# LOS Discovery for Highly Directional Full Duplex RF/FSO Transceivers

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*Abstract*—**Full duplex directional Radio Frequency (RF) / Free-Space-Optical (FSO) transceivers are envisioned to play a great role in future generation wireless networks. They provide benefits in terms of better throughput, enhanced spectrum utilization and lower interference from unwanted sources. However, the stringent requirement of line-of-sight (LOS) communication makes it tough for a mobile node to maintain a link without a-priori information about its neighbor's position. Hence, neighbor discovery takes a very crucial role in mobile ad hoc networks with directional transceivers. In this paper, we focus on neighbor discovery using full duplex directional transceivers. We consider two nodes that can discover each other by steering their transceivers with a randomly chosen angular speed and performing a simple three way handshaking protocol. We provide a theoretical analysis of the proposed neighbor discovery method. Additionally, we propose an algorithm where each node chooses its transceiver's angular speed and renews it if the neighbor is not discovered within an optimal time interval. We evaluate the algorithm via simulations and show its effectiveness under various scenarios.**

*Keywords*—*Full duplex, directional, RF, FSO, neighbor discovery, ad hoc, VANET, MANET*

## I. INTRODUCTION

In recent years, high gain directional antennas have attracted strong interest from the wireless community especially for ad hoc networks [1]-[2]. Directional antennas provide higher gain for signal reception and higher throughput than the traditional omnidirectional ones. Also, using directional antenna for signal reception reduces interference caused from unwanted directions as well as jamming. This directionality further improves spatial reuse. The directional antenna brings another advantage in terms of security as the transmission can not be intercepted or detected from a point that is not in the direction of the transmission beam. All these advantages of directional antennas are suitable for tactical ad hoc networks where multiple entities desire to transmit high bandwidth data streams simultaneously with a requirement of lower interference and reduced probability of being jammed or intercepted.

Alongside providing huge benefits, directional transceivers pose a unique challenge in maintaining links with neighbors. These transceivers require maintenance of line-of-sight (LOS) between neighbors particularly for small wavelength bands such as free-space-optical (FSO) (infrared or visible) and millimeter-wave bands. Due to the reduced field-of-view compared to the omni-directional case, a close-to-perfect alignment between the transmitter and the receiver may be required for the communication link to work. So, a node has to steer its transceiver to face it towards the neighbor it wants to communicate with. Even if two nodes are within each others' communication range, they can not communicate if their transceivers are not facing each other.

Various strategies have been proposed to maintain links between neighbors using directional antennas. All these methods consider the mode of operation to be half-duplex [1], [3]. The wireless signal transmitted by a full-duplex transceiver
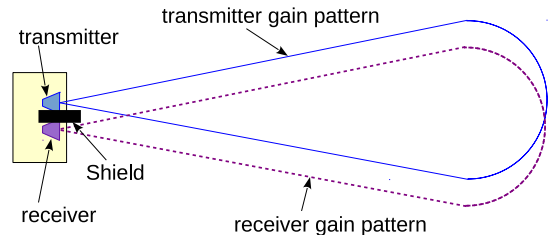


Fig. 1: Schematic diagram of a full duplex directional transceiver

causes a high powered interference at its own receiver. Despite this disadvantage, full-duplex operation provides enormous advancement for wireless networks where spectrum demands can be significantly reduced. Recently many works have focused on designing directional RF transceivers that show the feasibility of having full duplex communication [4]-[5]. In FSO communication (FSOC), full duplex can be achieved by placing non-transparent material (e.g., aluminium foil, plastic tape, or filters) between the transmitter and the receiver of a node [6]. So, full duplex and/or directional operation on both RF and FSO transceivers has become possible and deserves a revisiting of some of the protocol designs in wireless systems. Figure 1 illustrates the gain pattern of a full duplex RF/FSO directional transceiver. Here, the transmitter and receiver are separated by a small distance and they face towards the same direction. A shield is placed to attenuate the feedback signal from the transmitter that can reach the receiver.

In this paper, we focus on discovering a neighbor node without any prior knowledge about its location. We consider two mobile nodes each with a highly directional FSO/RF transceiver mounted on a head/arm. The head/arm is mechanically steerable with which the FSO/RF transceiver can scan $2\pi^c$. We also assume that there is no GPS or omni-directional RF link available to exchange orientation information. That is, we assume that the nodes operate in-band and use only the directional transceivers to discover each other. Both nodes operate in full-duplex mode. The nodes rotate their transceivers with randomly chosen angular speeds. Each node starts a three way handshake by sending a beacon message. Upon reception of a beacon a node stops rotating and complete the handshake. The main contribution of our work is to design and evaluate the first protocol that enables two neighbors with directional full duplex transceivers to discover each other. In particular, we:

- prove that the proposed method discovers a neighbor with very high confidence within a very small amount of time;
- propose a protocol where the nodes choose angular speed randomly and reinstates the speed after a threshold time; and
- show through simulation that the proposed mechanism

works well for both stationary and mobile ad hoc networks.

The simulation results confirm that, with the proposed protocol, the average discovery time can be as small as $6s$ for mobile nodes with divergence angle of $\pi/36^c$ and $1.22s$ for mobile nodes with divergence angle of $\pi/15^c$ (Here $^c$ denotes angle in radian).

The rest of the paper is organized as follows: Section II surveys the relevant background on directional transmission and neighbor discovery. The proposed methodology, theoretical analysis and the algorithms are described in Section III. Section IV illustrates the simulation scenarios and discusses the results. Finally, Section V concludes the paper.

## II. BACKGROUND

In this section, we first discuss the motivation for directional transmission using both FSO and RF communications. Then, we present the already proposed neighbor discovery protocols for directional transmission and their shortcomings.

### A. Directional Transmission

In [7], a new technology involving FSOC between unmanned aircrafts (e.g., Aquila - UAV developed by Facebook) is proposed, that will help connect areas of the world that currently do not have Internet infrastructure. A method for establishing and maintaining an FSO link among nearby balloons with the aid of GPS, RF, camera, and communication with a ground station is presented in [8].

Unlike these out-of-band techniques, in [9], we proposed an in-band method that deals with the problem of maintenance of LOS alignment between two autonomous mobile nodes moving on 2D plane with mechanical steering of FSO transceivers. For RF-challenged environments, such in-band techniques that only use the FSO link itself with no dependence on RF-based links are necessary.

### B. Directional Neighbor Discovery

Neighbor discovery for directional RF has been well explored. Choudhury *et al.*[1], [3] have designed a MAC protocol for ad hoc networks with directional transmitter and omnidirectional receivers. They suggested that nodes can transmit their positional information with omni-directional transmitters in order for all nodes to be aware of their neighbors' positions. Ramanathan *et al.*[10] presented UDAAN, the first full system deployment of ad hoc network utilizing directional antennas. It uses heartbeat messages to exchange the position information and uses GPS clock cycle synchronization for neighbor discovery. This prototype uses omni-directional antennas for establishing the connection with new neighbors.

Zhang *et al.*[2], [11] proposed two algorithms for neighbor discovery with directional RF communication. The authors considered that the nodes are synchronized and use synchronized slots to transmit neighbor discovery requests. Although [2] provides a good analysis on number of slots required to complete the neighbor discovery, the consideration of all nodes using synchronous slots is not very practical. Pei *et al.*[12] proposed another neighbor discovery protocol for directional MANETs based on synchronous search.

Jakllari *et al.*[13] is the only earlier work we found that deals with directional transmitter and receiver. It proposed a polling based MAC protocol for MANETs where all nodes are synchronized in terms of the polling slots. It allocates slots for discovering new neighbors when all nodes in a MANET points

to random direction and advertise for neighbor discovery. It also provides a framework to compute neighbor discovery time. We assume no synchronization among nodes.

Most of the proposed neighbor discovery algorithms consider either omni-directional transmission or omni-directional reception, and immobile nodes. Also, some works consider availability of GPS and some consider that all nodes have prior information about neighbors' movement. To the best of our knowledge, this is the first work on directional neighbor discovery protocol with full-duplex mode of communication and without any out-of-band support like GPS or an extra communication channel.

## III. METHODOLOGY

### A. Assumptions

We assume the followings for our proposed model:

1) **Node IDs:** Each node is assigned with an unique identifier (such as MAC address).
2) **Full Duplex:** The communication between the nodes is full-duplex.
3) **Mobility:** The nodes can move autonomously and are within transmission range of each other in a 2D plane.
4) **Frequency:** The discovery phase use in-band communication and does not require a separate control channel.
5) **Directional:** Both the transmitter and the receiver of a node face towards the same direction and rotate together as shown in Figure 1. The receiver can receive signal from a neighbor that is within its main beam and the transmission beam of the neighbor must face towards the receiver. As a node's own transmitter and receiver face the same direction, its own transmission will not cause any interference to its receiver.
6) **Gain:** We consider that the nodes use highly directional transceivers with fixed beam width. We consider very high transmission gain in the direction of the main lobe and zero gain outside in the direction that is outside of main lobe.
7) **Transceiver rotation:** The nodes can rotate their transceivers using mechanically steerable heads. While performing neighbor discovery, both nodes rotate in the same manner (both clockwise/both counterclockwise).
8) **Asynchronous algorithm:** The nodes run the proposed algorithm in a distributed manner without any synchronization mechanism.

### B. Neighbor Discovery by Continuous Rotation

The main lobe is considered to be bordered by two angles namely lower border $(b^l)$ which is the border in the clockwise manner and higher border $(b^h)$ which is the border in the anticlockwise manner as shown in Figure 2. A node can face its main lobe towards any direction $\theta \in [0^c, 2\pi^c)$. The beam borders are at a distance of divergence angle $(\beta)$ from the normal of the lobe. We base our model with unit in radian denoted by $^c$.

The proposed discovery protocol uses a three way handshake for neighbor discovery. A node rotates its transceiver at a constant angular speed and transmits a Beacon or Hello message. If a node receives a Beacon message from its neighbor, it stops rotating its transceiver and replies to the neighbor with a B-ACK message. The node receiving the B-ACK message also stops rotating its transceiver and replies with an ACK message to the neighbor denoting completion of

TABLE I: List of used symbols

| Symbol | Description |
|--------|-------------|
| $\beta$ | divergence angle of a transceiver |
| $\omega_x$ | chosen angular speed of transceiver of node $x$ |
| $\tau$ | minimum time required to complete three way handshake |
| $\theta_x$ | initial angle at which $x$ directs its transceiver |
| $b_x^l$ | beam border in clockwise direction |
| $b_x^h$ | beam border in anticlockwise direction |
| $\alpha$ | chosen statistical confidence |
| $T_\alpha$ | time required to have $\alpha$ confidence for neighbor discovery |

neighbor discovery. Upon completion of neighbor discovery, the nodes move to link maintenance phase as proposed in our earlier work [9].

### C. Theoretical analysis

In this section we investigate the probability of neighbor discovery within a bounded time. The used symbols are listed in Table I. Let us consider that the total time required to send Beacon, receive B-ACK and then to send ACK is $\tau$. It incorporates the transmission ($t_{tran}$), propagation ($t_{prop}$) and processing ($t_{proc}$) delays at both ends. $\tau$ can be calculated as:

$$t_{tran} = \frac{\text{Beacon size} + \text{B-ACK size} + \text{ACK size}}{\text{data rate}}$$
$$\tau = t_{tran} + 3 \times t_{prop} + 2 \times t_{proc} \qquad (1)$$

Now, $t_{prop}$ will vary with distance but we can consider a maximum propagation delay as the time required for the signal to propagate within transmission range which is in the order of nano seconds. $t_{proc}$ can also vary depending on the hardware and the work load on the processor at that moment.

**Theorem 1:** If the angular speed of either of the transceivers is greater than $2\beta/\tau$, neighbors can not be discovered.

*Proof:* Let us consider the case of two stationary nodes $x$ and $y$ as depicted in Figure 2. At time $t = t_0$, $x$ is facing its transceiver at an angle of $\theta_x$ and $y$ is facing its transceiver at $\theta_y$. Now, we need to find out when $x$ and $y$ would be able to discover each other. It is obvious that the nodes can discover each other if at a certain time $x$ and $y$ both face their transceivers towards each other for at least $\tau$ amount of time. As it takes $x$'s beam $2\beta/\omega_x$ seconds to scan across $y$, the maximum angular speed for $x$ should not be more than $2\beta/\tau$ so that the transceivers of $x$ and $y$ can hear each other for at least $\tau$ amount of time. As shown in Figure 2, lower beam border of $x$, $b_x^l$, will reach $aa'$ in $(\theta_x - \beta)/\omega_x$ seconds. Let's say $l_x^n$ and $h_x^n$ denotes the time when $b_x^l$ and $b_x^h$ respectively reaches the LOS axis $aa'$. Then:

$$l_x^n = \frac{(\theta_x - \beta) + 2n\pi}{\omega_x}; \quad n \in [0,1,2,....] \qquad (2)$$

$$h_x^n = \frac{(\theta_x + \beta) + 2n\pi}{\omega_x}; \quad n \in [0,1,2,....] \qquad (3)$$

Similarly, for $y$, the beam borders will reach $aa'$ at:

$$l_y^m = \frac{(\theta_y - \beta) + (2m-1)\pi}{\omega_y}; \quad m \in [0,1,2,....] \qquad (4)$$

$$h_y^m = \frac{(\theta_y + \beta) + (2m-1)\pi}{\omega_y}; \quad m \in [0,1,2,....] \qquad (5)$$

Thus, the discovery can be completed if for any value of $n$ and $m$, the following condition is satisfied

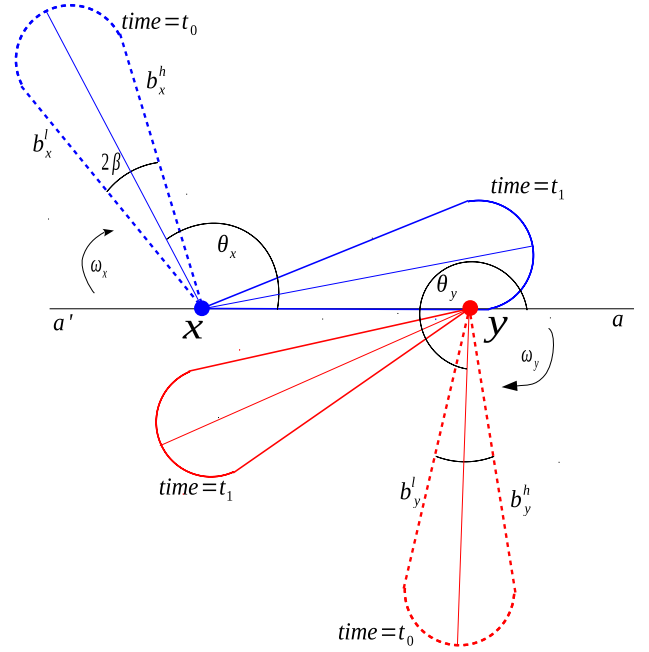$$\min(h_x^n, h_y^m) - \max(l_x^n, l_y^m) \geq \tau \qquad (6)$$



Fig. 2: Schema for neighbor discovery

For successful neighbor discovery the main beam of a node has to face its neighbor for at least $\tau$ time, i.e. $\forall_n \ h_x^n - l_x^n \geq \tau$. Replacing these values from (2) and (3), we can derive that $2\beta/\omega_x \geq \tau$. Thus $\omega_x \leq 2\beta/\tau$. Similarly, we can prove that $\omega_y \leq 2\beta/\tau$. Thus, they can not discover each other if any one of them has a angular speed greater than $2\beta/\tau$. ∎

**Theorem 2:** If nodes $x$ and $y$ rotate their transceivers with same angular speed $\omega$, then they can be discovered iff

$$\theta_x - 2\beta + \omega\tau \pm \pi < \theta_y < \theta_x + 2\beta - \omega\tau \pm \pi \qquad (7)$$

*Proof:* Let the orientation of the transceivers of nodes x and y with respect to x-axis be $\theta_x$ and $\theta_y$ respectively. As shown in Figure 2, $\theta_x^l = \theta_x - \beta$, $\theta_x^h = \theta_x + \beta$, $\theta_y^l = \theta_y - \beta$ and $\theta_y^h = \theta_y + \beta$.

Case I: $\theta_x + \pi < \theta_y$. Then, $b_x^l$ will reach $aa'$ before $b_y^l$ does. Here, $\theta_x^l$ will reach $aa'$ at $t = (\theta_x - \beta)/\omega$ seconds. $\theta_x^h$ will reach $aa'$ at $t = (\theta_x + \beta)/\omega$ seconds. Then, $\theta_y^l$ has to reach $aa'$ before $t = (\theta_x + \beta)/\omega$ - $\tau$. So, $(\theta_y - \beta)/\omega < (\theta_x + \beta)/\omega - \tau + \pi$ or, $\theta_y < \theta_x + 2\beta - \omega\tau + \pi$.

Case II: $\theta_x + \pi > \theta_y$. Then $b_y^l$ will be aligned with $aa'$ before $b_y^l$. Then, $\theta_y^h$ must leave $aa'$ only after $(\theta_x - \beta)/\omega + \tau$, which yields, $\theta_y > \theta_x - 2\beta + \omega\tau + \pi$. Thus, the condition for successful neighbor discovery is, $\theta_x - 2\beta + \omega\tau + \pi < \theta_y < \theta_x + 2\beta - \omega\tau + \pi$. Similarly, we can prove that, $\theta_x - 2\beta + \omega\tau - \pi < \theta_y < \theta_x + 2\beta - \omega\tau - \pi$. Consolidating these two equations will yield (7). ∎

**Lemma 1:** The probability that the nodes discover each other increases as the $t_{lcm}$ increases, where $t_{lcm}$ is the Least Common Multiple (LCM) of the time required for each of the transceivers' full rotation.

*Proof:* The transceivers of nodes $x$ and $y$ will complete a circle in $2\pi/\omega_x$ and $2\pi/\omega_y$ seconds respectively. Both nodes will come to same formation after every LCM($2\pi/\omega_x$,$2\pi/\omega_y$) seconds. So, we can say that the probability of discovery $P_d$ is equal to the probability of discovery within $t_{lcm}$, $p_{lcm}$. Within

this time, $b_x^l$ will touch $aa'$ $n_x$ times where,

$$n_x = \left\lfloor \frac{t_{lcm}}{2\pi/\omega_x} \right\rfloor \tag{8}$$

where, $t_{lcm} = LCM(2\pi/\omega_x, 2\pi/\omega_y)$. Let us assume that at time $t_1$, $b_x^l$ touches $aa'$. If $b_y^l$ can touch $aa'$ within $\frac{2\beta}{\omega_y} - \tau$ time, then it can receive the beacon and complete the handshake. So, for a successful discovery $b_y^l$ can be at most at $\pi + \omega_y(\frac{2\beta}{\omega_x} - \tau)$. Thus, we can write probability of discovery in the first rotation $p_0$ as

$$p_0 = \frac{\omega_y(\frac{2\beta}{\omega_x} - \tau)}{2\pi} \tag{9}$$

Since, within $t_{lcm}$ time, the transceiver will rotate $n_x$ times, it will have as many chances to complete the discovery. So, probability of discover in $t_{lcm}$ can be written as:

$$p_{lcm} = 1 - (1 - p_0)^{n_x} \tag{10}$$

Combining (8), (9) and (10), it is clear that if $t_{lcm}$ is high then the probability of detection is high. ∎

**Corollary 1:** Probability of discovery within time $t$ can be approximated as:

$$p_t = p_{lcm}^{\lfloor t/t_{lcm} \rfloor} + (1 - p_{lcm})p_{t'} \tag{11}$$

*Proof:* As $b_x^l$ will cross the same position every $t_{lcm}$, we can say that the probability of discovery within a time that is a multiple of the $t_{lcm}$ will be same as $p_{lcm}$. Let us assume, after spending $t_{lcm} \times \lfloor t/t_{lcm} \rfloor$ time, node $x$ will have $t'$ time left for discovery. The number of full rotations of $x$ within $t'$ can be derived as:

$$n_{t'} = \left\lfloor \frac{t'}{2\pi/\omega_x} \right\rfloor \tag{12}$$

where, $t' = t - t_{lcm} \times \lfloor t/t_{lcm} \rfloor$. Then, probability of discovery within $n_{t'}$ rotation,

$$p_{n_{t'}} = 1 - (1 - p_0)^{n_{t'}} \tag{13}$$

Let us assume, after $n_{t'}$, there is $t''$ time left. Similar to (9), we can say that $b_x^l$ can touch the $aa'$ line anytime between $0$ and $2\pi/\omega_x - \tau$. Thus, the probability of discovery within a time $t''$ where $t''$ is less time than a full rotation, can be derived as:

$$p_{t''} = p_0 \times \frac{t''}{2\pi/\omega_x} ; \qquad \tau \leq t' \leq 2\pi/\omega_x \tag{14}$$

where, $t'' = t' - \frac{2\pi}{\omega_x} \times n_{t'}$. Then we can calculate the probability of discovery in $t'$ as:

$$p_{t'} = p_{n_{t'}} + p_{t''} \tag{15}$$

Since, probability of discovery in first n $t_{lcm}$ time is same as probability of discovery in first $t_{lcm}$, we can write, probability of discovery within time $t$ can be written as (11). ∎

### D. Rotational Speed Reset Time

A node randomly chooses its transceiver's rotational speed without any knowledge about its neighbor's location or rotational speed. Now, for some combinations of the rotational speeds of a pair of neighboring nodes, the discovery time can be very high (for an example if they choose equal speed). Therefore, if a node does not discover its neighbor within a given time period it resets it's rotational speed.

Let $p_t(\omega_{min}, \omega_{max})$ be the probability of discovery within time $t$ where $\omega_{min}$ and $\omega_{max}$ are the lower and the upper limit of choosing the angular speed $\omega_x$ and $\omega_y$. Since having a strict range $(0, 2\beta/\tau)$ for choosing a rotational speed may not be optimal, the range is chosen as $[\omega_{min}, \omega_{max}]$ at the starting of the neighbor discovery phase. Let $\alpha \in (0, 1)$ be a statistical significance for neighbor discovery (i.e., the probability of neighbor not being discovered is $\alpha$). Then under the base model assumption, we can find out the time required, $T_\alpha$, to ensure the probability of neighbor discovery of at least $1 - \alpha$.

$$T_\alpha(\omega_{min}, \omega_{max}) = \quad \min \quad t \tag{16}$$
$$s.t. \quad P_t(\omega_{min}, \omega_{max}) \geq 1 - \alpha$$

Now, for a given $\alpha$, the optimal values for $T_\alpha$ can be observed as:

$$T_\alpha^{opt} = \min_{\omega_{min}, \omega_{max}} T_\alpha(\omega_{min}, \omega_{max}) \tag{17}$$
$$s.t. \quad \omega_{min} \in [0, 2\beta/\tau)$$
$$\omega_{max} \in (0, 2\beta/\tau]$$
$$\omega_{min} < \omega_{max}$$

Now, from the optimal value of $\omega_{min}$ and $\omega_{max}$ are:

$$\omega_{min}^{opt} = \arg\min_{\omega_{min}}(T_\alpha(\omega_{min}, \omega_{max})) \tag{18}$$
$$\omega_{max}^{opt} = \arg\min_{\omega_{max}}(T_\alpha(\omega_{min}, \omega_{max})) \tag{19}$$

The mathematical model for obtaining $\mathbb{P}(discovery)$ within a given time, resembles a continuous space markov chain as the initial position for the nodes are in $[0, 2\pi)$. We observed the effect of $\omega_{min}, \omega_{max}$ on $T_\alpha$ through rigorous simulations. The simulation results are discussed in Section IV-A3.

### E. Randomized Neighbor Discovery

Algorithm 1 presents the steps of neighbor discovery whereas Figure 3 illustrates the state diagram of a node. The main idea behind this algorithm is to rotate the transceivers in a steady speed $\omega$ and if the neighbor is not discovered within a given amount of time then $\omega$ is changed.

As the first step, a node chooses an optimal confidence level, $\alpha$, given $\beta$ and $\tau$. The optimal value of $\alpha$ is observed through simulation described in Section IV-B. The node uses (17) to determine optimal values for $\omega_{min}$ and $\omega_{max}$ and randomly selects an angular speed from $(\omega_{min}, \omega_{max})$. At this point the node can forecast that within $T_\alpha$ seconds the neighbor can be discovered with a probability greater than $1 - \alpha$. A *timeout* value is set as the current time with addition to $T_\alpha$. Now, the node starts rotating its transceiver clockwise and sends beacon messages. Since we are considering full duplex communication, the node can receive beacon from the neighbor while transmitting beacons. If a beacon is successfully received from the neighbor node, it stops rotating its transceiver and sends an B-ACK message. Similarly, if B-ACK is received from a neighbor, it stops rotating and sends a ACK message to denote completion of the three way handshaking. The node transitions to link maintenance phase after successful completion of the handshaking. If neither B-ACK nor a beacon is received, the node keeps transmitting beacon messages while maintaining the angular speed. If the handshaking procedure is not complete during the timeout interval, the node changes to a new rotational speed for the transceivers. This new rotational
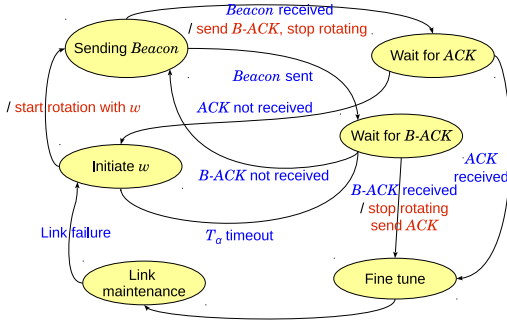
Fig. 3: State transition diagram

speed is again randomly picked from $(\omega_{min}, \omega_{max})$.

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**Algorithm 1:** Algorithm for neighbor discovery

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1 Choose optimal confidence level $\alpha$
2 Determine $\omega_{min}$ and $\omega_{max}$ from the optimal point
3 Choose an angular speed $\omega \in (\omega_{min}, \omega_{max})$
4 $Timeout \leftarrow current\_time + T_\alpha$
5 Start rotating the transceiver with $\omega$
6 Send the Beacon
7 **if** *Beacon received from other node* **then**
8  stop rotating and send *B-ACK*

9 **else if** *ACK received from neighbor* **then**
10  stop rotating send *ACK*
11  Start link maintenance phase

12 **else if** $current\_time > Timeout$ **then**
13  Goto step 3

14 **else**
15  Goto step 6

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## IV. SIMULATIONS AND RESULTS

We performed simulations using Python and MATLAB to analyze the effectiveness of the proposed neighbor discovery algorithm. We considered both stationary (both nodes stationary) and mobile (one or both nodes mobile) scenarios. We assumed the nodes to be in the transmission range $(100m)$ of each other. Different divergence angles $(\pi/60^c, \pi/36^c, \pi/24^c, \pi/15^c)$ were considered for the simulations.

We consider the MAC layer frame structure of the nodes to be similar to that of WiFi. A frame consists of preamble, header, payload (data) and CRC field. For the three hand-shaking messages (Beacon, B-ACK and ACK) of the neighbor discovery protocol the payload size is zero. In this case, frame size is considered to be 38 bytes long. Considering 1 Mbps data rate, the transmission time for one packet is $304\ \mu s$. Since, propagation delay is negligible compared to other delays, the value of $\tau$ can be determined from (1) as: $\tau = 3\times 304 + 2\times 100 = 1112\ \mu$ s.

### A. Both nodes stationary

*1) Obtaining statistical significance $\alpha$:* As the first step, we run a pilot simulation to see if neighbor discovery can be achieved within a short time with high confidence. Note that, here the nodes do not apply periodic reset of the angular speed. In every simulation, the nodes are initialized with their initial transceiver orientation randomly chosen from $[0, 2\pi)^c$.

Also, each node randomly chooses its rotational speed from $[0, 2\beta/\tau)\ ^c/s$. The simulation monitors when the two nodes discover each other. This simulation is repeated 1,000,000 times to obtain reliable results. Here, the packet processing time is considered to be $100\ \mu s$. Figure 4a plots the probability of neighbor discovery within a given time. Here, x-axis represents time spent in seconds and y-axis represents the cumulative probability of neighbor discovery within time $t$. Four divergence angles of transceivers are being considered here. It is clear from the figure that the higher the divergence angle, the lower the amount of time is required for neighbor discovery. Note that, for some cases the neighbor discovery might never happen (for example if both the nodes choose same angular speed). In this case, the time taken for discovery will be $\infty$. Thus, the cumulative distribution function will never reach 1. We can see that the neighbor can be discovered with a probability $> 0.9$ within a short period of time. However, to obtain a discovery probability of 0.95, a node needs significantly longer period of time. This necessitates the periodic reset of the angular speed.

*2) Effect of packet processing delay:* Figure 4b depicts the effect of packet processing delay on the performance of the neighbor discovery protocol. Here, x-axis represents the processing delay in $\mu s$ and y-axis represents the rotational speed reset time that is required to obtain 0.1 confidence $(T_{0.1})$, i.e. neighbor discovery probability of 0.9. For each set of parameters the simulation is repeated 1,000,000 times to obtain reliable results. At each simulation a node chooses an angular speed, $\omega \in (0, 2\beta/\tau)$, where $\tau$ is calculated according to (1). We can clearly see that for a very narrow beam transceiver $(\beta = \pi/60)$, an increase in the processing time significantly increases the reset time; thus, increasing the neighbor discovery time. For transceivers with wider beam $(\beta = \pi/36^c$ or $\pi/24^c$ or $\pi/15^c)$, the increase in reset time as the processing delay increases is less significant.

*3) Choosing optimal $\omega_{min}$ and $\omega_{max}$:* Figure 4c illustrates the effect of choosing different range of the angular speed. Here the results are plotted for two different values of divergent angle and three different ranges of the angular speed. It is very clear from the picture that choosing a hard range of $(0, 2\beta/\tau)$ does not provide optimal result as probability of discovery is lower in this case than that for the range of $(0.25\frac{2\beta}{\tau}, 0.75\frac{2\beta}{\tau})$.

In this section, the simulation is intended to obtain optimal values of $\omega_{min}$ and $\omega_{max}$ as a function of $\beta$, $\tau$ and $\alpha$. The processing time is $100\ \mu s$ and $\tau$ is calculated as in (1). Simulations are performed with different values of $\alpha$. Figure 5 presents the relationship between the range of angular speeds $(\omega_{min}, \omega_{max})$ and the time required for neighbor discovery with probability of 0.95 or $\alpha = 0.05$. Note that, in this plot both $\omega_{min}$ and $\omega_{max}$ are chosen from $[0, 2\beta/\tau]$. The results demonstrate that $T_\alpha$ is a concave function with respect to $\omega_{min}$ and $\omega_{max}$. We found that $\omega_{min} = 0.25 \times 2\beta/\tau$ and $\omega_{max} = 0.75 \times 2\beta/\tau$ provides the optimal point $(T_\alpha^{opt})$. Table II provides the obtained $T_\alpha^{opt}$ for different values of $\alpha$ and $\beta$.

### B. Both nodes mobile

Here, we consider both nodes to be mobile. The nodes' initial positions, speed (between 0-2.5m/s) and transceiver orientation are randomly chosen. The divergence angle $\beta$ is chosen as $\pi/36$. The simulator assumes a packet processing delay of $100\ \mu s$. The transceivers use Algorithm 1 for dis-
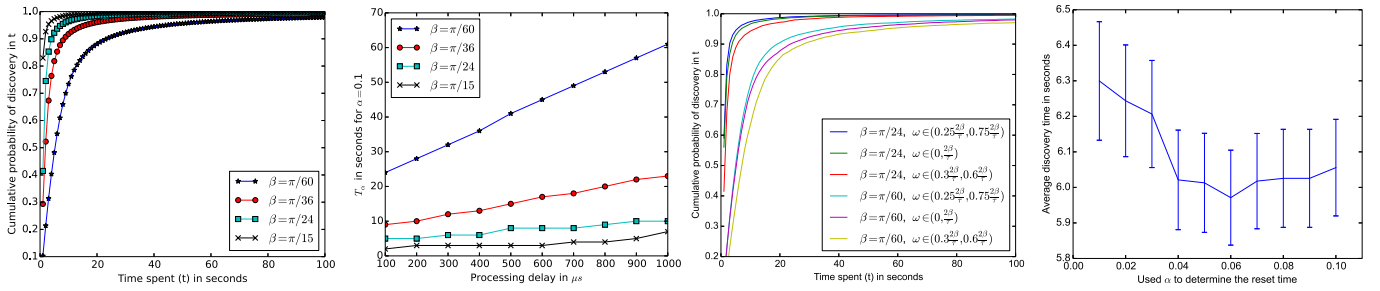
(a) Cumulative probability of discovery within a time $t$

(b) Time required to obtain 90% probability of discovery

(c) Example of the effect of different $\omega_{min}$ and $\omega_{max}$

(d) Average discovery time. Two mobile nodes with $\beta = \pi/36$.
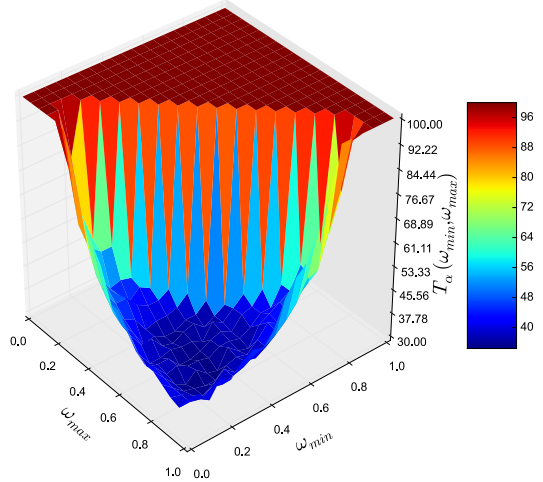
Fig. 4: Simulation Results



Fig. 5: Depiction of optimal $T_\alpha$ for $\beta = \pi/60$

TABLE II: $T_\alpha^{opt}$ in seconds for different $\alpha$ and $\beta$

| $\alpha$ | $T_\alpha^{opt}$ | | | |
|---|---|---|---|---|
| | $\beta = \pi/60$ | $\beta = \pi/36$ | $\beta = \pi/24$ | $\beta = \pi/15$ |
| 0.1 | 19.0 | 7.0 | 3.0 | 2.0 |
| 0.09 | 20.0 | 8.0 | 4.0 | 2.0 |
| 0.08 | 22.0 | 8.0 | 4.0 | 2.0 |
| 0.07 | 25.0 | 9.0 | 4.0 | 2.0 |
| 0.06 | 29.0 | 10.0 | 5.0 | 2.0 |
| 0.05 | 33.0 | 12.0 | 6.0 | 3.0 |
| 0.04 | 40.0 | 15.0 | 7.0 | 3.0 |
| 0.03 | 51.0 | 20.0 | 9.0 | 4.0 |
| 0.02 | 74.0 | 28.0 | 13.0 | 5.0 |
| 0.01 | 100.0 | 51.0 | 23.0 | 10.0 |

covering the neighbor. Note that $T_\alpha^{opt}$ is chosen from Table II and used as the rotational speed reset time. The simulation results are plotted in Figure 4d. Here x-axis denotes the chosen confidence level $\alpha$ and y-axis denotes the average time required to complete neighbor discovery. The figure also depicts 95% confidence interval of the time required for neighbor discovery. It can be observed from the figure that at $\alpha = 0.06$, the average neighbor discovery time is the lowest. So, for $\beta = \pi/36$ and processing delay of 100 $\mu s$, the optimal $\alpha = 0.06$.

## V. CONCLUSION

We proposed a novel approach for neighbor discovery in both stationary and mobile scenarios. We consider two nodes, each equipped with a mechanically steerable head/arm on which a highly directional FSO or RF transceiver is mounted. The nodes rotate the transceivers and send search signals to discover the neighbor. We proposed a method for finding optimal rotational speeds for the node's heads mounted with transceivers. Through extensive simulations we showed that the nodes can discover each other within reasonable period of time. We plan to perform real test-bed experiments to evaluate the effectiveness of the proposed method. Another possible line of future work is to consider a ground-to-air link or consider LOS discovery between two airborne mobile nodes using directional FSO or RF transceivers.

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