the number of the femtocell access points. Using the proposed scheme, the interference tolerable threshold can be controlled and is able to achieve the adaptation of the highest available value without needing knowledge about the number of femtocell access points in the vicinity of MUEs. For future work, a more flexible interference tolerable threshold can be considered, e.g. I_{th} per channel resource used by macrocell user equipment around femtocell access points. In addition to that functional enhancement, the integration with more realistic scenarios is necessary, e.g. multiple spectrum allocation which needs additional decision to select the appropriate spectrum, multiple macrocells environment which needs typical radio resource management providing the macrocell Tx power control with inter-macrocell interference, and practical propagation model providing user mobility, fading and shadowing.

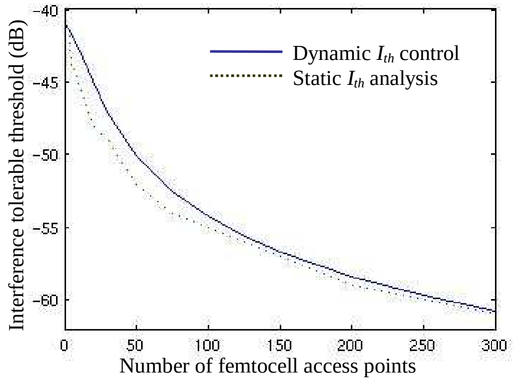


Fig. 4. Interference tolerable threshold

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