Mitigation of Inter-Femtocell Interference with Adaptive Fractional Frequency Reuse

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Abstract—In this paper, we consider the use of fractional frequency reuse (FFR) to mitigate inter-femtocell interference in multi-femtocell environments. The use of universal frequency reuse can be said optimum in terms of the ergodic system spectral efficiency. However, it may cause inter-femtocell interference near the cell edge, making it difficult to serve the whole cell coverage. To alleviate this problem, we adjust the frequency reuse factor with the aid of femtocell location information. The proposed scheme can provide reasonably high ergodic system spectral efficiency, while assuring a desired performance near the cell boundary. Simulation results show that the proposed scheme is quite effective in indoor environments such as residential or office buildings.

I. INTRODUCTION

It has recently been reported that roughly 80% of wireless communication traffic is generated in indoors [1]. However, penetration loss makes it difficult for existing cellular network systems to sufficiently handle the demand of indoor multimedia traffic. To resolve this problem, the use of indoor base station, referred to as femtocell or Home NodeB, has been considered [2]. Femtocell is a low-power consuming base station connected to the service provider’s network via broadband such as DSL or cable. It can improve the indoor coverage and data performance by means of spatial reuse of spectrum.

As femtocells can be densely deployed in a small area such as an office building or apartment, interference from other femtocells, called inter-femtocell interference (IFI), might significantly deteriorate the overall system performance. Traditionally, mitigation of inter-cell interference in macro cellular networks has been widely studied mainly by means of frequency resource allocation [3]-[5]. Unlike the macro base station, femto base stations can be installed by users in their own premises (i.e., in a random manner), making it difficult to handle the IFI problem. The use of universal frequency reuse with adaptive power control can be applied to the mitigation of IFI when femtocells are deployed in a systematic way with low density [6]. However, when multiple femtocells are densely deployed in a building environment, they are more likely to interfere with each other.

A femtocell server referred to as femto gateway manages operation and maintenance (OAM) information such as the identification (ID) and location of femtocells through a backhaul link [2]. The femto gateway can handle the IFI using a fractional frequency reuse (FFR) technique by selecting a favorable operating band with the aid of OAM information [7][8]. However, the use of frequency reuse factor (FRF) less than one may yield a poor system spectral efficiency.

To resolve the IFI problem, we consider the use of FFR that adjusts the FRF according to the operating environment. The femto gateway analyzes the effect of mutual interference among femtocells by means of interference graph modeling with the aid of femtocell location information. Based on the mutual interference information, it classifies femtocells into a number of groups according to the amount of interference to others. Then it determines the minimum number of orthogonal subchannels for each group to provide target performance near the cell boundary. After the allocation of subchannels to femtocells in each group, the transmit power of each femtocell is adjusted based on the received signal strength indication (RSSI) in a distributed manner. By making the use of the highest FRF (i.e., close to 1) with the least number of orthogonal subchannels according to the deployment environment, the proposed scheme can provide reasonably high ergodic system spectral efficiency while assuring a target performance near the cell boundary.

The rest of the paper is organized as follows. Section II describes the system model. Section III proposes the adaptive FFR algorithm in multi-femtocell environments. Section IV verifies the performance of the proposed scheme by computer simulation. Finally, Section V summarizes the conclusions and further work.

II. SYSTEM MODEL

A. Spectral Efficiency Trade-off

Consider the downlink of a femtocell in a femtocell network, where \( N \) frequency subchannels are shared by \( K \) femtocells for data transmission. We assume that femtocells are located in an isolated or shadowed area or use separated frequency band so that interference from macrocell can be neglected [9]. The femtocells are connected to a femto gateway
which manages the OAM information, including the location and ID information of adjacent femtocells.

It was shown that the spectral efficiency of femtocell $k$ is upper-bounded as [10]

$$C_{FBS,k} \leq \frac{1}{N} \sum_{n=1}^{N} \alpha_k^{(n)} \log_2 \left(1 + \gamma_k^{(n)}\right)$$

(1)

where $\alpha_k^{(n)} \in \{0, 1\}$ is the subchannel allocation indicator and $\gamma_k^{(n)}$ is the average signal-to-noise plus interference power ratio (SINR) of femtocell $k$ at subchannel $n$ represented as

$$\gamma_k^{(n)} = \frac{P_k^{(n)} 10^{-L_k/10}}{\sum_{n=1}^{N} \sum_{l=1}^{K} \alpha_l^{(n)} P_l^{(n)} 10^{-L_l/10} + \sigma_n^2}.$$  

(2)

Here $P_k^{(n)}$ denotes the transmit power of femtocell $k$ at subchannel $n$ and $L_k = 10 \log_{10}(d_k^2) + \mu + \nu$ denotes the path loss in dB, where $d_k$ denotes the distance from femtocell $k$, $\omega_k$ denotes the wall loss in dB, and $\mu$ and $\nu$ denote the path loss constant and the path loss exponent, respectively. In this paper, we only consider heavy wall losses and neglect light wall losses [6]. It can be seen from (1) and (2) that performance degradation due to the IFI can be mitigated by adjusting $\alpha_k^{(n)}$. The FRF of femtocell $k$ can be represented as

$$\eta_k = \frac{\sum_{n=1}^{N} \alpha_k^{(n)}}{N}. \quad (3)$$

The ergodic system spectral efficiency for a certain period of time $T_0$ can be represented as [10]

$$C_{\text{system}} = \int_0^{T_0} \frac{\bar{C}_{FBS}(t)}{T_0} dt \quad (4)$$

where $\bar{C}_{FBS} = \sum_{k=1}^{K} C_{FBS,k}/K$. The use of universal frequency reuse (i.e., $\eta_k = 1 \forall k$) provides higher ergodic spectral efficiency than that of FFR (i.e., $\eta_k < 1$) [5]. However, it may not provide desired spectral efficiency near the cell boundary due to interference from neighboring femtocells. The cell edge spectral efficiency is defined by 5% point of the CDF of the spectral efficiency as [11]

$$C_{\text{edge}} = \arg_x \left(\int_0^x f(C_{FBS}) d\bar{C}_{FBS} = 0.05\right). \quad (5)$$

On the other hand, the use of FFR can provide higher cell edge spectral efficiency than the use of universal frequency reuse since it can mitigate the IFI by means of spectrum reuse. Therefore, it may be desirable to employ a frequency reuse approach considering the trade-off between the system spectral efficiency and cell edge spectral efficiency.

B. Orthogonal Area and Ratio of Orthogonal Area

We consider a simple femtocell environment comprising two femtocells as illustrated in Fig. 1. Let femtocell $k$ and $l$ be the target and interfering femtocell with coverage radius $r_k$ and $r_l$, respectively. For the ease of description, define orthogonal area (OA), $\Psi_{k,l}$, by the portion of the coverage area of femtocell $k$, where the average signal-to-interference power ratio (SIR) associated with the interference from femtocell $l$ is lower than a given threshold level $\lambda_{th}$. To provide desired cell edge spectral efficiency, it may need to allocate frequency resource to users in OA in an orthogonal manner. The shape of the border where the average SIR is equal to $\lambda_{th}$ is shown in Fig. 1 as a circle with radius $R_0$ [12]. Define Ratio of Orthogonal Area (ROA), $\Omega_{k,l}$, by the ratio of the OA to the entire femtocell coverage with radius $r_k$ (i.e., $\Omega_{k,l} = \Psi_{k,l}/\pi r_k^2$). If users are uniformly distributed in femtocell $k$, the probability of users to be located in OA $\Psi_{k,l}$ is $\Omega_{k,l}$. Note that the OA and ROA are a function of the distance. With the uploaded OAM information that includes the distance between femtocells, the femto gateway can successfully allocate frequency resource to femtocells by estimating mutual IFI.

III. PROPOSED FRACTIONAL FREQUENCY REUSE

A. Calculation of ROA between Femtocells

We calculate the ROA between femtocells in the network to estimate the IFI. As shown in Fig. 1, when a user is away from femtocell $k$ with distance $d_k$ ($\leq r_k$), the received signal power from femtocell $k$ can be represented as [10]

$$P_{r,k} = P_k/\left(10^{(\mu + \omega_k)/10} d_k^{\nu}\right). \quad (6)$$

When the user is served by the femtocell $k$ in the presence of the adjacent femtocell $l$, it can be shown that the condition for the SIR lower than $\lambda_{th}$ is [12]

$$SIR_{k,l} = \frac{P_k}{P_l} \left(\frac{d_k}{d_l}\right)^\nu \left(10^{(\omega_l - \omega_k)/10}\right) < \lambda_{th} \quad (7)$$

which can be rewritten as

$$c_{th} = \left(10^{(\omega_k - \omega_l)/10} \lambda_{th} P_l/P_k\right)^\nu > \left(\frac{d_l}{d_k}\right)^2 \quad (8)$$

As shown in Fig. 1, if femtocell $k$ and $l$ are located at $x_k = (0, 0)$ and $x_l = (d, 0)$, respectively, and a user served
by femtocell $k$ is located at an arbitrary position $x = (x, y)$, the distance from femtocell $k$ and $l$ can be represented as, respectively,

$$
\begin{align*}
d_k &= \sqrt{x^2 + y^2}, \\
d_l &= \sqrt{(x - d)^2 + y^2}.
\end{align*}
$$

Thus, it can easily be shown that

$$
P = \begin{cases}
\{ (x, y) | c_{th} (x^2 + y^2) > (x - d)^2 + y^2 \} & , c_{th} > 1 \\
\{ (x, y) | (x - p_x)^2 + y^2 > R_0^2 \} & , c_{th} = 1 \\
\{ (x, y) | (x - p_x)^2 + y^2 < R_0^2 \} & , c_{th} < 1
\end{cases}
$$

where $p_x = -d/(c_{th} - 1)$ and $R_0 = d/\sqrt{c_{th} |c_{th} - 1|}$. Note that when $c_{th} \neq 1$, (10) becomes a general expression of a circle [12]. Note that $P$ is a set of elements $(x, y)$, where the SIR is lower than $\lambda_{th}$. Thus, the OA can be calculated considering the set $Q$, which is within the coverage radius of femtocell $k$, given by

$$
Q = \{ (x, y) | x^2 + y^2 < r_k^2 \}.
$$

The OA of femtocell $k$ can be represented as

$$
\Psi_{k,l} = \text{area of } \{ P \cap Q \}
$$

by

$$
\Psi_{k,l} = \begin{cases}
-p_x r_k \sin \theta_2 - \theta_1 R_0^2 + 2 \theta_2 r_k, & c_{th} > 1 \\
r_k^2 \arccos \left( \frac{\sin \theta_2}{2 \sqrt{r_k^2}} \right) - \frac{1}{2} \sqrt{r_k^2 - (d/2)^2}, & c_{th} = 1 \\
-p_x r_k \sin \theta_2 + (\theta_1 - \theta_2) R_0^2 + 2 \theta_2 r_k, & c_{th} < 1
\end{cases}
$$

where

$$
\theta_1 = \arccos \left( \frac{d^2 (c_{th} + 1) - r_k^2 (c_{th} - 1)^2}{\text{sgn} (c_{th} - 1) 2 d^2 \sqrt{c_{th}}} \right)
$$

and

$$
\theta_2 = \arccos \left( \frac{d^2 - r_k^2 (c_{th} - 1)}{2 d r_k} \right).
$$

The ROA of femtocell $k$ to femtocell $l$ can be represented as

$$
\Omega_{k,l} = \begin{cases}
\Psi_{k,l} / \pi r_k^2 & , k \neq l \\
0 & , k = l
\end{cases}
$$

Assuming users are uniformly distributed, the ROA $\Omega_{k,l}$ can be considered as the probability that users served by femtocell $k$ with SIR lower than $\lambda_{th}$ are within the OA. Note that the probability can also be considered as the needed number of orthogonal subchannels to mitigate IBI near the cell edge.

**B. Femtocell Grouping**

Based on the ROA, femtocells are classified into a number of groups to determine the number of subchannels and to set the priority order for the allocation by per group basis. The femtocells can be grouped by means of an interference graph modeling method [3] [13]. Let $G = (V, E)$ be an interference graph, where a $(1 \times K)$ node set $V$ denotes the femtocell index (i.e., $V = \{1, 2, \cdots K\}$), and a $(K \times K)$ edge set $E$ represents the ROA between the neighboring femtocells (i.e., the $(k, l)$-th component $E_{k,l}$ is $\Omega_{k,l}$).

Define $\sigma_k$ by the sum of ROAs of femtocell $k$, i.e.,

$$
\sigma_k = \sum_{l=1, l \neq k}^{K} \Omega_{k,l}
$$

which is proportional to the amount of aggregated interference from neighboring femtocells. Thus, it is desirable to allocate the frequency resource to femtocells in an order from the highest $\sigma_k$ to the lowest $\sigma_k$ to reduce the interference in an average sense. We sort the node set $V$ in terms of $\sigma_k$ to modify the interference graph. Letting $V'$ be a sorted version of $V$ in terms of $\sigma_k$ and $E'$ be the edge set corresponding to $V'$, the $(k, l)$-th component of $E'$ can be represented as

$$
E_{k,l}' = \Omega_{V'(k), V'(l)}
$$

where $V'(k)$ is the $k$-th component of $V'$.

Based on the interference graph, the nodes are classified into $M$ number of groups as follows. Let $G = \{g_1, \cdots, g_M\}$ be a set of groups, where $g_m, m = 1, 2, \cdots, M$, comprises a set of nodes interfering with each other. First, initiate $g_1$ as

$$
g_1 = \{ V'(1) \}.
$$

Note that $V'(1)$ is the node having the largest sum of ROAs (i.e., $V'(1) = \arg \max \{ \sigma_1, \cdots, \sigma_K \}$). Then, $g_1$ is updated by considering the edge $E_{k,l}'$ between the nodes in $g_1$ (i.e., $V'(1)$) and the rest of the nodes (i.e., $V'(l), l = 2, 3, \cdots, K$). Since only nodes with $E_{k,l}' > 0$ interfere with $V'(1)$, $g_1$ is updated when the first node having $E_{k,l}' > 0$ is found, i.e.,

$$
g_1 = g_1 \cup \{ V'(l) \} , \quad \text{if } E_{k,l}' > 0 .
$$

Similarly, $g_1$ is continuously updated by adding node $V'(l)$ if $V'(l)$ has edges larger than zero with all nodes in $g_1$, i.e.,

$$
g_1 = g_1 \cup \{ V'(l) \} , \quad \text{if } E_{k,l}' > 0 \ \forall \ V'(k) \in g_1 .
$$

After the generation of the first group $g_1$, the second group $g_2$ is initiated with node $V'(l)$ having the largest $\sigma_{V'(l)}$ among the nodes excluding ones belonging to $g_1$. $g_2$ is updated similarly to the first group, and the rest of the groups $g_3, g_4, \cdots, g_M$ are also generated in a similar manner. Fig. 2 illustrates an example of femtocell grouping. Note that each node can belong to multiple groups.

**C. Subchannel Allocation**

From the ROA and the grouping results, we can determine the subchannel allocation indicator $a_{k}^{(n)} \in \{0 , 1\}$ considering the number of subchannels assigned to each group. Note that nodes in the same group are interfered with each other more intensively than those in other groups in an average sense.

Let $g_m(k)$ be the $k$-th node of $g_m$, and $K_{g_m}$ be the number of nodes in $g_m$. Since an edge exists between every pair of nodes chosen from the same group, the total number of edges in $g_m$ can be represented as

$$
\Delta_m = \sum_{k=1}^{K_{g_m}} \sum_{l=1}^{K_{g_m}} \left[ \Omega_{g_m(k), g_m(l)} \right] = 2 \left( \frac{K_{g_m}}{2} \right).
$$
where \([x]\) is the nearest integer value larger than \(x\).

Since the range of the edge is between 0 and 1, if the total sum of edges in \(g_m\), i.e., \(\sum_{k=1}^{K_m} \sum_{l=1}^{N_{g_m}(k)} \Omega_{g_m(k),g_m(l)}\), is close to \(\Delta_m\) (i.e., interference among femtocells is strong), it may be desirable for nodes in \(g_m\) to share the frequency resource in an orthogonal manner to guarantee the cell edge spectral efficiency. On the other hand, if the total sum of edges in \(g_m\) is nearly zero (i.e., interference among femtocells is tolerable), it may be desirable for all the nodes in \(g_m\) to use the whole frequency resource with universal frequency reuse. It can be shown by means of linear interpolation that the FRF for \(g_m\) to guarantee the cell edge spectral efficiency is represented as

\[
\eta_{g_m} = \left[1 + \frac{\sum_{k=1}^{K_m} \sum_{l=1}^{N_{g_m}(k)} \Omega_{g_m(k),g_m(l)}}{\Delta_m} (K_m - 1)\right]^{-1}.
\]  

(22)

For a given FRF \(\eta_{g_m}\) for each group, the number of subchannels needed to be determined in an order from the group with the lowest \(\eta_{g_m}\) to one with the highest \(\eta_{g_m}\) for the reduction of IFI. Letting \(g'_m\) be a sorted version of \(g_m\) with respect to \(\eta_{g_m}\), the number of subchannels for \(g'_m\) can be determined as

\[
N_{g'_m} = \left\lceil \eta_{g'_m} N \right\rceil \quad \text{(23)}
\]

where \(\lceil \cdot \rceil\) denotes the integer round operator. Note that all the nodes in the same group have the same number of subchannels (i.e., \(N_{g'_m}(k) = N_{g'_m}\)). However, some nodes can belong to multiple groups with different \(N_{g'_m}\). In this case, it may be desirable to make such nodes use the number of subchannels determined in the former group (i.e., the group having the lowest FRF). For a number of subchannels \(\tilde{N}_{g'_m}(k)\) determined for node \(g'_m(k)\), the minimum number of subchannels orthogonal to node \(g'_m(l)\) can be represented as

\[
\tilde{N}_{g'_m(k),g'_m(l)} = \left\lceil \tilde{N}_{g'_m}(k) \Omega_{g'_m(k),g'_m(l)} \right\rceil \quad \text{(24)}
\]

Subchannels are allocated to node \(g'_m(k)\) to have the minimum number of orthogonal subchannels \(\tilde{N}_{g'_m(k),g'_m(l)}\) to previously allocated node \(g'_m(l)\) whose edge \(\Omega_{g'_m(k),g'_m(l)}\) is larger than 0. To improve the ergodic system spectral efficiency while providing desired cell edge spectral efficiency, it is desirable to allocate only the minimum number of orthogonal subchannels to each node. Fig. 2 illustrates an example of the proposed scheme where \(N = 10\) and \(K = 5\).

### D. Power Control of Subchannel

For further improvement of performance, we adjust the transmit power of the femtocell based on the received signal strength indication (RSSI). Similarly to the water filling technique [10], the transmit power of femtocell \(k\) at subchannel \(n\) can be controlled as

\[
P_k^{(n)} = \left(\frac{\text{RSSI}_k^{(n)} + \varepsilon}{\sum_{m=1}^{N} \alpha_k^{(m)} (\text{RSSI}_k^{(m)} + \varepsilon)}\right)^{-1} P_k^{(total)}
\]  

(25)

where \(P_k^{(total)}\) denotes the total transmit power of node \(k\) (i.e., \(P_k^{(total)} = \sum_{m=1}^{N} P_k^{(m)}\)), and \(\varepsilon\) is a small value to prevent an overflow of the inverse RSSI in the presence of little interference at subchannel \(n\). Note that the transmit power can be controlled at each femtocell in a distributed manner with the aid of subchannel allocation indicator \(\alpha_k^{(n)}\) received from the femto gateway.

### IV. PERFORMANCE EVALUATION

The performance of the proposed scheme is verified by computer simulation considering a building environment that comprises 15 rooms each of which has an area of \((30 \times 30)\) m\(^2\) (i.e., 3 by 5 rooms in a floor). We assume that a femtocell is randomly located at each room and serves a single user at a random location, which is a modified simulation scenario of [6] in a residential area. We also assume that the total femtocell transmit power is 0 dBm (i.e., \(P_k^{(total)} = 0\) dBm), the number of subchannels is 16, and a modified ITU-R P.1238 residential path loss model with heavy wall loss of 7 dB is applied. For the validation, the proposed scheme is compared with two conventional schemes, universal frequency reuse with transmit power control and FRF 1/3 scheme [7][8]. We consider the resource allocation to maximize the system spectral efficiency while providing a cell edge spectral efficiency of 1bps/Hz (i.e., 5\% point of the CDF of spectral efficiency is 1bps/Hz) [11].

Fig. 3 depicts the ergodic system spectral efficiency \(C_{system}\) (4) and the cell edge spectral efficiency \(C_{edge}\) (5) of the proposed scheme according to the SIR threshold \(\lambda_{th}\). It can be seen from Fig. 3 (a) that as the SIR threshold \(\lambda_{th}\) increases, the ergodic system spectral efficiency of the proposed scheme decreases. This is mainly due to the fact that the higher the value of \(\lambda_{th}\), the less the reuse of subchannels, resulting in a use of low FRF. It can be seen from Fig. 3 (b) that the proposed scheme yields a peak cell edge spectral efficiency at a value of \(\lambda_{th}\) around 10 dB. This is mainly due to the fact that although the interference can be reduced by allocating the frequency resource using a low FRF when \(\lambda_{th}\) exceeds 10 dB, femtocells may not have enough frequency resource to support users with the use of a low FRF. Thus, it may be desirable to use an appropriate value of \(\lambda_{th}\) to achieve high system spectral efficiency while achieving desired cell edge spectral efficiency.
femtocells. The proposed scheme allocates the frequency properly according to the operating environments. This scheme shows it is possible to adjust the FRF of each femtocell FRF 1/3. This performance is achievable because the proposed scheme with \( \lambda \) provides relatively low system spectral efficiency. It can be seen that the proposed scheme with \( \lambda \) can provide desired cell edge spectral efficiency, but it cannot guarantee desired cell edge spectral efficiency. On the other hand, the use of FRF 1 provides a cell edge spectral efficiency similar to the use of FRF 1 while \( \lambda \) = 10 dB. It can be seen from Fig. 3 and Fig. 4 that the use of universal frequency reuse provides the highest system spectral efficiency but it cannot guarantee desired cell edge spectral efficiency. We have also considered the adaptation of transmit power of each subchannel in a distributed manner for better spectrum usage. The simulation results show that the proposed scheme provides desired performance in residential building environments. However, when each femtocell has different loads or the frequency resource is not sufficiently large, the frequency resource allocation based on long term channel condition may not work properly. This problem may be alleviated by means of a distributed IFFI mitigation technique such as cooperative spatial multiplexing which is on further investigation.

Fig. 4 depicts the CDF of the spectral efficiency when \( \lambda_{th} \) is set to a value of 10 dB. It can be seen from Fig. 3 and Fig. 4 that the use of universal frequency reuse provides the highest system spectral efficiency but it cannot guarantee desired cell edge spectral efficiency. On the other hand, the use of FRF 1/3 can provide desired cell edge spectral efficiency, but it provides relatively low system spectral efficiency. It can be seen that the proposed scheme with \( \lambda_{th} = 10 \) dB provides a system spectral efficiency similar to the use of FRF 1 while providing cell edge spectral efficiency similar to the use of FRF 1/3. This performance is achievable because the proposed scheme shows it is possible to adjust the FRF of each femtocell properly according to the operating environments.

V. CONCLUSIONS AND FURTHER WORK

In this paper, we have considered the design of an adaptive FFR scheme to mitigate interference from randomly deployed femtocells. The proposed scheme allocates the frequency resource based on the femtocell location and a desired cell edge spectral efficiency. We have also considered the adaptation of transmit power of each subchannel in a distributed manner for better spectrum usage. The simulation results show that the proposed scheme provides desired performance in residential building environments. However, when each femtocell has different loads or the frequency resource is not sufficiently large, the frequency resource allocation based on long term channel condition may not work properly. This problem may be alleviated by means of a distributed IFFI mitigation technique such as cooperative spatial multiplexing which is on further investigation.

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