A Mobility Management Scheme to Reduce the Impact of Channel Heterogeneity in Cognitive Radio Femtocell Networks

Wahida Nasrin and Jiang Xie
Department of Electrical and Computer Engineering
The University of North Carolina at Charlotte
Email: {wnasrin, Linda.Xie}uncc.edu

***Abstract*—Combining femtocell networks and cognitive radio (CR) technology is one of the most promising solutions to offload emerging traffic from cellular networks. Mobility management is an essential function to support traffic offloading in heterogeneous networks. In traditional femtocell networks, numerous solutions have been proposed to support mobility. However, in CR femtocell networks, the mobility management issue remains unexplored. More importantly, due to the channel heterogeneity in CR femtocell networks, some unique challenges of channel underutilization and interference are introduced. Although channel heterogeneity is considered for spectrum handoff and spectrum sharing in pure CR networks, the impact of channel heterogeneity on mobility management is never addressed in CR femtocell networks. In this paper, we propose a mobility management scheme for both macro-to-femto and femto-to-macro handoffs while taking channel heterogeneity into account. Additionally, we propose an adaptive HO-threshold selection scheme combined with our proposed mobility management scheme by taking the interference from PUs and neighboring femtocells into account. An analytical model is proposed to calculate the interference. Simulation results show significant performance improvement of the proposed mobility management scheme. To the best of our knowledge, this is the first work that considers mobility management and channel heterogeneity jointly in CR femtocell networks.**

I. Introduction

The volume of mobile data traffic is increasing exponentially in recent years due to the popularity of various mobile devices [1]. This increment of data traffic leads to a spectrum scarcity problem in cellular networks. As a result, operators are becoming interested in offloading cellular traffic to other networks, such as femtocells. Although the low-powered, short-ranged, and low-cost femtocells are considered as a promising solution to provide cellular traffic offloading [2], [3], densely deployed femtocells may increase the demand of the cellular spectrum and interference to macrocell networks. The cognitive radio (CR) technology is then proposed to combine with femtocell networks in order to overcome these issues [4]–[9]. This combined network is called CR femtocell network, where the CR femto-base stations (FBSs) act as secondary users (SUs) and they are capable of accessing the licensed spectrum of both macrocell networks and TV white space in an opportunistic manner.

To support seamless traffic offloading, when an active user moves towards a femtocell, it is desirable that the user is handed off to the femtocell. On the other hand, while an active femtocell user (known as FUE) moves out of the femtocell coverage area, it should be handed off to the macrocell in order to avoid service disconnection. Therefore, mobility management is a very important issue in femtocell networks [10]. Besides the existing challenges in traditional femtocell networks, such as transmission power difference and interference, adding cognitive capabilities to FBSs introduces more challenges in mobility management. Choosing channels from heterogeneous frequency bands is one of them. Each frequency band has different path-losses, transmission rates, channel-error rates, etc. Though heterogeneous channels are considered in spectrum sharing [11]–[14] and spectrum handoffs (HOs) [15]–[19] in traditional CR networks, mobility management and the effect of heterogeneous channels on mobility management are never considered in CR femtocell networks.

In this paper, we consider the impact of channel heterogeneity on mobility management in CR femtocell networks and propose a novel mobility management scheme for both inbound (macro-to-femto) and outbound (femto-to-macro) scenarios. In this scheme, we address some unique challenges caused by the channel heterogeneity and propose to use HO-threshold adaptation which considers the probability of interference from both primary users (PUs) and other CR femtocell networks. In this way, our proposed scheme is able to provide seamless offloading with reduced HO time and at the same time, enhanced femtocell utilization without interfering any PU or any neighboring FBS. We adapt the HO-threshold in a way that it can adjust the femtocell coverage area. This coverage area adjustment is challenging, because the CR FBS can only sense within its sensing area and when the coverage area expands with an increased transmission power, it cannot extend the sensing area. As a result, the CR FBS and its users can be affected by the interference from PUs and neighboring CR femtocells. In order to cope with this interference, we propose a threshold-based adaptive HO scheme. We also propose an analytical model to calculate the probability of interference from PUs and neighboring CR FBSs and integrate this model to adapt the HO-threshold. To the best of our knowledge, this is the first work that considers channel heterogeneity and mobility model together in CR femtocell networks.

The rest of the paper is organized as follows. In Section II, system model and research motivation are introduced. Related work and our contributions are explained in Section III. In

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Section IV, the proposed HO decision scheme is described. In Section V, the performance evaluation of the proposed model is given, followed by the conclusions in Section VI.

II. System Model and Research Motivation

A. System Model

We consider a communication system that includes multiple primary networks and a femtocell-based heterogeneous network. Primary networks consist of macrocell networks, TV networks, macrocell users, and TV users. Users in primary networks are known as PUs. We consider an extension of the conventional femtocell concept under which FBSs are equipped with cognitive radios. Each cognitive radio femtocell has a number of FUEs. FUEs act as traditional femtocell users and they have no cognitive capabilities. The network architecture of such a CR femtocell network is shown in Fig. 1.

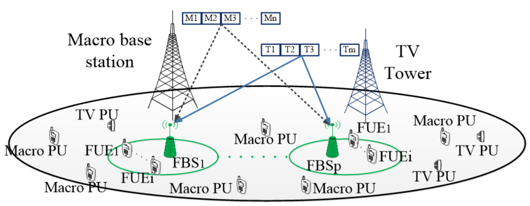


Fig. 1. A cognitive radio femtocell network.

In this model, PUs use the licensed spectrum whenever necessary. CR FBSs actively sense the spectrum and allocate the available spectrum resources to FUEs which are not being used by any PU. CR FBSs maintain a list of the available spectrum based on the sensing outcome and update it in a time-to-time manner. Whenever a FUE becomes active within the femto-coverage area, the CR FBS assigns an available channel from the list to the FUE. If a PU appears on the channel the FUE is using, the CR FBS will ask the FUE to perform a spectrum handoff. To support multiple FUEs, a CR FBS may access different spectrum bands from different networks based on their availabilities. Therefore, the CR femtocell network acts as a multi-carrier multi-radio system with heterogeneous channels.

Under this system, we assume that there are p heterogeneous primary networks which consist of both cellular (macrocell) and TV networks. Denote M_i as the set of channels used by the ith macrocell and T_j as the channels of the jth TV tower, where $i, j = \{1, 2, 3, \dots\}$. Assume that there are q CR femtocells available in the system. Each CR FBS individually detects the available channels. The set of available channels is different from one CR FBS to another depending on their location. Consider a CR FBS within the coverage area of the ith and jth primary networks. Denote c as the set of available channels observed by femtocell r. Hence, $(c \subseteq M_i) \cup (c \subseteq T_j)$, which means that the list of the available channels for CR FBSs are either from macrocell frequency band or from TV white space or both. Each time a FUE becomes active or moving towards the femtocell, the CR FBS assigns a channel to the FUE by considering the channel heterogeneity and adjusts its transmission power for the selected channel when necessary.

B. Research Motivation

The impact of spectrum heterogeneity on mobile users in CR femtocell networks is investigated in this section. Heterogeneous spectrum have very different path-losses which may result in significantly different transmission ranges. The relationship between the transmission ranges (shown as coverage radius) and transmission frequencies under a *constant transmission power* is shown in Fig. 2. In the figure, we use the ITU-RP.1238-7 indoor path-loss model [20] and assume that the cell coverage is defined as the region in which the received signal strength indicator (RSSI) is greater than the RSSI at the cell boundary of traditional femtocell networks. From the figure, it is shown that the cell coverage reduces drastically at high frequencies due to poor propagation. This reduction of cell coverage may cause poor cell utilization when CR FBSs operate at channels with high frequencies. On the other hand, at low operating frequencies, the increment of cell coverage may cause users experiencing interference from PUs or other neighboring femtocells.

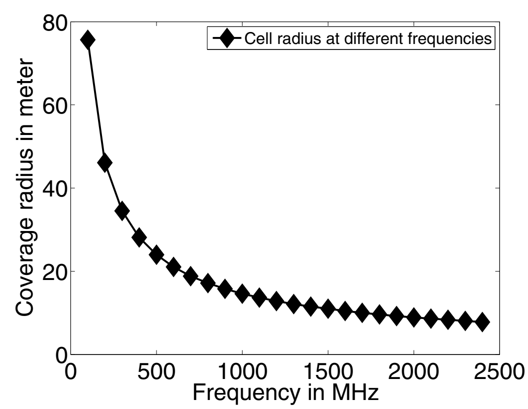


Fig. 2. Transmission coverage under different transmitting frequencies.

How this change of coverage area caused by spectrum heterogeneity affects the mobility management of FUEs during inbound HOs and outbound HOs is shown in Fig. 3. In this figure, we use two transmission ranges to show the effect of heterogeneous channels. When a user (FUE_1) connecting to a macrocell moves towards a femtocell, the moment a macro-to-femto HO should be triggered depends on the channel availabilities. If the CR FBS chooses a low operating frequency for the FUE (which means that the coverage area of the femtocell is large due to a weak path-loss), the HO will be triggered early (at point A) if using a fixed HO-threshold. This early HO can enhance the femtocell utilization. However, this can also cause a number of unnecessary HOs at the cell boundary. On the other hand, if the CR FBS chooses a high operating frequency for the FUE, the coverage area of the femtocell will be small. As a result, the HO should be triggered late (at point B). This late HO may lead to a low femtocell utilization. Although a proper channel selection algorithm can overcome these problems, it is possible that the selected proper channel might not be available at a certain time.

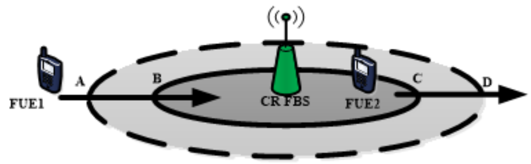


Fig. 3. Effects of heterogeneous channels on mobile FUEs.

Similarly, when a user (FUE_2) moves out of a femtocell to a macrocell, either the femtocell utilization becomes low in the case of a high operating frequency or the probability of interference and unnecessary HOs is high in the case of a low operating frequency. To improve the femtocell utilization, a spectrum HO to a low frequency channel can be triggered (at point C). However, this spectrum HO may cause a high HO delay because of the additional sensing and channel switching delay. Another approach is the power control. However, increasing transmission power of the CR FBS can also increase the probability of interference to PUs and neighboring femtocells which are using the same channel. Moreover, a CR FBS may select different frequency channels at the same time. As a result, it is difficult for a CR FBS to adjust its transmission power for each frequency channel separately. Therefore, we propose an adaptive HO-threshold selection scheme which considers the probability of interference from PUs and neighboring femtocells to address these issues and design an analytical model based on this.

III. Related Work and Our Contribution

A. Related Work

Existing work on CR femtocell networks is mainly focused on addressing the problem of spectrum sharing, resource allocation and management, interference avoidance, and power control. There is almost no existing work on mobility management in CR femtocell networks. Works on spectrum sharing take energy efficiency [9], dense deployment of femtocells [21], power allocation [22], and spatial reuse gain [23] into account. In addition, resource allocation and interference are considered together in CR femtocell networks [7], [24]. However, none of these existing work considers channel heterogeneity in CR femtocell networks. Additionally, although research on mobility management in traditional femtocell networks is rich, mobility management in CR femtocell networks still requires further investigations. All of the mobility management works in femtocell networks are designed to avoid frequent and unnecessary HOs, to reduce HO failure rate, and to minimize ping-pong effects [10], [25]. None of these techniques are suitable for CR femtocell networks when considering the channel heterogeneity (which has great impacts on mobility management as shown in Section II-B).

In pure CR networks, the impact of heterogeneous channels on spectrum sharing and spectrum HOs is investigated in [11]–[19]. The energy constraint for heterogeneous channels during spectrum access is discussed in [12] where authors propose two schemes for spectrum allocation by taking propagation conditions of channels into account. A spectrum sharing algorithm based on spectrum heterogeneity is presented in [13] where users are free to move and they perform channel HOs during multi-hop communications. In addition, the effects of heterogeneous spectrum during spectrum HOs in CR ad-hoc networks are considered in [17]–[19] where SUs are mobile. However, the CR femtocell network, which is an infrastructure based CR network, needs further investigations to address the issue of channel heterogeneity to support a number of mobile users which do not have cognitive capability.

B. Contributions

In this paper, we propose a mobility management scheme for both macro-to-femto and femto-to-macro HOs by taking heterogeneous channels into consideration. The contributions of this paper are summarized as:

- The impact of the channel heterogeneity on mobility management in CR femtocell networks is considered for the first time.
- We propose HO algorithms for both inbound (macro-to-femto) and outbound (femto-to-macro) users in order to provide seamless offloading.
- An adaptive HO-threshold selection scheme is integrated with both inbound and outbound HO algorithms to provide better femtocell utilization, to improve throughput, and to reduce the transmission time.
- We propose an analytical model to calculate the probability of interference from both PUs and neighboring femtocells and apply these probabilities of interference to adapt the HO-threshold of CR FBSs in a way that both HO schemes can avoid interference from any PU and any FUE in neighboring femtocells using the same channels.
- Realistic simulation scenarios are considered for evaluating the performance of the proposed scheme in terms of femtocell utilization, throughput, and transmission time. Simulation results show significant performance improvement of our proposed scheme as compared to the traditional mobility management scheme.

IV. Proposed HO Decision Scheme

In this section, an adaptive HO-threshold selection scheme for different operating frequencies is proposed for both inbound (macro-to-femto) and outbound (femto-to-macro) HO algorithms. Our design goal is to utilize available channels as long as they are not occupied by PUs within the femtocell coverage area and at the same time, avoid possible interference from undetected PUs and from neighboring femtocells that are using the same channels. The notations used in the algorithms for our proposed scheme are shown in Table I.

TABLE I
NOTATIONS USED IN THE ALGORITHMS

$RSSI$	Received Signal Strength Indicator
$RSSI_f$	RSSI of a CR femtocell
$RSSI_{minFemto}$	RSSI at a traditional femtocell boundary
$RSSI_m$	RSSI of a macrocell
$RSSI_{minMacro}$	RSSI at a macrocell boundary
r_f	Coverage radius of a CR femtocell at frequency f
$P(I)$	The probability of interference
r_I	The radius of the interfered area
I_{Th}	The threshold of the probability of interference
Th_{adp}	The threshold of the adaptive RSSI
Δr	The radius of the extended interference-free area
δr	The radius of the reduced interference-free area

A. HO Threshold Adaptation and HO Algorithms

In order to avoid early and late HOs, an adaptation of the HO-threshold to the operating frequency is very important for CR FBSs. In this scheme, we adapt the HO-threshold of a CR FBS based on the current operating frequency in order to compensate the difference in signal propagations on different frequency channels and to improve the femtocell utilization. The detailed spectrum sensing and selection design is out of the scope of this paper. We consider that each CR FBS has a proper sensing strategy and the channel selection is random. The selection varies based on PU activities. Parameters required for this adaptive HO-threshold scheme are $RSSI_{minFemto}$, r_f, $P(I)$, r_I, and I_{Th}.

After selecting an operating frequency, the CR FBS can calculate its coverage radius, r_f, from the ITU indoor path-loss model for urban area [20]. The path-loss is

$$PL = P_{tx} + G_t + G_u - RSSI_{minFemto}, \tag{1}$$

and

$$PL = 20log(f) + Nlog(r_f) + L_f(n) - a(n), \tag{2}$$

where P_{tx} is the transmission power of a CR FBS, G_t and G_u are the antenna gains for the CR FBS and the FUE, respectively, f is the operating frequency, L_f is the floor penetration loss factor, N is the distance power-loss coefficient, n is the number of floors/walls, and $a(n)$ is the shadow fading. Therefore, the cell radius can be calculated from (1) and (2) as

$$r_f = 10^{\frac{P_{tx}+G_t+G_u-RSSI_f-20log(f)-L_f(n)+a(n)}{N}}. \tag{3}$$

Now, from [26] we get

$$r_I = 1.5 r_f. \tag{4}$$

The algorithm to determine the adaptive HO-threshold is shown in Algorithm 1.

In this algorithm, Δr is the extended distance in cell radius for which $P(I)$ is below the threshold. Δr can be calculated in two different ways. In the first approach, $\Delta r(i) = ivcos\theta$, where $i = \{1, 2, \dots\}$ represents increments in time, v is the speed of the FUE in m/s, and θ is measured in degree and is used to represent the direction of the FUE movement. However, it is not practical for a CR FBS to know the speed and the moving direction of a FUE. Considering this fact, we adopt the second approach to find Δr. In this approach, $\Delta r(i) = i$, where $i = \{1, 2, 3, \dots\}$ represents increments in distance. Now, the distance Δr can be calculated using Algorithm 2. Additionally, δr is the distance in radius for which the value of $P(I)$ is lower than the threshold. Now, δr can be calculate using Algorithm 3.

Algorithm 1: Calculation of Th_{adp}

```
Inputs: f, RSSI_minFemto, I_Th;
The CR FBS determines r_f and r_I using (3) and (4), respectively;
Calculate P(I) based on r_I; // the calculation is shown in Section IV-C
if P(I) < I_Th then
    Calculate Δr using Algorithm 2;
    r_fnew = (Δr + r_I)/1.5;
else
    Calculate δr using Algorithm 3;
    r_fnew = δr/1.5;
End;
Calculate Th_adp for r_fnew using (5) and (6);
```

Algorithm 2: Calculation of Δr

```
i = 1;
while i ≠ 0 do
    Δr(i) = i;
    Calculate P(I) for Δr(i) + r_I (as explained in Section IV-C);
    if P(I) < I_Th then
        i = i + 1;
    else
        i = 0;
End;
Δr = Δr(i) − 1;
```

Algorithm 3: Calculation of δr

```
i = 1;
while i ≠ 0 do
    δr(i) = r_I;
    Calculate P(I) for δr(i) (as explained in Section IV-C);
    if P(I) > I_Th then
        r_I = r_I − 1;
        i = i + 1;
    else
        i = 0;
End;
δr = δr(i);
```

The adapted HO-threshold Th_{adp} can be obtained from

$$Th_{adp} = P_{tx} + G_t + G_u - PL_{new}, \tag{5}$$

where PL_{new} is the path-loss for distance r_{fnew} and

$$PL_{new} = 20log(f) + Nlog(r_{fnew}) + L_f(n) - a(n). \tag{6}$$

After determining the value of the adaptive HO-threshold, the serving CR FBS checks the HO decision criteria. Similar to the LTE-Advanced system, in CR femtocell networks, the Radio Resource Control (RCC) protocol manages the event that a UE reports its HO measurement to the serving BS

[27]. The measurement includes UE's ID, CR femtocell's ID, and their RSSIs. When a UE sends a measurement report to the CR FBS, the CR FBS makes a decision of whether to HO or not, based on the HO decision criteria. Our proposed inbound (macro-to-femto) and the outbound (femto-to-macro) HO algorithms are given in Algorithm 4 and Algorithm 5.

Algorithm 4: Inbound HO-decision algorithm

if $RSSI_f > Th_{adp}$ **or** $RSSI_m < RSSI_{minMacro}$**, and** $RSSI_f > RSSI_m + HM$ **then**
  Perform a HO to the femtocell;
else
  Remain connected to the macrocell;
End;

Algorithm 5: Outbound HO-decision algorithm

if $RSSI_f < Th_{adp}$ **or** $RSSI_m > RSSI_{minMacro}$**, and** $RSSI_f + HM < Th_{adp}$ **then**
  Perform a HO to the macrocell;
else
  Remain connected to the femtocell;
End;

The selection of $RSSI_{minFemto}$, $RSSI_{minMacro}$, and I_{Th} are shown later in the paper. The calculation of $P(I)$ is also presented in Section IV-C in the paper. The value of HM is taken from [25].

B. Calculation of HO Parameters

The values of $RSSI_{minFemto}$, $RSSI_{minMacro}$, and I_{Th} are determined in this section. To calculate $RSSI_{minFemto}$, we consider the traditional LTE femtocell networks operating at the 1700MHz frequency band. Fig. 4 presents the RSSI values for different distances from the FBS. The ITU-R.P.1238-7 indoor path-loss model is used for the RSSI calculation [20]. From the figure, it is shown that at the cell boundary, which is considered as 15m for our simulations, the $RSSI$ is -60.54dB. This $RSSI$ value is considered as $RSSI_{minFemto}$.

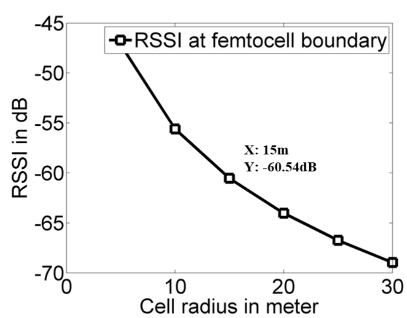


Fig. 4. Selecting $RSSI_{minFemto}$ at the femtocell boundary.

The Okumura-Hata propagation model is used for calculating the RSSI of macrocell networks against different distances, which is shown in Fig. 5. The $RSSI$ at macrocell boundary, which is considered as $500m$ for our simulations, is taken as $RSSI_{minMacro}$.

On the other hand, since the probability of interference depends on various factors, such as noise, femtocell placement, and neighboring femtocells, it is difficult to select a single threshold for the probability of interference. Considering this fact, we take I_{Th} from a range of 0.1 to 0.3.

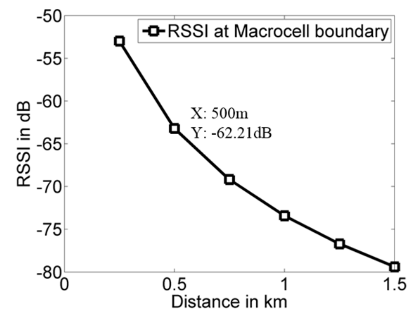


Fig. 5. Selecting $RSSI_{minMacro}$ at the macrocell boundary.

C. Calculation of the Probability of Interference

In this section, the probability of interference from PUs and from neighboring femtocells which are using the same channels as the serving CR FBS is calculated. The probability of interference from PUs is denoted as $P(I_{PU})$ and the probability of interference from neighboring femtocells is denoted as $P(I_n)$. Now, the total probability of interference is

$$P(I) = P(I_{PU}) + P(I_n). \tag{7}$$

1) The Probability of Interference from PUs: We assume that the sensing area of a CR FBS is similar to the interference area of the CR FBS. Therefore, the CR FRS can sense the presence of any PU within the interference area. Now, to calculate the probability of interference from PUs, we consider two different scenarios. In the first scenario, PUs appear in the interference area of CR FBSs. In this case, the CR FBS can sense the appearance of PUs. Therefore, the probability of interference from PUs in this case is $P(I_{PU}) = 0$. This first scenario is applicable for Algorithm 1, where we consider the probability of interference for r_I and for Algorithm 3, where we consider the probability of interference for δr. In both cases, the PU is within the sensing area. In the second scenario, PUs appear within the area which is larger than the sensing area of the CR FBS. We use this scenario to calculate the P(I) for Algorithm 2.

To determine $P(I_{PU})$ for the second scenario, we consider the Venn diagram shown in Fig. 6. We assume that K PUs are evenly distributed within the coverage area of a primary network A_m, which is equivalent to the coverage area of the macrocell with a radius of r_m. The interference area of a CR femtocell is $A_f = \pi(r_I)^2$ and the extended area is $A_{new} = \pi r_{new}^2$, where $r_{new} = \Delta r + r_I$. Since the probability of interference from PUs is equal to zero in the interference area, to calculate $P(I_{PU})$ we need to calculate the probability of interference from PUs within the extended area. Now,

$P(A^c \cap B) = \frac{r_{new}^2 - r_I^2}{r_m^2}$ is defined as the probability that an event happens in the extended area. Therefore, the probability that k_1 PUs are within the extended area of A_{new} is

$$P(k_1) = \binom{K}{k_1}(\frac{r_{new}^2 - r_I^2}{r_m^2})^{k_1}(1 - \frac{r_{new}^2 - r_I^2}{r_m^2})^{K-k_1}. \quad (8)$$

The probability that k_2 PUs are active given that k_1 PUs are within the new interference area of a femtocell is

$$P(k_2|k_1) = \binom{k_1}{k_2}\sigma^{k_2}(1-\sigma)^{k_1-k_2}, \quad (9)$$

where σ is the probability that a PU is active. And

$$\sigma = \frac{E[ON]}{E[ON] + E[OFF]}, \quad (10)$$

where $E[\cdot]$ is the average value of the ON period and OFF period. If c channels are available for a CR femtocell and each CR femtocell can support M users, the probability that a CR FBS chooses a set M channels from c channels is equal to $1/\binom{c}{M}$. Then the probability that any PUs are using the same channels = $1-$ the probability of no PUs are using the same channels = $1 - \binom{c-M}{1}/\binom{c}{1}$, because a PU can only choose one channel at a time. Therefore, the probability that k_3 PUs are using the same channels as the serving CR femtocell given that k_2 PUs are active is

$$P(k_3|k_2) = \binom{k_2}{k_3}(1 - \frac{\binom{c-M}{1}}{\binom{c}{1}})^{k_3}(\frac{\binom{c-M}{1}}{\binom{c}{1}})^{k_2-k_3}. \quad (11)$$

Hence, the probability that any PUs are using the same channel within the femtocell extended area is

$$P(I_{PU}) = \sum_{k_1=1}^{K}\sum_{k_2=1}^{k_1}\sum_{k_3=1}^{k_2} P(k_1)P(k_2|k_1)P(k_3|k_2). \quad (12)$$

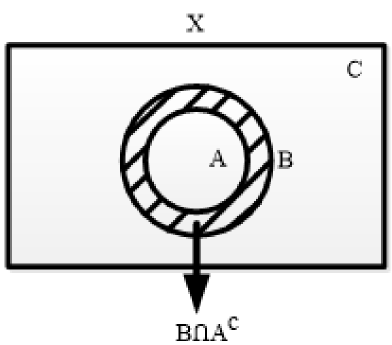


Fig. 6. A Venn diagram representing the coverage area of a primary network denoted by C, A denotes the interference area of a CR femtocell, and B denotes the extended area of the CR femtocell, for which the $P(I_{PU})$ needs to be calculated.

2) The Probability of Interference from Neighboring Femtocells: Similar to the probability of interference from PUs, we consider two different scenarios for determining the probability of interference from neighboring femtocells. For the first scenario, we consider the Venn diagram shown in Fig. 7 to calculate $P(a)$, which is the probability that an event happens within the overlapping interference area of the serving femtocell and its neighboring femtocells. From the figure, we determine the overlapping area between the serving CR femtocell A and neighboring femtocells as $\{(A \cap f_1) \cup (A \cap f_2) \cup \cdots \cup (A \cap f_m)\}$. However, neighboring femtocells may also overlap with each other. Considering this overlap, the total overlapping area is $\{(A \cap f_1) \cup (A \cap f_2) \cup \cdots \cup (A \cap f_m)\} - \{(f_1 \cap f_2) \cup (f_2 \cap f_3) \cup \cdots \cup (f_{m-1} \cap f_m) \cup (f_m \cap f_1)\}$. Therefore, we calculate the probability that an event happens in the overlapping area between neighboring femtocells for the first scenario as

$$P(a) = \{P(A \cap f_1) + \cdots + P(A \cap f_m)\} -$$
$$\{P(f_1 \cap f_2) + \cdots + P(f_{m-1} \cap f_m) + P(f_m \cap f_1)\}. \quad (13)$$

Since the placement of neighboring femtocells is random, it is nearly impossible to determine the actual overlapping area between neighboring femtocells. Therefore, we consider $P(a)$ as a variable and $0 \leq P(a) \leq 1$.

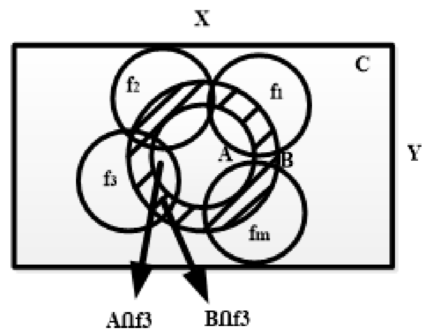


Fig. 7. A Venn diagram representing the transmission area of a primary network denoted by C, a serving CR femtocell, which is surrounded by m neighboring femtocells, and the interference area of femtocell as A and the extended area as B.

In the second scenario, as the area is extended, the probability that any event happens within the overlapping area will be equal to the summation of the probability that any event happens within the overlapping interference area and the probability that any event happens within the extended area. Therefore, the probability that an event happens within the overlapping area of the expanded area of a femtocell and its neighboring femtocells is

$$P(b) = P(a) + \frac{r_{new}^2 - r_I^2}{r_m^2}. \quad (14)$$

Now, we obtain the probability that any FBS is within that overlapping area. We assume that Q CR FBSs are evenly distributed among the coverage area of πr_m^2. The probability of t_1 FBSs from Q FBSs within the overlapping area as

$$P(t_1) = \binom{Q}{t_1}P(b)^{t_1}(1 - P(b))^{Q-t_1}. \quad (15)$$

The probability that t_2 FBSs are active given that t_1 FBSs are within the overlapping area and the probability of t_3 FBSs using the same channels as the serving femtocell given that t_2 FBSs are active can be calculated as

$$P(t_2|t_1) = \binom{t_1}{t_2} \lambda^{t_2} (1-\lambda)^{t_1 - t_2}, \quad (16)$$

and

$$P(t_3|t_2) = \binom{t_2}{t_3} (1 - \frac{\binom{c-M}{M}}{\binom{c}{M}})^{t_3} (\frac{\binom{c-M}{M}}{\binom{c}{M}})^{t_2 - t_3}, \quad (17)$$

where λ is the probability that a CR FBS is active, c is the number of channels available for a CR femtocell, and M is the total number of channels used by a CR femtocell as described before. Using these probabilities, $P(I_n)$ can be found as

$$P(I_n) = \sum_{t_1=1}^{Q} \sum_{t_2=1}^{t_1} \sum_{t_3=1}^{t_2} P(t_1) P(t_2|t_1) P(t_3|t_2). \quad (18)$$

Then, $P(I)$ can be calculated using (7).

V. Performance Evaluation

In this section, we evaluate the performance of the proposed mobility management scheme. First, we introduce the setting of scenarios in the simulation. Then, the performance of the proposed scheme is evaluated in terms of femtocell utilization, required transmission time, and throughput.

A. Simulation Setup

We simulate the HO process of a closed-access (only the registered users have access to a femtocell) CR femtocell network. We use Net Logo 5.0.5 [28] to simulate our proposed scheme in an indoor environment. We investigate the HOs, triggered by FUEs, in an area of πr_m^2 for a certain simulation time. A single-floored two-bedroom apartment is designed to have a CR FBS which has the capacity of supporting up to eight FUEs. The CR FBS has six neighboring CR femtocells and all of them are within the coverage area of primary networks containing a macrocell and a TV tower. We consider 20 users with a probability of 0.7 to enter and exit the apartment in a random manner. The neighboring CR FBSs are placed in a way that the overlapping area is between 0 and 0.3 with the serving CR femtocell. All users are placed randomly and they follow a modified version of the Random Waypoint mobility model [29]. The mobility model is modified in such a way that users only use the door to get in/out of the apartment and none of them cross the walls. The values of the parameters used in the simulation are listed in Table II.

We mainly investigate the following three metrics to evaluate the performance of our proposed scheme. These metrics are 1) *femtocell utilization*: the probability that a FUE stays connected to the femtocell while within the coverage of its home FBS, 2) *required transmission time*: total transmission time required to transmit a specific length of video traffic including all delays, and 3) *Throughput*: the amount of traffic the CR FBS can transmit in a unit time. In addition, we compare our proposed scheme with the traditional mobility management scheme, where the HO RSSI threshold is fixed and does not change with the variation of operating frequencies. We take three different values for both $P(a)$ and I_{Th} to show the variation and the comparison of the proposed scheme with the traditional scheme.

TABLE II
SIMULATION PARAMETERS

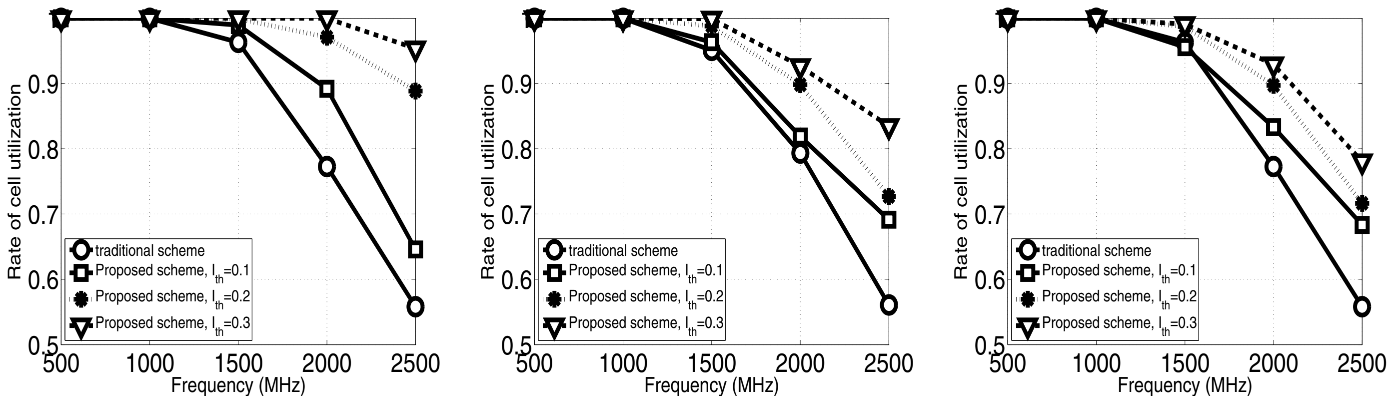
Macrocell transmission power, P_m	45 dBm [3]
Radius of macrocells	500 m
Femtocell transmission power, P_{tx}	15 dBm [3]
Radius of femtocells	15 m [25]
Operating frequencies of PUs	$500 - 2500$ MHz
Users speed	5 km/hr [25]
Minimum femtocell RSSI, $RSSI_{minFemto}$	-60.54 dB
Minimum macrocell RSSI, $RSSI_{minMaco}$	-62.21 dB
Interference threshold, I_{Th}	0.1 to 0.3
Overlapping area, $P(a)$	0.1 to 0.3
Floor penetration loss, L_f	5 dB [20]
Distance power loss coefficient, N	28 [20]
Shadow fading, $a(n)$	28 [20]
Antenna gain of FBSs, G_t	2 dB [20]
Antenna gain of FUEs, G_u	0 dB [20]
Total number of PUs, K	20
The probability that a PU is active, σ	0.7 [19]
Total number of femtocells, Q	7
The probability that a femtocell is active, λ	0.6
Number of channels in the system, c	200
Delivered data	10000000 bps
Channel bandwidth	5 MHz
Total simulation time	20000 secs

B. Femtocell Utilization

The femtocell utilization is determined as the average time an active FUE is served by the CR femtocell while it is within the area of the femtocell. As CR femtocells are deployed for offloading cellular traffic and to provide cost-effective service to FUEs, it is expected that when a FUE is within the coverage area of its home CR FBS, it should be connected to it. The femtocell utilization is shown in Fig. 8 with respect to different operating frequencies. From the figure, it is shown that the femtocell utilization decreases when the serving CR FBS interferes more with the neighboring femtocells. A high value of $P(a)$ shows a high probability of overlapping area, therefore, a high interference from neighboring femtocells. On the other hand, the selection of a high I_{Th} represents a high femtocell utilization. This is because a high value of I_{Th} means a more interference tolerant network. We also observe that the traditional mobility management scheme shows worse femtocell utilization in each of these scenarios as compared to the proposed mobility management scheme.

C. Required Transmission Time

To simulate the performance of the required transmission time, we use the method from [16]. When a FUE performs a HO, it requires a high transmission time due to the HO delay. Our proposed mobility management scheme uses the adaptive HO-threshold to reduce unnecessary HOs, which are caused by the channel heterogeneity in CR femtocell networks, therefore, reduces HO delay. In the simulation, we determine the required



(a) Femtocell utilization for $P(a) = 0.1$

(b) Femtocell utilization for $P(a) = 0.2$

(c) Femtocell utilization for $P(a) = 0.3$

Fig. 8. Comparison of the femtocell utilization.

transmission time for a traffic of 10 Mb for both proposed and traditional schemes. Fig. 9 shows the required transmission time with respect to various operating frequencies. From the figure, it is observed that the traditional scheme requires more time to transmit the same data traffic than the proposed one. We also observe that the required transmission time increases with the interference from the neighboring femtocells and it decreases with the I_{Th}.

D. Throughput

Throughput is calculated as the total size of transmitted data divided by the total required time to transmit the data. A high throughput indicates a more reliable network. The comparison of throughput of our proposed mobility management scheme and the traditional mobility management scheme is shown in Fig. 10. It is observed from the figure that the increment of both $P(a)$ and I_{Th} reduces the throughput of CR femtocell networks. The reason behind this is that the increment of $P(a)$ and I_{Th} increases interference in femtocell networks.

VI. Conclusion

In this paper, we addressed the channel heterogeneity problem during mobility management in CR femtocell networks. We proposed a mobility management scheme with an adaptive HO-threshold to support both inbound and outbound mobility. In addition, a HO-threshold selection scheme is proposed with the interference from PUs and neighboring femtocells taken into account and integrated with the proposed mobility management scheme. The probability of interference from both PUs and neighboring femtocells is calculated analytically. The performance of the proposed mobility management scheme is analyzed in terms of femtocell utilization, required transmission time, and throughput. The proposed scheme is compared with a traditional mobility management scheme where the channel heterogeneity is not considered. Simulation results show significant performance improvement as compared to the traditional scheme in CR femtocell networks. Our proposed scheme can reduce the channel under-utilization and required transmission time. On the other hand, it can improve the throughput.

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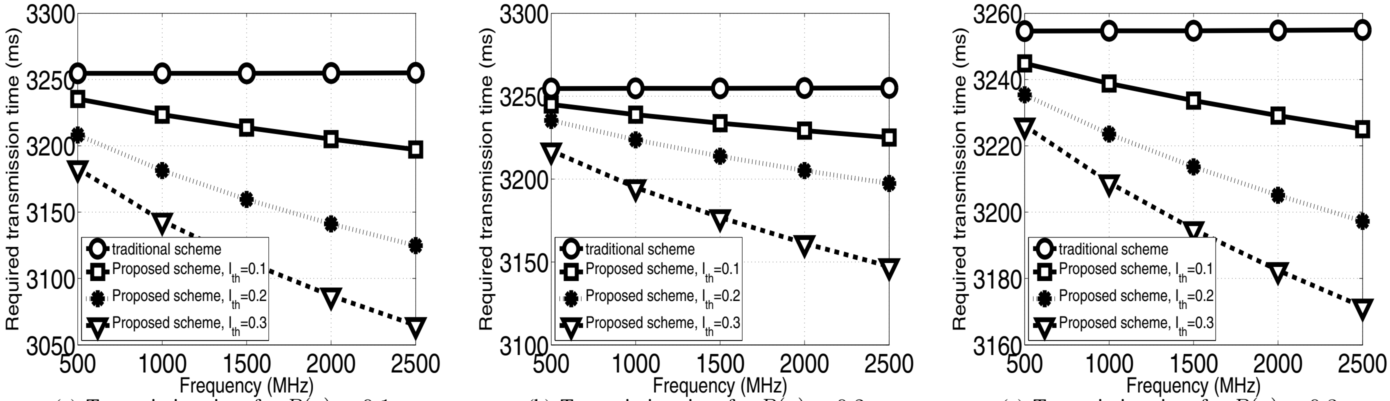
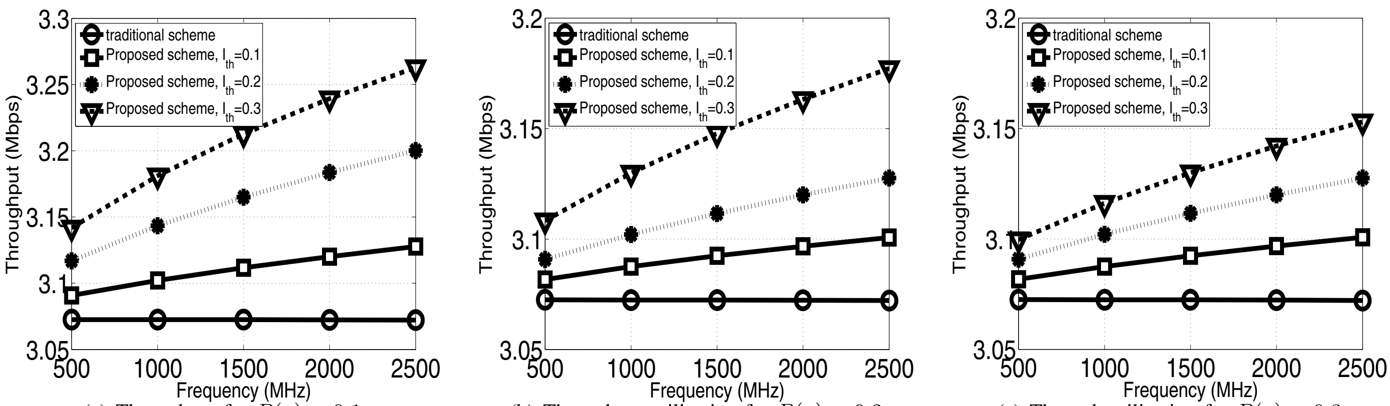


(a) Transmission time for $P(a) = 0.1$ (b) Transmission time for $P(a) = 0.2$ (c) Transmission time for $P(a) = 0.3$

Fig. 9. Comparison of the required transmission time.



(a) Throughput for $P(a) = 0.1$ (b) Throughput utilization for $P(a) = 0.2$ (c) Through utilization for $P(a) = 0.3$

Fig. 10. Throughput comparison.

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