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<td><strong>Author(s)</strong></td>
<td>Jangsher, S; Li, VOK</td>
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<td><strong>Issued Date</strong></td>
<td>2014</td>
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<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10722/217393">http://hdl.handle.net/10722/217393</a></td>
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Resource Allocation in Cellular Networks with Moving Small Cells with Probabilistic Mobility

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Abstract—Passengers in city buses are possibly one of the main contributors to the increase in mobile traffic in cellular networks. Instead of each passenger accessing the cellular base station, we may deploy a small cell on the bus to serve these passengers. To reap the benefits of this deployment in the cellular network, resource allocation of the network needs to be addressed carefully. We call the small cells deployed in city buses as moving small cells. In this paper, we propose a probabilistic graph based resource allocation (PGRA) algorithm in a cellular network with moving small cells. We exploit the headway characteristics of city buses to study the interference relationship between different moving small cells. Our performance metric is the number of resource blocks used. Our performance evaluation shows an average decrease of 19.84% in the number of RBs used with moving small cells in the network as compared to a scenario without moving small cells, requiring each passenger to access the base station.

Index Terms—Resource Allocation, Moving small cells, Probabilistic graph, Possible Graphs.

I. INTRODUCTION

Ubiquitous high quality cellular services is desired by mobile subscribers. But in confined and crowded places, this requirement cannot be satisfied completely. City buses of a cosmopolitan city is one example of a confined and a crowded place. On the other hand, small cells (femto, mini, micro) are mini base stations to provide coverage to crowded and confined spaces. Earlier the term femtocell was used to describe the cell for residential users, picocell for enterprise and commercial premises and metrocell for public areas. Later the term small cell was adopted to cover all these aspects as the underlying technology is the same [1]. The good coverage providing capability of small cells makes it a perfect candidate to be employed in city buses. We call a small cell in a city bus as a moving small cell.

In [2], [3], [4] authors have discussed the idea of placing a femtocell in a moving vehicle and have shown that spectral efficiency can be increased. In [5] and [6] a handover scheme for mobile femtocell network is discussed. The authors utilize coordinated multiple point transmission, one of the features of Long Term Evolution-Advanced (LTE-Advanced), in their handover scheme. To fully utilize the benefits of mobile small cells in a cellular network, the resource allocation has to be done carefully. The scarce resources in cellular network and the dynamic interference pattern formed with mobile small cells make the resource allocation challenging.

In [7], the authors have discussed resource allocation with mobile femtocells and the mobility is deterministic and uniform (as that of a train). A frequency allocation scheme for mobile small cell network is proposed in [8]. They considered a bus scenario for their frequency allocation scheme. They divided the frequency into two parts, one for users inside the bus and the other for the outside. The inside of all the buses are allocated the same frequency, assuming the buses are quite far apart and will not interfere with each other. However, in reality the buses do tend to bunch together and interference may occur.

In this paper, we study resource allocation in cellular networks with small cells deployed in city buses. Trains and city buses are the commonly used modes of public transportation. But the resource allocation with small cells in city buses is different from that of a train. Both train and city buses move on a predefined route, but with different speed patterns. Trains move with uniform speed whereas the speed of the city buses is non-uniform as it is affected by the dynamics of the traffic around it. Therefore, it is difficult to compute the exact position of a city bus at a certain time and thus, a deterministic interference relationship cannot be computed. We propose a graph colouring based resource allocation algorithm and called it Probabilistic Graph based Resource Allocation (PGRA) algorithm. Our resource are the resource blocks (RB) of Orthogonal Frequency Division Multiple Access (OFDMA). Our objective is to minimize the number of RBs used in the network such that demand is fulfilled and interference is avoided. We represent the interference relationship between mobile small cell and macrocell users as a probabilistic conflict graph. We exploit the time headway characteristic of the city buses to form this probabilistic conflict graph. Our performance metric is the number of resource blocks used. Our performance evaluation shows an average decrease of 19.84% in the number of RBs used with moving small cells in the network as compared to a scenario without moving small cells, requiring each passenger to access the base station.

The rest of the paper is structured as follows. Section 2 discusses the system model, Section 3 studies the interference graph generation, Section 4 proposes the PGRA algorithm, Section 5 shows performance evaluation and Section 6 concludes the paper.
II. SYSTEM MODEL

In this section, we discuss the system model for resource allocation in cellular network employing small cells. Table I shows the parameters of the system model. The cellular network is employing both fixed and moving small cells. We consider a macro cell with $S$ fixed small cells and $M$ moving small cells. We use $i$ to denote any small cell in the network, where $i = 1, 2, \ldots, S + M$. Fixed small cell are stationary, and may be deployed at bus stations, while the moving small cells are deployed on city buses in our model. The ID’s of all the small cells are unique. Time is divided into equal size discrete intervals. Channel condition is considered quasi static in each interval.

<table>
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<th>Parameters</th>
<th>Explanation</th>
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<tr>
<td>$S$</td>
<td>total number of fixed small cell</td>
</tr>
<tr>
<td>$M$</td>
<td>total number of mobile small cell</td>
</tr>
<tr>
<td>$U$</td>
<td>total number user associated to macro cell</td>
</tr>
<tr>
<td>$R$</td>
<td>total number of routes in a cell</td>
</tr>
<tr>
<td>$B$</td>
<td>total number of RBs</td>
</tr>
<tr>
<td>$Q$</td>
<td>total number of possible graphs</td>
</tr>
<tr>
<td>$R_i$</td>
<td>time interference of a small cell</td>
</tr>
<tr>
<td>$g$</td>
<td>time headway between two buses</td>
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Both macro cell and small cells are using OFDMA technology. The smallest unit in an OFDMA is a RB. We considered RB as our resource in the model. Assume, we have a total of $B$ resource blocks and we use $j$ to represent a resource block, where $j = (1, 2, \ldots, B)$. The power in all the RBs is uniformly distributed. We have three different types of users in the network, which are

1) users directly connected to the macro cell
2) users connected to outdoor fixed small cells
3) users connected to indoor mobile small cells.

The city bus schedule and headway characteristics help determine the interference relationship between any two small cells. The exact position of a bus at a given point in time is not known. Thus, we cannot compute the exact interference relationship between two small cells. Instead, we can define a probability of interference between two small cells. We use time-headway distribution to compute the probability of interference. Time-headway is defined as,

Definition I (Time-headway): It is defined as the time between vehicles in a transit system. We assume the time headway distribution of city buses follow a Wigner distribution as proposed in [9]. If $T_0$ is the original headway when buses depart the bus terminus called regular schedule of two bus then, the time headway distribution is given as,

$$P(h) = \frac{32 \pi^2}{h^2} \exp\left(-\frac{4h^2}{\pi T_0^2}\right),$$

where $h$ is the time-headway between two buses with a regular schedule of $T_0$.

Each city bus deployed with a small cell has an interference range; users and other small cell present in that range will have conflict with each other and cannot use the same RB.

We converted the interference range to time to compare it with time-headway and defined it as,

Definition II (Time-interference): It is defined as the time taken to traverse the interference range of a small cell. We represent time interference of each small cell $i$ as $R_i$

We study the problem of allocating RBs to all users (connected directly to macro cell, connected to fixed small cell and connected to moving small cell) in the network such that the demand of all the users are satisfied and interference is avoided in the network.

III. INTERFERENCE GRAPH GENERATION

In this section, we will discuss the generation of interference graph. As the moving small cells are deployed in city buses, the route and speed of a bus characterize the mobility of a moving small cell. Due to the mobility of small cells, a dynamic interference relationship can be observed between different small cells over time. If we represent the interference relationship in the cellular network as a conflict graph then, Figure 1 shows an example of moving small cell network scenario at two different time instants $T_1$ and $T_2$; and their

![Fig. 1. Example of changing interference relationships between moving small cells.](image1.jpg)

![Fig. 2. Effect of time interference radius and initial headway on probability of interference between two buses.](image2.jpg)
respective conflict graphs. The time instants $T_1$ and $T_2$ are a few seconds apart. We can observe that the two graphs have changed over time. The key points to note here are that the interference relationship is changing and the change is not deterministic. Keeping in mind these points, we represented the conflict graph as a probabilistic graph. We exploited the following two characteristics of the city bus:

- The routes of the buses are fixed;
- The buses are usually interfered by the bus ahead of it or the bus behind it;

In this section, we represent the interference relationships between fixed and moving small cells, and users directly connected to the base station, as a probabilistic graph $G(V, P)$ where $V$ is a set of vertices of the graph and represents a set of small cells, and $P$ is the set of probabilities associated with the edges of a graph. An edge represents interference between two vertices. $P_{i,j}$ represents the probability of interference between small cells $i$ and $j$. As already mentioned, time is divided in discrete equal size time intervals and an interference graph is formed at the start of each time interval.

We use the headway distribution between city buses employing small cells to compute the probability of interference between two city buses. The two small cells are said to interfere if the time-headway between two buses’ (with small cells in them) has become less than the time-interference of a small cell. For any two small cells, we represent the probability of interference as $p_{i,j}$ and define it as follows,

$$p_{i,j} = P(h \leq R_i)$$

$$= \int_0^{R_i} P(h) \, dh,$$

where $P(h)$ is the headway distribution of a city bus. Here, we assume a wiener distribution as given in (1) [9]. Using (1) in (2), we get the probability of interference between two buses as,

$$p_{i,j} = \frac{32}{\pi^2 T_0^3} \int_0^{R_i} \frac{1}{\sqrt{\pi}} \exp \left( -\frac{\sqrt{a}}{a^2} R \exp \left(-a R^2 \right) \right) \, dh,$$

where $a = 4/\pi^2 T_0^3$. If we define $e_r(t)$ as the error function, then $\int_0^{R_i} e_r(R) \, dh$.

Figure 2 shows the effect of time-headway and time-interference on the probability of interference between two buses. For a time-headway, as the time-interference increases the probability of interference between two buses increases exponentially and; for a time-interference, as the time-headway increases the probability of interference decreases.

A probabilistic graph is computed at the start of each time interval and the exact positions of the buses at the start of each interval is known through a Global Positioning System (GPS) receiver in all the buses with the small cells.

### IV. Probabilistic Graph Based Resource Algorithm

In this section, we propose an algorithm to allocate RBs to users and small cells. We name the algorithm as probabilistic graph based resource allocation (PGRA) algorithm. PGRA starts with a probabilistic graph representing the interference relationships in the cellular network. The time is divided into discrete time intervals of equal length. At the start of each time interval a probabilistic graph is formed.

**Algorithm 1: Probabilistic Graph based Resource Allocation (PGRA)**

| Input: Demand of femtocells $D$, interference graph for time window $G^P(V, P)$, |
| Output: Resource allocation matrix $\mathcal{R}_{(S+M+U) \times K}$ |

1. Compute a table of the possible combinations, $Q = 2^K$
2. For each possible combination $q$, calculate $G_q^P(V, E) \leftarrow G^P(V, E)$
3. $\beta_q = P(G_q^P)$ is calculated.
4. Arrange the $G_q(V, E)$ in descending order of their probabilities.
5. Allocate RBs to $G_q^P$ greedily

The algorithm is based on the extraction of a best possible deterministic graph from the probabilistic conflict graph. A probabilistic graph generates multiple deterministic graphs, corresponding to all possible scenarios of interference relationships. The extracted deterministic graph should approximately represent the best possible interference relationship between small cells and mobile users. The extracted deterministic graph is used to allocate the resources using a greedy graph colouring algorithm to fulfill the demands of the users. The input to the algorithm is a probabilistic graph $G^P(V, P)$ which is generated at the start of each time interval. The generation process of the probabilistic graph is discussed in Section III. The algorithm outputs an RB allocation matrix $\mathcal{R}_{(S+M+U) \times B}$.

Algorithm 1 shows the pseudo code of the algorithm. The first step in PGRA is the transformation of a probabilistic graph $G^P(V, E)$ into a number of possible graphs. Each possible graph formed will have a probability associated to it. Lines 3–6 in the algorithm show this step. The transformation is

$$G^P(V, P) \rightarrow \{G_1^P(V, E), G_2^P(V, E), \ldots, G_K^P(V, E)\},$$

where $Q$ represents the total number of possible graphs formed out of a probabilistic graph and $Q$ can be calculated using $2^K$ and $K$ is the number of edges in $G^P(V, P)$ with $p_{i,j} \neq [0, 1]$. If $Z$ is the number of edges with probability 0, i.e. two nodes are not connected, and $L$ with probability 1, i.e., the two nodes are surely connected then,

$$K = \frac{(S + M + U)(S + M + U - 1)}{2} - Z - L.$$
A vector $\vec{P}_{1×Q}$ is also computed, which represents the probability of each possible graph.

Figure 3 shows an example of probabilistic graph. Here $K = 2$ and therefore $Q = 4$. Each possible graph $q$ will have a probability associated with it. Let $A$ and $B$ represent the edge probability between vertices 1 and 2, and 1 and 5, respectively, further $\bar{A}$ and $\bar{B}$ represent the complement of these events, respectively. Then the possible combinations in this example are $AB, \bar{A}B, \bar{A}B$ and $\bar{A}B$ which will give us 4 possible graphs. The probabilities associated with these 4 graphs can be calculated as $P(AB) = P(A)P(B)$, $P(\bar{A}B) = (1 - P(A))(1 - P(B))$, $P(\bar{A}\bar{B}) = P(A)(1 - P(B))$ and $P(\bar{A}B) = (1 - P(A))P(B)$. The sum of the probabilities is 1.

Once we have $Q$ possible graphs, we arrange them in descending order of their probabilities. A vector $W_{1×Q}$ represents the indices of the graphs in descending order of their probabilities as done in Line 7. From the $Q$ graphs available, PGRA algorithm has to select possible graphs such that the sum of their probabilities is approximately equal to a threshold $f$. Lines 9–15 shows the selection process. The graphs are selected strictly based on their probabilities. In our case, we considered the threshold $f = 0.7$. Alternatively, if the number of combinations are high, then the algorithm in [10] can be used to generate the graphs in order of decreasing probabilities, until the threshold is reached, without first enumerating all the graphs. A threshold of 0.7 means that at least 70% of the instances are covered. For the example shown in Figure 3, the threshold condition is satisfied with $G^D_1$ and $G^D_2$, and we can see that 100% of the instances are covered with these two graphs. Using the chosen $Y$ possible graphs, a deterministic graph $G^D_V(E)$ is formed, using

$$G^D_T(V,E) = G^D_{w_1}(V,E) \cup G^D_{w_2}(V,E) \cup ... \cup G^D_{w_Y}(V,E). \ (7)$$

The deterministic graph contains all the edges present in the $W$ chosen graphs.

Finally, the resources are allocated to $G^D(V,E)$ based on their demands. An analogy between resource allocation and a multicolor graph colouring exists and it is an NP hard problem. Here, we use greedy graph colouring algorithm in [11] to solve it.

V. PERFORMANCE EVALUATION

In this section, we discuss the performance evaluation of the PGRA algorithm. We compared the performance of PGRA with moving small cells in the network to PGRA without any moving small cells in the network. In PGRA without moving small cells deployed in the city buses, the passengers using cellular services will connect to the base station directly.

We consider a cellular network with a macro cell radius of 1 km. Figure 4 shows the scenario considered. There is one base station (●) in the middle, and 200 users (+) uniformly spreaded in the cell. In addition, two routes, for city buses exist in the macro cell shown with red lines. Small cells are deployed in the city buses and these city buses can move on the defined path only. We divide the time into intervals of 5 minutes each. At the start of each time interval a probabilistic graph is formed based on the time-headway between city buses at that time. The standard length of the bus is considered as 12m.
The simulations are conducted for 100 different realization of users’ position in the network. The number of city buses on the path varies and depends on the regular schedule and headway distribution as discussed earlier. Each city bus has 10 passengers who require cellular services. We consider that each user requires 1 RB.

Figure 5 shows the effect of time-headway on the number of RBs used in the network. As the time headway changes, the number of city buses present on the path will be different but each time-interference is considered as 5 minutes. We can observe that as the time-headway between city buses increases the number of RBs used decreases for both PGRA and PGRA without moving small cells. Note that the number of RB for PGRA without moving small cells is more then that of PGRA with moving small cells. An average decrease of 19.84% is observed. This decrease depends on the number of users present in the city bus, for this case we are considering only 10 users in each city bus. If small cells are not present in the network, the cellular users in the city buses are directly connected to the base station and interference observed is more, thus more RBs are required.

Figure 6 shows the effect of time-interference on the number of RBs used in the network. A time-headway of 10 minutes is considered. As the time-interference increases, the number of RBs to be used in the network also increases and again the number of RBs for PGRA is less as compared to PGRA without moving small cells. An average decrease of 11.48% can be observed in the number of RBs with moving small cells. Intuitively, more time-interference means a larger interference range. Therefore, the selected graphs will have more conflict and thus more RBs will be required.

We can conclude that, a) as time-headway increases, the number of RBs will decrease; b) as the time-interference increases, the number of RBs will increase; and c) PGRA with moving small cell in the scenario uses less RBs as compared to PGRA without moving small cells.

VI. CONCLUSION

We studied the resource allocation problem in a cellular network with moving small cells deployed in city buses. The path of the moving small cell is fixed but it moves at non uniform speed. We exploited the head-way characteristics of city buses to study the interference relationship of the moving small cell and proposed to represent the interference relationship between users and moving small cells in the network as a probabilistic graph. We studied the formation of the graph. We then proposed a PGRA algorithm to solve the problem of allocating RBs in the network. The main idea behind our PGRA algorithm is the transformation of a probabilistic graph into deterministic graphs and use them to allocate resources.

REFERENCES