A Semi-Blind Neighbor Discovery Algorithm Based on the Chinese Remainder Theorem

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***Abstract* - The process of obtaining the positions of neighbors in narrow beam width directional MANET is important in both blind and semi-blind situations, and the process of which is called neighbor discovery. In this article, a semi-blind neighbor discovery algorithm based the Chinese Remainder Theorem was proposed and designed. Firstly, the node model of directional antennas for sector distributions was constructed and evaluated. Then, the corresponding receiving and sending ID sequence was designed. Finally, the performance of the CRT semi-blind algorithm was evaluated and compared with the scan based algorithm-deterministic and the semi-blind completed randomized algorithm using MATLAB. The simulation results shows that the proposed algorithm has better overall performance than that of the other two algorithms.**

Keywords* – *MANET, directional antenna, neighbor discovery, semi-blind, the Chinese Remainder Theorem

I. INTRODUCTION

Transition from wired network to wireless one has been a global trend since the last century. Two types of wireless networks can be distinguished based on whether there is a fixed network infrastructure. The conventional network architecture requires established infrastructures. Mobile Ad hoc NETwork (MANET), on the other hand, has no such requirement. It is a collection of nodes that all serve as transmitters and receivers in the network. This topology has several advantages over the conventional architecture. One is that it is decentralized. Each network node possesses terminal and routing capabilities and can be independently distributed for networking and connection control. Even if one of the nodes is damaged, the others can continue to function normally. Aside from that, the nodes in the network are subject to change throughout time in positions and numbers. However, the network is limited by its transmitters' capabilities. Once the distance between two nodes exceeds their transmission range, they will be unable to interact. MANET adds intermediate nodes to maintain communications in order to resolve this issue. Each node in the single hop network is in the range communicate directly with one another. Whereas multi hop networks which consist of nodes beyond the range and must rely on intermediate nodes for communication [1]. Due to this handoff mechanism, there will be delays generated in multi hop cases [2].

With the above characteristics, MANET is widely used in battlefield communications, urgent communications and IoT (Internet of Things). Omni-directional antennas are often used to communicate in conventional MANET due to their simplicity and lower cost [3,4]. However, this leads to high energy requirement, limited transmission range and susceptibility to interference [2,3,5]. By using directional antennas, not only can network capacities and power efficiency be improved, but security of which will also be increased [4,5]. Thus, adopting MANET with directional antennas is necessary in occasions requiring high confidentiality and efficiency.

There are numerous advantages that directional antennas have over omnidirectional antennas as shown above. However, it also brings several problems due to movements of nodes in the networks [6]. It is impossible to communicate before antennas of both nodes pointing toward each other [6]. Thus, a process of obtaining positions of other nodes is necessary [6]. This method is called neighbor discovery [6]. In [7], the author mentioned another problem that there might be collision effect when the beam width of the directional antennas is relatively

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large. When the beam width is small (under 5 degrees), this effect can be ignored [7]. Thus, we mainly discuss directional antennas with small beam width in this article.

The existing algorithms for Neighbor Discovery are mostly on two dimensions, which could not satisfy three dimensional occasions such as airborne ad hoc network. Apart from that, most of them are blind discovery algorithms which require scanning process in every direction [6]. When it comes to three-dimensional occasions, due to the significant increase of sectors, performance of these blind algorithms will drop considerably. In order to eliminate this problem, the semi-blind situation is introduced.

The semi-blind situation refers to the scenes under which each node can obtain the approximate location of other nodes in advance of discovering each other through some means such as route planning or node formations. For example, A may have the geolocation of B through routing updates or an explicit position information protocol [8]. Through these means, most of the sectors can be excluded and the scanning range of neighbor discovery can be greatly narrowed down.

In [9], the author proposed a Hunting-based Directional Neighbor Discovery (HDND) scheme for ad hoc networks, which is designed for directional steerable antennas with no prior information and control channel. This scheme adopts the Chinese Remainder Theorem to limit the discovery time to a bounded value. Although the HDND is designed for steerable antennas in two-dimensional situations, it could be borrowed to redesign the neighbor discovery algorithms for three-dimensional directional antennas.

A semi-blind algorithm based on the Chinese Remainder Theorem is designed in this paper and named as the CRT algorithm. In this algorithm, a coding method is used to generate a transceiver sequence for nodes, and a sweep sequence is designed to ensure that any two possible sectors of any two nodes in the network can achieve at least one alignment within a bounded value MTTD (maximum time-to-discover). In addition, the ATTD (average time-to discover) of the CRT algorithm should be lower than its MTTD. Based on MATLAB, the performance of the CRT algorithm is compared with that of the SBA-D algorithm and the semi-blind CRA algorithm [6]. According to the results of simulation, the CRT algorithm has better performance over the CRA algorithm. In addition, under conditions with small number of nodes, it performs even better than the SBA-D algorithm.

II. ALGORITHM

A. Node Model

The common method for sector distribution problem of three-dimensional directional antennas is to distribute points uniformly on the sphere, with lines connecting the center to these points as the central axis of each sector [10]. One implementation of this method is through selecting circles of fixed latitude difference dθ on the sphere. Then, select points with distance of dφ on the circles, where dθ ≈ dφ. However, this method has very poor performance when simulating the antenna sector distribution. That is, with the same number of divided sectors, using this method leads to large radius for each sector and excess overlay of these sectors. In this paper, the Type I polyhedral link is used to perform the model of sector distribution of direction antennas [11]. In Fig.1, the polyhedron was divided it into 162 faces, with the centers of these 162 faces as the centres of the beams.

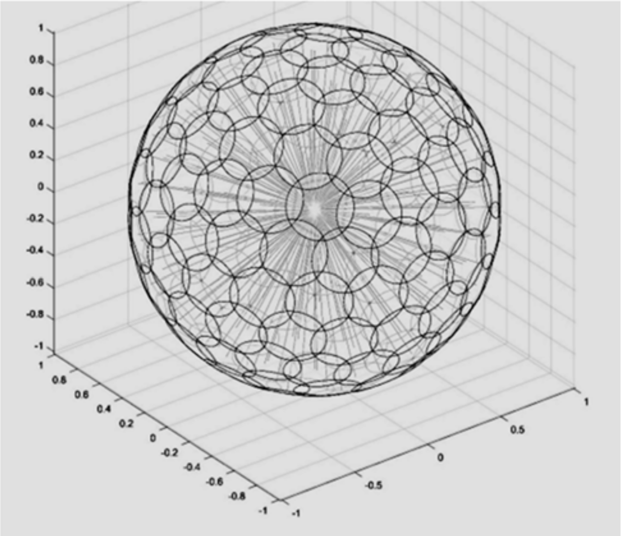


Figure 1. The sector distribution when M = 162.

In [7], the author states that the collision effect can be ignored if the beam width of the antenna is smaller than 5°. When the beam width is 5°, the required number of sectors M to fully cover the unit sphere is 2100. At 4°, that number becomes 3300. Thus, the number of sectors will increase significantly if the beam width of the directional antenna is small. Performance (MTTD) of existing Neighbor Discovery algorithms will be greatly impacted.

With prior information, node i can narrow down the range of neighbor discovery and obtain the sector set Si which contains Mi sectors and needs to be scanned through. In Si , the number of sectors in which a node will appear neighboring is the number of neighbor nodes Nnei for that node. The semi-blind ambiguity r is the ratio of Nnei and Mi . This parameter represents the precision and level of detail of prior information pertaining to auxiliary equipment, scene reality, etc.

In semi-blind situation, only the possible sectors are scanned through. Initially, the possible sectors are renumbered to rectify the disorganized and dispersed sector numbers in the collection of possible sectors. For example, S = {1, 4, 6, 22, 78, 100, 198}, and the renumbered set should be S′ = {1, 2, 3, 4, 5, 6, 7}, in which each renumbered sector is aligned with the old one. This situation can be simplified as a two-dimensional situation with discontinued sectors as shown in Fig 1. According to this, any two nodes in the network might have different number of possible sectors, which makes it impossible to use the SBA-D presented in [7]. In order to realize discovery, any two nodes should point to each other at least one time.

B. The Chinese Remainder Theorem

The Chinese Remainder Theorem (CRT) states that if p and q are pairwise coprime, then in the following equations:

$$\begin{cases} t \equiv x \bmod p, & 0 \le x < p \\ t \equiv y \bmod q, & 0 \le y < q \end{cases} \tag{1}$$

there is t ∈ $\{0, 1, \ldots, pq-1\}$, satisfying (1). Apart from that, this theorem can be generalized to systems of multiple equations. If pi are pairwise coprime, and if $x_0, x_1, \ldots, x_{n-1}$ are any integers, then the following system:

$$\begin{cases} t \equiv x_0 \mod p_0, & 0 \le x_0 < p_0 \\ t \equiv x_1 \mod p_1, & 0 \le x_1 < p_1 \\ \ldots & \\ t \equiv x_{n-1} \mod p_{n-1}, & 0 \le x_{n-1} < p_{n-1} \end{cases} \tag{2}$$

has a solution $t \in \{0, 1, \ldots, \prod_{k=0}^{n-1} p_k - 1\}$.

C. Specifications of the CRT Algorithm

The Chinese Remainder Theorem has the characteristics of matching any two arbitrary integers less than p and q. This satisfies the semi-blind neighbor discovery problem that two nodes have a distinct number of potential sectors. Consequently, it is utilized to create the semi-blind neighbor discovery algorithm.

In [9], the author designed a scheme of setting communication modes for steerable antennas. It solves the problem of unsynchronized time of different nodes. In the semi-blind situation, the time of nodes is synchronized. However, if any two sectors of any two nodes are matched within a period T it will be necessary to continuously match the sending and receiving states. To guarantee that any two nodes can match each other at $t = t0 + kL$, that is $id^a_{t0} \neq id^b_{t0}$ for $0 \le t_0 \le L$, the receiving and sending ID sequence is designed to be the periodical expanding of *L*-length sequence id_i.

Firstly, the *N* nodes were numbered. The first *N/2* nodes were numbered from 0 to ⌊N/2⌋. The rest were numbered from $2^{\lceil \log 2\ N \rceil} - (N - \lfloor N/2 \rfloor)$ to $2^{\lceil \log 2\ N \rceil} - 1$. The ID sequence of each node is the L-length binary code of its number, with L = ⌈log2 N⌉. That is:

$$id_i = \begin{cases} \mathrm{bin}_L\,(i) & i \le \frac{N}{2} \\ \mathrm{bin}_L\left(i + 2^{\lceil \log_2 N \rceil} - N\right) & i > \frac{N}{2} \end{cases} \tag{3}$$

By applying this method of numbering, the number of receiving and sending nodes are equal, that is N/2, at any specific moment, which can realize that there are as many nodes matching each other as possible.

In order to limit the MTTD, the scanning sequence of each node is designed. For example, node a is in the ma sector of node b (ma ∈ Sb), and node b is in the mb sector of node a (mb ∈ Sa). With any combination of ma and mb, in a bounded interval T there exists t0 < T which satisfies:

$$\begin{cases} u^a_{t_0} = m_b \\ u^b_{t_0} = m_a \end{cases} \tag{4}$$

To achieve this, one method is to divide the period into a fixed number of time slots of equal span. In each slot, the sending node a is fixed at a certain sector, and the receiving node b scans all the sectors in Sb. In the whole period, two nodes should discover each other. However, in the semi-blind situation, any of the two nodes might have different quantities of potential sectors, with each node only having the information of the quantity of potential sectors of itself, which makes it hard to choose a fixed number of small time slots. The other method is to use the CRT to design the scanning sequence. From observation, (4) is very similar to the Chinese Remainder Theorem. Thus, by choosing two pairwise coprime numbers pi and qi based on Mi of the node itself, the scanning sequence can be properly designed.

To ensure that each sector in Si will be selected, and each sector can be aligned with each sector of another node, pi and qi should be equal to or larger than Mi so that every sector can be chosen at least once. At sending state, the modulo operation is performed on pi . While at receiving state, the modulo operation is performed on qi. The number of two nodes used to take the modulo operation must be pairwise coprime.

Let p_i be the minimum odd number greater than *Mi*, and qi be the smallest power of 2 greater than *Mi* . That is, let bi denote the smallest integer which satisfies $2^{bi} \ge$ Mi, qi = 2bi. pi and qi must be pairwise coprime.

The scanning sequence is designed as:

$$u^i_t = \begin{cases} k \bmod p_i, & e^i_t = 1, (k \bmod p_i) < M_i \\ k \bmod q_i, & e^i_t = 0, (k \bmod q_i) < M_i \\ \mathrm{rand}(0, 1, \ldots, M_i - 1), & \text{otherwise} \end{cases} \tag{5}$$

P_i is the cycle length of the sending state, and q_i is that of the receiving state. When (k mod p_i) or (k mod q_i) is not smaller than Mi, a random integer within (Mi − 1) is chosen as the sector number for the time slots. Thus, the CRT algorithm is one with combination of certainty and uncertainty. According to the CRT, any two nodes a and b are supposed to align with each other within the cycle T = L max(paqb, pbqa).

To further optimize the algorithm, the dynamic adjustment of Mi is added to the algorithm. In the CRT algorithm, after nodes a and b discovering each other, the potential sectors of each other will be erased from their Mi , and Mi will be reduced automatically after neighbor discovery. Pi and qi will be adjusted continuously along with the process of neighbor discovery. This can significantly reduce both MTTD and ATTD in every situation. When the number of nodes is large, the influence of the dynamic adjustment can be further reflected.

III. PERFORMANCE EVALUATION

In this part, the CRT algorithm was evaluated through simulation analysis in different scenarios using MATLAB. Also, they were compared to the SBA-D algorithm and the semi-blind CRA algorithm. There are several parameters that have great impact on the performance of the algorithms:

1) The length of the ID sequence for each node: $L = \lceil \log 2\ N \rceil$.

2) The number of potential sectors Mi , the number of neighbor nodes Ninei and the semi-blind ambiguity r.

3) the cycle length of sending state pi and that of receiving state qi, which is determined by the number of potential sectors Mi directly in the CRT algorithm.

A. Theoretical Analysis

There are several indicators that represent the performance of algorithms. One is the ability to discover neighbors. It describes the ability of neighbor discovery algorithms without considering the performance of antenna, relative position of nodes or time drifting, that is, in ideal situation. This ability is directly related to the design of algorithms, and the CRT algorithm can ensure that the network can reach neighbor discovery within the MTTD. The MTTD denotes the maximum time the network used to discover all the nodes within it. For two nodes, the MTTD should be T = L max(paqb, pbqa). In a network with multiple nodes, the MTTD is L max(piqj). Nodes i and j have the maximum cycle length of the sending and receiving state, respectively. That is, they have the largest number of potential sectors while they are neighbors. Another indicator is the ATTD mentioned in the former section. It describes the average time the network uses to discover all the nodes within. Due to the uncertainty added in the algorithm, ATTD should be shorter than the MTTD.

For a network with certain ID sequence length using the CRT algorithm, both pi and qi only relate to *Mi*. The MTTD can be approximated as *L* max (*MiMj*). N^i_{nei} is the number of neighbors for node *i,* and the maximum number of which is max (*Ninei*). Suppose that the semi-blind ambiguity is r, thus, max (Mi) = r max (Ninei). As a result, the MTTD of the network is approximated as:

$$\mathrm{MTTD} \cong Lr^2 \max\left(N_{\mathrm{nei}}^i\right)^2 \tag{6}$$

It can be observed that the MTTD is strongly related to the ID sequence length L (number of nodes N), the semi-blind ambiguity r and the maximum number of neighbors for one node max (Ninei) existing in the network. When max (Ninei) is fixed, the performance (MTTD) is negatively and linearly correlated to the length of the ID sequence, that is, it is negatively correlated to the number of nodes logarithmically inside the network.

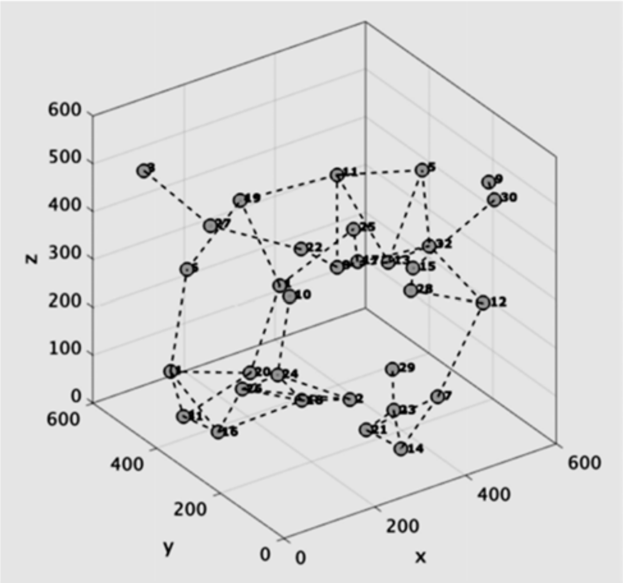


Figure 2. An example of generated scenarios.

When the number of nodes is reduced, the algorithm should have better performance. When the ID sequence length L (number of nodes N) and the semi-blind ambiguity are fixed, in a sparser network with smaller density of nodes and less potential sectors, the MTTD is smaller, and the algorithm has better performance.

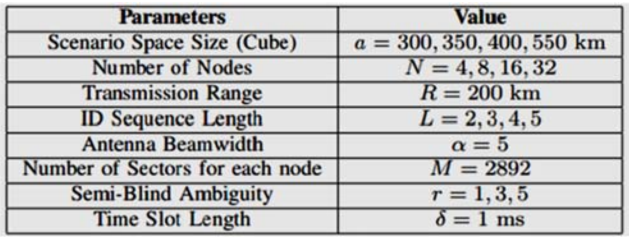
B. Important Parameters

In the simulation, the parameters of the random scenarios were set as shown in the Table I.

The densities of nodes in the scenarios were kept at a certain value. With low densities, the generation of scenarios would be extremely slow in the simulation, and the generated ones might be those with uneven distributions. The transmission range was set to be 200km. The density of nodes was $\Delta = N\ a3$. For each node, there were $D = 4/3\pi R^3\Delta$ nodes in average within their transmission range. In the simulation, D = 6. This guaranteed that the unconnected topologies were avoided. When the number of nodes is N = {4, 8, 16, 32}, the corresponding scenario space size should be a = {300, 350, 400, 550}km, respectively.

The antenna beam width was set to be $\alpha = 5^\circ$ so that the collision effect could be ignored. The Type I polyhedral link was adopted as the distribution of sectors. With 5° beam width, each node has 2892 directional sectors.

TABLE I. SIMULATION PARAMETERS



Parameters	Value
Scenario Space Size (Cube)	$a = 300, 350, 400, 550$ km
Number of Nodes	$N = 4, 8, 16, 32$
Transmission Range	$R = 200$ km
ID Sequence Length	$L = 2, 3, 4, 5$
Antenna Beamwidth	$\alpha = 5$
Number of Sectors for each node	$M = 2892$
Semi-Blind Ambiguity	$r = 1, 3, 5$
Time Slot Length	$\delta = 1$ ms

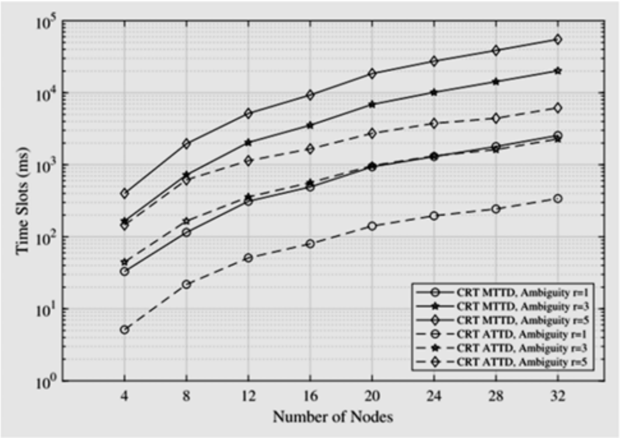


Figure 3. ATTD and MTTD of the CRT algorithms.

In the simulation, 100 random scenarios were generated, with three algorithms tested in each of these scenarios, respectively.

In addition, the two semi-blind algorithms (CRT and CRA) were tested under different semi-blind ambiguity (r = 1, 3, 5), respectively.

C. Numerical Simulation Results

The ATTD is calculated as the arithmetic mean of the Time-to-Discovery of the each algorithm in the 100 scenarios while the MTTD is the maximum results. The First Time-to Discovery (FTTD) refers to the time at which any node in the network first discovered its neighbors.

Fig.3 shows the trend of the MTTD and ATTD of the CRT algorithm varying with the number of nodes in the network.

The MTTD and ATTD share the same trend with regard to the increase of nodes. Due to the random component and dynamic adjustment in the CRT algorithm, the ATTD is smaller than the theoretical value MTTD.

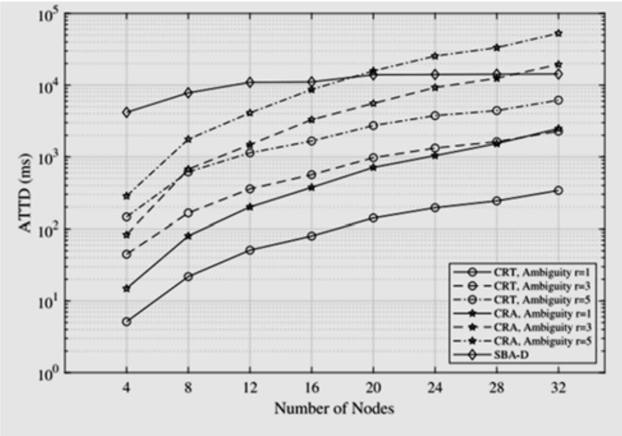


Figure 4. ATTD of three algorithms.

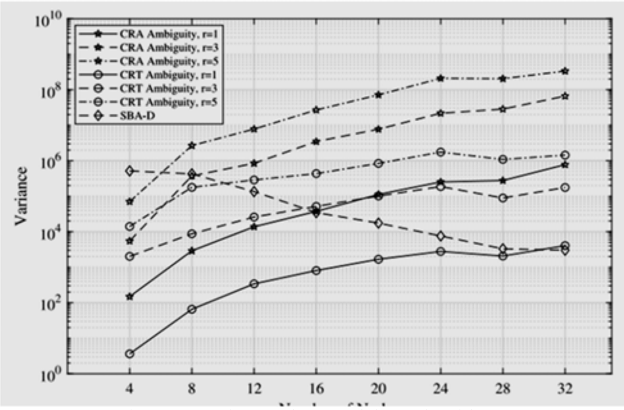


Figure 5. Variance of TTD of three algorithms.

This difference is further amplified with higher semi-blind ambiguity. When r = 5, the difference of MTTD and ATTD becomes significant.

According to Fig.4, both semi-blind algorithms have better performance than that of the SBA-D algorithm when the ambiguity is small. However, with the increase of ambiguity or the number of nodes, the advantage of the CRA algorithm over the SBA-D algorithm is no longer manifested. When r = 5, the CRA algorithm performs worse than the SBA-D algorithm with over 20 nodes in the network. Even when r = 3, it shows no advantage with 32 nodes in the network. In contrast, the CRT algorithm demonstrates comprehensive benefits in all circumstances.

This paper also compares the variance of the simulation results in Fig.5. The increase of number of nodes and ambiguity leads to increase the variance of simulation results of the CRA and CRT algorithms in Fig.5. However, under identical conditions, the variance of results of the CRT algorithm is significantly lower than that of the CRA algorithm.

Fig.6 shows that the FTTD performance of the three algorithm varied considerably. Both CRA and CRT algorithms have much shorter FTTD compared with that of the SBA-D algorithm. In addition, when the number of nodes increases, the FTTD of the CRA algorithm decreases; when the ambiguity increases, the FTTD decreases. In contrast, the FTTD of the CRT algorithm increases with both ambiguity r and the number of nodes.

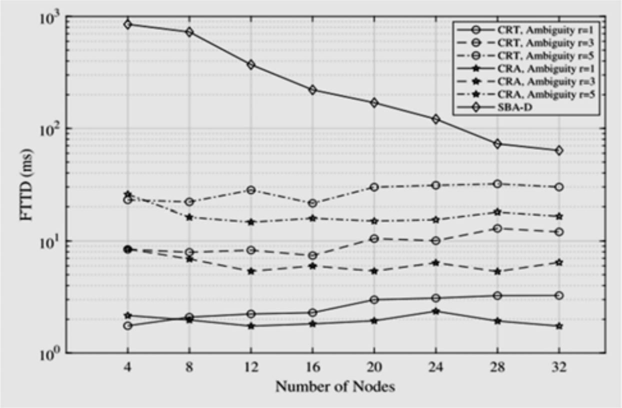


Figure 6. FTTD of the three algorithms.

D. Results and Discussion

The CRT algorithm is one contains deterministic and randomized parts. The former helps to limit the Time to-Discovery to a definite range (MTTD), and the latter can further optimize the algorithm and reduce the practical Time-to-Discovery. By adding the dynamic adjustment, the CRT algorithm further reduces the ATTD. According to the simulation results, the CRT algorithm was able to reduce and limit the Time-to-Discovery compared to the CRA algorithm. The CRT algorithm has better performance over the other two algorithms in all circumstances. In addition, due to the optimization of its randomized part, the ATTD is far smaller than the MTTD. The FTTD performance of the three algorithms has significant difference. The CRA algorithm can reduce the FTTD with the number of nodes increased. This is because the CRA is a completely randomized algorithm. When the number of nodes and links in the network increases, nodes in the networks will have better chance to discover their neighbors. In conclusion, for the CRT algorithm, the increase of nodes basically has no significant impact on its performance. Under lower ambiguity r, the CRT algorithm has even better performance. That is, with more accurate prior information, the performance of the CRT algorithm can be greatly improved.

V. CONCLUSION

This paper focuses on narrow beam width directional neighbor discovery algorithms in semi-blind situations. The directional antenna model and the semi-blind algorithm model was firstly introduced. Then, the CRT semi-blind algorithm was proposed and designed, with the algorithm model, the receiving and sending ID sequence and algorithm process introduced. Finally, the performance of the CRT algorithm was evaluated and compared with that of both the CRA and SBA-D algorithms. In conclusion, the CRT algorithm has better overall performance over the CRA algorithm, and it exceeds the SBA-D algorithm when there are small number of nodes in the network.

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