Neighbor Discovery in a Free-Space-Optical UAV Network

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***Abstract*—Neighbor discovery is an essential part of the communication link establishment process for any wireless ad-hoc network. This problem of discovering neighbor nodes becomes even more challenging when the transceivers are highly directional. In this paper, we consider a 3D network of unmanned-aerial-vehicles (UAVs) that uses free-space-optical (FSO) transceivers for establishing high speed highly directional communication links. We consider that each UAV is equipped with a spherical structure on which multiple FSO transceivers are placed. The UAVs can electronically steer their communication beams by switching from one transceiver to another. We provide analysis on how optimally placing the transceivers with the appropriate divergence angles can help establish an FSO link at any direction in the 3D space. We also present a neighbor discovery algorithm that ensures discovery within a limited time. We demonstrate through extensive simulations that a UAV with FSO transceivers can successfully discover its neighbor UAVs even without prior location information about them and without any additional omnidirectional radio frequency (RF) channel.**

***Index Terms*—Free-space-optical, line-of-sight, neighbor discovery, unmanned-aerial-vehicles, wireless ad-hoc network.**

I. Introduction

Free-space-optical (FSO) communication systems are envisioned to play a significant role to address the capacity crunch faced by radio-frequency (RF) wireless technologies [1]. FSO communication (FSOC) is a major candidate to complement traditional omnidirectional RF networks. It uses the license-free optical spectrum and can provide very high communication speeds [2, 3]. The highly directional FSO transceivers not only provide longer communication ranges but also reduce the probability of interference and jamming. Moreover, compared to RF, FSO transceivers improve spatial reuse and enable much higher bandwidth channels to transfer large volumes of data. All these aspects of FSO communication can be very advantageous for future generation UAV ad-hoc networks [4].

A network of UAVs or drones can be deployed for both civil and military missions (Fig. 1). Applications such as monitoring forest fires and forest ecology, remote sensing, precision agriculture, broadcasting at sports events, observing behind the enemy lines, or even 360^o virtual reality (VR) capture rich amounts of data [5–7]. FSO transceivers can help transfer these data at very high speeds. Facebook's project 'internet.org' [3] aims at delivering Internet service using drone networks connected via laser links and Google's project 'loon' [8] aims to do the same through FSO communication among high altitude balloons. Thus, UAV networks equipped with FSOC systems are emerging as a promising technology.

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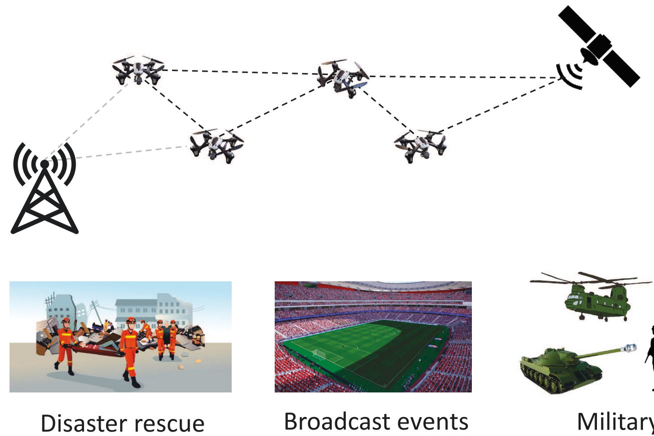


Fig. 1: Applications of UAV networks.

Despite the advantages, communication using FSO transceivers can be very challenging due to their high directionality. The communication beam of two UAVs with FSO transceivers must face towards and cover each other for successfully establishing a communication link. Hence, the primary task for a UAV in an FSO network is to establish line-of-sight (LOS) or discover its neighbors.

In this paper, we propose a neighbor discovery algorithm for UAVs hovering in a 3D ad-hoc network (Fig. 2a). We consider that each UAV is equipped with a spherical structure on which multiple FSO transceivers are placed (Fig. 2b). A UAV can point its communication beam towards any direction by activating the appropriate transceiver. Thus, it can scan its surrounding 3D space by electronically switching ('electronic steering') from one transceiver to another for communicating with neighbor UAVs hovering at different locations. There is no clock synchronization among the UAVs and they cannot use any additional omnidirectional communication channel. We first present analysis on how the transceivers should be placed on a spherical structure and how the beamwidth should be chosen to ensure that a neighbor UAV is covered by at least one of the transceiver's beams. Then, we present the conditions for two UAVs to point their transmission and reception beams towards each other within the same time interval to complete

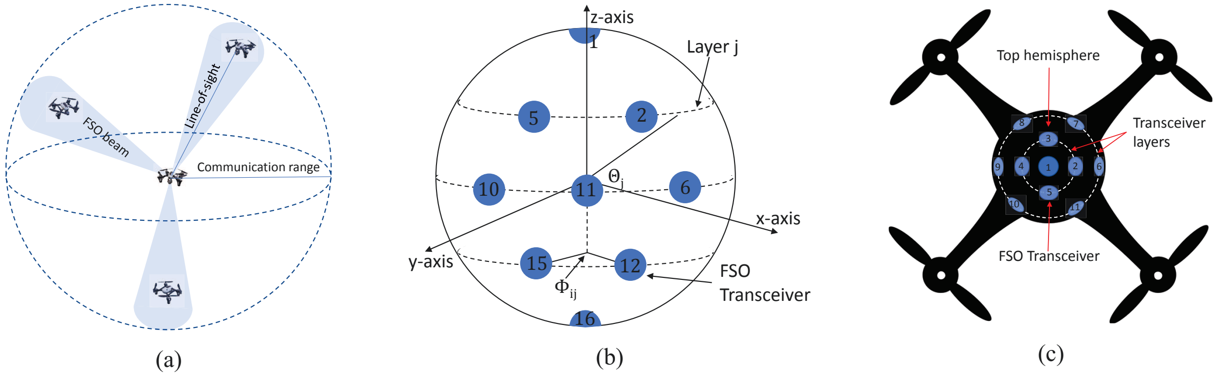


Fig. 2: (a) 3D UAV FSO network (b) Transceiver placement on a spherical structure. (c) UAV equipped with FSO transceivers.

a three-way handshake. We utilize a special sequence design presented in [9, 10] which guarantees that two UAVs facing their communication beams towards each other are in different modes, i.e., when one UAV is in transmission mode, the other is in reception mode. Then, we provide the conditions of a successful neighbor discovery within a finite time duration and validate the effectiveness of the proposed neighbor discovery method through extensive simulations.

II. Related Work

A. Free-space-optical communication

FSO communication has been considered for both stationary and mobile scenarios. It can enable high speed communication links among buildings [11], data centers [12], and even virtual reality arenas [7]. Hybrid RF-FSO networks are also being deployed for high altitude balloon and drone networks [3, 8]. Different methods for discovery [13–15] and maintenance [16, 17] among unmanned ground and aerial vehicles with FSO transceivers have been proposed that uses mechanical steering for scanning the surrounding environment. In [18] and [19], spherical designs of FSO transceiver structures were proposed aiming at the LOS maintenance problem between two nodes. In this paper, we focus on the problem of neighbor discovery among multiple UAVs.

B. Directional neighbor discovery

Neighbor discovery for directional RF networks has been well explored. In [20–23] neighbor discovery methods for nodes with omnidirectional receivers and directional transmitters were proposed. The use of omnidirectional receivers shortens the communication range and can result in severe interference due to packet collisions. Another design approach has been to consider both directional transmitter and directional receiver where the neighbor discovery process can be either synchronous or asynchronous. In [24] and [25], two neighbor discovery algorithms for a 3D ad hoc network were proposed which rely on GPS clock synchronization among the nodes. In [13], another synchronous LOS discovery algorithm was presented where the synchronization was performed using an additional omnidirectional RF channel. In [9], [10], and [15], asynchronous neighbor discovery algorithms were proposed for 2D ad hoc networks with mmWave and FSO transceivers. In [14], an asynchronous discovery algorithm was presented for a 3D UAV network where each UAV mechanically steers a single FSO transceiver to scan the surrounding space. Similarly, an asynchronous neighbor discovery method for a UAV network is proposed in [23], but considers omnidirectional reception and directional transmission. Neither [14] nor [23] can guarantee discovery within a bounded time.

In this paper, we consider a 3D UAV network where each UAV is equipped with multiple FSO transceivers (both transmitter and receiver are highly directional) placed on a spherical structure. There is no clock synchronization or any omnidirectional RF channel available and the UAVs are totally unaware of each other's location. We present a method that can **guarantee neighbor discovery among the UAVs within a bounded time period**.

III. Technical Approach

A. Assumptions

- **3D UAV network:** The UAVs hover in 3D space and each UAV can communicate with other UAVs within its range of transmission/reception.
- **Multi-FSO-transceiver spherical structure:** Each UAV is equipped with multiple highly directional FSO transceivers placed on a spherical structure.
- **Unique ID:** The UAVs are assigned unique IDs by a central UAV or a base station before joining the network.
- **Electronic steering:** A UAV can transmit at or receive from a specific direction by activating the appropriate transceiver. It can switch to a different transceiver to communicate towards another direction. Thus, it can scan the surrounding 3D space by electronic beam steering.
- **Mode:** The UAVs operate in half-duplex mode, i.e., they can transmit and receive, but not simultaneously.

B. Spherical FSO transceiver structure

1) Transceiver placement: We present a spherical FSO transceiver design as shown in Fig. 2b. It can also be implemented by using two hemispherical structures, one on top of the UAV and the other at the bottom of the UAV (Fig. 2c). In this paper, we consider one spherical structure for simplicity. The proposed design consists of multiple FSO transceivers, where one transceiver is placed on top, one at

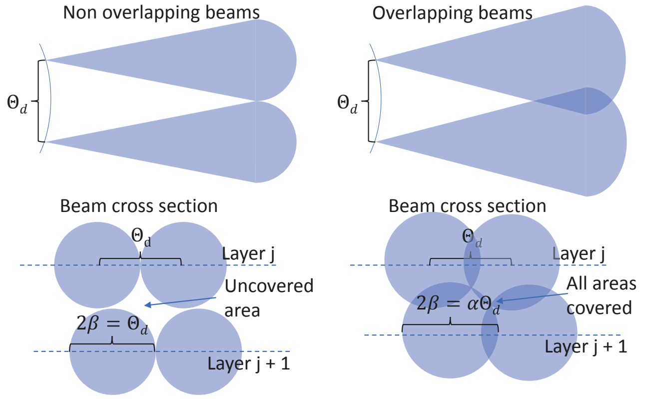


Fig. 3: FSO beams should overlap to provide communication coverage to whole surrounding 3D space.

the bottom, and the rest of the transceivers are placed at different spherical layers on the structure. Considering circular shaped transceivers of the same radius r_{TR}, the minimum angular distance between two such transceivers is $\Theta_{min} = 2 \times \tan^{-1}(\frac{r_{TR}}{r_{SP}})$, where r_{SP} is the radius of the spherical structure. Now, for an angular distance $\Theta_d \geq \Theta_{min}$, the total number of transceiver layers $N_L = \lceil \frac{180^o - \Theta_d}{\Theta_d} \rceil$. The angular distance between two such layers is:

$$\Theta_z = \begin{cases} \frac{180^o - \Theta_d}{N_L}, & \text{if } \Theta_d \times N_L > 180^o - \Theta_d, \\ \Theta_d, & \text{otherwise.} \end{cases} \quad (1)$$

The top transceiver is placed at both inclination and azimuth angle of 0^o. The bottom transceiver is placed at an inclination angle of 180^o and azimuth angle of 0^o. A transceiver placed at layer j has an inclination angle of Θ_j and the number of transceivers in that layer, $N_j = \lfloor \frac{360^o}{\Theta_d} \times \sin(\Theta_j) \rfloor$, where, $j = 1, 2, ..., N_L$. Here,

$$\Theta_j = \begin{cases} \Theta_z \times j, & \text{if } j \leq \lceil N_L/2 \rceil, \\ \Theta_z \times (N_L - j + 1), & \text{otherwise.} \end{cases} \quad (2)$$

The azimuth angle of the i-th transceiver on layer j is $\Phi_{ij} = \frac{360^o}{N_j} \times (i-1)$, where, $i = 1, 2, ..., N_j$. So, the total number of transceivers on the headset for an angular distance of θ_d can be determined as, $N_{TR} = 2 + \sum_{j=1}^{N_L} N_j$.

The transceiver on top of the spherical structure is labeled as 1 and the one at the bottom as N_{TR}. The transceiver i at layer j is labeled as $N_{j-1} + i$. For example, if there are three ($i = 1, 2, 3$) transceivers in the f rst ($j = 1$) layer, they are labeled as *1+1, 1+2, 1+3* or *2, 3, 4*. Here, $N_{j-1} = 1$ represents the transceiver on top of the sphere.

2) Beamwidth selection: We consider that all the FSO transceivers have the same transmission and reception beamwidth, i.e., the respective divergence angle and half-angle f eld-of-view (FOV) are both β^o. For an angular distance Θ_d between two transceivers, the value of β should be chosen in such a way that a neighbor UAV is covered by at least one of the transceiver beams. As shown in Fig. 3, when $FOV = \Theta_d$ or $2\beta = \Theta_d$, some areas surrounding the UAV may not be covered by any of the beams. So, there should be overlaps among the transceiver beams that are placed next to each other. We def ne this overlap as $\alpha = 2\beta/\Theta_d$. If α_{min} is the minimum value of α for which any space surrounding a UAV is covered by at least one of its beams, then $\alpha \geq \alpha_{min}$.

C. 3D Neighbor Discovery

1) UAVs pointing beams towards each other: We consider that each UAV in the network has N_{TR} transceivers with beamwidth 2β. So, they can point their beams at N_{TR} different directions. In transmission mode, a UAV transmits 'Hello' messages and waits for 'Ack' messages for τ_T duration in each direction. In reception mode, a UAV listens for 'Hello' messages for $\tau_R \neq \tau_T$ duration in each direction. All the UAVs are set with the same τ_R and the same τ_T before being deployed in the network. These parameters should be chosen to satisfy the relation, $m\tau_T = n\tau_R$, where m and n are positive integers, prime numbers, and not equal to each other.

We consider a deterministic approach where the UAVs point at different directions following a specif c sequence. Each UAV chooses the initial transceiver *p* (the direction to point its beam) randomly. After τ_R duration in reception mode (τ_T duration in transmission mode), it switches to the transceiver labeled as *p+1*. This continues until the transceiver labeled N_{TR} is reached. Then it switches to the transceiver labeled 1. Hence, it takes a UAV a duration of $N_{TR} \times \tau_R$ in reception mode and $N_{TR} \times \tau_T$ in transmission mode to make one full scan of the surrounding 3D space. Let us consider that UAV A is hovering within beam *b* of UAV B, and UAV B is hovering within beam *a* of UAV A. Now, UAV A transmits at UAV B for τ_T period during each scan. After n scans UAV A has transmitted towards direction *a* for $n\tau_T$ duration and UAV B has received for $m\tau_T$ duration from direction *b*. It takes UAV A $n\tau_T N_{TR}$ duration to complete *n* scans, UAV B $m\tau_R N_{TR}$ duration to complete *m* scans, and $n\tau_T N_{TR} = m\tau_R N_{TR}$. The two UAVs will be able to communicate if there is overlap between their transmission and reception intervals while they point towards each other. The condition for this overlap can be written as follows:

$$\tau_T > \frac{mN_{TR}\tau_T - m\tau_R}{m} \quad (3)$$

As stated earlier, after communicating via transceiver N_{TR}, the UAV switches to transceiver 1. Hence, $mN_{TR} = N_{TR}$ and considering the relation $m\tau_T = n\tau_R$, we re-write (3) as: $\tau_T > \frac{N_{TR}\tau_T - n\tau_T}{m}$ or $m + n > N_{TR}$.

2) Three-way handshake time: Let us assume that UAVs A and B point their respective beams towards each other at time intervals (t_A^l, t_A^h) and (t_B^l, t_B^h) respectively, where,

$$\begin{cases} t_A^l = t_1 + c\tau_M N_{TR}, & c = 0, 1, 2, ... \\ t_A^h = t_1 + \tau_M + c\tau_M N_{TR}, & c = 0, 1, 2, ... \\ t_B^l = t_2 + c\tau_M N_{TR}, & c = 0, 1, 2, ... \\ t_B^h = t_2 + \tau_M + c\tau_M N_{TR}, & c = 0, 1, 2, ... \end{cases} \quad (4)$$

Here, t_1 and t_2 are the respective time instances when UAVs A and B f rst point at each other. Also, $\tau_M = \tau_T$ for transmission

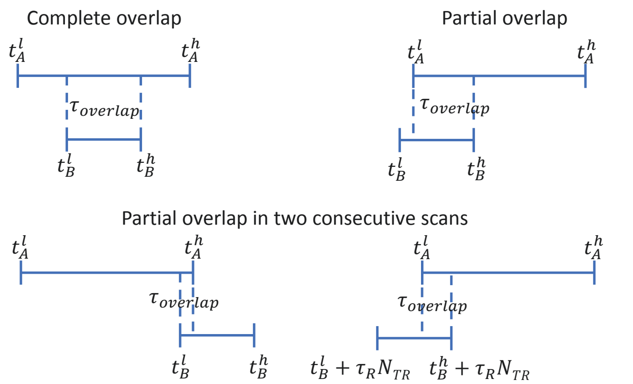


Fig. 4: Overlap between time intervals while two UAVs point beams at each other.

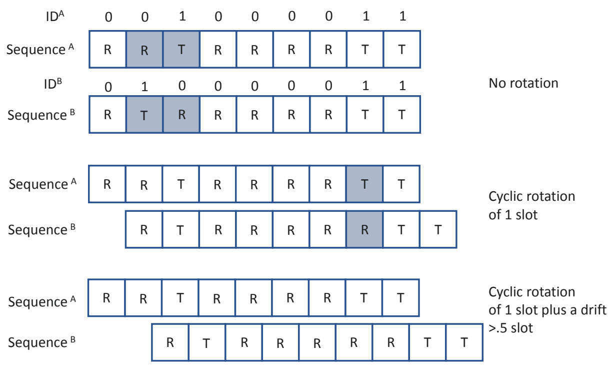


Fig. 5: Sequences generated from unique IDs guarantees complementary transmission and reception modes.

mode and $\tau_M = \tau_R$ for reception mode. The overlap $\tau_{overlap}$ between these intervals can happen in three ways as shown in Fig. 4. In the first scenario, there is a complete overlap and $\tau_{overlap} = \tau_T$ (assuming, $\tau_T < \tau_R$). In the second scenario, partial overlap happens between transmission and reception intervals. And, in the third scenario, partial overlap occurs in two consecutive scans and we select the longer overlap. For the cases of partial overlaps $\tau_{overlap}$ is uniformly distributed in the interval $[\frac{(m+n-N_{TR})\tau_T}{2m}, \tau_T]$.

Now, the time required to transmit a 'Hello' message, receive an 'H-Ack', and reply with an 'Ack' is the three-way handshake time τ. For a successful neighbor discovery, $\tau \leq \tau_{overlap}$. But, UAV A may not start transmitting a 'Hello' right at the beginning of the overlap. So, to ensure a three-way handshake, we must have $2\tau \leq \tau_{overlap}$. Thus, neighbor discovery can be guaranteed within n full scans of transmission or m full scans of reception, given the condition: $\tau \leq \frac{(m+n-N_{TR})\tau_T}{4m}$.

3) Complementary modes: Two neighbor UAVs must be in complementary communication modes, i.e., one in transmission mode, the other in reception mode, to discover each other. We adopt the method provided in [9] to ensure this mode matching between the UAVs. Considering nodes with unique IDs of the same length l, a sequence can be created, with this ID, followed by $l^0 = \lfloor l/2 \rfloor + 1$-bit segment of *0*s and $l^1 = \lceil l/2 \rceil$-bit segment of *1*s. For example, for UAV A with ID *0010*, the sequence is *001000011*, and for UAV B with ID *0100*, the sequence is *010000011*. In [10] and [9], it was proved that two such sequences are guaranteed to have at least one bit location with different values under all possible ways of cyclic rotation within L continuous bits, where $L = l + l^0 + l^1$ and $l^0 + l^1 \geq l$.

Next, let us consider each bit of such sequences as a *slots* of duration $m\tau_R N_{TR}$ which is also equal to $n\tau_T N_{TR}$. When the bit is *0*, the corresponding UAV operates in reception mode, and when the bit is *1*, the UAV operates in transmission mode. Within one *slot* duration the transmitting UAV performs n scans and the receiving UAV performs *m* scans. The sequences assigned to the UAVs ensure that they are in different communication modes during at least one *slot*. Thus, if the conditions provided in III-C1 and III-C2 are met, a successful neighbor discovery can be guaranteed. Now, the *slots* of two UAVs may not be aligned. A drift larger than 0.5 can cause mismatch of communication modes. Hence, we redefine the *slot* duration as $2m\tau_R N_{TR}$ or $2n\tau_T N_{TR}$ to guarantee discovery even when the *slots* are not aligned. Fig. 5 shows examples of mode matching, cyclic rotation, and drift.

D. Discovering multiple neighbors

We considered neighbor discovery between two UAVs so far. In this scenario, once a three-way handshake is accomplished neighbor discovery is complete. On the other hand, when multiple UAVs are present in a network, every time a UAV completes a three-way handshake with a neighbor, it logs the neighbor's ID and the direction where it was discovered. Then, it continues the discovery process until the end of the discovery window. Now, with an ID length of *l*, unique IDs can be assigned to 2^l UAVs. A UAV will be able to discover its $2^l - 1$ neighbors within *L slots*. So, the maximum discovery time can be written as:

$$T_{max} = 2n\tau_T N_{TR} L \quad (5)$$

Our discovery algorithm is provided in Algorithm 1.

IV. Simulation Results and Analysis

We evaluated the proposed spherical FSO multi-transceiver structure design and the neighbor discovery method via MATLAB simulations. We considered a 3D UAV network region of $R_{max}/\sqrt{3} \times R_{max}/\sqrt{3} \times R_{max}/\sqrt{3}$, where R_{max} is the maximum communication range of the FSO transceivers. We conducted 1000 iterations of the simulation using different seed values and randomly selected the hovering position of the UAVs. We assumed a maximum of 128 UAVs in the network and ID length of 7 bits (*0000000* to *1111111*). The received power and transmission range of FSO transceivers are affected by atmospheric and geometric attenuation, and Lambertian loss. The received power P_r can be calculated from the following relation [26].

$$P_r = \cos\delta \times (P_t - 10\log_{10} e^{-\sigma R \cos\delta} - 20\log_{10} \frac{\zeta}{\xi + 200\beta R \cos\delta}) \quad (6)$$

Here, δ is the angular distance of a UAV from a neighbor beam's propagation axis and R is the distance between two

UAVs. The transmitted power P_t is determined for receiver's sensitivity of *-49 dBm* and *R=100 m*. Table I provides the rest of the parameters [26].

Algorithm 1 3D UAV Neighbor Discovery

1: Generate sequence *Seq* of length L from unique ID
2: $Timeout_{slot} \leftarrow current\_time + 2nN_{TR}\tau_T$
3: $Timeout_{tran} \leftarrow current\_time + \tau_T$
4: $Timeout_{recv} \leftarrow current\_time + \tau_R$
5: $k \leftarrow 1$
6: $p \leftarrow random(1, N_{TR})$
7: **if** $k \leq L$ **then**
8:   **if** $Seq(k) = 0$ **then**
9:     Keep listening through transceiver *p*
10:     **if** *Hello* is received **then**
11:       Reply with *H-Ack* and listen for *Ack*
12:       **if** *Ack* is received **then**
13:         A neighbor UAV is discovered
14:         Go to Step 9
15:       **end if**
16:     **else if** $current\_time \geq Timeout_{recv}$ **then**
17:       $p{+}{+}$
18:       Go to Step 9
19:     **else if** $current\_time \geq Timeout_{slot}$ **then**
20:       $k{+}{+}$
21:       Go to Step 7
22:     **end if**
23:   **else**
24:     Keep transmitting *Hello* and listen for *H-Ack* through transceiver *p*
25:     **if** *H-Ack* is received **then**
26:       Reply with *Ack*
27:       A neighbor UAV is discovered
28:       Go to Step 24
29:     **else if** $current\_time \geq Timeout_{tran}$ **then**
30:       $p{+}{+}$
31:       Go to Step 24
32:     **else if** $current\_time \geq Timeout_{slot}$ **then**
33:       $k{+}{+}$
34:       Go to Step 7
35:     **end if**
36:   **end if**
37: **else**
38:   Current discovery window ends
39: **end if**

A. Finding α_{min}

We first conducted simulations to find α_{min} (Section III-B2) which helps us to select the appropriate FSO transceiver beamwidth to ensure that any space surrounding a UAV is covered by at least one of its beams. Fig. 6 displays the percentage of time two UAVs discover each other within T_{max} (5) duration for different values of α and β. We can observe that for $\alpha \geq 1.5$, two UAVs hovering at random locations discover each other in 100% of the cases for any value of

TABLE I: Simulation Parameters

Transmitter radius, ξ	0.3 cm
Receiver radius, ζ	1 cm
Attenuation coefficient, σ	0.0508
Half-angle Beamwidth, β	5^o-35^o
FSO-sphere radius, r_{SP}	7.62 cm

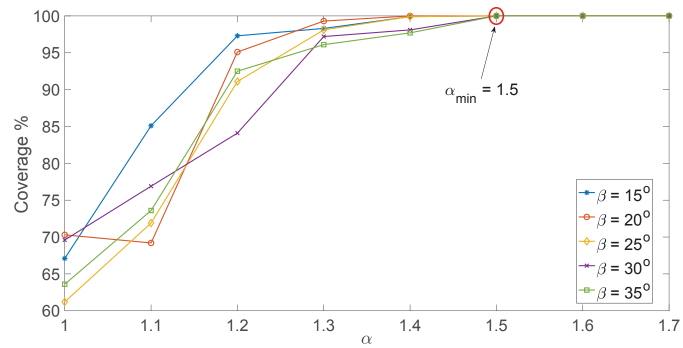


Fig. 6: $\alpha \geq \alpha_{min}$ for 100% communication beam coverage.

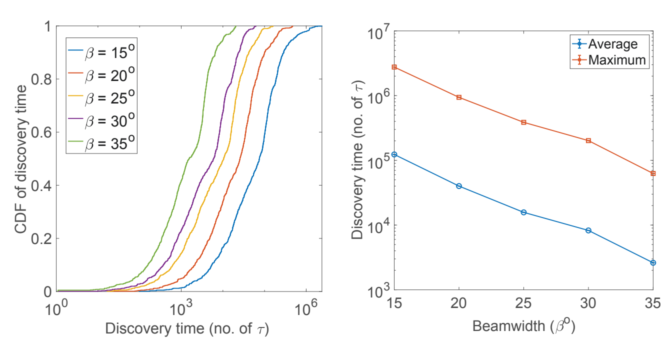
β. On the other hand, for $\alpha < 1.5$, all areas surrounding a UAV are not covered by at least one of its transceiver beams, thus, resulting in failure to discover a neighbor. Hence, we use $\alpha_{min} = 1.5$ for the rest of the simulation analysis.

B. Single neighbor discovery

In this section, we observe how the neighbor discovery time changes with the transceiver beamwidth for a network with two UAVs. We present the discovery time in terms of factor of three-way-handshake time τ. Fig. 7a portrays the cumulative probability distribution of discovery time and we can observe that the discovery time reduces with increase in beamwidth. A larger beamwidth provides larger communication coverage and thus results in smaller discovery times. Fig. 7b displays the average and maximum discovery times. We observe that two UAVs discover each other within the bounded time T_{max} for any relative hovering position and for all values of β.

C. Multiple neighbor discovery

We performed further simulation analysis to observe how the neighbor discovery algorithm performs when multiple



(a) (b)

Fig. 7: (a) CDF of discovery time (b) Average and maximum discovery times.

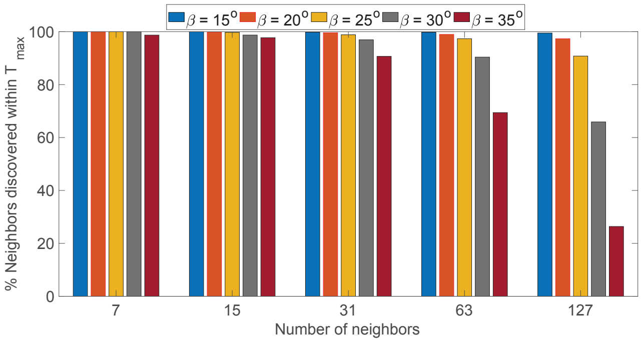


Fig. 8: Percentage of neighbors discovered within T_{max} considering packet collision.

UAVs are present in the network. We considered different number of neighbors (7, 15, 31, 63, and 127), and scenarios with and without packet collision. We observed that a UAV discovers any number of neighbors within the bounded time T_{max} following the proposed method when there is no collision of packets. In Fig. 8, we portray the percentage of neighbors a UAV discovers within T_{max} considering the effect of packet collision. We can see that, when the network size is small (7 or 15 neighbors), almost all the neighbors are discovered within the bounded time. We also observe that, unlike the single neighbor scenario, larger beamwidth reduces the probability of discovering all neighbors within T_{max}. When the number of UAVs in the network is high and the beamwidth is larger, multiple UAVs can try to communicate with the same UAV at the same time. This results in packet collision and delays the discovery. We can see that a UAV can discover all of its neighbors even considering packet collisions when the beamwidth is relatively smaller (e.g., 15^o or 20^o).

V. Conclusion

We proposed the design of a multi-transceiver FSO spherical structure and a neighbor discovery algorithm for a 3D UAV ad hoc network. We presented the necessary conditions for discovering multiple neighbors within a given time T_{max}. We showed how the beamwidth of the FSO transceivers should be chosen to ensure that all areas surrounding a UAV is covered by one of its beams. We evaluated the effectiveness of the proposed discovery method through simulations and showed that a UAV can discover all of its neighbors within a bounded time. We also showed that packet collisions can delay the discovery of neighbors if the transceiver beamwidth is large or the number of neighbors is high. This can be avoided by choosing the beamwidth appropriately and maintaining a limit on the number of nodes in the network. As future work, we will explore a comparison of the proposed neighbor discovery method with the state-of-the-art, which could not be included here, due to the limited space. Similarly, we will investigate the effect of hovering UAV's oscillations on the discovery process. Another possible line of future work is to develop a proof-of-concept prototype of the spherical FSO transceiver structure and evaluate the proposed neighbor discovery method through test-bed experiments.

References

[1] A. Sevincer, M. Bilgi, and M. Yuksel, "Automatic realignment with electronic steering of free-space-optical transceivers in MANETs: A proof-of-concept prototype," *Ad Hoc Networks*, vol. 11, no. 1, pp. 585–595, 2013.

[2] "Connectivity for the skies and beyond," 2019, https://mynaric.com.

[3] "Internet.org," 2015, https://info.internet.org/en/story/connectivity-lab/.

[4] D. Zhou, P. G. LoPresti, and H. H. Refai, "Enlargement of beam coverage in FSO mobile network," *IEEE JLT*, vol. 29, no. 10, pp. 1583–1589, 2011.

[5] E. Leitgeb, K. Zettl, S. S. Muhammad, N. Schmitt, and W. Rehm, "Investigation in free space optical communication links between unmanned aerial vehicles (UAVs)," in *Proc. IEEE ICTON*, vol. 3, 2007, pp. 152–155.

[6] J. Chakareski, "Drone networks for virtual human teleportation," in *Proc. ACM DroNet*, 2017, pp. 21–26.

[7] M. Khan and J. Chakareski, "Visible light communication for next generation untethered virtual reality systems," in *Proc. IEEE ICC Workshops*, 2019, pp. 1–6.

[8] Google, "Project loon," https://x.company/loon/.

[9] Y. Wang, S. Mao, and T. S. Rappaport, "On directional neighbor discovery in mmwave networks," in *Proc. IEEE ICDCS*, 2017, pp. 1704–1713.

[10] L. Chen, Y. Li, and A. V. Vasilakos, "Oblivious neighbor discovery for wireless devices with directional antennas," in *Proc. IEEE INFOCOM*, 2016, pp. 1–9.

[11] M. Curran, M. S. Rahman, H. Gupta, K. Zheng, J. Longtin, S. R. Das, and T. Mohamed, "FSONet: A wireless backhaul for multi-gigabit picocells using steerable free space optics," in *Proc. ACM MobiCom*, 2017, pp. 154–166.

[12] N. Hamedazimi, Z. Qazi, H. Gupta, V. Sekar, S. R. Das, J. P. Longtin, H. Shah, and A. Tanwer, "Firef y: A reconf gurable wireless data center fabric using free-space optics," *ACM SIGCOMM CCR*, vol. 44, no. 4, pp. 319–330, 2014.

[13] M. R. Khan, S. Bhunia, M. Yuksel, and L. Kane, "Line-of-Sight discovery in 3d using highly directional transceivers," *IEEE TMC*, 2018.

[14] M. Khan and M. Yuksel, "In-band LOS discovery between drones using highly directional transceivers," in *Proc. ACM DroNet*, 2018, pp. 51–56.

[15] S. Bhunia, M. Khan, M. Yuksel, and S. Sengupta, "In-band LOS discovery using highly directional transceivers," *Ad Hoc Networks*, vol. 91, p. 101875, 2019.

[16] M. Khan, M. Yuksel, and G. Winkelmaier, "GPS-free maintenance of a free-space-optical link between two autonomous mobiles," *IEEE TMC*, vol. 16, no. 6, pp. 1644–1657, 2016.

[17] M. Khan and M. Yuksel, "Autonomous alignment of free-space-optical links between UAVs," in *Proc. ACM HotWireless*, 2015, pp. 36–40.

[18] A. Kaadan, H. H. Refai, and P. G. LoPresti, "On the development of modular optical wireless elements (MOWE)," in *Proc. IEEE GLOBECOM Workshops*, 2015, pp. 1–7.

[19] B. Nakhkoob, M. Bilgi, M. Yuksel, and M. Hella, "Multi-transceiver optical wireless spherical structures for MANETs," *IEEE JSAC*, vol. 27, no. 9, pp. 1612–1622, 2009.

[20] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, "On designing MAC protocols for wireless networks using directional antennas," *IEEE TMC*, vol. 5, no. 5, pp. 477–491, 2006.

[21] R. Ramanathan, J. Redi, C. Santivanez, D. Wiggins, and S. Polit, "Ad hoc networking with directional antennas: a complete system solution," *IEEE JSAC*, vol. 23, no. 3, pp. 496–506, 2005.

[22] S. Vasudevan, J. Kurose, and D. Towsley, "On neighbor discovery in wireless networks with directional antennas," in *Proc. IEEE INFOCOM*, vol. 4, 2005, pp. 2502–2512.

[23] Z. Wei, X. Liu, C. Han, and Z. Feng, "Neighbor discovery for unmanned aerial vehicle networks," *IEEE Access*, vol. 6, pp. 68 288–68 301, 2018.

[24] Z. Zhang and B. Li, "Neighbor discovery in mobile ad hoc selfconf guring networks with directional antennas: algorithms and comparisons," *IEEE TWC*, vol. 7, no. 5, 2008.

[25] M. E. Steenstrup, "Neighbor discovery among mobile nodes equipped with smart antennas," in *Proc. Scandinavian Workshop on Wireless Adhoc Networks*, 2003, pp. 1–6.

[26] M. Yuksel, J. Akella, S. Kalyanaraman, and P. Dutta, "Free-space-optical mobile ad hoc networks: Auto-conf gurable building blocks," *Springer Wireless Networks*, vol. 15, no. 3, pp. 295–312, 2009.