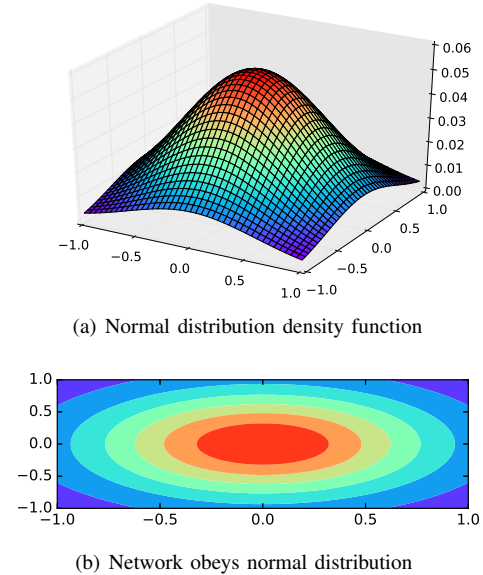


[illegible]

A more crucial issue is that neither deterministic or probabilistic approaches consider a partially-connected networks in reality, the devices of which can only possess a fraction neighbors among all the nodes. Deploying a fully-connected network in a large-scale area, such as campus networks, wireless sensor networks, mobile gaming community, etc., 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. Thus a practical



situation is that in a network , the nodes are partially connected with its detectable neighbors.

*****To be dealt with details later*****

How we deal with partially-connected networks:

1. Consider distribution of network devices: uniform distribution normal distribution
2. propose a distribution based Alano algorithm

*
*
*
*

***Motivation of energy-efficient networks:**

Among the partially-connected networks, there is a special one named energy-efficient network. Nodes in this type of networks have to maintain strict power budgets to attain years of lifetime [9]. Duty circle mechanism, the , is utilized to power-awareness ought to be fully taken into consideration. Correspondingly, the neighbor discovery process needs adjustment to deal with the dilemma between a balance of energy-efficiency and low- latency.

Contribution conclusion

In this paper, we first focus on the mathematical analysis of the distribution of the nodes in the networks. We give a expectation of neighbor number for each node in a network

which obey**** propose Alano¹, a RDS-Alano algorithm for partially-connected networks as well as a TP-Alano algorithm for the energy-efficient networks.

The contributions of this paper are as follows:

- 1) We model the distribution of nodes in their networks and analyse the expectation number of neighbors of a node in uniform distribution and normal distribution and then propose Alano, a strategy
- 2) We propose a Relaxed DifferenceSet based Alano algorithm (RDS-Alano) for the global duty cycle scenario.
- 3) We propose a Traversing Pointer based Alano algorithm (TP-Alano) for the local duty cycle scenario.

*Rest part structure

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

Introduce the representative existing algorithms.

1. Birthday Alg.
2. BlindDate Alg.
3. Disco Alg.
4. Hello Alg.
5. Searchlight Alg.
6. Talk More Listen Less Alg.
7. Todis&Hedis Alg.
8. U-Connect Alg.
9. ALOHA-like Alg.

(Note : Introduction and Related Work are expected to be 2 pages)

III. PRELIMINARIES

In this section, we first give some notion definitions and introduce the collision detection mechanism. Then we formulate the Neighbor Discovery problem formally.

A. Sensor Node Model

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 sensor 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 assume that each node has a unique identifier ID_i which is aware by themselves, while the total amount of sensors N is not necessary to be known. 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 $S = \{s^t\}_{0 \leq t < T}$ of period T and

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

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 defined to restrict the energy consumption.

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

$$\theta = \frac{|\{0 \leq t < T : s^t = T \mid s^t = L\}|}{T}.$$

B. Collision Detection Mechanism

A collision detection mechanism allows a node to distinguish between the case where two or more nodes are transmitting and one where no node is transmitting. Indeed, practical solutions for collision detection have been proposed.

C. Problem Definition

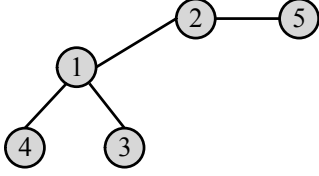
We consider a partially-connected sensor network, where two nodes are neighbors if they locate within the radio range of each other. A symmetric matrix $M_{N \times N}$ is used to record the neighboring relations as:

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

Each sensor follows its duty schedule to achieve neighbor discovery. In a synchronous scenario, sensors start their neighbor discovery process at the same time, while in a asynchronous scenario all nodes start at different time slots.

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 sensor 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:

¹Alano is the god of luck in Greek mythology



(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.

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

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

Thus the neighbor discovery problem can be formulated as:

Problem 1: For a sensor node with identifier $ID\ i$, design a strategy of constructing a duty schedule with duty circle θ , which satisfies : for \forall node $j_{M_{i,j}=1}$:

$\exists\ t\ s.t. :$

$$S_i(t) = L$$

$$S_j(t) = T$$

\forall node $k_{M_{i,k}=1 \& k \neq j} :$

$$S_k(t) = L || S_k(t) = S$$

An example of neighbor dicoverly process is given in Fig.2. Fig.2(a) shows the topology of a partially-connected wireless sensor networks, 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 $S_1 = \{1, 0, 0, 0, 0, 0, 1, 0, 0, 1, 0, 0, 0, 1, \dots\}$. 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 sense a rang

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.

For \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 the furthest detection distance.

Thus, we can obtain the expectation neighbor number 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:  $\hat{n}_i = N \iint_{R_i} \varphi(x, y) dx dy;$ 
2:  $p_t^i = \frac{1}{\hat{n}_i};$ 
3: while  $True$  do
4:   A random float  $\epsilon \in (0, 1);$ 
5:   if  $\epsilon < p_t$  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 normal distribution, we present a approximately 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 dimension 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:

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

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 that a new neighbor is discovered after the node has discovered $(j - 1)$ neighbors, 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:

$$E(W_j) = \sum_{j=1}^{\hat{n}} \frac{1}{p_s} H_n \approx ne(\ln n + O(1)) = O(n \ln n).$$

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

We get the expectation discovery latency is within $O(n \log n)$ 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,

$$W = O(n \ln n). \quad (1)$$

In a word, Alano-NCD and Alano-WCD both are bounded by $O(n \ln n)$.

The expectation neighbor number of each node:

B. Normal Distribution

For , denote the neighbors of

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

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 circle is a key technique to deal with the dilemma between a balance of energy-efficiency and low-latency.

We first consider the homogenous energy-arrangement situation that all the nodes share a global duty circle 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 circle 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 circle 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 [10], [11]. The definition can be described as:

Definition 4: A set $R = \{a_1, a_2, \dots, a_k\} \subseteq Z_n$ (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 $|R| \geq \sqrt{N}$ [11]. We present a simple linear algorithm for RDS construction under Z_N with $\lceil \frac{3\sqrt{N}}{2} \rceil$ cardinality in Alg. 2.

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

```

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.

1	2	3	...	λ
$1 + \lambda$
$1 + 2\lambda$	
...
$1 + (\mu - 1)\lambda$		$N/2$
$1 + \mu\lambda$...
...
$1 + (\lambda - 1)\lambda$...	N	λ^2

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

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

Theorem 1: The 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: We first reach a consensus that if there exists one ordered pair (a_i, a_j) satisfying $a_i - a_j \equiv d \pmod{N}$, then we can get an opposite pair (a_j, a_i) 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 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 circle 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.

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 $O(\frac{n \log}{\theta^2})$ w.h.p.

Algorithm 3 RDS Based Alano Algorithm

```

1:  $T := \lceil \frac{9}{4\theta^2} \rceil$ ;
2: Invoke Alg. 2 to construct the RDS  $R = r_0, r_1, \dots, r_{\lceil \frac{3\sqrt{T}}{2} \rceil}$  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

```

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

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

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 $r_i - r_j \equiv \delta_t \pmod{T}$, 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 $O(\frac{n \log n}{\theta^2})$. ■

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 circle 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:  $T := \text{Find the smallest prime} \geq \frac{2}{\theta_i}$ ;
2:  $t := 0$ ;
3: while True do
4:   $t_1 := t \% T$ ;
5:   $t_2 := (t/T) \% (T - 1) + 1$ ;
6:  if  $t_1 = 0 || t = t_2$  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 $T_i T_j$. 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 circle $\tilde{\theta}_i$ 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 circle θ .

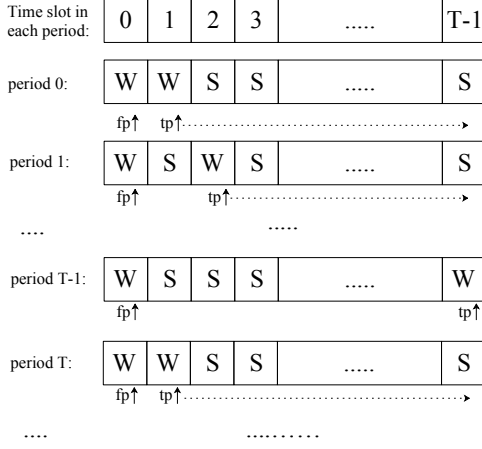


Fig. 4. An Sketch of TP construction in Alg. 4

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

Theorem 3: Alg. 4 guarantees the discovery latency to be bounded within $O(\frac{n \log n}{\theta_i \theta_j})$ w.h.p., where θ_i and θ_j are the duty circles 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 $T_i T_j$.

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 $t_\tau \in [0, T_i T_j)$ satisfying:

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

$$\delta = t_\tau \mod T_j. \quad (3)$$

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

Equation 2 and 3 implies there exists a fixed pointer of node i and a fixed pointer of node j rendezvous in every $T_i T_j$.

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 $T_i T_j$. Regarding the whole period $T_i T_j$ as a time slot in Alg. 1, we obtain the latency bound as $O(\frac{n \log n}{\theta_i \theta_j})$. ■

VI. EVALUATION

(Note : Evaluation is expected to be around 1 page)

VII. CONCLUSION

The conclusion goes here.

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(Note : Conclusion and Reference are expected to be less than 1 page)