Neighbor Discovery in 60 GHz Wireless Personal Area Networks

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***Abstract*—60 GHz radio is a promising technology which can handle the data rate of the order of gigabits-per-second. Hence, it is an attractive candidate for wireless personal area networks (WPANs). Due to the high path loss, directional antennas are recommended for use in 60 GHz systems. To set-up directional communications, it is essential to obtain the knowledge of direction of the surrounding devices. However, a neighbor discovery process using directional antennas is nontrivial. In this paper, we provide a comprehensive investigation of using directional antenna for neighbor discovery process. We demonstrate the performance of neighbor discovery using different antenna modes combining different neighbor discovery mechanisms. Our results may aid in designing directional antennas for 60 GHz WPANs.**

I. Introduction

To cater to emerging wireless multimedia applications like uncompressed HD video streaming in the in-door environment, data rate of the order of gigabits per second (Gbps) is required. This requirement is difficult to achieve with the current wireless technologies, for instance, IEEE 802.11x WLAN. Therefore, the current focus of many research is to exploit the new 60 GHz frequency band. Till now, multi-GHz bandwidth has been allocated worldwide for 60 GHz radio, and it is capable of supporting Gbps-based wireless communication. In March 2005, the IEEE 802.15.3 Task Group 3c (TG3c) [1] was formed to develop a 60 GHz based alternative physical layer for the existing IEEE 802.15.3 standard to enable Gbps-based wireless personal area networks (WPANs). It was approved as a standard in Sept. 2009. Therefore, 60 GHz radio may play an important role in future for in-home networks and consumer electronic markets. To use the 60 GHz radio for short-range high-speed wireless communication, its unique properties pose many special challenges to the higher layer protocol design. For instance, the 60 GHz radio suffers from high path loss. To obtain sufficient link budget for multi-Gbps data rates, directional antennas are adopted in 60 GHz systems. Especially, for the adaptive array based directional antenna, its capability of beam-forming provides the flexibility to align the antenna's transmitting and receiving directions. Directional antennas are not only applicable for 60 GHz systems, they are also widely used in wireless systems to increase transceiving gain and reduce the interference area [2][3][4][5]. Although directional antennas offer many advantages over omni-directional antennas, their deployment is very challenging for WPANs. WPANs are envisioned to be self-organized, which means, devices are expected to set-up and maintain networks without relaying on any external infrastructure, system administrator, or users. Neighbor discovery (ND) is an essential process to realize self-organization in wireless ad-hoc networks [6]. An ND process allows in-range devices to establish links with each other and form a connected network, and it cooperates with the medium access, service discovery, and routing protocols that require specific information about neighbors. The required duration and efficiency of a ND process directly affects the network setup time, route establish duration, etc. ND protocols can be generally classified as *direct ND* protocols and *gossip-based ND* protocols [7]. For direct ND protocols, devices should receive the advertisement messages directly from its neighbor to discover it. By using gossip-based ND protocols, a device not only broadcasts its own advertisement message, it also broadcasts information about its neighbors to speed up ND process. Hitherto, Omni-directional antennas are widely addressed in ND protocols [8][9][10]. ND process using omni-directional antennas is quite straightforward. Once a device accesses the channel and broadcasts its advertisement message, which is also called as HELLO message, all the receiving devices that are in the transmission range of the transmitter may receive its advertisement message. If multiple advertisement messages arrive at the receiving device simultaneously, none of them can be received. To set-up a directional communication, a device not only needs to know who its neighbor is, it also requires to know the position of its neighbor.. Therefore, it is necessary for the devices to determine the direction of each other. In this circumstance, gossip-based ND protocols are not suitable for a device to know its neighbor's exact direction via the information relayed by a third party. Therefore, direct ND protocols are the main concerns in this paper.

According to the reply mechanism, direct ND protocols can be further classified as one-way ND and handshake-based ND [11]:

- *One-way ND*: In one-way ND protocols, each device periodically transmits advertisement messages to announce its presence, and discovers its neighbors by receiving advertisement messages from the other devices.
- *Handshake based ND*: In handshake based ND protocols, once a device receives an advertisement message, it

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provides active response to its neighbor. Compared to one-way ND protocols, handshake based ND protocols are more complex to implement, but they are easy to construct symmetric neighborhood by exchanging advertisement messages especially for direction-aware links.

Although directional antennas offer many advantages over omni-directional antennas, their deployment for neighbor discovery is not a trivial matter. For instance, *deafness* is a typical problem caused by use of directional antennas [5]. It refers to the phenomenon that when a device, say A, fails to communicate with the other device B, because device B points its antenna's main lobe to a direction away from A. Thus performance of Directional ND (D-ND) might be affected by this deafness. However from another aspect, by using directional mode for receiving, a device can nullify the interference from undesired directions. Therefore, the deafness phenomenon may help to alleviate the collisions of advertisement messages especially, for a network with high node density. This issue is worthy of investigation in detail. To achieve the best link quality, devices need to find out the best beam path to communicate with its neighbors. Therefore, during the ND process, advertisement messages are either transmitted or received in a *blind* way. Blind means that the ND process is executed without the pre-knowledge of the location information of the neighbors, which helps the devices to align antennas with each other. In [12] D-ND process is discussed to setup directional links, however, no analytical model or study for the performance analysis is provided. In [7], the authors presented several probabilistic models for D-ND protocols, but their approach is only applicable to one-way D-ND processes. In [11], authors proposed a simplistic analytical model for handshake and scanning based D-ND. They assumed that in each beam sector only one potential neighbor is present, which makes the analysis only applicable to sparse networks with narrow beam antennas. In our work, we will extend the analysis for more than one potential neighbor in each beam sector. The one-way D-ND process is not investigated in their work. D-ND in 60 GHz indoor wireless networks was investigated in [13]. The method used there is also based on one-way D-ND mechanism. Moreover, they assume that reception failure is only caused by packet collisions, in which the effect of channel model is not considered. In [14], authors emphasized the neighbor location discovery via direct path or non-direct path using linear and circular polarization and different responses to reflections with directional antennas operating in the 60 GHz band. The standardization activities like IEEE 802.15.3c and IEEE 802.11ad also involve device discovery aspect as shown in [15] [16]. However, none of them provides detailed performance analysis of their proposed protocols.

The main contributions of this work involve the following aspects:

- We provide an in-depth method to model the performance of D-ND protocols by combing different ND mechanisms with different antenna modes.
- We show the D-ND performance for a peer-to-peer (two-device) discovery process, and we also provide the D-ND performance for a distributed ad-hoc network with multiple devices.
- The accuracy of our theoretical model is validated by extensive simulations.

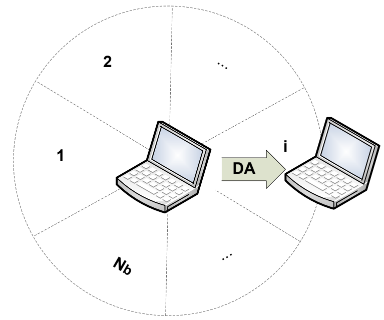

Fig. 1. Scan-based directional ND process illustration

The rest of the paper is organized as follows. In Section II, we introduce assumptions in our work and the system models. In Section III, we discuss the D-ND protocols based on a specific two-device model. In Section IV, we extend the two-device model to a generic model. Finally, we conclude our work in Section V.

II. System Model and Assumptions

To quantify the performance of an ND process, the following metrics are defined first. *ND ratio* is defined as the ratio between the number of discovered neighbors and the number of all the surrounding neighbors. ND ratio determines the network topology and robustness. For any device, it is easy to maintain the connectivity with the entire network if it has a higher ND ratio. *ND time* is an important metric to characterize the duration of one ND process. It can be viewed as the average time spent to let any newly entering device to discover and incorporate all or most of the neighboring devices. For our analysis, we define that a ND process is considered as complete if the ND ratio reaches 99%. *ND overhead* is the number of generated advertisement messages during ND process. Since in our work, we only consider advertisement messages that are transmitted using directional antennas, we call them as directional advertisement (DA) messages.

Due to the weak penetration property of 60 GHz radio, the coverage range of 60 GHz signal is normally limited within one room for indoor environment. It is possible that the devices within the same room are within the coverage range of each other. Hence we assume a full mesh network model in the following analysis. An idealized directional antenna pattern with negligible side lobe is used for our analytical model, which is also called as "flat-top" antenna model. Although flat-top is an idealized antenna pattern, it provides an easy way to deduce the analytical model. Antenna beamwidth is denoted as θ. The horizontal space around a device is divided into N_b sectors, where $N_b = \frac{2\pi}{\theta}$. For a device, it is either in the *transmitting* state or in the *receiving* state. A scan-based mechanism is defined for D-ND. *Scan* means that if a device is in the transmitting state, it randomly selects a beam sector to transmit its DA message, and moves clockwise to transmit the next DA message in the next sector until it covers all the beam sectors. An example is shown in Fig 1. The considered D-ND protocols could operate in both synchronous and asynchronous systems. To simplify the analytical process, a slotted synchronous system is assumed. The duration of each slot is equal to the transmission time of a DA message τ. For one-way D-ND, every N_b slots are grouped together as a frame, so the time duration of a frame is τN_b. For handshake-based D-ND, the duration of each handshake process is defined as the duration for transmitting a DA message and a DA Acknowledgment (ACK) message from the receiver. We assume that a DA ACK is just the DA message of the receiver. Every $2N_b$ slots are grouped together as a frame, and the length of a frame is equal to $2\tau N_b$. Therefore, the number of slots required for a ND process can be used as an indicator of ND time. At the beginning of each frame, a device has a probability p_t to be in the transmitting state or has a probability $1 - p_t$ to be in the receiving state.

There are two antenna modes investigated in this work. If the devices use directional antennas to transmit and use omni-directional antennas to receive, this mode is called as DO mode. If the devices use directional antennas for both transmitting and receiving, this mode is called as DD mode. Using directional receiving mode makes the ND process more difficult. Especially when the antenna beamwidth is narrow, the probability for two devices exactly pointing to each other's direction during the blind discovery process is dramatically decreased. Therefore, we define that, if a device is in the directional receiving state, it randomly picks up a direction to listen and listen to the same direction in the entire frame. In this way, the chance that it can receive a DA message from its neighbor within a frame is increased.

According to the combination of ND protocols and antenna modes, there are four D-ND protocols that are examined in the following studies: one-way DO-ND, one-way DD-ND, handshake-based DO-ND and handshake-based DD-ND.

III. D-ND Performance for Two-Device Model

Two-device model is a simple and realistic scenario for a ND process. For instance, when a blue-ray recorder tries to set up connection with a HDTV for video streaming, or two laptops connect with each other for high speed content downloading, the latency of a ND process directly influences the user's experience of the consumer products. Therefore, it is necessary to model the ND performance using directional antennas for a two-device model first.

A. One-way DO-ND and DD-ND

For one-way DO-ND, devices transmit from directional antenna, and receive from omni-directional antenna. Assume that device m and device n are one-hop neighbors. The condition for m to discover n in a certain frame is that m is in the receiving state and n is in the transmitting state, the probability of which is given by $p_f = (1-p_t)p_t$. Assume that one of the two devices, say m, discovers its neighbor n in the j^{th} frame with probability $p_f(1-p_f)^{j-1}$. This one-way DO-ND process is over at the j^{th} frame if device n discovers m in the i^{th} frame and $i < j$, the probability of which is given by,

$$p_{1DO}^{(j)} = \binom{2}{1} p_f \left((1-p_f)^{j-1} - (1-2p_f)^{j-1}\right). \quad (1)$$

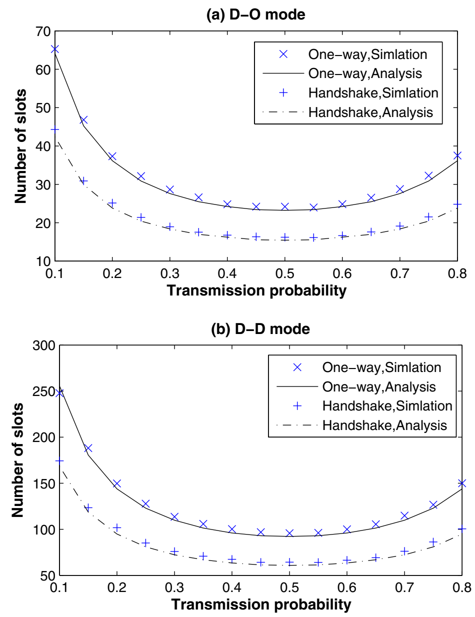

Fig. 2. Neighbor discovery time for two-device model, $\theta = 90°$, 10000 iteration time

The probability for the two devices to discover each other within J frames is given as $p_J = \sum_{j=2}^{J} p_{1DO}^{(j)}$. Note that the two devices cannot discover each other within the same frame, therefore, it requires at least two frames hence we have the summation starting from $j = 2$. The expected number of slots required for this one-way DO-ND process is given by,

$$N_{1DO} = \sum_{j=2}^{J} N_b j p_{1DO}^{(j)}. \quad (2)$$

Now, let us talk about one-way DD-ND. In this case, both transmitting and receiving devices use directional antenna mode to discover device n in a certain frame, except for the condition that m and n are in the receiving and transmitting state, respectively. Moreover, the device m should point its antenna to the direction of device n. The probability for this event is $p_f = \frac{1}{N_b}(1-p_t)p_t$. We denote $p_{1DD}^{(j)}$ as the probability for the two devices discovering each other in the j^{th} frame. We use N_{1DD} as the expected number of slots for the one-way DD-ND process. These two parameters $p_{1DD}^{(j)}$ and N_{1DD} can be calculated by substituting p_f in (1) and (2).

B. Handshake-based DO-ND and DD-ND

By using handshake-based mechanism, active response should be provided if a device receives a DA message from the other device. Hence for the two-device model, it is possible for device m and n discovering each other within the same frame, and this probability is given by $p_f = 2(1 - p_t)p_t$. Let us represent the probability that the two devices discover each other in the j^{th} frame for the first time as $p_{2DO}^{(j)}$, and it is calculated as,

$$p_{2DO}^{(j)} = p_f \left((1 - p_f)^{j-1}\right). \tag{3}$$

The expected number of slots for a handshake-based DO-ND process is expressed as,

$$N_{2DO} = \sum_{j=1}^{J} 2N_b j p_{2DO}^{(j)}. \tag{4}$$

Based on the above concepts, it is easy to understand that for handshake-based DD-ND, p_f is obtained as $p_f = \frac{2}{N_b}(1 - p_t)p_t$, and then $p_{2DD}^{(j)}$ and N_{2DD} can be obtained by substituting p_f into (3) and (4).

C. Validation using Simulation

To validate the accuracy of the analytical model, we simulated the four D-ND protocols at the algorithmic-level[1] using Matlab (R2007b). The ND process is defined according to the scenario explained in Section II. The analytical results and simulation results are compared in Fig 2 when the antenna beamwidth is fixed at 90°. The simulation results are based on the average value of 10000 iterations. The one-way and handshake-based ND mechanisms are compared when they combine with DO mode and DD mode, respectively, as shown in Fig 2 (a) and (b). The two sub-figures show the relationship between the expected number of slots required for a ND process and the transmission probability p_t. It is shown that, there exists an optimized value for p_t. If the transmission probability is too small, the two devices are both in the receiving state most of the time. If the transmission probability is too high, the two devices might miss the DA messages from each other because they both are in the transmitting state. It is also observed that, the handshake-based ND protocol is superior to the one-way ND protocol in both DO mode and DD mode. Comparing sub-figures (a) and (b), we can see that using DD mode leads to a longer ND time than the DO mode.

We presented a two-device model for different D-ND protocols. However, it is not straightforward to extend the analytical model from two-device to multiple-device model. Instead, to obtain the ND time for multiple devices, we focus on the ND process for a target device. In the following sections, we will present a generic model for one-way and handshake-based D-ND protocols with multiple devices within a distributed ad-hoc network.

[1]In this work, the physical layer simulation is not considered, which means, in a certain time slot, if a DA message is transmitted without experiencing any DA collision, it can be received by all the in-range receiving devices for sure.

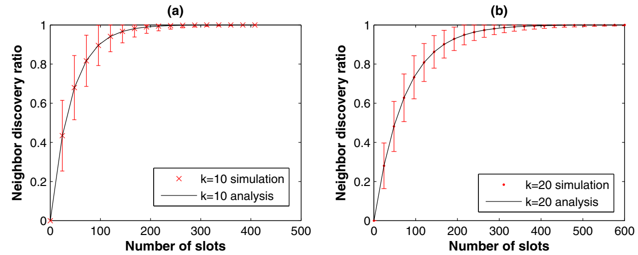

Fig. 3. Validation through simulation for the ND ratio of one-way DO-ND, 10000 iterations, $\theta = 60°$, $p_t = 0.3$

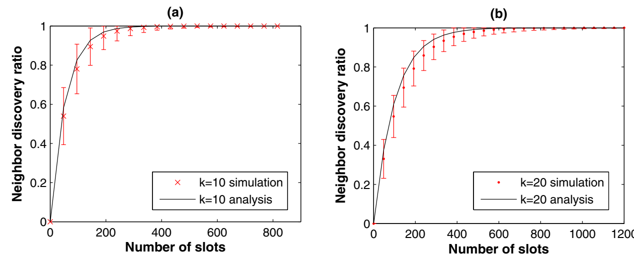

Fig. 4. Validation through simulation for the ND ratio of handshake-based DO-ND, 10000 iterations, $\theta = 60°$, $p_t = 0.3$

IV. D-ND Performance for a Generic Model

A. One-way DO-ND

To construct a scenario involving multiple devices, we assume a circular full mesh network. Device m is considered as the target device to be investigated in the following study, and it is located in the middle of the network. The node degree (the number of direct neighbors of a device in the network) of the target device is k, and the k neighbors are uniformly distributed within the circular network. By using one-way DO-ND, device m can detect its neighbors by receiving DA messages from them. In a certain frame i, the probability for the event that device m is in the receiving state and its w neighbors are in the transmitting state and is denoted as p_w, which is given by,

$$p_w = (1 - p_t)\binom{k}{w} p_t^w (1 - p_t)^{k-w}. \tag{5}$$

We denote $n_{i,x}$ as the number of DA messages that arrive at device m in the x^{th} slot of the i^{th} frame, so we have $\sum_{x=1}^{N_b} n_{i,x} = w$. For a certain occupancy combination $\mathcal{N}_i = [n_{i,1}, ..., n_{i,N_b}]$, we denote $l_{i,z}$ as the number of elements in $\mathcal{N}_i$, the value of which is equal to z, and we have $\sum_{z=0}^{\max(\mathcal{N}_i)} l_{i,z} = N_b$. Therefore, the probability to obtain a given occupancy number $\mathcal{N}_i$ on the condition that all the occupancy numbers appear in an arbitrary order is given by,,

$$p_i = \frac{w!}{\prod_{z=1}^{\max(\mathcal{N}_i)} l_{i,z}!} \frac{N_b!}{\prod_{x=1}^{N_b} n_{i,x}!} N_b^{-w}. \tag{6}$$

For the detailed deduction please refer to Appendix. If multiple DA messages arrive in a time slot simultaneously ($z > 1$), these messages collide with each other and cannot be received by the receiver. Therefore, the average number of received DA messages in one frame is given by,

$$n_{rt} = \sum_{w=0}^{k} \sum_{i=1}^{\varpi} l_{i,1} p_i p_w, \tag{7}$$

where, ϖ is the total number of occupancy combinations of $\mathcal{N}_i$, which is a function decided by node degree k and the number of slots in one frame N_b. The number of distinguishable occupancy of $\mathcal{N}_i$ is denoted as A_{w,N_b}, where $A_{w,N_b} = \binom{w+N_b-1}{N_b-1}$ [17]. The relation between A_{w,N_b} and ϖ is given by,

$$A_{w,N_b} = \sum_{i=1}^{\varpi} \frac{w!}{\prod_{z=1}^{\max(\mathcal{N}_i)} l_{i,z}!} \tag{8}$$

Therefore, the ND ratio in consecutive J frames are formulated as:

$$P(J,m) = \sum_{j=0}^{m} \sum_{x=0}^{m-j} P(J-1, m-j) \rho(x+j) \frac{\binom{m-j}{x}\binom{k-m+j}{j}}{\binom{k}{x+j}}, \tag{9}$$

where, $\rho(x+j)$ is the probability of device m receiving $x+j$ DA messages within the J^{th} frame, in which x messages are from known neighbors and j messages are from unknown neighbors, and $\rho(x) = \sum_{w=1}^{k} \sum_{i=1}^{\varpi} 1_{(l_{i,1}=x)} p_i p_w$, where $1_{(\Omega)}$ is an indicator function, which is given by,

$$1_{(\Omega)} = \begin{cases} 1 & \text{if } \Omega \text{ is true} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Simulation is used to verify the analytical results. Following the previous defined scenario, we simulated a full mesh network, in which the device m is in the middle of the network and its neighbor uniformly distributed within the network. The analytical results of ND ratio are compared with the simulation results in Fig 3 and Fig 4, in which we depicted the ND ratio when node degree is 10 and 20, respectively. These two figures illustrate a good accuracy of our analytical model. Being different with the two-device model, the handshake-based ND mechanism performs worse than the one-way ND mechanism, this is because multiple receiving devices might be in the same beam sector and transmit multiple DA ACKs simultaneously. Therefore DA ACK collision compromises the D-ND performance.

To maximize the algorithm performance, the optimal transmission probability p_{opt} is obtained to maximize the number of detected neighbors in one frame. The relationship between node degree and p_{opt} is depicted in Fig 5. Therefore, when a device knows its node degree, it may estimate the optimized transmission probability to get better ND performance. The comparison between using pre-defined transmission probability and the optimized probability is shown in Fig 6. It is observed that, p_{opt} reduces the number of frames required for a ND process significantly. The influence of antenna beamwidth on the ND duration by using the optimized transmission probability is shown in Fig 7. With the increase in the antenna beamwidth, although the expected number of frames for a ND process is increased, the entire ND time, which is related to the number of expected slots used for a ND process, is decreased.

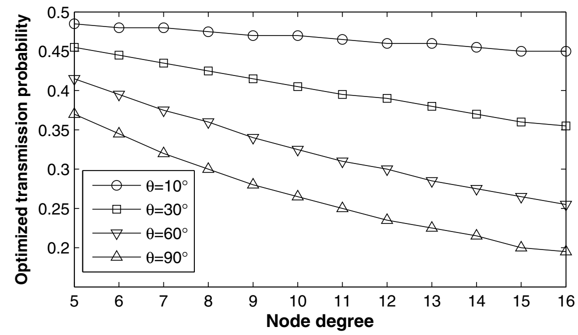

Fig. 5. Relation between node degree and the optimized transmission probability with for various antenna beamwidth

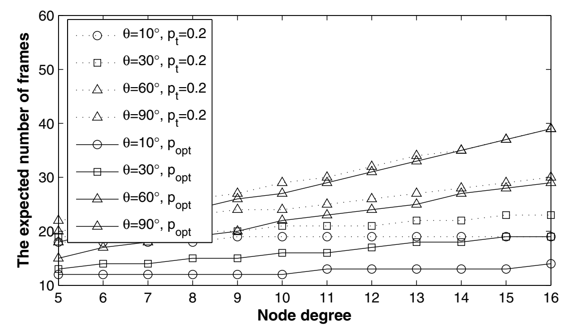

Fig. 6. Relation between node degree and the expected number of frames for a ND process

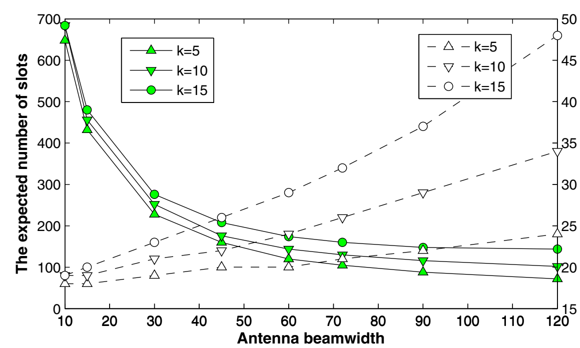

Fig. 7. Relationship between antenna beamwidth and the duration of a ND process

B. Handshake-based DO-ND

By using handshake-based DO-ND, device m can detect its neighbors in two scenarios: First, m is in the receiving state and receives DA messages from its neighbors. Second, m is in transmitting state and receives DA ACKs from its neighbors. We denote that device m receives n_h DA messages in a frame. The number n_h can be expressed as $n_h = n_{rt} + n_{tr}$, where n_{rt} is the number of DA messages received if m is in the receiving state, which can be obtained from (7), and n_{tr} is the number of DA messages received if m is in the transmitting state, which is derived as follows. When device m is in the transmitting state, the number of received DA ACKs depends on the number of successful transmissions in one frame, and also depends on the number of neighbors that reply the DA message in a certain slot. For the sake of simplicity in analysis, we assume that a device always replies to the received DA messages from its neighbors.

Let p_x be the probability for x neighbors within a certain beam sector of device m, and y out of the x neighbors are in the receiving state and,

$$p_x = \binom{k}{x} \frac{1}{N_b}^x \left(1 - \frac{1}{N_b}\right)^{k-x} \binom{x}{y} (1-p_t)^y p_t^{x-y}. \quad (11)$$

The condition for the device m to receive one DA ACK is that only one out of y neighbors replies to m and the other $(y-1)$ neighbors cannot reply due to DA collisions. The probability of this event is denoted as

$$p_y = \binom{y}{1} p_{succ}(1-p_{succ})^{y-1}, \quad (12)$$

where, p_{succ} is the probability that a neighbor which is in the receiving state correctly receives a DA message from device m in a certain time slot. For a device, say n, on the condition that m is in the transmitting state and n is in the receiving state, device n receives a DA message from device m if there are no other devices transmitting in the direction of n. Therefore, we have,

$$p_{succ} = \left(1 - \frac{p_t}{N_b}\right)^{k-x-1} \left(1 - \frac{1}{N_b}\right)^{x-y}. \quad (13)$$

Hence the average number of received DA message when device m is in the transmitting state is

$$n_{tr} = \sum_{x=1}^{k} \sum_{y=1}^{x} p_t p_x p_y. \quad (14)$$

C. One-way DD-ND

For the one-way DD-ND, devices transmit and receive directionally. At the beginning of a frame, if a node is in the receiving state, it randomly choses a beam sector to listen. If multiple DA messages arrive at a device simultaneously, only the packets from the listening direction can be received. The average number of received DA messages in one frame can be modified according to (7) as,

$$n_{rt} = \sum_{w=0}^{k} \sum_{i=1}^{\varpi} \sum_{x=1}^{N_b} 1|_{n_{i,x} \geq 1} \binom{n_{i,x}}{1} (1 - \frac{1}{N_b})^{n_{i,x}-1} \frac{1}{N_b} p_i p_w, \quad (15)$$

in which, according to the definition in Section IV-A, $n_{i,x}$ is the number of DA messages that arrive at device m in the x^{th} slot of the i^{th} frame.

D. Handshake-based DD-ND

Similar to the handshake-based DO-ND, devices can detect their neighbors in both transmitting and receiving state. When device m is in the receiving state, the number of received DA messages is obtained according to (15). We take Fig 8 for example to deduce the number of received DA ACKs when device m is in the transmitting state. Within a certain frame, assume that device m is in the transmitting state and one of its neighbor, say device n, is in the receiving state and listens to the direction where device m is covered as shown in Fig 8. Being different from the handshake-based DO-ND protocol, not all the devices that are in the transmitting state and transmitting to device n's direction can cause DA collisions at device n. This is because n selects a certain direction to listen and nullifies interference from the other directions, only devices within n's listening direction may interfere the reception of the DA message from m. We take the radius of the circular full mesh network as R. As shown in Fig 8, the white area I is the intersection area between device n's receiving sector and the circular network, which can be considered as the potential interfering area for device n. If the other transmitting devices are located in this area, and they point to n's direction, device n cannot receive m's DA message due to DA collision. The size of the potential interfering area is given by

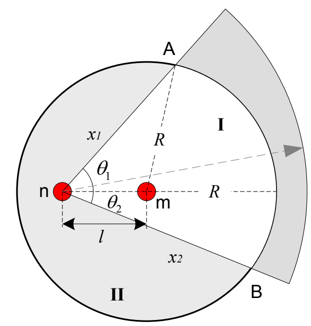

Fig. 8. The illustration for the circular network and the effective interfering area of device n

$$S = \frac{1}{2} \int_0^R \int_0^\theta \left(l x_1 \sin\theta_1 + R^2 \arcsin\left(\frac{x_1 \sin\theta_1}{R}\right) + l x_2 \sin\theta_2 + R^2 \arcsin\left(\frac{x_1 \sin\theta_2}{R}\right)\right) f(\theta_1) f(l) d\theta_1 dl \quad (16)$$

where, the summation of θ_1 and θ_2 is the antenna beamwidth θ, and l is the distance between device m and device n. $f(\theta_1)$ and $f(l)$ are the distribution for the angle θ_1 and distance l, where $f(\theta_1) = \frac{1}{\theta}$ and $f(l) = 2l/R^2$. Device n's receiving beam sector is intersected with the circular network at point A and point B. The distance from device n to A is x_1, and the distance from device n to N is x_2, where x_1 and x_2 are the solutions of the polynomial equations

$$\begin{cases} x_1^2 + l^2 - R^2 = 2\cos\theta 1 x_1 l \\ x_2^2 + l^2 - R^2 = 2\cos(\theta - \theta 1) x_2 l. \end{cases} \quad (17)$$

The value of S is determined by the location of n and its main lobe pointing direction. In a certain time slot when device m transmits a DA message to device n, the condition for device

n correctly receiving this DA message is that, device n listens to m's direction and no the other devices within n's listening direction transmit to n. The probability of this event is given as,

$$p_{succ} = \sum_{x=0}^{k-1} \frac{1}{N_b} \binom{k-1}{x} \left(\frac{S}{\pi R^2}\right)^x \left(1 - \frac{p_t}{N_b}\right)^x \times \left(1 - \frac{S}{\pi R^2}\right)^{k-x-1} \quad (18)$$

According to (11), (12), and (14), the expected number of received DA ACKs n_{tr} can be calculated when device m is in the transmitting state. The analytical results for the ND ratio obtained by using one-way DD-ND and handshake-based DD-ND are depicted in Fig 9 and Fig 10, respectively, which are compared with the results from simulations. These two figures also indicate a good accuracy of our proposed analytical model.

In Fig 11 and Fig 12, the four D-ND protocols, one-way DO, one-way DD, handshake DO, and handshake DD, are compared together in terms of ND overhead and ND ratio using simulations. Each generated result is the mean of 10000 iterations. The node degree is fixed at 15 and the transmission probability is 0.3. As shown in this figure, we observe some interesting properties:

- In general, using DO mode has higher ND ratio and lower ND overhead than using DD mode.
- Smaller the antenna beamwidth is, the bigger is the ND performance difference between DO mode and DD mode.
- Compared to DO mode, the antenna beamwidth variance impacts more on the overhead using DD mode.
- When antenna mode is fixed (DO or DD), one-way mechanism has higher ND ratio than handshake-based mechanism.
- When antenna beamwidth is small, the ND ratio difference between one-way and handshake-based mechanisms is also small. With the increase in antenna beamwidth, the ND ratio difference is also increased.
- By using DO mode, one-way mechanism generates fewer overhead than handshake-based mechanism. In comparison, using DD mode, one-way mechanism generates more overhead than handshake-based mechanism.

V. Conclusion

In this paper, we have studied the performance of neighbor discovery (ND) processes using directional antennas in WPANs. We proposed a comprehensive analytical model to demonstrate the ND performance through different mechanisms (one-way based and handshake-based) and also different antenna modes (DO mode and DD mode). We have performed extensive simulations to validate the accuracy of our model. Based on our study, we observe that, handshake-based D-ND protocol is suitable for a user model which only requires one-to-one discovery. Within an ad-hoc network with multiple devices, one-way D-ND protocol normally performs better than handshake-based D-ND. For a network only equipped

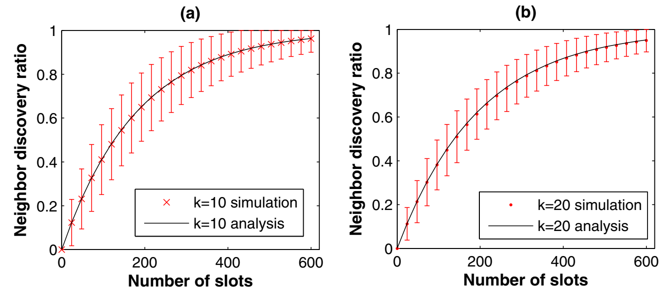

Fig. 9. Validation through simulations for the ND ratio of one-way DD-ND, 10000 iterations, $\theta = 60°$, $p_t = 0.3$

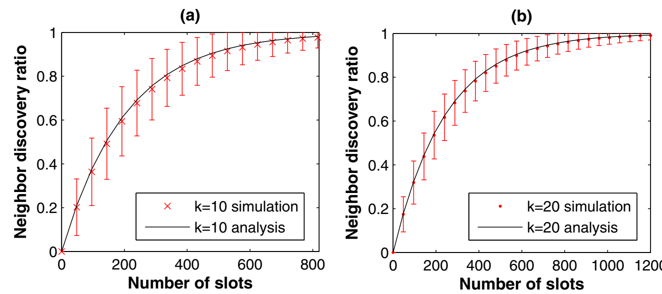

Fig. 10. Validation through simulations for the ND ratio of handshake-based DD-ND, 10000 iterations, $\theta = 60°$, $p_t = 0.3$

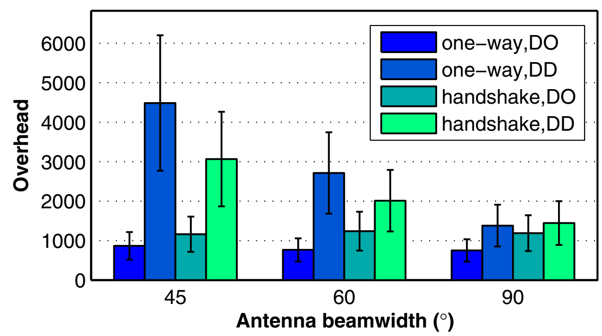

Fig. 11. Overhead comparison, 10000 iterations, $k = 15$ $p_t = 0.3$

with directional antennas with narrow antenna beamwidth, one-way DD-ND has similar ND ratio as that of handshake-based DD-ND however, handshake-based mechanism has less overhead.

Appendix

In one round of scanning during the neighbor discovery process, if device m is in the receiving state, the number of directional advertisement messages that arrive at m in the x^{th} slot of one frame is denoted as n_x. Hence we have $n_1 + n_2 + ... + n_{N_b} = w$, where N_b is the number of beam sectors which is also equal to the number of slots in one frame, and w is the number of neighbors that are in the transmitting state. This problem is an occupancy problem that randomly places indistinguishable r balls into n cells, where $r_1 + r_2 + ... + r_n = r$, and the number of elements in one cell can be zero. The number of ways to separate r elements into n sub-groups is

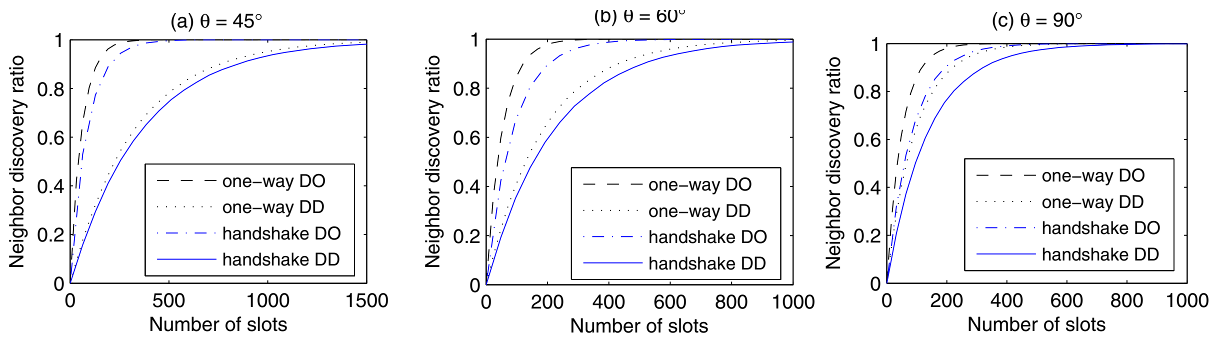

Fig. 12. ND ratio comparison with different antenna beamwidth, 10000 iterations, $k = 15$ $p_t = 0.3$

given by [17],

$$\begin{aligned}&\binom{r}{r_1}\binom{r-r_1}{r_2}\binom{r-r_1-r_2}{r_3}\ldots\binom{r-r_1-\ldots-r_{n-2}}{r_{n-1}}\binom{r_n}{r_n}\\=&\frac{r!}{r_1!(r-r_1!)}\frac{(r-r_1)!}{r_2!(r-r_1-r_2!)}\\&\times\frac{(r-r_1-r_2)!}{r_3!(r-r_1-r_2-r_3!)}\cdots\frac{(r-r_1-\ldots-r_{n-2})!}{r_{n-1}!(r-r_1-r_2-\ldots-r_{n-1}!)}\\=&\frac{r!}{r_1!r_2!\ldots r_n!}. \qquad (19)\end{aligned}$$

Let us denote w as the maximum number of balls in one cell, where $w = \max(r_n)$. Therefore, we have $n_0+n_2+\ldots+n_w = n$, where n_i is the number of cells which contain i balls in them, $0 \le i \le w$. According to (19), the number of ways to participate in cells is given by,

$$\frac{n!}{n_0!n_1!\ldots n_w!} \qquad (20)$$

Therefore, the total number of distributions of the occupancy numbers with $\mathcal{N}_n = [r_1, r_2, \ldots, r_n]$ is given by,

$$\mathbb{N}_{r,n} = \frac{r!}{r_1!r_2!\ldots r_n!} \times \frac{n!}{n_0!n_1!\ldots n_w!} \qquad (21)$$

In total, there are n^r possible placements which are equiprobable, hence the probability p to obtain the given occupancy number $\mathcal{N}_n$ is $p = \mathbb{N}_{r,n} n^{-r}$.

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