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Author(s)	Jangsher, S; Li, VOK
Citation	The 2013 IEEE Wireless Communications and Networking Conference (WCNC 2013), Shanghai, China, 7-10 April 2013. In IEEE Wireless Communications and Networking Conference Proceedings, 2013, p. 819-824
Issued Date	2013
URL	http://hdl.handle.net/10722/191611
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Resource Allocation in Cellular Networks Employing Mobile Femtocells with Deterministic Mobility

Sobia Jangsher and Victor O.K. Li

Department of Electrical and Electronic Engineering,
The University of Hong Kong, Pokfulam, Hong Kong, China
Email: {sobiaj, vli}@eee.hku.hk

Abstract—Improvement in signal quality and service quality by femtocells offers a natural opportunity for them to be deployed in vehicles. However, resource allocation with mobile femtocells becomes challenging due to the dynamic interference patterns as the mobile femtocells move. In this paper, we introduce the problem of allocating resources in a cellular network with mobile femtocells. We consider two types of femtocells in the scenario, a) fixed femtocells (deployed in stationary location e.g train stations); and b) mobile femtocell with deterministic mobility (e.g deployed on trains). We use the speed and path information of the mobile femtocells to determine the interference relationships between different femtocells at different time instants and represent it as a time interval dependent interference graph. Finally using the interference graph, we proposed a cluster-based resource allocation algorithm. Performance analysis shows that the allocated resources with mobile femtocell in the scenario are close to the ones without mobile femtocells and much less than a random allocation.

Index Terms—Mobile femtocells, Resource allocation, Time interval dependent graph, Cluster-based resource allocation.

I. INTRODUCTION

People in vehicles are potentially the most important customers for cellular services. But these users suffer from low signal quality as the coverage of the macro antennas is quite poor inside vehicles with metallic walls. As femtocell promises to provide better indoor coverage and improved network capacity, the idea of deploying femtocells in vehicles was proposed in [1] and the term mobile femtocell is used.

Mobile femtocells are defined as small cells in vehicular environment. Mobile femtocells can improve the performance of mobile users in vehicular environment as the signal now does not have to penetrate the metallic walls of the vehicle and can be received outside by the transceiver and transmitted over a wired connection to the femtocell access point inside the vehicle. A few studies have discussed the idea of mobile femtocell [1], [2], [3]. Haider et al. [1] introduced the concept of mobile femtocells and investigated the spectral efficiency of orthogonal and nonorthogonal resource partitioning schemes for mobile femtocells. Zaman et al. [2] also discussed the same concept and proposed different service scenarios for its deployment. They also analyzed the capacity and outage probability of mobile femtocells. In another paper [3], they discussed the handover scenarios and proposed a bandwidth

adaptation and dynamic bandwidth reservation policy for handovers. They showed that with their scheme, handover dropping probability decreased and bandwidth utilization stayed the same as compared to the non adaptive schemes. However, allocating resources between fixed femtocells and mobile femtocells has still not been studied.

Femtocells are added on top of the existing cellular architecture and therefore, resource allocation (RA) of the femtocell network is important [4], [5], [6]. Some work in allocating resources to fixed femtocells network have been done [7], [8], [9], [10], [11], [12]. These studies are working with an objective of maximizing the demand fulfillment or maximizing the rate of the femtocells. Due to high density of femtocells, the number of resource blocks in Orthogonal Frequency Division Multiple Access (OFDMA) are limited compared to the demand of the femtocells. Here by resource block, we mean an OFDMA block used for transmission of data. If two femtocells are present in each other's interference range, they must use different resource blocks; otherwise, they can use the same resource block. Resource spectrum is expensive as femtocell works in licensed band. Therefore, the resource blocks should be utilized efficiently.

Note that resource allocation for fixed femtocell networks is in itself a challenging problem but there are additional challenges with mobile femtocells in the network. These challenges are:

- The interference set is constantly changing due to the movement of the vehicle the mobile femtocell is in.
- The mobile femtocell is affiliated with different base stations at different instants, i.e handoff for femtocell is taking place.

In this paper, we have formulated an optimization problem to minimize the number of resource blocks used such that interference between all femtocells is avoided and the demand of resource blocks for each femtocell (with both fixed and mobile femtocells) is satisfied. In other words, we answered the following question: *How to allocate resource blocks to femtocell network (with both fixed and mobile femtocells) such that the resource blocks are efficiently utilized while satisfying the demand and interference constraints?* Our contribution is

as follows:

- Formulation of a resource allocation problem accounting for mobile femtocells.
- Generation and determination of interference relationship between femtocells and representing it as a time interval dependent graph.
- Proposing a Cluster-Based Resource Allocation (CBRA) algorithm to allocate resources for fixed and mobile femtocells such that the resources are utilized efficiently.

The rest of the paper is structured as follows. Section 2 discusses the system model and problem formulation, Section 3 describes the algorithm used to solve the problem, Section 4 shows the performance evaluation and Section 5 concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we will define the system model, list our assumptions and formulate the problem for resource allocation.

A. System Model

We consider a macrocell with S fixed femtocells and P mobile femtocells. Both macrocell and the femtocells are using OFDMA technology, which divides time and frequency into time and channel slots. One time-channel slot is known as a Resource Block (RB). The total number of RBs, K , in an OFDMA system with τ time slots and C channel slots can be calculated as,

$$\begin{aligned} \# \text{ of RBs} &= \# \text{ of time slots} \times \# \text{ of channel slots} \\ K &= \tau \times C. \end{aligned} \quad (1)$$

A certain RB is represented by j where $j = [1, 2, \dots, K]$. Each RB is of fixed size and transmit power is considered equal in all blocks. One or more RBs are assigned to each femtocell according to its demand. We consider that the demand of each femtocell is known prior to resource allocation.

We have considered that the ID's of all the femtocells are unique. We have a total of S fixed femtocell ID's and P mobile femtocell ID's. Hence we have a total of $S + P = N$ ID's. A certain femtocell's ID is represented by i and $i = [f_1, f_2, \dots, f_S, m_1, \dots, m_P]$ and the demand for each is represented as D_i . If the femtocell ID i has left the network or there is no femtocell with ID i , then $D_i = 0$.

For mobile femtocells, we have considered that they are moving with uniform speed and the path they are traveling on is also known. This assumption is realistic. For example, for a train moving with uniform speed and on a fixed track with femtocells in each of its car, then each car of the train will behave as a mobile femtocell.

We took a conservative approach in defining the interference range, as the range around a femtocell in which it can hear back from other femtocells. In addition, each femtocell is aware of the IDs of the femtocells present in its interference range. We denote the list of ID's present in an interference range of a femtocell i as R_i . The set R_i is changing for all those i which are mobile and for those fixed femtocell with mobile femtocells moving within their interference range.

We solve the problem of resource allocation for a window of size ℓ . At the start of each window the central node collects the set D_i and R_i from all femtocells and determine the interference matrix R for the whole window. The algorithms to collect and determine R and its representation is discussed later. The important thing to note here is that although D_i remains constant, the set R_i is varying within the time window. Table I summarizes the parameters of the model.

TABLE I
MODEL PARAMETERS

Parameter	Explanation
S	No. of fixed femtocells in a macrocell
P	No. of mobile femtocells in a macrocell
N	Total no. of femtocells in a macrocell
K	Total number of resource blocks
R_i	Interference set of a femtocell i
R	Interference matrix of all femtocells during a time window
D_i	Demand of femtocell i
D	Demand set of all femtocells during a time window
ℓ	Size of a time window
ℓ_q	Size of a sub-interval q within a time window
Q	Total number of sub-intervals in a time window

B. Problem Formulation

We now present the mathematical formulation of assigning K RBs to N femtocells. Our objective is to minimize the number of RBs used such that the request of all femtocells are fulfilled.

1) *Optimization Variable:* We have defined a 0-1 RB allocation variable

$$x_i^j(q) = \begin{cases} 1 & \text{RB } j \text{ is assigned to femtocell } i \text{ in sub-interval } q \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

$$i = \{f_1, f_2, \dots, f_S, m_1, m_2, \dots, m_P\}$$

2) *Objective Function:* Our objective function is to minimize the number of RBs used or, in other words, maximize the RB reuse.

$$\min \sum_{j=1}^K \left(x_{f_1}^j(q) \oplus \dots \oplus x_{f_S}^j(q) \oplus x_{m_1}^j(q) \oplus \dots \oplus x_{m_P}^j(q) \right), \quad (3)$$

where \oplus is a modular OR.

3) *Constraints:* The constraints under which the RBs should be minimized are:

- *Interference Constraint:* This constraint says that any resource block assigned to a femtocell cannot be assigned to any other femtocell in the interference range of the femtocell to which it was assigned.

$$\sum_{i \in R_i} x_i^j(q) \leq 1, \text{ for all } j, i \text{ and } q \quad (4)$$

where $j = [1, 2, \dots, K]$.

- *Demand Satisfaction Constraint:* This constraint says that the demand of each femtocell should be fulfilled.

$$D_i(q) \leq \sum_{j=1}^K x_i^j(q), \text{ for all } i \text{ and } q \quad (5)$$

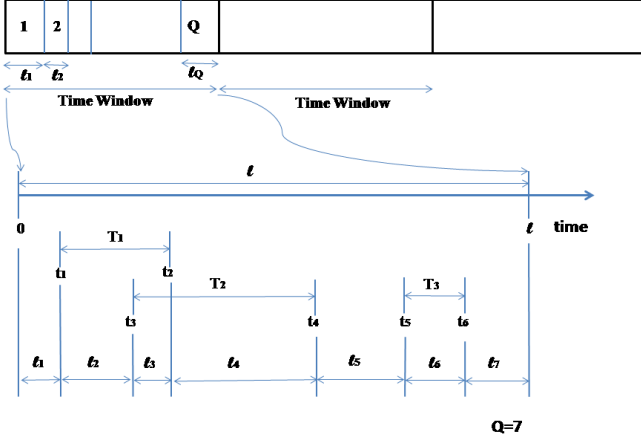


Fig. 1. The time window and the sub-intervals.

where $D_i(q)$ is the demand of a femtocell i which is known in advance.

- *Integer Constraint:* The optimization variable x_i^j can take only two values i.e, 0 or 1.

The problem formulated is NP-hard. We can prove this by reduction and mapping it to a graph coloring problem. First we reduce the problem into a single demand problem, i.e. each femtocell has a demand of 1 RB.

A graph coloring problem, proved to be NP-hard [13], attempts to minimize the number of colors used to color all the nodes of a graph. No two adjacent nodes can have the same color. Now the nodes in the graph coloring problem correspond to the femtocells in our problem, and the colors correspond to RBs. The adjacent nodes of a certain node in a graph coloring problem correspond to the interfering femtocells of a certain femtocell in the resource allocation problem. Thus, a resource allocation problem with a single RB demand can be completely mapped to a graph coloring problem. A multi-coloring graph problem is a special case of a graph coloring problem and is also NP hard, and hence a resource allocation problem with more than one RB demand is also NP-hard. Therefore, a heuristic has to be proposed to solve the problem.

III. ALGORITHM

In this section, we explain in detail the algorithm adopted to solve the RB assignment problem. We consider a central node which collects the data from all femtocells, run the algorithm and then distribute the output to the femtocells. The algorithm solves the resource allocation problem for a window of size l . The window is further divided into different sub-intervals l_q , $q = 1, 2, \dots, Q$ as shown in Figure 1, where Q is the number of sub-intervals in this time window. During each window the demand is considered constant whereas the interference graph is time varying and is constructed at the start of each window as a time interval dependent graph. The sub-intervals l_q are

formed such that the interference is constant within each sub-interval.

The input to our algorithm are number of RBs K , number of femtocells N , interference relationship over the time window $G(V, E, T)$ and demand of all femtocells for the time window D . Both K and N are already known to the central node. The demand is known to each femtocell and this is communicated to the central node at the start of each window. R is generated using the collected information of R_i for each femtocell and predicted by the central node based on the speed and path information of the mobile femtocells. The interference relationship of all femtocells for each time window is represented as a time interval dependent graph $G(V, E, T)$ and is discussed later.

The algorithm returns Q resource allocation matrices X_q , $q = 1, 2, \dots, Q$, of dimension $N \times K$ as,

$$X_q = \begin{bmatrix} x_1^1(q) & \dots & x_1^K(q) \\ x_2^1(q) & \dots & x_2^K(q) \\ \vdots & \ddots & \vdots \\ x_N^1(q) & \dots & x_N^K(q) \end{bmatrix}. \quad (6)$$

Next, in this section we will discuss the interference graph generation and then use the interference graph to explain the cluster-based algorithm for resource allocation.

A. Interference Graph Generation

The interference graph for each time window is generated at the start of each window. As stated earlier, we have represented interference between femtocells as a time interval dependent graph $G = (V, E, T)$. Here V is a set of vertices and each vertex represents a femtocell (both fixed and mobile), E is the set of edges and each edge connecting two femtocells represents interference between the two and $T = [t_s, t_f]$ is the time interval for which the interference (edge) exists between the two femtocells (vertices), where t_s and t_f represents the starting and ending time of an edge. Different interference intervals can be labelled as T_1, T_2, \dots . There may be multiple edges between two vertices corresponding to different time intervals of interferences.

A femtocell F_i generates a list of its interfering members using the following steps:

- 1) Send a broadcast message with its own ID;
- 2) Any femtocell which receives this message replies with its own ID;
- 3) Based on the received replies each femtocell will determine its interference set (All the IDs from which it has heard back will be present in its interference set);
- 4) Femtocell F_k which receives an F_i broadcast will update its interference set as

$$R_k = R_k \cup \{i\}. \quad (7)$$

Each femtocell will generate its interference set and communicate it to the central node. With this information, the central node can form a static graph, with vertices and edges. Now it has to determine the time interval during which the edges will

exist and the time interval new edges will exist. Now there are three different types of edges that will be present in the graph. Edge between

- 1) Fixed femtocell-fixed femtocell
- 2) Fixed femtocell-mobile femtocell
- 3) Mobile femtocell-mobile femtocell;

Algorithm 1: Determination of interference relationship over the time window $G(V, E, T)$

Input: Interference set for all femtocells R_i , interference radius of femtocells r , speed of vehicles with mobile femtocells ν and path information of the Mobile femtocell \mathbf{P}

Output: Time interval dependent interference graph $G(V, E, T)$

```

1 begin
2   Initialize  $G(V, E)$  using the  $R_i$  information for all femtocells .
3   Time Interval T for edges with both vertices as fixed femtocells is  $[0 - l]$ 
4   foreach (time instant ) do
5     pos.t=Compute the new position of all mobile femtocells using  $\nu$  and
      P.
6     foreach (femtocell  $i$  ) do
7       if pos.t is inside the interference range of  $i$  then
8         Update  $R_i$ ;
9         note the time instant  $t_{si}$ 
10      end
11      if pos.t left the interference range of  $i$  then
12        Update  $R_i$ ;
13        note the time instant  $t_{fi}$ 
14      end
15    end
16  end
17  Now allocate the time interval instants to the initialized  $G(V, E)$  to get
       $G(V, E, T)$ 
18 end

```

The time interval of any edge between any two fixed femtocells i and j will be ℓ for that time window. For the other two cases, two processes will take place, 1) deletion of edges as the mobile femtocell moves out of the interference range and 2) formation of edges as it enters any other femtocell range. Considering the fact that the path and speed of the femtocell is known the process of formation and deletion of edges is deterministic. Algorithm 1 shows the pseudo code for the determination of the time interval dependent interference graph. We determine the interference relationship for each time instant. The spacing between the instants depend on the speed of the femtocells. In the performance analysis in Section 4 the time instants are spaced 1 second apart. An example of a time interval dependent graph is shown in Figure 2. Here f_1, f_2 and f_3 represent fixed femtocells and m_1 and m_2 represent mobile femtocells. A solid edge represents the interference between two fixed femtocells whereas a dotted edge shows that at least one of the vertices is a mobile femtocell. For a solid edge the time interval is ℓ whereas the time interval for the dotted edge is as shown.

B. Cluster-Based Resource Allocation (CBRA)

Within each time window, the resource allocation has to be performed for different sub-intervals based on the interference at each sub-interval. The time window is divided into Q sub-intervals of size ℓ_q such that the interference relationship

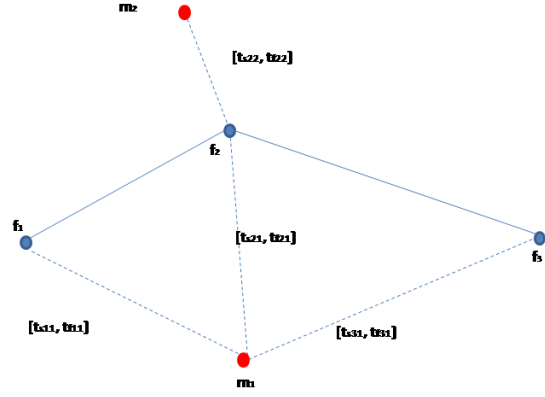


Fig. 2. An example of a time interval dependent graph.

between the femtocells within a sub-interval is constant. To do so, arrange start times and end times of all edges of the interference graph in ascending order. Let $t = [t_1, t_2, \dots, t_Q]$ represent all start and end times such that $t_1 < t_2 < \dots < t_Q$. Now the size of time intervals within the time window will be $[\ell_1, \ell_2, \dots, \ell_Q]$, computed as

$$\begin{aligned}
 \ell_1 &= t_1 - 0 \\
 \ell_q &= t_q - t_{q-1}, \text{ where } q = 1, 2, \dots, Q \\
 \ell_Q &= \ell - t_Q
 \end{aligned}
 \tag{8}$$

An example is shown in Figure 1 for $Q = 7$.

The central node forms clusters of femtocells within each sub-interval such that the members of each cluster will not interfere with each other. Algorithm 2 shows our proposed heuristic to solve the problem. The central node starts making cluster C_h by choosing the femtocell (vertex) with the minimum number of interfering members (edges) in the interference graph for the sub-interval. Then it puts all other femtocells in the same cluster which are not the interfering members of this femtocell. Next, the central node starts checking for each femtocell if any of its interfering members are present in this cluster. If there is any interfering member, then it keeps the femtocell with minimum edges in this cluster C_h and remove the other. Similarly, clusters are formed until there is no femtocell left. Different clusters will interfere with each other so they cannot use the same RB whereas within a cluster the same RB can be used. This will give us a resource allocation matrix X_{t_1} for the first sub-interval ℓ_1 . Now for the next sub-interval, the central node will allocate resources using the same RBs as used in the previous sub-interval.

Similarly, the RB allocation for all sub-intervals within a window takes place keeping in view the allocation of the previous sub-interval. At the end of each time window, the interference graphs are regenerated and demand is collected and then resources are allocated accordingly. Hence, the algorithm ensures the reuse of RBs is maximized.

Algorithm 2: Cluster-Based Resource Allocation (CBRA)

Input: Demand of femtocells D , interference graph for time window $G(V, E, T)$, total no. of femtocells N , and total number of RBs available K .

Output: Q resource allocation matrix $X_{N \times K}$.

```

1 begin
2   Form  $Q$  sub-intervals .
3   foreach (sub-interval  $q$ ) do
4      $edg = \text{sort}(\varepsilon)$ ; where  $\varepsilon = [e_{f_1}, e_{f_2}, \dots, e_{m_M}]$  represents the number
      of edges of a femtocell.
5      $pre = 0$ ; vector array of femtocell already part of previous clusters.
6      $h = 1$ ; cluster number.
7     foreach (edg  $i$ ) do
8       Cluster.q.i = create list of non interfering member of  $min - pre$ ;
9       Cluster.q.i = Cluster.q.i - Interfering member within the cluster;
10       $pre = [pre \text{ Cluster.q.i}]$ ;
11    end
12    foreach (edg  $i$ ) do
13      if  $length(Cluster.q.i) > 0$  then
14        Cluster.q.h = Cluster.q.i;
15         $h = h + 1$ ;
16      end
17    end
18     $X_q = \text{Allocate the same RB to members within the cluster}$ ;
19  end
20 end

```

As we have already mentioned, we have taken a heuristic approach to solve the problem, and may not achieve the optimal solution. The complexity of the algorithm is $O(QN)$.

IV. PERFORMANCE ANALYSIS

In this section, we compare the RBs utilized for CBRA (with mobile femtocells) with CBRA (without mobile femtocells) and a random RA (without clustering but with mobile femtocells).

- *CBRA without mobile femtocells:* It is the same as our proposed scheme but we do not have mobile femtocells in the scenario. As there are no mobile femtocells, the interference relationship within a time window is not changing, sub-intervals are not formed.
- *Random RA:* We have mobile femtocells in the scenario. In Random RA, we are forming sub-intervals within the time window but no clustering is done. For each sub-interval, we are allocating the RBs just by checking the interference relationship with the femtocells who have already been allocated with the RBs. If interference exists we add more RBs, else reuse the existent ones.

For evaluation, we define resource utilization (RU) as

$$RU = \frac{\text{Demand of femtocells fulfilled}}{\# \text{ of different RBs used} \times N}. \quad (9)$$

Here the only variable parameter is no. of different RBs used, therefore we will be using this as our performance evaluation parameter. The simulations were carried out in MATLAB.

We have a macro cell with a radius of 1km, with a railway track passing through the macrocell. The length of the track

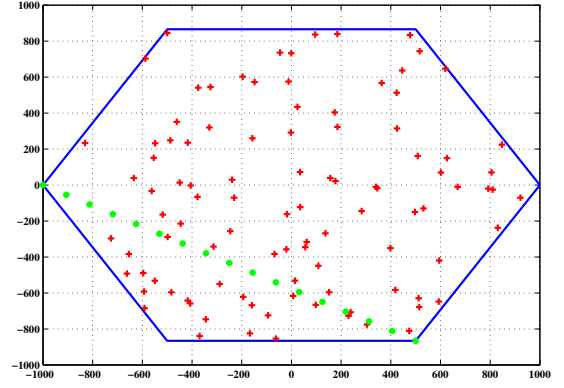


Fig. 3. Scenario description and location details of femtocells.

is 1.7km. A train consists of 25 cars, each of length 40m (this also include the joints between two cars). The train is moving with a speed of 20m/s on the track. Figure 3 shows the location of the railway track (marked with circles on the lower left part of the figure) in the macrocell. Each car of the train has a femtocell in it. There are a total of 100 fixed femtocells distributed in the macrocell (marked with crosses in the figure). We evaluated the performance of CBRA for a time window of 5min. The service requested by the user is mapped in terms of number of RBs. We run a total of 50 simulations and are reporting the mean value with $\geq 95\%$ confidence interval.

Figure 4 shows the relationship between the average demand per femtocell versus the number of different RBs used by the network. For each simulation, we vary the position of the fixed femtocell or in other words the interference relationship between femtocells. For CBRA and random RA with mobile femtocells the results reported are averaged over all sub-intervals within the time window. A linear relationship can be observed between demand and number of different RBs used. The average degradation (increase in RBs) with the addition of mobile femtocells is 19.73%. A significant decrease in number of different RBs used is also observed as compared to random RA. The decrease is enhanced as the average demand per femtocell increases and the random RA curve is more sharp. This is due to the non-existence of interference-free clustering.

Figure 5 shows the relationship between average interference radius of a femtocell versus RU. We have considered the positions of the femtocells fixed in each simulation but the users affiliated with the femtocell are changing or in other words the demand of a femtocell is changing in each simulation. For each simulation a femtocell chooses a number from $[0 - 8]$ as its number of users and the demand of each user is the same. The location of the femtocell is kept constant for each simulation.

Figure 6 shows how the number of RBs allocated by CBRA with mobile femtocells is changing over the time window. This is due to the different interference relationships in different sub-intervals during the time window. For CBRA without mobile femtocells, the RBs used are constant. This is due to

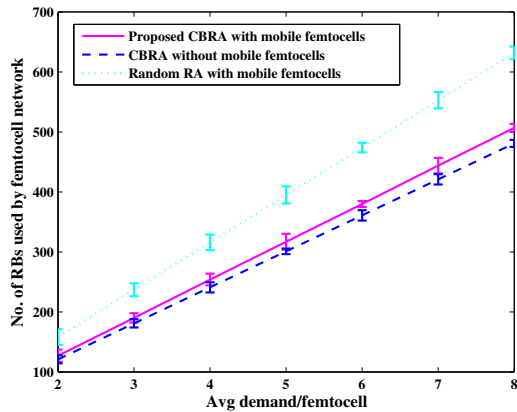


Fig. 4. Relationship between demand and resource blocks used at average interference radius of 50m for femtocells.

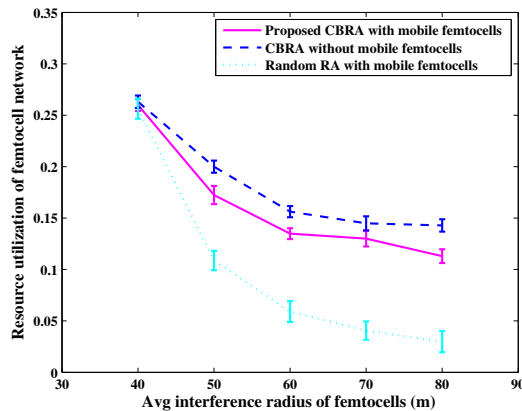


Fig. 5. Relationship between interference radius and resource utilization of the femtocell network

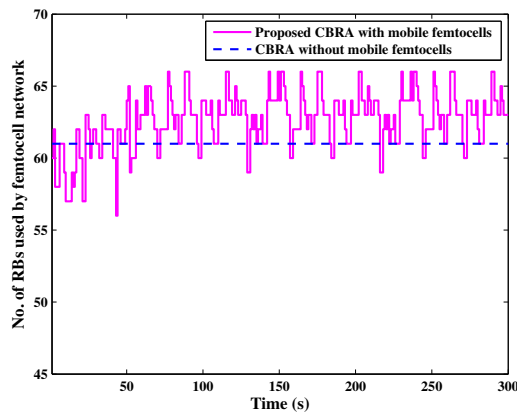


Fig. 6. Change in the number of RBs within the time window.

the constant interference relationship between femtocells.

Hence, we conclude that: a) CBRA with mobile femtocells provides performance significantly close to CBRA without mobile femtocells and at the same time is significantly better than a random RA scheme; b) the larger the interference set the lesser is the resource utilization; and c) change in the number of RBs used between sub-intervals is not significant.

V. CONCLUSION AND FUTURE WORK

We formulated a resource allocation problem for mobile and fixed femtocells with the objective of minimizing the resource usage. Since the interference relationship between femtocells plays a vital part in the resource utilization efficiency, we determined the dynamic interference relationships between femtocells for the time window. Using the interference relationships, we proposed an algorithm to solve the resource allocation problem for mobile femtocells. The proposed scheme is shown to provide significantly better performance than the random RA scheme whereas the degradation from CBRA without mobile femtocells is not significant at all.

In the future, we plan to eliminate the central node and develop a distributed architecture for resource allocation, in which each femtocell is able to select its resources with local information available to it.

ACKNOWLEDGEMENTS

This research is supported in part by the University of Hong Kong Strategic Research Theme of Information Technology.

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