Resource Optimization for 60 GHz Indoor Networks Using Dynamic Extended Cell Formation

Bao Linh Dang, R. Venkatesha Prasad, Ignas Niemegeers
Electrical Engineering, Mathematics, Computer Science Faculty – Delft University of Technology
Email: {l.baodang, vprasad, i.g.m.m.niemegeers}@ewi.tudelft.nl

M. Garcia Larrode, A. M. J. Koonen
COBRA Research Institute, Eindhoven University of Technology
{m.garcia.larrode, a.m.j.koonen}@tue.nl

Abstract

With the advent of opening up 60 GHz Radio with 5 GHz of available spectrum, many bandwidth-hungry applications can be supported. The immediate concern, however, is the constraint on the line-of-sight transmission as well as the short transmission range of signals. As a result, in an indoor network, a mobile user might experience frequent breaks or losses of connection when one moves from one cell to another. To mitigate this problem, the Extended Cell (EC) architecture is proposed. In this paper, a dynamic Extended Cell formation algorithm is proposed based on the actual floor plan and the traffic situation under the network. Moreover, by applying this dynamic EC formation algorithm, we show that the call blocking probability is reduced. The dynamic EC formation also eases the deployment and maintenance cost due to its adaptability to the changing environment.

1 Introduction

Over the past decade, the ubiquitous communication dream is becoming more and more realistic. The telecommunication industry has come a long way from narrowband cellular systems to broadband wireless networks. A number of standards, e.g., IEEE 802.11 and IEEE 802.16, for Wireless Local Area Networks (WLAN) and Wireless Metropolitan Area Networks (WMAN) have also been approved and widely deployed to deliver data, voice and video services to customers in realtime. Mobile users, which we refer to as Mobile Stations (MS), can now get broadband Internet access everywhere and anytime in buildings, campuses, airports etc. Together with the emerging mobile WMAN standards such as IEEE 802.16e and IEEE 802.20, MSs moving at speeds as high as 60 Mph on highways or in remote areas can still be provided with broadband connections.

However, along with these new technologies, a number of bandwidth-hungry applications are also emerging, especially in the home and office environments. Typical examples of such applications are High Definition Television (HDTV), Internet Protocol Television (IPTV) or Online Gaming etc. The required datarates and Quality of Service (QoS) of these applications are posing serious challenges to the network designers. For instance, the datarate required by a raw HDTV stream is about 1.5 Gbps. Consequently, a future-proof system should be able to offer datarate in the range of Gbps to be able to support multi-user scenarios in which users watch, play and share concurrently.

To cope with this increasing demand, the IEEE 802.11n amendment is being standardized to improve the system performance by employing Multiple Input Multiple Output (MIMO) technique. However, the expected actual datarate offered by the standard is about 200 Mbps [8].

Generally, there are two main approaches to achieve the required huge datarate; either to increase the available spectrum or the spectrum efficiency. While many techniques, e.g., diversity, coding schemes etc. are being extensively studied to improve the spectrum efficiency, researchers are also looking at the possibility of exploiting vacant frequency ranges, e.g. 17 GHz or 60 GHz. The 60 GHz band is of special interest since there is as much as 5 GHz of spectrum available in this band. Besides the vast available spectrum, this band also presents many other attractive properties, e.g., large oxygen absorption enabling transmission at higher power levels, short propagation distances enabling higher frequency reuse or millimeter wavelength enabling small size antennas [6].

One of the main drawbacks that prevents the 60 GHz band from being deployed for LANs is the considerable

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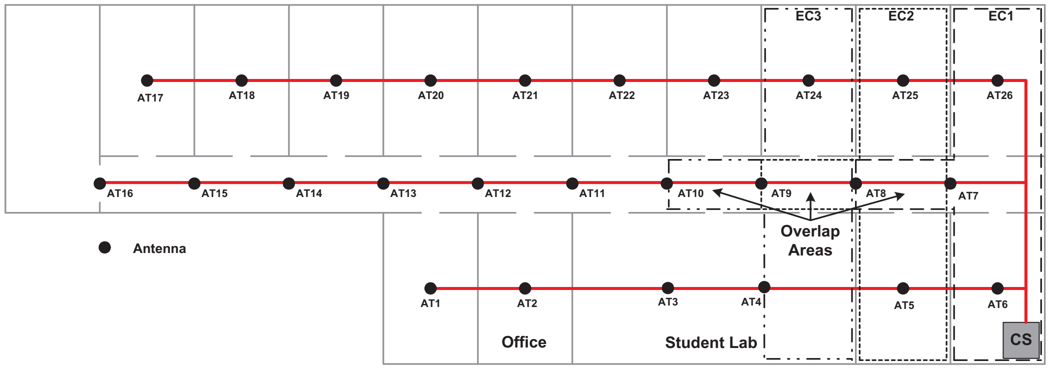

Figure 1. Broadband In-building Networks employing Radio over Fiber

propagation attenuation of signals. This is especially severe in the indoor environment, where signals can be easily obstructed by movement of people, furniture, walls etc. A person standing in between a line-of-sight connection can easily cause 20 dB attenuation from the link budget [7]. As a result, in an indoor network operating at the 60 GHz band, walls can be considered as reliable cell boundaries. To obtain a good coverage, at least one Access Point (AP) is required per one closed indoor area, e.g., a room, a hall or a corridor. This configuration poses the problem of insufficient overlap areas between cells since overlap areas exist only around open areas, e.g. windows, doors etc. Moreover, the overlap areas are normally narrow and directional. As a result, an MS will lose connection when he/she goes out of a room and turns immediately. We term this problem as the "corner effect" [4].

To solve the problem of insufficient overlap areas between cells, an architecture for broadband in-building networks operating at millimeter-wave bands was presented in [4]. The proposed architecture is based on a Radio-over-Fiber (RoF) infrastructure, where each AP is connected directly by fiber optic links carrying the RF signal. The APs will be very simple in the sense that it will only have to convert the optical signals into RF and transmit. Each AP operating in different frequency band will increase the capacity of the system due to frequency reuse. The concept of Extended Cell (EC) that groups multiple adjacent APs together and allows them to transmit the same content over the same frequency channel was also proposed to ensure sufficient overlap areas between cells. In other words, signals are simulcast in an EC. Each EC is designated to cover a number of adjacent rooms and a part of the transitional area, such as a corridor or a hallway. By doing so, overlap areas are created along the transitional areas where MS moves from one cell to another. However, this will also bring down the total capacity of the system because of lower frequency reuse. Now, using ECs one can reduce the number of HOs and thus the possibility of a session (call) drop.

In this article, we briefly discuss the concept of EC architecture first. With ECs one can achieve higher session continuity. Nonetheless, there are some problems with respect to having a static EC formation which we explain first. To counter this aspect we propose an algorithm for dynamic EC formation. We show that the dynamic EC formation yields better performance and moreover, adapting to the environment based on the traffic characteristics is always a greatly desired solution.

The rest of the paper is organized as follows. Section 2 will briefly re-introduce the EC architecture for indoor networks operating at the 60 GHz band. Section 3 discusses the problem with the static configuration in detail. Next, the dynamic EC forming algorithm will be presented in Section 4. Section 5 will discuss the simulation setups and results. Finally, Section 6 concludes the paper.

2 The Extended-Cell Architecture

Figure 1 illustrates the proposed architecture when applied to the floor-plan of the Wireless and Mobile Communications (WMC) group, TU DELFT. As can be seen in the figure, the floor consists of a number of offices and a student lab located along the corridor. In each office, one antenna is installed in the middle of the room. In bigger areas, such as the student lab and the corridor, a number of antennas need to be installed to obtain sufficient signal coverage. The antennas are connected to a central processing point - the Central Station (CS) through an optical fiber distribution network. In this architecture, a cost-effective and flexible RoF technique called Optical Frequency Multiplying (OFM) [5] is used to generate signals remotely at the antennas. In other words, digital signals are processed in the CS and are then converted into optical format and transmitted to the antennas. At the antenna sites, the optical signals are converted back to the electrical signal and transmitted out on the air medium. As a result, the complexity of an antenna is largely moved to the CS. The CS now has all the intelligence of the network [4].

As mentioned above, the Extended Cell (EC) concept is proposed to solve the "corner effect" problem. For example, in Figure 1, the antennas $AT6$, $AT7$ and $AT26$ can be grouped into the extended cell $EC1$. Similarly, $EC2$ can contain $AT5$, $AT8$ and $AT25$. Consequently, between $EC1$ and $EC2$, a sufficiently large overlap area is created in the corridor where MSs need to pass through to move from one room to another. This EC configuration offers the following advantages. (1) It creates large enough overlap areas between cells to ensure a seamless communication environment. (2) The larger the average EC's size is, the smaller number of HOs will be required when an MS moves in the floor. (3) Since signals are simulcast in an EC, a form of diversity is created allowing better signal coverage. However, it also poses some problems that will be discussed in the next section.

3 Problem Description

In [3], mobility and traffic model for the proposed architecture were analyzed. The analysis showed that the size of an EC, i.e., number of rooms included in an EC, should neither be too large nor too small. On one hand, the size of an EC should be as large as possible to reduce the number of handovers (HO) when MSs move from one EC to another. On the other hand, since all the APs in an EC utilize the same frequency channel, the channel bandwidth is now shared by a larger number of users. As a result, the channel can be filled up more quickly and thus new connections can not be admitted into the channel without closing the existing sessions. Further, it is imperative that the QoS of the existing sessions need to be maintained.

The ECs are formed by taking into account many aspects: measurement and/or estimation of bandwidth requirement, number of Mobile Stations (MS), the density of MSs, and the movement or the (room) boundary crossing rate of the MSs. By taking into account the steady state measures of these parameters, ECs were formed and analyzed in [3]. The call drop percentage and the blocking probabilities were also calculated. However, the main draw back of this approach is that the ECs once formed based on the steady state estimates will not be able to cope with the demands of changing situations due to extra traffic, such as movement of MSs into one particular room. For example, a seminar or a class or a meeting can make many user handheld devices to aggregate in a small area.

Thus in this paper, we propose to dynamically define and form ECs based on realtime traffic measurements in the network to optimize the performance of the system. In this solution, MSs constantly reports its connections' status to the CS. As a result, the CS has the full knowledge of the network's traffic characteristics, such as signal quality, the number of ongoing and blocked connections etc. We also present an algorithm that is able to automate the EC planning process and to perform dynamic EC forming/switching adapting to the changing traffic in the network.

Without the EC concept and a dynamic EC formation algorithm, antenna stations' positions will have to be carefully planned and installed to yield sufficient coverage. This technical process can be impracticable to the majority of end-users. Moreover, the network cannot be responsive to any changes made to the environment where it is deployed, such as changes in interior design. Since different buildings have different floor plans that can be changed from time to time, an automation method to form ECs is required. In the next section, we present a method to perform dynamic EC formation based on the network setup and the realtime traffic.

4 Dynamic Extended Cells Formation

As mentioned above, in an in-building network operating at millimeter-wave bands, a number of antennas are required. Each antenna covers a confined area, a cell, e.g., a small room or a part of a larger area. As a result, an in-building network can always be presented by a graph $G = (V, E)$ whose nodes $\{v\} \in V$ correspond to the antennas/radio cells/APs and edges, $\{e\} \in E$ correspond to the presence of an overlapped area amongst neighboring radio cells; an edge $e_{i,j}$ is present only if two vertex pair $\{i, j\}$ (cells) are connected by an overlapping area. $e_{i,j} = 1$ if there is a overlapped area between i and j, and 0 otherwise. Figure 2 illustrates such a graph representing the right half of the floor plan shown in Figure 1. There are two ways of

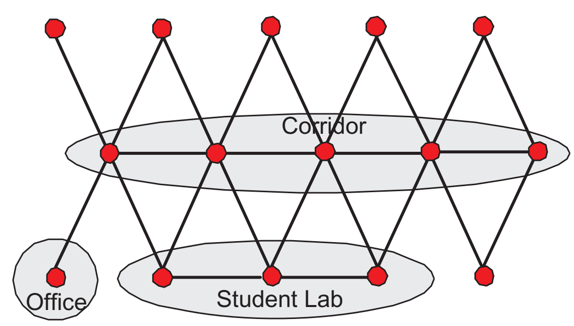

Figure 2. Represents of a floor plan as graph

handling changing traffic in some rooms: (a) adapting the bandwidth in turn T for the particular ECs and (b) adapting the number of rooms in an EC. Selectively increasing the bandwidth for particular ECs or rooms is difficult since CS becomes complex. Therefore, we take the second option. To focus on the dynamically changing traffic patterns we present a study using combinatorial optimization technique to form dynamic ECs.

We now define a weight w_i for each node $i \in V$ in the graph as a function of the traffic Λ_i under the radio cell i and its connectivity degree that is the total overlap area $A_i = \sum \mathcal{A}\{e_{i,j}\}$ of the cell i with its neighboring cells j. $\mathcal{A}\{e_{i,j}\} = 0$ if $\{e_{i,j}\} = 0$. Thus we can represent $w_i = f(\Lambda_i, A_i)$. In this paper, we use the modified weighted set-cover algorithm to form different EC plans dynamically. Forming an "optimum" number of ECs is an NP-Complete problem. We preclude the proof since it is a simple variant of well known Set Cover problem. The problem formulation is given below.

Algorithm 1 Dynamic EC forming

Input: $U = \{At_1,\ At_2,\ \cdots,\ At_m\}$
Input: $S = \{s_1,\ s_2,\ \cdots,\ s_k\}$, $s_i \subseteq U$ *and* $\bigcup_{\forall i} s_i = U$
Input: $W = \{W_1,\ W_2,\ \cdots,\ W_k\}$
Output: $C \subseteq S,\ \bigcup_{s \in C}\{s\} = U$ that maximizes $\sum_i W_i$

1: $C \leftarrow \emptyset$ {Initialize C as an empty set}
2: $U' \leftarrow S$ {Initialize U' with set S for use in next iteration}
3: **while** 1 **do**
4:   **while** $\bigcup_{s \in C}\{s\} < U$ **do**
5:     $k \leftarrow \text{argmax}_{x \in S}\big\{\{x \cap U \neq \emptyset\}\ \&\&\ \{W_x\}\big\}$
6:     $\forall j$
7:     **if** $\big\{\{At_j \subseteq s_k\}\ \&\&\ \{At_j \subseteq C\}\big\}$ **then**
8:       **if** At_j is the head of s_k **then**
9:         $c_j \leftarrow c_j \backslash At_j$
10:       **else**
11:         $s_k \leftarrow s_k \backslash At_j$
12:       **end if**
13:     **end if**
14:     $C \leftarrow C \cup s_k$ {Put s_k into the set-cover C}
15:     $S \leftarrow S \backslash s_k$
16:   **end while**
17:   **return** C {Sets c in C are the Extended Cells (ECs)}
18:   **if** Traffic in a cell i in any $c \in C$ increases beyond the threshold T **then**
19:     Adjust the weight w_i of the cell i as explained earlier
20:     Recalculate $w_i = f(\Lambda_i, A_i)$
21:     $S \leftarrow U'$
22:     $\forall i$, if s_i has $\sum \Lambda_j > T$ and, j = rooms in the subset s_i; randomly delete some rooms in s_i except the head to keep them fit, thus changing the setcover problem.
23:     $C \leftarrow \emptyset$ {Reset C and return to Step 4}
24:   **end if**
25: **end while**

Problem Formulation 1 *Given a universal set of nodes as* $U = \{At_1,\ At_2,\ At_3,\ \cdots,\ At_n\}$ *where* At_i *represents antenna/cell* i. *We define a number of subsets* s_i *as* $S = \{s_1,\ s_2,\ \cdots,\ s_k\}$, $s_i \subset U$ *and* $\bigcup_{\forall i} s_i = U$. *Where each subset* $s_i = \big\{At_i, \bigcup\{At_j\}\big\} \ni e_{i,j} = 1$ *corresponds to a node* At_i.

The problem is to find a set cover $C \subseteq S, \ni \bigcup_{s \in C}\{s\} = U$ *that maximizes* $\sum_i W_i$, *where each subset* s_i *is associated with a weight* W_i.

In this paper, we define $W_i = \max\{w_i\}\ \forall i \ni At_i \in s_i$; i.e., weight of a subset to be equal to the biggest weight of the members of the subset s_i. The idea here is to isolate those cells that are connected and has higher traffic and overlapped area. With higher traffic and overlapped area, a cell's weight increases. We can show that this algorithm results within $\ln n$ optimal. One can define different W_i to tune the results to suite for a particular situation.

Remark: Since the traffic can be varying inside the building as well as many MSs from outside may come into a smaller area at some instants, some of the ECs formed during static assignment will not be valid since some ECs might have much higher traffic density above T. Therefore, the algorithm given here takes care of rearranging the rooms to ECs and ECs to tackle this situation. We assume that in a room we do not see the traffic higher than the capacity threshold T. The detailed algorithm is given below in Algorithm 1.

5 Simulation

5.1 Simulation setup

The floor plan (Figure 1) represented by the graph shown in Figure 2 consists of 26 nodes representing the 26 antennas. From this initial 26 nodes, 26 subsets are constructed with the "head" element of the subset as the node that has the highest weight w_i. At the beginning, since there is no traffic in the network, the weight of each subset is set to be equal to the number of edges connected to the head of the subset. This is equal to the one less than the cardinality of the subset. The Algorithm 1 starts with the subset with the biggest weight to find the corresponding setcover - the EC plan. As a result, given the fixed graph, the initial EC plan is also fixed.

Each EC is assigned a radio channel which has 20 slots that are able to accommodate 20 multimedia connections. Each MS when active, consumes one slot. At any moment t_i, abrupt traffic is introduced into a room selected randomly. This represents the case where a meeting or a class takes place in one of the rooms on the floor. As the available resources in the corresponding EC is consumed fast and gets below a threshold, the system triggers the Dynamic EC forming Algorithm 1, to form a new suitable EC plan.

For this simulation study, the floor plan shown in Fig. 1 is used. An antenna operating at 60 GHz with the gain of 0 dBm is installed in every office room. Number of antennas is installed along the corridor with a spacing of 5 m. All the antennas are connected to the CS via an OFM optical distribution network. Firstly, a database of signal strength values for all the positions in the floor is built by placing a receiver grid with a spacing of 20cm onto the floor plan. For each vertex of the grid corresponding to a receiver position, the signal strength values contributed from the surrounding antennas are collected using the ray tracing simulation package - RPS [1]. We assume that OFDM with sufficiently large cyclic prefix is used to eliminate the multipath effect.

Next, to simulate mobility, MSs are uniformly distributed around the floor. Each MS starts a call after a Poisson-distributed idle interval with the mean of 60 s. Call duration is also a Poisson-distributed random variable with the mean of 60 s. MSs move around the floor according to the random walk with reflection mobility model [2]. The velocity of a user is randomly selected in the range $[v_{min}, v_{max}]$ and it remains constant for the duration of the call. At every step during the movement, the MS checks the signal strength values contributed from the surrounding antennas that have been recorded in the first step and decides whether to stay with the current connection or to initiate a HO.

5.2 Results

By applying the floor plan as shown in Figure 1 to the dynamic EC forming algorithm, the initial EC plan is formed containing 9 ECs. In this simulation study, we investigate two scenarios. In the first scenario, 150 MSs are placed on the floor to create an under-utilized network since capacity of an EC is 20. In the second scenario, the number of MSs is increased to 200. In all the following figures, the results of the first scenario is shown in the left group of bars and the results of the second one is illustrated in the right group. Moreover, the figures also show the results when the average velocity of MS varies from 0 to 2 m/s and from 2 to 4 m/s.

Figure 3 shows the blocking probability of a call. The figure clearly shows that the blocking probability is significantly reduced when dynamic EC forming is applied. Moreover, with dynamic ECs, the blocking probability is small in all cases even when the average velocity of MS is increased. Meanwhile, as predicted the blocking probability in the second scenario is much higher when the fixed initial EC plan is used and when the average velocity of MSs increases.

In Figure 4, the probability of call drop caused by HO is

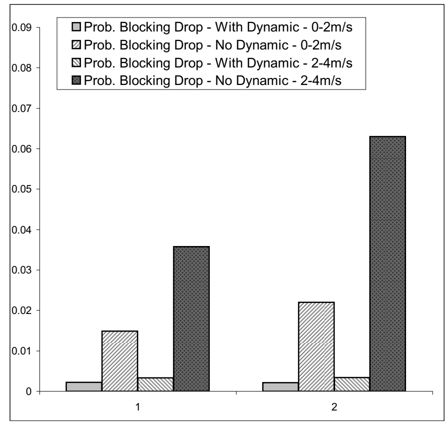

Figure 3. Call Blocking Probability - For (1)150 Calls and (2)200 Calls

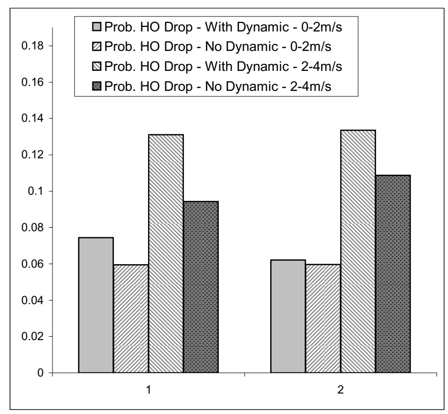

Figure 4. Probability of a drop caused by Handover - (1)150 Calls and (2)200 Calls

shown. Here, a call is dropped during a HO process showing that there was not enough overlapped area. Since the initial EC plan is created based entirely on the connectivity degree of each cell[1], it is also the one which offers best signal coverage in terms of overlapped areas. As a result, the probability of a call drop caused by HO for the case in which dynamic EC forming is applied is higher than in the case with fixed EC plan. This can be reasoned by the fact that since more ECs are created by the algorithm due to the extra traffic, the corner effect is also more significant. However, the total probability of a call drop (shown in Figure 3 and 4) for the case with dynamic EC formation is still much lower compared to the case where no dynamic EC forma-

[1]Transitional cells, e.g., cells in the corridor, have higher degree of connectivity; while office rooms have lower degree.

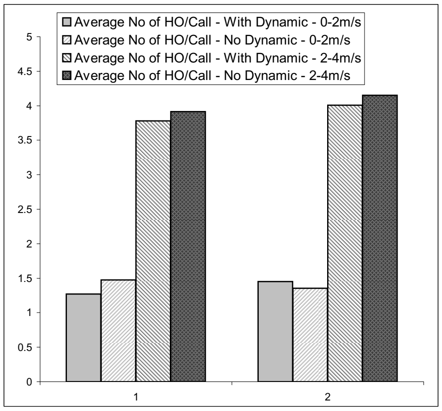

Figure 5. Average No of HOs per Call - For (1)150 Calls and (2)200 Calls

tion is used.

Finally, the average number of HOs per call is illustrated in Figure 5. As can be seen in the figure, since the extra traffic is introduced into the network only once in this simulation study, the average numbers of HOs per call, with and without dynamic EC formation, are similar. As predicted, this number is increased drastically when the average velocity of MSs increases.

6 Conclusions

In this paper, we have proposed an algorithm to dynamically form EC plans based on the connectivity degree and the traffic of each cell. A simulation study of the proposed algorithm applied to a real floor plan is also carried out. The results show the effectiveness of the solution for reducing the probability of call drop caused by blocking. More importantly, the algorithm can be applied to any floor plan and can be adaptive to the traffic situation under a network.

There are some issues that requires attention . (a) How and when to trigger the dynamic EC formation algorithm, e.g., as soon as an EC/room is overloaded or when we see more MSs entering the EC/room in a period of time, i.e., average number of MSs arriving into the EC. (b) How to fix the weight W_i of an EC? In this paper, the weight W_i of a subset is set to be equal to the highest weight w_i of a node/room in the subset. However, it can be formulated as a function of many parameters, such as, rate of arrivals of MSs, current MS density. The weight, W_i, significantly influences the way ECs are formed. Thus there is a need to understand its effect as well as select the best way to find W_i. These issues implore our attention. Currently studies on these issues are under consideration.

7 Acknowledgement

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