# Self-Adaptive Neighbor Discovery in Ad Hoc Networks with Directional Antennas

Xueli An and Ramin Hekmat

***Abstract*—In this paper we present a novel neighbor discovery protocol for networks with directional antennas. The novelty of this protocol lies in two aspects. Firstly, in order to cope with mobility issues, we adjust the frequency of neighbor discovery attempts according to the dynamics of the network. Secondly, to improve power efficiency and reduce overhead, the protocol has the ability to limit neighbor discovery attempts in directions where no new neighbors are likely to be found. The superior performance of our protocol is shown through simulations. Furthermore, we provide an analytical model to analyze directional neighbor discovery protocols in general. This model reveals the impacts of using directional antennas in neighbor discovery process. The accuracy of this analytical model is validated through simulations.**

***Index Terms* — directional antenna, neighbor discovery, performance analysis**

## I. INTRODUCTION

SELF-ORGANIZATION is the ability for ad hoc networks to create and maintain themselves without relying on any external infrastructure, system administrator, or users. Neighbor discovery (ND) is a hinge point to realize self-organization in ad hoc networks. ND process allows in-range nodes to link with each other and form a connected network. ND protocols are generally classified as one-way ND and handshake-based ND [1]. One-way ND requires that each node periodically sends out advertising packets to announce its presence and discovers neighbors by receiving advertising packets. For handshake-based ND, a node needs to provide active response to the sender after receiving an advertising packet from an unknown neighbor. Compared to one-way ND, handshake-based ND is more complex to implement, but symmetric neighborhood is established by exchanging advertising packets.

A well-designed ND protocol needs to be closely related to the characteristics of the physical layer. Nowadays, directional antennas are widely used to extend transmission range and increase wireless system capacity [2]-[6]. Although directional antennas offer many advantages over omni-directional antennas, their deployment for directional neighbor discovery (D-ND) is not a trivial matter. The use of directional antennas complicates the analytical modeling of ND process. For example in [7], authors presented several probabilistic models for D-ND, but their approach is only applicable to one-way ND. In [1], the author provided an analytical model for handshake-based D-ND, however, based on the assumption that in each beam sector only one potential neighbor was present, which made the analysis only applicable to sparse networks.

Mobility is also a problematic issue in directional antenna based networks. A node can easily lose track of its neighbors in a certain direction because of the mobility of the neighbors. Most of the previous works do not consider mobility effects in a proper way. In [8], authors attempted to solve mobility by periodical polling of neighbors to ensure that each node is continuously aware of its neighbors' positions. However, the frequency of polling is not well-defined in that paper.

In this paper, we propose a novel Self-Adaptive Directional Neighbor Discovery (SA-DND) protocol which is handshake based. This protocol distinguishes itself from previous D-ND protocols in two ways. First, our protocol copes with mobility by self-adjustment of the ND execution frequency according to the dynamics of the network. Second, in order to achieve power efficiency and reduce overhead, our protocol is able to avoid the repetition of neighbor discovery attempts in directions where no new neighbors are likely to be found. To the best of our knowledge, such self-organization scheme is first proposed in a D-ND protocol.

In addition, we also provide an analytical method to analyze D-ND protocols. This analytical model is suitable for sparse as well as dense networks. Furthermore, our model can be extended for protocols that use *Sleep* state in order to provide energy conservation in ad hoc sensor networks. Using this analytical model, handshake-based D-ND is compared with one-way D-ND. Despite the general belief that handshake-based D-ND is less attractive for sensor networks, due to its overhead, our comparisons indicate that in certain scenarios (when node degree is low and antenna beamwidth is narrow), handshake-based D-ND outperforms one-way D-ND.

The rest of this paper is organized as follows. In section II, we introduce SA-DND and its main properties. In section III, we describe an analytical model for a general handshake-based D-ND protocol and extend it with *Sleep* state. The analytical model is validated by simulations. Finally, in Section IV we conclude this work and discuss future directions.

## II. SELF-ADAPTIVE DIRECTIONAL NEIGHBOR DISCOVERY

In this section, we introduce the Self-Adaptive Directional Neighbor Discovery (SA-DND) protocol. A single channel network is considered in this work. Nodes in the network are placed randomly but uniformly in a two-dimensional plane. Each node is identified by a unique node ID, e.g. MAC address. Multi-hop system is not considered. Neighbor

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discovery only considers one-hop neighbors. In our scheme, global synchronization is not required. Transceiver works in half-duplex mode.

### *A. Antenna Model*

All the nodes in the network are equipped with directional antennas with beamwidth $\theta$ ($0 < \theta \le 360^\circ$). For a certain node, the entire transmission angle is covered by $N_B$ beam sectors, where $N_B = 360^\circ / \theta$, and each beam sector is labeled by a pre-defined index $i$ ($i \in [1,\ N_B]$). Both directional and omni-directional modes are possible for transmission and reception.

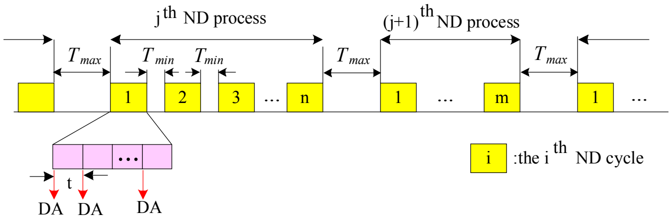

Fig.1. SA-DND protocol illustration

### *B. Protocol Description*

SA-DND is a handshake-based ND protocol. As shown in Fig.1, after a node is powered on, it operates alternately between *ND cycle* and *ND interval*. In each *ND cycle*, a node is in *Transmit* state. It takes the initiative for neighbor discovery by sending out Directional Advertising (DA) packets. When a node is in *ND interval*, it is in *Listen* state and listens omni-directionally. If it receives a DA from an unknown neighbor, it replies directionally with a Directional Advertising Response (DAR) packet in the reception direction. DA and DAR exchange is supposed to finish within a predefined time length *t*. DA and DAR contain the basic information of a node, e.g. node ID. If multiple packets arrive at a receiver at the same time, collision happens. Especially, we define that, multiple DAs simultaneously arriving at a node causes *advertising collision* and multiple DARs arriving at a node at the same time causes *response collision*.

#### *1) Neighbor List*

Each node keeps a list to record in-range neighbors' ID and direction information (e.g. the index of a beam sector from where to receive a neighbor's DA or DAR).

#### *2) ND Interval Adaptation*

ND protocol should be triggered periodically. However, frequently executed ND protocol leads to severe overhead which could counteract the merit by using directional antennas. Otherwise, the network can not cope with topology changes. SA-DND addresses this issue by appointing nodes to self adapt *ND interval* according to the dynamics of the network. The general idea is that when a node experiences topology changes, it triggers *ND cycles* more frequently than when it is in stable state. For example, the network topology is changed when the neighbors are powered off, move to other directions or the transmission channel is disturbed. In order to realize *ND interval* adaptation, two *ND interval* durations are introduced: ($T_{min}$, $T_{max}$). When a node is powered on, *ND interval* is defaulted as the short value $T_{min}$. After the node cannot detect more new neighbors, it supposes itself being in stable state and *ND interval* adapts from $T_{min}$ to the long value $T_{max}$. As the illustration in Fig.1, the interval from the beginning of the 1st *ND cycle* (or from the instance $T_{max}$ adapting to $T_{min}$) to the instance $T_{min}$ adapting to $T_{max}$, is defined as one ***ND process***. A ***ND process*** is consisted by several *ND cycle*s, and a new ***ND process*** is scheduled after each interval $T_{max}$.

#### *3) ND Cycle Adaptation*

When a *ND cycle* is initially triggered, DAs are sent sequentially from all the $N_B$ beam sectors to guarantee the discovery of all the potential neighbors. However, because DAs may be sent to an empty area or an area without unknown neighbors, a full-circle scan wastes transmission power, increases overhead and prolongs neighbor discovery time. Therefore, SA-DND designs that DAs are only sent to the directions with high probability for neighbor detection. This is realized from the following aspects:

- Antenna Beam Sector (ABS) List

Each node keeps a list to record the indexes of available beam sectors to send out DAs. At the beginning of each ***ND process***, the ABS list contains the entire indexes from 1 to $N_B$. In each *ND cycle*, DAs are only sent out from the beam sectors whose indexes are in the ABS list.

- ABS Remove Policy

In a ***ND process***, if a node cannot detect a new neighbor in a certain beam sector within successive $K$ rounds of *ND cycle* and no *response collision* is reported from physical layer, this beam sector's index is removed from its ABS list. $K$ is defined as *Threshold Factor*. If the ABS list is null, the current ***ND process*** is finished and *ND interval* adapts from $T_{min}$ to $T_{max}$.

- ABS Re-add Policy

In order to cater for network topology change caused by the mobility of the nodes, in a ***ND process***, if a node receives an unknown DA from a beam sector whose index is not in the ABS list, its index will be added into the list again from the next round of *ND cycle*.

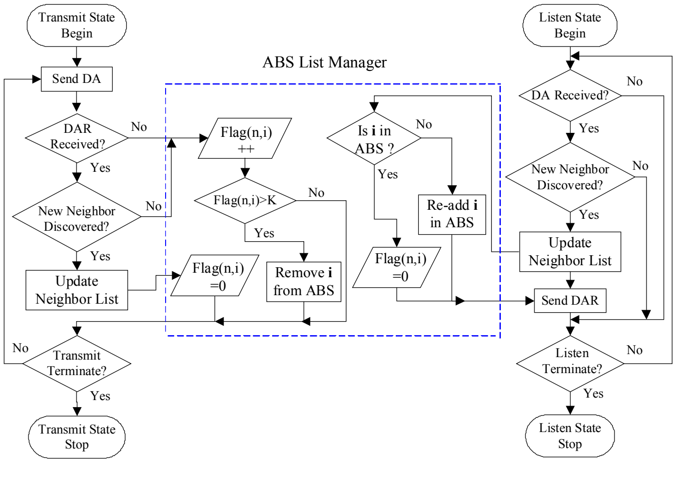

Fig.2. Flow chart for *ND cycle* adaptation

The flow chart for *ND cycle* adaptation is shown in Fig.2. In the ABS List Manager module, the ABS list is updated automatically according to the feedback from D-ND operations. In the module, Flag(n,i) is used to monitor the D-ND operations on the $i^{\text{th}}$ beam sector of node *n*, e.g. if Flag(n,i) grows larger than *K*, the $i^{\text{th}}$ beam sector's index *i* is removed from node *n*'s ABS list.

### *C. Quality of Neighbor Discovery Protocol*

In this work, the considered system parameters are node degree ($k$) and antenna beamwidth ($\theta$). Node degree refers to the number of one-hop neighbors within a node's transmission range. And the quality of a ND protocol can be measured by the following metrics:

- Neighbor discovery time ($T_{ND}$): is an important metric that denotes the duration of one ***ND process***. For instance, ND time can be viewed as the average time spent by a new-joined node to discover and incorporate with all or most of its neighboring nodes.
- Neighbor discovery ratio ($\eta$): is defined as the ratio between the number of discovered neighbors and its node degree. ND ratio determines the network topology. If ND ratio is high, this node has more feasibility to maintain the connectivity with the whole network.

## III. ANALYTICAL MODELING FOR D-ND PROTOCOL

In this section, we deduce an analytical method to model a general handshake-based D-ND algorithm. According to the analytical model, one handshake-based D-ND algorithm is compared with another two one-way D-ND algorithms. All the proposed algorithms can operate in both synchronous and asynchronous systems, however, in order to simplify the analytical process, a slotted synchronous system is assumed. The transmission of DA or DAR packet is within one time slot. The asynchronous analysis can be extended as the same consideration in [7].

### *A. One-way Random (1-R)*

1-R is a simple and basic one-way D-ND algorithm. It assumes that, at the beginning of each slot, a node has probability $p_t$ to be in *Transmit* state, or has probability (1- $p_t$) to be in *Listen* state. When a node is in *Transmit* state, it randomly chooses an antenna beam sector to transmit a DA packet. When a node is in *Listen* state, it listens omni-directionally for DA packets.

### *B. Wheeled-Iteration Neighbor Discovery*

Wheeled-Iteration Neighbor Discovery (WIND) protocol requires that if a node is in *Transmit* state, it transmits DA packets sequentially to all the possible directions.

#### *1) One-way WIND (1-W)*

In 1-W, the system is frame-based and each frame consists of $N_B$ slots. At the beginning of each frame, a node has probability $p_t$ to be in *Transmit* state or has probability (1- $p_t$) to be in *Listen* state. In *Transmit* state, a node randomly chooses an antenna beam sector to send a DA packet in the first slot and moves to the next beam sector clockwise to transmit the next DA in the next slot until it covers all the beam sectors. A node in *Listen* state listens omni-directionally to receive DA packets.

The analytical model for 1-R can be found in [1] or [8]. The analytical model for 1-W is a simplified version of Handshake-based WIND (H-W) introduced in the following section. Due to lack of space, we do not provide the details here.

#### *2) Handshake-based WIND (H-W)*

The only difference between 1-W and H-W is that, H-W requires a node to reply with a DAR packet in the reception direction after receiving a DA packet. Therefore, in H-W, each frame consists of $2N_B$ slots.

Assume that all the nodes are within transmission range of each other. For particular node *A* and node *B*, suppose that node *A* has a probability $p_f$ to discover node *B* in a certain frame. Consequently, node *A* has a probability $p_j$ to firstly find node *B* in the $j^{\text{th}}$ frame, where $p_j = p_f\,(1-p_f)^{j-1}$. Thus, in consecutive *J* frames, node *A* has a probability $p_J$ to find node *B*, where $p_J = \sum_{j=1}^{J} p_j$. Therefore, for a certain node, its ND ratio in consecutive *J* frames is formulated as:

$$\eta_J = \mathbb{F}\left(p_f, k\right) = \frac{\sum_{m=1}^{k} m \binom{k}{m} p_J{}^{m} \left(1-p_J\right)^{k-m}}{k} \tag{1}$$

ND ratio performs as a function of $p_f$ and node degree $k$. Suppose $k$ as a known system parameter, and we emphasize on the modeling of $p_f$ in the following work.

In a certain frame, node *A* can discover node *B* in two situations:

- *A* is in *Listen* state and *B* is in *Transmit* state:

Node *A* can discover node *B* only by correctly receiving a DA from *B* without *advertising collision*, which means that other neighbors are either in *Listen* state or in *Transmit* state but not pointing to node *A*. This probability is denoted as:

$$P_{\{A:L,B:T\}} = \left(1-p_t\right) p_t \left(1-\frac{p_t}{N_B}\right)^{k-1} \tag{2}$$

- *A* is in *Transmit* state and *B* is in *Listen* state:

In this situation, node *A* needs two steps to discover node *B*: Firstly, node *B* receives node *A*'s DA without *advertising collision* (A→B); secondly, node *A* receives node *B*'s DAR without *response collision* (B→A). This probability is denoted as:

$$P_{\{A:T,B:L\}} = P_{A\to B} \cdot P_{B\to A} \tag{3}$$

Node *A* has *k* neighbors within transmission range. Suppose *m* neighbors (including node *B*) are located in a certain beam sector of *A* with probability $p_m$ ($m \in [1,k]$), where,

$$p_m = \binom{N_B}{1}\binom{k-1}{m-1}\left(1-\frac{1}{N_B}\right)^{k-m}\left(\frac{1}{N_B}\right)^{m} \tag{4}$$

Equation (4) means, except node *B*, select ($m$-1) nodes from ($k$-1) neighbors and they are in the same beam sector as node *B*. In the ($m$-1) nodes, denote *i* nodes in *Transmit* state and ($m$-1-$i$) nodes in *Listen* state ($i \in [0, m-1]$). The probability for event A→B being true is:

$$P_{A\to B} = \left(1-\frac{p_t}{N_B}\right)^{k-m} \left(p_t(1-\frac{1}{N_B})\right)^{i} \qquad (5)$$

The first item means that the ($k$-$m$) neighbors in the other beam sectors are either in *Listen* state or in *Transmit* state but not pointing to $B$. The second item means that the $i$ nodes, which are in the same sector as $B$, are in *Transmit* state and do not point to $B$. Consequently, the probability for *advertising collision* at node $B$ is expressed as: $P_{DA-collision} = 1 - P_{A\to B}$ .

Suppose that all the nodes in the network are homogenous. The only condition for event B→A being true is that, except node $B$, all the ($m$-1-$i$) listening nodes that are in the same beam sector as $B$ encounter *advertising collisions* with probability $P_{DA-collision}$ . On condition that node $B$ has received node $A$'s DA packet, and then the probability for event B→A being true is:

$$P_{B\to A} = \mathrm{P}_{DA-collision}{}^{m-i-1} \qquad (6)$$

Consequently, the probability for node $A$ discovering node $B$ in this situation is:

$$P_{\{A:T,B:L\}} = \sum_{m=1}^{k}\sum_{i=0}^{m-1} P_{A\to B}\cdot P_{B\to A}\Big|_{(m,i)}$$
$$= \sum_{m=1}^{k}\sum_{i=0}^{m-1} p_m \left(\binom{m-1}{i} p_t\left(1-p_t\right)^{m-i}\right) P_{A\to B}\cdot P_{B\to A} \qquad (7)$$

To sum up, in a particular frame, node $A$ can discover node $B$ with probability $p_f$, where,

$$p_f = P_{\{A:L,B:T\}} + P_{\{A:T,B:L\}} \qquad (8)$$

Therefore, node $A$ has a probability $P_w$ to discover node $B$ at least once within $w$ consecutive frames, where,

$$P_w = 1-(1-p_f)^w \qquad (9)$$

In order to maximum the algorithm performance, the optimal transmission probability $p_{t,max}$ is deduced by differentiating equation (9) and equating it to 0. The relationship between node degree $k$ and $p_{t,max}$ is plotted in Fig.3. And we use $p_{t,max}$ to get $p_f$ and substitute $p_f$ in equation (1) to formulate ND ratio $\eta$ .

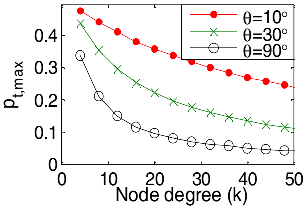

Fig.3. Relationship between node degree ($k$) versus $p_{t,max}$

### 3) *Handshake-based WIND with Sleep state (H-W/S)*

The main problems for energy conservation in ad hoc network are collision and idle listening [9]. Collision has been defined in previous content. A solution to deal with collisions is to let part of the nodes fall into *Sleep* state (shut down transceiver) and wake up periodically. Idle listening means that a node is in *Listen* state and ready to receive, but it is not receiving currently. The cost of idle listening is not as much as transmitting, but still much higher than *Sleep* state. Therefore, in ad hoc sensor network, *Sleep* state is considered to increase power efficiency and prolong battery lifetime.

In the following part, we extend the analytical model of H-W with *Sleep* state. At the beginning of each frame, a node has a probability $p_t$ to be in *Transmit* state, $p_s$ to be in *Sleep* state and (1- $p_t$ - $p_s$) to be in *Listen* state. Therefore,

$$P_{\{A:L,B:T\}} = (1-p_t-p_s)\,p_t\left(1-\frac{p_t}{N_B}\right)^{k-1}$$

$$P_{\{A:T,B:L\}} = \sum_{m=1}^{k}\sum_{i=0}^{m-1}\sum_{s=0}^{m-1-i}\left[p_m\left(\binom{m-1}{i}p_t\left(1-p_t-p_s\right)^{m-i-s}p_s{}^{s}\right)P_{A\to B}\cdot P_{B\to A}\right]$$

$$p_f = P_{\{A:L,B:T\}} + P_{\{A:T,B:L\}}$$

where,

$$p_m = \binom{N_B}{1}\binom{k-1}{m-1}\left(1-\frac{1}{N_B}\right)^{k-m}\left(\frac{1}{N_B}\right)^{m}$$

$$P_{A\to B} = \left(1-\frac{p_t}{N_B}\right)^{k-m}\left(p_t(1-\frac{1}{N_B})\right)^{i}$$

$$P_{B\to A} = \left(1-P_{A\to B}\right)^{m-1-i-s}$$

## C. *Algorithm Comparisons*

For a certain node, $N_{slot}$ is defined as the expected number of slots to find 95% of its neighbors ( $\eta = 95\%$ ). ND time is defined as $T_{ND} = t_{slot} \times N_{slot}$, where, $t_{slot}$ is the time duration of one time slot. In each experiment, transmission probability is set to the optimal value.

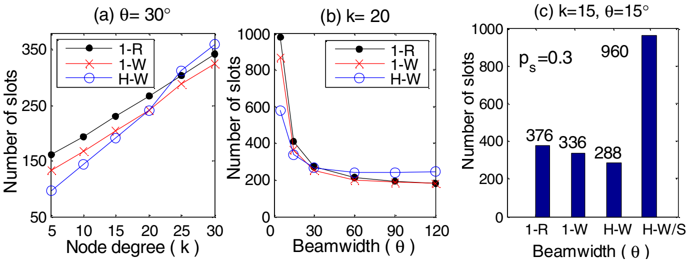

Fig.4. Algorithm Comparisons

In Fig.4 (a), 1-R, 1-W and H-W are compared by fixing $\theta$ at 30°. This figure shows the relationship between node degree $k$ and $N_{slot}$. When $k$ is low, H-W outperforms 1-R and 1-W. That is because active replied DARs increase the ND ratio. However, when $k$ becomes higher, H-W performs worse. That is because, according to Fig.3, when $k$ becomes higher, $p_{t,max}$ becomes lower, which means that most of the nodes are in *Listen* state. The probability for *response collision* becomes higher, degrading the performance of H-W. In Fig.4 (b), algorithms are compared by fixing $k$ at 20. This figure indicates the relationship between antenna beamwidth $\theta$ and $N_{slot}$. Generally speaking, for all the three algorithms, $N_{slot}$ decreases while $\theta$ increases. Specifically, H-W outperforms 1-R and 1-W when $\theta$ is narrow. That is because the possibilities for both *advertising* and *response collision* are low, and active replied DARs increase the ND ratio. When $\theta$ becomes wider, the higher possibility for *response collision* degrades the performance of H-W. In Fig.4 (c), we compare H-W/S with the other algorithms. Because each node falls into *Sleep* state during the ND operation, it is not surprising that H-W/S experiences longer ***ND process*** than the other algorithms.

### D. Simulations

#### 1) Simulation Validation

In order to validate the analytical model, we simulate H-W with the same assumptions proposed in the analytical model and only static network is concerned. The simulations with mobility consideration are encouraged in the future research. The analytical model is validated in both sparse (Fig.5(a)) and dense (Fig.5(b)) situations.

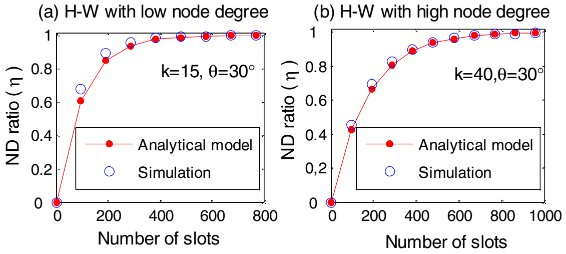

Fig. 5. Analytical results and simulation comparisons

#### 2) Implementation of ND Cycle Adaptation

In this section, we implement *ND cycle* adaptation in H-W and regard it as Improved H-W (I-HW). In a *ND cycle*, the number of transmitted DAs is controlled by the *Threshold Factor* $K$. The impacts of $K$ are shown in Fig.6, in which the expected number of frames $N_{frame}$ is related to ND time and is defined as $N_{frame} = N_{slot} / 2N_B$. Fig.6 (a) indicates the relation between $K$ and $N_{frame}$. The bigger the choice of $K$, the longer a ***ND process***. Fig.6 (b) indicates the corresponding ND ratio for different values of $K$.

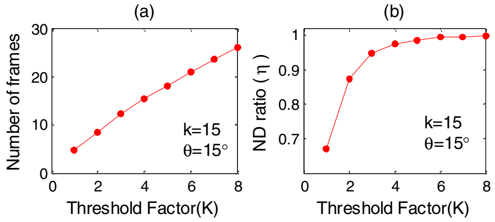

Fig.6. The impact of Threshold Factor ($K$) in I-HW

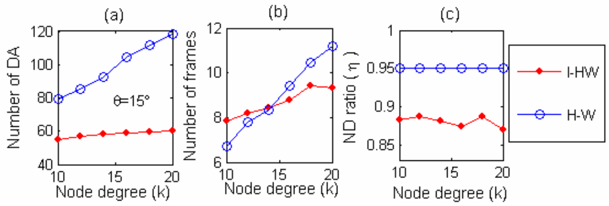

Fig. 7. Performance comparison between I-HW and H-W

The comparisons between H-W and I-HW are shown in Fig.7 by fixing θ at 15° and $K$ at 2. The total number of transmitted DA packets from a certain node in one ***ND process*** is denoted as $N_{DA}$, which is a parameter related to power consumption and protocol overhead. The relationship between node degree $k$ and $N_{DA}$ is plotted in Fig.7 (a), which indicates that I-HW sends out much less DA packets than H-W. This means that I-HW is more power-efficient and has lower protocol overhead. Fig.7 (b) indicates the relationship between node degree $k$ and $N_{frame}$. It shows that the $N_{frame}$ of I-HW is more tolerable to the change of node degree. From Fig.7(c) we can see that, for I-HW, ND ratio can achieve around 88% when $K$ is set to 2.

## IV. CONCLUSION

In this paper we have proposed a handshake-based Self-Adaptive D-ND protocol. The nodes in the network can adjust the frequency of neighbor discovery attempts and transmission directions of DA packets according to the network dynamics and ND operation feedback. Furthermore, we have provided an analytical method to model handshake-based D-ND protocols. According to the analytical model, three algorithms are compared to each other: One-way Random, One-way WIND and Handshake-based WIND. Our results indicated that the performance of Handshake-based WIND highly depends on the node degree and antenna beamwidth. By properly setting the system parameters, Handshake-based WIND can outperform One-way Random and One-way WIND. The analytical model is validated through simulations. Furthermore, we have implemented *ND cycle* adaptation in Handshake-based WIND. Simulation results indicate its power efficiency.

For future work, the study of higher layer management of antenna beamforming is an interesting research direction. Devices are expected to be able to automatically control the physical layer parameters according to the actual network situation. Furthermore, it is needed to investigate how the knowledge obtained from neighbor discovery processes can be efficiently used for topology control, MAC and routing protocols.

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