LOS Discovery in 3D for Highly Directional Transceivers

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***Abstract*—Directional Radio Frequency (RF) / Free-Space-Optical (FSO) transceivers have the potential to play a significant role in future generation wireless networks. They are advantageous in terms of improved spectrum utilization, higher data transfer rate, and lower probability of interception from unwanted sources. Despite these advantages, communications using directional transceivers require establishment and maintenance of line-of-sight (LOS). Thus, establishment of the communication link or neighbor discovery plays an important role in mobile ad hoc networks with RF/FSO directional transceivers. We consider two nodes (Unmanned Aerial Vehicles (UAVs) or Quadcopters) hovering in 3D space, each with one directional transceiver mounted on a mechanically steerable spherical structure/head, with which they can scan 360^o in the horizontal plane and 360^o in the vertical plane. We propose a novel scheme that deals with the problem of automatic discovery and establishment of LOS alignment between these nodes. We performed extensive simulations to show the effectiveness of the proposed neighbor discovery method. The results show that, using such mechanically steerable directional transceivers, it is possible to establish communication links to similar neighboring nodes within minimal discovery times.**

Keywords*—*Directional; 3D; RF; FSO; Neighbor Discovery; Ad Hoc; VANET; MANET.

I. Introduction

The application of high gain directional antennas have attracted strong interest from the wireless research community especially for mobile ad hoc networks in the recent years [1], [2]. Directional antennas not only provide higher gain for signal reception but also makes faster data transfer possible compared to the traditional omni-directional ones. Using directional antennas for signal reception reduces interference caused from unwanted directions. This directionality further improves spatial reuse and also lowers the probability of interception or detection by sniffers. 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. Equipping UAVs with such high-speed directional transceivers can enable a large set of applications involving transfers of very large wireless data. There are many different applications of UAVs, like surveillance for a military mission (e.g., observation behind the enemy lines) or a civil mission (e.g., monitoring of a traffic jam or a disaster area, or to broadcast critical data at some sport events) which require many sensors. UAVs with several sensors generate a lot of data which has to be delivered to either another UAV or a ground station [3]. The higher data rate required for communication links to transmit more

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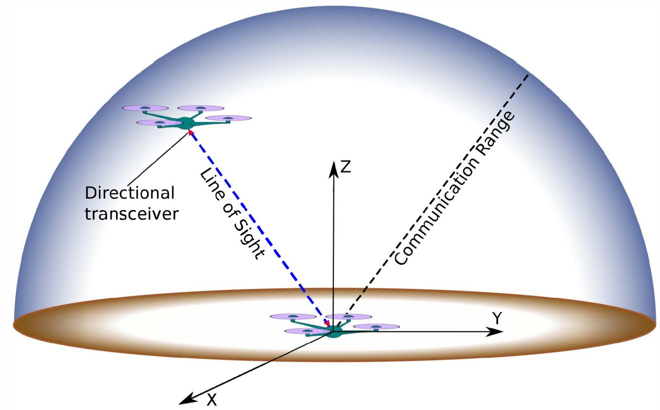


Fig. 1: Schema of UAVs communicating with directional antennas

information between UAVs triggered the idea of employing directional transceivers to meet the increasing demand [4].

Although directional transceivers provide the aforementioned benefits, communications using these transceivers are limited by the strict requirement of LOS alignment. Due to the reduced field-of-view compared to the omni-directional case, the transceiver of a node must face directly towards the neighboring node and vice versa. Even if the two directional antennas are within the communication range of each other, they can not establish a link if they are not facing each other. Thus, the first and foremost thing to do for establishing a directional RF/FSO communication link is neighbor discovery.

In this paper, we propose a novel method for neighbor discovery and establishing a communication link between two nodes hovering in 3D (Figure 1). We assume that each node is equipped with highly directional FSO/RF transceivers mounted on mechanically steerable spherical heads. Thus, the transceivers can be steered for scanning 360^o in the horizontal plane and 360^o in the vertical plane. Further, we assume that there is no GPS available for exchanging location information. We show that using the mechanical steering capability to control the rotation of the transceivers, the problem of neighbor discovery or detection of LOS and link establishment can be dealt with effectively. But, we assume the availability of an omni-directional RF link with which the nodes can exchange the orientation information of their respective mechanical heads once before starting to search for each other. Once the orientation information is exchanged, the nodes operate in-band and only use the directional transceivers to discover each other.

The basic idea for our neighbor discovery approach is to rotate the transceivers of each node with a given angular speed. One node (Master) starts a three way handshake by sending a Beacon message and the other node (Slave) waits for the

Beacon message. Upon reception of the Beacon, the slave node stops rotating its transceiver and sends an acknowledgment (B-ACK). When the master receives the B-ACK, it also stops scanning and sends an ACK message completing the handshake.

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 present the motivation for using directional transceivers in both FSO and RF communications. Then, we discuss existing literature on neighbor discovery protocols for directional transmission.

A. Directional Link Maintenance

In [5], a new technology involving FSO communication (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 the Internet infrastructure. The authors have reported about testing a new laser that can transmit data at 10 Gbps. A method for establishing an FSO link among nearby balloons with the aid of GPS, an out-of-band RF channel, camera, and communication with a ground station is presented in [6]. In [7], the authors used a predicted movement for maintaining optical-communication lock with nearby ballons, which also uses the availability of camera, GPS, and RF. In both of these works, LOS alignment between the communicating nodes is first achieved using GPS information or using a camera to localize the neighbor node. During this phase, omni-directional RF communication is used. Only after locating the neighbor node, a pointing mechanism is used to align the FSO transceivers of the neighboring nodes. Then FSO is used only for exchanging data and not for discovering or maintaining the link.

Unlike these out-of-band techniques, in [8], we proposed an in-band method that deals with the problem of maintenance of LOS alignment between two autonomous UAVs moving in 3D 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], [9] have designed a MAC protocol for ad hoc networks with directional transmitter and omni-directional receivers. An *et al.*[10] proposed a handshake based self adaptive neighbor discovery protocol for ad hoc networks with directional antennas. This paper also considers directional transmitters and omni-directional receivers for neighbor discovery while frequency of operation is determined on the run. Ramanathan *et al.*[11] presented UDAAN, the first full system deployment of an 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], [12] proposed two algorithms for neighbor discovery with directional RF communication. Although [2] provides a good analysis on the number of slots required to complete the neighbor discovery, the consideration of all nodes using synchronous slots is not very practical. Pei *et al.*[13] proposed another neighbor discovery protocol for directional MANETs based on synchronous search and positional information available from GPS.

Jakllari *et al.*[14] is the only earlier work we found that uses directional transmitters and receivers. 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. Also, some studies consider availability of GPS and some consider that all nodes have prior information about neighbors' position. In this work, we consider the availability of an omni-directional RF only for exchanging orientation information of the nodes' heads at the beginning of the directional discovery process. A node is neither aware of its own position nor the neighbor's position. Once the orientation information is exchanged, the RF link becomes inactive and the nodes use only the directional transceivers for discovering each other.

III. Theory

A. Assumptions

We make the following assumptions for our proposed neighbor discovery model:

i) **Mode:** The mode of communication between the nodes can be either half-duplex or full-duplex. We considered half-duplex communications for this work.
ii) **Nodes in 3D:** The nodes hover in 3D space and are within the communication range of each other.
iii) **Directional:** Both the transmitter and the receiver of a node face towards the same direction and rotate together. The receiver can receive signal from a neighbor that is within its main beam and the transmission beam of the neighbor must face towards it.
iv) **Transceiver rotation:** The nodes can rotate their transceivers 360^o in the horizontal plane and 360^o in the vertical plane using mechanically steerable heads. While performing neighbor discovery, both nodes rotate in the same direction on the horizontal plane, i.e., both clockwise or counterclockwise.
v) **Supplementary channel:** At the start of the discovery phase an additional omni-directional RF channel is used. The nodes are not equipped with any location tracking device such as GPS.

B. Transceiver Rotation in 3D space

As the distance between the transmitter and receiver of a node is very small compared to the communication range, we use one beam pattern to indicate both the transmission and field-of-view areas. Figure 2 shows such a beam. We approximate the beam with a cone of height r and radius $r \tan \beta$, where r is the maximum communication range of the transceiver and β is the divergence angle for transmissions and the angle of field-of-view for receptions.. The orientation of the beam is denoted by r, θ, ϕ. In this paper we shall use

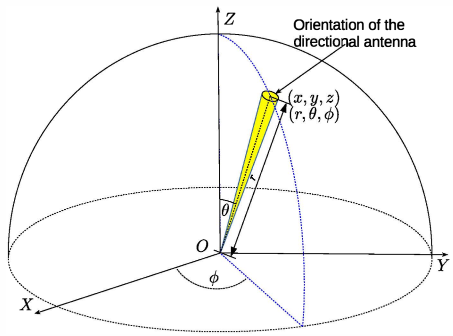


Fig. 2: Orientation of directional antenna in 3D sphere

the Polar and Cartesian coordinates interchangeably and the corresponding conversion rules are given below.

$$\begin{cases} r = \sqrt{x^2 + y^2 + z^2} \\ \theta = \arccos(z/r) \\ \phi = \arctan(y/x) \end{cases} \Leftrightarrow \begin{cases} x = r \sin\theta \cos\phi \\ y = r \sin\theta \sin\phi \\ z = r \cos\theta \end{cases} \tag{1}$$

C. Neighbor Discovery

As stated earlier, we consider two nodes hovering in 3D space. There are two main stages in the proposed neighbor discovery method: i) initialization and ii) 3D scanning.

In the initialization stage, the nodes use their omni-directional transceivers to find the existence of a neighbor node through a common RF channel (very low data rate compared to directional transceivers). Since we consider the absence of GPS, the nodes can not share their location information to each other. In this stage, the nodes agree on a starting time for the 3D scanning stage to synchronize the discovery process (figure 4). Moreover, one of the nodes (Master) agree to only transmit Beacon messages, the other one agrees to act as a receiver (Slave). The master node starts the 3D scanning with its transceiver facing in the upward direction ($\phi = 0^o$, $\theta = 0^o$). The slave node faces its transceiver downward ($\phi = 0^o$, $\theta = 180^o$) at the start of 3D scanning. The nodes decide to rotate their transceivers at the same angular speed of ω in the same direction on the horizontal plane.

After completing the initialization, the nodes stop using the common RF channel and progresses to the 3D scanning stage. In this stage, the nodes use only their directional very high data rate RF/FSO transceivers for LOS discovery. The master node starts the 3D scanning by rotating its transceiver following a modified spiral path (explained in Section III-D) as shown in Figure 3a. While rotating the transceiver, it sends a Beacon message periodically. The slave node also rotates its transceiver in a similar modified spiral path starting from the bottom end of the sphere. It waits for a Beacon message to arrive from the master node. Once a Beacon message is received, it stops rotating its transceiver and sends an acknowledgment message (B-ACK) to the master. Upon receiving the B-ACK message, the master also stops rotating its transceiver and does not send anymore Beacon messages. It sends an ACK message to the slave completing the three-way handshake (figure 4). This completes the neighbor discovery and a communication link is established between the nodes.

D. Modified Helix Movement

To make the motor rotation smooth, we consider the transceiver beams to rotate in a spiral pattern and scanning in the 3D space for discovering the LOS between neighbor nodes. Figure 3a ilustrates a sample path taken by the beam. The dotted blue line denotes the path of the normal of the beam. We consider the range of the beam to be the radius of the sphere created by the modified spiral. We can simply imagine the idea of covering a tennis ball with a narrow tape. In that case, the width of the tape is same as the diameter of the transceiver beam. For better coverage, the distance between two lines in Figure 3a has to be equal for all the lines.

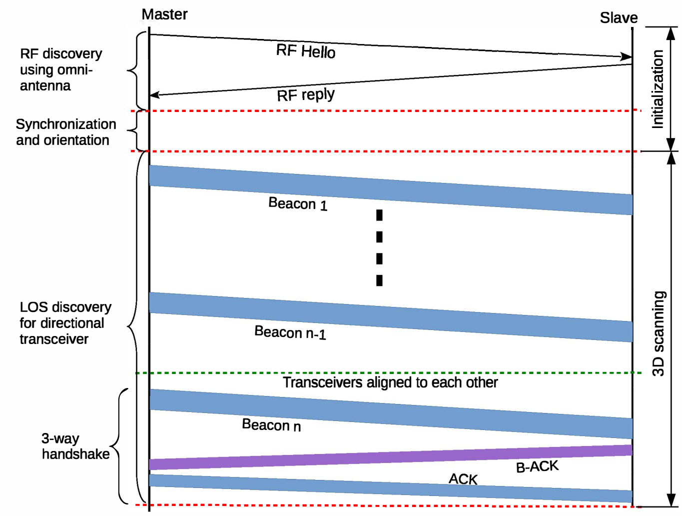


Fig. 4: Timing diagram of neighbor discovery

Figure 3b provides a side view of the transceiver beam. Figure 3c provides the 2D projection of the cross section of the beam in (θ: vertical, ϕ: horizontal) plane. At some time t, the normal of the beam is directed at point e. The path or trajectory of the normal is plotted in the picture. As the beam normal is rotating in a spiral, the path taken by the beam in the upper floor of the spiral is also plotted in the picture. As the beam moves from right to left (from h to g) in a continuous motion, a point within the square abcd will be inside the circle with origin at e for longer a period of time, compared to a point lying outside the square abcd but within the circle with origin at e. Thus, the width of the coverage of the beam movement (γ) can be calculated as follows:

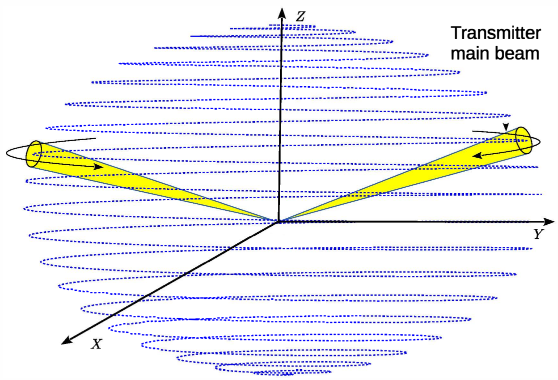
$$2\gamma^2 = (2\beta)^2 \quad \Rightarrow \gamma = \sqrt{2}\beta \tag{2}$$

As we have determined the width of the coverage, the number of rotations of the spiral (n) can be determined as:

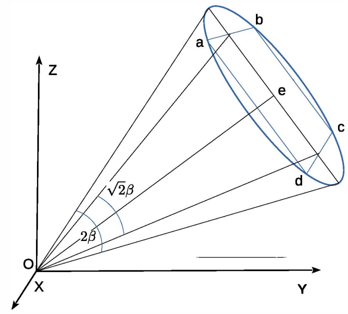
$$n = \frac{\pi}{\gamma} = \frac{\pi}{\sqrt{2}\beta} \tag{3}$$

With n rotations, the whole 3D space will be scanned and if there is a neighbor within the communication range, it will be discovered.

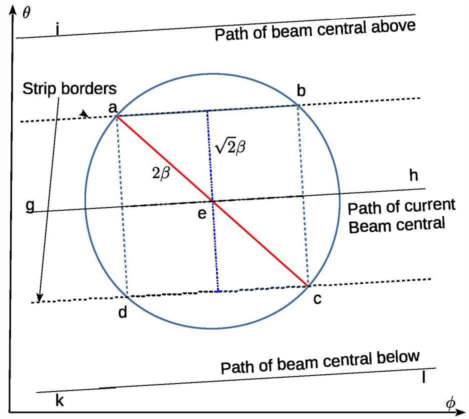
1) Rotational speed: We have found the trajectory to be followed by the transceiver beam to scan the whole 3D sphere. Now, we need to find out the angular speed of the transceiver. The maximum angular speed will depend on the time required to complete 3 way handshake. Let us consider that the total time required to send Beacon, receive B-ACK and then to send ACK is τ. Incorporating transmission delay (t_{tran}), propagation delay (t_{prop}) and processing delay (t_{proc}) at both ends. τ can be calculated as:



(a) Spiral path



(b) Side view



(c) Beam Cross Section

Fig. 3: Depiction of beam scan trajectory

$$
\begin{aligned}
t_{tran} &= \frac{\text{Beacon size + B-ACK size + ACK size}}{\text{data rate}} \\
\tau &= t_{tran} + 3 \times t_{prop} + 2 \times t_{proc} \qquad (4)
\end{aligned}
$$

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.

Now, let us look at Figure 3c When the normal of the beam is moving in (θ, ϕ) plane, the coverage area is denoted by the square $abcd$. If the neighbor node lies anywhere inside this square, the nodes will have $\omega \times \gamma$ time to face each other. Now, when they start facing each other they might not start transmitting beacon, rather they were still transmitting the last beacon. So, to discover themselves successfully, this time must be grater than the minimum time required for discovery 2τ. Thus, the necessary condition for discovery is:

$$
\frac{\gamma}{\omega} \geq 2\tau \Rightarrow \quad \omega \leq \frac{\beta}{\sqrt{2}\tau} \qquad (5)
$$

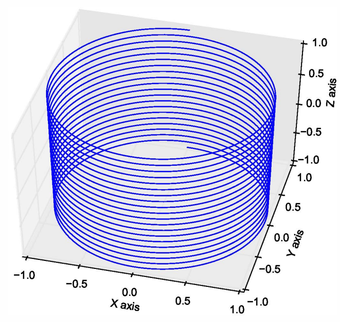
Since the nodes synchronizes themselves at the beginning and rotate the transceivers with same angular speed ω, they will be able to discover themselves as long as (5) holds true.

Theorem 1: If two nodes are within the communication range(r), then they will be able to discover each other within one complete scan of their respective surrounding spherical volume with radius r.

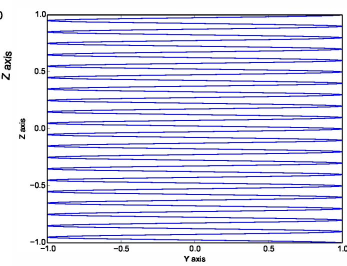
Proof: We prove this by contradiction. Let us assume that two nodes A(Master) and B(Slave) are within the communication range of each other and follow the proposed neighbor discovery method. Then there are only 3 possible scenarios which can result in the nodes not discovering each other:

(i) B is not covered by A's transmitting beam.
(ii) B is covered by A's transmitting beam but they do not have enough time to complete the three way handshake.
(iii) When A's transceiver is pointing towards B, B's transceiver is not pointing towards A.

Let us first look at Figure 3c. The path of the beam's normal follows the gh line. The θ and ϕ coordinates have a range between [$-\pi$-π]. For a point to be not covered by the transmitting beam, it must be located at a point further than β from the line gh (i.e., outside the circle centered at e). Now, we know that, the distance between two paths like ab and cd is $2\pi/n$, which (from (3)) is less than 2β. As the distance between two such lines is less than 2β, a point cannot be at a distance more than β from line gh. Thus, (i) is not possible.



(a) 3D view



(b) YZ projection

Fig. 5: Modified helix using 6

Now, a nodes within the area $abcd$ will have at least $\omega \times \sqrt{2}\beta$ amount of time for completing the three way handshake. From (5), we know that the nodes will have at least τ amount of time for completing the discovery. Thus, (ii) is also not possible.

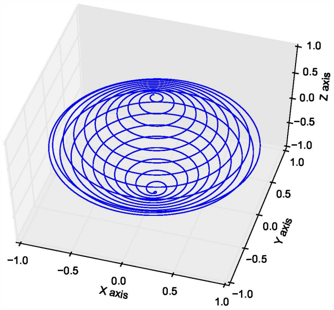
If (i) and (ii) are not possible, then the only possibility for the nodes to not discover each other is, if they were not synchronized with each other. Let us assume node B is at θ', ϕ' with reference to A. Since nodes A and B synchronize with each other in the $initialization$ phase, then, when A faces to θ', ϕ', Node B faces $\theta', \phi' + \pi$. So, both nodes point their respective transceiver towards each other at the same time. Thus, (iii) is not possible as well. ■

E. Suitable Modified Helix Equation

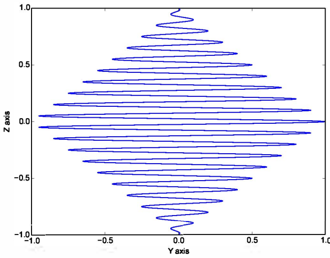
We have discussed the working principle of the beam scanning and the transceiver rotation in 3D space. Now we need to determine the path for the beam and its corresponding equations. We start with the equation of helix as provided in 6. A variable s is varied from $-\pi$ to π and the position is calculated in Cartesian coordinates (x, y, z). Figure 5 plots the 3D view and the 2D projection of the path with this equation.

$$
\begin{cases}
s & \in [-\pi, \pi] \\
\rho & = 1 \\
x & = \rho \sin(sn\pi) \\
y & = \rho \cos(sn\pi) \\
z & = \rho s
\end{cases} \qquad (6)
$$

Note that for normal helix, the diameter of the spiral

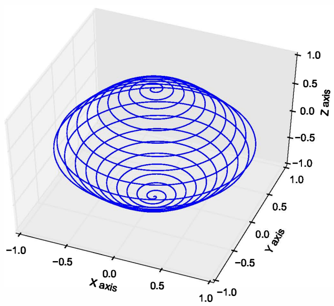


(a) 3D view

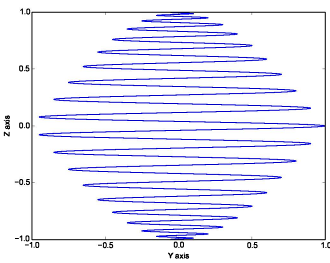


(b) YZ projection

Fig. 6: Modified helix using 7



(a) 3D view



(b) YZ projection

Fig. 7: Modified helix using 8

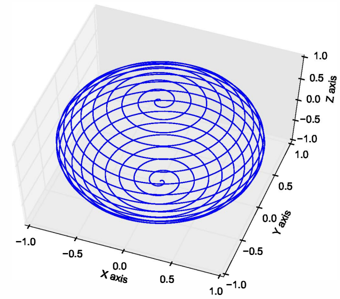
stays the same on the horizontal plane. Now, we modified the equation of the helix and linearly vary the diameter of the helix on the horizontal plane. In this case, the diameter of the spiral is 1 at the equator and 0 at the two poles. The corresponding position can be calculated as in 7. Figure 6 illustrates the trajectory in 3D and 2D projections.

$$\begin{cases} s & \in [-1, 1] \\ \rho & = 1 - |s| \\ x & = \rho \sin(sn\pi) \\ y & = \rho \cos(sn\pi) \\ z & = s \end{cases} \tag{7}$$

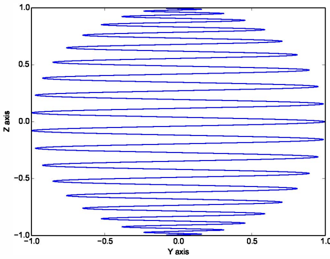
The modified helix presented in 7 does not satisfy our requirement of having same distance for 2 lines. So, we modified the equations and try to vary the the movement in z axis to be varying with $\sin(s/2)$ instead of linearly varying with s. The equations are given in 8 and the corresponding trajectories are presented in Figure 7.

$$\begin{cases} s & \in [-1, 1] \\ \rho & = 1 - |s| \\ x & = \rho \sin(sn\pi) \\ y & = \rho \cos(sn\pi) \\ z & = \sin(s\pi/2) \end{cases} \tag{8}$$

The distance between two lines are now very similar. However, a particle moving along this line is not maintaining the same distance from the center. So, we further modified the equations as presented in (9). Here the width of the spiral varies also in z axis as a cos function of s. Figure 8 illustrates the trajectory in 3D and 2D projection. We have verified that the distance of a particle following this trajectory, from the center is the same for all values of s. If we vary s from $-\pi$ to π, the beam scans the whole sphere.



(a) 3D view



(b) YZ projection

Fig. 8: Modified helix using 9

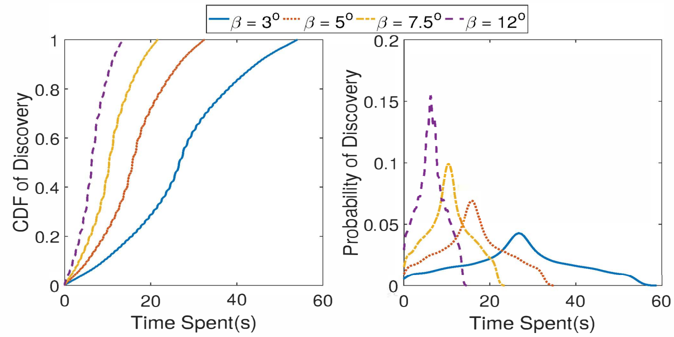


Fig. 9: CDF and probability of discovery for $\omega = 30$ rpm

$$\begin{cases} s & \in [-\pi, \pi] \\ \rho & = \cos(s/2) \\ x & = \rho \sin(ns) \\ y & = \rho \cos(ns) \\ z & = \sin(s/2) \end{cases} \tag{9}$$

IV. Simulations and Results

We performed MATLAB simulations to analyze the effectiveness of the proposed neighbor discovery method. We considered master node's hovering position as the origin. We randomly chose the position of the slave node for each simulation run. We assumed the communication range ($100m$) to be same for all cases. Moreover, we considered different divergence angles (3^o, 5^o, 7.5^o, 12^o) and different angular speeds ($30rpm - 300rpm$) for the transceivers (rpm stands for rotations per minute).

Figure 9 shows the cumulative distribution function (CDF) and the probability of neighbor discovery for different divergence angles for angular speed $\omega = 30rpm$. We can observe from the CDF that, the discovery time reduces with increase in the divergence angle. Thus, the probability of discovery also increases as divergence angle is increased. It is clear from the figure that, transceivers with divergence angle of 12^o finds each other faster than transceivers with divergence angle of 3^o.

In figure 10, we show the CDF of the discovery time for different divergence angles and angular speeds of the transceivers. We can observe that, for a fixed divergence angle, increasing the rotational/angular speed of the transceiver reduces the neighbor discovery time, thus, improves the performance of the proposed method. For example, when $\beta = 12^o$,

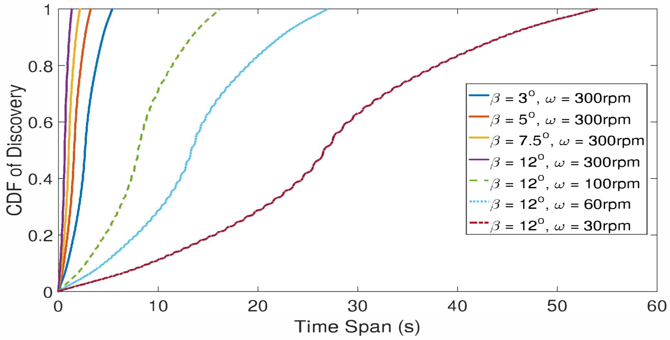


Fig. 10: CDF of discovery for different β and ω

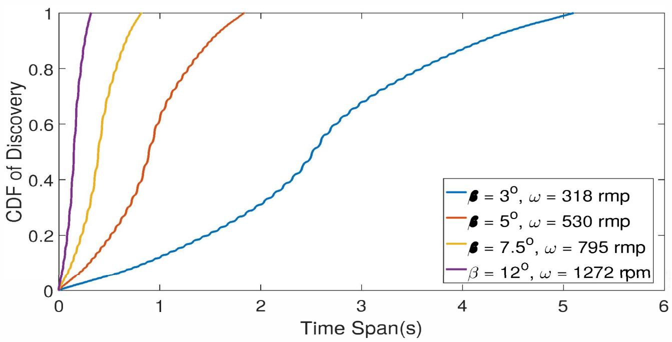


Fig. 11: CDF of discovery for $\omega = \beta/\sqrt{2}\tau$ rpm

the discovery time is less for $\omega = 300rpm$ than that for $\omega = 100rpm$. We also observe that, for $\omega = 300rpm$, discover time is smaller for $\beta = 12^o$ than that for $\beta = 3^o$. This result is consistent with the one shown in figure 9.

Figure 11 shows the simulation results where ω is calculated using 5. Similarly to the previous results we observe that, higher values of divergence angles yields smaller discovery time. Moreover, we observe that, if the angular speed is very high ($\approx 800rpm$ for $\beta = 7.5^o$, $\approx 1300rpm$ for $\beta = 12^o$) then the neighbor discovery can be completed in less than even one second.

Lastly, in figure 12, the combined effect of ω and β on average discovery time is presented. We can observe that, the neighbor discovery time reduces as divergence angle is increased. And also, increasing the angular speed of the transceivers also reduces discovery time, thus, improves the performance. The figure in the inner box shows the result with the y-axis in logarithmic scale. This result shows that, the difference in average discovery time for different divergence angles remains very consistent as rotational speed is varied.

V. Conclusion

In this paper, we proposed a novel approach for neighbor discovery in 3D scenario. We consider two nodes (UAVs or quadcopters) hovering in 3D space, each equipped with a mechanically steerable head/arm on which a highly directional FSO or RF transceiver is mounted. The nodes rotate their transceivers following a modified spiral path and send/receive search signals to discover each other. Through extensive simulations we showed that the nodes can discover each other within a reasonable period of time. We showed that, for very fast rotational speeds of the transceivers, neighbor discovery can be performed even in less than a second. The simulation results show that, using the proposed method, neighbor discovery in 3D space can be performed successfully. As part of our future work, we plan to perform real test-bed experiments to evaluate the effectiveness of the proposed method.

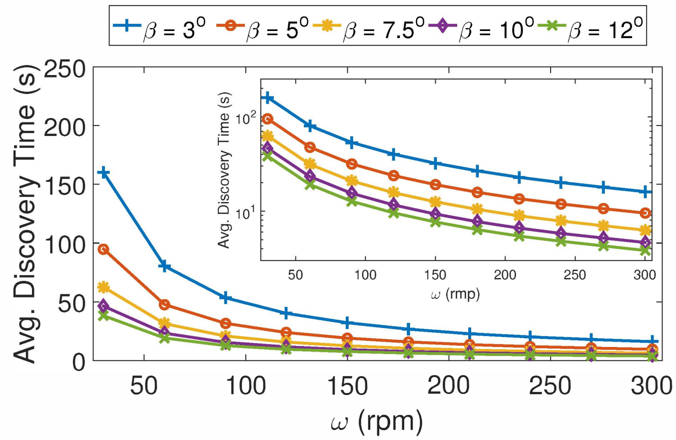


Fig. 12: Discovery Time vs ω for different β

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