Toward A Seamless Communication Architecture for In-building Networks at the 60 GHz band

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Abstract

This paper addresses the issues of designing an infrastructure to support seamless in-building communication at the 60 GHz band. Recently, the 60 GHz band has received much attention due to its 5 GHz of available spectrum. However, the propagation of signals in this band is strongly hindered by attenuation and line-of-sight requirements. The situation gets worse in the in-building environment where signal propagation is obstructed by physical objects such as walls, furniture etc. In this paper, we present a novel Radio over Fiber (RoF) architecture that is cost-effective and is able to deliver high data-rate of the order of gigabits. To ensure a seamless communication environment at the 60 GHz band, we propose the concept of Extended Cells (EC) in order to create sufficient overlap areas. Finally, we illustrate the effectiveness of the proposed architecture by simulating an in-building network at the 60 GHz band employing the RoF and EC concepts.

1 Introduction

In recent years, the communication industry has been witnessing enormous growth in the area of Wireless Local Area Network (WLAN) – in terms of both the number of users and the diversity of services. It is predicted that this will continue at a higher pace in the near future, and it will be driven by a multitude of multimedia applications. As a result, the required capacity of the future wireless networks can be 10 to 100 times as much at the present [9]. To deliver this massive data rate, either the spectrum efficiency must be increased or more spectrum space is required. In the quest for more available bandwidth, much attention has been paid to the 60 GHz band where as much as 5 GHz of spectrum has been allocated worldwide. This unprecedented amount of available spectrum holds the potential for much higher data rate ever compared to other bandwidth-limited channels that are currently used. Wireless data rate in the range of 1 Gbps will be the order of the day. Since the propagation of 60 GHz radio wave (millimeter wave in general) is strongly hindered by attenuation, radio cells are more well-defined and compact making the band very suitable for short-range broadband communications. Moreover, Inter Channel Interference (ICI) is less and thus frequencies can be reused more often in a given smaller geographical area.

One of the most promising niches for 60 GHz networking can be for providing wireless services in the indoor environment. Since walls attenuate millimeter waves considerably, a radio cell will typically be confined to a room where walls and floors can be automatically defined as reliable boundaries [7, 2]. Consequently, at least one Access Point (AP) will be required in a confined indoor area, such as a room, a hall or a corridor etc. This configuration poses the following major challenges:

Challenge 1 - A large number of APs will be required to cover a building. In addition, the complexity of the signal processing functions, e.g. macro-diversity, Multiple-input Multiple output (MIMO) etc., required for each antenna station is also increasing. As a result, the cost of APs is a major contributor for the total cost of the infrastructure and the task of simplifying APs is also becoming increasingly important [14].

Challenge 2 - At a millimeter wave band, a radio cell typically spans only a room. Overlap areas between two adjacent cells exist only around open areas such as doors or windows. Consequently, overlap areas are often narrow and directional. In a multi-channel communication system, where handovers (HO) are required when a Mobile Station (MS) roams from one cell to another, these overlap areas can be too small to allow an MS sufficient time to trigger and complete a handover. It is therefore crucial that large enough overlap areas are created in the system in order to guarantee a seamless communication environment.

In this paper, we propose a novel architecture which is able to guarantee a reliable in-building communication environment at the millimeter wave band. The architecture is based on a new millimeter-wave delivery technique called Optical Frequency Multiplying (OFM) [5, 4]. By carrying radio signals over optical fiber, the complexity of APs can be simplified significantly. Instead of placing all the signal processing functions in the APs, it is now possible to concentrate those complex functions in a single processing block called as a *Residential Gateway* (RG).

The architecture is cellular in which each radio cell is covered by a separate frequency channel. To achieve sufficient overlap areas between cells, we propose to group several adjacent radio cells into one *Extended Cell* (EC). In other words, multiple adjacent antennas are allowed to transmit the same content over the same frequency channel. 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 mobile users move from one cell to another. Multipath and shadowing effects can be effectively mitigated by using Orthogonal Frequency Division Multiplexing (OFDM). Moreover, since multiple antennas are allowed to transmit the same signals over an EC, a diversity gain can be obtained to reduce the effect of shadowing at the millimeter band. To illustrate the effectiveness of the proposed architecture, we have simulated such a WLAN at the 60 GHz band for an office building. We discuss that the system has large enough overlap areas to perform handover and the number of drop calls is therefore minimized. Moreover, the results also show the improvement of the system in combating against shadowing.

The paper is organized as follows. Section 2 highlights the contributions and drawbacks of the related work. Next, the characteristics of the in-building environment and the 60 GHz band will be elaborated in Section 3. To address the two challenges stated above, an architecture for in-building broadband networks at 60 GHz is proposed in Section 4. Section 5 presents a simulation study of the proposed architecture. Finally, Section 6 concludes the paper.

2 Related Works

Extensive research has been carried out on the physical aspects of the radio propagation channel at the millimeter band by Smulders [7, 12] or Giannetti [2]. Nevertheless, the issues of designing an infrastructure supporting a seamless pico-cellular communication at the millimeter band have not been thoroughly considered yet. To the best of our knowledge, there is no reported work in the literature that attempts to solve the problem of signal coverage for a multi-room indoor environment at the 60 GHz band.

Ghai and Singh [11] proposed a three-level hierarchical architecture for pico-cellular networks. In this system, MSs are at the lowest level and are monitored by Mobile Support Stations (MSS) which again are connected to supervisor machines called the Supervisor Hosts (SH). The main purpose of this classification is to simplify the MSSs as their complexity can be moved to a small number of SHs. In this approach, packets for an MS are multicast to all the MSSs in the neighboring cells so that there will be no packet loss during a handover. However, since a Layer 2 (L2) HO is always required, there will still be a delay and thus a break in service if the L2 handover procedure is not completed before the Layer 3 (L3) handover starts. The problem gets more profound when radio signals drop so fast that an MS cannot even trigger the L2 handover procedure.

In [3], the authors proposed an innovative architecture called a Virtual Cellular Network (VCN). The architecture utilizes the ideas of Single Frequency Networks (SFN) and distributed APs to form an adaptive wireless infrastructure. In a VCN, there is no conventional Base Station (BS) that manages the channel and handovers. Instead, the notion of “ports”, which are essentially simple antennas, is introduced. For a network area, all the ports are connected to and controlled by a Port Server (PS). In this system, a virtual cell (VC) is dynamically formed for each and every MS. It is defined as the area in which the signals sent from the MS are strong enough to capture a port. Packets destined to an MS are dynamically routed by the PS to all the ports inside the VC. Since the network operates at a single frequency channel and a VC is always created to follow an MS, there will be no conventional handover. Each time the MS moves to a new position, a new VC is created and the routing table must be updated in the PS. The drawbacks of this system are twofold. First, the whole spectrum is shared by a large number of users. Second, a lot of traffic overhead is required to handle the ports dynamically when the number of mobile users is large. In [6], the authors extended the concept of VCN with multiple receiving antennas to form a MIMO system.

Different from the previous work, the proposed architecture in this paper is a cellular multi-channel system that is able to optimize the utilization of the available spectrum. Moreover, we propose the concept of Extended Cells (EC) in order to solve the problem of small and directional overlap areas encountered in indoor WLAN systems at millimeter wave band. In the next section, the propagation characteristics of the 60 GHz band in the in-building environment will be elaborated in more details.

3 The in-building environment and the 60 GHz band

The in-building environment can be characterized by grids of rooms, corridors, hallways etc. Rooms are typically of the order of a few meters. Geographically, a floor layout is well-planned and exposes some levels of regularity. For example, rooms or office spaces in an office building or in a living quarter are normally arranged along corridors and have the same size and structure. As mentioned in the previous section, a radio cell at 60 GHz typically spans a room and is separated from neighboring cells by walls. An overlap area between two adjacent radio cells exists only around doors or windows. Due to the high propagation loss caused by walls, the overlap area is normally *narrow and directional*. To verify this claim, a propagation simulation at the 60 GHz band has been carried out using the popular ray-tracing software named Radiowave Propagation Simulator 5.3 (RPS) [10]. This simulation package has been shown to be accurate in terms of statistical properties [8].

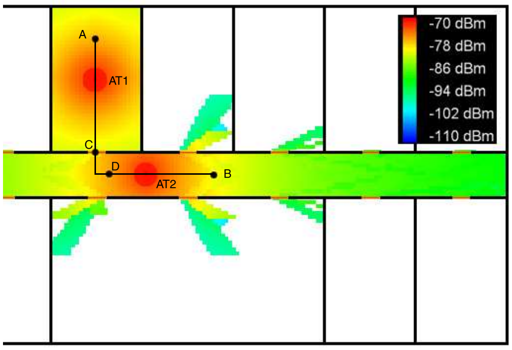

Figure 1. The overlap area simulation

Figure 1 shows the simulation configuration. The floor plan of the Wireless and Mobile Communication (WMC) group, TU DELFT is considered in this analysis. Two rows of $5m \times 8m$ office-rooms are arranged along a long corridor. A student lab ($15m \times 8m$) situates in the middle of the lower row. Walls are made of concrete and are 10 cm thick. Doors are assumed to be completely opened. Two transmitters operating at 60 GHz are placed in the floor. The transmitter (AT1) is placed in the center of a room and another transmitter (AT2) is placed in the corridor under the ceiling (3m high). A mobile user moves from the point A inside the room to the point B in the corridor. The point C is where the user crosses the door and the user loses the line-of-sight connection with AT1 at the point D.

The signal strength contributed from AT1 and AT2 is collected along the user's path and is shown in Figure 2. As predicted, the user receives good signals from AT1 from the point A to D. After the point D, the user loses the line-of-sight connection with AT1 and consequently, the signal strength drops sharply. Contrarily, signal strength from AT2 rises when the user starts seeing AT2 (at the point C). The distance between the point C and D determines how much time it takes the user to cross the overlap area. To guarantee a seamless multi-channel communication environment, a handover is required to be triggered and complete during this amount of time. The distance between the point C and D can be very short when a user makes a sharp turn when he/she gets out of a door. In this case, the system will not have enough time to trigger or to complete a handover thus resulting in packet loss (a break in call) or a call drop. In this paper, this effect is termed as *the corner effect.*

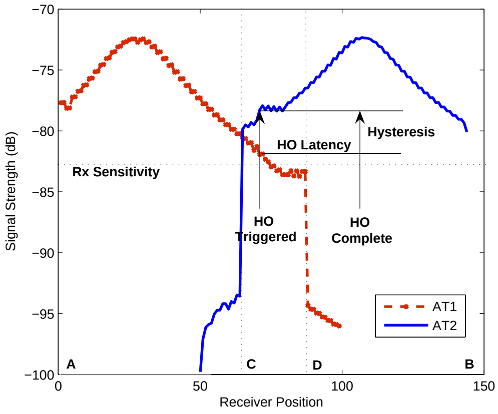

Figure 2. Signal Strength at 60 GHz

Assuming the average speed of a mobile user is $2m/s$, a handover will have to be performed every $5s$ as the mobile user passes through the grid of picocells. Due to the corner effect, a call might be dropped or it might experience a number of breaks as the user might take a number of turns along the path from one room to another. In the next section, an hybrid radio fiber architecture is proposed to solve the problem of shadowing and the corner effect.

4 Broadband In-building Networks at 60 GHz - The architecture

The proposed architecture of a broadband network employing RoF is illustrated in Figure 3. Each radio cell will be served by an antenna connected with a remote Residential Gateway (RG) by an optical distribution network. Physically, the optical distribution network can have a bus or tree topology. However, a link between the Residence Gateway and an antenna can be considered to be dedicated since Wavelength Division Multiplex (WDM) is used along with Optical Frequency Multiplying (OFM) for optical signal transportation [14].

As mentioned earlier, the introduction of an optical fiber feeder network into a wireless LAN is actually the process of simplifying the complexity of antenna sites and concentrating their processing functions into a single processing point (the RG). For a system operating in a millimeter wave band, the simplification of antenna stations is necessary since a large amount of antenna stations are required to cover a certain area. Moreover, since all the processing functions are concentrated into one point, it is easier and cheaper to maintain, upgrade and consolidate the networks. As a result, this proposed hybrid architecture is potential alternative to address Challenge 1 mentioned in Section 1.

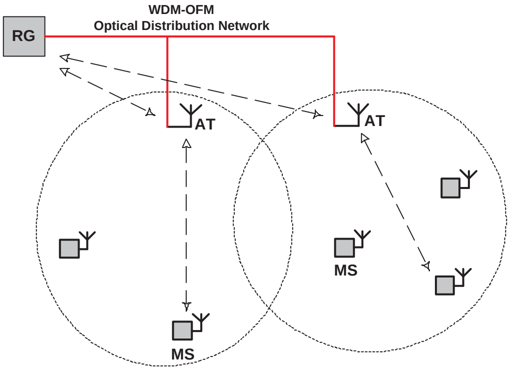

Figure 3. Broadband In-building Networks employing Radio over Fiber

In this architecture, every antenna has an Identification Number (AT_i). Since WDM is used for the optical distribution network, at least one pair of wavelengths, i.e., λ_{DLk} and λ_{ULk}, is fed to each radio cell. A table containing information about the pair of wavelengths and the corresponding AT_i is maintained in the RG (Table 1). Due to the flexibility of the WDM optical distribution network [4], more than one pair of wavelengths can be assigned to an antenna. As a result, it is possible to dynamically allocate more spectrum to each radio cell by assigning more wavelengths to the antenna. Each MS has its own globally unique address (MS_p). To assist the switching of packets to/from a MS, another table containing information about the address of the MS (MS_p) and the corresponding antenna (AT_i) to which the MS is connecting with is also maintained in the RG (Table 2).

Mobile stations periodically collect the Radio Signal Strength Indicators (RSSI) of its current and neighbor antennas. Depending on the collected data, an MS will decide to stay with its current connection or to initiate a handover.

Downlink	Uplink	Antenna ID
λ_{DLk}	λ_{ULk}	AT_i

Table 1. Wavelength-Antenna pairing information

antenna ID	MS addressantenna ID
MS_p	AT_i

Table 2. MS address and corresponding Antenna pairing information

In this system, handovers are initiated by MSs. Whenever an MS decides to perform a handover from the current cell (AT_i) to another cell (AT_k), the MS sends a request to the RG that will subsequently update the above two tables. Since the address of an MS is kept unchanged, it is required to perform only an L2 handover when the MS moves from one cell to another. As discussed above, to guarantee a seamless L2 handover, large enough overlap areas between cells are required (Challenge 2). In the next part, the concept of Extended Cells (EC) is proposed to address this challenge.

The Concept of Extended Cells (EC)

To create better overlap areas, we propose to group multiple adjacent antennas into an Extended Cell (EC) and to allow the antennas to transmit the same content over the same frequency channel. An EC is designed to cover several adjacent rooms and a part of a transitional area. By doing so, an overlap area between two ECs can always be created in the transitional zone. This concept of Extended Cells is supported by the following reasoning.

- In an in-building environment, a mobile user has to pass through a transitional area, e.g., a corridor, a hallway etc., to get from one room to another. It is therefore important to optimize the overlap areas in these transitional areas.
- Due to the flexibility of the optical distribution network, frequency channels can be dynamically allocated to an antenna [5, 4].
- Moreover, since the available spectrum at the 60 GHz band is abundant, larger channels ($\sim$ 100 MHz) can be used to accommodate a large number of mobile users.

Using this concept, the corner effect will be avoided as a mobile user is still in the EC when he/she moves out a room and turns. The number of HOs will therefore be substantially decreased. Further, a form of spatial diversity can also

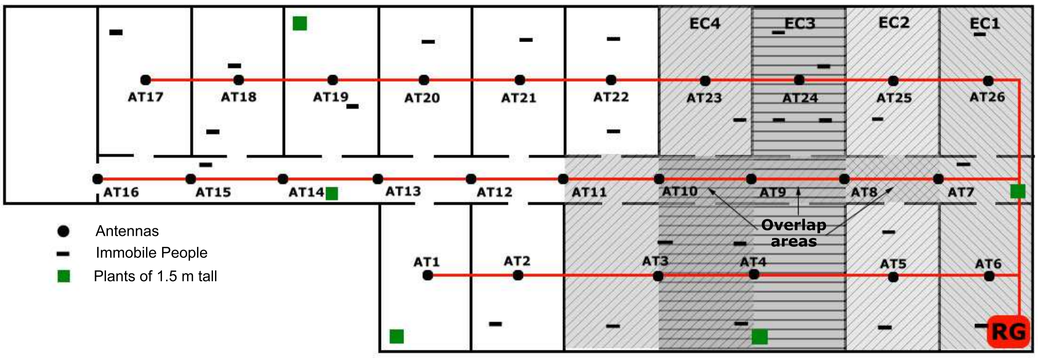

Figure 4. A broadband in-building network employing the RoF and EC concepts

be achieved with the EC concept since multiple copies of a signal are concurrently sent by all the antennas in an EC. Shadowing is reduced since there is a better chance that a mobile station receives a good signal.

The main problem with this approach is that a mobile user will receive multiple replicas of a signal at the same time. This is equivalence to receiving a signal in a strong multipath environment which causes frequency-selective fading and Inter-Symbol Interference (ISI). To mitigate this effect, OFDM is used. In an OFDM system, data is distributed over a large number of orthogonal sub-carriers. As a result, each sub-carrier operates at a much lower bit-rate over a much narrower and flatter channel. The guard period which is a cyclic extension of each OFDM symbol is an effective method to remove ISI, provided it is longer than the delay spread of the radio channel. The size of an EC is therefore restricted by the design of the OFDM system.

For example, a broadband in-building network is designed to deliver a datarate of $1\ Gbps$ using OFDM and 16 QAM modulation. Consequently, the symbol period is $4\ ns$. The OFDM system uses 256 subcarriers that effectively increase the symbol period up to $1\ \mu s$. A guard period of $1/4$ of the symbol period is used to provide $250\ ns$ of protection against ISI. If only the line-of-sight propagation paths from the antennas in an EC are considered, the lengths' difference of any two paths cannot exceed $250 * 10^{-9} * 3 * 10^{8} = 75\ m$. Therefore, the maximum diameter of an EC is $75\ m$. In this system, the received signals from all the antennas in an EC can be combined as OFDM is used with a sufficient guard period to mitigate the effect of phase differences.

Applying this Extended Cell concept, another table needs to be maintained by the RG. The table contains the Extended Cell identification and the antennas that are included in the EC (Table 3). This table can also be updated as wavelengths/frequency channels can be dynamically allocated and switched to different antennas. This dynamic allocation can be based on a numerous of factors, such as the traffic requirement in each EC. However, this topic requires further research and thus will not be included in this paper.

antenna ID	EC ID
AT_i	EC_i
AT_m	EC_i
AT_n	EC_q

Table 3. MS address and corresponding Antenna pairing information

5 Simulation Results

To illustrate the effectiveness of the proposed architecture, a simulation for an in-building network at the 60 GHz band employing the proposed concepts has been developed in C++.

5.1 Simulation setup

Figure 4 illustrates the configuration of the broadband in-building network used in this simulation study. The floor plan of the Wireless and Mobile Communications group presented in Section 3 is used. An antenna operating at 60 GHz with the gain of $0\ dBm$ is installed in every office room. For the student lab, two antennas are installed to provide sufficient coverage. A number of antennas is installed along the corridor with a spacing of $5m$. All the antennas are connected to the Residential Gateway (RG) via an OFM optical distribution network. As shown in Figure 4, the antennas AT_6, AT_7 and AT_{26} are grouped into the extended cell EC1. Similarly, the extended EC2 contains the antennas AT_5, AT_8 and AT_{25}. The overlap area between EC1 and EC2 is created in the corridor between the AT_7 and AT_8. The detailed assignment of extended cells is: EC_1={AT_6, AT_7, AT_{26}}, EC_2={AT_5, AT_8, AT_{25}}, EC_3={AT_4, AT_9, AT_{24}}, EC_4={AT_3, AT_{10}, AT_{23}}, EC_5={AT_{11}, AT_{22}}, EC_6={AT_2, AT_{12}, AT_{21}}, EC_7={AT_1, AT_{13}, AT_{20}}, EC_8={AT_{14}, AT_{19}} and EC_9={AT_{15}, AT_{16}, AT_{17}, AT_{18}}.

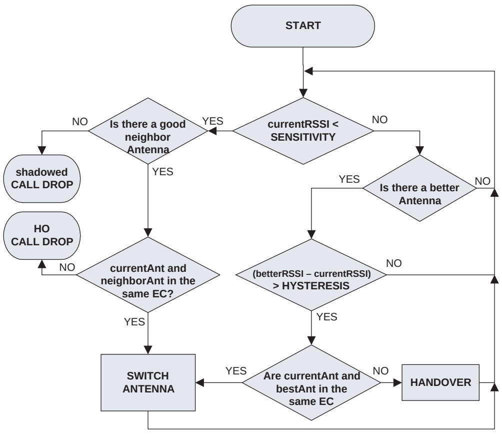

Figure 5. Flow chart of the Handover algorithm

A square grid with a spacing of 20 cm is mapped on the floor plan. For each vertex of the grid, the signal strength values contributed from surrounding antennas are collected using the RPS simulation package [10]. We assume that OFDM with sufficiently large cyclic prefix is used. As a result, the phase component of a signal can be ignored. For this simulation study, two scenarios are introduced.

1. **The scenario without Shadowing** - In this scenario, no obstacle is placed onto the floor. As a result, signals are good at all points.

2. **The scenario with Shadowing** - In this scenario, objects, such as plants and immobile people, are introduced randomly around the floor to create shadowed regions (Figure 4).

Mobile users are uniformly distributed in the floor. Each mobile user starts a call with a mean duration value of $200s$. Mobile users move around the floor according to the Random Walk with Reflection mobility model [13]. The velocity of an user is randomly selected in the range $[v_{min}, v_{max}]$ and remains constant during the whole duration of the user's call. The velocity decides how fast the user moves from one vertex of the grid to another. As a result, only eight directions are used in this mobility model.

At every step during the movement, the MS checks the signal strength values contributed from surrounding antennas and decides whether to stay with the current connection or to initiate a handover. This decision algorithm is shown in Figure 5. For this simulation study, the receiver's sensitivity is assumed to be -85 dBm and the hysteresis level is set to 0 since the spacing between antennas is very closed. The following metrics are measured during the simulation.

1 – **Average No. of HOs per Call**
2 – **Probability of a shadowed Call Drop** - the probability of a drop call caused by shadowing.
3 – **Probability of a HO Drop** - when a MS passes through an insufficient overlap area, it will have to experience a number of packet losses or a break in call. However, in this simulation study, this will be counted as a Drop during HO (termed as a HO Drop).
4 – **Average Call Duration** - A larger call duration indicates a better quality of service.
5 – **Average No. of HOs saved by applying the EC concept** - since multiple adjacent radio cells are groups into an EC, the number of HOs decreases.

5.2 Results and Discussion

We have simulated the movement of a user, in a call, and the floor coverage using multiple antennas connected to the RG with fibers. The speed of a user influences the number of time steps that the user must takes to cross one grid step. Thus the variations in the signal strength seen by the MS are higher if the mobility of the user is high. As we have indicated earlier, the simulation of our proposed architecture is carried out with respect to (a) presence or absence of shadowing, and (b) with or without Extended Cells (EC) concept. We collected statistics for the above metrics for different scenarios which we take up for discussion in the sequel.

In Figure 6(a) we take an ideal case of no shadowing. We can see that the average number of handovers per call increases linearly with the speed of mobile users for the case where the concept of EC is employed [1]. On the contrary, the number of HOs is remarkably lower for the case of not using EC. This is due to the fact that many calls are dropped as soon as MSs move out of a room and turn. We also compare the probability of a call being dropped. Since there is no shadowing in this case, the probability of a shadowed drop is always zero. The probability of a HO drop for the case with EC is much less than in the case where the concept of EC is not applied. As can be seen in the Figure, the probability difference can be up to 70%.

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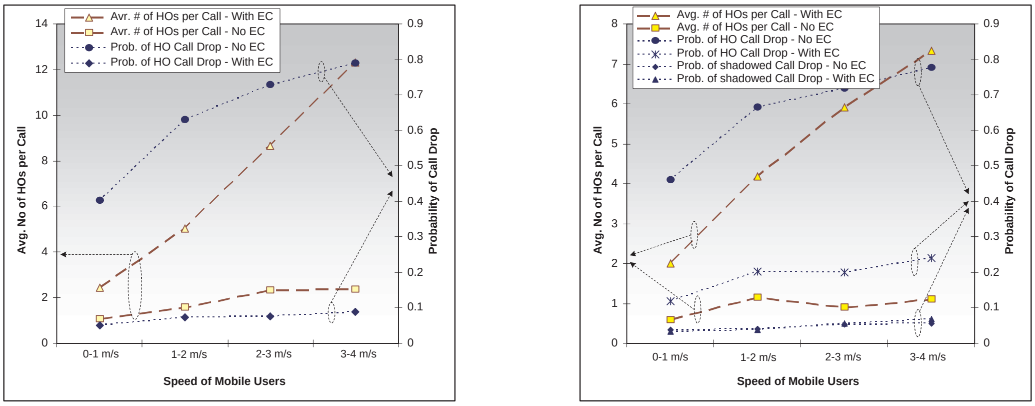
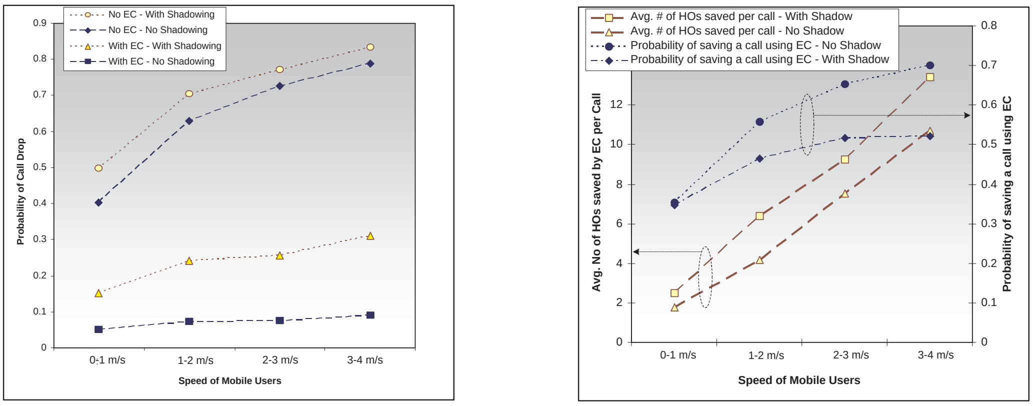
[1] For the ease of interpreting the figures, arrows are drawn pointing to the corresponding y-axis used for the selected data sets.



(a) No Shadowing Scenario

(b) With Shadowing Scenario

Figure 6. Average number of HOs per Call and Probabilities of a Call Drop



(a) Comparison of Probabilities of a Call Drop

(b) Average number of HOs and probabilities of a Call Drop saved by EC

Figure 7. Comparison between the two scenarios

Figure 6(b) shows the simulation results of the scenario where shadowing effect is introduced. The average number of HOs with the concept of EC is much larger than that when no EC is used. However, this numbers are smaller than in the case of no shadowing since more calls are dropped by shadowing and during handovers. As mentioned before, a distinction that a call can be dropped during handover or because of shadowing is made in this simulation study. Both these values are presented in the diagram. We can see that the introduction of EC does not effectively influence the probability of a call drop caused by shadowing. This can be reasoned by the fact that the signal strength at a position is dominant by the line-of-sight propagation path. Therefore, the contribution of other signals from other antennas in the EC is not significant. However, the more antennas are included in an EC, the better this contribution will be. In this shadowing scenario, the probability of a HO call drop in the case with EC is higher than that in the scenario of no shadowing since whenever a call experience packet drops due to shadowing, the call is dropped (Figure 5) [2].

To clearly see the effects of shadowing and the application of the EC technique, the comparison of the probabilities of a call drop in two scenarios is shown in Figure 7(a). We see that shadowing without EC will result in a higher possibility of a drop compared to all other combinations. With

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[2] We should note that the MS can move through an area where the signal is very weak, say a sharp bend around a corner. This will cause some breaks in service even if a new antenna with a higher power is available. We account these instances also as HO call drop. Even if we somehow solve the problem of losing connectivity for a short duration, by nature it is a blackout of packets and will cause disturbances. Since we are aiming at indoor environment and if a user experiences frequent interruptions it would be annoying and is detrimental to the cause of providing the seamless connectivity. Thus we have taken this as a call drop and we try to minimize it.

the concept of EC we also save many handovers. In Figure 7(b) we plot both the handovers saved and probability of saving a call by using EC which would have otherwise been dropped. We can see that with shadowing, larger numbers of HOs are saved since the MS is able to switch to a good antenna in the same EC when it is in a shadowed area. As expected shadowing does reduce the performance, however, it is interesting to note that at lower speed the probability of avoiding a drop call is similar for both cases – with and without shadowing.

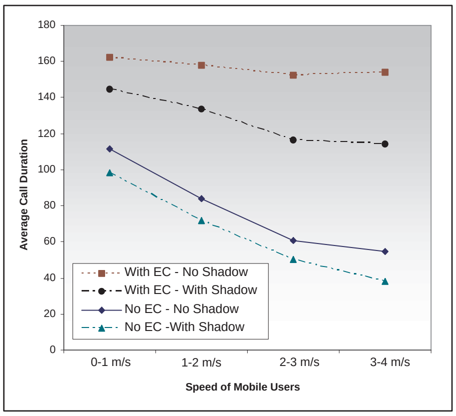

Figure 8. Average Call Duration

A very important aspect of this setup and our proposal is to see whether the quality of service improves with the introduction of ECs. In Figure 8, we can clearly see that the average life time of calls is longer in the cases where the EC concept is applied. It is also interesting to note that the average life time of calls in the case of EC decreases much less when the speeds of mobile users increase.

6 Conclusions and Future works

We have presented a future-proof architecture for broadband in-building WLAN at the 60 GHz band. We discuss that the proposed architecture can overcome the shadowing and corner effects to ensure a seamless communication environment. To support this argument, we have performed a number of simulations of a practical example of in-building network employing the proposed concepts. The results show that our proposed architecture is not only able to optimize the overlap areas but also able to improve the signal coverage at 60 GHz. To our best knowledge, the work reported in this paper is the first attempt to apply the concept of Extended Cells together with Radio-over-Fiber infrastructure to the in-building communications environment at the millimeter wave band. Thus, this preliminary study opens a wide range of research issues that have to be further investigated, as for instance, dynamic procedures to define and form ECs, to optimize network coverage and network resources.

7 Acknowledgement

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