Directional Neighbor Discovery in 60 GHz Indoor Wireless Networks

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ABSTRACT

The unlicensed 60 GHz band brings the promise of multi-gigabit data rates to support new applications such as high definition video over wireless links. Signal propagation in the 60 GHz band significantly differs from that in the traditionally used 2.4 and 5 GHz bands. The propagation and penetration losses in the 60 GHz band are much higher. Furthermore, the signals are often *reflected* in indoor settings. Previous physical layer studies show that the use of directional antennas can significantly help in coping with these effects. In this paper, we address the problem of neighbor discovery in the 60 GHz band. We account for not only discovery via direct line-of-sight paths, but also via reflected beams. To the best of our knowledge, none of the previous efforts on higher layer protocols for use with directional antennas account for reflections. We consider two approaches for neighbor discovery (a) direct discovery where each node explicitly discovers its neighbors and, (b) gossip-based discovery where nodes exchange information with regards to their already discovered neighbors. We develop analytical models to capture the performance of the two approaches and validate the models via simulations in indoor settings with obstacles that reflect the transmitted signals. As one might expect, the gossip based discovery incurs a lower neighbor-discovery latency than direct discovery. We examine the impact of system parameters such as varying beamwidth and node density. Our study provides insights on the right choice of system parameters for efficient neighbor discovery in the 60 GHz regime.

Categories and Subject Descriptors

C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Networks—*Access schemes*

General Terms

Design, Performance

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Keywords

Directional antennas, 60 GHz, Neighbor discovery

1. INTRODUCTION

The unlicensed 60 GHz band has been the focus of recent attention as a candidate for materializing the transport of multimedia applications such as high definition (HD) video streaming over the wireless medium [1, 2, 3]. One may envision the construction of a wireless gigabit ethernet using the 60 GHz band. Compared with the maximum data rate of 54 Mbps supported by current wireless networks operating in the 2.4 GHz band (IEEE 802.11 b/g) or the 5 GHz band (IEEE 802.11a), the 60 GHz band can potentially support multi-gigabit data rates using 7 GHz of bandwidth; for the unlicensed 60 GHz band, the 57-64 GHz spectral regime in the US and the 59-66 GHz regime in Europe and Japan are reserved.

The 60 GHz band has distinct signal propagation characteristics as compared with the 2-5 GHz band. In particular, the propagation loss in the 60 GHz band (with the same transmitter and receiver antenna gains) is about 20-30 dB higher than in the 2-5 GHz bands. The penetration loss is also higher in the 60 GHz band. In addition, oxygen absorption is intensified as compared to the other bands. This absorption attenuates signals over distance by about 15 dB per km. The diffraction effects are much smaller in the 60 GHz band in comparison to the 2-5 GHz bands. The electromagnetic (EM) field of the 2-5 GHz signals is composed of diffracted and reflected waves and thus, has a complex structure with no traceable directions of arrival and departure of the signals. On the other hand, the EM field of a 60 GHz signal has a structure consisting of a few rays coming from the direct path (if available) and from first-order reflections; thus, the directions of arrival and departure are very close to what can be predicted with ray tracing (geometrical optics) laws. The experiments performed in indoor scenarios (such as in conference room, library, cubicle and aircraft environments) in [4, 5, 6] suggest that due to these reasons, communications between a transmitter and a receiver in this band are established via both direct and reflected beams.

The use of high-gain directional antennas can be especially attractive in the 60 GHz band, given the above propagation effects. They can significantly increase communication range and this can be especially useful given the high propagation loss in typical indoor 60 GHz environments [3, 6]. Furthermore, the use of directional antennas can limit the number of reflected beams and thereby increase space reuse [4]. Given the higher spectral regime of the 60 GHz band the requirement on the size of the antennas is drastically relaxed [1][2]; in this band, it is easy to fit many antenna elements on a small platform to create a high gain antenna array. In practice, an antenna array with more than 20 elements can achieve a gain of more than 13 dB [3]. In addition, the mitigated diffraction effects make it possible for highly directional antennas to focus most of the transmitted energy at the intended recipient; this drastically reduces the interference between links in the same geographic area.

We consider a 60 GHz wireless network in an indoor setting; we assume that nodes are equipped with antenna arrays that are capable of generating high gain focused beams. The distinct characteristics of the 60 GHz band make the problem of networking these nodes different from what has been considered before in the 2.4 and 5 GHz bands. In particular, one has to account for reflected beams when designing and evaluating protocols for neighbor discovery and media access control.

In this work, our objective is to analyze neighbor discovery in the 60 GHz band. Neighbor discovery in the considered setting is much different from that in traditional 2-5 GHz bands. *In this band, neighbors can be discovered not only via direct line-of-sight beams, but also via reflected beams; this possibility has not been considered before.* We consider two possible approaches for neighbor discovery viz., direct and gossip-based discovery, which were previously introduced for neighbor discovery with directional antennas in wireless networks [7] (the setting considered in [7] however, did not account for reflections that arise due to operations in the 60 GHz band). With direct discovery, a node discovers a neighbor only when it successfully receives a transmission from that neighbor. With gossip-based discovery, a node can discover a neighbor either via direct discovery or from some other node (possibly a different neighbor) that has information about that neighbor. Our work provides a basis for establishing links in the 60 GHz regime and insights on the choice of operational parameters to employ under different conditions (such as different node densities).

In more detail, the major contributions of our work are as follows:

- **We develop analytical models for both direct discovery and gossip-based discovery in the 60 GHz band.** The proposed models take into account both direct and reflected beams. These models can effectively characterize the performance of the considered approaches in different settings; in particular, variations in node density, and directional beamwidth can be characterized.
- **We build a simulation framework that reflects operations in the 60 GHz band and validate our analysis through extensive simulations.** In particular, our simulation framework accounts for the presence of obstacles (such as exterior and interior walls) in an indoor wireless network. We use a ray-tracing method to simulate the interactions between signal propagation and the obstacles. Our implementation accounts for penetration and reflection with proper loss. The behaviors of directional antennas with varying beamwidth are also captured in the simulations.
- **We comprehensively examine the impact of various key parameters (such as node density and antenna beamwidth) on the performance of the neighbor discovery schemes.** Our extensive studies in a typical indoor scenario reveal interesting trade-offs in performance, resulting from tuning the above parameters.

The rest of the paper is organized as follows. In Section 2, we discuss prior related work in 60 GHz band. Related work on the use of directional antennas in wireless networks is also discussed. In Section 3, we describe the two considered neighbor discovery approaches, namely, *direct discovery* and *gossip-based discovery*. In Section 4, we present our analytical models corresponding to the two neighbor discovery methods. The performance evaluations of the considered neighbor discovery methods via both simulations and using our models, are described in Section 5. We conclude in Section 6.

[1]The elements of an antenna array should be separated by a distance that is of the order of the wavelength in use.

2. RELATED WORK

Prior research efforts on the 60 GHz band have primarily focused on measuring and modeling the channel between a transmitter and a receiver in indoor and short range outdoor scenarios. In this section, we first review previous work on measurement and channel modeling. We then discuss related work on networking with directional antennas and in particular directional neighbor discovery in wireless networks.

Measurement Studies in the 60 GHz band: We categorize the previous work on measurements as follows:

A. Path Loss and Coverage: Channel measurements in [4, 8, 9] indicate that transmissions in the 60 GHz band experience a fixed loss (loss in the first meter or so) that is greater than 70 dB. This imposes stringent restrictions on the range of 60 GHz transmissions. The path-loss exponent is around 2 or smaller, but obstacles can cause significant variations in loss (e.g. from 6 dB for plywood panels to up to 48 dB for a brick wall) [8, 10]. The range and thus, interference from other transmissions that impact a given transmission are heavily environment dependent. Longer ranges are possible in open space as compared to indoor areas. Reflections that bypass the obstacles can also result in better coverage. Consequently, a receiver that is further (say $2x$ m) away may have an excellent link to a transmitter whereas a closer receiver (say just x m away) may not hear the transmitter. These artifacts have an impact on neighbor discovery.

B. Propagation mechanisms: Measurements in [4, 5, 6] show that in the 60 GHz band signal propagates via both a direct path and by means of reflections from objects. The work in [4] provides measurement results and analyzes the 60 GHz space-time channel in LOS (line-of-sight) room and hallway environments. Power delay profiles (PDPs) and power angle profiles (PAPs) are measured. The multipath structure retrieved from PDPs and PAPs demonstrates a strong correlation with the propagation environment. The measurement results in an aircraft [5] and in a conference room [6] reveal that a received 60 GHz signal is mainly a combination of the direct and first-order reflected (reflected only once) signals. The first-order reflected signals bounce off walls, the ceiling and the floor. Signals that penetrate through cubicle walls have been found to be sufficient for establishing communication links [6]. The work in [4] suggests that image-based ray tracing of first order reflections can be used for channel prediction in LOS applications. The work in [11] obtains a good match between the spatial and temporal characteristics of measured signals and those simulated using ray tracing.

Modelling the 60 GHz channel: With plenty of measurements, the IEEE 802.15.3c group [12] developed a 60 GHz channel model for library environment [13]. Based on the generalized Saleh-Valenzuela channel model (or S-V model for short), this statistical channel model accounts for both LOS and NLOS components, in both the time and angular domains. Most recently, a conference room channel model for 60 GHz WLANs was proposed in [14]. This model is partially based on experimental measurements in [6]. The proposed model structure again adopts the clustering approach (as with the S-V model) in both time and angular domains. Different types of

(a) Discovery via direct beam

(b) Discovery via reflected beam

Figure 1: Discovery via either direct beam or reflected beam

antennas with diverse antenna patterns can be characterized by the model. Furthermore, the model allows for antenna beamforming to be applied both at the transmitter and at the receiver. The proposed structure of the channel model can be applied to model other scenarios like cubicles and living rooms, if statistical characteristics specific to the scenario are available. The problem with the above two statistical models is that for each specific scenario, extensive experimental measurements are required. In contrast, our simulations are based on a simple partition based path loss model [15] and a ray tracing method used in conjunction. The partition based path loss model and simple deterministic ray tracing are reported to be efficient in terms of describing the general channel properties of the 60 GHz band. With this model, signal transmission between a transmitter and a receiver can be approximated as rays in different directions. For each specific ray, the total path loss can be calculated as the sum of the log-distance path loss and the partition attenuation factors (PAF), which correspond to the reflection or penetration losses.

Directional antennas in wireless networks: While protocols for directional antennas in wireless networks have received a lot of attention, most of the efforts are based on omni-directional receptions. There is limited work on fully directional communications [16][17]. As discussed earlier, the use of a directional antenna is desirable for 60 GHz operations since its beamforming ability can combat higher propagation losses and provide longer communication range. Some recent efforts address directional communications in the 60 GHz band [18, 19]. However, either outdoor networks are assumed [18] or only the blockage of beams by objects is considered [19]; reflections are ignored in these efforts. The key differences between prior efforts and our work are as follows: (a) all of the previous efforts assume that only a LOS path between a transmitter and its intended receiver is possible. However, NLOS (non-line-of-sight) communications are possible in the 60 GHz band due to reflections. (b) most previous efforts assume that a transmitted beam has a perfect conical shape and is of a fixed radial and angular range; any receiver within this range will receive the signal in the absence of interference. However, in the 60 GHz band, there are reflected beams which suffer different levels of attenuation from reflectors and thus, the previous assumption is no longer satisfied.

Neighbor discovery in wireless networks: There has been work in neighbor discovery (we refer to it as ND for short) using omni-directional and directional antennas [7, 17, 20]. Previous efforts on developing a ND algorithm simply assume that the omni-directional footprint is a circle and the directional footprint is a perfect cone. In addition, only a single LOS communication link between a transmitter and a receiver is assumed. However, neighbor discovery becomes much more complicated in 60 GHz indoor settings since a neighbor can be discovered not only via a direct beam, but also with reflected beams. Furthermore, interference also arises due to both direct and reflected beams.

3. NEIGHBOR DISCOVERY METHODS

In this section, we provide an overview of neighbor discovery (ND) first. Two approaches for ND, direct and gossip-based discovery that are considered in this paper, are then introduced. As mentioned earlier, these approaches are derived from what was proposed in [7] for directional antennas in line-of-sight settings.

3.1 Background

ND is an essential process in the self configuration of multi-hop wireless networks; MAC, routing, and topology-control in wireless networks require the discovery of neighbors. The discovery process should be as rapid as possible and typically facilitates the bootstrapping of other protocols that utilize the knowledge derived from ND. There are trade-offs between using omni-directional and directional communications for ND. An omni-transmission can potentially reach a larger group of neighbors; however, the interference effects are likely to be more pronounced than with directional communications. With fully directional communications, a lower level of interference is incurred since the beamwidth used for ND is usually much smaller than 2π. However, ND is more difficult since a pair of nodes must align their antennas for successful discovery. Even if two nodes are within range, they cannot discover each other if their antennas do not align.

ND algorithms can be categorized in the following ways: (1) the way in which a node responds to a broadcast message [20] and (2) the way a node gains access to medium [21].

In the first category, ND algorithms can be further classified into one-way ND and handshake-based ND. In one-way ND, a node periodically transmits a broadcast packet containing its ID and possibly its location, to announce its presence. Neighbors are discovered by receiving broadcast packets from other nodes, and neighbor lists are then updated. Handshake-based ND is more complex; a receiver needs to provide an acknowledgement to an undiscovered transmitter upon receiving a broadcast packet from that transmitter.

In the second category, ND methods can be further sub-divided into two classes: synchronized slotted ND and random access based ND. In synchronized slotted ND, a node chooses to transmit or receive at the beginning of each time slot. In contrast, with random access based ND a node receives for a random time interval. Upon interval timeout, the node transmits and then, returns to the receive mode.

The two ND methods that we consider in this paper, direct discovery and gossip-based discovery, belong to one-way and synchronized slotted ND classes.

3.2 Direct discovery

At the beginning of each time slot, a node chooses to be in one of two states: **transmit** or **receive**. In the transmit state, a node transmits a broadcast packet with its identity, in a randomly chosen direction with a given beamwidth. In the receive state, a node lis-

Notation	Description
k	Number of directions
f	Direction index ($1 \leq f \leq k$)
N	Number of nodes in the network with the exception of the node performing the neighbor discovery (total number of nodes = $N + 1$)
$c_{i,j}$	Expected number of directions in which node i's beam covers a particular neighbor j
A	Area of the network
$A_l(i, f)$	Area where nodes can communicate with node i using beam direction f only via a direct beam. See Fig. 2
$A_r(i, f)$	Area where nodes can communicate with node i using beam direction f only via a reflected beam. See Fig. 2
$A_b(i, f)$	Area where nodes can communicate with node i using beam direction f via either direct or reflected beams. See Fig. 2
$A_s(i, f)$	Area that a beam of node i covers with the antenna pointed in direction f (i.e., $A_s(i, f) = A_l(i, f) \cup A_r(i, f) \cup A_b(i, f)$)
P_t	Probability that a node transmits in a slot
$P^L_{i,j}(f)$	Probability that i discovers a neighbor j in area $A_l(i, f)$ in a slot by using beam direction f
$P^R_{i,j}(f)$	Probability that i discovers a neighbor j in area $A_r(i, f)$ in a slot by using beam direction f
$P^B_{i,j}(f)$	Probability that i discovers a neighbor j in area $A_b(i, f)$ in a slot by using beam direction f
$P_{i,j}$	Probability that i discovers a neighbor j in a slot
$D_{i,j}(T)$	Probability that i discovers a neighbor j directly within the first T slots
$I_{i,j}(T)$	Probability that i discovers a neighbor j indirectly (with gossip-based discovery) within the first T slots
$S_{i,j}(T)$	Probability that i discovers a neighbor j either directly or indirectly within the first T slots
$P_i(d, T)$	Probability that i discovers d neighbors within the first T slots
$F_i(T)$	Expected fraction of neighbors discovered by node i within time T

Table 1: Notation used in analysis

tens for broadcast packets from a randomly chosen direction; if the received signal experiences a collision, the node fails to discover any neighbor. If the broadcast packet is received successfully and the transmitter is an unknown neighbor, the receiver records the angle of arrival and the transmitter's identity. The transmitter is then said to be discovered.

Figure 1(a) and 1(b) depict neighbor discovery with the direct discovery method. We see that the directional footprint is not a perfect cone[2] when there is a reflector (obstacle) within the footprint; instead, the footprint is *folded* at the reflector, forming a new *reflection area*. In Figure 1(a), the receiver cannot discover transmitter A because its reception range does not cover transmitter A; note that this is the case even though transmitter A's transmission range covers the receiver. On the other hand, since transmitter B and the receiver are within each other's footprint, and since there are no interfering transmissions, the receiver discovers transmitter B. Figure 1(b)[3] illustrate the process of discovery via a *reflected beam*. We see that neither the transmitter nor the receiver's antenna directly point towards each other. However, the receiver can discover the transmitter in this case due to the fact that transmitter's reflected beam is aligned with the direction of antenna at the receiver.

3.3 Gossip-based discovery

Gossip-based discovery consists of two steps. In the first step, like direct discovery, a node chooses to transmit or receive at the beginning of each time slot. In this step, unlike direct discovery, a node in the transmit state not only broadcasts its own identity and location (possibly obtained with GPS), but also "gossips" about the neighbors that it has discovered so far. The gossip information includes the identity and location of each discovered neighbor. In this way, a node that successfully hears a transmission not only discovers the transmitter, but also learns about the neighbors that the transmitter has discovered so far. If these *indirectly* discovered neighbors are within the maximum transmission range of the recipient node, the node stores the information (discovered neighbors and their locations) obtained in this step, temporarily, in a table (called the gossip table). Note that nodes in the gossip table are *not yet* accepted as neighbors. In the second step, for each node in the gossip table, a node sends out probe packets in the direction of the discovered node (the direction is calculated based on the location information obtained in the previous step). If the response from the discovered node is obtained within a given number of tries, it is accepted as a *genuine* neighbor and is removed from the gossip table. Otherwise, it is just removed from the gossip table. The rationale for this step is that *not* every node in the newly acquired neighbor list can be guaranteed to be the recipient node's neighbor. This is because neighbor discovery depends on environment around the nodes; the presence of physical obstacles may even cause two geographically close nodes to not be "logical" neighbors. Note that this step is not required in direct discovery.

As evident from the above discussion, compared with the simple direct discovery method, the gossip-based discovery method raises some implementation challenges. First, the procedure of sifting genuine neighbors from the gossip (the second step above) inevitably incurs complexity to some extent in terms of implementation. In addition, the procedure can consume extra time in the discovery process. A second issue that could arise with gossip-based discovery is increased packet size. In very dense network settings, the neighbor list will need to accommodate more neighbors, leading to increased packet size. As a result, the transmission of packets take longer times. This would impair the performance of discovery. In typical office and home settings however, given the short range of 60 GHz signals, this is unlikely to be a significant problem.

4. ANALYSIS OF NEIGHBOR DISCOVERY

In this section, we analytically model the considered neighbor discovery methods. The key performance metric for a ND algorithm should capture *the time it takes for nodes to discover their neighbors from scratch*. Thus, our analysis is aimed at deriving the expected fraction of neighbors discovered within a certain time. We begin with describing the system model under consideration and subsequently present our analysis for direct discovery and gossip based discovery.

4.1 System model

We consider indoor environments (e.g., offices or homes), where nodes are static and uniformly distributed. Each node is equipped with directional antennas with the same transmission power and antenna gain, and function in a half-duplex mode (i.e., it can *either* transmit or receive signals but cannot do both simultaneously). We assume that nodes are placed on a two-dimensional plane; the variation in the antenna beam pattern over the elevation angle is not considered (thereby, reflection occurs only at walls and not at the floor and ceiling).[4] The angular footprint of a directional antenna

[2]We ignore sidelobes in this work for ease of discussion and tractability of our analysis.

[3]We do not show the signal that penetrates the reflector for clarity.

[4]An extension of the analysis to consider three dimensional effects will be considered in future work.

corresponds to a sector with a radius equal to the directional transmission range. Within its beamwidth the antenna has unit gain and a zero gain outside the beam. We assume that there are k available non-overlapping directions ($k > 4$) for an antenna and thus, the beamwidth for each direction is $2\pi/k$.

As mentioned earlier, we also assume that time is slotted and that nodes are synchronized; for a small number of nodes, synchronization can be achieved using one of the previously proposed methods [22]. In each time slot, nodes are in either in a transmit state or in a receive state. A node chooses the transmit state with probability of P_t, and the receive state with probability of $1 - P_t$. For transmitting or receiving, a direction for pointing the antenna is randomly chosen from among the k directions. We assume that reception failure at a receiver is caused only due to collisions (and not by signal degradation due to channel induced effects). A collision occurs at a receiver when two or more transmissions are simultaneously received.In Section 5, we show that the collision model assumed effectively captures indoor environments by comparing the analytical results to that obtained by simulating an indoor channel model (the partition based path loss model) driven by measurements in the 60 GHz regime.

Only first-order reflections are considered for the analysis. This is because, generally, higher order (more than two) reflections suffer from high degrees of signal attenuation to successfully establish communication links. We also ignore reflection after penetration of signals through obstacles for the same reason. Reflections occur at the boundaries of the deployment area (e.g., exterior walls) and at obstacles (e.g., interior walls). Table 1 summarizes the notation used in the following analysis.

4.2 Direct discovery analysis

Given a time slot, the event that node i discovers a particular neighbor j, occurs only when i's (the receiver) beam covers j (the transmitter). The probability $P_{i,j}$ that node i discovers a particular neighbor j is calculated by first conditioning on the probability that node i's beam covers j:

$$P_{i,j} = P(i\text{'s beam covers } j) \cdot P(i \text{ discovers } j \mid i\text{'s beam covers } j). \quad (1)$$

Let u denote the number of directions (from the perspective of i) in which node i's beam covers a particular neighbor j. The value of u is determined by the locations of i and j, the positions of the reflectors, as well as the beamwidth. Let us consider as an example, an indoor room with node i located in the center of the room with four walls (reflectors) as shown in Fig. 3(d). One can divide the room into four areas in terms of the value of u when a beamwidth of 30 is used. In order to find these areas, we consider a transmission by i in each of its sectors and use ray tracing tools [23] to find the coverage region for that transmission [5]. Parts of the room that are covered by the same number of transmissions are grouped into an "area". We assume that the wireless channel is reciprocal. In the example considered, we can find four such areas. If the transmitter is in area (1) or (3), node i can receive signals from directions 4, 7, 9 and 12, and u has a value 4 (Fig. 3(a)) [6]. Similarly for area (2) (Fig. 3(b)) and area (4) (Fig. 3(c)), the values of u are 5 and 3, respectively. Then, expected number of directions $c_{i,j}$ in this case can be calculated by

$$c_{i,j} = 4 \cdot \frac{\text{area of ((1)+(3))}}{A} + 5 \cdot \frac{\text{area of (2)}}{A} + 3 \cdot \frac{\text{area of (4)}}{A}.$$

Since there are totally k possible directions to choose from, P(i's beam covers j) in Eq. (1) is given by $\frac{c_{i,j}}{k}$.

Now, we derive $P(i \text{ discovers } j \mid i\text{'s beam covers } j)$. The event that node i discovers node j is affected by the direction in which i points its antenna (we call it the beam direction of i) and the location of j. For each beam direction f, the beam areas (defined in Table 1) $A_l(i,f)$, $A_r(i,f)$ and $A_b(i,f)$, containing possibly different numbers of interfering nodes, are created. These interferers affect the probability of interest. The location of j also affects the probability. If j is within $A_l(i,f)$ or $A_r(i,f)$, node i can discover j only via a direct beam or a reflected beam, respectively. If j is within $A_b(i,f)$, node i can discover j via either a direct or a reflected beam. Conditioning on the beam direction f, we have

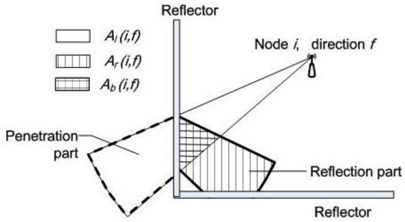


Figure 2: An illustration of $A_l(i,f)$, $A_r(i,f)$ and $A_b(i,f)$

$$\begin{aligned} P(i \text{ discovers } j \mid i\text{'s beam covers } j) &= \sum_{f=1}^{k} P(i \text{ points at direction } f) \\ &\cdot P(i \text{ discovers } j \mid i \text{ points at direction } f \text{ and } i\text{'s beam covers } j), \end{aligned} \quad (2)$$

where $P(i \text{ points at direction } f) = \frac{1}{k}$ since the direction is randomly chosen. We condition on the location of j in the second term in the right-hand side of Eq. (2) and have:

$$\begin{aligned} &P(i \text{ discovers } j \mid i \text{ points at direction } f \text{ and } i\text{'s beam covers } j) \\ &= P(i \text{ discovers } j \mid j \text{ is in } A_l(i,f)) \cdot P(j \text{ is in } A_l(i,f) \mid j \text{ is in } A_s(i,f)) \\ &+ P(i \text{ discovers } j \mid j \text{ is in } A_r(i,f)) \cdot P(j \text{ is in } A_r(i,f) \mid j \text{ is in } A_s(i,f)) \\ &+ P(i \text{ discovers } j \mid j \text{ is in } A_b(i,f)) \cdot P(j \text{ is in } A_b(i,f) \mid j \text{ is in } A_s(i,f)). \end{aligned} \quad (3)$$

Referring to the notation in Table 1, Eq. (3) can be further expressed as:

$$\begin{aligned} &P(i \text{ discovers } j \mid i \text{ points at direction } f \text{ and } i\text{'s beam covers } j) \\ &= P^L_{i,j}(f) \cdot P(j \text{ is in } A_l(i,f) \mid j \text{ is in } A_s(i,f)) + P^R_{i,j}(f) \cdot P(j \text{ is in } \\ &A_r(i,f) \mid j \text{ is in } A_s(i,f)) + P^B_{i,j}(f) \cdot P(j \text{ is in } A_b(i,f) \mid j \text{ is in } A_s(i,f)). \end{aligned} \quad (4)$$

Given that j is within area $A_s(i,f)$, the probability that j is within $A_l(i,f)$ is $\frac{A_l(i,f)}{A_s(i,f)}$. Similarly, $\frac{A_r(i,f)}{A_s(i,f)}$ and $\frac{A_b(i,f)}{A_s(i,f)}$ are the probabilities for the cases where j is within $A_r(i,f)$ and $A_b(i,f)$, respectively. Substituting these expressions in Eq. (4), we have:

$$\begin{aligned} &P(i \text{ discovers } j \mid i \text{ points at direction } f \text{ and } i\text{'s beam covers } j) \\ &= P^L_{i,j}(f) \cdot \frac{A_l(i,f)}{A_s(i,f)} + P^R_{i,j}(f) \cdot \frac{A_r(i,f)}{A_s(i,f)} + P^B_{i,j}(f) \cdot \frac{A_b(i,f)}{A_s(i,f)}. \end{aligned} \quad (5)$$

Using Eqs. (2) and (5), $P_{i,j}$ in Eq. (1) can be expressed as:

$$\begin{aligned} P_{i,j} = \frac{c_{i,j}}{k} \cdot \frac{1}{k} \cdot \sum_{f=1}^{k} \Big(&P^L_{i,j}(f) \cdot \frac{A_l(i,f)}{A_s(i,f)} + P^R_{i,j}(f) \cdot \frac{A_r(i,f)}{A_s(i,f)} \\ &+ P^B_{i,j}(f) \cdot \frac{A_b(i,f)}{A_s(i,f)} \Big). \end{aligned} \quad (6)$$

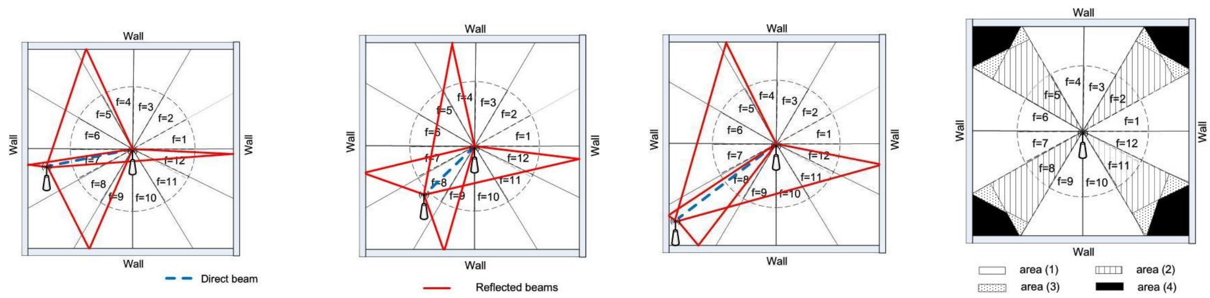
Note that $A_l(i,f)$, $A_r(i,f)$, $A_b(i,f)$ and $A_s(i,f)$ in Eq. (6) are easy to calculate when the direction of f, the coordinates of node i, the boundaries of deployment and the obstacles are given.

Next, we derive $P^L_{i,j}(f)$, $P^R_{i,j}(f)$ and $P^B_{i,j}(f)$ in Eq. (6). Following the direct discovery method described in Section 3, $P^L_{i,j}(f)$ can be expressed as:

$$\begin{aligned} &P^L_{i,j}(f) \\ &= P(j \text{ transmits, } i \text{ receives, and } j\text{'s beam covers } i) \cdot P(\text{no collision}). \end{aligned} \quad (7)$$

[5] A ray corresponds to the antenna boresight.

[6] For clarity, we show the direction of transmission as opposed to beams.



(a) Case of $u = 4$: j is in area (1) or (3)

(b) Case of $u = 5$: j is in area (2)

(c) Case of $u = 3$: j is in area (4)

(d) Different beam areas

Figure 3: Illustration of how $c_{i,j}$ is computed for different transmitter positions

Since the three events in the first term on the right-hand side of Eq. (7) are independent of each other, we have:

$$P(j \text{ transmits}, i \text{ receives, and } j\text{'s beam covers } i) = \frac{1}{k} \cdot P_t \cdot (1 - P_t). \tag{8}$$

In addition:

$$\begin{aligned} &P(\text{no collision}) = P(\text{no transmission from } A_s(i, f) \text{ except from } j) \\ &= P(\text{no transmission from } A_l(i, f) \text{ except } j) \\ &\cdot P(\text{no transmission from } A_r(i, f)) \cdot P(\text{no transmission from } A_b(i, f)). \end{aligned} \tag{9}$$

For the calculation of the first term on the right-hand side of Eq. (9), let us suppose that there are m nodes (excluding j) in $A_l(i, f)$. These m nodes in $A_l(i, f)$ should not transmit with the beam pointing at i. This corresponds to:

$$\begin{aligned} &P(\text{no transmission from } A_l(i, f) \text{ except } j) \\ &= \sum_{m=0}^{N-1} \left(1 - \frac{1}{k} \cdot P_t\right)^m \cdot P(\text{there are } m \text{ nodes in } A_l(i, f)). \end{aligned} \tag{10}$$

The above expression can be computed if the distribution of nodes within the deployment area is known. The analysis can be applied with any distribution; we assume that the nodes are uniformly distributed in the area of interest, A. With this assumption, the probability that there are m nodes (excluding j) in $A_l(i, f)$, $P_{A_l(i,f)}(N-1, m)$, can be expressed as:

$$P_{A_l(i,f)}(N-1, m) = \binom{N-1}{m} \cdot \left(\frac{A_l(i, f)}{A}\right)^m \cdot \left(1 - \frac{A_l(i, f)}{A}\right)^{N-1-m}. \tag{11}$$

Inserting Eq. (11) into Eq. (10), we have:

$$\begin{aligned} &P(\text{no transmission from } A_l(i, f) \text{ except } j) \\ &= \sum_{m=0}^{N-1} \left(1 - \frac{1}{k} \cdot P_t\right)^m \cdot P_{A_l(i,f)}(N-1, m). \end{aligned} \tag{12}$$

The derivations of the following expressions are similar to the one above. Note that the maximum possible number of nodes in $A_r(i, f)$ (and in $A_b(i, f)$) later) changes in order to account for those nodes in $A_l(i, f)$.

$$\begin{aligned} &P(\text{no transmission from } A_r(i, f)) \\ &= \sum_{n=0}^{N-m-1} \left(1 - \frac{1}{k} \cdot P_t\right)^n \cdot P_{A_r(i,f)}(N-m-1, n) \end{aligned} \tag{13}$$

and,

$$\begin{aligned} &P(\text{no transmission from } A_b(i, f)) \\ &= \sum_{q=0}^{N-m-n-1} \left(1 - \frac{2}{k} \cdot P_t\right)^q \cdot P_{A_b(i,f)}(N-m-n-1, q). \end{aligned} \tag{14}$$

The probability that (i) i receives "no" transmission from $A_b(i, f)$ and, (ii) when there are q nodes in $A_b(i, f)$ is $\left(1 - \frac{2}{k} \cdot P_t\right)^q$. This implicitly assumes in addition to the direct beam, there is only one beam received due to a first-order reflection. With small beamwidths ($< 90^o$) this is typically the case. For larger beamwidths this expression can easily be refined. Furthermore, in our simulations, we find that multiple reflected beams are incident on a receiver only when its beam covers the intersection of two adjacent walls and the transmitter is at such a corner; the probability of this is small.

Substituting (10) (13) and (14) in (9), we have:

$$\begin{aligned} &P(\text{no transmission from } A_s(i, f) \text{ except from } j) \\ &= \sum_{m=0}^{N-1} \sum_{n=0}^{N-m-1} \sum_{q=0}^{N-m-n-1} \left(1 - \frac{1}{k} \cdot P_t\right)^{m+n} \cdot \left(1 - \frac{2}{k} \cdot P_t\right)^q \\ &\cdot P_{A_l(i,f)}(N-1, m) \cdot P_{A_r(i,f)}(N-m-1, n) \\ &\cdot P_{A_b(i,f)}(N-m-n-1, q). \end{aligned} \tag{15}$$

Inserting Eqs. (8) and (15) into Eq. (7), we have:

$$\begin{aligned} P_{i,j}^L(f) &= \frac{1}{k} \cdot P_t \cdot (1 - P_t) \cdot \Bigg\{ \sum_{m=0}^{N-1} \sum_{n=0}^{N-m-1} \sum_{q=0}^{N-m-n-1} \left(1 - \frac{1}{k} \cdot P_t\right)^{m+n} \\ &\cdot \left(1 - \frac{2}{k} \cdot P_t\right)^q \cdot P_{A_l(i,f)}(N-1, m) \cdot P_{A_r(i,f)}(N-m-1, n) \\ &\cdot P_{A_b(i,f)}(N-m-n-1, q) \Bigg\}. \end{aligned} \tag{16}$$

Using an approach similar to what was used to compute $P_{i,j}^L(f)$, $P_{i,j}^R(f)$ and $P_{i,j}^B(f)$ are obtained as shown below.

$$P_{i,j}^R(f) = P_{i,j}^L(f) \tag{17}$$

$$P_{i,j}^B(f) = 2 \cdot P_{i,j}^L(f) \tag{18}$$

Substituting (16),(17) and (18) into (6), we finally obtain a closed form expression for $P_{i,j}$. Using $P_{i,j}$ thus derived, the probability $D_{i,j}(T)$ that node i discovers a particular neighbor j within the first T slots is given by:

$$D_{i,j}(T) = 1 - (1 - P_{i,j})^T. \tag{19}$$

The event that node i discovers a particular neighbor within the first T slots is independent of the event that i discovers a different neighbor within the same T slots. Thus the probability $P_i(d, T)$ that i discovers d neighbors within the first T slots is given by:

$$P_i(d, T) = \binom{N}{d} \cdot D_{i,j}(T)^d \cdot (1 - D_{i,j}(T))^{N-d}, \qquad d \le min(T, N). \tag{20}$$

Based on $P_i(d, T)$ obtained above, the expected fraction of neighbors (from among the N neighbor nodes) discovered by node i within time T is:

$$F_i(T) = \sum_{d=1}^{min(T,N)} \frac{d \cdot P_i(d, T)}{N}. \tag{21}$$

4.3 Gossip-based discovery analysis

Recall that with gossip-based discovery, i obtains information about a neighbor not only via a direct reception, but also indirectly from other neighbors. As discussed earlier, node i deems node k to be an indirectly discovered neighbor, if this node lies within the maximum coverage area of node i. It is however possible that this node (node k) is not reachable due to obstacles either directly or via reflections. However, as we show via simulations, in typical scenarios, the probability of such an event is very small (< 0.1 in all the cases that were simulated). Thus, for ease of analysis, we assume that i simply considers every node that is within its coverage, discovered indirectly via a directly discovered node, to be its neighbor. Let $D_{i,j}(T)$ and $I_{i,j}(T)$ denote the probabilities that i discovers a neighbor j within T slots directly and indirectly, respectively. Then, the probability $S_{i,j}(T)$ that i discovers j *either* directly *or* indirectly is given by:

$$S_{i,j}(T) = D_{i,j}(T) + (1 - D_{i,j}(T)) \cdot I_{i,j}(T), \qquad (22)$$

where, $D_{i,j}(T)$ can be calculated by Eq. (19). We calculate $I_{i,j}(T)$ by solving the following recursive equation:

$$I_{i,j}(T) = I_{i,j}(T-1) + (1 - I_{i,j}(T-1)) \cdot \sum_{r \neq i,j} P_{i,r} \cdot S_{r,j}(T-1) \qquad (23)$$

The rationale behind the recursion in Eq. (23) is as follows. If a node j is discovered by node i within T time slots, it can do so indirectly with help from a different neighbor (1) within the first $T-1$ slots or, (2) in the T^{th} slot. The first case corresponds to $I_{i,j}(T-1)$ in Eq. (23). In the second case, i could learn about j from any neighbor node r except j; r is to be discovered in the T^{th} time slot and should have j in its neighbor list. The probability of this event is $P_{i,r} \cdot S_{r,j}(T-1)$, where $P_{i,r}$ is the probability i discovers r in the T^{th} slot, and $S_{r,j}(T-1)$ is the probability that node r has discovered j within the first $T-1$ slots.

Replacing $D_{i,j}(T)$ with $S_{i,j}(T)$ in Eq. (20), we obtain the expressions for $P_i(d,T)$ and $F_i(T)$; these correspond to the probability that node i discovers d neighbors and the expected fraction of neighbors discovered by node i within time T, respectively, using gossip-based discovery.

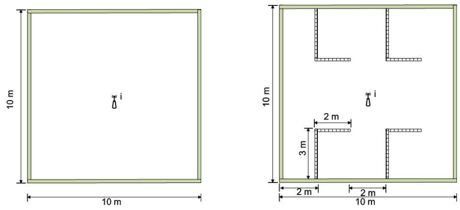
The analytical results and the impact of the assumptions made, are validated via simulations in Section 5.

5. PERFORMANCE EVALUATION

In this section, we evaluate the two neighbor discovery methods considered in this paper in the 60 GHz setting. To this end, we present both numerical and simulation results for a room scenario that we consider. In particular, the impact of a realistic 60 GHz channel and other key parameters on performance are investigated with numerical and simulation results.

5.1 Simulation Setup

Simulations are performed in OPNET version 14.5 [24]. For the evaluations, we consider two scenarios, wherein the network of interest is deployed in a room of area 10 m by 10 m. In first scenario, there are four exterior walls with orthogonal intersections but with no interior walls (see Fig. 4(a)); in second scenario, four interior walls are also present (see Fig. 4(b)). Our first set of evaluations are done with the scenario without interior walls; later we consider the second scenario. Note that, for the second scenario, the thickness and materials used for the interior walls can affect the reflection and penetration losses. In our simulations, we use values of thickness and materials which result in 10 dB reflection loss and 15 dB penetration loss (as observed in measurements in [4]). For both scenarios, node i is located in the center of the room, and 10 neighbor nodes are randomly distributed in the room. Time is slotted



(a) without interior walls

(b) with interior walls

Figure 4: Scenarios with and without interior walls

as discussed and the slot length is chosen such that all the signals transmitted in a slot are received in the same slot; in other words delay spread is ignored and a transmission does not interfere with communications in the next slot. By default every node uses the same transmit probability P_t which is set to 0.5 (this is relaxed later to study the impact of varying P_t). In the default setting, we also assume that the number of directions, k, is 12, corresponding to a beamwidth of 30^o (this is also relaxed later for a study of the impact of beamwidth).

5.2 Results

5.2.1 Impact of a realistic channel model

In Section 4, we assume that multiple simultaneous transmissions in a receiver's beam range leads to a collision. However, realistically, this would depend on the signal strength the receiver perceives, from both the intended transmitter and the interferers. A packet loss occurs if and only if the ratio of received signal strength to the interference (i.e., SIR) is less than a given threshold. If the interferer's signal is via a reflected beam while the transmitter's signal is direct, a reception could be possible. Thus, the analysis may overestimate the number of collisions and thus, the discovery process may in fact be more efficient than what is predicted. To investigate the impact of this on the neighbor discovery efficiency, we perform simulations to obtain $F_i(T)$ over a number of time slots T with the SIR based model; the channel model incorporates the losses due to reflections as per the measurements reported in [4]. We compute an average over 30 runs, of random neighbor deployments. We set the transmit power to 10mW, antenna gains to 24 dBi at both transmitter and receiver, and the SIR threshold is set to 15 dB as in [18]. From Fig. 5, we observe that the $F_i(T)$ achieved with the analytical model is very close to what is achieved with simulations. This demonstrates the efficacy of our model in estimating the performance in realistic scenarios. Given this conformance, in what follows we selectively present either analytical or simulation results for clarity.

5.2.2 Impact of discovery method

Fig. 5 shows the fraction of discovered neighbors by node i, $F_i(T)$, as a function of the number of time slots T, with the use of direct and gossip-based discovery. Both numerical (based on the analysis proposed in Section 4) and simulation results are plotted. The simulation results are averaged over 30 runs with different neighbor placements. We see that the analytical results conform with the simulation curves with both direct and gossip-based discovery.

Comparing the results, one can see that with gossip-based discovery a node finds its neighbors much faster than with direct discovery. At the end of 100 time slots, the fraction of neighbors discovered by direct discovery is only about 0.554 while the fraction with gossip-based discovery is 0.994. We see that with direct discovery, it takes 633 time slots to reach the fraction of 0.994; thus, direct discovery is over six times slower than gossip-based discovery. The reason is attributable to the contribution from indirect discovery (recall the gossip-based subsection in Section 4). We observe that (Fig. 6) the

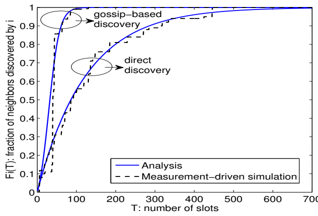


Figure 5: $F_i(T)$ in direct and gossip-based discovery

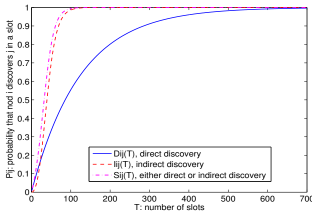


Figure 6: The probability of discovery by time T

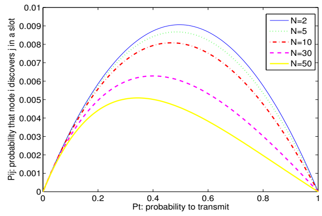


Figure 7: Impact of P_t on $P_{i,j}$ with different N

curve depicting $I_{i,j}(T)$, the probability that i discovers j indirectly within T slots, is above the curve depicting $D_{i,j}(T)$, the probability that i discovers j directly within T slots, and in fact, approaches the curve depicting $S_{i,j}(T)$, the probability that i discovers j directly or indirectly within T slots. This demonstrates that indirect discovery dominates the discovery process in gossip based discovery. In our simulations, we observe that a node typically acquires about 2-4 neighbors in a single slot with gossip-based discovery; this contributes to its rapid discovery rate.

5.2.3 *Impact of the probability of transmission P_t*

In order to investigate the impact of P_t, we plot the value of $P_{i,j}$ from the proposed analysis [7] while varying P_t from 0.0 to 1.0 in Fig. 7.

Irrespective of the network density, generally speaking, a higher P_t increases the probability that a node transmits. This increases the chance of being discovered, but interference also grows due to the increased number of transmissions. In particular, interference effects dominate if P_t is close to 1, leading to a discovery probability of zero. On the other hand, small values of P_t result in low levels of interference but also result in a lower chance of nodes being discovered. As one might expect, the discovery probability goes to zero as P_t gets close to zero. We see that P_t needs to be carefully chosen to balance the the chance of being discovered and the level of interference generated.

We also find that the right choice of P_t (to induce a high $P_{i,j}$) also depends on the network density. When the number of nodes N increased from 2 to 5, 10, 30 and 50, the value of P_t that results in the peak value of $P_{i,j}$ deceases from 0.51 to 0.50, 0.49, 0.43 and 0.38, respectively. This implies that as the network density increases, it is better for nodes to be less aggressive in performing transmissions.

5.2.4 *Impact of network density*

In Fig. 8, we plot $P_{i,j}$, the neighbor discovery probability for node i in a slot, while varying the number of nodes N in the deployed area, from 2 to 50. It is observed that as the number of nodes increases, the node discovery probability typically starts decreasing. This decrease in the probability is due to increased interference effects, which is captured in Fig. 9. In this figure we observe that the collision probability increases as the number of nodes grows. From these results, we also find that for a given N, an optimal operating P_t exists and needs to be carefully chosen for best performance.

We also investigate the impact of network density on the two considered discovery methods in Fig. 10 and 11, respectively. With direct discovery (Fig. 10) the performance gets worse as the number of nodes increases. This is attributed to increased interference

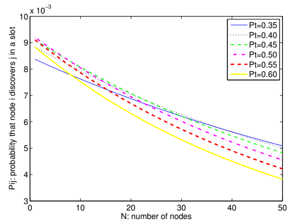


Figure 8: Impact of N on $P_{i,j}$ with different P_t

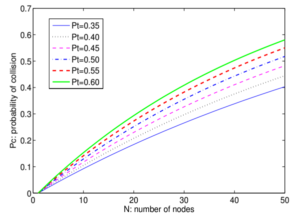


Figure 9: Probability of collision

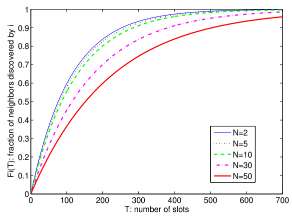


Figure 10: Impact of N on direct discovery

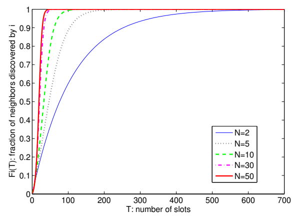


Figure 11: Impact of N on gossip-base discovery

levels in the network (nodes have to explicitly discover each neighbor). On the contrary, this phenomenon is not observed with gossip-based discovery (Fig. 11). The performance of neighbor discovery in terms of the fraction of discovered nodes, is the highest with $N = 50$. This is because an increase in node density increases the chances of a node discovering its neighbors indirectly. This gain with gossip-based discovery dominates the effects of increased interference (each success drastically increases the fraction of discovered neighbors).

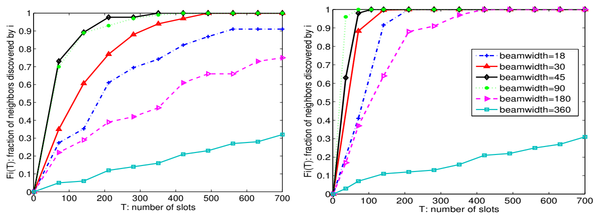
5.2.5 *Impact of beamwidth*

To see the impact of beamwidth on the performance of neighbor discovery, we find the fraction of discovered neighbors as a function of slots while varying the beamwidth. We present simulation results[8] over six distinct degrees (18, 30, 45, 90, 180, 360) in Figure 12(a) and 12(b). Note that a beamwidth of 360 corresponds to the omni transmission-reception mode. We run the simulations ten times for each beamwidth with both direct-discovery and indirect-discovery and compute average values.

We again observe a trade-off between "the chance of discovery" and "level of interference" with changing beamwidth with both direct and gossip based discovery. A wider (narrower) beamwidth leads to a higher (lower) chance of discovering nodes, but results in a greater (smaller) chance of collisions. We observe that a beamwidth of 90^o almost achieves the best performance for both direct and gossip-based discovery for the density considered; this may differ if we further vary the density. The performance of omni-transmission and

[7] Simulation results are observed to be consistent with the analysis results; we do not present simulation results for clarity of presentation.

[8] Analytical results are similar.



(a) Direct discovery (b) Gossip-based discovery

Figure 12: Impact of beamwidth on discovery methods

reception modes is the worst due to a very high collision rate. This suggests that omni-mode neighbor discovery does not perform with high efficacy in the 60 GHz band.

5.2.6 *Impact of obstacles*

The results thus far do not consider the presence of interior obstacles in the room. In order to study the impact of obstacles, we consider a 10 m by 10 m room where four interior walls are deployed as shown in Fig. 4(b). We perform 30 simulation runs for both direct and gossip-based discovery, and the results are compared with that with the empty room scenario in Fig. 13. The figure shows that the performance in terms of the fraction of neighbors discovered (with both direct and gossip-based discovery) in the obstacle scenario is inferior to that in the empty room scenario. The reason for this can be explained as follows. Compared to the empty room scenario, with obstacles the number of communication links (via either direct or reflected beams) between any pair of nodes is likely to be reduced due to possible blockage by obstacles. For example, in the empty room, the number of paths between any pair of nodes is always five (including one direct beam and four reflected beams). However, in the room with obstacles, the number of paths varies from zero to five, depending on the environment around the pair of nodes. This results in a lower chance of discovering or being discovered. Note that as a by-product of the reduced number of communication links, the level of interference is also mitigated. The contribution of such mitigated interference is however, observed to be insignificant when compared to the loss in connectivity.

We also observe that by the end of the simulation time (700 slots), with both direct and gossip-based discovery in the obstacle scenario, not all the neighbors are discovered. Thus, the schemes achieve a fraction of less than 1.0; in the empty room scenario, this fraction is 1.0. This is because in some scenarios, some of the neighbors do not have communication links with i due to the obstacles. In particular, ray tracing reveals that in this scenario about 6 % of the area is uncovered (Fig. 14). If a node is in the uncovered area it is not a neighbor of node i. Here we point out that in our analysis we assumed that an indirectly reported neighbor is considered a neighbor. In this case, on average, 6 % of the reported neighbors are not the neighbors of i. In other scenarios that we considered (not shown due to space limitations) we found that this fraction was between 5 % and 10 %.

6. CONCLUSIONS

In this paper, we consider the problem of directional neighbor discovery in 60 GHz wireless networks. The existence of possible communication links due to reflected beams in the 60 GHz band makes neighbor discovery more complicated than if only direct line of sight paths exist (as considered in previous work). We analytically model two neighbor discovery methods namely, direct discovery and gossip-based discovery. Our analysis accounts for reflections that exist in an indoor 60 GHz network. We validate our analytical models via simulations that incorporate a measurement based 60 GHz channel model. We examine the impact of various

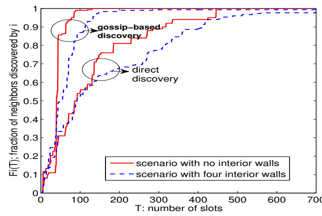


Figure 13: Impact of obstacles on discovery

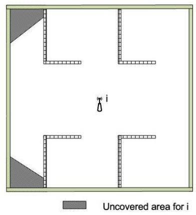


Figure 14: Uncovered area for node i

factors on neighbor discovery; our study reveals a number of interesting trade-offs that have to be considered when choosing system parameters.

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