

FUTURE HOME NETWORKS

CONNECTIVITY IN 60 GHz HOME NETWORKS

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Master of Science Thesis

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Abstract

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Currently, common frequency spectrum is densely allocated and this leads to search for alternative frequency bands. 60 GHz band attracts attention for its potential in future communication. It offers globally available, license-free, very large bandwidth for high data rate communication.

At 60 GHz frequency band, severe attenuation of the signals can significantly degrade communication performance. To cope with the attenuation problem, relays or directional antennas with high directive gains can be utilized. Both methods have additional challenges among their benefits. It is analytically and through simulations shown that having a relay node in the middle of a 60 GHz network decreases the average free-space path loss 33% in the worst case scenario. To the best of our knowledge this is the first study to address effect of relay on path loss analytically in a generic form. When network nodes use directional antennas, the neighbor discovery process becomes more complicated and time consuming. There are not many studies assuming pure directional transmission and reception at all steps of communication. Random selection among sectors is generally used for pure directional communication. To reduce the neighbor discovery time, we propose a smart neighbor scanning algorithm in this work. It is observed that the proposed strategy discovers 70% of the links 81% faster and 90% of the links 15% faster than random scanning strategy for a typical home network scenario. A condition to have a path between any two nodes and a stochastic model to observe isolation trend in home networks are also presented. The results of this thesis motivate the multi-hop communication, use of directional antennas for 60 GHz indoor networks.

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“Science is the most genuine guide in life.”

— *M. K. Atatürk, 1881 - 1938*

Chapter 1

Introduction

Home Network (HN) is a residential local area network providing communication between heterogeneous electronic devices deployed in the home. Usually a small number of personal computers and devices are deployed in the network such as printer, mobile computing device, game console and HD TV. An important function of home networks is sharing services provided by the devices in the network like internet connection, voice communication, video streaming. Additionally, home server and home communication controller may be employed in home network to increase functionality.

Wireless Local Area Network (WLAN) type of communication is limited to 100 Mbps but higher data rate communication will be required for applications such as HD TV in Future Home Networks (FHN). Intense allocation and unavailability of large bandwidth at low frequencies such as 2.4 GHz and 5 GHz lead to search for alternatives at high frequencies. IEEE 802.15.3 standardization process is a candidate to satisfy data rate and QoS requirements of potential applications that will be used in FHN. Context awareness and cognition techniques will be utilized for resource optimization, energy saving and more flexible and smarter applications. EU (FP7) and DARPA also support and pursue studies on cognitive networking. Cognitive functions and context awareness are also important to support various types of devices (from low data rate sensors to HD TV) and inter-room services. For instance a moving user should be traced for continuity of services [1,2].

High frequency signals such as millimeter wave signals at 60 GHz have an inherent security feature due to penetration incapability. Wall penetration attenuation is so high for 60 GHz that in-room communication cannot be eavesdropped from outside. There is also high oxygen absorption around 60 GHz band which makes it more suitable for short range communications [3]. Hardware which can operate at 60 GHz frequency used to be very expensive compared to WLAN hardware but with recent developments silicon based solutions are possible for 60 GHz devices with WLAN comparable cost [4].

1-1 Motivation

60 GHz technology has a great potential to provide wireless communication at multi-gigabit rates in Future Home Networks. High speed data transfer requires large bandwidth which is only available at high frequencies. 5 GHz bandwidth is available at 60 GHz range in globally license-free spectrum, which makes it a unique candidate for future high data rate, short range applications [5]. This high frequency has severe attenuation problem which degrades communication performance but it also have directivity advantage due to short wavelength [6,7]. Recent developments in manufacturing of 60 GHz compatible components also enabled commercial use of 60 GHz networking devices. High data rate, inherent security, scalability and compact size components properties also makes 60 GHz technology a candidate for data cable (e.g. cat5 and HDMI) replacement [8,9].

Maintaining the network connectivity in a desired quality with 60 GHz links, which are highly susceptible to propagation and penetration losses, is still a major challenge. The quality and the robustness of the 60 GHz links can be improved by placing relay nodes, using nodes with directional antennas or applying both of these methods. Use of relay and directional antennas increase received power, energy efficiency, SNR and directional antennas offer other benefits such as longer transmission ranges, interference reduction, better spatial reuse, more simultaneous communications [10,11]. Benefits of directional antennas are proven for cellular networks but they are not elaborated for indoor communication yet.

Although high frequency channel characteristics have been studied thoroughly in the last two decades relay configuration and use of directional antennas are paid attention recently. Regular MAC protocols apply CSMA/CA schemes which is not suitable for directional antennas [12]. Methods in line with characteristics of directional communication is required. Topology discovery and topology management with directional antennas are generally studied for lower frequency bands such as 2.4 GHz [13–15]. General consequences of using directional antennas are analogous but 60 GHz band also has its unique quasi-optical properties which should be taken into account. Behavior of 60 GHz rays are referred as quasi-optical since reflected, diffracted or scattered rays do not contribute received power significantly and most of the energy is provided by direct path.

1-2 Problem Definition

Connectivity is one of the major issues for 60 GHz networks due to the fragile nature of the high frequency wireless links. Using relay nodes provides advantages in terms of path loss due to nonlinear relation between distance and path loss. Despite extra required processing capacity and imposed delay; using a relay device in the network shall be evaluated since throughput of the network would decrease drastically with severe loss when throughput decrease due to relaying is always less than former case. For instance, to maintain same reliability in case of 20 dB power loss, data rate should

be reduced 100-fold [7]. Using directive antennas also helps to cope with attenuation since high frequency has the advantage for building narrower beam antennas to focus better on the receiver.

It is possible to bypass an obstacle and keep connectivity of network via relay. Considering the spread of network nodes in a home network two hop communication is satisfactory for majority of cases [16]. Thus, deployment of one relay can provide sufficient improvement on connectivity. High frequency signals suffer from severe attenuation problem compared to their low frequency counterparts. An example calculation is made to compare 5 GHz and 60 GHz signals considering free space loss. Frii's formula [17] is used to find path loss for unity gain antennas at a certain distance d which is denoted with $L(d)$,

$$L(d) = \left(\frac{4\pi d}{\lambda} \right)^2, \quad (1-1)$$

where λ is the wavelength of Electromagnetic (EM) wave. Let $L_1(d)$ and $L_2(d)$ denote path losses at distance d for $f_1=60$ GHz and $f_2=5$ GHz respectively. λ_1 and λ_2 are corresponding wavelengths and we would like to find $\frac{L_1(d)}{L_2(d)}$,

$$\frac{L_1(d)}{L_2(d)} = \frac{\left(\frac{4\pi d}{\lambda_1} \right)^2}{\left(\frac{4\pi d}{\lambda_2} \right)^2} = \left(\frac{\lambda_2}{\lambda_1} \right)^2 = \left(\frac{f_1}{f_2} \right)^2 = 144 = 21.6 \text{ dB}. \quad (1-2)$$

Advantages of using regenerative or non-regenerative relays are studied and issues are addressed in [5,18–21]. These research mainly focus on physical aspects of the problem and discuss the trade offs while utilizing relays in home networks.

Utilizing directive antennas is also a popular method to cope with attenuation of 60 GHz signals and cross layer approaches are currently considered [7,22–24]. Directional antennas provide the possibility to focus energy of signal to a certain direction. Deployment of directional antennas in 60 GHz home networks is crucial due to attenuation of millimeter waves. To fully utilize the benefits of directional communication in an indoor network, both ends of a 60 GHz link should have directional antennas with steering capability. Having directional antenna only at one end of communication cause asymmetry in range among parties and some neighbors reachable via directional transmission cannot be discovered in this case. High path loss of 60 GHz can be mitigated by using highly directional antennas in both ends which provides gain about 15-18 dB [25]. Information exchange is required with lower layers to achieve satisfactory performance in neighbor discovery. Physical aspects of connectivity problem has been studied and addressed extensively in the literature in last two decades but not satisfactory attention is paid to logical connectivity of 60 GHz networks, which refers the discovery of physically possible connections in network. Discovery of neighbors and initial signaling becomes more challenging when only directional transmission and directional reception are possible. We attempt to develop a neighbor scanning strategy to reduce latency in this phase of communication.

"Quantifying lower bound of relay benefits on received power and design of a scanning strategy to fully utilize directional antennas in 60 GHz home networks" is the main problem discussed in this thesis.

1-3 Contributions

In this work, the contribution of relaying to the physical connectivity of network and application of directional antennas in 60 GHz home networks is investigated. Use of relay nodes implies implementation difficulties which should be compensated by benefits of relaying. Lower bound for benefits of relaying on received signal level is addressed analytically and via simulations.

Communication of devices starts with handshake among parties which is referred as Neighbor Discovery in the scope of this thesis. When directional antennas are used, traditional neighbor discovery methods do not perform adequately because of the sectoral coverage of the nodes. Additional challenges emerge for neighbor discovery with directional antennas which requires appropriate modifications in current neighbor discovery methods used for indoor wireless communication. A new neighbor scanning method for neighbor discovery algorithm in FHN is proposed. A stochastic model to observe trends in network isolation specific to Home Networks operating with directional antennas is developed and presented.

1-4 Publications

- Z. Genc, G. M. Olcer, E. Onur, and I. Niemegeers, "Improving 60 GHz Indoor Connectivity with Relaying", in *Proceedings of IEEE International Conference on Communications (ICC)*, Cape Town, Gauteng, South Africa, May 2010. [26]
- G. M. Olcer, Z. Genc and E. Onur, "Smart Neighbor Scanning with Directional Antennas in 60 GHz Indoor Networks", submitted to *PIMRC'10*, Istanbul, Turkey, September 2010.
- G. M. Olcer, Z. Genc and E. Onur, "Analysis of Isolation in 60 GHz Directional Networks", to be submitted to *IEEE Communication Letters*, 2010.

1-5 Thesis Outline

The rest of the thesis is organized as follows:

- Chapter 2 is a literature survey related with thesis scope.
- Chapter 3 includes an analytical model about relaying benefits on path loss reduction and simulations for verification.
- Chapter 4 explains directional neighbor scanning problem and a smart scanning strategy for neighbor discovery with directional antennas. Connectivity and isolation in home networks are also discussed in this chapter.
- Chapter 5 concludes the thesis and addresses some future research questions related with subject of this thesis.

Literature Review

60 GHz technology has attracted significant attention from academia and industry for its potential use in future communication systems. The required data rates in future wireless home networks will possibly be much higher as the multimedia applications enhance. Since the common license-free spectrum is densely occupied and large bandwidth is not available in the ISM band, higher frequency bands are investigated to achieve multi-gigabit data rates in future home networks. The 60 GHz band is attractive because of the large bandwidth in the 59-64 GHz license-free spectrum which is globally available. Its physical characteristics also provides immunity to co-channel interference, better spatial reuse, high security advantages [3]. It is foreseen to achieve up to 4 Gbps data rate with this technology [12]. The 60 GHz band is promising for future use and its popularity can be perceived in recent standardization efforts [21, 27, 28].

Physical characteristics of high frequency band and directional antennas were firstly elaborated in the literature. Channel modeling, reflection, diffraction, scattering, attenuation, obstruction properties have been addressed thoroughly in [18, 25, 28–34]. Upper layer issues such as neighbor discovery, MAC protocol, topology management, routing are relatively new [7, 10, 35–41]. Standardization on higher layer issues of high frequency bands and directional antennas is infant compared to physical layer standardization process.

2-1 Related Work on Relaying

One of the major challenges for the adoption of the 60 GHz technology in the future home networks is the heavy attenuation characteristics of the millimeter waves [42]. A 60 GHz system has to deal with 22 dB greater free-space path loss than an equivalent 5 GHz system since the propagation loss increases with the square of the carrier frequency [43, 44]. Diffracted, scattered signals do not contribute to received power and the penetration loss in the 60 GHz band is also very high [9]. As diffracted, scattered

and second order reflection components are ineffective for 60 GHz channel AWGN channel model is sufficiently accurate for Line of Sight (LoS) link [7]. 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 [30,31,34,45]. Influence of human activity on 60 GHz wireless links in a real indoor environment is studied in [45] and it is observed that links are blocked for 1%-2% of overall time in a regularly crowded scenario. This is due to high attenuation in direct links in the presence of human bodies on the path. Despite this work does not include relay devices in the environment it can be seen alternate paths could be formed by repeaters when main path is blocked. When a 60 GHz link is blocked, reflections from the surfaces can be exploited to sustain the link connectivity between the devices [27]. In this case, the use of the reflected rays imposes additional reflection losses on already high free-space path loss. The growing propagation losses impact the critical link budget and the link connectivity adversely. A simple 60 GHz device, as defined in the Ecma specifications [46], may lack advanced antenna systems to automatically set up the broken links via reflections; therefore, the reflection-based approach cannot be implemented with simple systems. Another solution to preserve 60 GHz connectivity in case of obstructions is relaying the signal via an intermediate device to the Receiver (Rx). Relaying, in other words multi-hop communication via relays, has been well studied in the literature, especially in the context of the ad hoc networks [18,20]. Studies address different aspects of relaying as required number of relays or best location for a set of relays [7,26,47].

In general, relaying can be performed in two schemes, amplify-and-forward (AAF) or decode-and-forward (DAF). In the AAF scheme, the relay simply amplifies the signal prior to retransmission [48]. It is a very simple relay solution from the hardware complexity aspect but not efficient for the systems with critical link budgets since the noise is also amplified in this method. In the DAF scheme, the relay regenerates the signals by completely decoding and then re-encoding them before the transmission to the final destination. The regeneration of the signals in the DAF scheme can also help the system combat with large propagation losses and improve the quality of the links despite its relatively higher complexity. From the 60 GHz aspect, there are only a few significant studies exploring the opportunities of the relay concept for the millimeter-wave networks. A pyramid relay system is proposed by Leong *et al.* where a single access point is located at the top of pyramid and four repeaters are located at the corners of the base to increase the communication coverage [47]. This is to handle shadowing and increase capacity. A 3D ray tracing tool was used to make simulations which support proposals of authors. Singh *et al.* propose a multi-hop MAC architecture for 60 GHz Wireless Personal Area Network (WPAN) in which they use relaying with directional LoS links to overcome the link blockages [22]. The Ecma-387 standard defines the relay device for 60 GHz WPANs as an advanced "Type A" device with amplify-and-forward function to provide relay transmission for blocked paths [46].

Use of non regenerative relays for ad hoc networks is addressed; the contribution of relaying on power saving and multiple access interference reduction is illustrated in [18]. Covering longer distances while maintaining a certain channel quality without a relay device requires transmit power increase which is not preferred in most of the cases. Regenerative or non regenerative relays can be deployed according to complexity re-

quirements and available resources for specific applications. The authors address the use of non regenerative relays for ad hoc networks and illustrate the contribution on power saving and multiple access interference reduction in [18]. Using relay also provides opportunity to trade capacity, processing power for connectivity [20]. An indoor WPAN is examined and a multi-hop MAC architecture is proposed in [22] for 60 GHz communication. The link blocked by a human body or a regular indoor obstacle is thought to be disconnected due to high attenuation of millimeter range wavelength signal. Blockage of a link by a human body cause 20-30 dB reduction in link budget [7]. Despite multi-hop MAC architecture requires cross-layer approach which conflicts with OSI model, cross layer solutions has been rising trend recently [7, 22, 49, 50]. Although physical layer related aspects of PAN at 60 GHz has been studied for a while, multi-hop and relay structures are not thoroughly elaborated yet. These works attempt to foresee potential drawbacks of millimeter wave communication and a candidate mitigation method is proposed together with its performance analysis.

Various subjects in 60 GHz wireless communication are discussed and link performance is addressed in [5]. Best location for access point, beam forming, handover between access points, attenuation properties at 60 GHz frequency and SNR-BER relations are discussed. Measurements are done in a real room environment providing certain information specific to materials used in that room [51]. Although the channel characteristics of 60 GHz band have been extensively studied for last two decades, the multi-hop and relay communication in 60 GHz are not thoroughly elaborated yet. In this thesis, we investigate the effect of utilizing relay communication on the 60 GHz link connectivity in indoor settings. To the best of our knowledge, there is no prior study investigating the effects of relay communication analytically and through simulations on the 60 GHz indoor connectivity.

2-2 Related Work on Directional Networking

The link budget is a major handicap of 60 GHz band because of heavy attenuation by distance and limited capability of diffraction around the obstacles. High path loss of 60 GHz can be mitigated by using highly directional antennas. Critical link budget constraint requires the 60 GHz systems to obtain the maximum gains from the antennas, which can be achieved by directional transmission in both ends. Using directional antennas in both ends provides gain about 15-18 dB which almost compensates extra path loss compared to a 5 GHz wireless communication system [25]. Beam steering and use of directional antennas to compensate severe attenuation and multipath are more feasible at 60 GHz given the advantages of short wavelength. The characteristics of the millimeter waves enable the design of highly directive and steerable antennas in compact sizes [4]. Directional networking also has increased spatial reuse, interference and multipath reduction benefits. These provide higher capacity by supporting more simultaneous communications and fewer hops via longer transmission ranges. Decreased multipath leads smaller delay spread and this enables using simpler receivers.

A directional Rx is deaf to every direction except its main beam which is called *deafness* problem. Using directional antennas imposes extra challenges like deafness and more

frequent occurrence of hidden terminal problems. Deafness problem is more important when narrow beam antennas are applied. Sending RTS and CTS omni-directionally is suggested in [16] to reduce deafness problem but it should be noted that this would decrease number of possible simultaneous communications. Sequential polling by AP is suggested to keep track of neighbors in pure directional communication where carrier sensing mechanisms do not suffice [7]. To cope with additional challenges of directional communication additional information shall be supplied to nodes of the network. Indoor location information is a popular and locations of receivers are assumed to be known to transmitter in some studies [15, 52]. To establish a communication link between two nodes with directional antennas, the antenna beams should be steered to each other along the LoS path or the most dominant Non-Line of Sight (NLoS) path. When the right alignment is provided, the antennas should be in complementary transmission-reception modes to discover each other. This issue is referred as directional neighbor scanning problem and generally simplified in the literature by using omni-directional antennas in the neighbor discovery phase [15, 16, 49, 53].

Neighbor Discovery (ND) is required prior to data communication for wireless networks. A well designed neighbor discovery algorithm should take into consideration the characteristics of physical layer [54]. Discovery process is more challenging when communication entities only have sectoral coverage in both transmission and reception modes. Direct discovery and gossip-based discovery are two algorithms defined in the literature [24]. In both methods one node initiates discovery process by advertising its existence and waits for response. Direct discovery requires handshake between two parties but gossip-based allows to carry information about a third party (e.g. node ID, location) to advertising node. There are two types of gossip-based discovery methods. One suggests to add a gossiped neighbor directly to neighbor list while the other one proposes to use gossip information as guidance and to discover third node by its own before adding it to neighbor list. It is also shown that gossip-based ND which adds gossiped nodes directly to neighbor list is insensitive to node intensity in the network [55].

Some schemes use omni-directional modes for signaling in discovery process and directional modes for data communication [16]. RTS messages are broadcasted omni-directionally in this system; receivers are capable to detect signal's Angle of Arrival (AoA) and send CTS messages directionally in response. Antennas have longer transmission ranges in directional mode than omni-directional mode. Neighbors in the directional range but out of omni-range cannot be discovered with this method and it also implies asymmetric ranges in two ends of communication. Ability to detect AoA also increases antenna complexity. Only directional antennas at both ends are suggested to avoid those disadvantages [56]. Random ND is compared with synchronized ND (synchronization in alignment) for fully directional communication and latency advantage of synchronized ND is emphasized where a common reference is necessary for direction synchronization.

Direction information is not required for traditional Medium Access Control (MAC) protocols but it is necessary for directional communication. A ND algorithm utilizing polarization characteristics of Electromagnetic (EM) waves to assist MAC layer is proposed in [49]. Circular and linear polarized EM waves have different power loss in

reflection and this study exploits this fact to test existence of a LoS path between Tx and Rx in neighbor discovery phase. Detected LoS/NLoS information is sent back to Tx in ACK message to adjust communication parameters like data rate or reject reflected signals. These efforts are spent to detect and use direct link when possible, which is more suitable for 60 GHz data communication.

According to reciprocity of signaling in ND process, two types of neighbor discovery are defined: *one way neighbor discovery* and *handshake based neighbor discovery* [54]. In both schemes a node advertises its existence and a neighbor is discovered by receiving an advertisement in one way neighbor discovery. An active response from the receiver is required to conclude neighbor discovery in handshake based scheme. Execution frequency of ND algorithm depends on mobility conditions and sparseness of network. ND algorithm is designed to explore adaptively less likely directions and check them seldom compared to popular directions in this paper but it is based on omni-directional listening. This might fail when pure directional ND is applied.

A 60 GHz WPAN is considered as a piconet and priority is given to communication between piconet controller (PNC) and other devices (DEVs) of piconet in [12]. This paper is a proposal to IEEE 802.15.3 standardization process, which gives lower priority to communication between DEVs, assumes stable nodes during discovery and it does not support mobility (e.g. if a node moves away while the network is in operation it has to be re-discovered). Assumptions and simplifications in this paper are based on current IEEE 802.15.3 standard which implies that flexibility of 60 GHz networks has to be limited compared to low frequency counterparts (e.g. WLAN and Bluetooth based MANETs) due to physical characteristics of high frequency signals. This is a centralized topology proposal whereas distributed topology design, concerns about power efficiency, low probability of detection (LPD) for directional and 60 GHz networks are also mentioned in literature [57–59]. Apart from capacity and communication range increase properties of directional antennas LPD, anti-jamming, low probability of exploitation (LPE), low probability of interception (LPI) aspects are also emphasized [57].

Directionality is concerned for MAC protocols and Directional Medium Access Control (DMAC) schemes are discussed in several studies [6, 10, 15, 23, 52, 53]. Distributed and centralized MAC schemes are possible and there are pros and cons for each of them. Distributed scheme is more flexible and allows ad hoc operation better but it is more complicated than centralized scheme. Centralized MAC is less complicated to realize but a superior device like AP is needed to control and organize other devices in the network. Generally same channel is used for communication and MAC signaling but there are also proposals to use a dedicated channel for ND and MAC activities [46]. Regular carrier sensing mechanism is modified to support directional antennas and Directional Network Allocation Vector (DNAV) is designed to keep track of busy directions [15]. DMAC with polarization extension (DMAC-PDX) is suggested for direct path detection and utilizing this information in MAC protocol [23]. Cooperation is possible to realize in different layers of protocol stack to cope with numerous challenges posed by directional antennas. A cooperative MAC design is suggested for directional communication to make intermediate devices forward messages between two end parties [53]. The idea is using two hop fast communication instead of one hop slow communication to increase

throughput. This proposed protocol is based on existing IEEE 802.11 DCF protocol to be compatible with standardization process. a cooperation table is maintained by each node and nodes are assumed to be willing for cooperation. A different signaling packet, helper ready to send (HTS) is sent by intermediate nodes if they approve help request of other nodes. Impacts of data unit size and traffic load on throughput are also examined in this paper.

It is necessary to keep track of discovered neighbors in directional communication not to waste time to re-discover them and this is mostly done by polling. As the number of neighbors increases it becomes more difficult to follow all neighbors for each node. Topology management studies focus on keeping number of neighbors minimum without losing network connectivity and some of them have additional concerns during topology management like power efficiency [13, 37, 38, 58].

There are few studies considering pure directional transmission and reception during whole communication period. We investigated initial signaling opportunity between network nodes when only directional communication used. Some studies assume location information available during neighbor discovery but do not specify amount of advantage by means of location awareness. We quantify the benefits of location awareness in neighbor discovery process for different network parameters. We also present isolation model and connectivity condition specific for home networks with directional antennas.

Connectivity Improvement with Relaying

Using relay nodes provides advantages on amount of path loss due to nonlinear relation between distance and path loss. Despite extra required processing capacity and imposed delay; using a relay device in the network shall be evaluated for the sake of connectivity in the network. Delay imposed by relaying degrades network throughput by a factor of two where throughput degradation due to an obstacle causing 10 dB attenuation is a factor of ten [7]. It is possible to bypass an obstacle and keep connectivity of network via relay. Considering the spread of network nodes in a home network two hop communication is satisfactory for majority of cases [16]. One relay can enhance connectivity of home networks sufficiently which also enables simplification in multi-hop routing algorithms.

Decode-and-forward (DAF), amplify-and-forward (AAF) are two schemes for relay mechanisms. In AAF scheme noise penetrates to second relay link since it is also amplified together with communication signal. Although noise is cleared in decoding process in DAF scheme it has more processing load and it imposes more delay compared to AAF. Assuming DAF scheme for relay devices in this study to clear noise at relay, we relate the link quality with amount of path loss in transmission.

A circular network area is considered and two cases (with relay and without relay) are investigated analytically to compare amount of path loss and relate it to link quality improvement. Network nodes are assumed to be distributed uniformly in the area of interest and probabilistic models are used for deployment.

3-1 Analytical Model

In this section, an analytical model is presented to model the gains of employing relays in 60 GHz networks in terms of path loss. We devise two scenarios as shown in Figure 3-1. In the first scenario, we consider two randomly deployed nodes directly communicating with each other. We concentrate on the line-of-sight link and calculate the expected path loss as the link quality measure. In the second scenario, the randomly deployed nodes communicate via a relay device positioned in the center of the circular field. We compare link qualities in cases with and without relay device. Parameters used in the model are listed in Table 3-1. Communication without a relay device is discussed first.

Table 3-1: Nomenclature

Parameter	Explanation
C	Center of interest area and relay's location
R_0	Radius of interest area
\mathbf{R}	Distance between nodes (scenario without relay)
N_1, N_2	Communicating nodes
$\mathbf{R}_1, \mathbf{R}_2$	Distances from nodes to relay
\mathbf{R}_m	Greater distance among $\mathbf{R}_1, \mathbf{R}_2$ (scenario with relay)
λ	Wavelength
x	Dummy variable for integrations

Consider a circular area of interest with center C and radius R_0 where communicating nodes are deployed randomly as shown in Figure 3-1. Distribution of nodes are assumed to be uniform in the area of interest. Two devices are assumed to be able to communicate if they have at most $2R_0$ distance between them. A generic scenario is illustrated in Figure 3-1 and parameters are introduced.

For communication without a relay device, we denote the distance between two random points N_1 and N_2 in a circular area of radius R_0 with random variable \mathbf{R} . Then the PDF of \mathbf{R} [60] is

$$f_{\mathbf{R}}(r) = \frac{2r}{R_0^2} \left\{ 1 - \frac{2}{\pi} \sin^{-1} \left(\frac{r}{2R_0} \right) - \frac{r}{\pi R_0} \sqrt{1 - \frac{r^2}{4R_0^2}} \right\}, \quad (3-1)$$

where $0 \leq r \leq 2R_0$.

The CDF of the random variable \mathbf{R} is obtained via integration over the interval $[0, r]$

$$F_{\mathbf{R}}(r) = Prob(\mathbf{R} \leq r) = \int_0^r f_{\mathbf{R}}(x) dx$$

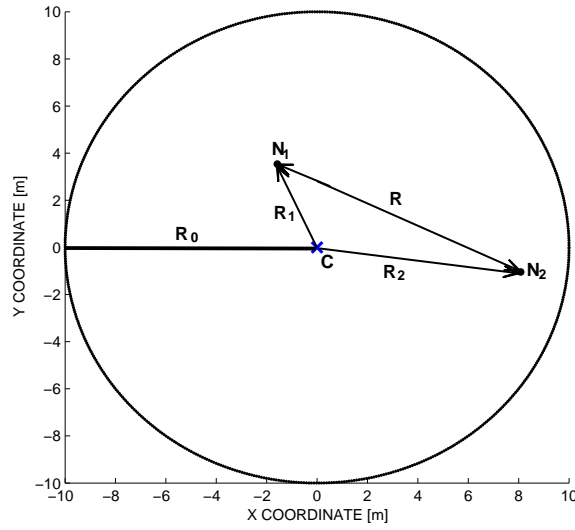


Figure 3-1: Generic scenario for $R_0=10\text{m}$

$$\begin{aligned}
 &= \int_0^r \frac{2x}{R_0^2} \left\{ 1 - \frac{2}{\Pi} \sin^{-1} \left(\frac{x}{2R_0} \right) - \frac{x}{\Pi R_0} \sqrt{\left(1 - \frac{x^2}{4R_0^2} \right)} \right\} dx \\
 &= \frac{1}{\Pi R_0^3} \left\{ 2(R_0^3 - R_0 r^2) \sin^{-1} \left(\frac{r}{2R_0} \right) - \frac{r}{4} \left\{ (2R_0^2 + r^2) \sqrt{\left(4 - \frac{r^2}{R_0^2} \right)} - 4\Pi R_0 r \right\} \right\}. \tag{3-2}
 \end{aligned}$$

For a simple scenario where the circular field of interest has a radius of 10 meters, the PDF and CDF of random variable \mathbf{R} are given in Figure 3-2.

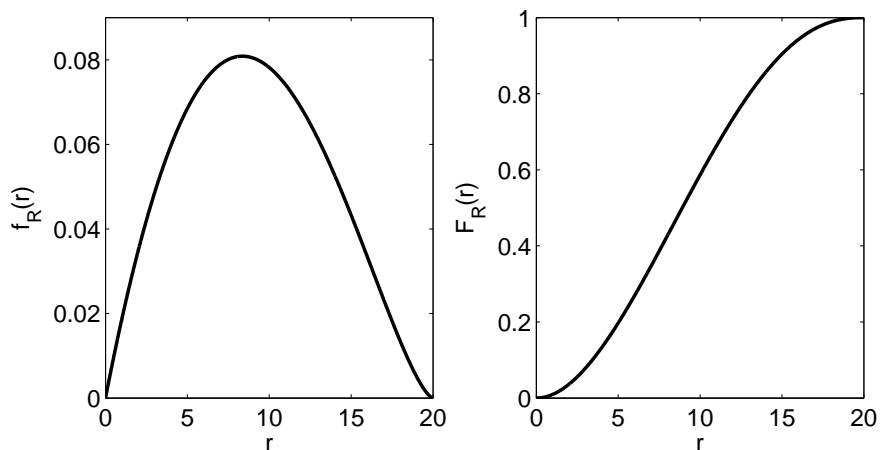


Figure 3-2: PDF and CDF of \mathbf{R} when $R_0=10\text{m}$

Received power is one of the measures to determine wireless link quality. Expected path

loss should be found for the area of interest to compare two cases with and without relay. Only free space loss is considered and Frii's formula [17] is used to find path loss at a certain distance r which is denoted with $g(r)$,

$$g(r) = \left(\frac{4\pi r}{\lambda} \right)^2, \quad (3-3)$$

where λ is the wavelength of the signal. Expectation of a function $g(r)$ of \mathbf{R} over interval $[0, r]$ is used to calculate expected path loss which is

$$E[g(r)] = \int_0^r f_{\mathbf{R}}(x)g(x)dx. \quad (3-4)$$

Expected path loss over $[0, r]$ interval is calculated by rewriting parameters,

$$\begin{aligned} E[g(r)] &= \int_0^r \frac{32\pi^2 x^3}{R_0^2 \lambda^2} \left\{ 1 - \frac{2}{\pi} \sin^{-1} \left(\frac{x}{2R_0} \right) - \frac{x}{\pi R_0} \sqrt{\left(1 - \frac{x^2}{4R_0^2} \right)} \right\} dx \\ &= \frac{16\pi}{R_0^3 \lambda^2} \left\{ (2R_0^5 - R_0 r^4) \sin^{-1} \left(\frac{r}{2R_0} \right) - \frac{r}{12} \sqrt{\left(4 - \frac{r^2}{R_0^2} \right)} (6R_0^4 + R_0^2 r^2 + 2r^4) + \frac{\pi R_0 r^4}{2} \right\}, \end{aligned} \quad (3-5)$$

where λ is wavelength and R_0 is radius of circular area. The expected path loss of the LoS path in the area of interest can be found by setting $r=2R_0$,

$$E[g(2R_0)] = 16 \left(\frac{\pi^2 R_0^2}{\lambda^2} \right). \quad (3-6)$$

This is the expected amount of path loss when nodes communicate directly on LoS path without using relay device.

For the scenario with a relay device, we consider the same circular area with center C and radius R_0 where relay device is located at the center as shown in Figure 3-1. Relay device is capable to communicate all nodes in the area of interest, which are at most R_0 unit away from relay. A pair of nodes N_1 and N_2 are located randomly in this circular area. We denote distances from the relay to these devices with random variables \mathbf{R}_1 and \mathbf{R}_2 respectively which are independent and identically distributed (i.i.d.) random variables. Assuming uniform distribution of nodes in the circular area, the cumulative distribution function of \mathbf{R}_i , $i=1,2$ can be calculated by dividing the areas of discs with radii r and R_0 [61, 62],

$$F_{\mathbf{R}_i}(r) = Prob(\mathbf{R}_i \leq r) = \frac{\pi r^2}{\pi R_0^2} = \frac{r^2}{R_0^2}. \quad (3-7)$$

Then the PDF of \mathbf{R}_i is

$$f_{\mathbf{R}_i}(r) = \frac{dF_{\mathbf{R}_i}(r)}{dr} = \frac{2r}{R_0^2}, \quad (3-8)$$

where $0 \leq r \leq R_0$. Note that square of random variable \mathbf{R}_i is uniformly distributed random variable which is a natural result of uniform distribution of nodes in circular area.

Assume that two nodes N_1 and N_2 , shown in Figure 3-1 always communicate via relay device positioned in the center. The longest link (i.e., the greatest among \mathbf{R}_1 and \mathbf{R}_2) has the largest free space path loss and hence it determines the quality of the overall route between two nodes N_1 and N_2 . Defining \mathbf{R}_m as the greatest of \mathbf{R}_i where $i=1,2$; $\mathbf{R}_m = \max\{\mathbf{R}_1, \mathbf{R}_2\}$, then CDF of \mathbf{R}_m is

$$F_{\mathbf{R}_m}(r) = Prob(\mathbf{R}_1 \leq r \text{ and } \mathbf{R}_2 \leq r) = \frac{r^2}{R_0^2} \frac{r^2}{R_0^2} = \frac{r^4}{R_0^4}. \quad (3-9)$$

The PDF of \mathbf{R}_m is

$$f_{\mathbf{R}_m}(r) = \frac{dF_{\mathbf{R}_m}(r)}{dr} = \frac{4r^3}{R_0^4}, \quad (3-10)$$

where $0 \leq r \leq R_0$. Matlab simulations were carried out to verify the analytical model of distribution of \mathbf{R}_m . PDF, mean and variance of \mathbf{R}_m were also examined to verify (3-10) using Matlab. Histogram of numbers generated in the simulation confirmed the shape of the PDF and same mean, variance values with analytic calculations obtained in numerical analysis. Simulation results closely match with analytical model as can be seen in Figure 3-3. It shows the shape match between derived PDF (3-10) and histogram which were obtained in simulations. 10^6 pairs of nodes were randomly deployed in a circular area with radius R_0 in simulation. Distances from nodes to center were measured for each pair and greater one among these two measurements was saved in a vector. This is repeated for each 10^6 pairs and histogram in Figure 3-3 shows distribution of entries in this vector. Mean and variance of entries in this vector were also recorded to compare with analytical results. Histogram obtained as a result of the numerical analysis was normalized to see match with PDF of \mathbf{R}_m , $f_{\mathbf{R}_m}(r)$.

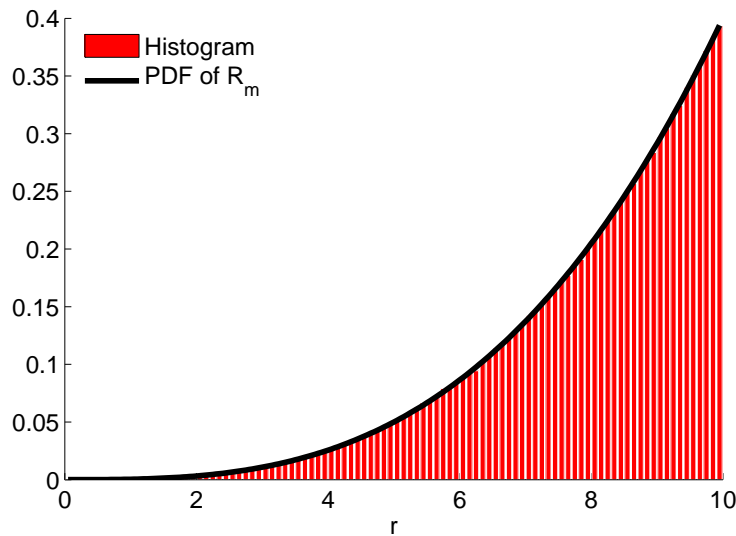


Figure 3-3: Match between PDF and histogram of \mathbf{R}_m when $R_0=10\text{m}$

Mean of \mathbf{R}_m in range $[0 R_0]$,

$$\mu = \int_0^{R_0} f_{\mathbf{R}_m}(r)rdr = \int_0^{R_0} \frac{4r^4}{R_0^4}dr = \frac{4}{5}R_0 = 0.8R_0. \quad (3-11)$$

Variance of \mathbf{R}_m in range $[0 R_0]$,

$$\begin{aligned} \sigma^2 &= E[\mathbf{R}_m^2] - \mu^2 = \int_0^{R_0} f_{\mathbf{R}_m}(r)r^2dr - \mu^2 \\ \sigma^2 &= \int_0^{R_0} \frac{4r^5}{R_0^4}dr - \mu^2 = \left(\frac{2}{3} - \frac{16}{25}\right) R_0^2 = 0.026667R_0^2. \end{aligned} \quad (3-12)$$

In simulations, mean and variance of \mathbf{R}_m are found by deploying 10^6 node pairs randomly to the area of interest and results are found to be $0.80002R_0$ and $0.026647R_0^2$ respectively which are consistent with analytical results. Matlab source code to implement these numeric analyses to see match with analytical results is given in Appendix A. After verifying $f_{\mathbf{R}_m}(r)$ with numerical analysis, we recall Frii's formula and the relation used to calculate expected path loss within area of interest.

$$\begin{aligned} E[g(r)] &= \int_0^r f_{\mathbf{R}_m}(x)g(x)dx = \int_0^r \frac{4x^3}{R_0^4} \left(\frac{4\pi x}{\lambda}\right)^2 dx \\ &= \int_0^r \frac{64\pi^2 x^5}{R_0^4 \lambda^2} dx = \frac{32}{3} \left(\frac{\pi^2 r^6}{R_0^4 \lambda^2}\right), \end{aligned} \quad (3-13)$$

where λ is wavelength and R_0 is radius of circular area. To find expected path loss for area of interest in this case, set $r=R_0$,

$$E[g(R_0)] = \frac{32}{3} \left(\frac{\pi^2 R_0^2}{\lambda^2}\right). \quad (3-14)$$

3-2 Results on Path Loss Reduction

Signal quality decreases with path loss and we quantify contribution of relaying in reduction of path loss analytically and by means of simulations. Comparing the amounts of path loss in two cases given in 3-6 and 3-14 it is seen that relay provides 33% less path loss which corresponds to 1.8 dB gain even without any obstacles. If the direct link is blocked with an obstacle and there exists an alternate path via relay device since direct link will suffer from severe attenuation; gain due to relay will be larger. In these scenarios, no intelligence is assumed for the nodes whereas there exist intelligent devices in practice capable to detect link quality. If the nodes are capable to select better path among two options, higher gains are achievable. 1.8 dB gain is the worst case gain provided by relaying among all possible cases. Path loss exponent is taken 2 in this work. Higher path loss exponent would also act in favor of gain obtained with relaying. This study provides a lower bound for relay gain and quantifies worst case benefit of relaying on reduction of path loss.

3-3 Verification by Simulations

3-3-1 Random Points in Circular Area

It was required to generate uniformly distributed points within a circular area of radius R_0 and center C . To realize this in simulations we utilized the fact that square of distances from these points to C is uniformly distributed (3-7). Source code lines 12 and 14 in Appendix A-1-1 show how it was applied. Assigning uniform distribution to distances from points to center yields a non-uniform point distribution in circular area as in Figure 3-4(a) but assigning uniform distribution to square of distances from points to center yields required uniform distribution of points as in Figure 3-4(b).

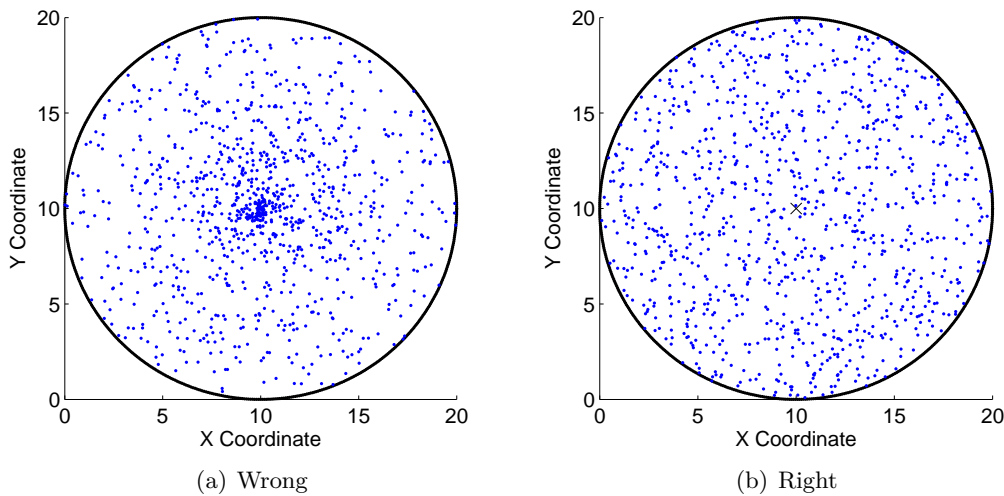


Figure 3-4: Non-uniform and uniform random points in a circular area

3-3-2 Matlab Simulations

Monte Carlo Simulations were done in Matlab environment with specified parameters for verification of the analytical model. In each trial, a pair of nodes are located randomly (uniform distribution in mentioned area) for both scenarios. Random deployment of 300 pairs of nodes is shown in Figure 3-4(b) where relay device is marked with "x" sign. More pairs were deployed in real simulations but only a part of them are shown for illustrative purposes.

For scenario without a relay device, distance between nodes is found then corresponding path loss is calculated using Frii's Formula for each randomly deployed node pair. This is repeated many times (10^5 times), path loss values are stored and average of individually calculated path loss values is found at the end.

For relay scenario, distances from each node to relay device are calculated and larger one is taken as the limiting factor, determining link quality. Path loss is calculated for this longer link using Frii's Formula and this is also done many times (10^5 times). Then

average of these path loss values is found to compare with average path loss without relay device.

These simulations confirmed the results obtained in the analytical model resulting 33% less path loss via relay node. Numeric simulations also provided the opportunity to observe path loss advantage via relay node in rectangular coverage area. Simulations were carried for rectangular areas while keeping these areas within coverage area of the relay device. In other words rectangular areas were drawn within the circular area shown in 3-1. When coverage area shape is close to a square almost 33% less path loss can still be obtained with relaying. As the aspect ratio (the ratio of a shape's longer dimension to its shorter dimension) of the covered area diverges from 1, path loss advantage provided by relay device gets worse as 25% for a rectangular area of which length is five times its width.

3-3-3 RPS Simulations

A deterministic ray tracing tool, Radiowave Propagation Simulator (RPS) was also used to verify analytical model [29,63,64]. A square $6m \times 6m$ room of which illustration is given in Figure 3-5 was used to measure gain provided by relay device. Each sphere represents a network transceiver that has a transmitter and a receiver. Many nodes were deployed during whole simulations to calculate average path loss advantage but only 25 of them are shown in figure for illustrative purposes. To accurately verify the analytical model with RPS simulator, we created a grid structure of dimensions 14×14 in a living room scenario and deployed 196 transceivers to this structure (e.g. one transceiver to each intersection). A relay node was located in the middle of the room. We turned on all possible node pairs among $\binom{196}{2}$ pairs one by one and calculated the path loss of each link between each pair of source and destination. Then we calculated the two path loss values for the same node pairs when the source node and the destination node are linked via the relay node. The greater path loss value was taken into account since it determines the link quality. Results were averaged in each case to be compared with each other. The comparison of the averaged path losses showed that the path loss is reduced by 32.45% when the nodes were connected to each other with the relay node. This result also verifies 33% path loss advantage predicted by the analytical model. Changing area of interest shape from circle to square excludes some border regions and it is not possible to deploy as many node pairs as 10^5 in RPS which might have caused 0.55% gap between simulations.

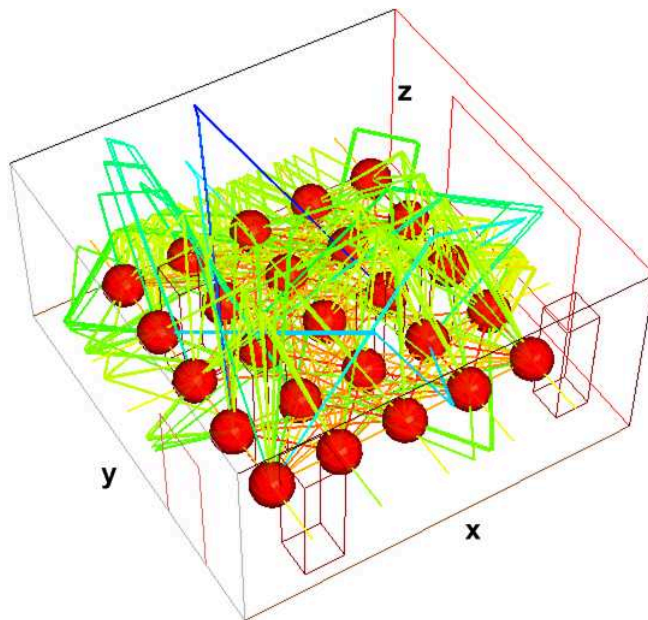


Figure 3-5: The visualized 60 GHz rays in a model room in RPS environment

We discussed the benefits of relay on link budget in 2-D as in many previous studies but it is possible to extend this approach to 3-D by modelling distance between two random points and distance to center in a sphere, hemisphere or a cube.

We pursued and presented an elaborate study on this subject covering location of relay device and results on amount of improvements for links in the network in [26].

Neighbor Scanning with Directional Antennas

Directional antennas provide the possibility to focus energy of signal towards a certain direction. Deployment of directional antennas in 60 GHz home networks is crucial due to high attenuation of millimeter waves. A 60 GHz communication system experiences 28 dB larger free-space path loss than a similar WLAN system operating at 2.4 GHz. To fully utilize the benefits of directional communication in an indoor network, both ends of a 60 GHz link should have directional antennas with steering capability. Having directional antenna only at one end of communication cause asymmetry in range among parties and some neighbors reachable via directional transmission cannot be discovered in this case. High path loss of 60 GHz can be mitigated by using highly directional antennas in both ends which provides gain about 15-18 dB [25]. A directional antenna is a collection of multiple components mounted in an array. For high frequencies these components can be small and the characteristics of the millimeter waves enable the design of highly directive antennas in compact sizes. A steerable antenna array formed by multiple directional elements can provide sufficient gains to establish reliable communication links in 60 GHz even in non-line-of-sight (NLoS) condition [27].

Using directional antennas cause additional challenges like increased hidden terminal problem and deafness in communication of nodes. Current communication protocols for WLAN systems are designed for omni-directional antennas and they are either inefficient or inapplicable for directional antennas. In this work we focus on *Neighbor Scanning* which is initial step for neighbor discovery and communication among network nodes. To establish a communication link between two nodes with directional antennas, the antenna beams should be steered to each other along the LoS path or the most dominant NLoS path. When the right alignment is provided, the antennas should be in complementary transmission-reception modes to discover each other. This issue is referred as directional neighbor scanning problem and generally simplified in the literature by using omni-directional antennas in the neighbor discovery phase [15, 49, 53].

The fully directional neighbor scanning with the use of directional steering antennas at both ends of communication links may introduce delays which are unacceptable for latency-sensitive applications. In this work, a smart neighbor scanning strategy is proposed to reduce the discovery duration by eliminating the scan of some sectors which are unlikely to accommodate neighbors. This elimination decisions are based on own positions of nodes.

A room can be considered as a cell for 60 GHz Home Networks as shown in Figure 4-1 since the signals cannot penetrate through the walls. In this work, the field of interest is a regular rectangular room and the number of nodes in network is not large. We expect less than 20 nodes in a typical 60 GHz home network. A generic scenario is illustrated in Figure 4-1 where $N=5$ nodes are positioned randomly in a rectangular room with length L , width W and aspect ratio L/W . Nodes are stationary and homogeneous with $k=6$ sectors where $\alpha=360^\circ/k$. Parameter list is also given in Table 4-1.

4-1 Directional Neighbor Scanning Problem

Neighbor Discovery (ND) algorithms can generally be classified in two groups as direct and gossip-based discovery algorithms. In the direct discovery, two nodes can discover each other if there is a direct transmission between them. In the gossip-based discovery, nodes can carry identity, direction and location information about their direct or indirect neighbors as well as announcing themselves. One approach suggests using gossips as guidance and handshaking with those nodes before adding them to neighbor list [57]. Another idea is adding a gossiped node directly to neighbor list [55]. Second one is faster but less reliable since a gossiped node may not be directly available to node itself. Direct discovery approach is followed in this thesis; Transmitter (Tx) and Receiver (Rx) are required to confirm discovery by handshaking directly. We consider fully directional neighbor scanning where both Tx and Rx can only communicate directionally. Directional transmission is common in the literature but reception is generally assumed to be omni-directional. This leads to *asymmetrical ranges* for Tx and Rx nodes which worsens hidden terminal problem and causes degradation in throughput [65].

A directional antenna can either be a switch-beam or a beam-steering antenna. The latter is more complex and it can be assumed to be capable to steer its beam continuously. Former can be considered as a modified version of the second one with discrete beam directions. It is not capable to focus on any directions but a predefined set of directions. In both cases, they are expected to sweep 360° in an indoor environment.

When two nodes attempt to perform neighbor discovery with directional transmissions and reception, their antenna beams should cover each other at the same time and their Tx-Rx states should be complementary to succeed forming a pair as can be seen in Figure 4-1 (e.g., *node 2* and *node 3*). An indoor network is modeled as an undirected graph $G=(V, E)$. For a complete graph with N nodes in vertex set V there are $n=\binom{N}{2}$ links in the edge set E of G . In this model, a link is assumed to be a direct connection between any two arbitrary nodes. Problem is modeled in two dimensions assuming all beams are wide enough in elevation to cover neighbors. A scanning strategy shall be

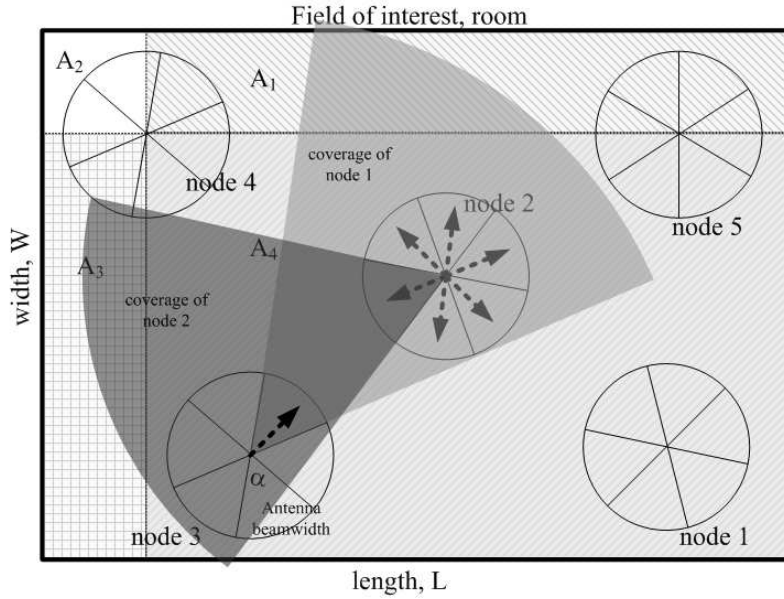


Figure 4-1: A generic 60 GHz home network scenario with randomly deployed 5 nodes

designed for nodes operating with directional antennas to assure discovery of sufficient links out of n and proper operation of network.

In most of the previous work on fully-directional (both transmitter and receiver have directional antennas) neighbor discovery, beam directions (sectors) are randomly chosen. Nodes determine probabilistically whether to be in transmission or reception states with pre-assigned probabilities [14, 24]. This strategy is called as Random Scan (RS) strategy in the rest of this document. Transmission and reception state probabilities can be optimized for faster discovery in RS strategy [55]. Scanning all sectors by following a pattern or adjusting beam directions based on time information are also proposed [53, 66]. Such deterministic scanning strategies may not find all possible neighbors. For example, Circular Scan (CS) is a deterministic scanning strategy where a pre-defined scanning pattern is repeated by nodes. If certain links cannot be discovered in this pattern, nodes would be unaware of these links indefinitely [53]. In [66], a reference direction common to all nodes is required for neighbor discovery but it is not explained how to provide direction synchronization among nodes.

Randomness is a requirement to deal with all cases where nodes could be in any position. The scanning strategy should allow discovery of any possible link within coverage area of nodes. By using the node positions and introducing intelligence to RS strategy, the performance of neighbor discovery can be enhanced. In the next, section we propose a smart scanning strategy which takes the node positions into consideration while scanning for neighbors.

Table 4-1: Parameters list for directional scanning

Parameter	Explanation
N	Number of nodes in network
L	Length of the area of interest
W	Width of the area of interest
A	Area of deployment, LW
L/W	Aspect ratio
k	Number of sectors for each node
α	Beam-width of a sector, $360^\circ/k$
n	Number of all possible links, $\binom{N}{2}$

4-2 Smart Directional Neighbor Scanning

In this work, the nodes are homogeneous and each node has k sectors with equal beam-width of $\alpha=360^\circ/k$ as seen in Figure 4-1. A node can choose any of these k sectors in one *search cycle* (τ) defined as the unit duration of the ND process. τ is a short time interval which allows sending an advertisement, getting the response if advertisement is received and sending back the acknowledgement. A typical duration for one search cycle (τ) can be 100 μ sec considered as *transmission opportunity* (TXOP) duration in [7]. These advertisement and response packets may include extra information like discovery tables and location information to enhance discovery process but our focus is on scanning strategy and not content of handshake packets. At each search cycle, a node selects a sector from its sector set $S=\{j: 1 \leq j \leq k\}$ with a probability p_j assigned to each of them. The transmitting and receiving modes are determined as in RS strategy based on pre-assigned probabilities. The discovery is successful when the selected sector of the transmitter is aligned with the selected sector of the receiver. According to the transmission states, one of the nodes must act as a transmitter while the other is acting as the receiver. Successful link discovery takes place in τ units of time. In this work, N nodes are positioned randomly in a rectangular area with length L , width W (Figure 4-1). The aspect ratio is defined as $\max\{L, W\}/\min\{L, W\}$. We assume that the nodes are stationary during the ND process and each node has a range long enough to communicate to any other node in the rectangular area to focus on scanning strategy not range. Transmission power is increased step by step during ND to achieve LPD in some methods but we assume fixed transmission power for all nodes.

In the RS strategy, the probability of selecting each sector at a search cycle is equal for all sectors. We enhance the RS strategy with the Smart Random Scan (SRS) strategy where the probability of choosing a specific sector is proportional to the area it covers in the room instead of assigning equal probabilities to all sectors. If the nodes are randomly deployed, scanning a sector which covers a large area increases the chance of discovering nodes since there will be more nodes in that area. We use an approximation which is explained in subsection 4-2-2, since the exact calculation for coverage area of each sector is cumbersome.

4-2-1 Indoor Location Awareness

For calculation of the sector areas, nodes may use present localization methods in the literature to be aware of their location and the environment [67–71]. With respect to a common indoor references, the nodes may obtain position information themselves. Nodes own locations will be assumed to be known for smart scanning strategy and this is relatively easier than obtaining locations of other nodes in the network. Indoor location awareness methods offer different accuracy in positioning and cost of implementation varies. Details of indoor location sensing methods will not be discussed here since it is out of scope of this thesis. Sectoral alignments are also important since a node may be directed to any direction and this changes sectoral coverage of a node. Locations of the initially discovered neighbors may be acquired to extract sectoral alignments or a hardware solution could be implemented which would make alignment information available beforehand.

Another technique to calculate the sectoral coverage areas may be the utilization of quasi-optical propagation characteristics of the 60 GHz signals. Geometrical optics are used to develop simulation tools for modeling propagation of high frequency signals exploiting quasi-optical characteristics of them [29]. Each node sends some pilot signals from its different sectors and gets reflections of these before beginning ND process to estimate distances to nearest walls. The distance of each node to the closest wall can be determined using the delay and the signal strength of the most dominant reflection returning from that wall. If this process is periodically repeated then the nodes do not need to employ additional methods for the location awareness. Quasi-optical characteristics of 60 GHz signals are exploited for similar purposes like detecting direction of transmitter [24].

4-2-2 Sector Selection Probability

Each node calculates A_i , $i=1..4$ (shown in Figure 4-1) areas according to its own location and determines which sectors are aligned towards those sub-areas. Rectangular A_i areas can be calculated easily when W , L and location information is available. For instance, assuming the lower-left corner of the room as the origin of the xy-plane, the location of *node 4* (Figure 4-1) is denoted with (x_4, y_4) ;

$$A_1 = (L - x_4)(W - y_4), A_2 = x_4(W - y_4), A_3 = x_4y_4 \text{ and } A_4 = (L - x_4)y_4, \quad (4-1)$$

for *node 4*. Direction of a sector is determined according to its boresight which is the center of the sector's angular span. Thus, a sector cannot be assigned to multiple areas. Number of sectors aligned towards area A_i is designated with k_i . Sum of k_i 's equals k and sum of A_i 's equals $A=LW$. Probability of choosing j^{th} sector which is directed to i^{th} area is denoted with p_j ,

$$p_j = \frac{A_i}{Ak_i}, \quad i \in \{1 \dots 4\} \text{ and } j \in \{1 \dots k\}. \quad (4-2)$$

As seen in (4-2) when multiple sectors are directed to same area A_i selecting each of k_i sectors is equally probable regardless of actual footprint overlapping with area A_i . This

approximation error which is larger for wide beam directional antennas is tolerated for the sake of calculation simplicity.

4-2-3 Comparison of RS and SRS Strategies

A simulation environment is created in Matlab to compare different scanning strategies. Performance comparison results are given in Figure 4-2 for a specific case where $N=15$ and $\alpha=30^\circ$. This choice is made considering a fairly crowded network environment and a practically available 60 GHz directional antenna. Highly directional 60 GHz antennas up to 20° beam-width are available in practice [25]. A rectangular room is chosen for this simulation with aspect ratio of 1.7 and results are average of 2000 runs for each different method. *CS* strategy is frequently referred in recent studies in which a node starts with a random sector and selects following sectors in a circular sequence. Counterclockwise sequence was followed in simulations but direction of circular sequence does not change results for *CS*.

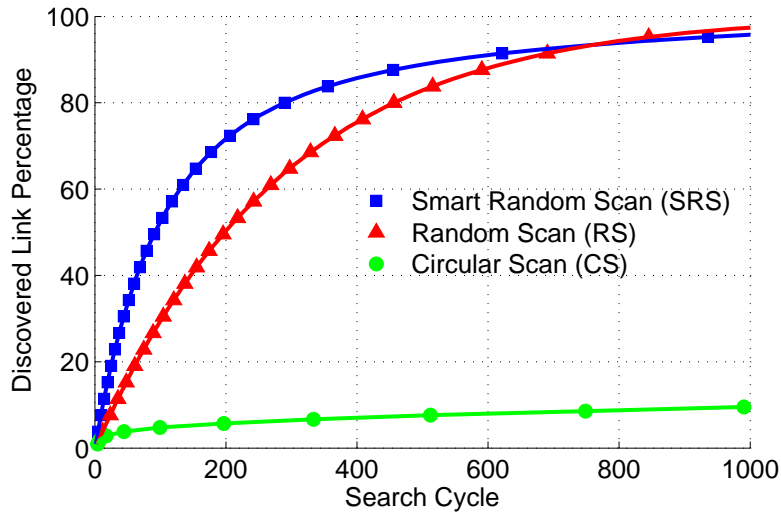


Figure 4-2: Performance comparison of RS, SRS, CS strategies for $N=15$, $\alpha=30^\circ$ and $L/W=1.7$

As can be seen in Figure 4-2, the SRS strategy outperforms the RS strategy until a certain portion of all possible $n=\binom{N}{2}$ links is discovered. Since some of the nodes are reluctant to check some directions in SRS, the nodes in those sectors remains undiscovered for a longer period compared to the RS method. When the SRS strategy is employed, 70% of the links are discovered 81% faster and 90% of the links 15% faster than RS where $N=15$, $\alpha=30^\circ$ and $L/W=1.7$ as can be seen in Figure 4-2. For a network to be operable, network connectivity should be provided. In the next section, we show that discovering 90% of all possible links is sufficient to achieve connectivity in a home network.

Matlab source codes are available in Appendix A to realize performance comparison simulations.

4-3 Link Discovery Requirement for Network Connectivity

Network connectivity is having a path between any two nodes in the network. The term *connectivity* refers logical discovery of physically possible links here unlike its use in Chapter 3 which is about physical quality of links. Even if all the possible links cannot be discovered, the network connectivity can still be achieved. Reliability of a small network depending on the ratio of discovered links is not addressed in the literature thoroughly whereas there are studies on reliability according to link and node failures for large networks with many nodes [72, 73].

In a network consisting of N nodes, assume that there are β isolated group of nodes. Isolated groups are clusters of nodes where the clusters are not connected to each other. Therefore, each of these β isolated groups are connected within the group but have no links to the other groups. Let $M_i, i=1 \dots \beta$ be the number of nodes in the i^{th} isolated group. Without loss of generality, we call the isolated group having the largest number of nodes as the *majority group* where the number of nodes in that group is denoted with $\Psi=M_1$. Number of all possible links among N, M_i and $\Psi=M_1$ nodes are denoted with $n=\binom{N}{2}$, $m_i=\binom{M_i}{2}$ and $\psi=\binom{\Psi}{2}$, respectively. These parameters are also listed in Table 4-2

Table 4-2: Parameters list for network connectivity

Parameter	Explanation
N	Number of nodes in network
β	Number of <i>isolated groups</i> in network, $\max\{\beta\}=N$
i	Isolated group index, $i=1 \dots \beta$
M_i	Number of nodes in i^{th} isolated group
Ψ	Number of nodes in <i>majority group</i>
n	Number of all possible links in network, $\binom{N}{2}$
m_i	Number of all possible links in i^{th} isolated group, $\binom{M_i}{2}$
ψ	Number of all possible links in majority group, $\binom{\Psi}{2}$
x	Number of discovered links
r	Ratio of discovered links, $\frac{x}{n}$

If the number of discovered links is x to provide network connectivity after some search cycles of the neighbor discovery process then the *ratio of discovered links* is

$$r = \frac{x}{n}. \quad (4-3)$$

The number of nodes in the majority group can be expressed as

$$\Psi = N - \sum_{i=2}^{\beta} M_i. \quad (4-4)$$

At the beginning of the neighbor discovery process, if no links are discovered yet in the network, then β has its maximum value, $\max\{\beta\}=N$. That is, all the nodes in the

network act as an isolated group. As the links are discovered, isolated groups merge with other isolated groups. Consequently, Ψ increases and β decreases. Any newly discovered link can either contribute to the connectivity within a group or contribute to the connectivity of the network by helping isolated groups to merge with other groups. The worst case for network connectivity occurs when additional links do not inter-connect the isolated groups until the isolated group becomes fully connected. In this worst case scenario, isolated groups merge with each other certainly when

$$x > \sum_{i=1}^{\beta} m_i. \quad (4-5)$$

A connected network of N nodes is formed when the last two isolated groups merge and β becomes 1. Last isolated group other than the majority group would be 2^{nd} one with M_2 nodes. Then for connectivity of whole network,

$$\begin{aligned} x &> \psi + m_2 \\ x &> \frac{(N - M_2)(N - M_2 - 1)}{2} + \frac{M_2(M_2 - 1)}{2} \\ 2x &> (N - M_2)(N - M_2 - 1) + M_2(M_2 - 1). \end{aligned} \quad (4-6)$$

The basic idea behind this condition is that initially, all the nodes start acting as an isolated group. As new links are discovered, the isolated groups merge. In the worst case, the new links contribute to the connectivity of the isolated groups until they make the isolated group fully connected. At an arbitrary point of time in the neighbor discovery process, if all the isolated groups are fully connected internally, then the additional links connect two of the isolated groups. At the end, there happens to be two isolated groups in the network. The additionally discovered link that connects these two residual isolated groups, makes the network connected. And the number of links till the discovery of that link is deemed as the worst-case required number of links that makes the network connected. Therefore, (4-6) holds true and if we divide both sides of (4-6) by $n = \binom{N}{2}$ and replace the variables that depict the link counts, we have

$$\begin{aligned} 2\frac{x}{n} &> 2\frac{(N - M_2)(N - M_2 - 1) + M_2(M_2 - 1)}{N(N - 1)} \\ r &> \frac{(N - M_2)(N - M_2 - 1) + M_2(M_2 - 1)}{N(N - 1)}, \end{aligned} \quad (4-7)$$

where r is the ratio of the discovered links to the total number of links in a network of N nodes (4-3). The worst case scenario occurs when there are two isolated groups with $N-1$ and 1 nodes in those last two isolated groups; that is, when $\Psi = N - 1$ and $M_2 = 1$. Then, the condition becomes simply $r > 1 - \frac{2}{N}$. We call $100r$ as the Required link percentage (RLP) for network connectivity which is the required percentage of links to make the network connected. For various values of M_2 and N , RLP values are shown in Figure 4-3.

Assume an indoor 60 GHz network, where there are 20 nodes in a room, $N=20$, then RLP becomes 90% as can be seen in Figure 4-3. Therefore, discovery of the 90% of all

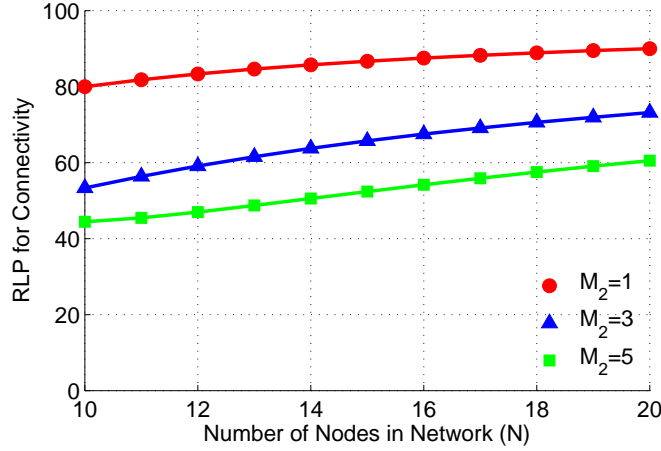


Figure 4-3: RLP values to assure connected network for different N and M_2 values

possible links assures connectivity for an indoor network. Consequently, in the worst case, discovery of 90% of all possible links assures the existence of a path between any two nodes in a network. In the sequel, we denote the required number of search cycles for discovering the 90% of all possible links with T_R^{RS} , T_R^{SRS} using the RS and SRS strategies, respectively. The reduction percentage of the neighbor discovery duration when SRS strategy employed instead of the RS strategy is called as neighbor discovery improvement (NDI) where

$$NDI = 100 \frac{T_R^{RS} - T_R^{SRS}}{T_R^{RS}}. \quad (4-8)$$

For successful discovery of links two nodes should be in complementary Tx-Rx states when they align their sectors in a search cycle. In the next section we investigate the impact of state probabilities and verify optimum state probability derived in [74] by means of simulations.

4-4 Impact of State Probabilities

The optimal state probabilities (probability of acting as a transmitter or receiver) for uniform random selection of sectors is analyzed in [74] which requires information about the number of nodes in the network. Ideal p_t values are calculated for a range of α and N values typical for home networks according to (4-9) [74]. This value of p_t also optimizes fraction of neighbors discovered within a certain duration of time. The optimal values of the state probabilities are not influential in a wide range for realistic beam-widths, α and number of nodes, N (see Figure 4-4). This implies that assigning a p_t value close to optimum value is possible without number of nodes information.

$$p_t = \frac{(2 + (N - 1) \frac{\alpha^2}{4\pi^2}) - \sqrt{(2 + (N - 1) \frac{\alpha^2}{4\pi^2})^2 - 4N \frac{\alpha^2}{4\pi^2}}}{\frac{N\alpha^2}{2\pi^2}}. \quad (4-9)$$

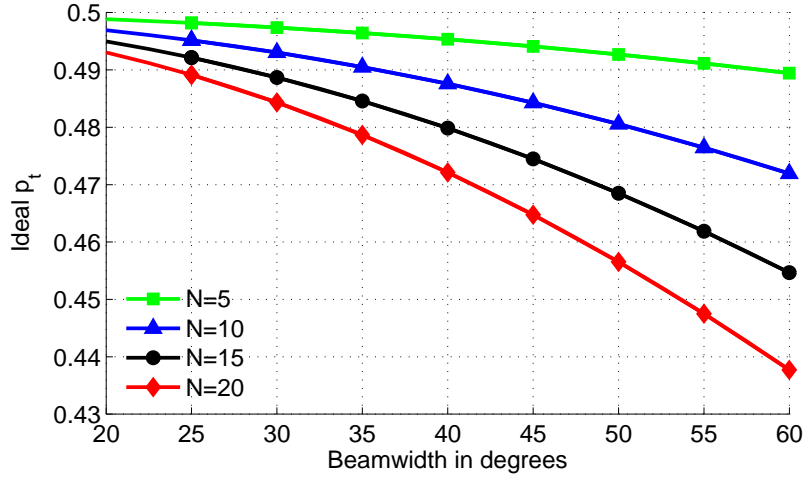


Figure 4-4: Range of ideal p_t values for different α and N

In this work, the nodes act as a transmitter with a probability p_t . Optimum value for p_t is calculated as in the reference and employed in the simulations but impact of p_t value is also investigated for a certain range (Figure 4-5). Although SRS is not making uniform selections among sectors in S , it is observed that its performance is better with this state selection method than using simply equal probabilities for transmission and reception states. Since there is no close form distribution formula for sector selection of SRS it is cumbersome to write down a cost formula for state selection to minimize search duration. Proposed state selection method could be close to optimal for SRS because of similar nature of RS and SRS. Simulation results show SRS performs better when optimum p_t suggested in [74] is used but mathematical verification is not trivial.

At each search cycle τ , a node acts as a transmitter with probability p_t or a receiver with probability $1-p_t$. We investigate impact of state transmission probability on ND and it is seen that assigning an optimum value which depends on N and α provides advantage to reduce discovery time. A specific case where $\alpha=30^\circ$, $N=10$ and $L/W=1.1$ is simulated for $[0.3 \ 0.7]$ range of p_t values. Optimum p_t value is calculated as 0.493 which is also shown in results in Figure 4-5.

4-5 Comparison of Scanning Strategies

In this section, we compare the NDI of SRS strategy over RS strategy. We simulate the neighbor discovery process for an indoor 60 GHz network where the room is modeled as a rectangular field with an aspect ratio of L/W . The transmitter and the receiver both use directional antennas where the beam-width is α . The impact of the network size on the required number of search cycles for network connectivity, T_R is shown in Figure 4-6 where $\alpha=30^\circ$ and $L/W=1.7$. The results are the averages of 2000 runs. As the number of deployed nodes in the room increases, the duration of the neighbor discovery process increases. However, if more than 10 nodes are deployed, the duration

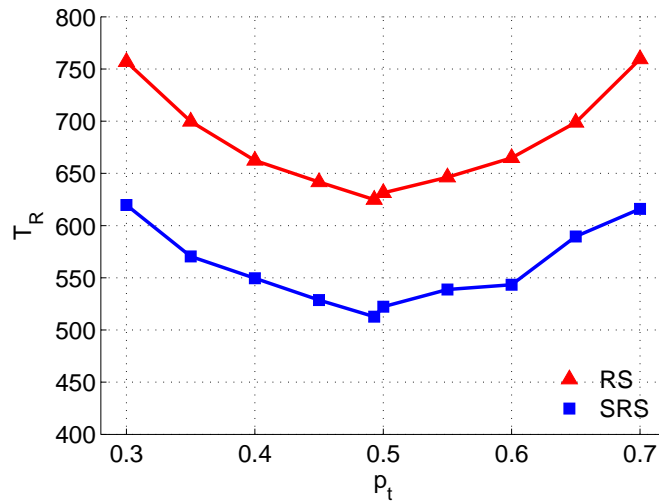


Figure 4-5: Impact of state probability, p_t on RS and SRS network connectivity achievement

stays steady. This is also the case for rooms with different aspect ratios but time to achieve network connectivity (T_R) is more insensitive to number of nodes if room shape is close to square. It should be noticed that strategies are compared for discovery of a certain portion of all links (e.g., 90%) and not the number of links. Larger number of nodes means more links to be discovered and there is more opportunity to discover multiple links at each cycle as the number of nodes increases. Increased number of nodes, randomness in node positions and random discovery create similar conditions for different scenarios. Divergence in performance occurs when finding last few links in scenarios with different number of nodes which is out of scope due to irrelevance with connectivity of network.

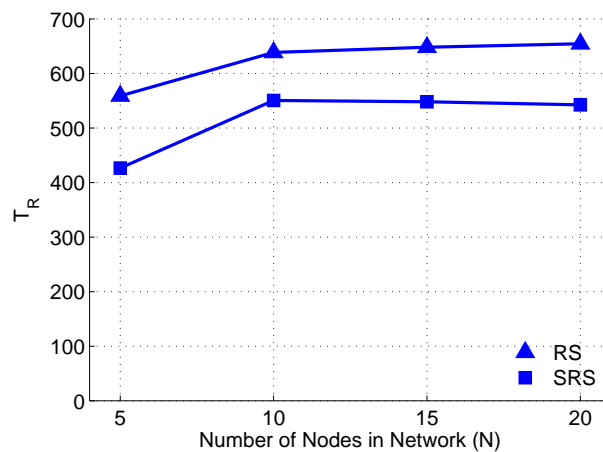


Figure 4-6: Performance comparison of RS and SRS strategies for discovering 90% of links

Effect of room shape is investigated by running simulations for rectangular fields with same area size and different aspect ratios. The NDI of SRS over RS is calculated ac-

According to simulations done for various aspect ratios. Different number of nodes are also considered and results can be seen in Figure 4-7. When the shape of the room is square (i.e., aspect ratio is 1), the NDI of SRS is larger and increasing number of nodes makes a slight effect in favor of SRS. Approximations errors on assigning p_j values are less in square areas which leads to an increase in the NDI. LW is kept constant at 60 in simulations of which results are given in Figure 4-7.

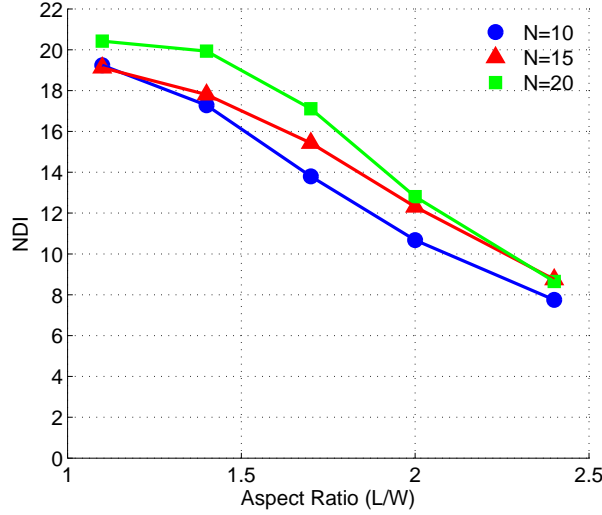


Figure 4-7: NDI for $\alpha=30^\circ$ and different N , L/W values

As SRS and RS methods are also investigated for different beam-widths it is seen that the NDI is larger when antennas with narrower beams are utilized. It is more advantageous to apply SRS with narrow beam antennas which can also be seen in Figure 4-8. Aspect ratio is 1.1 for these simulations.

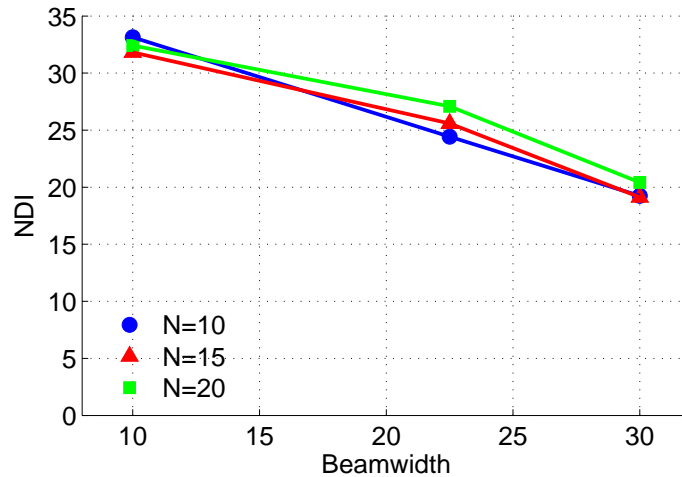


Figure 4-8: NDI comparison for various beam-widths and N values when $L/W=1.1$

4-6 Handling Extreme Cases

An extreme case causes degradation in the performance of the SRS strategy whereas it does not impact the performance of RS. The extreme case occurs when two nodes are close to same edge or corner of the room as shown in Figure 4-9 for *node 1* and *node 2*. The node which is closer to the center has to select its sectors towards small A_i to discover aforesaid neighbor (outlier neighbor). However, in the SRS, we increase the sector selection probability if its coverage area is large. For the case illustrated in Figure 4-9 when SRS is employed, *node 2* selects sectors towards *node 1* often but since A_3 is small compared to other sub-areas *node 1* is reluctant to check sectors towards *node 2*. Therefore, in this extreme case, the probability of selecting the sector towards the neighbor node which is closer to the corner is low. Consequently, in the SRS strategy, it takes longer to discover that neighbor.

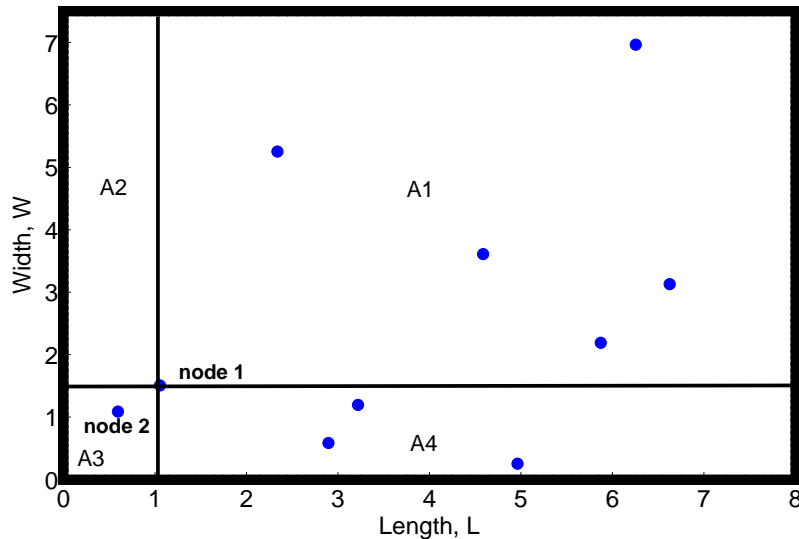


Figure 4-9: Extreme case illustration for $N=10$, and $L/W=1.1$

This extreme case becomes more influential when the approximation error in the calculation of sectoral coverage area increases especially if antennas with a larger beam-width are used. Note that, the degradation starts after the discovery of some neighbors. SRS always outperforms RS in initial phase of ND and discovers first neighbors faster. Collaboration among previously discovered nodes can be initiated to exchange the location information to mitigate the discovery performance in this extreme case. The nodes located closer to borders of the room may have mutual neighbors which are located close to middle of the room. These mutual neighbors could pass location information during the neighbor discovery process to each other and assist them to discover the other neighbors which are closer to the borders. If a node knows that there is another node which is closer to the border through the information obtained from a mutual neighbor, it may adjust the sector selection probability to facilitate rapid discovery of the outlier node.

Another approach to mitigate this extreme case is to employ a Hybrid Random Scan (HRS). In the initial phase of neighbor discovery SRS strategy always leads faster discovery regardless of beam-width and other parameters. After the discovery of some subset of the links, the neighbor discovery process may switch to employ the RS strategy. This approach can be empowered with results of prior simulations. For example, if $\alpha=60^\circ$ and $N>6$, our simulations show that SRS performs better than RS until 60% of links are discovered in all room shapes. A node can start with SRS and switch to the RS strategy when it discovers 60% of its expected neighbors. The number of nodes in the network should be known to each node in this case but even if this information is not available it is unlikely to have a vast number of nodes in a home network. Nodes may assume 6–7 nodes in the network and initiate strategy switch from SRS to RS after finding 2–3 of their neighbors. This would be early if there are more nodes in the network but it would still reduce discovery duration. An example comparison is given for $N=10$, $\alpha=45^\circ$ and $L/W=2.4$ in Figure 4-10 where strategy changing decision was made empirically. Scanning strategy was changed before intersection of SRS and RS performance curves to obtain HRS.

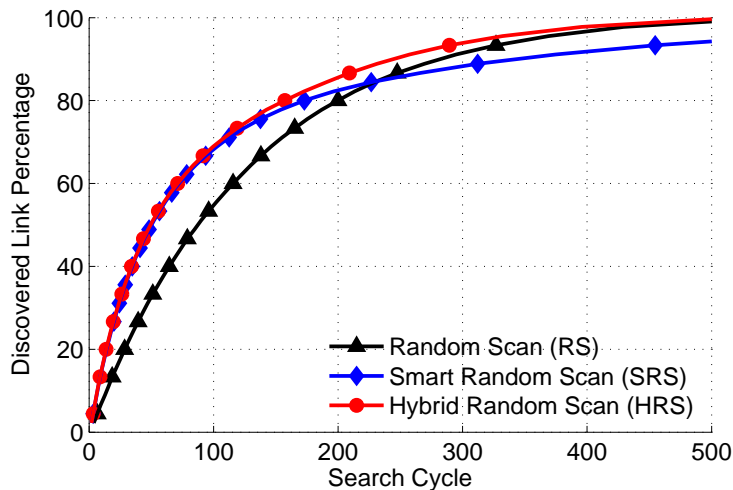


Figure 4-10: Performance comparison of strategies with HRS for $N=10$, $\alpha=45^\circ$ and $L/W=2.4$

4-7 Isolation in Network

Defining conditions for connectivity of a network with stochastic methods is cumbersome but isolation of nodes in a network also gives insight about network connectivity. A node is called *isolated* if it does not have any neighbor known to it. Isolation probability of all nodes in a network is relatively convenient to be investigated. Having degree $d>0$ for all N nodes in the network means no isolated node in the network [75]. Notice that this does not necessarily mean a connected network but if it is known that there is no isolated node, network is more likely to be connected. Nodes in the network may form clusters without connection to rest of the network and still having degree greater

than zero for all nodes but without providing connectivity of the network. Probability of a node discovering another node in a search cycle in a home network scenario as described in this work (see Figure 4-1) is defined in [74]. We start with this parameter to manipulate probabilistic isolation model for home networks composed of nodes with directional antennas. An expression for isolation probability of all N nodes until t^{th} search cycle is derived in this section. Without loss of generality a pair of nodes in discovery process are called node i and node j .

Probability that node i discovers node j in one search cycle, $p_{i,j}$ is given as [74],

$$p_{i,j} = \frac{1}{k^2} p_t \left(1 - \frac{1}{k^2} p_t\right)^{N-2} (1 - p_t), \quad (4-10)$$

where k is number of sectors for each node and p_t is optimum transmission state probability (4-9) [74]. We now define $q_{i,j}$ as probability that nodes i and j discover each other in a search cycle regardless of the initiator of handshake that is necessary for successful discovery. Probability that nodes i and j discover each other in one search cycle is

$$q_{i,j} = 2p_{i,j}. \quad (4-11)$$

Multiplication by 2 in (4-11) is due to the complimentary state probabilities. In derivation of $p_{i,j}$ it is assumed that node i is in transmission state and node j is in reception state when they are aligned [74]. But discovery process can also be successful if node j is in transmission state and node i is in reception state. That is why $q_{i,j}=2p_{i,j}$.

There are N nodes in the network and node i has $N-1$ potential neighbors to be discovered at each search cycle. For node i , the probability of discovering any of its neighbors in a search cycle and not specifically node j is

$$\binom{N-1}{1} q_{i,j}. \quad (4-12)$$

It is also possible to discover multiple neighbors in one search cycle. The probability of discovering u of neighbors in a search cycle, which is denoted with q_{iu} is

$$q_{iu} = \binom{N-1}{u} (q_{i,j})^u \left(\frac{1}{k}\right)^{u-1}, \quad (4-13)$$

where $u=1 \dots N-1$ and $\left(\frac{1}{k}\right)^{u-1}$ is the probability of having $u-1$ of selected u neighbors in the same sector of node i together with node j . Here, we ignore the probability of collisions when multiple nodes are sending handshake packets which is also the case for simulations. Then, the probability of discovering neighbors (one or multiple) in one search cycle, which is denoted with P is

$$P = \sum_{u=1}^{N-1} q_{iu} = \sum_{u=1}^{N-1} \binom{N-1}{u} (q_{i,j})^u \left(\frac{1}{k}\right)^{u-1}. \quad (4-14)$$

Neighbor discovery period is divided into search cycles and probability calculations were done for the first search cycle in ND period up to now. To generalize, discovering one or multiple neighbors in the t^{th} search cycle is also investigated. A specific pair of nodes may execute more than one successful handshake during ND period but only the first one is counted as neighbor discovery for that pair of nodes. The probability of node i finding one or more (at most $N-1$) neighbors in t^{th} search cycle is

$$(1 - P)^{t-1}P. \quad (4-15)$$

It should be noticed that node i does not find any neighbors until t^{th} search cycle according to (4-15). Discovery of neighbors within t search cycles is a different problem than the one considered in (4-15) but this will also be addressed to explain probability of isolation until t^{th} time slot. Probability of discovering neighbors within t search cycles can be found by adding probabilities of discovering one or more neighbors from 1^{st} to t^{th} search cycles. Then, the probability of node i discovering one or more neighbors within t search cycles is

$$\sum_{c=1}^t (1 - P)^{c-1}P. \quad (4-16)$$

Considering all N nodes are scanning for their neighbors independently, for all N nodes discovering one or more neighbors within t search cycles is investigated and P_{ni} is defined as probability of having no isolated nodes in the network. Then, the probability of having no isolated nodes among N nodes is

$$P_{ni} = \left(\sum_{c=1}^t (1 - P)^{c-1}P \right)^N. \quad (4-17)$$

An isolation occurs in a network if any of N nodes has degree $d=0$. Thus, isolation probability is $(1-P_{ni})$ and it is denoted with P_{iso} . Probability of isolation, P_{iso} can be written in open form by inserting previously found expressions as

$$\begin{aligned} P_{iso} &= 1 - P_{ni} \\ &= 1 - \left\{ \sum_{c=1}^t \left(1 - \sum_{u=1}^{N-1} \binom{N-1}{u} (2p_{i,j})^u \left(\frac{1}{k}\right)^{u-1} \right)^{c-1} \sum_{u=1}^{N-1} \binom{N-1}{u} (2p_{i,j})^u \left(\frac{1}{k}\right)^{u-1} \right\}^N. \end{aligned} \quad (4-18)$$

4-7-1 Isolation Model Results

P_{iso} values (4-18) are calculated for different beam-widths and N to see trend in isolation behavior. Figure 4-11 shows monotonically decreasing probability of isolation values for $\alpha=30^\circ$ ($k=12$) and various N . This figure illustrates analytical results of P_{iso} given in (4-18) and verification by simulations is given in subsection 4-7-2. As can be seen in Figure 4-11 for a network consisting of N nodes probability of being isolated (having

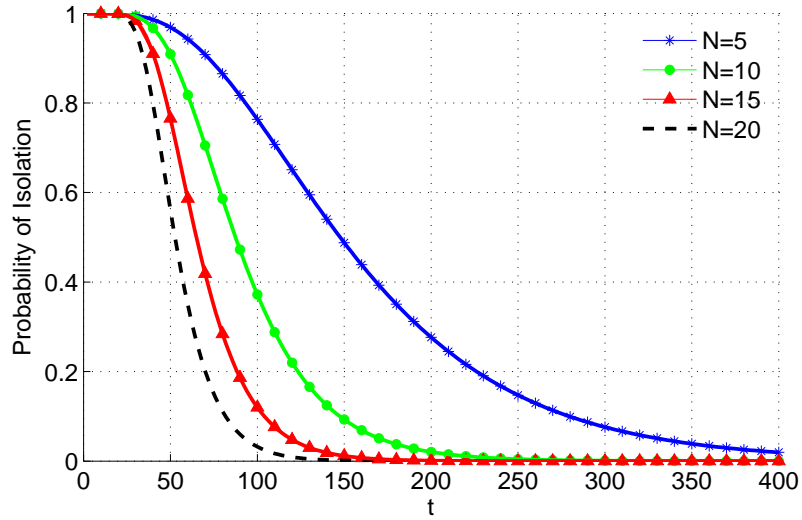


Figure 4-11: Probability of isolation, P_{iso} when $\alpha=30^\circ$ for different N values

at least one node without any neighbors) decreases as time progresses. Matlab source code to obtain Figure 4-11 is given in Appendix A.

If the network has nodes with larger beam-widths it takes less time to discover neighbors and get out of isolation state for each node. It can be seen in Figure 4-12 which shows P_{iso} values calculated according to (4-18) for $N=10$ and various beam-widths.

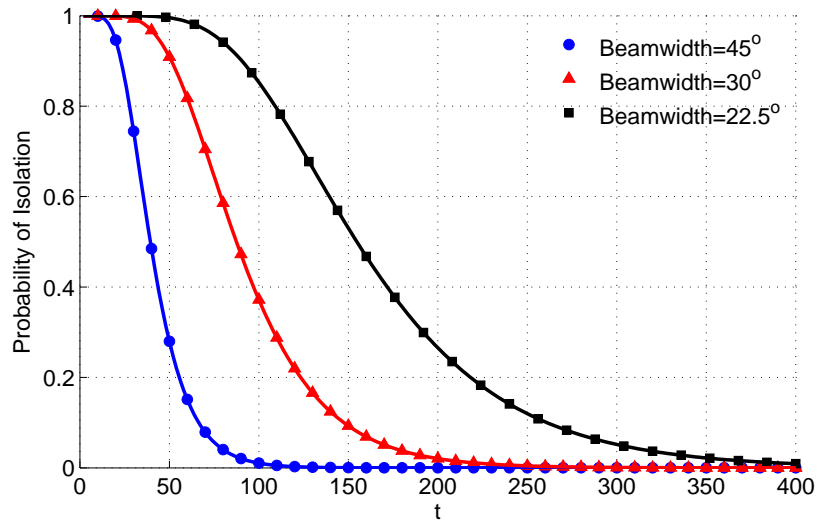


Figure 4-12: Probability of isolation, P_{iso} when $N=10$ for different α values

It is possible to use (4-18) to determine neighbor scanning duration for a certain probability of isolation. To obtain an isolation probability less than a specific value P^* neighbor scanning should continue more than a specific duration t^* . We use (4-18) to

find t^* which provides $P_{iso}=P^*$,

$$t^* = \log_{(1-P)} \left(1 - (1 - P^*)^{\frac{1}{N}} \right). \quad (4-19)$$

Selecting neighbor scanning duration $t \geq t^*$ provides $P_{iso} \leq P^*$. t^* values are shown for a range of N and α values in Figure 4-13 when $P^*=0.05$ and $P^*=0.2$.

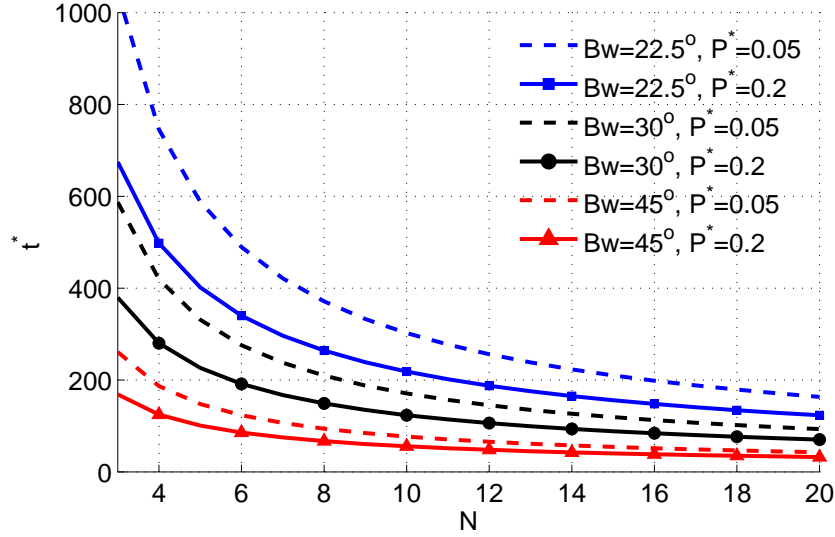


Figure 4-13: Neighbor scanning durations for various N , α values when $P^*=0.05$ and $P^*=0.2$

This model is created based on RS strategy and it has been shown that SRS strategy outperforms RS especially when finding first neighbors. P_{iso} values calculated according to this model forms an upper bound for SRS strategy and nodes are released from isolation faster with SRS strategy. This is also tested by means of simulations and it will be discussed in subsection 4-7-2.

4-7-2 Verification by Matlab Simulations

Extensive simulations were executed in Matlab environment to test validity of isolation model. Performance of SRS and RS strategies on releasing network from isolation is tested and compared with each other and with analytical results. Simulation environments were similar to previous performance evaluation simulations but different data which exhibits isolation behavior of network was collected. At each simulation run N nodes were randomly deployed in a rectangular area with aspect ratio L/W (e.g. Figure 4-1), RS and SRS strategies were applied to discover neighbors. A simulation was repeated 3000 times for a specific t value and probability of isolation were found with relative frequency calculation. In simulations probability of isolation after t search cycles is denoted with $Q_{iso}(t)$ and it is calculated as follows,

$$Q_{iso}(t) = 1 - \frac{\hat{s}(t)}{3000}, \quad (4-20)$$

where $\hat{s}(t)$ is number of simulations in which all N nodes managed to discover at least one neighbor within t search cycles and iso stands for *isolation*. Figure 4-14 shows $Q_{iso}(t)$ values for SRS and RS together with P_{iso} (4-18) when $N=10$, $\alpha=30^\circ$ and $L/W=1.1$. Line labeled as *Analytical* shows values of P_{iso} (4-18) and other two lines are simulation results. RS strategy simulations closely match with analytical results, which verifies derivation of P_{iso} . SRS provides faster relief from isolation as expected.

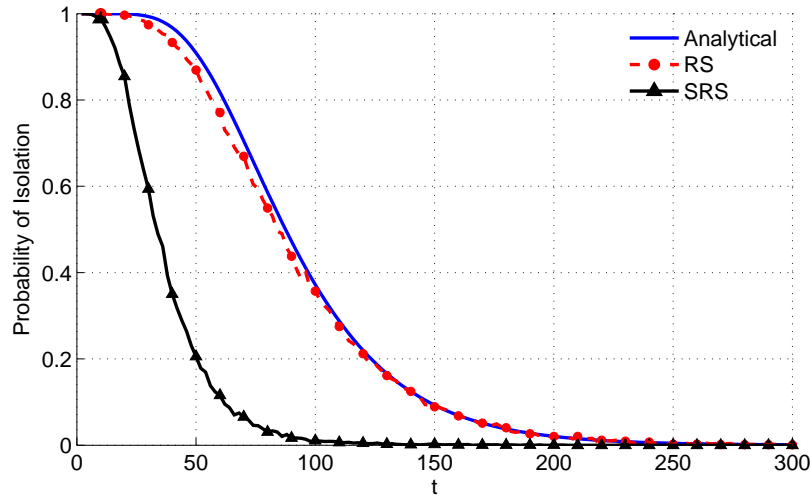


Figure 4-14: Verification of P_{iso} by RS and advantage of SRS for isolation when $\alpha=30^\circ$, $N=10$

Figure 4-15 depicts comparison between isolation model and simulations for $N=10$, $\alpha=45^\circ$ and $L/W=1.1$. Simulations for different N and aspect ratios were done and it is seen that aspect ratio does not effect the match between RS strategy simulations and isolation model which shall be taken granted. It should be noted alignment between two nodes does not depend on shape of the area as long as range of nodes are long enough to cover each other and P_{iso} expression does not include any parameters regarding shape of network environment. Some sample results are presented here for illustrative purposes but simulations also verified isolation model for different parameter values.

Verification of isolation model with same N , α values and different aspect ratios is depicted in Figure 4-16(a) and 4-16(b). Match between simulations and analytical model is insensitive to aspect ratio but SRS performs better when the aspect ratio is closer to 1 as mentioned before in section 4-5.

Verification of isolation model with same L/W , α values and different number of nodes is depicted in Figure 4-17(a) and 4-17(b). Simulations verify isolation model for different number of nodes as well. With 5 nodes in the network all possible number of links ($n=10$) is relatively low and the gap between having at least one neighbor for each node and reaching full connectivity (discovery of all neighbors for all nodes) is small. There are not many neighbors to discover. That is why leaving isolation takes longer for the network when $N=5$ and simulation result curves are not very smooth; because n is small.

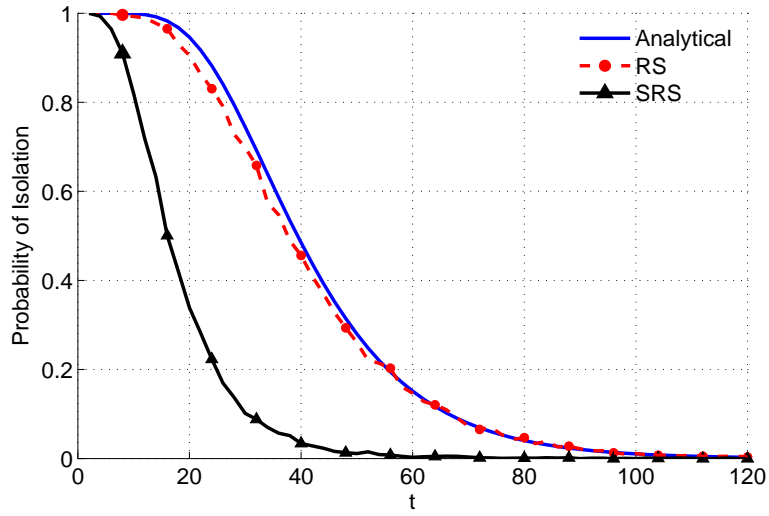
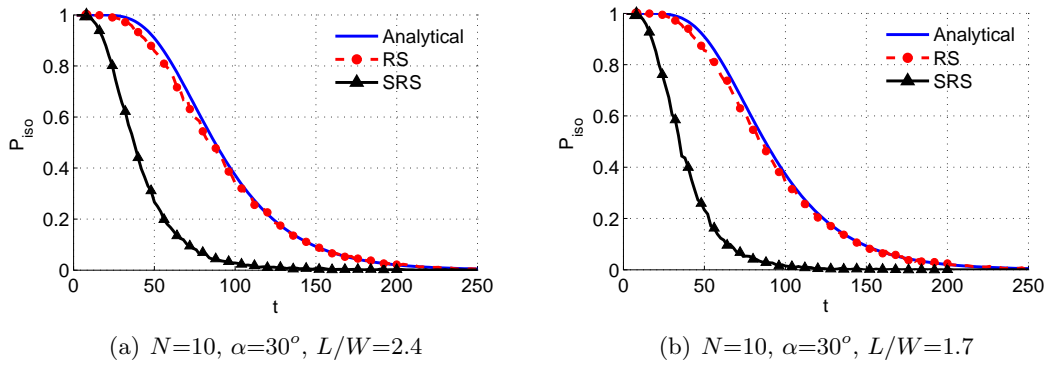


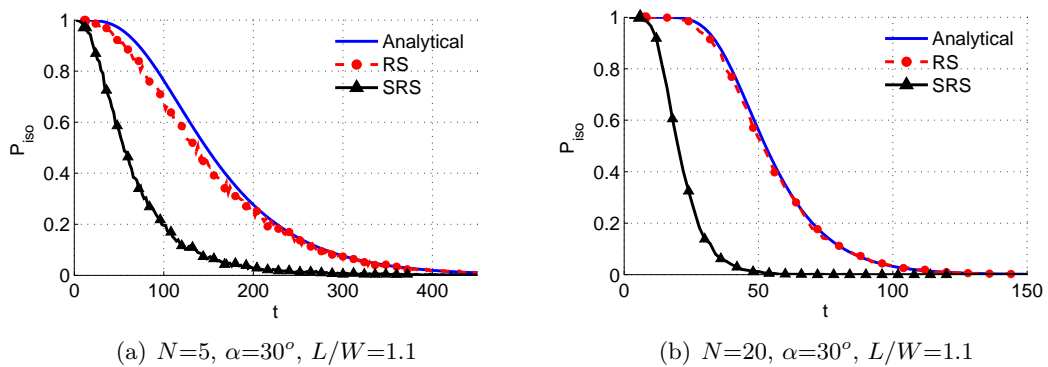
Figure 4-15: Verification of P_{iso} by RS and advantage of SRS for isolation when $\alpha=45^\circ$, $N=10$



(a) $N=10$, $\alpha=30^\circ$, $L/W=2.4$

(b) $N=10$, $\alpha=30^\circ$, $L/W=1.7$

Figure 4-16: Verification of P_{iso} for $N=10$, $\alpha=30^\circ$ and different L/W values



(a) $N=5$, $\alpha=30^\circ$, $L/W=1.1$

(b) $N=20$, $\alpha=30^\circ$, $L/W=1.1$

Figure 4-17: Verification of P_{iso} for $L/W=1.1$, $\alpha=30^\circ$ and different N values

4-8 Conclusions on Smart Neighbor Scanning

60 GHz frequency has advantage on directivity due to its millimeter range wavelength. Directional antennas are easier to realize for high frequencies and they can be used to compensate extra path loss disadvantage of 60 GHz band. Using directional antennas at both ends of communication increases deafness problem and prolongs neighbor discovery period. Smart algorithms should be developed to tackle neighbor discovery challenge of directional communication and fully utilize its benefits.

In this chapter, we proposed a smart directional neighbor scanning strategy to reduce the directional neighbor discovery time in indoor networks operating at 60 GHz. It is observed that the proposed strategy discovers 70% of the links 81% faster and 90% of the links 15% faster than random scanning strategy for a typical case (Figure 4-2) and variation of its benefits for different cases are mentioned. Additionally, a deterministic network connectivity relation between number of nodes and required ratio of links is derived. We also consider combining the SRS with a gossip-based collaboration scheme to tackle the extreme cases and further reduce the neighbor discovery time. Leaving isolation status for all nodes is a step in a network to provide a path between arbitrary two nodes, that is to say achieving network connectivity. We presented a stochastic model to examine trends in isolation for different parameter values in home networks and verified it with simulations.

Chapter 5

Conclusions

Benefits of 60 GHz directional communication are accompanied with new challenges specific for high frequency signals and directional communication. The major challenges for the future 60 GHz home networks, high propagation and penetration losses, have been addressed analytically and through simulations in the context of relay communication. We showed that a single relay device properly positioned in the middle of the network area at the same height with other nodes can reduce path loss 33%. This result motivates the multi-hop communication for 60 GHz indoor networks and two hops are generally sufficient for typical indoor scenarios.

To reduce the directional neighbor discovery time in indoor networks operating at 60 GHz, we proposed a Smart Random Scan (SRS) strategy. It is observed that the proposed strategy discovers 70% of the links 81% faster and 90% of the links 15% faster than Random Scan (RS) strategy for a typical case. Advantage of SRS over RS is not always sufficient and we proposed Hybrid Random Scan (HRS) to be used for those cases. Additionally, a deterministic connectivity relation between number of nodes and required ratio of links is derived. Isolation in home network is also discussed and a stochastic model illustrating isolation trends for home networks is presented. Isolation model was tested by means of simulations and it was verified for various values of network parameters like number of nodes, beam-width and shape of deployment area. These simulations also showed that SRS strategy relieves network from isolation state a lot faster compared to RS strategy for all cases.

It is observed that SRS strategy always outperforms RS strategy in the initial phase of neighbor discovery process whereas SRS has disadvantages on discovery of last few remaining links in the network compared to RS strategy (e.g. after discovering 80% of all links RS strategy can outperform for remaining links as in Figure 4-10). This problem gets more severe when aspect ratio or the room diverges from 1 and wider beam antennas are employed. Both of these increase the approximation error on sector selection probability assignment as mentioned in subsection 4-2-2. A different approach to sector selection probability assignment can mitigate this problem but SRS strategy

is still sufficiently fast for initial link discovery phase and discovery of all links is not required to have network connectivity as discussed in section 4-3. Advantage of SRS at initial stage can be exploited for more advanced techniques like cooperative communication. Fast discovered subset of a network can help each other to learn about the rest of the topology more efficiently and effectively.

Deterministic scanning strategies like Circular Scan (CS) strategy have the advantages of simpler realization and no need for external information but they do not deliver sufficient performance. We also attempted to develop a deterministic scanning strategy which can outperform Random Scan (RS) strategy. Assigning unequal scanning periods to nodes (e.g. half of the nodes scan fast and other half scan slow) in a distributed fashion (e.g. nodes with odd node IDs scan fast and nodes with even node IDs scan slow) was one of our approaches and this method managed to lead faster discovery between two groups. It was difficult to introduce the nodes with same scanning pattern and same scan period to each other with this method. Assigning a fixed scan pattern to nodes leads discovery process to get stuck before discovery of all links. We failed to find a generic scan pattern which can deliver sufficient performance for different networks with various values of network parameters (e.g. number of nodes, deployment area, beam width can all change). There was no significant finding in the results of this work. That is why these methods were not presented in this report. We concluded that randomness is required to cope with random nature of ad hoc networks.

Location awareness is a rising trend and indoor positioning is more challenging due to accuracy requirements and inapplicability of commonly used outdoor systems like GPS. Location information is used for various practical applications classified under Location-based services (LBS) title. We investigated the benefits of location information from neighbor scanning aspect for Future Home Networks. There are studies in literature utilizing location information in different steps of communication such as polling, routing and neighbor discovery. Any algorithm developed for those phases of communication should not merely depend upon location information, since it may not always be available. We proposed a smart algorithm which can be utilized when location information is available and can be switched to random strategy when location information is unavailable.

As future work, non-uniform deployment of the nodes, the impact of the other influential parameters on the neighbor discovery and the fine-tuning of strategy enhancements such as decision of switching strategies between Smart Random Scan and Random Scan in Hybrid Random Scan can be investigated. A new design for assignment of sector selection probabilities which may depend upon simpler information, like distance to center of the room instead of exact location information, worths to be studied. Combining SRS strategy with a gossip-based collaboration scheme to tackle the extreme cases and further reduce the Neighbor Discovery duration could be considered.

Appendix A

Matlab Codes

A-1 Appendix Section

A-1-1 MATLAB source code for verification of analytical model

```
1 %Numerical Analysis to verify analytical model
2 clear all;
3 close all;
4 clc
5 %R: radius of the coverage of relay node, in meters
6 R=10;
7 %N:number of trials
8 N=106;
9 %r has distribution 2r/R2
10 %square of r has a uniform distribution
11 %allowing us to use "rand" function
12 ri_square=(R2)*rand(2,N);
13 %obtain r_i values
14 ri_array= ri_square.0.5;
15 %select greater one among two r values for each pair
16 r_max_array=max(ri_array);
17 %display numerical analysis results
18 disp('Mean and Variance of r1 and r2')
19 average=mean(ri_array(1,:))
20 variance=var(ri_array(1,:))
21 average=mean(ri_array(2,:))
22 variance=var(ri_array(2,:))
23 disp('Mean and Variance of max{r1,r2}')
24 average=mean(r_max_array)
25 variance=var(r_max_array)
26
27 %horizontal axis for histogram
28 hor=[0.05:0.1:(R-0.05)];
```

```

29 %necessary vectors for plotting pdf of  $\max\{r_1, r_2\} = (4r_m^3)/(R^4)$ 
30 r_m=[0.05:0.05:(R-0.05)];
31 pdf_r_m=(4*r_m.^3)/(R^4);
32 %plotting figure
33 figure
34 title('Histogram together with scaled pdf')
35 hold on
36 hist(r_max_array, hor);
37 plot(r_m, (N/10)*pdf_r_m, 'r', 'LineWidth', 3);
38 legend('Histogram', 'PDF of R_m', 'Location', 'NorthWest')
39 legend BOXOFF
40 hold off
41 xlabel('r')

```

A-1-2 MATLAB source code for probability of isolation

```

1 % Calculation for Probabability of Isolation analytical values
2 clear all
3 close all
4 clc
5 %Number of nodes
6 N_values=[5:5:20];
7 %k : number of sectors
8 k=12;
9 %bw=beamwidth of antenna
10 bw=(2*pi)/k;
11 t_values=[2:2:500];
12 %allocation for result matrix
13 result=zeros(numel(N_values),numel(t_values));
14
15 for index_1=1:numel(N_values)
16     N=N_values(index_1);
17     for index_2=1:1:numel(t_values)
18         t=t_values(index_2);
19
20         %ideal transmission probabilitly
21         part_1=2+(N-1)*((bw^2)/(4*(pi^2)));
22         part_2= sqrt((part_1^2)- (N*(bw^2))/(pi^2));
23         part_3=(N*(bw^2))/(2*(pi^2));
24         ideal_pt=(part_1-part_2)/part_3;
25         %multiplication by 2 is included in p_ij not to use another
26         %variable q_ij unlike derivation in related section
27         p_ij=(k^(-2))*ideal_pt*(1-((k^(-2))*ideal_pt))^(N-2)*(1-ideal_pt)
            *2;
28         p_iu_array=zeros(1,(N-1));
29         %up to N-1 neighbor can be discovered in a search cycle
30         for index=1:1:(N-1)
31             p_iu_array(1,index)=nchoosek((N-1),index)*p_ij^index*k^(1-
                index);
32         end
33         p_iu_array;
34         P=sum(p_iu_array);
35         P_star_array=zeros(1,t);

```



```

36         for index=1:l:t
37             P_star_array(1,index)=((1-P)^(index-1))*P;
38         end
39         P_star_array;
40         P_star=sum(P_star_array);
41         P_ni=P_star^N;
42         result(index_1,index_2)=P_ni;
43     end
44 end
45 %set fonts in figure
46 set(0,'defaultaxesfontsize',13);
47 set(0,'defaulttextfontsize',13);
48 figure
49 hold on
50 plot(t_values,(1-result(1,:)),'LineWidth',2);
51 plot(t_values,(1-result(2,:)),'g','LineWidth',2);
52 plot(t_values,(1-result(3,:)),'r','LineWidth',2);
53 plot(t_values,(1-result(4,:)),'k','LineWidth',2);
54 xlim([0 400])
55 hold off
56 grid on
57 xlabel('t')
58 ylabel('Probability of Isolation')
59 legend('N=5','N=10','N=15','N=20','Location','NorthEast');
60 legend BOXOFF

```

A-1-3 MATLAB source code for directional scanning function

```

1 function [discovery, fold] = ND_scanv01 (sec_seq, Range, k, r_off, loc)
2 %ND scanning function
3 %Sec_seq will be filled in call file, strategy is not decided here
4 %discovery vector has length C(N,2) and includes cycle number of
   discovery
5 %moment for that link
6 %fold has size C(N,2) x trial and includes binary numbers to show if link
   is
7 %discovered or not at that specific cycle
8
9 %determining number of nodes and trial
10 [N trial]=size(sec_seq);
11 dim_combin=nchoosek(N,2);
12
13 bw=(2*pi)/k;%bw=beamwidth of antenna
14 phi=0;
15 tmp=0;
16 %sec_seq: sequence of chosen sectors by N nodes in search phase
17 %boresight is direction centers of nodes according to their sector
   selection
18 %in radians, with respect to positive x axis, in 0-2pi range
19 boresight=zeros(N,trial);
20 %ideal transmission state probability
21 part_1=2+(N-1)*((bw^2)/(4*(pi^2)));
22 part_2= sqrt((part_1^2)- (N*(bw^2))/(pi^2));

```

```

23 part_3=(N*(bw^2))/(2*(pi^2));
24 ideal_pt=(part_1-part_2)/part_3;
25 %filling boresight information
26 for row_index=1:1:N
27     for col_index=1:1:trial
28         tmp=r_off(row_index,1)+sec_seq(row_index,col_index)*bw-(bw/2);
29         if (tmp>(2*pi))
30             boresight(row_index,col_index)= tmp-(2*pi);
31         else
32             boresight(row_index,col_index)= tmp;
33         end
34     end
35 end
36 % direction angle is given in [-pi pi] range, boresight is in [0 2pi]
    range, it should be same to
37 % compare, temp_brsght is used for this
38 temp_brsght=zeros(N,trial);
39 for row_index=1:1:N
40     for col_index=1:1:trial
41         if( boresight(row_index,col_index)>pi)
42             temp_brsght(row_index,col_index)= boresight(row_index,
                col_index)-(2*pi);
43         else
44             temp_brsght(row_index,col_index)= boresight(row_index,
                col_index);
45         end
46     end
47 end
48 %seperation between dir angle and boresight: sep_angle
49 %check if second node is in cone of first one
50 %necessary number of range checks is C(N,2)
51 norm_check=zeros(dim_combin,1);
52 %dir angle: angle of vector from source to destination
53 %first column of dir_angle matrix saves angle from ith node to jth node (
    j>i)
54 %second column of dir_angle matrix saves angle from jth node to ith node
    (j>i)
55 dir_angle= zeros(dim_combin,2);
56 angle_check=2*ones((2*dim_combin), trial);
57 sep_angle=(2*pi)*ones((2*dim_combin),trial);
58 ch_vector=zeros(1,2);
59 %checking range and if counter node is in cone of scanning node
60 row_index=0;
61 for index_1=1:1:(N-1)
62     for index_2=(index_1+1):1:N
63         row_index=row_index+1;
64         %for the angle from ith node to jth node draw vector from j to i
65         ch_vector=loc(index_2,:)-loc(index_1,:);
66         if (norm(ch_vector)<Range)
67             norm_check(row_index,1)=1;
68         else
69             norm_check(row_index,1)=0;
70         end

```

```

71         dir_angle(row_index,1)=atan2(ch_vector(1,2),ch_vector(1,1));
72         dir_angle(row_index,2)=atan2(-ch_vector(1,2),-ch_vector(1,1));
73     end
74 end
75
76 for col_index=1:1:trial
77     row_index=0;
78     for index_1=1:1:(N-1)
79         for index_2=(index_1+1):1:N
80             row_index=row_index+1;
81             tmp=norm(temp_brsght(index_1,col_index)-dir_angle(row_index
82                 ,1));
83             if (tmp>pi)
84                 sep_angle(row_index,col_index)=norm(tmp-(2*pi));
85             else
86                 sep_angle(row_index,col_index)=tmp;
87             end
88         end
89     end
90
91     for col_index=1:1:trial
92         row_index=dim_combin;
93         for index_1=1:1:(N-1)
94             for index_2=(index_1+1):1:N
95                 row_index=row_index+1;
96                 tmp=norm(temp_brsght(index_2,col_index)-dir_angle((row_index-
97                     dim_combin),2));
98                 if (tmp>pi)
99                     sep_angle(row_index,col_index)=norm(tmp-(2*pi));
100                else
101                    sep_angle(row_index,col_index)=tmp;
102                end
103            end
104        end
105
106     for row_index=1:1:(2*dim_combin)
107         for col_index=1:1:trial
108             if (sep_angle(row_index,col_index)<bw/2)
109                 angle_check(row_index,col_index)=1;
110             else
111                 angle_check(row_index,col_index)=0;
112             end
113         end
114     end
115     fold_01=angle_check(1:dim_combin,:);
116     fold_02=angle_check((dim_combin+1):(2*dim_combin),:);
117     fold_tmp=fold_01.*fold_02;%check if both nodes are in coverage of each
118     other
119     fold_tmp2=3*ones(dim_combin,trial);%allocation
120     %fold_tmp3=3*ones(dim_combin,trial);
121     %flags to check if the parties are transmitting or listening

```

```

121 %if value is 1 that node is transmitting, if 0 node is listening
122 %initialize to an invalid value
123 tx_rx_flag01=3; %dummy flag variables
124 tx_rx_flag02=3;
125 for row_index=1:1:dim_combin
126     for col_index=1:1:trial
127         if (fold_tmp(row_index, col_index)==1) %check tx-rx conditions
128             only when antennas are aligned
129             tmp=rand; %to see if first node is tx or rx
130             if (tmp>ideal_pt) %then it is listening
131                 tx_rx_flag01=0;
132             else
133                 tx_rx_flag01=1;
134             end
135             tmp=rand; %to see if second node is tx or rx
136             if (tmp>ideal_pt) %then it is listening
137                 tx_rx_flag02=0;
138             else
139                 tx_rx_flag02=1;
140             end
141             if ((tx_rx_flag01+tx_rx_flag02)==1)
142                 fold_tmp2(row_index, col_index)=1;
143             else
144                 fold_tmp2(row_index, col_index)=0;
145             end
146         else
147             fold_tmp2(row_index, col_index)=0;
148         end
149     end
150 end
151 end
152
153 fold=3*ones(dim_combin,trial);
154 fold=fold_tmp2;
155 %pad 1s to last column to assume they found each other at last part if
156     they
157 %didn't before, this was done to prevent an error
158 fold(:,trial)=ones(dim_combin,1);
159 %norm check
160 % for index_1=1:1:trial
161 %     fold(:,index_1)=norm_check.*fold_tmp2(:,index_1);
162 % end
163 %node i and j are assumed to have same range, so norm check is done one
164     way only
165 discovery=zeros(dim_combin,1); %allocation for output
166 for index_1=1:1:dim_combin
167     discovery(index_1,1)=min(find(fold(index_1,:)==1));
168 end

```

A-1-4 MATLAB source code for calling scan function for RS and SRS

```

1  %calling code for ND scanning function
2  % this one will create desired sector selection matrix and give as an
   input
3  % to scanning function
4
5  %clear history
6  clear all
7  close all
8  clc
9  %width and length of room
10 W=7.5;
11 L=8;
12 Range=14;%range of nodes , long enough to cover all room
13 N=10;%N:number of nodes
14 monte_lim=2000;%number of Monte Carlo simulations
15 k=12;%k: number of sectors for each node
16 bw=(2*pi)/k;%bw=beamwidth of directional antennas
17 phi=0;
18 tmp=0;
19 trial=2000; %trial: number of trials to discover nodes
20 %all nodes give up after 'trial' number of search cycles
21 %allocation of necessary matrices
22 dim_combin=nchoosek(N,2);
23 discovery_matrix_SRS=zeros(dim_combin, monte_lim);
24 discovery_matrix_RS=zeros(dim_combin, monte_lim);
25 %sequence of chosen sectors by N nodes stored in sec_seq matrices
26 %'sec_seq' stands for sector sequence
27 sec_seq_SRS=zeros(N, trial);
28 sec_seq_RS=zeros(N, trial);
29
30 %start to Monte Carlo simulations
31 tic %time measurement of simulations
32 for index_monte=1:1:monte_lim
33     %random orientation for each node to simulate random alignment of
       nodes
34     r_off=bw*rand(N,1);
35     %loc: random locations of nodes within area of interest
36     loc=rand(N,2) .* [L*ones(N,1) W*ones(N,1) ];
37     %calculation of approximation areas, A_i's
38     %a1,a2,a3 and a4 are rectangular approximations
39     %names are given with coordinate system convention
40     % a2 | a1
41     % -----
42     % a3 | a4
43     %these are listed consecutively in each row of area_matrix
44     area_matrix=zeros(N,4); %allocation
45     %calculation of A_i areas for each node
46     for index=1:1:N
47         area_matrix(index,1)=(L-loc(index,1))*(W-loc(index,2));
48         area_matrix(index,2)=loc(index,1)*(W-loc(index,2));
49         area_matrix(index,3)=loc(index,1)*loc(index,2);

```

```

50     area_matrix(index,4)=(L-loc(index,1))*loc(index,2);
51     end
52
53     %area matrix normalized with area of room
54     %this is done to have 1 as sum of assigned probabilities
55     area_matrix_norm=area_matrix/(L*W);
56
57     %Assigning sectors to each region for SRS
58     %sectors from 1 to k will be assigned to one of 4 A_i regions
59     det_sec=zeros(N,k);
60     tmp_det_sec=zeros(N,k);
61     %boresight is direction centers of nodes according to their sector
        selection
62     %in radians, with respect to positive x axis, in 0-2pi range
63     %boresight of sectors from 1 to k is stored in 'tmp_det_sec'
64     for row_index=1:1:N
65         for col_index=1:1:k
66             %filling in all k boresights for N nodes
67             tmp=r_off(row_index,1)+col_index*bw-(bw/2);
68             %this check is to prevent obtaining angles larger than 2pi
69             if (tmp>(2*pi))
70                 tmp_det_sec(row_index,col_index)= tmp-(2*pi);
71             else
72                 tmp_det_sec(row_index,col_index)= tmp;
73             end
74         end
75     end
76     %determining sector directions WRT A_i regions
77     for row_index=1:1:N
78         for col_index=1:1:k
79             tmp=tmp_det_sec(row_index,col_index);
80             if ((0<=tmp)&&(tmp<(pi/2)))
81                 det_sec(row_index,col_index)= 1;
82             elseif (((pi/2)<=tmp)&&(tmp<pi))
83                 det_sec(row_index,col_index)= 2;
84             elseif ((pi<=tmp)&&(tmp<((3*pi)/2)))
85                 det_sec(row_index,col_index)= 3;
86             elseif (((3*pi)/2)<=tmp)&&(tmp<(2*pi)))
87                 det_sec(row_index,col_index)= 4;
88             else
89                 ;
90             end
91         end
92     end
93
94     %det_sec includes region information for each of k sectors for each
        node
95     %determining k_i values, this matrix includes k1,k2,k3,k4 values
96     %in each row in sequence for all N nodes
97     k_index=zeros(N,4);
98
99     for row_index=1:1:N
100         for col_index=1:1:4

```

```

101         k_index(row_index,col_index)=length(find(det_sec(row_index,:))
           ==col_index));
102     end
103 end
104 % a random real number will be chosen in [0 1]
105 %'limits' will be used to select sectors
106 %values in 'limits' are assigned according to p_j calculation
107 limits=zeros(N,(k+1));
108 limits(:,(k+1))=1;
109 for row_index=1:1:N
110     %note ai values are normalized values
111     a1=area_matrix_norm(row_index,1);
112     a2=area_matrix_norm(row_index,2);
113     a3=area_matrix_norm(row_index,3);
114     a4=area_matrix_norm(row_index,4);
115     %ki values
116     k1=k_index(row_index,1);
117     k2=k_index(row_index,2);
118     k3=k_index(row_index,3);
119     k4=k_index(row_index,4);
120     %initialization
121     col_index=1;
122     for tmp=1:1:k1
123         limits(row_index,(col_index+tmp))=(tmp*a1)/k1;
124     end
125     col_index=col_index+k1;
126     for tmp=1:1:k2
127         limits(row_index,(col_index+tmp))=a1+(tmp*a2)/k2;
128     end
129     col_index=col_index+k2;
130     for tmp=1:1:k3
131         limits(row_index,(col_index+tmp))=a1+a2+(tmp*a3)/k3;
132     end
133     col_index=col_index+k3;
134     for tmp=1:1:k4
135         limits(row_index,(col_index+tmp))=a1+a2+a3+(tmp*a4)/k4;
136     end
137     col_index=col_index+k4;
138 end
139 limits(:,(k+1))=1;
140 %intelligent selection of sectors
141 for row_index=1:1:N
142     for col_index=1:1:trial
143         %random number generation to assign sector selections
144         tmp=rand;
145         for index=1:1:k
146             %testing in which interval 'tmp' is
147             if ((tmp-limits(row_index,(index+1)))<=0)
148                 sec_seq_SRS(row_index,col_index)=index;
149                 break
150             else
151                 ;
152             end

```

```

153         end
154     end
155 end
156
157 %calling scanning function for SRS
158 [discovery, fold] = ND_scanv01 (sec_seq_SRS, Range, k, r_off, loc);
159 discovery_matrix_SRS(:,index_monte)=discovery;
160 %generating sector selection sequence for RS
161 sec_seq_RS=randint(N,trial,[1 k]);
162 %calling scanning function for RS
163 [discovery, fold] = ND_scanv01 (sec_seq_RS, Range, k, r_off, loc);
164 discovery_matrix_RS(:,index_monte)=discovery;
165 end %end of monte Carlo Simulations
166 toc
167 %average of outputs and saving them to txt files
168 avg_SRS=mean(sort(discovery_matrix_SRS)')';
169 avg_RS=mean(sort(discovery_matrix_RS)')';
170 dlmwrite('avg_SRS_N_10_k_12_W_15_L_16.txt', avg_SRS, 'delimiter','\t')
171 dlmwrite('avg_RS_N_10_k_12_W_15_L_16.txt', avg_RS, 'delimiter','\t')
172 dlmwrite('discovery_matrix_SRS_N_10_k_12_W_15_L_16.txt',
173         discovery_matrix_SRS, 'delimiter','\t')
174 dlmwrite('discovery_matrix_RS_N_10_k_12_W_15_L_16.txt',
175         discovery_matrix_RS, 'delimiter','\t')
176 %scaled y axis data
177 in=[1:1:dim_combin]*(100/dim_combin);
178 %plotting figure
179 set(0,'defaultaxesfontsize',13);
180 set(0,'defaulttextfontsize',13);
181 figure
182 hold on
183 plot(avg_SRS,in,'r','LineWidth',2)
184 plot(avg_RS,in,'b','LineWidth',2)
185 title('Performance Comparison')
186 xlabel('Search slot index/Time index')
187 ylabel('Percentage discovered links')
188 xlim([0 1000]);
189 hold off
190 grid on
191 legend ('Smart Random Scan (SRS)', 'Random Scan (RS)', 'Location', '
192         SouthEast')
193 legend BOXOFF

```

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Glossary

List of Acronyms

AAF	amplify-and-forward
ACK	Acknowledgement
AoA	Angle of Arrival
AP	Access Point
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CS	Circular Scan
CSMA/CA	Carrier sense multiple access with collision avoidance
CTS	Clear to Send
DAF	decode-and-forward
DARPA	Defense Advanced Research Projects Agency
DCF	Distributed Coordination Function
DMAC	Directional Medium Access Control
DNAV	Directional Network Allocation Vector
EM	Electromagnetic
FHN	Future Home Networks
GPS	Global Positioning System
HDMI	High-Definition Multimedia Interface
HD TV	High-Definition Television

HN	Home Network
HRS	Hybrid Random Scan
ISM	industrial, scientific and medical
LBS	Location-based services
LoS	Line of Sight
LPD	low probability of detection
LPE	low probability of exploitation
LPI	low probability of interception
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
Mbps	Mega bits per second
ND	Neighbor Discovery
NDI	neighbor discovery improvement
NLoS	Non-Line of Sight
PNC	piconet controller
QoS	Quality of Service
RLP	Required link percentage
RS	Random Scan
RTS	Request to Send
Rx	Receiver
SNR	Signal to Noise Ratio
SRS	Smart Random Scan
Tx	Transmitter
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network