Eavesdropper-Avoiding Neighbor Discovery for Multi-Sector Directional Wireless Systems

Md Asif Ishrak Sarder[1], Murat Yuksel[1], and Elizabeth Bentley[2]
[1]*University of Central Florida, Orlando, FL, USA*
[2]*Air Force Research Lab, Rome, NY, USA*
MdAsif.IshrakSarder@ucf.edu, murat.yuksel@ucf.edu, elizabeth.bentley.3@us.af.mil

Abstract*—Directional antenna systems are gaining widespread adoption in wireless communication solutions, particularly using super-6 GHz bands (e.g., millimeter-wave, Terahertz, or free-space optical) in the electromagnetic spectrum with highly directional beams due to high attenuation at such high frequencies. Hence, discovering neighbors using these beams and beam alignment between transmitter and receiver have attracted notable attention from researchers. However, *fast neighbor discovery* using directional wireless while maintaining covertness from eavesdroppers by *minimizing the probability-of-intercept (POI)* is an open research problem. Specifically, we seek to address this trade-off by proposing a sequential transceiver (or direction) selection protocol based on a tuning parameter that guides the probing transmitting nodes towards prioritizing either goal by selecting the next operational transceiver subset for probing. We consider a 2-dimensional multi-sector directional wireless system enabling electronic steering of transmission among sectors, assuming each sector is equipped with a transceiver and the sectors collectively cover the 2-D 360° horizon around the node. To this end, we design a time-slotted neighbor discovery protocol that employs a probabilistic approach to select only one transceiver to use for the next time interval. By changing the tuning parameter value, we study its impact on the control of probing direction and performances related to neighbor discovery and POI. The results indicate that random selection of the next transceiver offers the fastest neighbor discovery, however leaves the nodes vulnerable to passive eavesdropping. Selecting from the transceivers positioned opposite to the currently active one performs faster discovery completion compared to prioritizing the current one's adjacent transceivers as the next operational transceiver, but the latter offers enhanced covertness. Additionally, we see that incorporating more directional transceivers on board enhances covert communication capabilities, albeit at the cost of a prolonged neighbor discovery period. While employing random selection for extended periods results in quicker discovery with decreased POI, neither prioritizing rapid discovery nor minimizing POI over time proves to be optimal.

***Index Terms*—Neighbor Discovery, Probability-of-Intercept, Directional Wireless, Super-6 GHz**

I. Introduction

With the proliferation of wireless networks and the escalating demand for high-speed connectivity, the directional antenna systems have gained significant traction and are rapidly becoming mainstream. In response to the limitations posed by the conventional omni-directional antenna systems, directional antennas have emerged as a promising solution, offering noteworthy benefits including expanded transmission range, wide bandwidth with higher throughput, and enhanced security [1], [2]. However, due to its narrow beam pattern, the deployment of such directional wireless systems introduce unique challenges particularly in the context of neighbor discovery for mobile self-configuring networks [3]. Furthermore, recent adoption of super-6 GHz bands like millimeter-wave (mmWave), Terahertz (THz), or Free-space-optical (FSO) demands precise beam alignment between transmitter and receiver to avert substantial signal quality degradation caused by obstacles and mobility [4]. Consequently, a more sophisticated approach is necessitated to ensure efficient directional neighbor discovery while attaining covertness (ensuring relatively lower POI) from eavesdropping.

Nevertheless, there remains a notable research gap in simultaneously addressing both *fast neighbor discovery* and *covertness from eavesdropping* in directional wireless networks. A pivotal link between these goals involves determining the optimal level of exposure for transmitting (Tx) nodes. In this paper, we seek to address this trade-off between the two goals by proposing a sequential transceiver (or direction) selection protocol based on a tuning parameter (α) that guides the probing Tx nodes towards prioritizing either goals. We consider a 2-D multi-sector directional wireless system allowing electronic steering of transmission among sectors. Similar to [5], we assume each sector is equipped with a transceiver and the sectors collectively cover the 2-D 360° horizon around the node. We design a time-slotted neighbor discovery protocol to select a transceiver for the next time interval. The protocol attempts to find a balance between maximizing the probability of discovering a new neighbor and minimizing the POI. Key insights and contributions of this work include:

- Successful neighbor discovery completion using only one directional transceiver at a time instead of sending probe messages from multiple or all transceivers, without having any prior knowledge of neighboring nodes' positioning and CSI details.
- A heuristic transceiver selection protocol that guides the Tx node autonomously select the next operating transceiver in a probabilistic manner, without requiring synchronization with other nodes.

This work is supported in part by NSF award 2115215 and US Air Force Research Lab. Authors also acknowledge fruitful discussions with Mr. Sarwar Uddin Chowdhury.

- A mechanism to tune the transceiver selection protocol by a parameter, α, to balance the trade-off between the latency required to complete neighbor discovery and the POI by malicious nodes.

The rest of the paper is organized as follows: Section II provides an overview of relevant research studies. Section III presents the systematic overview, providing a comprehensive description of the channel and the directional antenna models. Section IV formulates the problem of operating transceiver selection for the following intervals. Section V delves into the proposed sequential transceiver selection protocol to solve the problem, encompassing its mathematical derivations, the related algorithms, then briefly describes the practical relevance and the procedure used for fine tuning the parameter α. Section VI outlines the simulation configurations, and the results obtained with a comprehensive discussion. Finally Section VII concludes our work.

II. Related Work

Several neighbor discovery protocols have been proposed to date for directional wireless systems. [6] reports the efficiency of scan-based directional systems using mechanically steerable transceiver over randomized omnidirectional data transmission, however, it requires prior knowledge of other nodes' location which may not always be feasible in practical scenarios. To mitigate interference encountered during neighbor discovery, [7] adopts supervised scheduling with directional data transmission using multiple on-board transceivers. To expedite neighbor discovery, [8] proposes gossip-based indirect discovery on top of direct discovery, but such solution may become particularly vulnerable to eavesdropping in adverse conditions. Authors in [9] leverages side-lobes in conjunction with main lobe information to achieve reduced neighbor discovery time compared to existing protocols relying solely on main lobe data, but such system can be highly susceptible to being exposed to nearby passive eavesdroppers.

In exploring possible countermeasures against eavesdropping using simpler physical layer security techniques [10] with directional antennas, [11] proposes decode-and-forward relaying strategy with best relay selection criterion based on channel state information (CSI) of both main and wiretap links. [12] recommends careful regulation of the transmit power during neighbor discovery to mitigate transmit beam exposure and attain lower POI, however such dependency on varying the transmit power necessitates sophisticated transceivers that adds to the cost and complexity of deploying the scheme in practical scenarios [7]. In a more pertinent study [13], using artificial noise (AN) with transmit power restriction is proven effective against hybrid eavesdroppers with imperfect CSI, but using multi-beam (e.g, phased array) and multi-antenna (e.g., MIMO Communications) systems for AN can at times increase computational complexity. Regardless, [11] and [13] assume that the transmitter possesses either partial or complete knowledge of eavesdropper location and their CSI, which is somewhat unrealistic [14].

The key novelty of our work is to consider the two goals of staying covert and fast neighbor discovery at the same time. We design a knob that can be tuned to attain a balance between these two conflicting goals.

III. System Model

A. Assumptions

- **Network Model:** *N* wireless directional nodes and *M* omni-directional eavesdroppers are randomly deployed in a 2-D geographical plane, where they can detect transmission and communicate within their transmission/reception range.
- **Directional Node Structure:** Each *N* node is equipped with a electronically steerable multi-sector antenna system, where each sector is covered with a directional transceiver. The nodes are homogeneous in terms of their sector count and each has *k* sectors/transceivers[1].
- **Duplex Mode:** Each *N* node operates in full-duplex mode, i.e., they can simultaneously transmit and receive.
- **Node ID:** Each *N* node is assigned a unique ID, e.g., a MAC address. Given their IDs, the wireless N nodes are expected to self-configure the network among themselves to facilitate subsequent operations effectively [6].
- **Node Setup:** All the *N* and *M* nodes are static in the air.
- **Nodes' Coordination and Awareness of Eavesdroppers:** In a fully decentralized network with no clock synchronization or prior coordination, all the *N* nodes are totally oblivious about their surroundings at the initial stage, therefore randomly choose their initial probing direction. To keep the environment more realistic, the directional nodes continue to remain completely unaware of eavesdropper presence as time progresses.

B. Channel Model

In order to establish successful communication link between Tx node $N_i \in N$ and its neighbor $N_j \in N$, both N_i and N_j must fall within their transmission ranges (*R*) and field-of-views (FOV), and the received powers $P_r(i,j)$ and $P_r(j,i)$ at N_j and N_i, respectively, must exceed a minimum threshold, P_o. For directional wireless channels, the received power $P_r(i,j)$ at N_j from the transmitter N_i can be calculated as [15]:

$$P_r(i,j) = P_t k_0 G_i^t(\theta_i - \phi_{i \rightarrow j}) G_j^r(\theta_j - \pi - \phi_{i \rightarrow j}) l_{ij}^{-\eta} \quad (1)$$

where P_t denotes the transmission power of node N_i, k_0 is a constant coefficient proportional to $(\lambda/4\pi)^2$ where λ denotes the wavelength, l_{ij} is the distance between N_i and N_j, η is the path loss exponent, and G_i^t and G_j^r are the directional antenna gains of the transmitter N_i and the receiver N_j, respectively. θ_i and θ_j are the beam steering angles of N_i and N_j, respectively. In our model, since we are assuming that FOV is equivalent

[1]Since we are assuming each sector is covered by one transceiver, we will use 'sector' and 'transceiver' interchangeably for the rest of the paper.

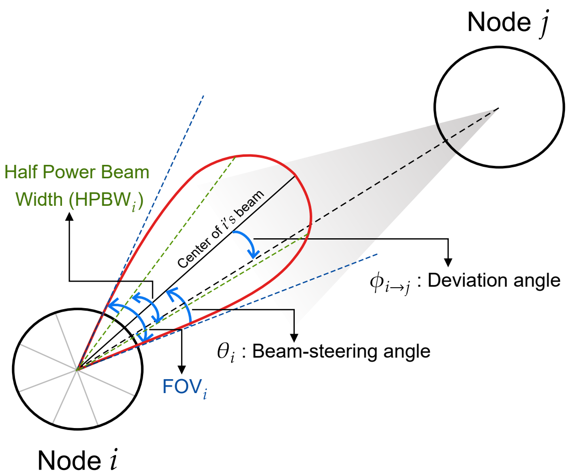


Fig. 1: Directional Antenna of Node i (with 8 on-board transceivers)

to the sector angle, the beam-steering angles are half of the corresponding FOVs. The deviation angle $\phi_{i\to j}$ between nodes N_i and N_j can be found given the coordinates and orientations of N_i and N_j, as shown in Fig. 1.

C. Directional Antenna Model

To model the directional gains needed for the channel model, we adopt the directional antenna model described in [16], which corresponds to the IEEE 802.15.3c standard. However, in this study we only focus on the main lobe as the side lobe can be safely ignored for highly directional wireless transmission systems operating at very high frequencies (e.g., 60 GHz or higher), Ch. 2 of [17]. The gain of such directional antenna, denoted as $G(\theta)$, is stated in terms of decibels (dB):

$$G(\theta) = G_0 - 3.01 \cdot \left(\frac{2\theta}{\theta_{\text{-3dB}}}\right)^2, \quad 0^\circ \le \theta \le \frac{\text{FOV}}{2} \tag{2}$$

where θ is an arbitrary angle within the range $[0^\circ, \frac{\text{FOV}}{2}]$, $\theta_{\text{-3dB}}$ denotes the half-power beamwidth (HPBW) angle, and $\theta_{\text{-3dB}} = \left(\frac{\text{FOV}}{2.6}\right)$ in degrees. G_0, the maximum antenna gain, can be acquired by $G_0 = 10\log\left(\frac{1.6162}{\sin\left(\frac{\theta_{\text{-3dB}}}{2}\right)}\right)^2$ in units of dB.

D. Transmission Scheduling and Neighbor Discovery

Since it is a self-configuring wireless network, no node has any prior knowledge of its neighboring nodes' locations or the network size. Hence, the nodes have to perform neighbor discovery to support data transmission among themselves. We assume each node periodically enters *Neighbor Discovery Mode* (NDM) by sending probe messages through a subset of its K transceivers. Without loss of generality, these probe messages could be similar to 3GPP's Synchronization Signal Blocks (SSBs) [18]. If a node can complete a handshake with another neighbor (i.e., a full and error-free exchange of probe messages) via one of its transceivers, it marks the neighbor as discovered and records the discovery. Considering the time interval for each NDM[2], a node is allowed to discover at most 1 neighbor per transceiver during each NDM interval.

We assume that the eavesdroppers are passive, omni-directional, and each eavesdropper is restricted to successfully detecting at most 1 directional communication from the directional nodes towards the eavesdropper up to a certain range, R_d, during each NDM interval.

IV. Problem Formulation

Assuming no centralized coordinator for coordinating the nodes during the neighbor discovery, the nodes have to decide which transceivers/sectors to use for probing existence of neighbors. Since nodes will be deciding which sectors to use at each NDM interval, the problem to be solved is to decide for the next NDM interval only. For a particular node, let $\mathcal{K} = 1, 2, .., K$ be the set of its sectors, $p^n_k(t)$ indicate the probability that a new neighbor exists at sector k at NDM interval t, and $p^e_k(t)$ indicate the probability that an eavesdropper exists at sector k at NDM interval t. Further, let $\epsilon(t) \subseteq \mathcal{K}$ be the set of sectors selected for probing at NDM interval t and $\mathcal{N}_k(t)$ be the number of unique neighbors found at sector k during probing at NDM interval t. Assuming that the past probing results are available for a window of W intervals, we can write the problem of selecting the sectors to probe for the next interval as follows:

$$\textbf{(P1):} \max_{\epsilon(t+1)} \sum_{j=t-W+1}^{t} \sum_{v\in\epsilon(j)} \mathcal{N}_v(j) + \sum_{v\in\epsilon(t+1)} p^n_v(t+1) - \sum_{j=t-W+1}^{t+1} \sum_{v\in\epsilon(j)} p^e_v(j) \tag{3}$$

such that

$$\epsilon(j) \subseteq \mathcal{K}, j = [t-W+1, .., t+1] \tag{4}$$
$$\mathcal{N}_k(j) = \{0,1\}, j = [t-W+1, .., t+1], \forall k \tag{5}$$
$$0 \le p^n_v(t+1) \le 1, \forall v, \text{ and} \tag{6}$$
$$0 \le p^e_v(j) \le 1, j = [t-W+1, .., t+1], \forall v. \tag{7}$$

Here, the first term in the objective function is the number of unique neighbors found during the window W, the last term is the total probability that an eavesdropper picked up the probing messages, and the middle term is the total probability of finding a new neighbor in the next interval. The first two terms quantify the finding of new neighbors and the last term quantifies the POI. Maximizing the difference is the baseline objective while it is possible to assign weights to attain a more specific balance between the two goals, which we will explore later. Constraint (4) makes sure either none or some of the sectors are selected for probing at any interval. Constraint (5) limits the number of new neighbors found at a sector (after probing that sector) to 1. This is based on the practical assumption that multi-access protocols necessitate that if there are multiple new neighbors at a sector, they will respond to the probe message and their response will collide and, hence, they will not be detected

[2] We will refer to the period at which the nodes probe for neighbors as 'NDM interval'.

by the probing node. It is possible to relax this assumption based on the specific multi-access protocol being used. Finally, constraints (6) and (7) assure that probabilities are in $[0, 1]$.

Two aspects make the problem (P1) difficult. *First*, the probabilities $p_v^n(.)$ and $p_v^e(.)$ are unknown and time-variant due to external factors such as mobility. *Second*, the probability of finding a new neighbor in future depends on the past sector selections, i.e., $p_v^n(t+1)$ depends on the sectors probed and the neighbors found in the past. In other words, $p_v^n(t+1) \sim \epsilon(j), j = [t-W+1, .., t]$ and $p_v^n(t+1) \sim \mathcal{N}_k(j), j = [t-W+1, .., t]$. Practical solutions lie in skillfully estimating these unknowns in real time, for which we provide a method in this effort.

(P1) considers the last W sector selections for probing and the outcomes of those probings. Also, it allows more than one sector to be probed at each NDM interval. A simpler version of (P1) is when only the sector probed at the last interval, t, is considered and only one sector per NDM interval is allowed. With these simplifying assumptions, we can rewrite the sector selection problem as:

$$\textbf{(P2):} \max_{\epsilon(t+1)} \mathcal{N}_{\epsilon(t)}(t) + p^n_{\epsilon(t+1)}(t+1) - p^e_{\epsilon(t)}(t) \tag{8}$$

$$\text{such that}$$

$$\epsilon(t) \subseteq \mathcal{K}, \tag{9}$$

$$|\epsilon(t)| \leq 1, \text{ and} \tag{10}$$

$$(5) - (7).$$

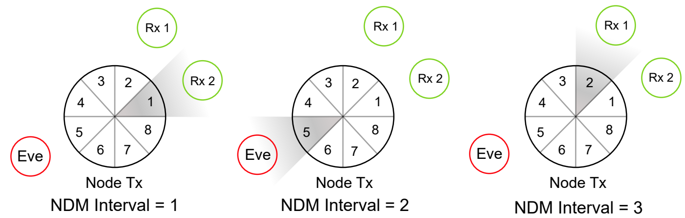
In the rest of this paper, we focus on designing practical heuristics that solve (P2).

V. Sequential Transceiver Selection Protocol

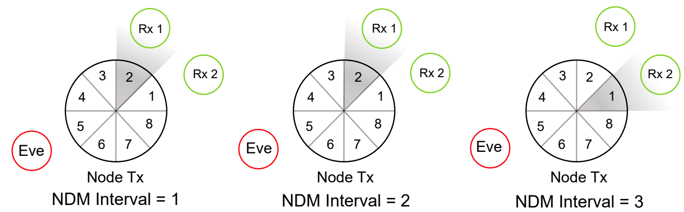
We consider the scenario when each node has to select *only one* of its transceivers to transmit and receive probe messages for neighbor discovery. Hence, the transceiver selection is sequential over NDM intervals, i.e., transceivers are selected sequentially over the intervals. Since no other guidance is available, we propose to probabilistically select the next transceiver at each NDM interval. To attain a balance between maximizing the likelihood of finding a new neighbor and minimizing POI by an eavesdropper, we introduce a tuning parameter, α = [-0.5, 0.5]. Based on α value, our protocol gives priority to certain subset of transceivers in the selection process as follows:

- when α is in [-0.5, 0), the current transceiver and the transceivers that are placed at proximity of the current transceiver will get more priority,
- when α is in (0, 0.5], transceivers that are placed at the opposite direction of the current transceiver will get more priority, and
- when $\alpha = 0$, all the transceivers will get equal priority.

Assuming random scattering of neighbors and eavesdroppers, the intuition behind this prioritization is simple: If the next transceiver (to use for probing) is close to the current one, it's likely to yield fewer finding of new neighbors. Each probe is, in a way, an exploration of the search space around the node. Therefore, sending a probe via a transceiver acts as a sample from this search space, contributing to the node's understanding of its neighboring environment. Fig. 2 illustrates the influence of α on the proposed transceiver selection protocol for the Tx node. In Fig. 2a, at NDM interval 1, node Tx uses sector 1 to send probe message and as the neighboring node Rx 2 falls within its FOV, it gets discovered (assuming Tx also falls within the FOV of Rx 2). For NDM interval 2, as $\alpha > 0$, Tx tends to select a transceiver from the transceiver subset placed at the opposite direction of the current one, ending up with sector 5, but gets eavesdropped by the passive eavesdropper Eve. Following the same procedure, after three NDM intervals, Tx manages to discover two of its neighbors Rx 1 and Rx 2, but also gets eavesdropped by Eve. In Fig. 2b, at NDM interval 1, Tx initially selects sector 2 and manages to find neighbor Rx 1. Following the protocol for $\alpha < 0$, Tx re-selects the current sector for NDM interval 2, and sends probe message towards Rx 1. For the NDM interval 3, it selects sector 1 that is in proximity with previously active sector 2, and discovers Rx 2. Such scenario indicates that for $\alpha > 0$ cases, there is a higher chance of quicker neighbor discovery completion in comparison to $\alpha < 0$ cases, however it posses substantial risk of eavesdropping unlike $\alpha < 0$ ones.



(a) Transceiver selection for different NDM intervals for $0 < \alpha \leq 0.5$



(b) Transceiver selection for different NDM intervals for $-0.5 \leq \alpha < 0$

Fig. 2: Transceiver selection based on α values (for nodes with 8 on-board directional transceivers)

A. *Prioritizing Probability Density Function*

To enable probabilistic selection of the next transceiver, we design a Probability Density Function (PDF) that can give differing priorities to transceivers. The proposed protocol selects one transceiver at a time and the PDF is to be used to guide the transceiver selection for the next time interval. The PDF should act as a versatile tool based on a tuning parameter, α, on either maximizing neighbor discovery or minimizing the

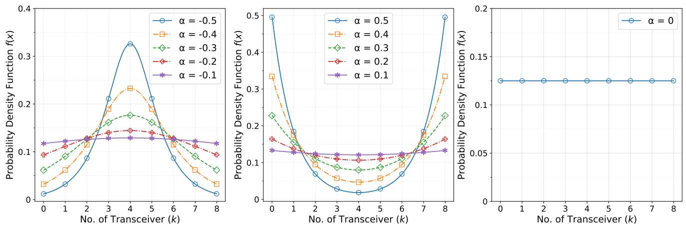


Fig. 3: PDF for different α values for 8 transceivers

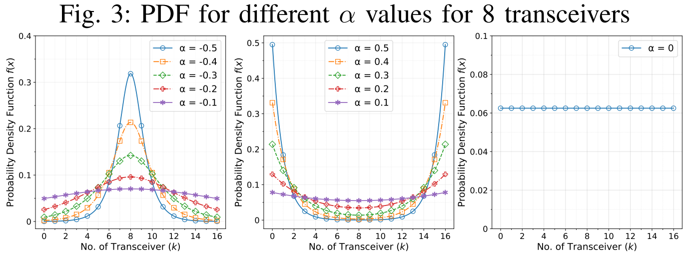


Fig. 4: PDF for different α values for 16 transceivers

POI. The PDF should assign probability of being selected for K transceivers, organized in a circular manner. The followings are the *required* features of this customized PDF, $g(x)$ with random variable $x = [0, K]$:

- For $0 \leq x \leq K$, *g(x)* must be non-negative.
- *g(x)* must be normalized so that it sums to 1 for the range $[0, K]$, i.e.,

$$\int_0^K g(x)dx = 1. \tag{11}$$

Further, we *desire* the shape of the PDF to be controllable by the tuning parameter, α. Let $f(x, \alpha)$ be such a PDF with a shape controlled by α. We assume that the current transceiver corresponds to the middle of the PDF, i.e., the ID of the current transceiver is $K/2$. Then, $f(x, \alpha)$ should decrease as x is going away from $K/2$ when α is in [-0.5, 0), and should increase as x is going away from $K/2$ when α is in (0, 0.5]. Also, when α is 0, $f(x, \alpha)$ should be the uniform distribution with $f(x, \alpha) = 1/K$.

To satisfy the above required and desired features, we use the following functional form utilizing two Exponential distributions:

$$f(x,\alpha) = \begin{cases} \Gamma^-(K,\alpha)\cdot \frac{2}{K}\left(e^{(\frac{\alpha}{1+\alpha})(x-\frac{K}{2})} + e^{-(\frac{\alpha}{1+\alpha})(x-\frac{K}{2})}\right)^{-1}, & -0.5 \leq \alpha < 0 \\ \frac{1}{K}, & \alpha = 0 \\ \Gamma^+(K,\alpha)\cdot \frac{1}{2K}\left[e^{-(\frac{\alpha}{1-\alpha})(x-\frac{K}{2})} + e^{(\frac{\alpha}{1-\alpha})(x-\frac{K}{2})}\right], & 0 < \alpha \leq 0.5 \end{cases} \tag{12}$$

where $\Gamma^+(.)$ and $\Gamma^-(.)$, functions of K and α, are normalizing factors so that the PDF attains the condition in (11) for all values of α in [-0.5, 0.5].

In $f(x, \alpha)$ above, for non-zero α values, the sum of the two Exponentials in the third term attains a peak or dip when $x = K/2$ for negative and positive α values, respectively. This is a feature we desire as we want to either prioritize or un-prioritize the selection of transceivers close to the current transceiver at $K/2$. Another benefit of the Exponentials is that they never go below zero, satisfying the non-negativity condition for a PDF. For $\alpha = 0$, $f(x, \alpha)$ maintains the uniform probability value of $\frac{1}{K}$. For $-0.5 \leq \alpha < 0$, the $\frac{2}{K}$ factor in the front ensures that the peak point of $f(x, \alpha)$ never goes below the value of $\frac{1}{K}$, which is the uniform probability. This is necessary to establish a skew in the function and give less probability to the x values away from $K/2$. Similarly, for the $0 < \alpha \leq 0.5$ case, the $\frac{1}{2K}$ factor in the front ensures that the dip of $f(x, \alpha)$ never goes above the value of $\frac{1}{K}$.

In order to find the normalizing components $\Gamma^+(.)$ and $\Gamma^-(.)$ in (13), we find the definite integral of $f(x, \alpha)$ for $x = 0...K$.

$$\int_0^K f(x,\alpha)dx = \begin{cases} \Gamma^-(K,\alpha)\cdot 2\cdot \frac{(1+\alpha)}{K\alpha}\cdot \\ \left[\tan^{-1}\left(e^{\frac{K\alpha}{2(1+\alpha)}}\right) - \tan^{-1}\left(e^{\frac{-K\alpha}{2(1+\alpha)}}\right)\right], & -0.5 \leq \alpha < 0 \\ \Gamma^+(K,\alpha)\cdot 2\cdot \frac{(1-\alpha)}{K\alpha}\cdot \sinh\left[\frac{K\alpha}{2(1-\alpha)}\right], & 0 < \alpha \leq 0.5 \end{cases} \tag{13}$$

To satisfy the condition (11), we then solve $\int_0^K f(x, \alpha)dx = 1$ and obtain $\Gamma^+(.)$ and $\Gamma^-(.)$ as follows:

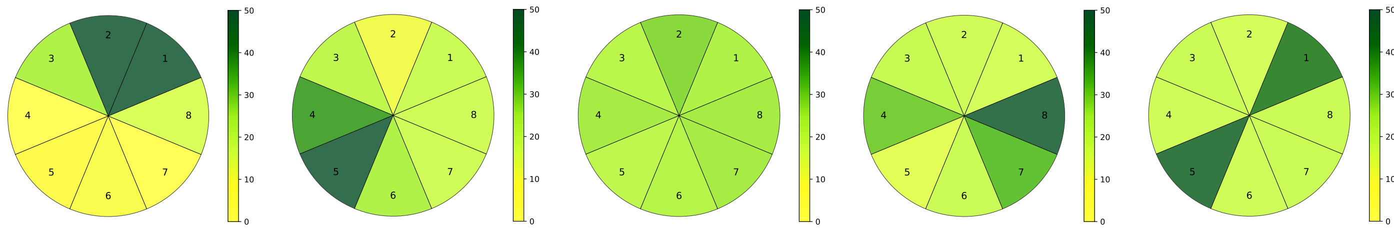
$$\Gamma^-(K,\alpha) = \frac{K\alpha}{2(1+\alpha)}\left[\tan^{-1}\left(e^{\frac{K\alpha}{2(1+\alpha)}}\right) - \tan^{-1}\left(e^{\frac{-K\alpha}{2(1+\alpha)}}\right)\right]^{-1} \tag{14}$$

$$\Gamma^+(K,\alpha) = \frac{K\alpha}{1-\alpha}\left[e^{(\frac{\alpha}{1-\alpha})(\frac{K}{2})} - e^{-(\frac{\alpha}{1-\alpha})(\frac{K}{2})}\right]^{-1} \tag{15}$$

Figs. 3-4 capture the influence of different α values over the variation in shapes of the PDF, $f(x, \alpha)$ different values of K.

B. Practical Relevance of α

The tuning parameter, α, enables N nodes to control their direction of probing, thereby serving as a significant factor influencing neighbor discovery and POI performance of the directional nodes. Fast neighbor discovery requires the probing node to frequently change its direction to ensure a nearly complete 360° coverage. However, to maintain low POI, it is important to keep the wireless signal radiation footprint as limited as possible, which ultimately directs Tx node towards covering a certain region rather than probing the entire search space. Different values of α can facilitate the probing node in adjusting its direction of transmission in accordance with situational demand, as depicted in Fig. 5. The heatmaps illustrate the total number of activation across 8 sectors for different α values observed over the initial 200 NDM intervals (here we select sector 1 as initial probing direction for observational purpose, in practice the initial sector selection is randomized), offering insight into the regions predominantly covered during the observation period. When covert communication with low POI is the priority, α guides the directional nodes to probe over a certain (green) region while leaving the opposite (yellow)



(a) α = - 0.5 (b) α = - 0.3 (c) α = 0 (d) α = + 0.3 (e) α = + 0.5

Fig. 5: Influence of different α values on N node's direction control with 8 transceivers

Algorithm 1: Transceiver Selection Protocol

Input: $\alpha, k, currentSector$
Output: $nextSector$

Function `Transceiver_Selection(`$\alpha, K, currentSector$`)`:
  xRange $\leftarrow$ array of integers from 0 to K
  PDF $\leftarrow$ array of K zeros
  CDF $\leftarrow$ array of K zeros
  `// Calculate the CDF for the prioritized probabilities in (13)`
  for $x \in xRange$ **do**
    PDF(x) = $f(x - currentSector + K/2, \alpha)$
    CDF(x) $\leftarrow$ CDF(mod(x-1+k,k)) + PDF(x)
  uniformSample $\leftarrow$ Uniform(0,1) `// Generate a Uniform random number in (0,1)`
  for $x \in xRange$ **do**
    if *uniformSample* $\leq$ *CDF(x)* **then**
      return x

Algorithm 2: Neighbor Discovery & Passive Eavesdropping

Function `Neighbor_Discovery(`$R, N_i, N_j, P_t, P_0, k_0, FOV_{sector_i}, FOV_{sector_j}$`)`:
  if $l_{ij} <= R$ **then**
    if $N_j(x_j, y_j)$ *within* FOV_{sector_i} **then**
      if $N_i(x_i, y_i)$ *within* FOV_{sector_j} **then**
        $P_r(i,j) = P_t k_0 G_i^t(\theta_i - \phi_{i \to j}) G_j^r(\theta_j - \pi - \phi_{i \to j}) l_{ij}^{-n}$
        if $P_r(i,j) > P_0$ **then**
          $i_{neighbor} \leftarrow j$
  return $i_{neighbor}$

Function `Passive_Eavesdropping(`$R_d, N_i, M_m, FOV_{sector_i}$`)`:
  if $l_{im} <= R_d$ **then**
    if $M_m(x_m, y_m)$ *within* FOV_{sector_i} **then**
      $m_{detect} \leftarrow i$
  return m_{detect}

region unexplored, as observed in Fig. 5a where α = -0.5, resulting in a limited coverage area with minimal vulnerability to passive eavesdropping compared to other scenarios. Comparing Fig. 5b and 5d, it is evident that α = +0.3 offers more coverage than α = -0.3, contributing more towards faster neighbor discovery completion, whereas α = -0.3 tends to focus more on a certain direction rather than looking around frequently. While α = 0 in Fig. 5c allows randomized selection and thus giving equal priority to all sectors at each NDM interval, positive α cases facilitate frequent scanning in different directions when rapid neighbor discovery is imperative. Following the proposed PDF, α = +0.5 allows the directional node to alter its probing direction from one region to its opposite counterpart after each NDM interval. This pattern is clearly visible from the predominance of coverage areas positioned opposite (nearly 180°) to each other in Fig. 5e.

C. Transceiver Selection Algorithm

Algorithm 1 summarizes the transceiver selection protocol run by N nodes in order to select one from K on-board transceivers for the next NDM interval. The procedure begins by calculating the probabilities for all the K transceivers, using equation (13) for a certain α, and storing the corresponding cumulative probabilities (CDF). We then iterate through all the CDF values and compare them with uniform random samples generated in between 0 and 1. Finally the transceiver with the CDF greater than or equal to the uniform sample is selected as the operating transceiver for the next NDM interval. After this procedure, each of N nodes enters NDM phase and uses the selected transceiver to send and receive probe messages. As outlined in Algorithm 2, two nearby directional nodes can only find each other if they lie within each others' FOV and the received power $P_r(i,j) > P_0$. Upon completion of successful discovery, the transmitter keeps record of the newly discovered node ID. In similar way, Tx node can be eavesdropped by a nearby passive eavesdropper if the eavesdropper falls within the FOV of the transmitter. Once detected, the eavesdropper records the detected node ID for the corresponding NDM interval.

D. Average POI Calculation

To quantify the effect of passive eavesdropping in the network, we find the average amount of eavesdropping occurrence over a certain NDM interval T for any given K, α:

$$\text{Avg. POI} = \frac{1}{T}\left(\sum_{t=0}^{T} \frac{\text{\# new nodes eavesdropped at interval } t}{N}\right) \tag{16}$$

TABLE I: Simulation Parameters

Parameter	Symbol	Value
# Directional Nodes	N	50
# Eavesdroppers	M	4, 6, 8
Transmission Range for N nodes	R	10 m
Detection Range for M nodes	R_d	10 m
# On-board Transceivers	K	4, 8, 16
Field-of-View	FOV	$360°/K$
Transmission Power	P_t	10 mW
Path Loss Exponent	η	2
Wavelength	λ	850×10^{-9} m
Minimum Received Power	P_o	0.5 mW
Tuning parameter	α	[-0.5,0.5]

where N is the total number of directional nodes in the network.

E. Tuning α

Based on the performance metrics of neighbor discovery and passive eavesdropping algorithms for all the values of α in (-0.5, 0.5), as delineated by the duration required to complete neighbor discovery and the fraction of nodes subjected to eavesdropping, respectively, finding the best α value to use for longer duration that ensures quicker discovery along with reduced POI can be considered as an optimization problem. The total number of transceivers per node, K, as well as the network parameters (i.e., the total number of directional nodes, *N*, and eavesdroppers, *M* in the network) contribute significantly in determining the optimal α.

Given the values of K, *N*, *M* and by taking into account total duration for neighbor discovery completion, performance of the neighbor discovery algorithm for a certain α can be quantified by using sum of differentials with decreasing value:

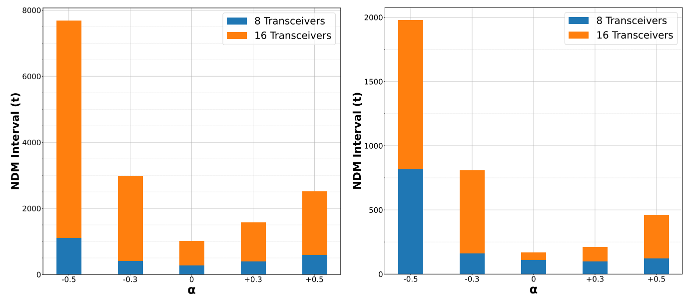
$$PND_\alpha = \sum_{i=1}^{T_{max}} \frac{n_i - n_{i-1}}{t_i}, \quad n_0 = 0, \quad -0.5 \leq \alpha \leq 0.5 \tag{17}$$

where T_{max} is the total time required to complete neighbor discovery, n_i and n_{i-1} are the corresponding cumulative count (i.e., from the CDF) of discovered nodes at times t_i and t_{i-1}, respectively. Here, the $n_0 = 0$ condition indicates no discovery happened at the beginning of the simulation. By dividing the difference $n_i - n_{i-1}$ with t_i, we reward quicker discoveries at the initial stages more than later discoveries, and as the time progresses the contributions of late discoveries to the performance are reduced. In essence, we want to set α such that discovering new nodes early on is more valuable.

Similar to the reasoning of (17) in rationing discoveries to the time they took, we want to reward eavesdroppings more if they take place later – indirectly punishing eavesdroppings taking place earlier. To do that, we leverage the performance of passive eavesdropping algorithm to quantify the probability-of-staying-covert (PSC):

$$PSC_\alpha = \sum_{i=1}^{T_{max}} \frac{I_i - I_{i+1}}{t_i}, I_0 = I_{max} = 1, -0.5 \leq \alpha \leq 0.5 \tag{18}$$

where T_{max} is the total time needed for all the possible neighbors getting eavesdropped, I_i and I_{i+1} are the corresponding complementary cumulative count (i.e., from the CCDF) of undetected nodes at times t_i and t_{i+1}, respectively. Here, $I_0 = 1$ condition indicates all nodes manage to stay covert or undetected and no eavesdropping has occurred at the beginning of the simulation.



(a) NDMs required to complete neighbor discovery (b) NDMs required to reach maximum possible fraction of eavesdropped nodes

Fig. 6: Performance comparison of neighbor discovery and POI for 8 and 16 transceiver-based directional nodes

Bringing the two goals together, the problem of tuning α can be written as:

$$C(\alpha) = \max_{-0.5 \leq \alpha \leq 0.5} \{PND_\alpha \times PSC_\alpha\} \tag{19}$$

By maximizing the product of the two performance goals, discovering more nodes as early as possible while staying undetected by the eavesdroppers as long as possible can be attained. It is possible to work with other weighted objective functions if more importance is to be given to either PND or PSC. In this paper, we focus on the case where PND and PSC are given equal weight as implied in (19).

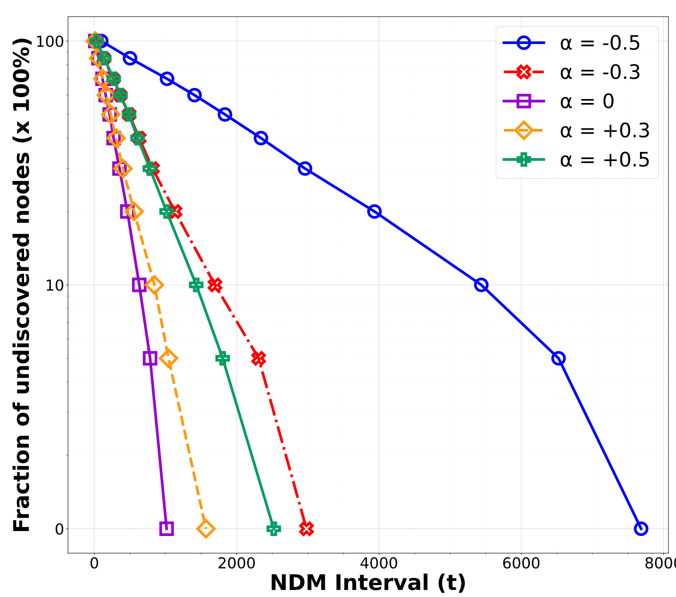
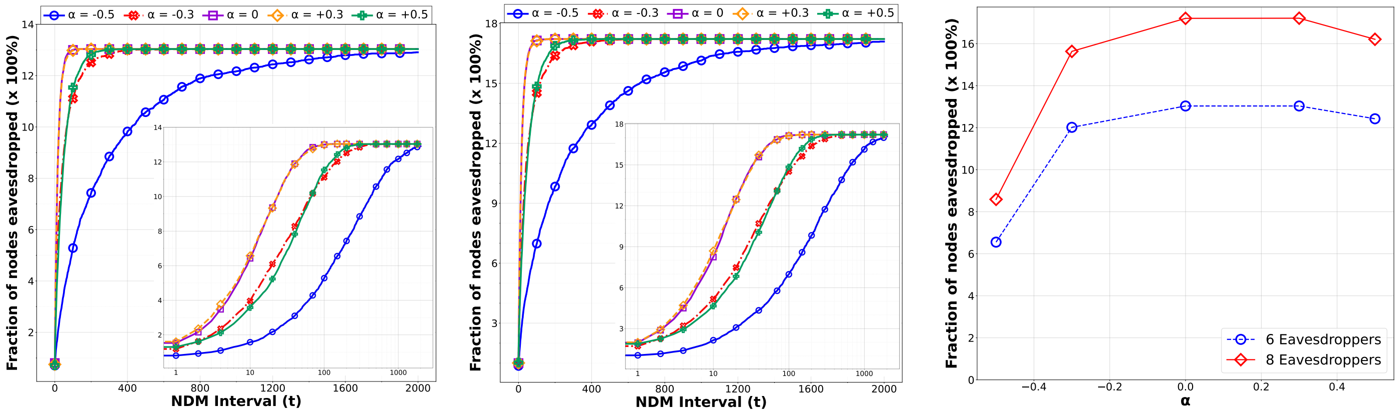


Fig. 7: Performance of neighbor discovery for 16 transceiver-based directional nodes



(a) POI with 6 eavesdroppers (b) POI with 8 eavesdroppers (c) POI comparison at 150th NDM interval

Fig. 8: POI analysis (based on fraction of eavesdropped nodes) for 16 transceiver-based directional nodes

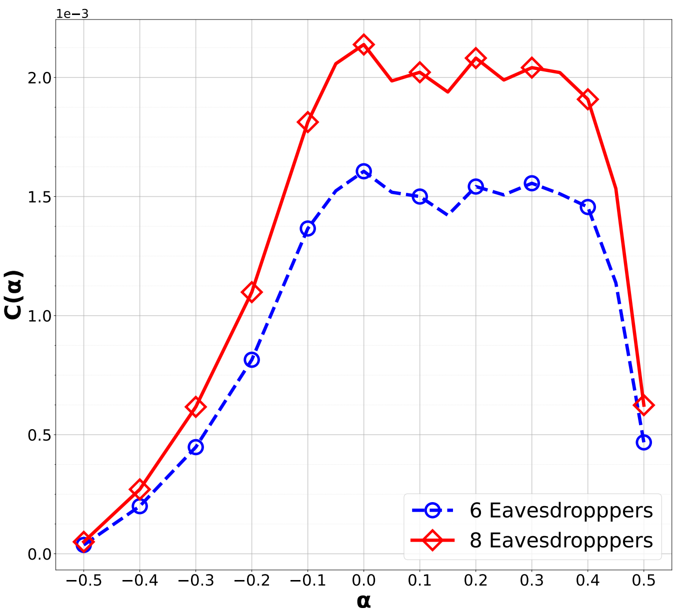


Fig. 9: Tuning α for N nodes with 16 on-board transceivers

VI. Simulation Results And Discussion

To study the influence of different tuning parameter (α) values on directional wireless systems in the presence of passive eavesdroppers, we develop a simulation environment using Python where some of the key parameters such as total number of on-board transceivers (K) can be varied. We assumed that each transceiver has an FOV of $\frac{360^\circ}{K}$. In the simulations, all N directional nodes and M eavesdroppers are randomly scattered in a 100m $\times$ 100m grid. Both the transmission range for the directional nodes and the detection range for the eavesdroppers are bounded by 10m. Currently, the FOV of any directional node is controlled by the total number of on-board transceivers (K). Other parameters are charted in Table I. After repeating each simulation 300 times with varying seed values, we study the average statistics for analysis.

The findings from Fig. 6 indicate a clear trend: As K increases and corresponding FOV decreases, it takes longer for the directional nodes to successfully complete their neighbor discovery, however their vulnerability to passive eavesdropping reduces simultaneously as it takes more NDM intervals to reach maximum possible eavesdropping occurrence for different α values.

The influence of tuning α on neighbor discovery operation for N nodes with any K values, as depicted in Fig. 7, show that randomized selection (i.e., for α = 0) exhibits faster discovery completion compared to the probabilistic search approach (for $\alpha \neq 0$ cases). When α falls within [-0.5, 0) or (0, 0.5], it becomes evident that in most cases $\alpha > 0$ outperforms $\alpha < 0$ in terms of latency required to finish discovery, due to the fact that positive α values enable directional nodes to scan the search space from varying angles, providing a more comprehensive coverage. Additionally, α values approaching α = 0 tend to achieve quicker discovery completion compared to those deviating further away from 0. In fact, as α slides further into negativity, a noticeable delay is observed even in making initial discoveries, validated particularly by α = -0.5 for any K values, as then the priority is given to the current or its adjacent transceivers in the selection process rather than constantly scanning different directions using other transceivers.

Observations from the POI plots, displayed in Fig. 8a and 8b, highlight the fact that, for any given K, α cases that require more time to complete discovery are more inclined to experience reduced exposure to passive eavesdropping as they tend to take more time meeting the maximum attainable fraction of nodes eavesdropped, especially in case of α = -0.5 where the directional nodes usually keep focusing on a certain area in the search space for several NDM intervals instead of frequently looking at different directions which eventually provide them with longer period to operate covertly from passive eavesdroppers. To further validate this observation, we take sample from the POI analyses for different K values at 150th NDM interval after initialization, depicted in Fig. 8c, where significantly reduced fraction of eavesdropped nodes is clearly visible for α = -0.5 case in comparison to other α cases. Moreover, for a certain K, with an increase in eavesdroppers in the network, the maximum possible fraction of eavesdropped nodes also rises.

Fine tuning the α value, when trying to optimize α to get both fast discovery and low POI (in other words, high PSC), is critical. We made a brute force search for the α values (with step size 0.05) solving the optimization problem in (19). Fig. 9 shows how α influences the joint objective $C(\alpha)$. The figure shows that α = 0 proves to be the most favorable scenario for 16 on-board transceiver based directional nodes surrounded by various eavesdroppers, offering quicker neighbor discovery along with lesser POI for a prolonged duration. It is clear that positive α values offer a better outcome. However, it is also clear that for both α = -0.5 and α = 0.5 cases, the corresponding $C(\alpha)$ values are significantly low, which underscores the notion that neither an exclusive focus on quick neighbor discovery completion nor sole emphasis on ensuring lower POI over an extended period prove to be the optimal solution.

VII. Conclusions

A sequential transceiver selection protocol for directional wireless systems is proposed that can steer the transmitting node towards either maximizing the probability of neighbor discovery or minimizing the probability-of-intercept (POI), by determining the next operational transceiver based on a probabilistic approach controlled by a tuning parameter, α. A Python based simulation environment is developed to study the influence of different α values on a wireless network populated with directional nodes and passive eavesdroppers. For a fixed α, prolongation of neighbor discovery completion yet lesser POI are observed as total number of on-board transceivers increases. While randomized selection of operating transceiver (for α = 0) exhibits the quickest discovery completion, prioritizing transceivers placed at opposite direction to current one (when $\alpha > 0$) as the next operational transceiver excels over prioritizing current or its adjacent transceivers (when $\alpha < 0$) in most cases in terms of finishing neighbor discovery. Moreover, α values being closer to 0 outperforms those deviating away from 0. However, α cases that facilitate faster neighbor discovery completion have shown more vulnerability to passive eavesdropping. Also the rise in total eavesdroppers in the network correlates with an increased average eavesdropping occurrence, while maintaining total number of on-board transceivers unchanged. When determining the best α to use for an extended period, α = 0 stands out for quicker discovery completion with reduced POI, nevertheless neither prioritizing quick discovery nor focusing solely on minimizing POI for a long stretch proves to be optimal.

As part of future works, we aim to enhance the transceiver selection protocol by implementing real-time tuning of α, leveraging insights gathered from recent observations made by the directional nodes. Additionally, we will explore the development of a reinforcement learning framework to dynamically adjust the tuning parameter α, particularly in scenarios involving node mobility.

References

[1] H.-N. Dai, Q. Wang, D. Li, and R. C.-W. Wong, "On eavesdropping attacks in wireless sensor networks with directional antennas," *Intern. Journal of Distributed Sensor Networks*, vol. 9, no. 8, p. 760834, 2013.

[2] M. Jean, M. Yuksel, and X. Gong, "Millimeter-wave software-defined radio testbed with programmable directionality," in *Proc. of IEEE INFOCOM Workshops*, 2023, pp. 1–8.

[3] A. Cornejo, S. Viqar, and J. L. Welch, "Reliable neighbor discovery for mobile ad hoc networks," *Ad Hoc Networks*, vol. 12, pp. 259–277, 2014.

[4] F. Tajrian, M. A. I. Sarder, M. S. Anzum, M. Rafique, and A. Bin Shams, "Impact of receiver antenna polarization and resource scheduler on the downlink performance of high velocity users in 5G millimeter wave small cell technology," in *Proc. of Intern. Conference on Electronics, Communications, and Information Technology*, 2021, pp. 1–4.

[5] 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.

[6] Z. Zhang and B. Li, "Neighbor discovery in mobile ad hoc self-configuring networks with directional antennas: algorithms and comparisons," *IEEE Transactions on Wireless Communications*, vol. 7, no. 5, pp. 1540–1549, 2008.

[7] S. H. Kumar and W. K. Seah, "Efficient neighbour discovery algorithm for maritime mesh networks with directional antennas," in *Proc. of IEEE International Conference on ITS Telecommunications*, 2008, pp. 6–11.

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

[9] Q. Xia and J. M. Jornet, "Expedited neighbor discovery in directional terahertz communication networks enhanced by antenna side-lobe information," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 7804–7814, 2019.

[10] F. Xu, S. Ahmad, M. N. khan, M. Ahmed, S. Raza, F. Khan, Y. Ma, and W. U. Khan, "Beyond encryption: Exploring the potential of physical layer security in UAV networks," *Journal of King Saud University - Computer and Information Sciences*, vol. 35, no. 8, p. 101717, 2023.

[11] Y. Zou, X. Wang, and W. Shen, "Intercept probability analysis of cooperative wireless networks with best relay selection in the presence of eavesdropping attack," in *Proceedings of IEEE International Conference on Communications (ICC)*, 2013, pp. 2183–2187.

[12] G. Pei, M. Albuquerque, J. H. Kim, D. P. Nast, and P. R. Norris, "A neighbor discovery protocol for directional antenna networks," in *Proc. of IEEE Military Communications Conference*, 2005, pp. 487–492.

[13] B. Qiu, W. Cheng, and W. Zhang, "Robust multi-beam secure mmWave wireless communication for hybrid wiretapping systems," *IEEE Tran. on Information Forensics and Security*, vol. 18, pp. 1393–1406, 2023.

[14] R. Melki, H. N. Noura, M. M. Mansour, and A. Chehab, "A survey on OFDM physical layer security," *Physical Communication*, vol. 32, pp. 1–30, 2019.

[15] L. X. Cai, L. Cai, X. Shen, and J. W. Mark, "Rex: A randomized exclusive region based scheduling scheme for mmWave WPANs with directional antenna," *IEEE Transactions on Wireless Communications*, vol. 9, no. 1, pp. 113–121, 2010.

[16] Q. Chen, X. Peng, J. Yang, and F. Chin, "Spatial reuse strategy in mmwave wpans with directional antennas," in *Proc. of IEEE Global Communications Conference (GLOBECOM)*, 2012, pp. 5392–5397.

[17] C. Hurley, R. Rogers, F. Thornton, D. Connelly, and B. Baker, *WarDriving and Wireless Penetration Testing*. Rockland, MA: Syngress, 2007.

[18] 3GPP, "NR; NR and NG-RAN overall description," Technical Specification (TS) 38.300, 3rd Generation Partnership Project, 2022.