PLACE: Protocol for Location And Coordinates Estimation --A Wireless Sensor Network Approach

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Abstract-In this paper a *Protocol for Location And Coordinates Estimation* (PLACE) is presented as a distributed multi-hop positioning approach based on wireless sensor networks without relying on GPS data at each sensor node. It is suitable for military applications where GPS services are unavailable, instable, or unreliable. PLACE conducts the positioning task in three phases: distance estimating, positioning, and refining. Issues caused by alias problems and measurement errors are discussed and solved in order to improve the practicability of the PLACE and its accuracy of the location and coordinates estimations. Simulation results comparing the PLACE approach with another popular multi-hop positioning approach, DV-Hop, show that (*i*) for the PLACE approach the average multi-hop positioning error is smaller than the corresponding one-hop range detection error and is also several magnitudes smaller than that of the DV-Hop; (*ii*) the average positioning error decreases as the average number of neighbor nodes increases in the PLACE approach while the relationship is random in the DV-Hop, which directly supports the design idea that the PLACE takes advantages of the network redundancy to improve the location estimation accuracy; and (*iii*) a dense wireless sensor network should be deployed when applying the PLACE for accurate location and coordinates estimations. Therefore this research contributes: (*i*) a distributed multi-hop positioning algorithm and an associated protocol; (*ii*) solutions to practical issues that increase the practicability of the multi-hop positioning approach; and (*iii*) investigations on relationships between network density, network scale, positionability, and positioning accuracy.

Key words—Wireless sensor networks, multi-hop positioning, range estimation, GPS.

I. INTRODUCTION

A. Motivations and Goals

A wireless sensor network (WSN) is defined as an ad-hoc wireless network composed of tiny nodes with sensing capabilities. In recent years, wireless sensor networks begin to show their potentials in many application scenarios, e.g. the smart battlefields. With the help of pre-distributed sensor nodes, commanders can automatically collect the information about positions, activities, and conditions of individual battle units, make decisions based on the real-time information, and send instructions, guidance, as well as commands to each unit accordingly. Meanwhile, the sensor network can aid the battle units to collect useful information, make correct decisions, and avoid certain dangerous conditions. In constructing such kind of applications, functionality for the sensor nodes to determine their locations is of extreme importance.

While GPS (Global Positioning System) and its successors can fulfill the positioning requirement in some cases, their services are unavailable instable or unreliable enough in some scenarios, e.g., inside jungles, large buildings or underground facilities where the satellite signals are blocked. As illustrated in Fig. 1, GPS based localization and coordinates estimation within smart battle fields can be augmented by technologies based on wireless sensor networking presented here. Thus it results in complete position-aware battle fields that cover both the GPS-covered area and the GPS-blocked area. Thus it is necessary to provide a complementary approach in such scenarios for successful and safe military operations. Current technology development and cost reduction of wireless sensor networks provide a promising platform to achieve the location estimation objective. For example, before engaging soldiers into an unknown targeted jungle area, a sheer amount of wireless sensors are distributed into the jungle by unmanned flights to form a dense wireless sensor network autonomously. By using certain approaches, such as the one presented in this paper, sensors decide their location information. When soldiers patrol into the jungle, their location information can be detected by the supports of the already-deployed wireless sensor networks.

This research will help providing key services of integrated mobility and ad-hoc networking in military networks, such as mobility management and object tracking [1] in tactical networks, intelligent network resource discovery, position-aware routing [12] [13] [15] [23] and security-architectures based on geo-location information. Therefore, location and coordinates estimation is a key issue in military networks. The goals of this study include: (*i*) to justify the possibility of providing accurate and scalable positioning services using wireless sensor networks; and (*ii*) to develop a distributed multi-hop location estimation protocol to fulfill the positioning requirements of various applications.

Three assumptions that have been widely accepted by researchers are made in this research:

- There are some nodes (called anchor nodes) in the system having position information. The anchor nodes provide solid references for the positioning procedure. The position information known by anchor nodes could either be the absolute coordinates obtained from GPS receivers attached on the anchor nodes or such information preset during the deployment.
- Nodes have the range measuring capability within a certain distance. The range measuring capability can help the positioning system to improve position estimation accuracy.

- The WSN is densely deployed. The densely deployment is an enabling factor in most positioning algorithm designs because the redundancy provision can help the algorithms to improve the reliability of location estimations and the fault-tolerance of the positioning system.

B. Related work

Many algorithms and protocols have been proposed in order to solve the problem of determining nodes' locations within sensor networks. These approaches can be roughly classified into two categories according to their assumptions on nodes' capabilities in obtaining range measurement data.

1) Range-free schemes

Consider the cost and availability of range-detection hardware on sensor nodes, some researchers have suggested range-free schemes to achieve the positioning of sensor nodes such as DV-Hop algorithms [18] and Centroid-based algorithms [4] [5]. In [18], a heterogeneous network consisting of sensing nodes and position-aware anchors is assumed. Sensing nodes estimate their distances to each anchor node by recording the minimum hop count to that anchor node and the average distance per hop. In [14], an amorphous algorithm is proposed in order to take advantages of neighbor information exchange and offline hop-distance estimations to improve the location estimates. Accuracy of the DV-Hop based algorithms are constrained by the fact that the average distance per hop is only a rough approximation for the actual distance between neighbor node pairs and it introduces inevitable errors into the system. We will use DV-Hop for performance comparison because of it is a popularly used multi-hop positioning approach [3] [10] [17] and other reasons mentioned in Section IV. The Centroid-based algorithm assumes that all anchor nodes keep beaconing their positions. A sensing node will record all received beacons and estimate its location to be the centroid of the anchors. The centroid model applied is a major source that limits the algorithms' accuracy [16].

2) Range-based schemes

Although range-free approaches have the advantages of low-cost and broader applicability, it is very challenging to improve their accuracy to fulfils the requirement of some applications. Therefore, range-based approaches are proposed as alternatives. Based on their range detection methods, range-based positioning and localization schemes can be classified into three categories, namely: Time of Arrival (TOA), Angle of Arrival (AOA), and Received Signal Strength (RSS). TOA is a technique utilizing the signal propagation time to determine the range information. It is widely used in commercial positioning systems such as GPS [6] [7] [22]. In order to relax the precise synchronization requirements for anchor nodes, Time Difference of Arrival (TDOA) technique is used in more and more positioning designs for wireless sensor networks, such as AHLos [3][20] and APS [16]. AOA is a technique that nodes can employ to obtain range information by measuring the relative angles between neighboring nodes. In [17], a protocol presented in [16] is revised in order to use nodes' AOA detection capability. RSS technique obtains the distance estimates by measuring the strength of received signals and applying a distance to signal-strength model. Many positioning protocols, such as RADAR [2], APTI [10], and SpotOn [11] [21], consider the RSS technique as their range detection method.

Most of the above-mentioned schemes are not designed for multi-hop positioning system so that the coverage areas and application scenarios are limited. Considering the above military scenarios, in this research, we have developed a scalable and distributed protocol called PLACE (Protocol for Locations And Coordinates Estimation). The PLACE approach provides an efficient means for nodes to exchange their incomplete position information in order to help other nodes to make more reliable position estimation. With the protocol, a node determines its position in a three-phase manner and takes advantages of the network redundancy to increase the accuracy of the location estimation.

Comparing to the existing work, our research contributes: (*i*) a distributed multi-hop positioning algorithm and an associated protocol; (*ii*) solutions to several practical issues that increase the practicability of the protocol; and (*iii*) investigations on relationships between network density, network scale, positionability, and positioning accuracy.

The rest of the paper will be organized as follows. Section II presents the PLACE approach including its algorithms and protocol specifications and Section III studied practical issues of the PLACE approach to improve its correctness and accuracy of location estimations. Simulation results and performance comparisons are illustrated in Section IV. Section V concludes the paper.

II. PLACE APPROACH

A. Basic Ideas

Fig. 2 shows the basic ideas of the PLACE approach to estimate the sensor node positioning information in a wireless sensor network. Nodes X, A1, A2, and A3 are sensor nodes that may be a number of hops away from each other. The node X is a target node and the nodes A1, A2, and A3 are anchor nodes. In the PLACE approach, the node X first estimates the relative distances to the anchor nodes A1, A2, and A3, respectively, by algorithms described below in Section II.B. The relative distances are estimated using multi-hop range detection information, not the hop counts. Based on the absolute location information of the anchor nodes A1, A2, and A3 distributed by protocol procedures, which are illustrated in Section II.C, the sensor node X decides its coordinates in a scalable multi-hop way.[1]

B. Algorithms and Working Phases

The PLACE approach works in a three-phase manner, namely, distance estimating, positioning, and refining phases.

1) Distance estimating phase

In this phase, each anchor node initiates a hop-by-hop flooding of distance measurements and estimations by beaconing its existence. When a sensor node V other than the anchor node receives a beacon or a distance estimation result from its neighbor nodes, it starts to measure the distances between itself and its neighbors and estimate its distance to the anchor node based on the measurement results. The distances between any two nodes in a direct neighborhood can be obtained by any range detection methods mentioned in the Section I. Once the distances between the sensor node V and its neighboring nodes are available, the distance between the node V and an anchor node can be estimated by applying a quadrilateral relation illustrated in Fig. 3.

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[1] For simplicity of idea illustration, without loss of generality, we confine our discussions in a 2-D location and coordinates estimation scenario.

In Fig. 3, nodes B, C, and E are within a direct neighborhood. The node E is the target node and the nodes B and C are the reference nodes. Node A, which is an anchor node, may be multiple hops away from the neighborhood introduced by the nodes B, C, and E. Without loss of generality, assume that the anchor node A is not in the direct neighborhood of the node E. When the distances between node pairs AB, AC, BC, BE and CE are known, the distance between the target node E and the anchor node A can be obtained by solving Eq. (1). If the nodes B and C are within the neighborhood of the anchor node A, then the distances AB and AC can be measured by any supported range detection method. Otherwise, the distances AB and AC can be estimated iteratively from their neighboring nodes that are closer to the anchor node A.

$$\begin{cases} b^2 = a^2 + p^2 - 2ap\cos\theta_1 \\ d^2 = c^2 + p^2 - 2cp\cos\theta_2 \\ q^2 = a^2 + c^2 - 2ac\cos\left(\theta_1 + \theta_2\right) \end{cases} \tag{1}$$

The hop-by-hop iteration of the distance estimation from the anchor node to other sensor nodes is shown in Fig. 4, which will be explained in details in protocol descriptions in Section II.C.

2) Positioning phase

The positioning process at a sensor node X evolves from the distance estimating phase to the positioning phase whenever the distances between the node X and three anchor nodes A1, A2, and A3 are obtained. In this phase, Eq.(2) will be solved to derive the location and coordinates of the target node X.

$$\begin{cases} \left\| X - X_1 \right\| = R_1 \\ \left\| X - X_2 \right\| = R_2 \\ \left\| X - X_3 \right\| = R_3 \end{cases} \tag{2}$$

In Eq. (2), X_1, X_2, and X_3 are the coordinates vector of the anchor nodes A1, A2, and A3, respectively. There is only one unknown vector $X=[x, y]$ and three equations will be sufficient to determine the target node's coordinates with redundancy. The positioning accuracy and stability can be improved in the following refining phase.

3) Refining phase

When there are more than three anchor nodes available and thus more corresponding distance estimations to the anchor nodes, a sensor node will check the validity of all the distance estimations and the positioning results that have been obtained in the positioning phase. Relatively unreliable information will be eliminated and a new position evaluation based on the more reliable information will be conducted in order to improve the positioning accuracy. The pseudo code for the refining process at a sensor node X is shown in Fig. 5.

C. Protocol Descriptions

The PLACE approach includes a protocol to achieve the positioning objectives efficiently and effectively based on the above mentioned algorithm.

1) Node configuration

Two tables are maintained at each node. In the neighbor-table, all neighbors of a node will have corresponding entries. Each entry contains the following information: (*i*) the node identification $A_{neighbor}$ of a neighbor node; (*ii*) the measured distance of the neighbor to the node; and (*iii*) the estimated distances from the neighbor node to all anchor nodes. In the anchor-table, all anchor nodes will have corresponding entries of their position vectors X_{anchor}. The information of X_{anchor} is obtained via exchanges of measure flooding packets.

2) Packet types

- Measure Flooding Packet (MFP). Five fields denoted as $\{A_{anchor}, X_{anchor}, A_{sender}, D_{s,a}, P\}$ exist in the MFP. They represent the address of the anchor node that initiates the measure flooding, the position vector or the coordinates of the anchor node, the identification of the node that sends this packet out, the distance between the sender and the anchor node, payload of the MFP, respectively. The payload is of variable length and carries the information of all the known distance measurement results between the sender and its neighbors. The results will be delivered in the format of $\{k, \{A_{n_1}, D_{s,n_1}\}, \{A_{n_2}, D_{s,n_2}\}, \ldots, \{A_{n_k}, D_{s,n_k}\}\}$, where *k* is the total number of distance measurement results, An_i the identification of the sender's neighbor *i*, and Ds,n_i the measured distance between the sender and its neighbor *i*.
- Positioning Request Packet (PRP). The PRP has a packet header containing an anchor node address $\{A_{anchor}\}$ without any payload. A node sending out a PRP will force all its neighboring nodes that receive the packet and know the distance to the specified anchor node $\{A_{anchor}\}$ to broadcast a MFP. Thus the sender of the PRP can calculate the distance to that specific anchor node accordingly. Specially, if $A_{anchor} = 0$, the neighbor nodes will send MFP according to all anchor nodes to whom it has estimated the distance.

3) Working procedure

As shown in the Fig. 4, the anchor node A initiates distance measuring by broadcasting a MFP with empty payload $\{0\}$. After six rounds of broadcast transmissions, the sensor node G, which is three hops away from the anchor node A, will get enough information to calculate its distance to the anchor node A.

In the first broadcasting round, anchor node A sends a MFP such that its direct neighbors, nodes B, C, and D can measure the distances AB, AC, and AD, respectively. Assume that nodes B, C, and D will win the channel competition in the order of nodes B, D, and C. Therefore, in the 2nd and 3rd rounds of the broadcast, nodes B and D will send out the distance measurement of AB and AD. Since node B and node D have never heard from any neighbors other than the anchor node A, their payloads would be empty. At the 4th round, node C gets the channel to send its MFP. By hearing the MFPs from its neighbor nodes B and D, the node C already knows the distances between BC and CD. As a result, the MFP from the node C will take BC and CD's distance measurements in the payload. By receiving the MFP from the node C, both node E and node F can solve the respective quadrilateral relations to calculate their distances from the anchor node A. They will broadcast MFPs in the 5th and 6th rounds, with corresponding payloads. At the end of the 6th round of broadcasting, by retrieving the information from the received MFPs and making the distance measurements, node G, which is three hops away from the anchor node A, has already got enough distance information (i.e. distances between AE, AF, EF, EG, and FG) to calculate the distance AG.

When a new node joins a sensor network that has been already established, rather than waiting for the next round of anchor node flooding, the new node sends an explicit PRP to request all its neighbors to resend their MFPs. Thus the newcomer can start its distance measurement right away. PRP can also be used by mobile nodes that want to get real-time position updates.

III. SOLUTIONS TO PRACTICAL ISSUES

A. Alias Issue

The alias issue emerges because both θ_1 and θ_2 in Eq. (1) can have two possible solutions: one with a positive value and the other negative. As shown in Fig. 6, one solution of q by Eq. (1) corresponds to the distance AE, and the other corresponds to the alias distance AE'.

According to the known distance between node pairs AB, AC, BC, BE and CE, the node E cannot make reliable decision on which one of AE and AE' is the correct distance estimation, not the alias distance. Therefore, other information will be necessary to help node E to make the right decision. One way to solve this issue is providing sensor nodes other kinds of measurement data (such as angle measurement data) together with the distance measurements. And then the distance of AE and AE' can be easily distinguished. However, this approach puts additional hardware requirements on the applicable system. The other way is taking more nodes as reference nodes to solve the alias issue as shown in Fig. 7.

In Fig. 7, another node F is taken as a reference node together with nodes B and C. Thus, as mentioned above, by knowing the distance values between node pairs AB, AC, BC, CE, BE, a quadrilateral equation set as shown in Eq. (1) can be solved and two possible results of the distance between nodes A and E are available. With additional knowledge of the distance between AF, FC, FE, another quadrilateral equation set can be constructed based on AF, AC, FC, FE, CE. By solving the second equation set, two possible results again can be derived, in which one will correspond to the correct distance AE and the other will be another alias result AE''. Now we have four possible results by solving two sets of quadrilateral equations, i.e., AE, AE', AE, AE''. Therefore the correct distance AE can be decided by choosing the common one in those four possible results.

The procedure depicted in Fig. 7 can be generalized as follows: by taking multiple nodes as reference nodes, there will be m distinct quadrilateral equation sets available. Solving the m equation sets, there will be m solution sets: $\{q, q_1'\}$, $\{q, q_2'\}$, …, and $\{q, q_m'\}$. Each set will include an alias solution q_i', where i=1, …, m, and an identical solution q, which is the correct distance estimation. Then based on the m sets of solutions, the common solution q will be chosen and all alias solutions will be eliminated. Note that this generalized idea to solve the alias issue is based on an assumption of error-free range estimations so that the common solution q can be found in these m sets of solutions.

B. *Measurement Error Issue*

The measurement error issue occurs when we consider error-prone practical environments where measurement errors are inevitable. Since the PLACE approach relies on the measured distance information to estimate the multi-hop distance between a sensor node and the anchor node, it is of practical importance for the PLACE to address this measurement error issue.

In most of the working conditions, the one-hop distance measurement error is bounded by a certain percentage of the measured distance, which is determined by the measurement method and working environment factors. With the presence of bounded measurement errors, the most significant challenge that a multi-hop distance estimation approach has to face is how to control the error propagation or how to effectively provide relative reliable multi-hop distance estimations based on the unreliable one-hop distance measurement information. Specifically, considering the measurement errors, the valid solution q_i in each solution set $\{q_i, q_i'\}$ will be slightly different from the actual distance q between the anchor node A and the target node E. Thus the measurement error issue traces back to the alias solution elimination issue: solving the m quadrilateral equation sets gives m solution sets: $\{q_1, q_1'\}$, $\{q_2, q_2'\}$, …, and $\{q_m, q_m'\}$, and the issue is how to decide a solution according to those $2m$ different values. Based on the observation that each solution set will include an alias solution q_i', where i=1, …, m, and a similar valid solution q_i, our approach is to estimate q such that an error estimation function defined as Eq. (3) is minimized:

$$e(q, q_1, q_2, \ldots, q_m, q_1', q_2', \ldots, q_m') = \sum_{i=1}^{m} [\min\{|q - q_i|, |q - q_i'|\}]^2 \quad (3)$$

By having a constraint $q \in \{q_i, q_i'\}$, where i=1, …, m, the computation needed to find the correct distance estimation q will be bounded.

IV. SIMULATION RESULTS

The following three aspects are studied by simulations of the PLACE approach for multi-hop positioning by wireless sensor networks:

- Relationship between the positioning accuracy and network scale;
- Relationship between the positioning accuracy and network density;
- Relationship between the positionability and network density.

The simulation results are compared with one of the multi-hop positioning approaches, DV-Hop [18], due to its multi-hop feature and popularity [3][10][17].

A. *Simulation configuration*

Simulations are conducted in a 2-D square area where sensor nodes are randomly deployed. There are four anchor nodes that are located at the four corners. Assume that all nodes, including the anchor nodes and the sensor nodes, have the same transmission range. Their transmission ranges are assumed to be round-shaped with a uniform radius within the sensing area. The distance measurement errors are assumed to obey unbiased uniform distribution with zero mean and the maximum absolute deviation of ε, which is proportional to the radius of the transmission range. Also assume that packet transmission collisions, delays, and loses can be neglected in order to simplify the simulation.

Important simulation parameters are listed in Table-I.

B. Results

1) Accuracy versus network scale

In this simulation the relationship between the maximum number of hops between any two nodes in a sensor network and the average error of location and coordinates estimations are studied. Let N=500, increase the radius of the radio transmission range from 1 to 4.5 with a step length of 0.5, and fix the error range as 1% of the radius. The change of the radius of the radio transmission range results in various average maximum numbers of hops, i.e., the diameter of the network, in each round of the simulations. The average error of the location and coordinates estimations is obtained by averaging the position deviation, which is formulated as Eq. (4).

$$\frac{\sum_{i=1}^{n}\sqrt{\left|x_i - x_i^{(actual)}\right|^2 + \left|y_i - y_i^{(actual)}\right|^2}}{n} \tag{4}$$

The results are depicted in Fig. 8. It is clear that the average error increases almost linearly with the increase of the maximum number of hops within the network, i.e., the network scale in terms of its network diameter. The result of PLACE is compared to that of DV-Hop [18]. Because the PLACE is a range based approach while the DV-Hop is a range free protocol, the positioing accuracy of the PLACE approach is several magnitudes better than that of the DV-Hop.

It is also noticeable that for the PLACE approach the average positioning error is smaller than the corresponding range detection error. This can be explained as the result of the alias eliminating algorithm presented in Section III. In fact, a sensor node will always try to choose the most likely solution for the distance estimation, which is helpful in controling errrors in later computations of the location and coordinates estimations.

2) Accuracy versus network density

The relationship between the positioning accuracy and the corresponding network density has also been investigated. In this simulation, a node waits for a period of time before it tries to estimate its distance to an anchor node. Any neighbor node whose distance estimations are received before the time period expires will be considered as a reference node.

The results are shown in Fig. 9. The average positioning error roughly decreases as the average number of neighbor nodes increases in the PLACE approach while the relationship is random in the DV-Hop case. The results directly support the design idea of the PLACE, which takes advantages of the network redundancy to improve the location estimation accuracy.

3) Positionability versus network density

Based on the discussions and the solutions for the alias and measurement error issues in Section III, it is intuitive that network density is an important design factor for the PLACE approach since it may require multiple neighboring nodes to be reference nodes. Simulations are conducted to support this consideration by studying the relationship between the network density and the probability that a node within the wireless sensor network can be positioned with the PLACE approach. The result is depicted in Fig. 10.

It is shown that there exist threshold values of the average number of neighboring nodes (i.e., the network density) for both PLACE and DV-Hop approaches to achieve satisfying positionability using the wireless sensor network. The higher the network density, the more nodes become positionable. The requirement of the network density for the DV-Hop comes from the necessity of maintaining the connectivity between sensor nodes to anchor nodes, while the network density requirement for the PLACE is because its distance estimation process requires multiple reference nodes.

Empirical data show that a good (positionability>99%) threshold of the network density for the PLACE approach is $10m$ if m represents the minimum number of reference nodes that are required to make valid distance estimation. Thus, by reducing m, the network density requirement can be relaxed. However, reducing m will also result in the increase of unreliability in the alias elimination, which has the potential effect to cause severe degradation of the positioning performance. Therefore the result suggests that a dense wireless sensor network should be deployed when applying the PLACE approach for accurate location and coordinates estimations.

V. CONCLUSIONS

Pinpointing individual battle units is an important function of smart battle fields. The availability of location and coordinates information can also facilitate key services of the military networks. Although GPS can provide positioning services in many applications, there are cases in which GPS signals are blocked such as inside jungles, large buildings and underground environments. Therefore, it is necessary to have alternative positioning approaches.

In this paper we present the Protocol for Location And Coordinates Estimation (PLACE) as a multi-hop positioning approach using wireless sensor networks based on several anchor nodes without relying on GPS data on each node in the positioning system. It is suitable for the military applications where GPS services are unavailable, instable, or unreliable. A cost-effective position aware system can be achieved by augmenting the GPS based positioning with wireless sensor networks deployed on-demand that cover areas without reliable GPS services.

Simulation results show that (*i*) for the PLACE approach the average multi-hop positioning error is smaller than the corresponding one-hop range detection error and is also several magnitudes smaller than that of the DV-Hop; (*ii*) the average positioning error decreases as the average number of neighbor nodes increases in the PLACE approach while the relationship is random in the DV-Hop, which directly supports the design idea of the PLACE, which takes advantages of the network redundancy to improve the location estimation accuracy; and (*iii*) a dense wireless sensor network should be deployed when applying the PLACE approach for accurate location and coordinates estimations.

This research contributes: (*i*) a distributed multi-hop positioning algorithm and an associated protocol; (*ii*) solutions to two practical issues that increase the practicability of the protocol; and (*iii*) investigations on relationships between network density, network scale, positionability, and positioning accuracy. In summary, PLACE can be an accurate complementary positioning estimation approach to the existing GPS systems for military applications.

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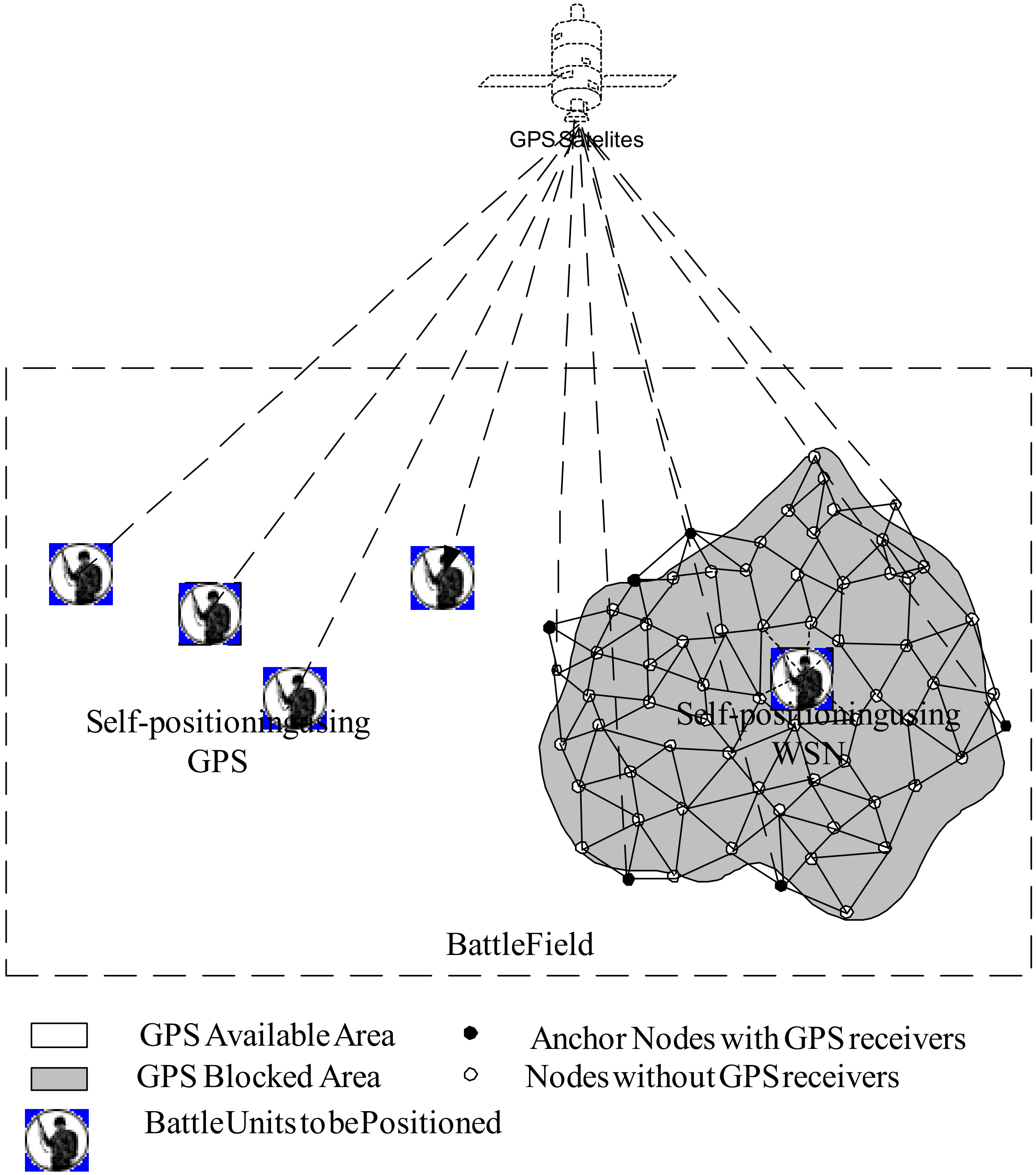


Figure 1. Battle unit positioning with GPS and WSN in smart battle fields.

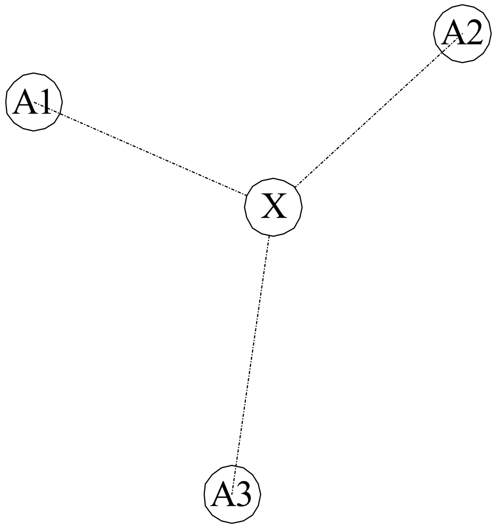


Figure 2. Basic ideas of PLACE for wireless sensor node positioning in WSN, where X is a target node and A1, A2, and A3 are anchor nodes. The dash-dotted lines represent multi-hop distance estimations.

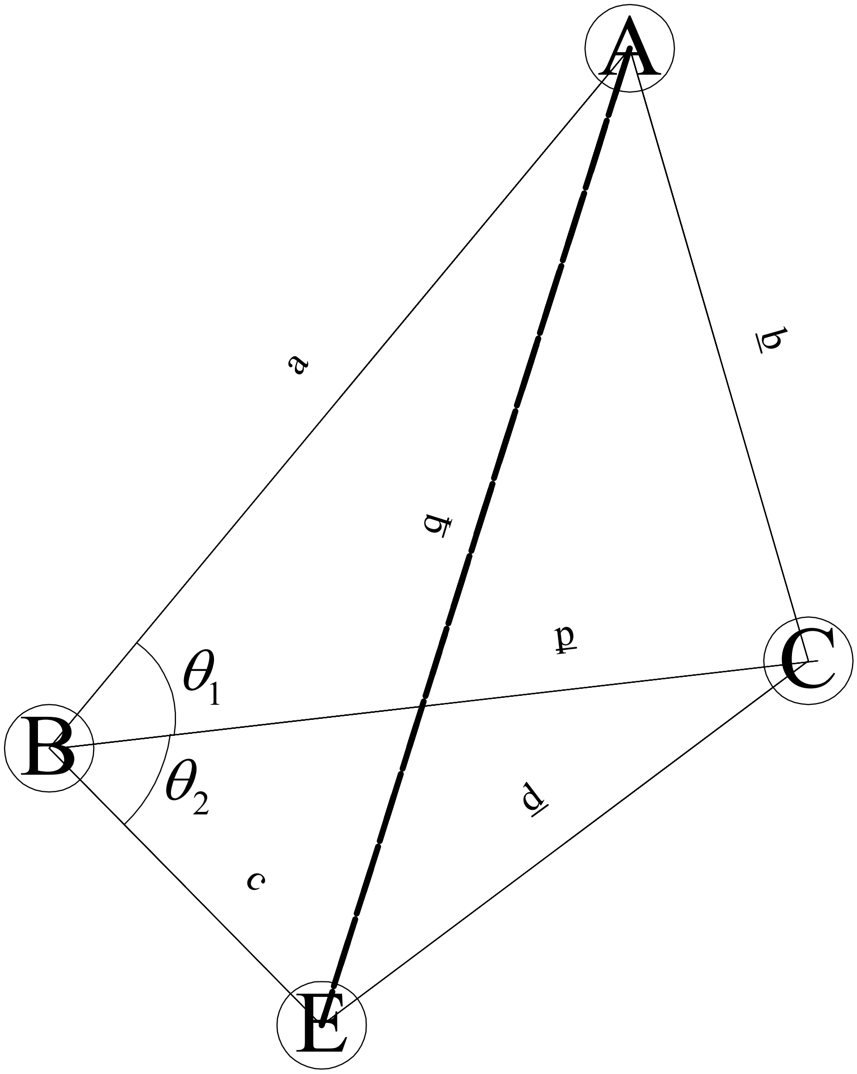


Figure 3. Quadrilateral relations among an anchor node A, reference nodes B and C, and a target node E.

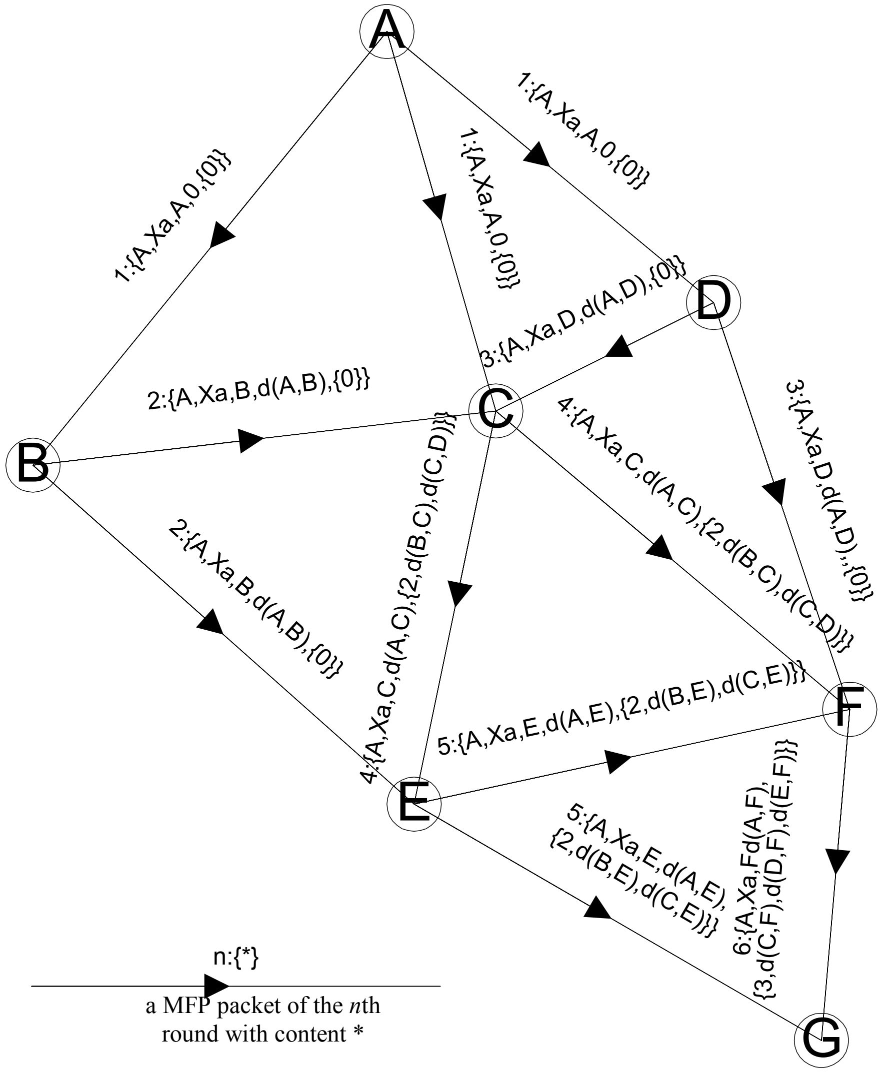


Figure 4. Multi-hop distance measurement and location estimation initialized by an anchor node A.

In: Initial position estimation result ($x^{(1)}, y^{(1)}$) of the positioning phase, total number of anchor nodes *N*, the position information of all anchor nodes ($x_1, y_1, x_2, y_2, ..., x_N, y_N$), and the distance estimates ($r_1, r_2, ..., r_N$) from node X to all the anchor nodes.

Out: Refined position estimation result (x, y).

```
j = 0;

do {
        j = j + 1; flag = 0;
        for(i=1;i<=N;i++) {
                if( $\left| r_i - \sqrt{\left(x^{(j)} - x_i\right)^2 + \left(y^{(j)} - y_i\right)^2} \right|$ >threshold) {

                        $r_i$ = - threshold;
                        flag = 1;
                }
        }
        if(flag==0) return $x^{(j)}, y^{(j)}$;

        if(Number of nodes with valid $r_i$ is less than three) {
                for(i=1;i<=N;i++)          {
                        if( $r_i$ == -threshold)
                                $r_i$=Send_Positioning_Request_Packet(anchor node i);
                }
        }

        $R_1, R_2, R_3$ = three distances randomly selected from $r_1, r_2, ..., r_N$;
        $x^{(j+1)}, y^{(j+1)}$ =positioning( $R_1, R_2, R_3$ );
} while (j < maxNumOfIterations)

return $x^{(j+1)}, y^{(j+1)}$;
```

Figure 5. Pesudo code for the refining phase at sensor node X.

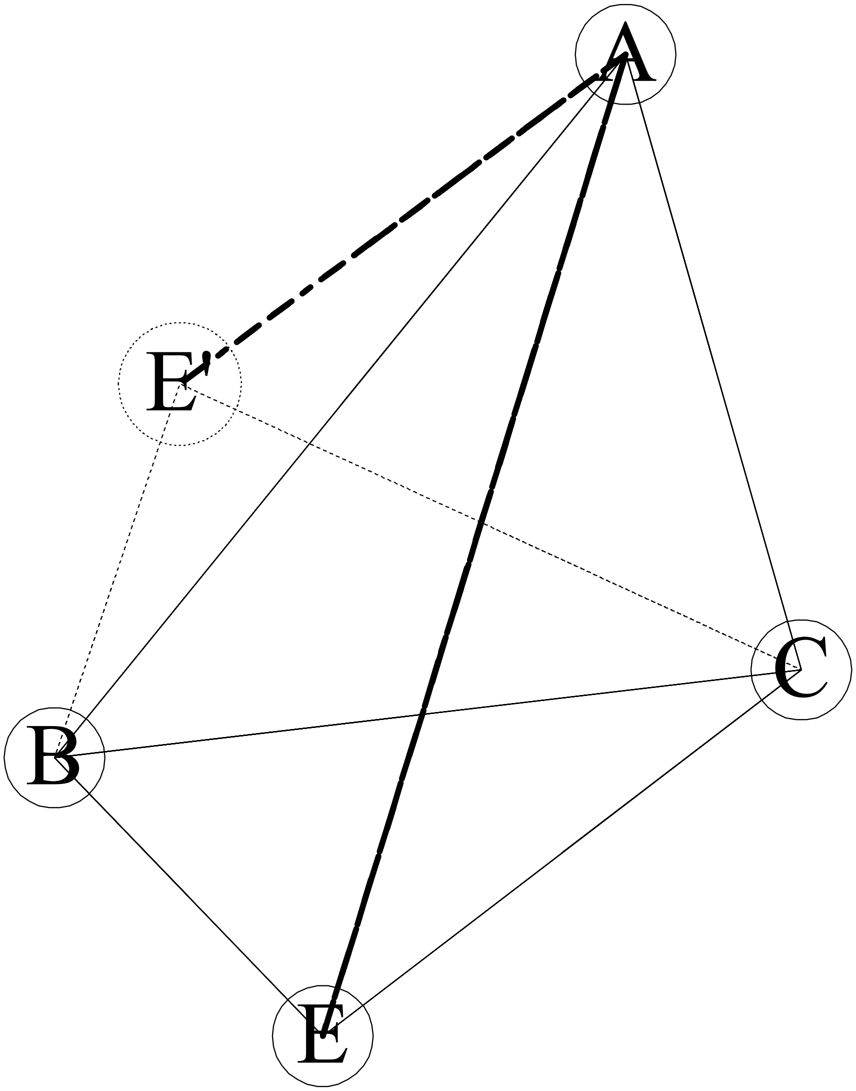


Figure 6. Alias issue of quadrilateral equation solving.

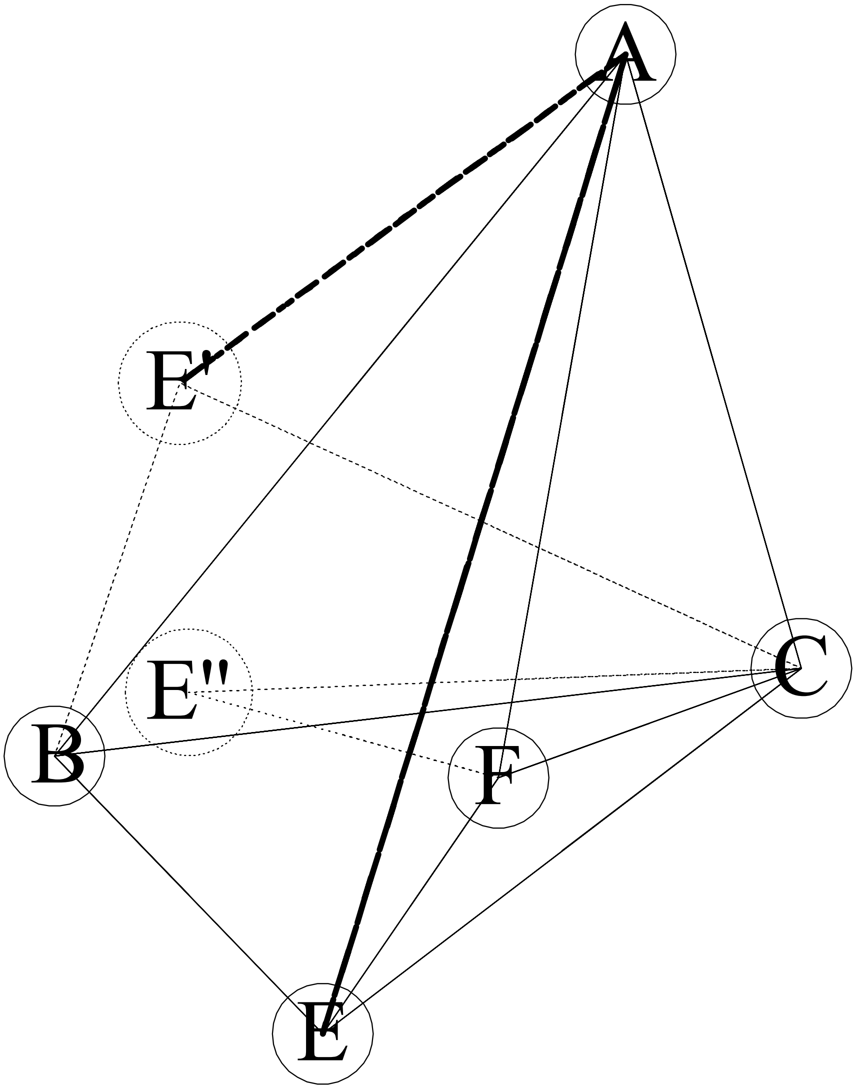
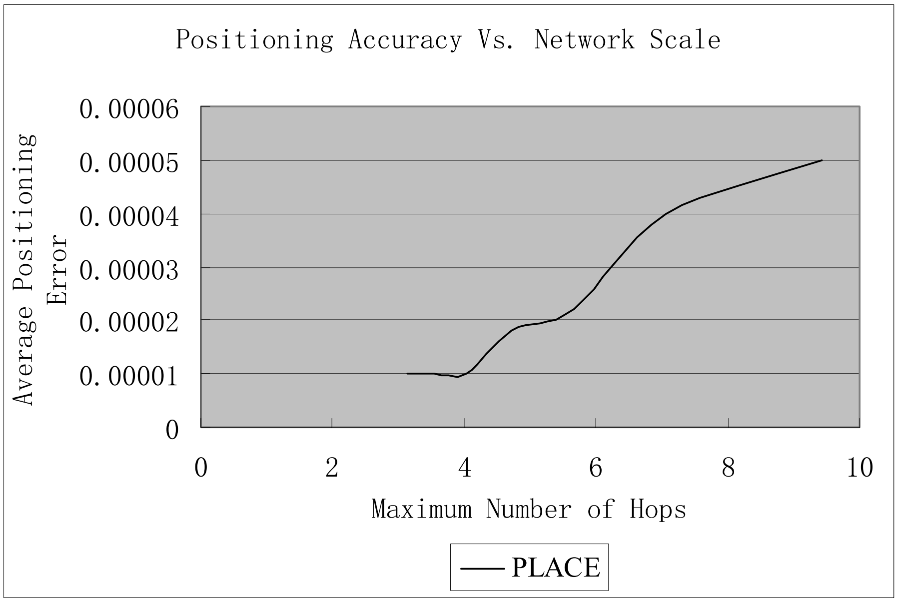
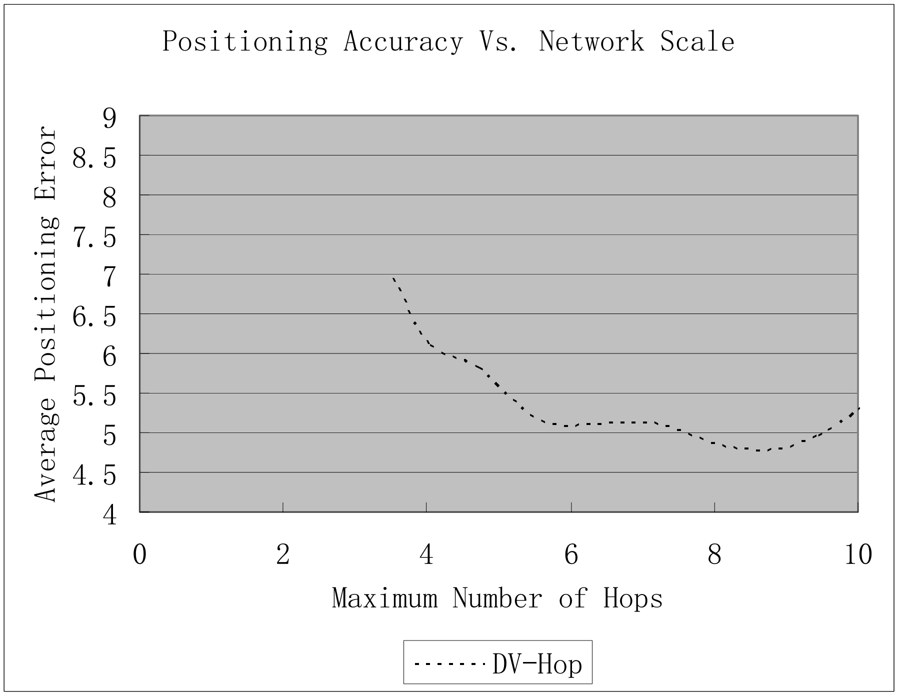


Figure 7. Solving alias issue by using more reference nodes.

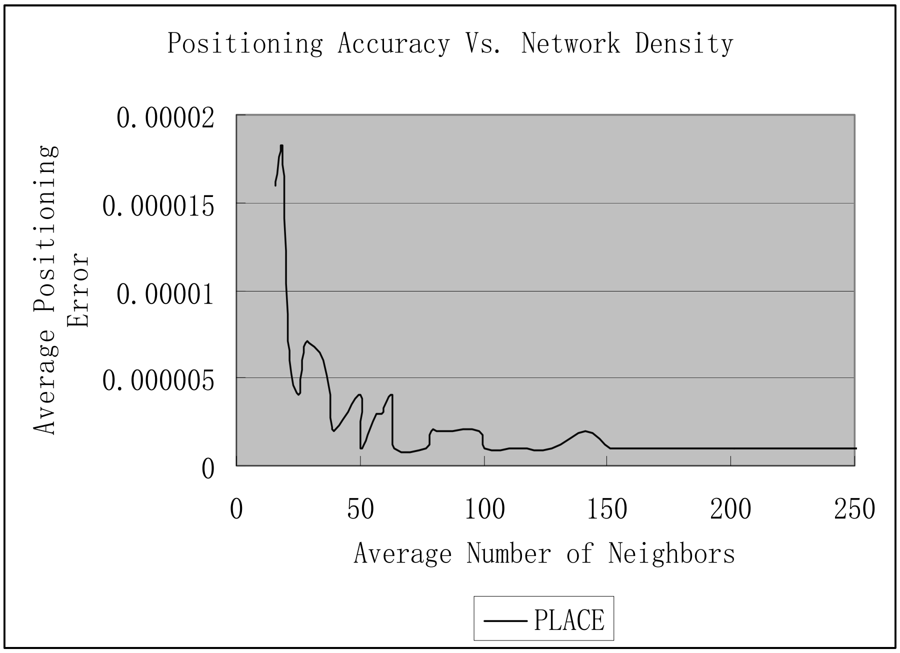


(a) PLACE

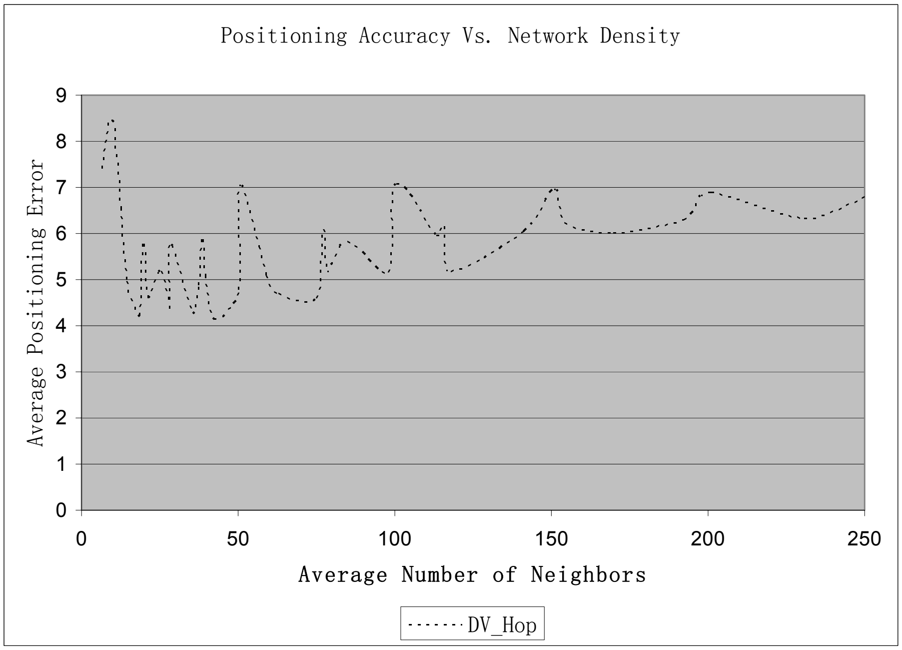


(b) DV-Hop

Figure 8. Relationship between the maximum number of hops and the average positioning estimation errors.



(a) PLACE



(b) DV-Hop

Figure 9. Relationship between the number of neighbor nodes and the average positioning estimation errors.

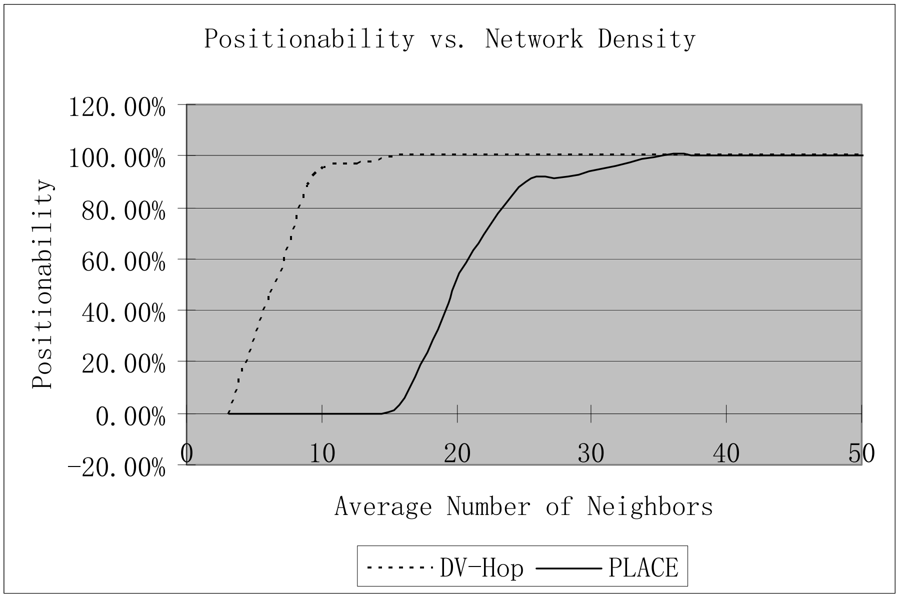


Figure 10. Relationship between the positionability and network density.

TABLE I. IMPORTANT PARAMETERS IN THE SIMULATIONS

Parameters	Values
Sensing area	10x10
Total number of nodes	100-500 (step size is 100)
Number of anchor nodes (*N*)	4
Positions of anchor nodes	(0,0),(0,10),(10,0),(10,10)
Radius of radio transmission range	1.0-4.5 (step size is 0.5)
Number of solution sets before making the distance estimation (*m*)	4
Error range (ε)	1% of the radius of radio transmission range
Repeating number of simulations for each set of parameters	100