Improving and Extending Indoor Connectivity Using Relay Nodes for 60 GHz Applications

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***Abstract*—a 60 GHz wireless system can provide very high data rates. However, it has a tremendous amount of both Free Space Path Loss (FSPL) and penetration loss. To mitigate these losses and extend the system range; we propose techniques for using relay nodes. The relay node has been positioned correctly in order to shorten the distance between a source and a destination, this gave a reduction in the FSPL value. In addition, the positioning of the relay node correctly gave an alternative Line of Sight (LoS) to overcome the penetration loss caused by human bodies. For the last challenge, the considerably short range of the wireless network in the 60 GHz band, the range has been extended by applying the multi-hop communication with the concept of relay nodes selection. The length of the room was doubled and still get the same losses as if there was no expansion. All three techniques were modeled inside 'Wireless InSite' by three scenarios. The first scenario was a conference room with no obstacles to focus on FSPL. In the second scenario, the same conference room was modeled but human bodies have been taken into consideration to check the penetration loss effect. The final scenario was the extended version of the first scenario to deal with the small range issue.**

Keywords—60 GHz; Indoor Wireless; Multi-hop; Relay; Relay Selection

I. INTRODUCTION

The millimeter wave technology has been known for many decades, and it has been deployed for military applications. With the advances of process technologies and low-cost integration solutions, this technology has started to gain a great deal of momentum from academia, industry, and standardization body [1].

The major quality of 60 GHz is the huge globally license-free spectrum between 57-66 GHz which will support very high data rate wireless applications [2]. One of the main challenges facing the 60 GHz technology is the heavy attenuation characteristics of the millimeter waves. As an example, a 60 GHz system has to deal with more than 20 dB greater FSPL than an equivalent 5 GHz system since the FSPL increases with the square of the carrier frequency [3]. Another challenge for using 60 GHz is the penetration loss which is also very high in the 60 GHz band. In a typical indoor environment, the LoS propagation path between two devices at 60 GHz may completely be blocked by surrounding objects and human bodies. When a 60 GHz link is blocked reflections from the surfaces can be exploited to sustain the link connectivity between the devices which will add more losses [4]. Short range is a huge challenge for 60 GHz system. For point-to-point indoor communication in order to get up to 10 m range, an antenna with high gain of 15 dBi or higher is required [5].

The effective interference levels for 60 GHz are lower than what for the congested 2–2.5 GHz and 5–5.8 GHz regions [6]. However, in some cases where dense 60 GHz wireless network existed, the interference level is considerable. So, interference mitigation techniques are needed [7]. Directional antenna proposed to overcome high values of FSPL in [8], but the signals with the proposed technique can be easily blocked by any obstacle. Beamforming or beam steering is proposed in [9] to overcome blockage in directional antennas and enhance their performance in 60 GHz system. However, the proposed scheme adds more overhead and complexity to the system. Many methods proposed to solve those challenges, but the easiest and most efficient method is the using of relay nodes [10]. The first study of using relay nodes with 60 GHz is provided in [4]. The paper shows that the value of FSPL can be reduced by more than 33% by using relay nodes. The proper positioning is provided in the paper. However, the simulation results based on device to device communication network. In [11] a relay selection scheme is proposed to replace a long direct path with several multi-hop paths to improve the network throughput. However, to the best of our knowledge, the small range mitigation by multi-hop communication isn't studied yet. By relaying signal from the source to the destination, the long bath between the source and the destination is then broken into short paths which in turn reduce the FSPL [12]. Indirect path via relay node can provide LoS in some cases where the direct link between the source and the destination is blocked. The main contributions of this paper include the following. (1) Finding the best position of relay node to reduce the FSPL between transmitter and receiver. (2) Finding the best position of relay node to reduce the penetration loss, human bodies, by providing LoS in case of blockage. (3) Extending range using same parameters by selecting relay nodes correctly in multi-hop communication. Interference mitigation mechanisms have been discussed in this paper.

This paper is divided into 6 sections. Section 1 gives the overview. Section 2 is the system model. Section 3 contains the positioning of relay nodes. Relay nodes selection and interference mitigation are in Section 4. Simulations setup and results are presented in Section 5. At the end conclusion is presented in Section 6.

II. System Model

A. FSPL Improvement Model

The chosen criterion to test improvement is the FSPL, because of its ease of being calculated and at the same time its importance in link budget [4]. In order to model the performance of the system with and without using of relay nodes, two cases need to be modeled. First case is the direct case, where the source can reach to the destination directly. The second case is the indirect case, where the source will reach to the destination through the relay. The Source (S) point is assumed to be fixed access point while the Destination (D) is assumed to be randomly placed in the area. The Relay Node (R) is assumed at the midpoint of the area where 60 GHz wireless system is going to be used. The suggested area for this study will take the shape of a circle with an appropriate radius value. So, the source can reach all points on the circle and the relay node will be at the center of the circle. The area has radius C. P is the link connecting source to destination which is the random variable, C is the link connecting source to relay node, and I is the link connecting relay node to destination, as shown in Fig. 1.

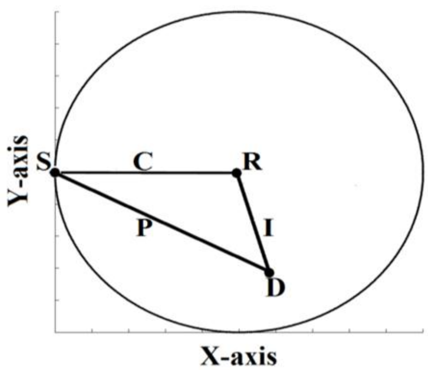

Fig. 1. Study area

Destination is randomly located in the circle, each location with different values on X and Y axis, the location of the destination is represented with the values (x, y). If the destination location considered to be uniformly distributed on the circle, then the Probability Density Function (PDF) of the location in the two dimensional plane as follows [13]:

$$f(x,y) = \begin{cases} \frac{1}{area} & for (x,y) \in area \\ 0 & otherwise \end{cases} \quad (1)$$

The factor that will decide if the link FSPL improved or not is the distance between the source and the destination according to the following formula [14]:

$$FSPL_{(dB)} = 32.4 + 20\log d_{km} + 20\log f_{MHz} \quad (2)$$

Where d is distance and f is frequency. So to get the distance, the conversion to polar coordination will be helpful. To get the PDF for r and θ from $f(x, y)$, this can be done using the Jacobian of the transformation matrix [15]:

$$J(x,y) = \frac{1}{r} \quad (3)$$

$$f(r,\theta) = \frac{f(x,y)}{|J(x,y)|} = \frac{r}{\pi C^2} \quad (4)$$

while θ is uniformly distributed over $0 - 2\pi$ then:

$$f(r) = \frac{2r}{C^2} \quad (5)$$

For the first case, where the link directly connects the source to the destination, the maximum link length is $P_{max} = 2C$. In the second case, there are two links: one that connects the source to the relay node which is C, this value is fixed because both of source and relay node are fixed. The other link connects the relay node to the destination, it's maximum length is $I_{max} = C$. So, longer one among the two links need to be compared with direct link in order to see whether the relay node made an improvement on the direct link or not. To find the maximum between two independent random variables, this can be done by multiplying their Cumulative Distribution Function (CDF) [16]. For first link, the CDF is $F(C) = 1$ because it is a constant value. For second link, the CDF is equal to the integral of $f(r)$, which is equal to $\frac{r^2}{C^2}$ and so:

$$F_{max}(r) = \frac{r^2}{C^2} \quad (6)$$

To inspect the reduction in the distance, expected value is a reasonable way:

$$E(r) = \int rf(r)dr \quad (7)$$

Since there is only one link in the first case then it's PDF equal $f(r)$, but for the second case we need the maximum PDF between the two links which is:

$$f_{max}(r) = \frac{dF_{max}(r)}{dr} = \frac{2r}{C^2} \quad (8)$$

Since $f(r)$ and $f_{max}(r)$ are equal, then $f(r)$ can be used as a PDF for both cases. By taking the extreme values of r in the two cases P_{max} and I_{max} then: (1) $E(r) = 2c * \frac{2*2C}{C^2} = 8$ for first case. (2) $E(r) = c * \frac{2*C}{C^2} = 2$ for second case. So, in the second case, where the relay node was fixed at the center, the distance can be reduced up to its one fourth of the no relay case. This reduction in distance could be translated to FSPL reduction by using (2). So, the reduction in FSPL could reach -12 dB at the extreme values of r.

B. Human Body at 60 GHz Model

In order to evaluate the performance of the system in the presence of humans a reliable characterization of propagation through human body at 60 GHz channel is needed. Indeed, the close proximity of antennas with the human body may result in significant changes in the input impedance, radiation patterns, antenna efficiency, and energy absorption of the signal induced in human bodies. Furthermore, the results might fluctuate due to differences and variations of the dielectric properties of biological tissues [17]. Typical values of the complex permittivity at 60 GHz for main human body tissues like skin, fat, muscles, and pure water at 20^{o} C are summarized in Table I [18].

TABLE II. HUMAN TISSUES COMPLEX PERMITTIVITY AT 60 GHZ

Human Tissues	ε_c
Skin	7.98 − j 10.91
Fat	2.51 − j 0.84
Muscles	12.85 − j 15.74
Pure Water (20 ° C)	11.9 − j19.5

Where:

$$\varepsilon_c = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_o} \tag{9}$$

ε_c is Complex permittivity, ε_r is relative permittivity, ω is angular velocity (rad/s), and ε_o is free space permittivity (8.85×10^{-12} F/m). The human body is simulated as a parallelepiped circumscribed with pure water cylinder model with the following dimensions: the lengths of sides of the basic rectangle is equal to 0.305 m, the height is equal to 1.7 m, and the thickness is equal to 0.305 m [19]. Based on (9), the conductivity of pure water at 20^o C is 65.06 S/m, the conductivity of skin is 36.4 S/m, the conductivity of fat is 2.802 S/m, and the conductivity of muscles is 52.51 S/m.

III. RELAY NODE POSITIONING

Calculations were performed in MATLAB [20] not only to prove the reduction of FSPL by using relay node, but also to find relay node location that gives maximum reduction. This was done on a room of 10 m x 10 m, the source is fixed at the top of the room with height of 3 m, the receivers are assumed to be at 1 m height and deployed all over the room with total number of 81 receivers, and the relay node fixed at the midpoint of the room with two different heights once at 1 m and once at 3 m, as shown in Fig. 2. Then a comparison between the direct link, which connects the source to a destination, with the corresponding link, that connects the source to the same destination but with relay node in between, have been calculated by (2). This procedure has been repeated at all destinations for two different heights and for different places of the relay nodes. Turned out there is no noticeable different in FSPL reduction between 1 m and 3 m height for relay node. So, the FSPL enhancement for both cases considered same. Midpoint position for relay node has achieved the best average of FSPL reduction with respect to the direct link case, as shown in Fig. 3.

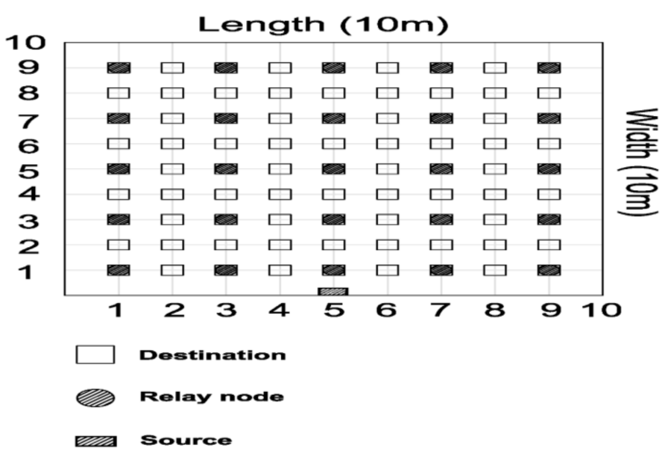

Fig. 2. Schematic of the procedure done via MATLAB

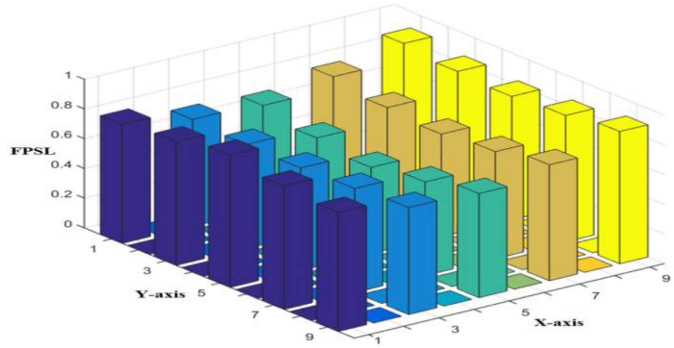

Fig. 3. Average percentage of FSPL reduction with Relay at 1m height

IV. RELAY NODES SELECTION AND INTERFERENCE MITIGATION

Coverage area is a big issue in 60 GHz wireless system, while the high frequency can cause high losses the distance can also cause very high losses since the FSPL increases with the square of the distance. Relay nodes can be used to solve this issue by the concept of multi-hop communication, where the relay that fits every hop's optimal distance need to be selected in order to increase the range of the system [21].

Relay nodes selection in this study is to select the relay node or group of relay nodes that will result in the smallest distance between any two communicating devices in the path between the source and the destination: source to relay node, relay node to another relay node, and relay node to destination. So, the path consists of source, destination, and relay nodes in between. All devices in the system are assumed to be capable of measuring the signal strength coming from other devices on their antenna elements. In order to make the comparison between distances that separate each two devices, device location should be known. In this paper, relay nodes are considered to be the reference devices where all communication going through them and they are assumed to be able to contact each other. Device location estimation in the system, while reference devices have information about their coordinates, can be done using the received signal strength which allows any two communicating devices to estimate the distance between them [22]. Each relay node will have a database that contains the signal strength, which can be translated to distance for all devices in its range [10], and distances between relay nodes are known because their coordinates are known. Since all relay nodes can contact each other, a replication of their databases can be available at each one of them. The Raspberry Pi, a full functioning computer, will be connected to the source. It will keep updating the databases received from the relay nodes and control the source. After the distances are available the next step is the comparison between them. This will be done by Raspberry Pi which will select the relay nodes that the message need to go through to get the best route from source to destination. To get the best route, the longest distance between two communicating devices in each path need to be compared together. So, the longest distance in path one will be compared with the longest distance in path two and path three and so on, then the path that have the smallest value of longest distance will be selected. Since the relay nodes are assumed to be fixed, it is easy to find the followings: best paths between source and each relay node (p_i), where i is the relay node number, the longest distance between two communicating devices in each $p_i(dmax_i)$, and the number of hops (n) to reach from source to each relay node. Raspberry Pi supports many programming languages; the following code is written to work in C++ environment:

Algorithm 1 Relay Selection Algorithm

```
Input: each relay database, p_i, dmax_i
Output: best route from source to destination
1: mindmax = dmax_1;
2: bestp = p_1;
3: for (int i = 1; i < L; i++) // L= # of relays
      {
4:       if (dij > 0) // dij is the distance between relay i and
         destination j
            {
5:            if (dmax_i < dij)
                 {
6:                 dmax_i = dij;
                 }
7:          }
8:       if (dmax_i < dmax_1)
            {
9:            mindmax = dmax_i;
10:        bestp = p_i; // bestp is the best route from source to
           destination
            }
11:   } // end for
```

If there are a neighboring networks to the network in study and they are operating in the same channel, the Signal to Interference plus Noise Ratio (SINR) values are degraded. Since the data rate is proportional to the value of SINR this reduction may prevent the supporting of the required data rates [7]. The effective interference levels for 60 GHz band are relatively low. So, it could be neglected in some cases. But in some other cases where dense 60 GHz wireless network existed, the interference levels are considerable and need to be mitigated. Although an antenna array with many antenna elements is mainly used to maximize the very low level of power received at receivers in 60 GHz band by beamforming, it can also be used to mitigate interference [23]. One of the famous interference mitigation mechanisms is based on coordinator setup, which consists of coordinator and several devices within its transmission range [24]. A coordinator setup is defined as a wireless data communication system which allows a number of independent devices to communicate with each other, one device is required to be the coordinator of the system. The devices measure their signal and interference power levels over multiple fixed periods of time and report back to the coordinator, the coordinator then determine the schedule of transmission that will avoid transmission in the presence of interference. The coordination could be for single network or for multi networks together [25]. The following technique is more related to this study, since it is considered a relay application. The basic idea is that by reducing the transmitted power, by sending data over a portion of the transmitting power, this will reduce the chance for interference to happen. Since relay can reduce the distance between source and destination, and so the required power to transmit data will be reduced. Mitigation can be done by getting the value of SNR for the direct link between source and destination, and SNR for link with relay, the link with the higher SNR need to be selected. The transmitting power of the relay is assumed to be changeable [26]. Same Raspberry Pi used in this section could be used here to compare the values of SNR and then select the best link. If the best link was the one with relay, Raspberry Pi will make the relay to transmit at lower power. At the same time Raspberry Pi will keep SNR value acceptable to get the promised data rate.

V. Simulation Results

'Wireless InSite' is a simulation tool [27], which will be used to analyze the impact of relay nodes on 60 GHz wireless system performance in the indoor environment.

A. Setup

1) FSPL Simulation: A conference room scenario will be modeled to study the effects of relay node and to verify that the best position for relay node is at the midpoint. Dimensions of the room is 10 m x10 m, source is mounted at the top with height of 3 m, destinations are spread all over the room at 1 m of height with 1 m separating space between them with total of 81 receivers. Relay nodes are positioned at five different places with 1 m of height, as shown in Figs. 4 to 6. Used antennas have an omnidirectional radiation pattern with gain of 8.5 dBi [28]. Since the maximum transmitted power is limited to 10 dBm by taking the Radio Frequency (RF) safety issues into account [6], the input power to the source is limited to 5 dBm in this paper, since 5 dBm makes the received power level at destinations in the range of -55 dBm, which necessary to satisfy the required gigabits per second data rate [29]. Channel 2 as defined by Institute of Electrical and Electronics Engineers (IEEE) 802.11 ad with carrier frequency of 60.48 GHz and 2.16 GHz of bandwidth is chosen because it is completely covered in all countries [30]. The electric parameters of the materials used to build the room are presented in Table II [27].

TABLE III. ELECTRICAL PARAMETERS OF THE MATERIALS

The User Interface	Material	Relative Electrical Permittivity	Conductivity, (S/m)	Thickness, (m)
Ceiling &Floor	Concrete	7	0.015	0.3
Walls	Brick	4.44	0.001	0.125
Doors	Wood	5	0	0.03
Windows	Glass	2.4	0	0.003

2) Penetration Loss Simulation: In this subsection the effects of the midpoint relay node, best position for FSPL, on penetration loss will be presented for two different relay heights. Same as the previous conference room scenario, but with only five destinations and two relays at midpoint with height of 1 m and 3 m with taking the obstacles into consideration, as shown in Figs. 7 and 8. The obstacles are the human bodies in the area, human bodies are modeled into 'Wireless InSite' based on the human model presented in Section 3.

3) Short Range Simulation: The dimensions of the conference room after extending is 10 m x 20 m. The source mounted at the top of the room with height 3 m. Three receivers are fixed at the far end of the room at 1 m height. Relay nodes are positioned at 4 different places. One at the midpoint of original room, since it has been proved to be the best position, the other 3 relay nodes are fixed in the new extension of the room, each one of them far from the midpoint relay node by same distance. All relay nodes at height 3 m, as shown in Figs. 9 to 11.

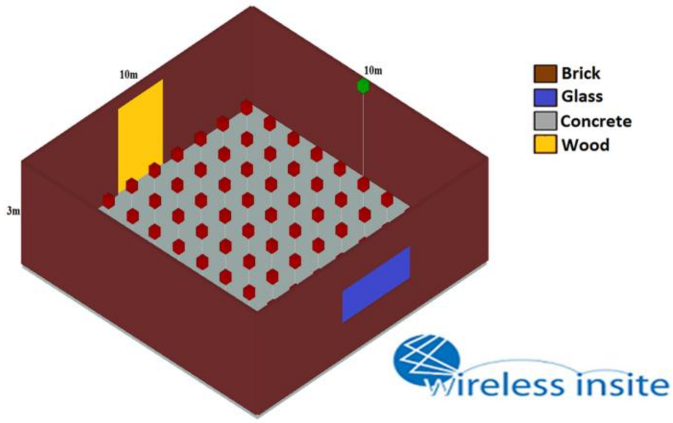

Fig. 4. 3D view of the room which green box is source and red is destination

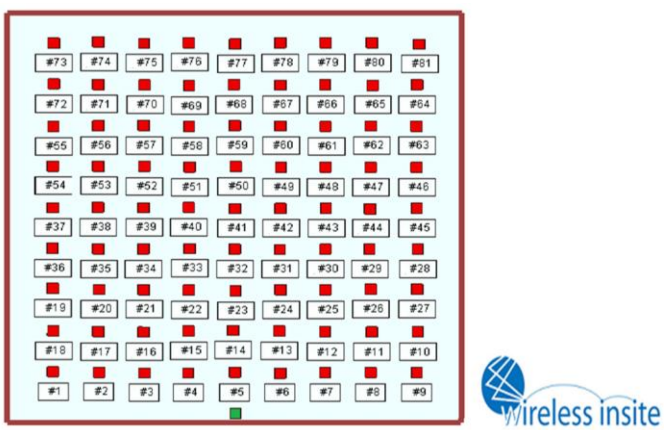

Fig. 5. 2D top view of the room which shows all destinations with the source

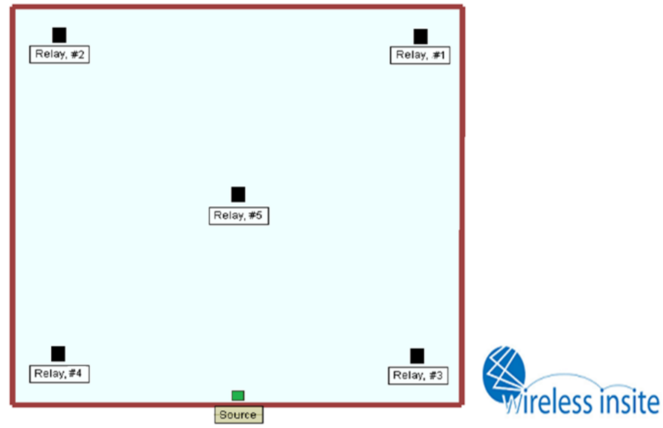

Fig. 6. 2D top view of the room which shows all relays with the source

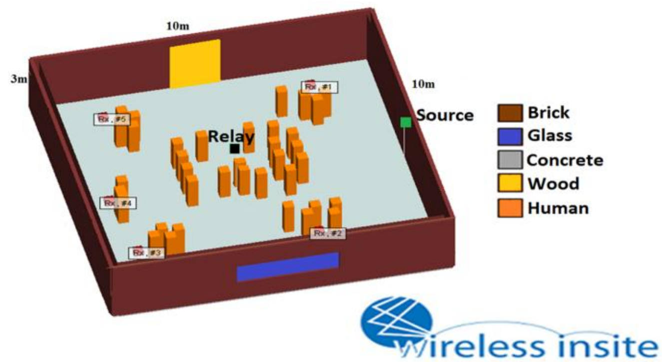

Fig. 7. 3D view of the room which green box is source, red is destination, and black is relay

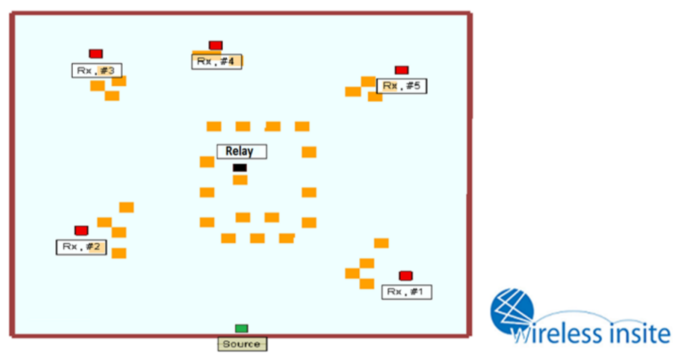

Fig. 8. 2D top view of the room which shows all destinations, humans, and source

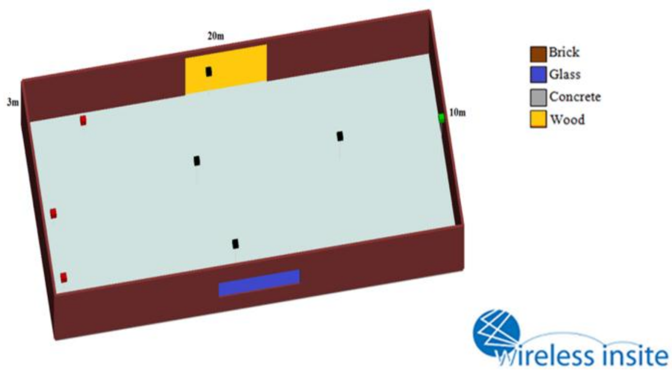

Fig. 9. 3D view of the room which green box is source, red is destination, and black is relay

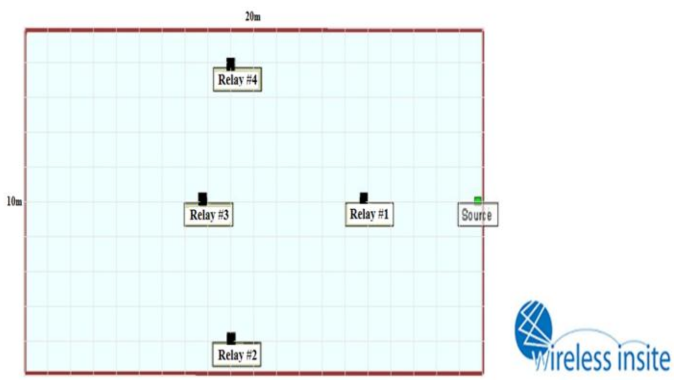

Fig. 10. 2D top view of the room which shows all relays with the source.

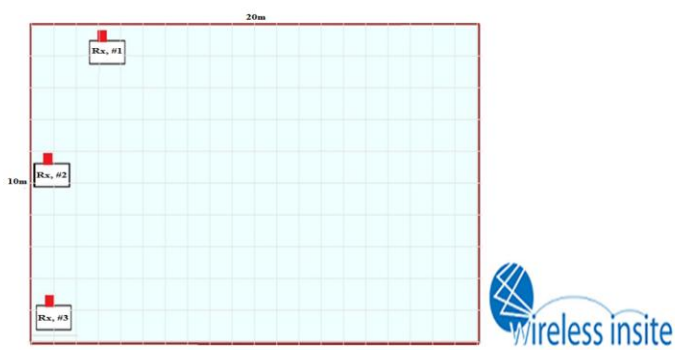

Fig. 11. 2D top view of the room which shows all destinations with the source

B. Results

For the first scenario the values of FSPL are keep going down while the relay node is getting closer to the midpoint of the room. Relay 1 and Relay 2 have same distance from the source, so they have same FSPL. Same thing with Relay 3 and Relay 4. The best FSPL values happened when the relay node was at midpoint which was the case for Relay 5, as shown in Figs. 12 and 13. For the second scenario, relay node at 3 m height can provide another path in the cases where the direct path is blocked. But for relay node at 1 m height the path can be blocked from the source by human bodies. This makes 3 m the best position to mitigate penetration loss, as shown in Fig. 14. So, the best location for the relay node in order to minimize the two types of losses is at the midpoint at the top of the room.

For the third scenario there are three hops: (1) From the source to Relay 1. (2) From Relay 1 to Relays 2, 3, and 4. (3) From Relays 2, 3, and 4 to the receivers. Since in first-hop FSPL is fixed and second-hop FSPL is fixed from Relay 1 to the other 3 relays. So, first and second hops have no effects in relay node selection procedure. This make the third-hop is the only hop that effects in relay node selection. So, the relay node in the third-hop which has the smallest FSPL to the destination will be selected, then the path will be like this: Source→Relay 1→ Selected relay from third-hop→Destination. The comparison shown in Figs. 15 and 16, Relay 4 will be selected if the destination is the Rx#1. This will make the path as the following: Source→Relay 1→Relay 4→Rx#1. Same procedure will be followed with Rx#2 and Rx#3, this will result in the selection of Relay 3 and Relay 2 respectively.

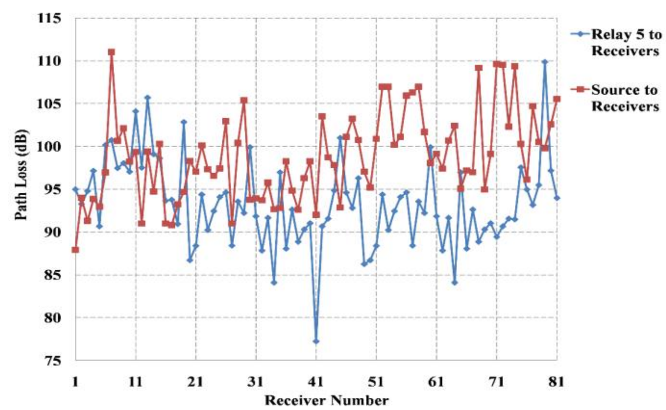

Fig. 12. FSPL comparison between the direct case and the Relay 5 case

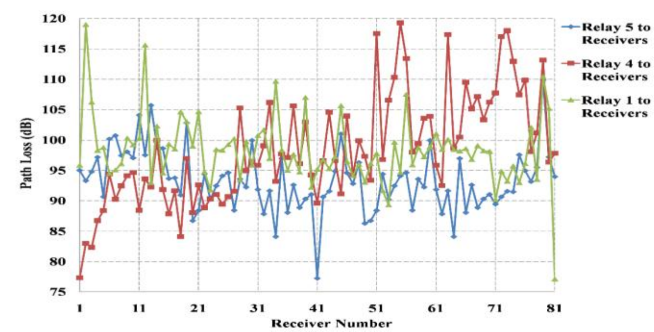

Fig. 13. FSPL comparison between from Relay 1, 4, and 5 to receivers

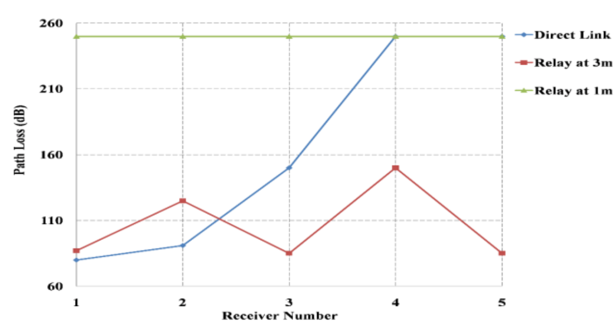

Fig. 14. Path loss, penetration loss and FSPL, at each receiver with and without relay

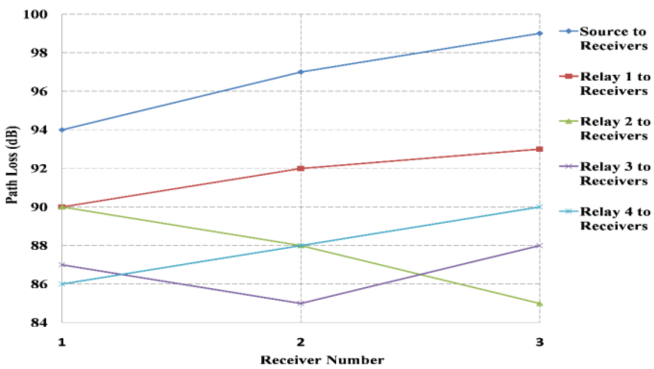

Fig. 15. FSPL for all paths from source and relays to receivers

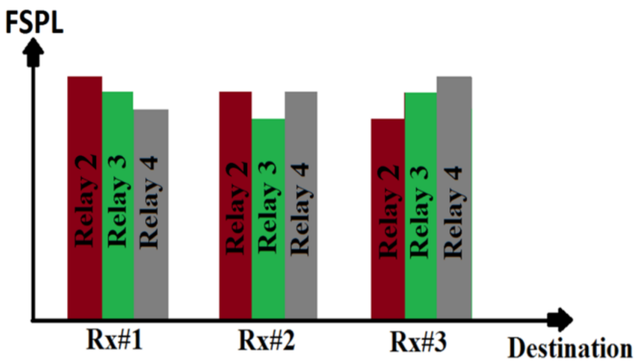

Fig. 16. FSPL comparison for third-hop paths

VI. CONCLUSIONS

In order to improve the performance in 60 GHz wireless networks, the relay nodes have been considered. Because of huge value of propagation loss, distance, and obstacles are the main metric for relay positioning. The results show that the best relay position for mitigating FSPL is the midpoint, the maximum reduction in FSPL is -12 dB. The best position for mitigating penetration loss is at the top of the room. So, in order to maximize the performance of the network and satisfy the promised high data rate the relay need to be positioned at the midpoint on the ceiling of the room. Another issue is the very short range of 60 GHz network, relay selection technique had been used to increase the coverage area. So, the room dimensions could be doubled and still get the same performance. Many interference mitigation mechanisms can be applied on this system to deal with interference at this communication band.

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