

# Alano: A Fast Neighbor Discovery Algorithm In An Energy-Restricted Large-Scale Network

**Abstract**—Neighbor discovery is a fundamental step in constructing wireless sensor networks and many algorithms have been proposed to minimize the latency of the implementation. Recent development of intelligent devices call for new algorithms, which are subject to energy restrictions. In energy-restricted large-scale networks, a node has limited power supply and can only discover nodes within its range. Additionally, the discovery process may fail if surplus communication exists on the wireless channel. These factors make neighbor discovery a very challenging task and only few of the proposed neighbor discovery algorithms can be applied to energy-restricted large-scale networks. In this paper, we propose Alano, a nearly optimal algorithm for a large-scale network on the basis of nodes' distributions. When nodes have same energy constraints, we modify Alano by Relaxed Difference Set (RDS), while we present a Traversing Pointer (TP) based Alano in case that the energy constraints are different. Besides, we compare Alano with the state-of-the-art algorithms through extensive evaluations, and the results show that Alano achieves at least 31.35% lower discovery latency and it has higher performance regarding quality (discovery rate) and scalability.

## I. INTRODUCTION

The popularity of Internet of Things (IoT) has drawn people's attention to wireless sensor networks [1], with a wide range of applications such as volcanic investigation [2], seismic detection [3], agriculture monitoring [4], etc.

Neighbor discovery is a fundamental step in constructing a wireless sensor network. In the task a node tends to discover its nearest neighbors before further processing like broadcasting and peer-to-peer communication. In this paper, we study it in an energy-restricted large-scale scenario, where nodes are aware of energy consumption and are connected via multi-hopping.

Despite extensive research, neighbor discovery in a large-scale network remains an open problem. The existing algorithms can be classified into two categories: deterministic, and probabilistic. On the one hand, the algorithms presented in Refs. [5]–[10], sensors take actions based on deterministic sequences. However, despite most deterministic algorithms being designed for two nodes only, they are applied to a multi-node scenario. On the other hand, probabilistic algorithms handle neighbor discovery in a clique of  $n$  nodes [11]–[14], i.e. every two nodes are neighbors, and utilize the global number  $n$  to compute an optimal probability for action decisions. However, a large-scale network is generally not a clique and nodes are subject to multi-hopping. In addition, prominent existing algorithms such as Birthday [11] and Aloha-like [12] do not consider energy consumption of the neighbor discovery process. Furthermore, in wireless

sensor networks, sensors are powered by battery and neighbor discovery will be constraint to energy limits.

To tackle these problems, we look into the existing neighbor discovery algorithms and find that the key issue lies in the way how collisions are dealt with in large-scale networks. This issue is due to three reasons. First, transmission signals fade with distance and simultaneous transmissions will cause collisions among various nodes. Deterministic algorithms aiming at two nodes [6], [9] fail to reduce such collisions. Some beacon-based algorithms [5], [7], [8], [10] do not have this problem but their time slot is 40 times larger [6] and still result in high latency. Second, a large-scale network is not one-hop connected and a node can only discover its neighbors within its range. Probabilistic algorithms [12]–[14] assuming a small clique network fail in estimating the number of neighbors, and thus can not reduced the collisions effectively since the number of neighbors plays a vital role in how many collisions will occur at the same time. Third, nodes are powered by limited energy and they typically try to find neighbors only for a fraction of time. Energy consumption and neighbor discovery quality are a paradox in existing algorithms, since collisions cause great energy consumption and if taken energy consumption into account, neighbor discovery may become even ineffective.

We conduct experiments for fundamental observation and confirm this issue. We deployed 16 EZ240 sensors [15] and found existing algorithms reduced collisions either insufficiently or excessively, both resulting in a high latency. As the number of neighbors increased, collisions of Hedis [9] happened as frequently as 10.1% to 19.96%, which called the CSMA [16] in MAC layer to wait for a random time. Hello [8] utilized beacon mechanism to avoid collisions but the time slot was 40 times larger and it resulted in 10 times higher latency. Aloha-like [13] showed a high idle rate (none of the neighbors are transmitting) as 18.92% of the time, which reduce the collisions excessively. That is, these algorithms could not achieve low latency and energy efficiency at the same time since they failed to deal with collisions effectively.

Our key idea is that, by estimating the expected number of neighbors of a node and synchronizing the time it turns on the radio with its neighbors, both low-latency and energy-efficiency for neighbor discovery can be achieved. We first take the distributions of nodes into consideration. As studied in [17], nodes in a wireless sensor network are likely to follow a uniform or a Gaussian distribution for detecting aims. According to the local density, a node can estimate the number of neighbors and calculate an optimal probability for action

decisions. Then based on this, we propose Alano, a nearly optimal probability based algorithm for a large-scale network. Finally, we involve the duty cycle mechanism [18], i.e. the fraction of time the radio is on (also called a sensor wakes up), and modify Alano by deterministic techniques to synchronize the wake-up time between neighbors. Specifically, if all nodes have the same (symmetric) duty cycle, such as a batch of sensors have a default duty cycle setting, we propose a Relaxed Difference Set based algorithm (called RDS-Alano); if nodes have different (asymmetric) duty cycles, such as a sensor adjusts the duty cycle by the remaining energy, we propose a Traversing Pointer based algorithm (called TP-Alano).

In simulations we have found Alano has 31.35% to 85.25% lower latency, higher discovery rate, and better scalability in large scale networks. In comparison to the state-of-the-art algorithms [7]–[9], [13] Alano reaches nearly 100% discovery rate twice as fast. When the number of nodes increases from 1000 to 9000, Alano shows 4.68 times to 6.51 times lower latency for neighbor discovery.

The contributions of the paper are summarized as follows:

- 1) We utilize the distribution of nodes and propose Alano, a nearly optimal algorithm that achieves low-latency neighbor discovery for a large-scale network;
- 2) In an energy-restricted large-scale network, we propose RDS-Alano for symmetric nodes and TP-Alano for asymmetric nodes. Both algorithms achieve low latency for discovering neighbors and can prolong node's lifetime;
- 3) We conduct experiments for fundamental observation and extensive simulations for large-scale networks. Alano achieves lower latency, higher discovery rate, and better scalability, which promises a potential scalability of IoT in the future work.

The remainder of the paper is organized as follows. The coming section highlights some related works and puts forward vital problems that the existing algorithms have. The system model and basic definitions are introduced in Section III. We present Alano and show the method to combine nodes' distribution in Section IV. We propose two modified algorithms (RDS-Alano, TP-Alano) for an energy-restricted large-scale network for both symmetric and asymmetric nodes in Section V. The extensive simulation results are shown in Section VI and we conclude the paper in Section VII.

## II. RELATED WORK

Existing neighbor discovery algorithms can be classified into two categories, deterministic algorithms and probabilistic algorithms.

Deterministic algorithms adopt certain mathematic tools to ensure discovery between every two neighbors. The first tool is called quorum system [19], [20]: for any two intersected quorums, two neighboring nodes could choose any quorum in the system to design the discovery schedule. Hedis [9] is a typical one. Another important tool is co-primality where two co-prime numbers are chosen by the neighbors to design the discovery schedule, and they can discover each other within a bounded latency by the Chinese Remainder Theorem [21].

Some representative algorithms are Disco [5], U-Connect [6], and Todis [9]. These algorithms hold an obvious advantage that they can guarantee fast discovery for two nodes within a bounded latency.

However, there are some weaknesses in these deterministic algorithms when they are applied to large-scale networks. Hedis [9] only assumes that when two nodes turn on the radio at the same time and then they find each other. However, in reality, neighbors play asymmetric roles that one is transmitting and the other is receiving. U-Connect [6] considers the transmitting and receiving roles. Nevertheless, different from the two-node scenario, collisions will happen when many nodes are transmitting simultaneously. Some deterministic algorithms propose a beacon-based transmission protocol. For example, Disco [5] assumes that a node has a capability to send a beacon (one or a few bits) at both the beginning and the end of an active time slot, and the assumption is adopted in SearchLight [7], Hello [8], and Nihao [10]. Under this assumption, the listening time slot is much larger than the transmitting time slot and collisions can be well avoided. Nevertheless, this mechanism makes a complete slot 40 times larger than that of U-Connect [6] and thus cannot promise an ideal discovery latency.

Another category is probabilistic algorithms [11]–[14] which utilize probability techniques to promote the randomness of discovering the neighbors. Birthday protocol [11] is one of the earliest algorithms that works on the birthday paradox, i.e. the probability that two people have the same birthday exceeds  $\frac{1}{2}$  among 23 people. Following that, smarter probabilistic algorithms are proposed, such as Aloha-like [12], [13], PND [14]. Particularly, Aloha-like [12] does not consider the energy consumption, which is later extended to an energy-restricted network by [13].

Unlike deterministic algorithms, probabilistic algorithms show a significant strength for a network consisting of multiple nodes. However, probabilistic algorithms only present an expectation discovery latency and they can not guarantee a good latency bound. In addition, most of the existing algorithms assume the network is a clique, which implies any two nodes are neighbors. This assumption can hardly depict a large-scale network due to the limited communication range of a node. Some work adopts the received signal strength to decide how far a node can transmit [22], and in the protocol model, it is simplified that two nodes can communicate if their distance is no larger than a threshold.

## III. PRELIMINARIES

In this section, we first describe the system model of an energy-restricted large-scale network. Then we formulate the Neighbor Discovery problem formally. The notations are listed in Table I.

### A. System Model

We introduce three important factors in an energy-restricted large-scale network.

TABLE I  
NOTATIONS FOR NEIGHBOR DISCOVERY

Notation	Description
$N$	The number of nodes in the network
$u_i$	Node $u_i$ with ID $i$
$\tilde{n}_i$	Node $u_i$ 's expected number of neighbors
$S_i$	The set of $u_i$ 's neighbors
$t_0$	The length of a time slot
$\delta_{ij}$	The transmission time drift between $u_i$ and $u_j$
$t_i^s$	The start time of node $u_i$
$L(i, j)$	The discovery latency that node $u_i$ discovers node $u_j$
$L(i)$	The discovery latency that node $u_i$ discovers all neighbors
$\theta$	The pre-defined global duty cycle
$\theta_i$	Node $u_i$ 's local duty cycle
$W$	The time slot spent by a node discovering all neighbors
$M$	Neighboring matrix, $M_{ij} = 1$ means $u_i$ and $u_j$ are neighbors

**Communication:** When multiple nodes communicate simultaneously, transmission may fail due to the communicational interference. We adopt the protocol model (also called graph model, unit-disk model [23], [24]) to describe the process, which assumes a node  $u_i$  can receive  $u_j$ 's message successfully if  $u_j$  is the only transmitter that is within  $u_i$ 's communication range. The protocol model is a popular one that enables the development of efficient algorithms for crucial networking problems. Some other models, such as the signal to interference plus noise ratio (SINR) model, are more complicated and lack good algorithmic features. In addition, it is shown that these models can be transformed to the protocol model by particular means in [25], [26].

**Network connectivity:** A node can only discover nodes that are within its range under the protocol model. In a large-scale network, two nodes may not be connected directly and we call two nodes connected by one-hop communication as *neighbors*.

**Energy-restricted:** A node in the network has limited energy, and can turn on or off its radio to save energy [18], [27]. When a node turns on the radio, it can transmit a message including its identifier (ID), or listen on the channel to receive a neighbor's message.

Technically speaking, we assume an energy-restricted large-scale network consisting of  $N$  nodes as set  $U = \{u_1, u_2, \dots, u_N\}$ . Nodes are distributed in a large area and they can communicate through a fixed wireless channel. We assume the locations of the nodes obey some distributions, such as uniform distributions and Gaussian distribution [17]. Suppose a node has a fixed communication range  $\Delta$  and two nodes  $u_i, u_j$  are neighbors if their distance suits  $d(u_i, u_j) \leq \Delta$ . We can use a symmetric matrix  $M_{N \times N}$  to represent nodes' neighboring relations as:

$$M_{i,j} = \begin{cases} 1 & u_i \text{ and } u_j \text{ are neighbors} \\ 0 & \text{otherwise} \end{cases}$$

Suppose time is divided into slots of equal length  $t_0$  [28], which is sufficient to finish a complete communication process (one node transmits a message including its ID and a neighbor

receives the message). A node who turns its radio on can choose to be transmitting state or listening state:

- **Transmitting state:** a node transmits (broadcasts) a package containing its ID on the channel;
- **Listening state:** a node listens on the channel to receive messages from neighbors.

In the protocol model, a node  $u_i$  can discover its neighbor  $u_j$  in time slot  $t$  if and only if  $u_j$  is the only neighbor of  $u_i$  that transmits and  $u_i$  listens in the slot.

A node has limited energy and it has to turn off the radio to save energy for most of the time. We assume a *duty schedule* for a node  $u_i$  is a pre-define sequence  $S_i = \{s_i(t)\}_{0 \leq t < T}$  of period  $T$ , in which

$$s_i^t = \begin{cases} S & u_i \text{ turns off the radio in slot } t \\ T & u_i \text{ is in transmitting state in slot } t \\ L & u_i \text{ is in listening state in slot } t \end{cases}$$

*duty cycle* is defined as the fraction of time a node turns its radio on, which is formulated as:

$$\theta_i = \frac{|\{t : 0 \leq t < T, s_i(t) \in \{T, L\}\}|}{T}.$$

If all nodes have the same duty cycle all the time, i.e.  $\theta_i = \theta_j$  for any nodes  $u_i, u_j$ , we call them *symmetric nodes*. Otherwise, they are *asymmetric nodes*. Denote the start time of node  $u_i$  as  $t_i^s$  and denote  $\delta_{ij}$  as the time drift between a pair of neighbors  $u_i, u_j$ , i.e.  $\delta_{ij} = t_i^s - t_j^s$ .

### B. Problem Definition

A node  $u_i$  executes operations (turning off radio, transmitting, or listening) according to the pre-defined duty schedule  $S_i$ . When  $u_i$  starts the neighbor discovery process, denote  $L(i, j)$  as the slot cost to find the neighbor  $u_j$  and we define **discovery latency** of node  $u_i$  as the time to discover all neighbors:

$$L(i) = \max_{j: M_{i,j}=1} L(i, j).$$

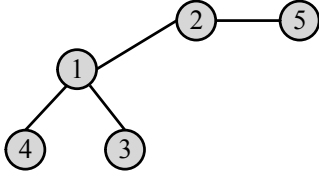
It is to be noted that, neighbor discovery is not bidirectional and any pair of neighbors have to discover each other separately. We formulate the neighbor discovery problem for node  $u_i$  as:

**Problem 1:** For a node  $u_i$  and the set of its neighbors  $S_i = \{u_j | d(u_i, u_j) \leq \Delta\}$ , design duty schedules for all nodes such that:  $\forall u_j \in S_i$  :

$\exists t$  s.t. :

$$s_i(t) = L, s_j(t) = T, \text{ and } \forall u_k \in S_i, u_k \neq j : s_k(t) \in \{L, S\}.$$

Fig.1 shows an example of 5 nodes, the topology is depicted in Fig.1(a), and Fig.1(b) describes the neighbor discovery process. The duty cycle is set as 0.25 and nodes start in different time slots. The designed duty schedule for node  $u_1$  is  $S_1 = \{T, S, S, S, S, S, T, S, S, T, S, S, S, T, \dots\}$ . Suppose time drift between node  $u_1$  and  $u_4$  is  $\delta_{14} = 1$ ;  $u_1$   $u_2$  start in the same time slot. In slot 12, node  $u_5$  discovers neighbor  $u_2$ , but node  $u_1$  cannot discover  $u_2$  since another neighbor  $u_3$  is in transmitting state simultaneously.



(a) The topology of a simple wireless network

Time	...	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	...
Node 1			T	S	S	S	S	S	L	S	S	L	S	S	S	T	...
Node 2			S	S	L	S	S	S	T	S	L	S	S	S	S	L	...
Node 3	...	S	S	S	T	S	S	S	T	S	L	S	S	S	L	S	...
Node 4				S	S	S	S	S	S	S	S	T	T	T	T	T	...
Node 5						S	S	L	S	S	S	T	S	S	S	...	

(b) Neighbor discovery process

Fig. 1. An example of neighbor discovering process. S, T and L represents Sleep pattern, Transmitting state and Listening state in wake-up pattern respectively.

#### IV. ALANO ALGORITHM FOR A LARGE-SCALE NETWORK

In large-scale networks, nodes are not fully-connected and thus communications may fail due to concurrent transmissions. When we do not consider the energy constraints of nodes, we propose a nearly optimal algorithm for a large-scale network, which implies  $\theta_i = 1$  for all node  $u_i$ . Suppose the locations of nodes obey some distribution, we propose Alano algorithm and analyze its performance for two common used distribution (uniform distribution and Gaussian distribution).

##### A. Alano Algorithm

Suppose the locations of nodes obey some distribution and each node  $u_i$  is aware of its position coordinates  $(x_i, y_i)$ . Then  $u_i$  could compute its local density by the following general function:

$$f(x, y) = \begin{cases} \varphi(x, y) & (x, y) \in D \\ 0 & (x, y) \notin D \end{cases}$$

where  $(x, y)$  is a position coordinate, and  $D$  is the network covering area. Denote the range of  $u_i$ 's neighbors' positions as  $R_i$ , and any neighbor with coordinates  $(x, y) \in R_i$  suits:

$$(x - x_i)^2 + (y - y_i)^2 \leq \Delta^2.$$

where  $\Delta$  is the communication range. Then, node  $u_i$ 's expected number of neighbors (denote as  $\tilde{n}_i$ ) is:

$$\tilde{n}_i = N \iint_{R_i} f(x, y) dx dy - 1.$$

In a large-scale network, we ignore the boundary area of the network. Note that, when the network covering area  $D$  is much larger than the area  $R_i$  of node  $u_i$ , we have:

$$\tilde{n}_i \simeq N\pi\Delta^2\varphi(x_i, y_i). \quad (1)$$

We present **Alano**, a randomized algorithm for node  $u_i$  in Alg. 1. By computing the expected number of nodes,  $u_i$  turn

##### Algorithm 1 Alano Algorithm

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1: Set transmit probability  $p_t^i := \frac{1}{\tilde{n}_i+1}$ ,  $t := 0$ ;
2: while  $t \leq T$  do
3:   Generate a random number  $\epsilon \in (0, 1)$ ;
4:   if  $\epsilon < p_t$  then
5:     Transmit a message containing  $u_i$ 's information
       including its ID through the channel;
6:   else
7:     Listen on the channel. If receive a message
       successfully, decode the message and record the
       sender's ID;
8:   end if
9:    $t := t + 1$ ;
10: end while

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to be in transmitting state or listening state according to the generated probability in Line 1.

In the following parts, we first consider a general situation that nodes in the network are uniform distributed. We derive a proof that the probability chosen in Alano is the optimal one and show the discovery latency will not be much larger than its expectation.  $T$  in Alg. 1 Line 2 is the time threshold and can be set as the latency bound. Then we analyze a more common situation that nodes obey Gaussian Distribution, we present an approximation analysis that the discovery latency is not much larger than that of uniform distribution.

##### B. Analysis for Uniform Distribution

Uniform distribution is basically used in deployment of wireless networks. For instance, to monitor an unknown area, many sensors are deployed uniformly to collect information, such as temperature and humidity [29]. The nodes are evenly deployed and the density function is:

$$f(x) = \begin{cases} \frac{1}{A} & (x, y) \in D \\ 0 & (x, y) \notin D \end{cases}$$

where  $A$  is the area of  $D$ . By Eqn. (1),  $u_i$ 's expected number of neighbors is  $\tilde{n}_i = \frac{N\pi\Delta^2}{A}$  and the probability in Line 2 is set as  $p_t^i = \frac{1}{\tilde{n}_i+1} = \frac{A}{N\pi\Delta^2+A}$ .

**Lemma 1:** Alg. 1 achieves optimal discovery latency for uniform distribution by setting  $p_t^i = \frac{1}{\tilde{n}_i+1}$ .

**Proof:** For any two nodes  $u_i$  and  $u_j$  in the uniform distribution, we get  $\tilde{n}_i = \tilde{n}_j = \tilde{n}$  and  $p_t^i = p_t^j = p_t = \frac{1}{\tilde{n}+1}$ .

From Alg. 1, the probability that node  $u_i$  discovers a specific neighbor (such as  $u_j$ ) successfully in a time slot (denote as  $p_s$ ) is:

$$p_s = p_t(1 - p_t)^{\tilde{n}-1}(1 - p_t).$$

In order to compute the maximum probability to discover a node, we compute the differential function of  $p_s$  as:

$$\frac{d(p_s)}{d(p_t)} = (1 - p_t)^{\tilde{n}} - \tilde{n}p_t(1 - p_t)^{\tilde{n}-1}.$$

It is easy to verify that when  $p_t = \frac{1}{\tilde{n}+1}$ ,  $p_s$  gets the maximum value:

$$p_s = \frac{1}{\tilde{n}+1} \left(1 - \frac{1}{\tilde{n}+1}\right)^{\tilde{n}} \approx \frac{1}{(\tilde{n}+1)e}.$$

Therefore, the probability chosen in Alano algorithm for transmitting is optimal. ■

*Theorem 1:* Alg. 1 discovers all neighbors for node  $u_i$  within  $T = \Theta(n \ln n)$  time slots with high probability.

*Proof:* First, we show that the expected discovery latency of a node  $u_i$  is bounded by  $O(n \ln n)$ .

Let  $W$  be a random variable that denotes the time a node spends discovering all neighbors. Denote  $W_j$  as a random variable representing the cost number of the time slots to discover a new neighbor after  $j-1$  neighbors have been discovered. It is easy to check that  $W_j$  follows Geometric distribution with parameter  $p(j)$  where  $p(j) = (\tilde{n} - j + 1)p_s$  [30]. The expectation of  $W_j$  can be computed as:

$$E[W_j] = \frac{1}{p(j)} = \frac{1}{(\tilde{n} - j + 1)p_s}.$$

Then, the expectation discovery latency of node  $u_i$  is:

$$E[W] = \sum_{j=1}^{\tilde{n}} E[W_j] \approx (\tilde{n}+1)e(\ln(\tilde{n}+1) + \Theta(1)) = \Theta(n \ln n).$$

Thus the expected discovery latency is bounded by  $O(n \ln n)$ .

Then, we show that node  $u_i$  can discovery all neighbors bounded by  $O(n \ln n)$  time slots.

Since  $W_j$  follows Geometric distribution,  $\text{Var}[W_j] = \frac{1-p_j}{p_j^2}$ , and the variance of discovery latency of  $W$  is computed as:

$$\text{Var}[W] = \sum_{j=1}^n \text{Var}[W_j] \leq \frac{\pi^2}{6p_s^2} - \frac{H_n}{p_s}.$$

By *Chebyshev's inequality*, the probability that the discovery latency is 2 times larger than the expectation is

$$P[W \geq 2E[W]] \leq \frac{\text{Var}[W]}{E[W]^2} \leq \frac{\pi^2}{6H_n^2} - \frac{p_s}{H_n}.$$

where  $H_n$  is the  $n$ -th Harmonic number, i.e.,  $H_n = \ln n + \Theta(1)$ . For a large  $n$ ,  $P[W \geq 2E[W]]$  is close to 0. That is, the time for a node to discover all neighbors is very likely to be smaller than 2 times of the expectation. Therefore,  $W$  is also bounded by  $O(n \ln n)$  with high probability. ■

### C. Analysis of Gaussian Distribution

Gaussian distribution is commonly adopted in wireless network. For instance, an intrusion detection application needs larger detection probability around important entities [17]. We assume the positions of nodes obey 2D Gaussian distribution, and we present a theoretical proof that the discovery latency is not much larger than that of uniform distribution. Without loss of generality, we consider  $(x, y) \sim N(0, 1, 0, 1, 0)$ .

*Theorem 2:* Alg. 1 discovers all neighbors for node  $u_i$  within  $T = \Theta(n \ln n)$  time slots with high probability.

*Proof:* Denote the approximate neighbors of node  $u_i$  as set  $S_i = \{u_j | d(u_i, u_j) \leq \Delta\}$ . When nodes obey Gaussian

distribution, the probability that node  $u_i$  discovers a certain neighbor node  $u_j$  successfully in a time slot (denote as  $p_s$ ) can be formulated as:

$$p_s^i = (1 - p_t^i) \cdot p_t^j \cdot \prod_{u_j \in S_i, u_j \neq u_k} (1 - p_t^k).$$

Denote  $p_t^{\max} = \max_{u_j \in S_i} \{p_t^j\}$ ,  $p_t^{\min} = \min_{u_j \in S_i} \{p_t^j\}$ , for every  $u_j \in S_i$ , we have:

$$(1 - p_t^i) p_t^{\min} (1 - p_t^{\max})^{\tilde{n}_i - 1} \leq p_s^i, \\ p_s^i \leq (1 - p_t^i) p_t^{\max} (1 - p_t^{\min})^{\tilde{n}_i - 1}.$$

Denote:

$$P = (1 - p_t^i) p_t^{\min} (1 - p_t^{\max})^{\tilde{n}_i - 1}, \\ Q = (1 - p_t^i) p_t^{\max} (1 - p_t^{\min})^{\tilde{n}_i - 1}.$$

We derive the expectation of  $W_j$  for  $1 \leq j \leq n_i$  as:

$$\frac{1}{(\tilde{n}_i - j + 1)Q} \leq E[W_j] \leq \frac{1}{(\tilde{n}_i - j + 1)P}.$$

Combine the equations to derive:

$$\frac{1}{Q} H_n \leq E\left[\sum_{j=1}^{\tilde{n}_i} W_j\right] \leq \frac{1}{P} H_n.$$

Since:  $p_t^{\min} = \frac{1}{\tilde{n}_{\max}+1}$ ,  $p_t^{\max} = \frac{1}{\tilde{n}_{\min}+1}$ , where  $\tilde{n}_{\max} = \max\{\tilde{n}_j | u_j \in S_i\}$ ,  $\tilde{n}_{\min} = \min\{\tilde{n}_j | u_j \in S_i\}$ .

And  $\tilde{n}_{\max}$ ,  $\tilde{n}_{\min}$  can be computed as follows:

$$\tilde{n}_i \simeq N\pi\Delta^2 \frac{1}{2\pi} e^{-\frac{x_i^2 + y_i^2}{2}}, \\ \tilde{n}_{\max} \simeq N\pi\Delta^2 \frac{1}{2\pi} e^{-\frac{(\sqrt{x_i^2 + y_i^2} - \Delta)^2}{2}} = \alpha \tilde{n}_i, \\ \tilde{n}_{\min} \simeq N\pi\Delta^2 \frac{1}{2\pi} e^{-\frac{(\sqrt{x_i^2 + y_i^2} + \Delta)^2}{2}} = \beta \tilde{n}_i.$$

where  $\alpha = e^{\frac{2\Delta\sqrt{x_i^2 + y_i^2} - \Delta^2}{2}}$ ,  $\beta = e^{-\frac{2\Delta\sqrt{x_i^2 + y_i^2} + \Delta^2}{2}}$ , both of which can be seen as constants. Therefore we get:

$$\frac{1}{Q} H_n \simeq \beta e^{\frac{1}{\alpha}} n \ln n, \quad \frac{1}{P} H_n \simeq \alpha e^{\frac{1}{\beta}} n \ln n.$$

Thus  $E[W]$  can be bounded within  $O(n \ln n)$  time slots with high probability. Similarly the bounded latency can be proved to be  $W = O(n \ln n)$  by *Chebyshev's inequality* in the same way as uniform distribution. ■

### V. MODIFIED ALANO FOR AN ENERGY-RESTRICTED NETWORK

In an energy-restricted network, nodes have limited energy and designing duty schedule for a node needs to take its duty cycle into account. Obviously, a lower duty cycle implies a larger discovery latency since the node turns its radio off for more time during the schedule.

In the preceding section, energy constraint is not a crucial factor in Alano; and we are to modify Alano for both symmetric nodes and asymmetric nodes. Our key idea is to synchronize the slots that the radio is on with the neighbors in a bounded time; then invoke Alano algorithm to achieve low-latency neighbor discovery.

### A. RDS-Alano for Symmetric Nodes

Symmetric nodes have the same duty cycle  $\theta_i = \theta_j = \theta$ ,  $\forall u_i, u_j$ . We utilize Relax Difference Set (RDS) to synchronize time slots that nodes are in transmitting or listening state.

RDS is an efficient tool to construct cyclic quorum systems [19], [20]. The definition is:

*Definition 1:* A set  $R = \{a_1, a_2, \dots, a_k\} \subseteq Z_n$  (the set of all non-negative integers less than  $n$ ) is called a RDS if for every  $d \neq 0 \pmod{n}$ , there exists at least one ordered pair  $(a_i, a_j)$  such that  $a_i - a_j \equiv d \pmod{n}$ , where  $a_i, a_j \in R$ .

It has been proved that any RDS must have cardinality  $|R| \geq \sqrt{N}$  [20]. We present a linear algorithm to construct a RDS with cardinality  $\lceil \frac{3\sqrt{N}}{2} \rceil$  under  $Z_N$  in Alg. 2.

---

#### Algorithm 2 RDS construction under $Z_N$

---

```

1:  $R := \emptyset$ ;  $\lambda := \lceil \sqrt{N} \rceil$ ;  $\mu := \lceil \frac{\lceil \sqrt{N} \rceil}{2} \rceil$ ;
2: for  $i = 1 : \lambda$  do
3:    $R := R \cup i$ ;
4: end for
5: for  $j = 1 : \mu$  do
6:    $R := R \cup (1 + j * \lambda)$ ;
7: end for
```

---

We show the correctness of the construction formally.

*Lemma 2:* Set  $R = \{r_0, r_1, \dots, r_{\lambda+\mu-1}\}$  constructed in Alg. 2 is a RDS, where  $|R| = \lambda + \mu = \lceil \sqrt{N} \rceil + \lceil \frac{\lceil \sqrt{N} \rceil}{2} \rceil \approx \lceil \frac{3\sqrt{N}}{2} \rceil$ .

*Proof:* Obviously, if there exists one ordered pair  $(a_i, a_j)$  satisfying  $a_i - a_j \equiv d \pmod{N}$ , an opposing pair  $(a_j, a_i)$  exists such that  $a_j - a_i \equiv (N - d) \pmod{N}$ . Thus we only need to find at least one ordered pair  $(a_i, a_j)$  for each  $d \in [1, \lfloor N/2 \rfloor]$ .

In the construction,  $\lambda$  in Line 1 is the smallest integer satisfying  $\lambda^2 \geq N$ . Every  $d$  within range  $[1, \lfloor N/2 \rfloor]$  can be represented as:  $d = 1 + j \times \lambda - i$ , where  $1 \leq j \leq \mu$ ,  $1 \leq i \leq \lambda$ . Thus, there exists  $a_j = 1 + j \times \lambda$  from Line. 3 and  $a_i = i$  from Line. 6 satisfying  $a_j - a_i \equiv d$ . Then, the lemma can be derived. ■

For symmetric nodes with duty cycle  $\theta$ , we present a RDS based Alano (RDS-Alano) algorithm as Alg. 3.

In Alg. 3, RDS is used to construct a deterministic schedule for a node to turn on its radio in every period of length  $T$ , and Alano is utilized as a probabilistic strategy to determine whether it is in transmitting state or listening state.

We derive discovery latency bound for RDS-Alano:

*Theorem 3:* RDS-Alano guarantees that the discovery latency of a node is bounded within  $O(\frac{n \log n}{\theta^2})$  with high probability.

*Proof:* First, we verify that the duty cycle in RDS-Alano (denote as  $\tilde{\theta}$ ) is

$$\tilde{\theta} = \frac{|RDS|}{|T|} = \frac{\lceil \frac{3\sqrt{T}}{2} \rceil}{T} = \theta.$$

For any pair of neighbor nodes  $(u_i, u_j)$ , we can find an ordered pair  $(r_i, r_j)$  from their respective RDS such that  $r_i - r_j \equiv \delta_{ij} \pmod{T}$ , where  $\delta_{ij}$  is the time drift. This implies any

---

#### Algorithm 3 RDS Based Alano Algorithm

---

```

1:  $T := \lceil \frac{9}{4\theta^2} \rceil$ ;  $t := 0$ ;
2: Invoke Alg. 2 to construct the RDS  $R = r_0, r_1, \dots, r_{\lceil \frac{3\sqrt{T}}{2} \rceil}$  under  $Z_T$ ;
3: while True do
4:   if  $(t + 1) \in R$  then
5:     Invoke Alg. 1 to determine transmission state;
6:   else
7:     Sleep;
8:   end if
9:    $t := (t + 1) \% T$ ;
10: end while
```

---

neighbor nodes can turn on their radios in the same time slot for at least once during every period of length  $T$ . Considering each period of  $T$  time slots to be a ‘super’ slot of Alano algorithm, we can derive that the discovery latency is bounded within  $O(\frac{n \ln n}{\theta^2})$  slots with high probability by combining the analysis of Alano. ■

*Remark 1:* In a RDS, a node can discovery its neighbors in different time slots. When treating a period of  $T$  as a ‘super’ slot of Alano, there may be less than the total neighbors in each wake-up sub-slot, resulting less collisions and lower latency compared to when all the neighbors wake up in the same sub-slot. Thus the latency bound can not be larger.

### B. TP-Alano for Asymmetric Nodes

Considering a more practical network where nodes can adjust their duty cycles, we present a traversing pointer method to synchronize time slots that nodes are in transmitting or listening state for asymmetric nodes.

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#### Algorithm 4 Traversing Pointer Based Alano Algorithm

---

```

1:  $T :=$  the smallest prime no less than  $\frac{2}{\theta_i}$ ;  $t := 0$ ;
2: while True do
3:    $t_1 := t \% T$ ;
4:    $t_2 := \lfloor t/T \rfloor \% (T - 1) + 1$ ;
5:   if  $t_1 = 0$  or  $t_1 = t_2$  then
6:     Invoke Alg. 1 to determine transmission state;
7:   else
8:     Sleep;
9:   end if
10:   $t := t + 1$ ;
11: end while
```

---

For a more practical scenario, the nodes in a wireless sensor networks for instance, are assigned to diverse tasks such as temperature measurement, sunshine collection, etc., and thus ought to have asymmetric capability of battery-management with local duty cycle  $\theta_i$ .

Suppose the duty cycle of node  $u_i$  is  $\theta_i$ , we present a traversing pointer based Alano (TP-Alano) algorithm as Alg. 4. In each period of  $T$  slots, a node turns on its radio in two different time slots, one of which is the first slot of each period

and the other one is a traversing slot that changes from period to period (as described in Line. 4).

We call the first time slot of each period as *fixed pointer* and the traversing slot as *traversing point*. The pointers are designed to guarantee that nodes  $u_i, u_j$  could turn on their radio simultaneously in very period of length  $T_i T_j$ . A sketch of the pointers is described in Fig. 2.

Note that, a period of  $T$  slots is constructed as Line 1 where we try to find the smallest prime  $\geq \frac{2}{\theta_i}$ , then it is likely to make the duty cycle of each period smaller than the expected one. This can be easily solved by selecting some random slots to turn on the radio for listening in each period  $T$ , to conform to the expected duty cycle.

Time slot in each period	0	1	2	3	...	T-1
Period 0	W	W	S	S	S	S
Period 1	W	S	W	S	S	S
...					...	
Period T-1	W	S	S	S	S	W
Period T	W	W	S	S	S	S
...					...	

Fixed Pointer
  Traversing Pointer
  S-Sleep
  W-Wake up

Fig. 2. A sketch of TP construction in Alg. 4

We show the discovery latency of TP-Alano algorithm as:

**Theorem 4:** TP-Alano guarantees that the discovery latency  $L(i, j)$  is bounded within  $O(\frac{n \log n}{\theta_i \theta_j})$  with high probability., where  $\theta_i$  and  $\theta_j$  are the duty cycles of a pair of neighbors  $(u_i, u_j)$  respectively.

*Proof:* We first prove that any pair of nodes  $(u_i, u_j)$  turn on their radios (for transmitting or listening) simultaneously for at least once in every period of length  $T_i T_j$ .

**Case 1:**  $T_i \neq T_j$ . Since  $T_i$  and  $T_j$  are different primes, according to Chinese Remainder Theorem [21], there exists a time slot  $t_\tau \in [0, T_i T_j)$  satisfying:

$$0 = t_\tau \mod T_i. \quad (2)$$

$$\delta_{ij} = t_\tau \mod T_j. \quad (3)$$

Thus, there exists a fixed pointer of node  $u_i$  and a fixed pointer of node  $u_j$  in which both nodes turn on the radios in every period of length  $T_i T_j$ .

**Case 2:**  $T_i = T_j$ . Since  $T_i = T_j = T$ , if the time drift between  $u_i$  and  $u_j$  is  $\delta_{ij} = 0$ , the fixed pointers of  $u_i$  and  $u_j$  will be the same in every period of length  $T$ . Otherwise, since the traversing point will traverse all the time slots once during period of length  $(T - 1)T$ , there exists a traversing point of  $u_i$  and a fixed pointer of  $u_j$  satisfying that both nodes turn on the radios simultaneously in every period of length  $(T - 1)T$ ; similarly a traversing point of  $u_j$  and a fixed pointer of  $i$  satisfying that they both turn on the radios.

Thus for any pair of neighbor nodes  $(u_i, u_j)$ , they turn on their radios for transmitting or listening for at least once

in every period of length  $T_i T_j$ . Considering the whole period  $T_i T_j$  to be a ‘super’ slot of Alano, we derive that the discovery latency is bounded within  $O(\frac{n \ln n}{\theta_i \theta_j})$  with high probability. ■

## VI. EVALUATION

In this section, we experimentally verify our basic analysis. Then we evaluate the algorithms in simulated large-scale networks.

### A. Experiments for Fundamental Observation

In our experiments, we implemented 16 EZ240 sensors [15], each of which uses 8MHz MSP430F1611 as the microprocessor and is equipped with 10K RAM, 48K ROM and 1 M Flash. CC2420 is used as the communication module with the IEEE 802.15.4 protocol. RTIMER\_ARCH\_CECOND is the clock frequency and a time slot is set as  $500/\text{RTIMER\_ARCH\_CECOND}$ , which is around 0.5ms in the real world. As discussed in section II, the time slot of beacon-based algorithms, e.g. searchlight [7], is set as 20ms. From the code in MAC layer we can see that CSMA mechanism makes the process to wait a random time when a collision happens, which implies that collisions result in a high latency.

TABLE II  
EXPERIMENTAL RESULTS OF DISCOVERY LATENCY. ALANO HAS 30.81% TO 87.31% LOWER LATENCY ON AVERAGE.

Algorithms	Alano	Hedis	Searchlight	ALOHA
Average latency	1.278	1.847	8.58	10.07
Maximum latency	1.52	3.11	10.11	16.13
Minimum latency	1.10	0.73	6.31	5.11

We compared Alano with Searchlight [7], Hedis [9] and Aloha-like [13] in the experiments. The result in the Table II shows that Alano outperforms the other algorithms. Hedis shows a low latency which results from it’s ideal latency bound for two nodes, and its weakness of handling collisions is not obvious in a small-scale network. However, as the number of neighbors increased, collisions of Hedis [9] happened as frequently as 10.1% to 19.96%. Searchlight is a typical beacon-based algorithm with larger time slots, which results in a high latency. Aloha-like is designed for a clique network and the probability adopted is not optimal.

### B. Simulations for energy-restricted Large-scale Networks

To simulate a large-scale network, we implemented Alano in C++ and evaluated the algorithms in a cluster of 9 servers, each equipped with an Intel Xeon 2.6GHz CPU with 24 hyper-threading cores, 64GB memory and 1T SSD.

We simulated a network that follows uniform distribution and Gaussian distribution respectively. For uniform distribution, we suppose 500 nodes are distributed in an area of  $100m \times 100m$  and each node’s communication range is  $\Delta = 10m$ . For Gaussian distribution, we suppose 1000 nodes are distributed in the same area, but each node’s communication range is  $\Delta = 5m$ . We set the Gaussian distribution to  $N(50, 15^2)$  in our evaluation. We set the duty cycle of a



node to be 0.1 for symmetric nodes; for asymmetric nodes, we set their duty cycle randomly from 0.05 to 0.15 with step 0.02. These settings make the network more complicated and realistic than that in [6]–[9], [11]–[14], [31].

We evaluated Alano, Aloha-like [13], Hello [8], Hedis [9], and Searchlight [7] in the generated networks. Since the neighbor discovery process will be stopped by CSMA after several failures, we set a latency threshold. Hello and Searchlight has a beacon transmission of  $0.54ms$  at the beginning and end of each slot, and a beacon makes up about  $1/40$  of a slot, so we divide each  $\{ON\}$  slot into 40 mini-slots, and the node transmits at the first and last mini-slot, and listens in other mini-slots. In the following parts, we show that Alano has lower latency, higher discovery rate, and better scalability.

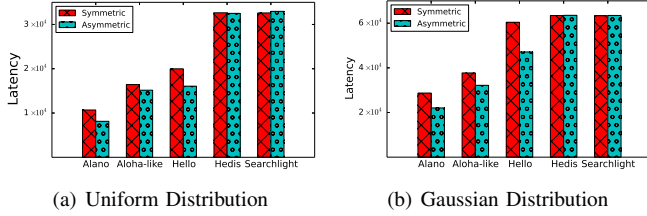


Fig. 3. Alano achieves 31.35% to 2.91 times lower latency.

1) *Speed-Discovery Latency*: When nodes follow uniform distribution, we show the discovery latency comparison for both symmetric nodes and asymmetric nodes in Fig. 3(a). From the figure, Alano achieves 54.64% to 1.95 times lower discovery latency for symmetric nodes, and 85.25% to 2.91 times lower discovery latency for asymmetric nodes. When nodes follow Gaussian distribution, as depicted in Fig. 3(b), Alano achieves 31.35% to 1.21 times lower discovery latency for symmetric nodes, and 45.94% to 1.88 times lower discovery latency for asymmetric nodes. The deterministic algorithms, Hello, Hedis and Searchlight, have high latency due to either collisions or larger time slots.

2) *Quality-Discovery Rate*: We use discovery rate to evaluate Alano's quality. Discovery rate of a node  $u_i$  is defined as the percentage of discovered neighbors over  $u_i$ 's all neighbors. In Fig. 4, we increase the number of nodes from 500 to 2000 for the uniform distribution, and increase the number of nodes from 1000 to 3000 for the Gaussian distribution, the results show that Alano has higher discovery rate during the whole process for both uniform and Gaussian distributions. In the uniform distribution, Alano achieves 90% discovery rate twice as fast as Aloha-like. It's remarkable that, the performance of Aloha-like is close to Alano in the Gaussian distribution. This is because a number of nodes gather around the center area which makes the network similar to a clique, and thus Aloha-like shows its strength.

3) *Scalability-Duty Cycle and Network Density*: We evaluated Alano's scalability regarding duty cycle and network density.

*Duty Cycle*. When symmetric nodes with different duty cycles, Fig. 5 shows that Alano has lower latency. Compared with Aloha, Alano has from 53.66% to 11.23 times lower

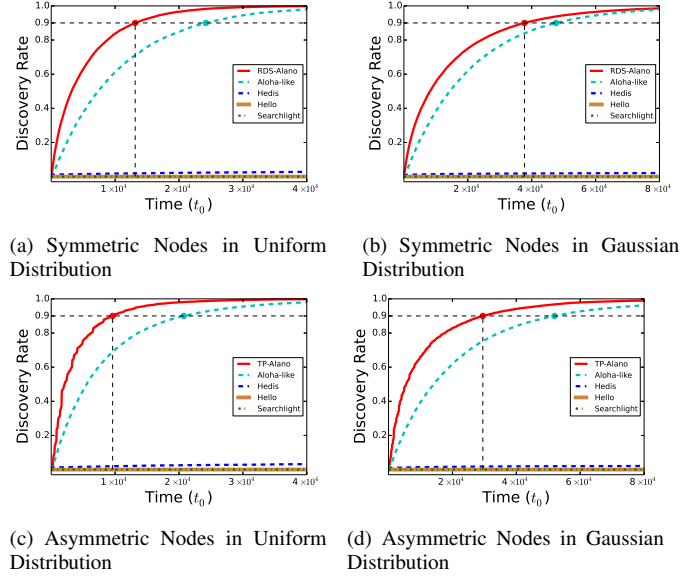


Fig. 4. Alano has higher discovery rate during the whole process for both uniform and Gaussian distributions.

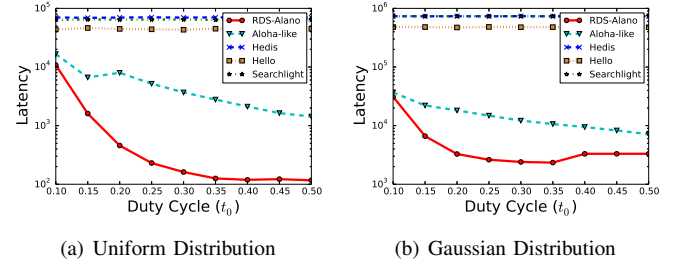


Fig. 5. Alano achieves 53.66% to 11.23 times lower latency in different duty cycle.

latency. The latency of Alano and Aloha generally decreases as the duty cycle increases, while Hello, Hedis and Searchlight have high latency due to the collision. In Gaussian distribution, Alano has a small twist with duty cycle 0.35, because when the duty cycle increases, nodes are more likely to transmit and therefore collide.

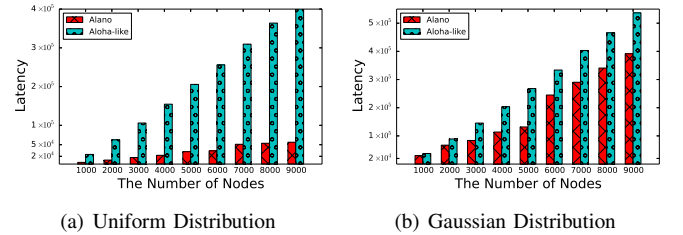


Fig. 6. Alano achieves 25.23% times to 6.51 times lower latency when the network becomes denser.

*Network Density*. When the number of nodes increases, the network becomes denser. We choose Aloha-like algorithm for comparison because Hello, Hedis and Searchlight already have higher latency than Aloha-like when there are 500 nodes in uniform distribution and 1000 nodes in Gaussian distribution.



As shown in Fig. 6(a), Alano achieves 4.68 times to 6.51 times lower discovery latency than Aloha-like algorithm for uniform distribution, when the number of nodes increases from 1000 to 9000. When the number of nodes increases from 1000 to 9000 for Gaussian distribution, Alano achieves 25.23% to 1.03 times lower discovery latency as shown in Fig. 6(b).

## VII. CONCLUSION

In this paper, we systematically study the process of neighbor discovery in an energy-restricted large-scale network. To begin with, we propose Alano for a large-scale network where nodes' distribution is utilized to decide a node's transmitting probability. For different distributions, such as uniform distribution and normal distribution, we show that Alano achieves nearly optimal discovery latency. Then, we propose two modified methods for an energy-restricted network on the basis of different duty cycle mechanisms: Relaxed Different Set based Alano (RDS-Alano) for symmetric nodes and Traversing Pointer based Alano (TP-Alano) for asymmetric nodes. We conduct extensive simulations to compare Alano with the state-of-the-art algorithms, the results show that Alano achieves better performance regarding discovery latency, discovery rate, and scalability.

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