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40 GHz Indoor Networks Using Relay and Directional Antennas

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Abstract: With the growing of wireless communication, all available frequencies are reserved that leads to search for a new band of frequencies. Because it is very attractive for future communication, 40 GHz is selected. The reasons of selecting 40 GHz are very large bandwidth, free license and available of high data rate communication globally. Because of severe attenuation, the communication performance is significantly low. To enhance this point, relay with directional antennas are used. By using this combination, the utilized gain increases. Despite their advantages, there are many challenges with this method. From simulation, it can be found that adding relay to the network will enhance the loss path by 30%. Using directional antenna making the neighbor discovery more complicated. Elite Scanning Strategy (ESS) is proposed for pure directional communication. The proposed algorithm compared to Random Scanning Strategy (RSS) to approve its robustness in terms of neighbor's discovery. The results show that ESS is performing better than RSS by 20% for the same network.

Key words: 40 GHz indoor network, relay, directional antenna, high frequency networks, Elite Scanning Strategy (ESS), Random Scanning Strategy (RSS)

INTRODUCTION

One of the local area networks is the home network which provides a communication between the electric devices in the home such as personal computers, HD TV, mobile phones and so, on. Sharing is the idea of home network. These devices are sharing the services of internet link, video streaming and voice communication. To connect all these devices with a network, sever is required for managing the services sharing within the home network. The available Wireless Local Area Network (WLAN) offering a 100 Mbps as a maximum bandwidth. This bandwidth is not enough for future technologies such as 5 and 8k displays which requires higher bandwidth. The used frequencies in the available devices are 2.4 and 5 GHz which are not enough for handling high bandwidth for future needs.

This leads to search on higher frequencies that can handle the requirements of future technology. A 40 GHz is proposed as a future solution due to its high frequency inherent security features and penetration incapability. About 40 GHz band is very interesting because of its wide range bandwidth from 39-45 GHz that is available for free. The characteristics of this band are high security advantages, co-channel interference and better spatial reuse (Katayama *et al*., 2007). For few coming years, 40 GHz will be the standard of wireless frequency band (Singh *et al*., 2007). The higher frequency means higher attenuation which means that this frequency is very suitable for a short-range communication only such as inside a room. Previously, the equipment of 40 GHz was very expensive compare to the WLAN but with silicon based development, the price of equipment is reduced and become a very close to the WLAN equipment prices. By using 40 GHz it is easy to get a bandwidth with a couple of gigabits rate for wireless communication because the large data transfer needs a high-speed data transfer which is available only with high frequencies (Mudumbai *et al*., 2009). About 40 GHz is even better than using direct cables because of the scalability, security, compact size and high data rate (Bourdoux *et al*., 2006). Because of the propagation and penetration losses, the major challenge of using 40 GHz is the connectivity maintenance. The quality and robustness of 40 GHz can be improved by using directional antenna and relaying nodes. Using directional antenna and relaying nodes will increase the efficiency, energy, SNR and the power. Using directional antenna offers some benefits that can be very useful in the network such as simultaneous communication interference reduction, better spatial reuse and longer transmission range (Korakis *et al*., 2008). Directional antennas are used in cellular networks but for indoor networks it is not tested yet. Many researches are done on using directional antenna with relay nodes for wireless networks, the only problem with directional antennas is that CSMA/CA scheme which is applied by regular MAC are not suitable with it (Lan *et al*., 2008). Some researchers are done on using directional antenna for topology management but these researches were dealing with low frequencies (Gelal *et al*., 2006).

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Using relay nodes giving a good advantage in terms of nonlinear relationship between the distance and path loss. Despite of extra processing capability and imposed delay, the throughput of the network will decrease by using relay nodes. Using one relay only can provide sufficient connectivity improvement. As mentioned before, the high frequency suffering from severe attenuation compare to low frequency (Friis, 1946). The possibility of focus the signal energy to a certain distance is provided by directional antennas. Due to attenuation, 40 GHz directional antennas deployment is crucial. To gain the full utilization of using directional antenna in indoor communication, both side should contain 40 GHz directional antennas. The network can research with one side 40 GHz directional antenna but it will be losses in accuracy because of asymmetry in range. The challenge of directional transmission and reception is discovery of neighbours and initial signalling. To reduce the communication latency, we propose new scanning strategy to find neighbours. The main problem of this research is to design a scanning strategy and quantify the lower bound relay to gain the full utilization of 40 GHz directional antennas.

The attenuation is the major challenge that is facing the 40 GHz indoor networks (Genc *et al*., 2010). The propagation loss increases with the square of carrier frequency. that means the 40 GHz greater than currently used 5 GHz by 18 dB in free space. The received power and the penetration loss at 40 GHz are very high (Bourdoux *et al*., 2006). Because of the second order reflection components and the ineffective, 40 GHz frequency is very accurate to the Line of Sight Link (LoS) (Singh *et al*., 2009). LoS doesn't use in indoor networks because it may be blocked by any object even human body (Akeyama *et al*., 2004). It is hard to implement a 40 GHz network for simple systems because of the complexity with reflection approach. One of the possible solutions for 40 GHz connectivity is the relay signal by intermediate device of the receiver. Relay is a multi-hop communication in the context of the ad hoc networks (Bendjaballah *et al*., 2006).

There are two schemes of relaying system; the first type is Amplifying and Forward (AAF) and the second type is the Decoding and Forward (DAF). In AAF the relay is working by amplifying the signal and retransmit it (Ettefagh *et al*., 2006). It has simple hardware design. Despite of being a simplest solution AAF is not efficient with the critical link budget because of the noise amplifying as well. The DAF working by decoding the signal first and regenerate a new signal then transmit it. DAF has much complex hardware design over the AAF. Despite its complexity it is used with large propagation losses to improve the link quality. There are only few studies on using relay with 40 GHz networks. A group of researchers proposed a multi-hop MAC architecture for Wireless Personal Area Network (WPAN) of 40 GHz to overcome the link blockages using relay with directional LoS links (Singh *et al*., 2007). The link budget is reduced by 20-30 dB if it is blocked by human body (Singh *et al*., 2009).

Directional antenna: Directional antennas provide the possibility to focus the energy of the signal to a certain direction. Compare to 2.4 GHz WLAN, 40 GHz is giving 28 dB of extra free space of path loss. To utilize the full benefits of 40 GHz network both the transmitter and receiver that are connected should contains directional antennas and these antennas should have steering capability as well. If the directional antenna is used in one side of the communication link the range will be asymmetry and this will lead to not covering all the neighbours. By using a high directional antenna in both sides will provide a high path loss and it will provide around 15-18 dB of gain in 40 GHz communication system (Maltsev *et al*., 2009).

The directional antenna is a collection of multiple components mounted in an array. These component are compact size with high frequencies which enable the design of highly directive antennas. There are additional challenges of using directional antennas such as hidden terminal problem and deafness in communication of nodes.

Direct discovery group and gossip based are the two groups that are used for neighbour discovery algorithms. In direct discovery, the two nodes can discover each other easily because the transmission between them is direct. Where in gossip based each node has the location information, direction and identity of the direct and indirect neighbours. There is a suggestion of using gossip based as a guide and handshaking with other nodes before adding them to the network (Pei *et al*., 2005). There is another suggestion which is adding the gossip based node to the neighbour list directly (Vasudevan *et al*., 2005). Despite the second suggestion is faster than first one but it is not a reliable because of the gossip node may not be available directly in it.

To confirm discovery Transmitter (Tx) and Receiver (Rx) are required to handshaking directly. By using fully directional neighbour scanning both Tx and Rx can communicate directly. Both beam steering or switch bean antenna can be used as a directional antenna. In both cases, they are expected to sweep 360 in an indoor environment. The antenna beams of the two nodes should cover each other at the same time to perform neighbour discovery with directional transmission and reception. The problem is modelled in two dimensions assuming all beams are wide enough in elevation to cover neighbours.

A scanning strategy for the node operation with directional antennas should be designed to assure sufficient link discovery. In most previous research, both transmitter and receiver beam direction were selected randomly. The probabilistic should be determined whether it's in transmission or reception which is called Random Scan Strategy (RSS) (Ning *et al.*, 2009). Both transmission and reception should be optimized for faster neighbour discovery in RSS. The problem is this scanning strategy may not find all the neighbours. To solve this issue, the randomness is required where the node can find its neighbours in whatever position it is. The scanning strategy should allow discovery of any possible link within coverage area of nodes. For that reason, a new strategy is proposed to reduce the discovery duration between the transmitter and receiver antennas. This strategy is called the Elite Scanning Strategy (ESS).

The idea of ESS is that when scanning in each search cycle τ which is the duration unit of the neighbor discovery any sector can be chosen by the node. τ is a short time interval which allows sending an advertisement, getting the response if advertisements received and sending back the acknowledgement. Each node is the network has four sectors (K = 4) with beam width of 90°. Each cycle search is taking 100 μsec duration to finish. The advertisement and respond packets includes extra information such discovery table and location information to enhance the discovery process. The sectors selection by the node in search is done with probability that is assigned to each sector in the node. The Tx and Rx are determined using RSS based on pre-assigned probabilities. The discovery is successes when both transmitter and receiver sectors are aligned. Successful link discovery takes place in units of time. The transmission power is increasing step by step during the neighbour discovery to achieve LPD. In RSS, the selection of each sector probability is equal for each search cycle. Elite Scanning Scan (ESS) is proposed to enhance the RSS where the probability of selecting specific sector is proportional to the covered area instead of assigning equal probabilities to all sectors. Scanning sector that is covering large area is increases the chance of discovery, this happens if the nodes are randomly deployed.

MATERIALS AND METHODS

In this research, a circular area is considered. The idea behind selecting a circular area is to make sure that all nodes are on same distance from the centre. There are two scenarios that considered in 40 GHz network with relays which are two random nodes the are connected to each other directly where the link quality is depending on line of link sight and the expected path loss calculation. The second scenario is connecting two random nodes via. relay device locates in the centre of the circle and the link quality will be determined as pervious scenario. Table 1 shows the proposed model's parameters.

Table 1: Proposed model's parameters

Parameters	Explanation
C	Relay location in the centre of study area
R_0	The Radius of the circle
R	Distance between two nodes without relay
N_1, N_2	Connected nodes
R_1, R_2	Distance between relay and Nodes
Rm	The greater distance
λ	Wavelength
x	Random variable

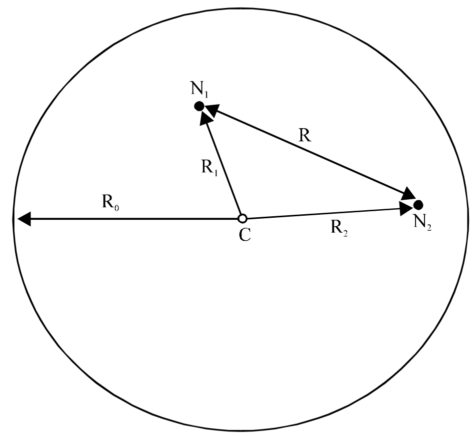

Fig. 1: Proposed network

We assumed that the network area is circular with centre C and radius R_0. Inside this area there are two nodes N_1 and N_2 which are placed randomly in the network area. Figure 1 shows the proposed network.

As mentioned before, there are two proposed scenarios which are without and with relays. For the first scenario, the communication link between the two nodes is directly with R distance. The PDF of R is calculated by Eq. 1:

$$f\,R(r) = \left\{1-\frac{2}{\pi}\sin^{-1}\left(\frac{r}{2R_0}\right)-\frac{r}{\pi R_0}\sqrt{\left(1-\frac{r^2}{4R_0}\right)}\right\} \quad (1)$$

where, $0 \le r \le 2R_0$. The integration over interval will obtained the CDF of the random variable R. Figure 2 shows the assumed scenario's PDF and CDF with 5m radius of the network are.

Frii's formula is used to determine the path loss where, it is the only formula that can determine the certain distance:

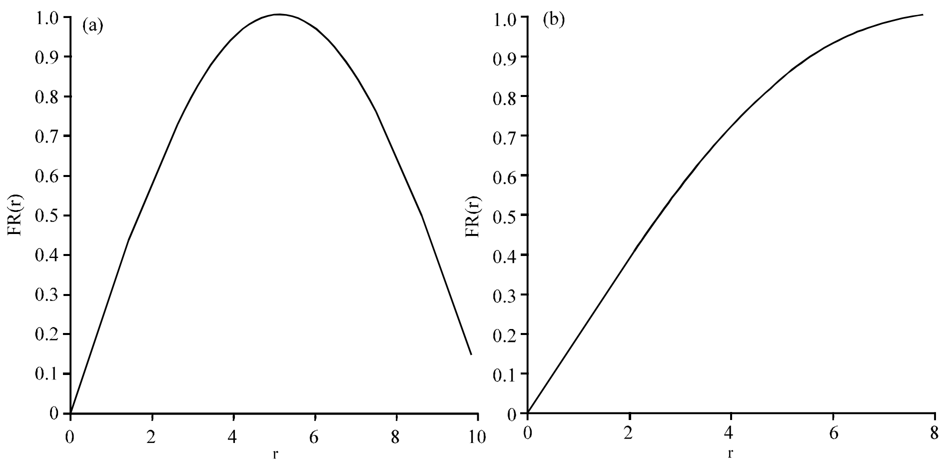

Fig. 2: PDF and CDF for R = 5 m

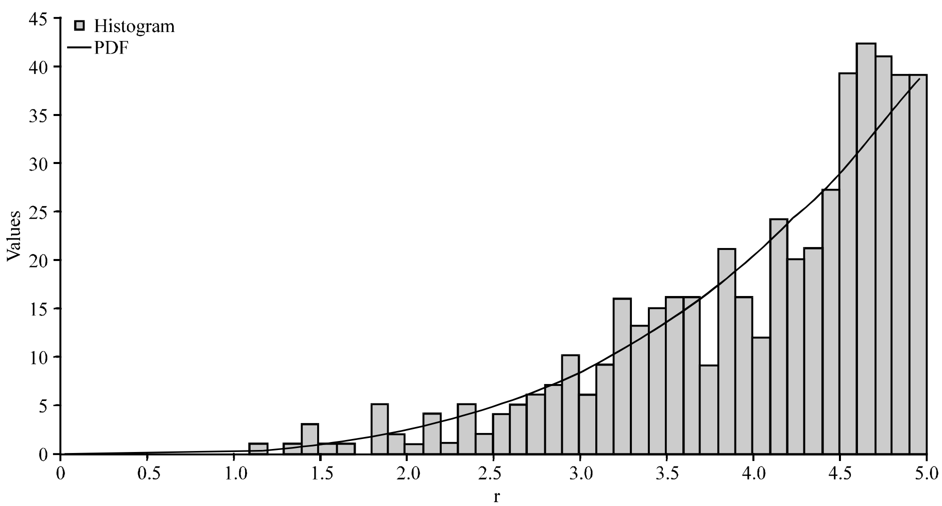

Fig. 3: PDF histogram of analytical model

$$g(r) = \left(\frac{4\pi r}{\lambda}\right)^2 \quad (2)$$

where λ is the wavelength for the signal. Depending on the expectation of g(r) function of R, the expected path loss is calculated. The path loss is calculated by Eq. 3:

$$E[g(r)] = \int_0^r f R(x) g(x) dx \quad (3)$$

By taking the same area that is selected in first scenario and use it with second scenario which is contains relays in the communication, the two nodes can communicate with R_0 distance. The distance from relay which we assumed that it is in centre of the circle to the N_1 is R_1 and the distance between the relay and N_2 is R_2. MATLAB is used to implement and simulate the model.

The 500 randomly nodes are tested within a circular area with 5 m of radius. The distance between each node and the centre which contains the relay is measured and stored. The implementation will give the PDF, variance and mean that are calculated using the numerical analysis. Figure 3 shows the histogram of PDF of analytical model. From Fig. 3, it can be noticed that the depending histogram and proposed model are very close to each other. It is also shows that the distribution reputation of the 500 nodes in the tested area.

RESULTS AND DISCUSSION

The results of this research will be classified into two sections, the first one is for calculating the loss path of the link and the second section is the scanning for the nodes.

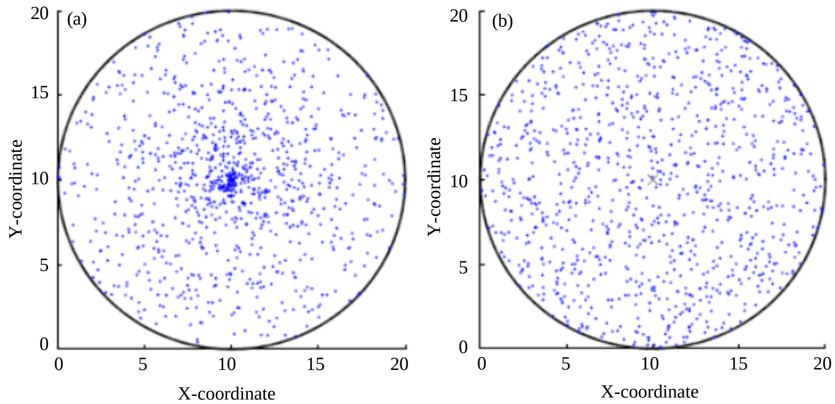

Fig. 4: Nodes distribution

Calculating loss path: The signal quality decreases with increasing of loss bath. Adding relays to the network reduces the loss path by 33% of the same network but without using relays. This reduction will give a gain to the network by 1.8 dB. Due to the relay, the gain will be larger if the direct link is blocked and the alternate path was via relay. By adding the relays, the network communication quality will be higher. The relaying gives the node ability to select between available links to choose the better path for communication. The two important things that should be taken in consideration with loss path are the reduction of loss path and the gain with relay.

As mentioned before, a circular area is selected with centre C and radius R_0 for both scenarios. The nodes selected randomly within this area. Figure 4 shows the random distribution of the nodes within the selected area where the right side represents the non-uniform distance distribution of the nodes and the left side represent the nodes with uniform distance distribution which is equal to the square of distance from the centre C of the circular area.

By running the algorithm for 500 nodes that are selected randomly within the proposed circular area, we found the mean is equal to 3.9987 and the variance is 0.6255 which is very close to the analytical results. The right side of Fig. 4 shows the 500 pair of nodes that are selected with relay device. Monte Carlo with specific parameters is simulated in MATLAB to verify the model. In each trail, a pair of randomly nodes located with a uniform distribution are selected for both scenarios. The test is done for 10 times, each time the value of path loss and average value is stored to calculate the mean value and variance. The final results of average path loss are founded by comparing the average path loss with and without relay device. Table 2 shows the results of ten trails average path loss for both scenarios.

Table 2: Path loss for proposed scenarios

Without relay		With relay	
Average	Variance	Average	Variance
3.3607	1.1297	4.1051	0.5208
3.3793	1.0365		
3.3261	1.2937	1.5424	0.6525
3.2356	3.7975		
3.2392	1.3967	4.0580	0.4662
3.2131	1.3413		
3.1721	1.3646	3.9658	0.6717
3.1353	1.2422		
3.3063	1.1836	3.9768	0.5117
3.2413	1.3344		
3.3583	1.5284	4.0572	0.7590
3.1385	1.4573		
3.3309	1.4048	3.8978	0.7750
3.3653	1.4362		
3.2385	1.1388	3.8909	0.6317
3.4342	1.2104		
3.4336	1.7839	4.1073	0.6573
3.5357	1.3543		
3.4037	1.5370	4.0308	0.6088
3.3320	1.5465		

There are two results in each trail for the scenario without relay which is shown in Table 2 where the first one is for N_1 with R_1 distance and the second is for N_2 with R_2 distance. For the scenario with relay there is only one result for each trail because the distance between the nodes and the centre is fixed. By applying a statistical analysis on these result, it can obtain that adding relay to the network will enhance the loss path by 33%.

Neighbor scanning strategies: Two scanning strategies are compared which are the Random Scanning Strategy (RSS) which is selected as a benchmark for comparison and the Elite Ccanning Strategy (ESS) using MATLAB simulation. Figure 5 shows the performance of the two selected scanning strategies using same specifications in both cases which are the number of nodes N = 5 with four sectors in each node K = 4 where each one with 90° angle within an area of L = 5 and W = 4.

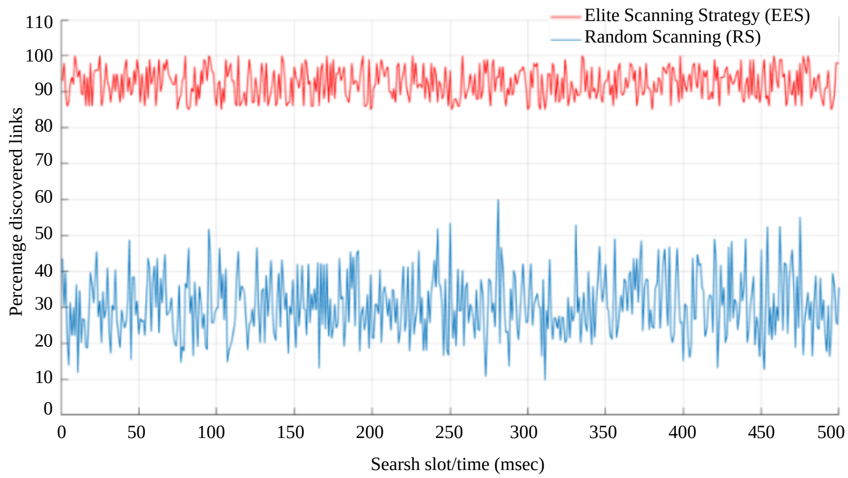

Fig. 5: Performance comparison

With practical 40 GHz directional antenna, the number of selected nodes makes the network busy. The 100 iterations were the number of tests for each method in a rectangular room with 1.2 aspect ratio. In practice, the beam width is available for 40° with 40 GHz high directional antenna. Figure 5 shows that the ESS performs better than RSS in terms of link discovery. The link discovery in ESS is between 80-100% where the normal RSS is between 20-60%. That means in worst cases ESS is faster than RSS by 20% in same conditions.

Link discovery: The path between any two nodes in the network is known as link connectivity such as the connection between router and PC. Even if all the possible links are not discovered, the network connectivity can be achieved. If we assumed that there are groups of isolated nodes in the network that are not connected to each other, the nodes within each isolated group are connected between them but there is no link connection between the groups. Initially, each node is acting as an isolated group in the network. The isolated groups start merging with each other when the links are started to be discovered. The parameters of isolated groups are listed in Table 3.

The ratio of the discovered links r is calculated by dividing the discovered links x over the number of possible links n. during the discovering if there aren't links to discover, the network will behave as an isolated group. If links are discovered the isolated groups will merge with each other within the network. Depending on network's behaviour, the number of groups may be increases or decreases. If there is any newly discovered link it can be either contribute as a connection in the network by merging the isolated groups orto contribute as a connection within the groups itself. The worst

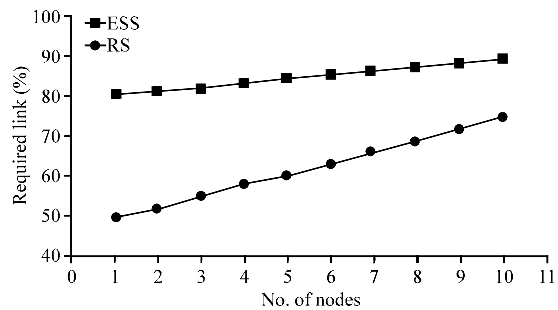

Fig. 6: Required link percentage

Table 3: Parameters of isolated group

Parameters	Explanation
N	Number of nodes
β	Number of isolated group
i	Index of isolated group
Mi	Number of nodes in isolated group
n	Number of possible links
x	Number of discovered links
r	Ratio of discovered link

scenario that it may facing the network is that the additional link is not connecting to any group until it became full. If all isolated groups are fully connected, additional links will generate to connect two isolated groups. The network is formed when the last two isolated groups are merged together. To make sure that the nodes within the network is connected, Required Link Percentage (RLP) is used to measure the link connectivity. Figure 6 shows the LRP for different number of nodes for both RSS and ESS methods.

Figure 6 shows that ESS is behaving better than RSS in 40 GHz indoor networks where the RLP is between 80-90% for ESS and between 50-70% for normal RSS. The

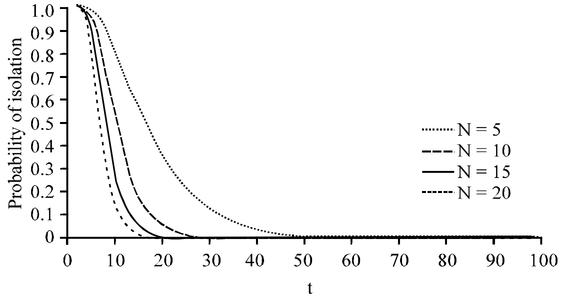

Fig. 7: Probability of isolation

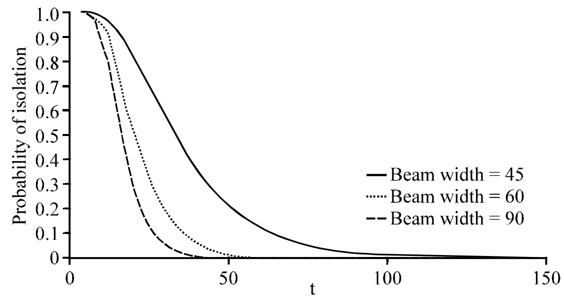

Fig. 8: Probability of isolation for different beam width

80% which the lowest percentage is a good value for link discovery which assures that the connectivity in the networks occurs in almost all cases.

Network isolation: To calculate P_{iso} the beam width and number of nodes are using for focusing on trending isolation behaviour. Figure 7 shows decreasing in the probability of isolation with $\alpha = 90°$, K = 4 for different number of nodes N.

Figure 7 shows during process time the network isolation with N nodes is decreasing. On the other hand, using smaller beam width antennas will increase the isolation state and the neighbour discovery time for each node. Figure 8 shows the effect of beam width on the isolation for the same number of nodes which is this process set to N = 5.

Figure 8 shows that the larger beam width gives better scanning for neighbour nodes. P_{iso} is calculated according to the number of nodes of the model forms and it shows that ESS is isolates faster than RSS. To validate the model, both RSS and ESS method's performance are tested by comparing them to the analytical results. The simulation is repeated for 500 times and it is managed to discover at least one neighbour within exact time. Figure 9 shows P_{iso} comparison for RSS and ESS with the analytical results for N = 5 nodes, K = 4, aspect ratio = 1.2 and $\alpha = 90°$.

Figure 9 shows that the RSS method is closer to the analytical results than ESS which is normal where the ESS

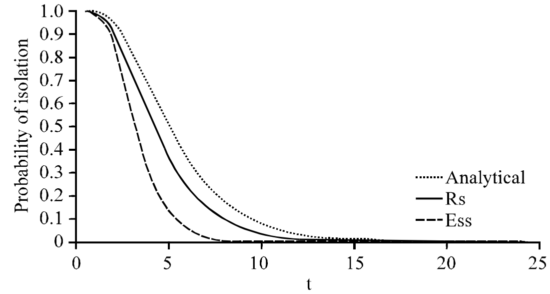

Fig. 9: P_{iso} verification for RSS and ESS methods

is faster in terms of isolation. The simulation is repeated many times with different numbers of nodes and aspect ratio which shows that there no effect on the results as long as the range between the nodes is enough to cover each one of them. In summary, the 40 GHz frequency has an advantage over the directivity regarding to its millimetre wavelength range. It is easy to realize the directional antennas with high frequencies such as 40 GHz and it can be used for compensating the loss path that occurs.

CONCLUSION

The benefits of 40 GHz with directional communication appears with the new challenges of high frequency communication. The major challenges of high frequency indoor networks especially 40 GHz are the penetration losses and high propagation. To reduce these challenges, relay is one of the solution that can be added to the network. A single relay is used in this research which is set in the middle of the network area for connecting the nodes to each other. By adding relay, the loss path is reduced to around 30%. To reduce the discovery time of the links within the network an Elite Scanning Strategy (ESS) is proposed and compared to traditional Random Scan Strategy (RSS) that it's used as a benchmark to approve the accuracy of the proposed method. By comparing the two methods, the results show that the ESS is discovering the link for 80% in worst cases which is faster by 20% than RSS.

The simulation shows that there is a relationship between the area of the network and number of nodes within this area. Network isolation is discussed as well for the ESS. The isolation was tasted using different scenarios then it verified by changing the number of nodes inside the network, the shape of selected area and the beam width. Overall ESS performs better than RSS in all cases.

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