Alano: May You Discover Your Neighbors

***Abstract*—The abstract goes here.**

I. Introduction

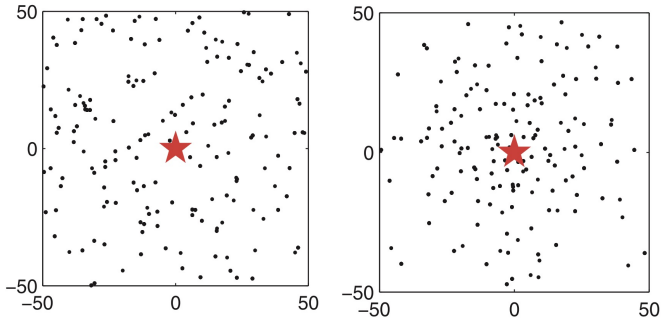
Information and Communication Technology (ICT) equipment [1] has exploded on the scene in the last twenty years, leading to an obvious ascent of Internet-of-Things [2], such as wireless sensor networks[], mobile campus networks[], mobile gaming community[], etc.

Neighbor discovery is a fundamental step of constructing a wireless network, based on which the network can implement further applications such as routing and broadcasting. The core target is for each node in the network to discover the nodes in its radio sensing range with one-hop communication, which are called neighbors. A number of existing methods [3]–[13] have been proposed to deal with this issue, some of which are based on deterministic techniques while others are probabilistic approaches.

Unfortunately, there are some discrepancies between the current research network and the actual situation. The deterministic methods deal with the neighbor discovery problem for two nodes and the probabilistic approaches are designed for the networks where all the nodes can communicate with each other.

In a large-scale and practical network, each node is only able to sense the nodes located nearby itself based on received signal strength [16]. We call this network connection structure as partially-connected networks.

As for the deterministic approaches, when transferred to partially-connected networks, they can not solve the collision issue when more than one neighbors are transmitting simultaneously. Relatively, the probabilistic approach can well deal with multiple nodes discovery but only consider the network is fully-connected, the topology of which is a complete graph. Thus the probability adopted in these approaches can not be desirable.



(a) uniform distribution (b) Gaussian distribution

Fig. 1. WSN deployments following uniform and Gaussian distribution.

To our best knowledge, no relevant researches have focused on neighbor discovery problem in the partially-connected networks. More practically, in a wireless sensor network the distribution of sensors' deployment consequently plays a vital role in determining the intrusion detection capability of a sensor node. Thus the distribution of the nodes in the network needs to be fully taken into consideration.

In this paper, we propose Alano[1], a nearly optimal probability based algorithm to discover neighbors in partially-connected networks. As fully studied in [16] , the nodes in wireless sensor networks are likely to follow a uniform or a Gaussian distribution as showed in Fig. 1, depending on the specific network applications, which is in consideration of the proposed Alano algorithm.

In addition, among the partially-connected networks, there is a special type named energy-efficient network. Wireless sensor network is a typical energy-efficient network that all the sensor nodes have to maintain strict power budgets to attain years of lifetime [14]. Duty cycle mechanism, the fraction of time the radio is turned on, is utilized to raise the power-awareness of the nodes in the network. Correspondingly, the neighbor discovery process needs adjustment to deal with the dilemma between a balance of energy-efficiency and low-latency.

For energy-efficient networks, we design deterministic methods to align the wake-up time slot between the neighbors to achieve lower latency bound. Specifically, We propose RDS-Alano algorithm for the global duty cycle scenario,

[1]Alano is the god of luck in Greek mythology

where all the nodes share a identical duty cycle θ and TP-Alano for the local duty cycle scenario where each node holds a distrinct duty cycle θ_i.

Our simulation under the practical distribution of networks [16] shows the proposed Alano algorithm holds significant strengths than the state-of-the-art methods, based on the evaluation of speed, quality and scalability. Alano achieves 31.35% to 32.32 times lower latency and has higher discovery rate during the whole course of neighbor discovery, with either global or local duty cycle in both uniform and Gaussian distribution. When the number of nodes increases and the network becomes denser, Alano still keeps its high performance.

The main contributions of this paper are summarized as follows:

1) We model the distribution of node deployment with mathematical analysis and analyse the expectation number of neighbors of a node in uniform distribution and Gaussian distribution.
2) We propose Alano, a low-latency strategy to achieve neighbor discovery process in a partially-connected network.
3) We propose a Relaxed DifferenceSet based Alano algorithm (RDS-Alano) to achieve low-latency neighbor discovery process in the global duty cycle scenario.
4) We propose a Traversing Pointer based Alano algorithm (TP-Alano) achieve low-latency neighbor discovery process in the local duty cycle scenario.

The remainder of the paper is organized as follows. The next section highlights some related work and puts forward some serious problems. Some notion definitions and the system model are given in Section III. We analyse the node's expectation number of neighbors and propose Alano algorithm in IV as a foundation. Section V describes the RDS-Alano algorithm for global duty cycle scenario and TP-Alano algorithm for local duty cycle scenario respectively in energy-efficient networks. We have conducted extensive simulations, and the results are shown in Section VI. Finally, we conclude the paper in Section VII.

II. Related Work

Neighbor discovery problem has raised a great deal of attention of scholars [15]. A number of neighbor discovery methods have been proposed in the past decade. Technically, these approaches can be classified into two categories, probabilistic and deterministic.

In the deterministic methods [3]–[9], some mathematical techniques, such as co-primality, quorum system, etc., are utilized to promote the discovery performance. The deterministic methods holds an obvious advantage that they can achieve neighbor discovery process within a bounded time latency.

Nevertheless, there exists some crucial weak points in the deterministic algorithm. Firstly, Disco [3] proposes a discovery protocol that each node has a capability to send a beacon at both beginning and end of an active slot, which is widely adopted by the later algorithms such as SearchLight [5], BlindDate [8] and Hello [6], Nihao [9]. It is quite an efficient way for two nodes to discover each other within an ideal time latency. However, they do not solve the collision issues when receiving packages from multiple neighbors. Furthermore, when they are extended for multiple nodes, only sending a beacon to discover the neighbors is totally insufficient. A node needs to send a complete package containing all its information, otherwise the neighbor can not identify which neighbor the beacon belongs to[][][]. Thus a complete time slot is necessary for a node to transmit a package or listen to the channel to receive a package.

Another category is probabilistic methods [10]–[13]. These approaches utilize probability techniques to promote the randomness to discover the neighbors. Different from the deterministic algorithms, this kind of method shows an significant strength in the multiple nodes scenario. Relatively, probabilistic methods only present an expectation discovery latency and can not guarantee a latency bound in the worst case. In addition, almost all the existing methods consider the network is fully-connected, the topology of which is a complete graph. Deploying a fully-connected network in a large-scale area is technically impractical due to the limited sensing range of devices communication. How far the other nodes can be detected as a neighbor for a mobile equipment depends on criterion such as the received signal strength. From our analysis and simulations, they have a poor performance in the partially-connected networks, which is more practical in the reality world.

To the best of our knowledge, neighbor deterministic nor probabilistic methods are designed for partially-connected networks. In this paper, we present a low-latency, energy-efficient neighbor discovery algorithm for partially-connected networks.

The proposed RDS-Alano and TP-Alano in this paper are a combination of both two categories. We compare our proposed algorithm with both deterministic and probabilistic algorithms. Particularly as mentioned above, the deterministic approaches need some adjustment when transferred to partially-connected networks. Details will be introduced in Section VI

III. Preliminaries

In this section, we first describe the network and node model. Then we formulate the Neighbor Discovery problem formally.

A. Network and Node Model

In a network, the location of the nodes are likely to obey uniform distribution[][], Gaussian distribution[][] or other combinatorial distributions.

In reality, since the network is deployed in a vast area, each node has a capacity to sense a fraction of nodes within its sensing range. These networks are defined as *Partially-Connected Networks*.

Among the partially-connected networks, there is a particular type called *Energy-Efficient Networks*. A typical one of energy-efficient networks is the wireless sensor network. The wireless sensor network consists of a number of sensors

distributed separately in a target area. The deployed sensor nodes keep their most time in sleep pattern to avoid quick energy consumption and wake up timely to work on duty.

When a node wake up on a time slot, it can turn to either the transmitting state or listening state.

- **Transmitting state**. A node turn to transmitting state will broadcast a package containing its own identify information to all neighbors.
- **Listening state**. A node turn to listening state will monitor the frequency channel to collect its neighbors' packages. However collision will occur when two or more neighbor nodes transmit concurrently and thus no valid information will be gathered

Transiting between the states only costs little time, compared to one complete time slot.

In our model, we denote the node set in the network as $U = \{u_1, u_2, ..., u_N\}$. Time is divided into slots of equal length t_0, which is sufficient to finish one communication process (transmit or receive a piece of package). In each time slot, a node transform its pattern according to a pre-defined duty schedule.

Definition 1: **Duty Schedule** is a pre-defined sequence $S = \{s^t\}_{0 \le t < T}$ of period T and

$$s^t = \begin{cases} S & Sleep \\ T & Transmit \\ L & Listen \end{cases}$$

Each node construct its own duty schedule according to a specific strategy and repeats it until finding all the neighbors. Since the waking-up duration has a significant affect on the battery's lifetime, duty cycle is utilized to restrict the energy consumption.

Definition 2: **Duty Cycle** represents the fraction of one period T where a node turns its radio on. It can be formulated as:

$$\theta = \frac{|\{t : 0 \le t < T, s^t \in \{T, L\}\}|}{T}.$$

A homogeneous energy-arrangement case is that all the nodes in the network share a common global duty cycle θ, while each nodes holding a local duty cycle θ_i is a heterogeneous

B. Problem Definition

We consider a partially-connected network, where two nodes are neighbors if they locate within the radio range of each other. A symmetric matrix $M_{N \times N}$ is used to record the neighboring relations as:

$$M_{i,j} = \begin{cases} 1 & connected \\ 0 & disconnected \end{cases}$$

Each node follows its duty schedule to achieve neighbor discovery. In a synchronous scenario, nodes start their neighbor discovery process at the same time, while in a asynchronous scenario all nodes start at different time slots. We focus on the asynchronous case while still applicable for the synchronous situation.

Notice that the neighbor discovery process is not bidirectional, which means any pair of neighbors need to find each other separately. The time slots within which a node u_i find one of its neighbors u_j can be formulated as $L(i, j)$. Then we define the discovery latency that node u_i discovers all neighbors as:

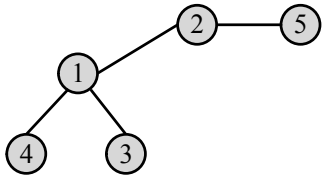
Definition 3: **Discovery Latency** of node u_i is the time to discover all neighbors:

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

Thus the neighbor discovery problem can be formulated as:

Problem 1: For a node u_i with its neighbor set $S = \{u_{i1}, u_{i2}, ...u_{ij}, ...\}$, design a strategy to construct a duty schedule, which satisfies $\forall$ neighbor nodes u_{ij} :

$$\exists t \ s.t.: \quad S_i(t) = L, S_{ij}(t) = T, \forall k \neq j : S_{ik}(t) \in \{L, S\}.$$



(a) The topology of a wireless sensor networks

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	S	T	T	T	T	…
Node 5							S	S	L	S	S	S	T	S	S	S	…

(b) Neighbor discovery process

Fig. 2. An example of neighbor discovering process. S, T and L represents Sleep pattern, Transmitting state and Listening state in wake-up pattern respectively.

An example of neighbor discovery process is given in Fig.2. Fig.2(a) shows the topology of a partially-connected wireless sensor network, which consists of 5 sensor nodes. Fig.2(b) describes the neighbor discovery process in the asynchronous scenario, as we can see the nodes start their process at different time slot. The duty schedule of node 1, for example, is $S_1 = \{1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 1, ...\}$. At time slot 12, node 5 find its neighbor node 2 while node 1 could not find node 2 due to a collision from its another neighbor node 3.

IV. Partially-Connected Networks

A practical scenario is that in a network, all the nodes are partially connected with each other. A node can discover a fraction of nodes within its sensing range.

In a partially-connected network for $\forall$ node u_i, its position coordinate (x_i, y_i) obeys a certain probability distribution

depending on the characteristic of the network, with the density function as :

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

where D is the network covering area.

$\forall$ node $u_i(x_i, y_i)$, its sensing range area R_i can be formulated as:

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

where r is the detection radius.

Thus, we can obtain the expected number of neighbors of node u_i as :

$$NB(u_i) = N \iint_{R_i} f(x,y)\, dx\, dy - 1.$$

We ignore the boundary area of the network and assume the nodes in the network is of an enormous quantity, so the expectation neighbors can be formulated as:

$$NB(u_i) = N \iint_{R_i} \varphi(x,y)\, dx\, dy.$$

Note that, when the network area is far more larger than the sensing area of the nodes, we can approximately get:

$$NB(u_i) = N\pi r^2 \varphi(x,y).$$

Then we propose **Alano**, a randomized neighbor discovery algorithm. We describe the algorithm for $\forall$ node u_i in Alg. 1. Alano algorithm indicates that what probability for a node choose to turn to tramisitting state or listening state is determined by the expectation neighbor number varying from node to node.

Algorithm 1 Alano Algorithm

```
1: n̂_i = N ∬_{R_i} φ(x,y) dx dy;
2: p_t^i = 1/n̂_i;
3: while True do
4:    A random float ε ∈ (0,1);
5:    if ε < p_t then
6:       Transmit a message containing node information of
         u_i;
7:    else
8:       Listen on the channel and decode the node
         information if receive a message successfully;
9:    end if
10: end while
```

In the following section IV-A, we first consider a general situation that the nodes in the network are uniform distributed. We derive a proof that the probability chosen in Alano is the optimal one and show the bounded latency will not be much larger than its expectation. Then in the section IV-B we describe a more common situation that the nodes in the network obey Gaussian Distribution, we present a approximation analysis that the discovery latency will not be much larger than uniform distribution.

A. Uniform Distribution

There are a part of partially-connected networks obeying uniform distribution. For instance, consider there is a wireless sensor network carrying out a task of measuring temperature and humidity in a target area, thus the sensors are supposed to be evenly deployed and the density function can be formulated as:

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

where A is the area of D.

Every node in the network has the same expectation of neighbor number and transmit with the same probability as:

$$\hat{n} = \frac{N\pi r^2}{A}, \quad p_t = \frac{1}{\hat{n}} = \frac{A}{N\pi r^2}.$$

According to Alano, the probability that node u_i discover a specific neighbor successfully in a time slot can be formulated as:

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

Let:

$$p_s' = (1 - p_t)^{\hat{n}-1} - (\hat{n} - 1)p_t(1 - p_t)^{\hat{n}-2} = 0.$$

It is easy to confirm that when

$$p_t = \frac{1}{\hat{n}}.$$

p_s gets the maximum value:

$$p_s = \frac{1}{\hat{n}}(1 - \frac{1}{\hat{n}})^{\hat{n}-1} \approx \frac{1}{\hat{n}e}.$$

Thus we can conclude that the probability chosen in Alano to transmit is the optimal one.

Next we analyse the expectation latency for a node to discover all its neighbors. We denote W_j to be a random variable representing the number of the time slots needed to discover a new neighbor after $(j-1)$ neighbors have been discovered, which follows Geometric distribution with parameter $p(j) : p(j) = (\hat{n} - j + 1)p_s$. Then the expectation of W_j is computed as:

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

The expectation time latency of discovering all the neighbors can be formulated as:

$$E[W_j] = \sum_{j=1}^{\hat{n}} \frac{1}{p_s} H_n \approx ne(lnn + \Theta(1)) = \Theta(nlnn).$$

where H_n is the n-th Harmonic number, i.e., $H_n = lnn + \Theta(1)$.

We get the expectation discovery latency is within O(nlogn) and then we show the bounded latency will not be much larger than its expectation.

If W_i is given, the value of W_j will not be affected for $i < j$. That is, for $i \neq j$, W_i and W_j are independent and they satisfy $P(W_j = w_j | W_i = w_i) = P(W_j = w_j)$. Since

W_j follows Geometric distribution, and $Var[W_j] = \frac{1-p_j}{p_j^2}$, the variance of W is

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

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

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

For large n, $P[W \geq 2E[W]]$ is close to 0. That is, the time for a node to find all neighbors is very likely to be smaller than 2 times of expected latency. Therefore,

$$W = O(nlnn).$$

B. Gaussian Distribution

A common scenario is that the nodes in a network obey 2D Gaussian distribution. For example, an intrusion detection application may need improved detection probability around important entities [16].

In this section, we present a theoretical proof that the latency performance will not be much larger than uniform distribution. The analysis is not only applicable for Gaussian distribution but also flexible for all the other distributions.

We first denote the approximate neighbors of node u_i as set $S(u_i) = \{u_{i1}, u_{i2}, ..., u_{i\hat{n_i}}\}$. When the nodes obey Gaussian distribution, according to Alano, the probability that node u_i discovers a certain neighbor node u_{ij} successfully in a time slot can be formulated as:

$$p_{suc} = (1 - p_t^i)p_t^{ij} \prod_{k=1}^{\hat{n_i}, k \neq j} (1 - p_t^{ik})$$

Denote:

$$p_t^{imax} = \max_{1 \leq j \leq \hat{n_i}} \{p_t^{ij}\}, \quad p_t^{imin} = \min_{1 \leq j \leq \hat{n_i}} \{p_t^{ij}\}.$$

Thus for $\forall j$, $1 \leq j \leq n_i$:

$$\begin{aligned} &(1 - p_t^i)p_t^{imin}(1 - p_t^{imax})^{\hat{n_i}-1} \\ \leq &(1 - p_t^i)p_t^{ij} \prod_{k=1}^{\hat{n_i}, k \neq j} (1 - p_t^{ik}) \\ \leq &(1 - p_t^i)p_t^{imax}(1 - p_t^{imin})^{\hat{n_i}-1} \end{aligned}$$

Denote:

$$\begin{aligned} P &= (1 - p_t^i)p_t^{imin}(1 - p_t^{imax})^{\hat{n_i}-1} \\ Q &= (1 - p_t^i)p_t^{imax}(1 - p_t^{imin})^{\hat{n_i}-1} \end{aligned}$$

Thus we get:

$$\begin{aligned} \frac{1}{\hat{n_i}Q} \quad &\leq \quad E[W_1] \quad \leq \quad \frac{1}{\hat{n_i}P} \\ \frac{1}{(\hat{n_i}-1)Q} \quad &\leq \quad E[W_2] \quad \leq \quad \frac{1}{(\hat{n_i}-1)P} \\ &\cdots\cdots\cdots \\ \frac{1}{Q} \quad &\leq \quad E[W_{\hat{n_i}}] \quad \leq \quad \frac{1}{P} \end{aligned}$$

Sum all the equations above, and we will get:

$$\frac{1}{Q}H_n \quad \leq \quad E[\sum_{j=1}^{\hat{n_i}} W_j] \quad \leq \quad \frac{1}{P}H_n$$

Since the sensible neighbors are within a close distance of the node compared to the total network area, which implies the density function values are within the same order of magnitude. Thus we can conclude that the expectation of the time latency in the normal distributed networks are still $E[W] = O(nlnn)$. Similarly the bounded latency can be proved to be $W = O(nlnn)$ in the same way as uniform distribution.

V. Energy-Efficient Networks

In an energy-efficient network (i.e., wireless sensor networks), the battery-consumption is a crucial factor to be taken into account. Duty cycle is a key technique to deal with the dilemma between a balance of energy-efficiency and low-latency.

We first consider the homogeneous energy-arrangement situation that all the nodes share a global duty cycle θ, and propose a RDS based Alano algorithm. Then we propose a traversing pointer based Alano algorithm for a more general scenario, where nodes have heterogeneous battery-scheduling capability with local duty cycle θ_i.

Our initiative idea is to align the wake-up slots of the neighbor nodes within a bounded time, and then invoke the Alano algorithm to achieve neighbor discovery process w.h.p. More specifically, we utilize the property of RDS and traversing pointer to guarantee a wake-up slot rendezvous in each period T.

A. Global θ: A RDS Based Alano Algorithm

When a global duty cycle θ is shared by all the nodes in the network, we utilize relaxed difference set (RDS) to align the wake-up time slots.

Relaxed difference set (RDS) is an efficient tool to construct cyclic quorum systems [17], [18]. The definition can be described as:

Definition 4: A set $R = \{a_1, a_2, ..., a_k\} \subseteq Z_n$ (the set of all nonnegative integers less than n) is called a Relaxed Difference Set (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 $a_i, a_j \in D$.

It has been proved that any RDS must have cardinality $|R| \geq \sqrt{N}$ [18]. We present a simple linear algorithm for RDS construction under Z_N with $\lceil \frac{3\sqrt{N}}{2} \rceil$ cardinality in Alg. 2.

The initiative idea of Alg. 2 can be described as Fig. 3. The framed elements are selected as in Alg. 2 Line. 4 and Line. 7.

We give a formal correctness proof of the construction as following:

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

Algorithm 2 RDS construction under Z_N

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

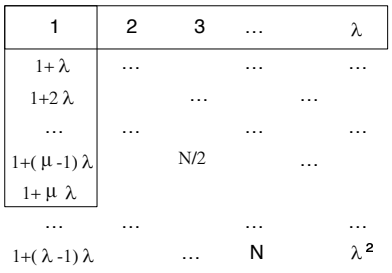


Fig. 3. An Sketch of RDS construction in Alg. 2

Proof: We first reach a consensus that if there exists one ordered pair (a_i, a_j) satisfying $a_i - a_j \equiv d$ (mod N), then we can get an opposite pair (a_j, a_i) such that $a_j - a_i \equiv (N - d)$ (mod n). Thus we only need to find at least one ordered pair (a_i, a_j) for each d from 1 to $\lfloor N/2 \rfloor$.

The λ in Line 2 is the smallest integer satisfying $\lambda^2 \geq N$. Then every d from 1 to $\lfloor N/2 \rfloor$ can be represented as: $d = 1 + j \times \lambda - i$, where $1 \leq j \leq \mu, 1 \leq i \leq \lambda$. Thus there exists $a_j = 1 + j \times \lambda$ added in Line. 4 and $a_i = i$ added in Line. 7 satisfying $a_j - a_i \equiv d$. ■

Next, we present a RDS based Alano algorithm (RDS-Alano) in Alg. 3, to achieve neighbor discovery process in a partially-connected and energy-efficient network with global duty cycle θ.

In Alg. 3, RDS is used to construct a deterministic schedule for the node to wake up in every period T, and Alano is utilized as a probabilistic strategy to determine the transmission state (transmit or listen) in each wake-up slot.

Algorithm 3 RDS Based Alano Algorithm

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

We show a proof of time latency bound for Alg. 3 as following:

Theorem 2: Alg. 3 guarantees the discovery latency to be bounded within $O(\frac{nlog}{\theta^2})$ w.h.p.

Proof: It is easy to confirm that the duty cycle $\widetilde{\theta}$ in Alg. 3 corresponds to θ as:

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

For any pair of neighbors (node i, node j), we can find an ordered pair (r_i, r_j) from their respective RDS such that $r_i - r_j \equiv \delta_t$ (mode T), which indicates any neighbor pair can wake up in the same time slot at least once in every period T. Regarding the whole period T as a time slot in Alg. 1, we obtain the latency bound as $O(\frac{nlogn}{\theta^2})$.

■

B. Local θ: A Traversing Pointer Based Alano Algorithm

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 heterogenous capability of battery-management with local duty cycle θ_i.

We propose a traversing pointer based Alano algorithm(TP-Alano) in Alg. 4. In each period T, every node wakes up in two different time slots, one of which is the first slot of each period and another is a traversing slot different from period to period, as Alg. 4 Line . 5 indicates.

Algorithm 4 Traversing Pointer Based Alano Algorithm

1: T :=Find the smallest prime $\geq \frac{2}{\theta_i}$;
2: $t := 0$;
3: **while** $True$ **do**
4: $t_1 := t\%T$;
5: $t_2 := \lfloor t/T \rfloor\%(T - 1) + 1$;
6: **if** $t_1 = 0 || t_1 = t_2$ **then**
7: Invoke Alg. 1 to determine transmission state;
8: **else**
9: Sleep;
10: **end if**
11: $t := t + 1$;
12: **end while**

We call the first time slot in each period T as a *fixed pointer* and the traversing slots as a *traversing point*. These pointers are used to guarantee a wake-up time rendezvous in every period T_iT_j. A sketch of the pointers is described in Fig. 4.

Note that, since the period of T is selected as: *find the smallest prime* $\geq \frac{2}{\theta_i}$, which is likely to result in the consequence that the duty cycle $\widetilde{\theta_i}$ in Alg. 4 is smaller than the expected θ. This can be easily solved by selecting some random wake-up time slots in each period T to conform to duty cycle θ.

We give a correctness proof of the time bound to achieve neighbor discovery process as following:

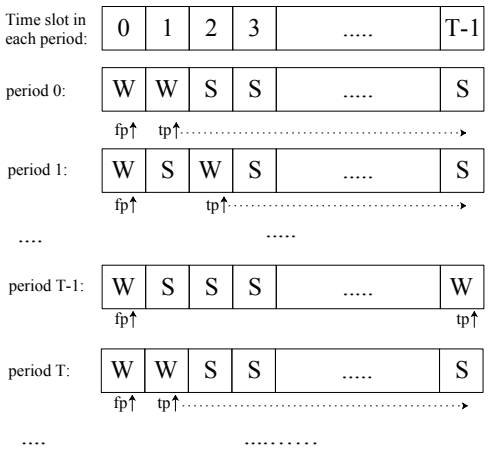


Fig. 4. An Sketch of TP construction in Alg. 4

Theorem 3: Alg. 4 guarantees the discovery latency to be bounded within $O(\frac{nlogn}{\theta_i\theta_j})$ w.h.p., where θ_i and θ_j are the duty cycles of a pair of neighbors (node i,node$j$) respectively.

Proof: We first prove that any pair of nodes (node i,node$j$) will wake up at the same time slot every period T_iT_j.

Case 1: $T_i \neq T_j$. Since T_i and T_j are different primes, according to Chinese remainder theorem, there exists a time slot $t_\tau \in [0, T_iT_j)$ satisfying:

$$0 = t_\tau \mod T_i. \tag{1}$$

$$\delta = t_\tau \mod T_j. \tag{2}$$

where δ is the asynchronous drift between node i and node j.

Equation1 and 2 implies there exists a fixed pointer of node i and a fixed pointer of node j rendezvous in every T_iT_j .

Case 2: $T_i = T_j$. Since $T_i = T_j = T$, if the asynchronous drift between node i and node j $\delta = 0$, the fixed pointers of node i and node j will rendezvous with each other in every period T. Otherwise since the traversing point will traverse all the time slots once during period $(T-1)T$, there exists a traversing point of node i rendezvous with a fixed pointer of node j every period $(T-1)T$, and a traversing point of node j will consequentially rendezvous with a fixed pointer of node i once every period $(T-1)T$ as well.

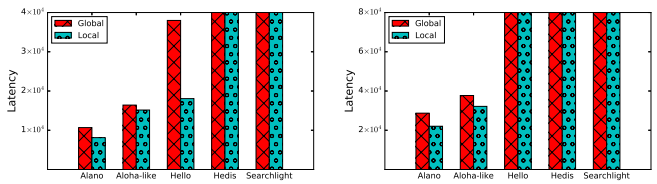
Thus for any pair of neighbor (node i, node j), they can wake up at the same time slot at least once in every period T_iT_j. Regarding the whole period T_iT_j as a time slot in Alg. 1, we obtain the latency bound as $O(\frac{nlogn}{\theta_i\theta_j})$. ■

VI. Evaluation

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 the network that follows uniform distribution and normal distribution respectively. We consider 500 nodes with radio range 10 in 100×100 area following uniform distribution, and more generally, 1000 nodes with radio range 5 following normal distribution $N(50, 15^2)$. The duty cycle is 0.1, and each time slot represents $20ms$. These settings make the network more complicated and realistic than that in [4]–[13].

We evaluated discovery latency of Alano, Aloha-like [12], Hello [6], Hedis [7], and Searchlight [5] in partially-connected network. As the deterministic algorithms, Hello, Hedis and Searchlight, only have two states, $\{ON, OFF\}$, we generally assume that when nodes are in $\{ON\}$ state, they transmit and listen with equal probability. We show that Alano has lower latency, higher discovery rate, and better scalability.

A. Speed: Discovery Latency

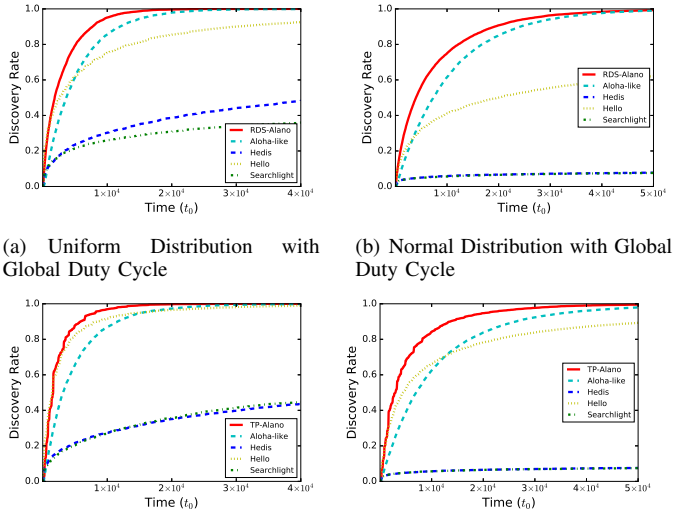


(a) Uniform Distribution (b) Normal Distribution

Fig. 5. Alano achieves lower latency.

In Fig. 5, when nodes follow uniform distribution, Alano has 53.67% to 5.33 times lower latency with gloabal duty cycle, and 86.49% to 7.43 times lower latency with local duty cycle. When nodes follow normal distribution, Alano has 31.35% to 24.57 times lower latency with gloabal duty cycle, and 45.94% to 32.32 times lower latency with local duty cycle. The deterministic algorithms Hello, Hedis and Searchlight have high latency, because their design just considered the bounded latency within two nodes. When the network becomes denser and some nodes have more than one neighbors, they cannot discover rapidly, because collisions happen so frequently.

B. Quality: Discovery Rate



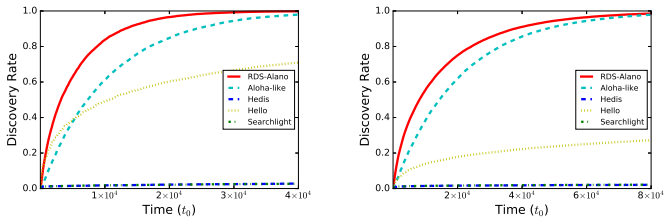
(a) Uniform Distribution with Global Duty Cycle

(b) Normal Distribution with Global Duty Cycle

(c) Uniform Distribution with Local Duty Cycle

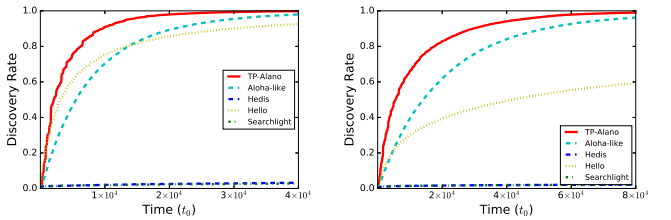
(d) Normal Distribution with Local Duty Cycle

Fig. 6. Alano achieves higher discovery rate.



(a) Uniform Distribution with Global Duty Cycle

(b) Normal Distribution with Global Duty Cycle



(c) Uniform Distribution with Local Duty Cycle

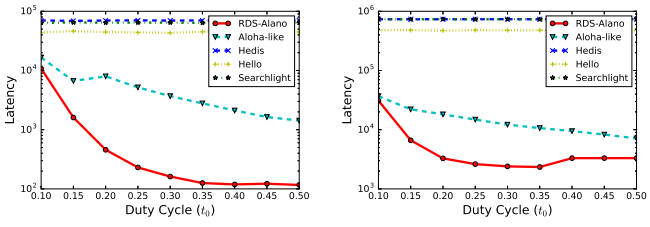
(d) Normal Distribution with Local Duty Cycle

Fig. 7. Alano achieves higher discovery rate in larger networks.

Fig. 6 shows Alano with either global or local duty cycle, has higher discovery rate during the whole course of neighbor discovery in both uniform and normal distribution. The deterministic algorithms Hello, Hedis and Searchlight cannot discover all channels, because of the occurence of collisions. Aloha-like discovers more slowly than Alano when it has discovered a certain number of channels, such as 80% channels in Uniform Distribution with Global Duty Cycle, because it is difficult for pure probabilistic algorithm to deal with the small amount of undiscovered neighbors.

When we increase the number of nodes in the uniform distributed network from 500 to 1000, and the number of nodes in the normal distributed network from 1000 to 2000, Fig. 7 shows that Alano still reaches higher discovery rate all the time with either global or local duty cycle.

C. Scalability: Duty Cycle and Network Density



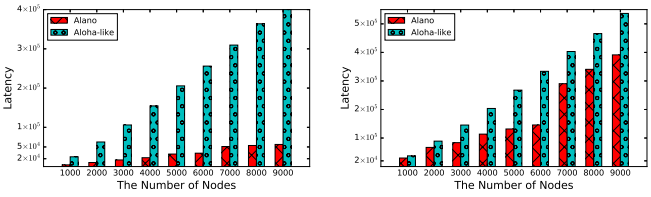
(a) Uniform Distribution

(b) Normal Distribution

Fig. 8. Alano achieves lower latency in different duty cycle.

Duty Cycle

With different duty cycle, Fig. 8 shows that Alano has lower latency. Compared with Aloha, Alano has from 53.66% to 11.23 times lower 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 normal 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.



(a) Uniform Distribution

(b) Normal Distribution

Fig. 9. Alano achieves lower latency with different number of nodes.

Network Density

When the number of nodes increases and the network becomes denser, Alano still shows 50.16% to 4.52 times lower latency than Aloha-like in uniform distribution and up to 47.03% in normal distribution in Fig. 9. Here we compare Alano with Aloha-like, because Hello, Hedis and Searchlight can hardly discover neighbors in denser networks.

VII. Conclusion

The conclusion goes here.

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