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Chapter 7

TPSS: A Time-based Positioning Scheme for Sensor Networks with Short Range Beacons

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1 Introduction

A wireless sensor network is composed of a large number of small and inexpensive smart sensors for many monitoring, surveillance and control applications. Each sensor makes its own local observation. All active sensors in the network coordinate to provide a global view of the monitored area. It is anticipated that such a network can be used in unattended environments or hostile physical locations. Applications include habitat monitoring [8, 27], infrastructure surveillance [42], target tracking in tactical environments [13], etc.

Almost all these applications require sensors to be aware of their physical locations. For example, the physical positions should be reported together with the corresponding observations in wildlife tracking, weather monitoring, location-based authentication, etc [20, 26, 36]. Location information can also be used to facilitate network functions such as packet routing [10, 24] and collaborative signal processing [17], in which the complexity and processing overhead can be substantially reduced. Further, each node can be uniquely identified with its position, thus exempting the difficulty of assigning a unique ID before deployment [38].

However, many challenges exist in designing effective and efficient sensor self-positioning schemes for sensor networks. First, a localization algorithm must scale well to large sensor networks. Further, the location discovery scheme should not aggravate the communication and computation overheads of the network, since the low-cost sensors have limited resource budget such as battery supply, CPU, memory, etc. What's more, the localization scheme should not raise the construction cost of sensor nodes. Finally, the positioning scheme should be robust enough to provide high precision even under noisy environments. In this chapter, we present TPSS, a time-based scheme that meets many of the requirements mentioned above.

TPSS is different from TPS [9] and iTPS [40], even though all three rely on TDoA measurements to calculate a sensor position through trilateration. The beauty of TPSS lies in that there is no requirement for base stations to cover the entire network by powerful long-range beacons. Only short-range beacon nodes with known positions need to be deployed. A beacon node could be a typical sensor mounted with a GPS. Recall that TPS (iTPS) requires three (four) long-range beacon stations with each being able to cover the entire network. TPSS releases this restriction while retaining many nice features of the other two. For example, all these three schemes require no time synchronization among sensors and beacons. In TPSS, each sensor listens passively for signals from the beacons in its neighborhood. A sensor computes the range differences to at least three beacons and then combines them through trilateration to obtain its position estimate. This procedure contains only simple algebraic operations over scalar values, thus incurs low computation overhead. Since a beacon signal is transmitted within a short range only, the communication overhead is low, too. Whenever a sensor resolves its own position, it can work as a beacon and help other nodes on location computation. Simulation results indicate that TPSS is an effective self-positioning scheme for sensor networks with short range beacons.

This chapter is organized as follows. Section 2 summarizes the current research on location discovery. The network model to be studied is described in Section 3. The new positioning scheme, TPSS, is proposed in Section 4.

Simulation results are reported in Section 5. And we conclude our chapter in Section 6.

2 An Overview on Current Location Discovery Schemes for Sensor Networks

The popular Global Positioning System(GPS) [41] localization system may not be a practical solution for outdoor sensor networks. It is infeasible to install GPS on each sensor due to cost, form factors, power consumption and antenna requirements. Further, GPS requires direct Light-Of-Sight (LoS) communication, which renders it unfeasible for many outdoor application environments. Therefore in the past several years, extensive research has been directed to designing GPS-less location discovery schemes [1–3, 5, 6, 9, 14–16, 18, 19, 21–23, 28–37, 39]. These positioning algorithms differ in their assumptions on network deployment, device capabilities, node mobility, signal propagation, error requirement, etc. Thus, they can be classified differently. For example, some methods are designed for static sensor networks, where sensors remain stationary after deployment, while others are for dynamic sensor networks where sensors and beacons are mobile [2, 19]. These localization schemes can also be classified as centralized [11,39], where all computations are performed by a central point (e.g the base station), or distributed, where sensors estimate their positions independently with each other. Centralized methods have poor scalability and thus infeasible for large sensor networks. In this section, we will focus on distributed location discovery schemes for stationary sensor networks, which can be further classified as beacon-based and beacon-less depending on whether or not beacons are used, or classified as range-based and range-free according to the type of knowledge used in position estimation.

2.1 Beacon-based and Beacon-less Localization Schemes

2.1.1 Beacon-based Localization

The majority of current location detection systems assume the existence of beacons, whose positions are known through GPS receivers or manual configuration. A typical sensor first measures the distances or angles from itself to several beacons, then obtains position estimation through techniques such as *triangulation, trilateration, multilateration*, etc. Based on the coverage capabilities of beacons, these localization systems can be further classified as systems with long-range beacons or systems with short-range beacons.

Systems with long-range base stations [3, 9, 30] have a fixed set of powerful beacons, whose transmission range can cover the entire network. Usually these base stations are manually deployed, are time-synchronized, and are equipped with special instruments such as directional antennas. In systems with short-range beacons [21, 22, 36, 37], a small number of sensors with known positions are randomly deployed amongst with other ordinary sensors. Some of them rely on transmitting both RF and ultrasound signals at the same time [15, 36, 37], where the RF is used for time-synchronizing the sender and the receiver.

If a sensor cannot receive signals from enough beacons, none of the previous techniques will work. In this case, network connectivity can be exploited for range estimation [31, 32, 35, 39]. The connectivity information can be broadcasted using global flooding to notify all sensors of the locations of base stations [31, 32, 35]. A sensor node measures its distance to each beacon in terms of hop counts, then estimates its position based on the average distance per hop which is computed by base stations. Ref. [39] describes a localization scheme based on multidimensional scaling, which requires global connectivity information and centralized computation. These connectivity-based location discovery schemes require either long-range beacons or short-range beacons, but they have poor scalability due to the use of global flooding.

2.1.2 Beacon-less Localization

For a beacon-less localization system, some special nodes must be identified to provide reference for others to compute their positions. Such special sensors can be the perimeter nodes [33], whose distance (hops) to the other nodes can be estimated through flooding. Each non-perimeter node determines its location through an iterative procedure and periodically updates its coordinates as the average of its neighbors' coordinates. A more efficient position estimation algorithm is proposed in [14], which uses *deployment points* to provide reference for location estimation. Sensors are divided into groups. A group of sensors are dropped at the same deployment point. Relying on the prior knowledge about the probability distribution of the sensors' resident positions within each group, a sensor can estimate its location by observing the group memberships of its neighbors.

This method requires only one-hop broadcasting, thus involves light communication overhead. However, such a scheme has a strict demand on *a prior* knowledge of the deployment distribution, which is usually not possible in many applications.

2.2 Range-based and Range-free Localization Schemes

2.2.1 Range-based Localization

Range-based localization relies on the availability of point-to-point distance or angle information. The distance/angle can be obtained by measuring Time-of-Arrival (ToA), Time-Difference-of-Arrival (TDOA), Received-Signal-Strength-Indicator (RSSI), and Angle-of-Arrival (AOA), etc. The range-based localization may produce fine-grained resolution, but have strict requirements on signal measurements and time synchronization.

ToA measures the signal arrival times and calculates distances based on transmission times and speeds. GPS [41] is the most popular ToA-based localization system. By precisely synchronizing with a satellite's clock, GPS computes node position based on signal propagation time.

Compared to ToA, TDoA has an advantage as the former's processing delays and non-LOS propagation can introduce larger errors [7]. Ref. [36] proposes a TDoA based scheme (AHLos) that requires base stations to transmit both ultrasound and RF signals simultaneously. The RF signal is used for synchronization purposes. A sensor first measures the difference of the arrival times between the two signals, then determines the range to the base station. Finally, multilateration is applied to combine range estimates and generate location data.

RSSI computes distance based on transmitted and received power levels, and a radio propagation model. RSSI is mainly used with RF signals [1,18], but the range estimation can be inaccurate due to multipath fading in outdoor environments [36].

AoA-based methods first measure the angle at which a signal arrives at a base station or a sensor, then estimate the position using triangulation. The calculation is quite simple, but AoA techniques require special antenna and may not perform well due to omni-directional multipath reflections. Further, the signals can be difficult to measure accurately if a sensor is surrounded by scattering objects [7]. Ref. [28] proposes a prototype navigation system for autonomous vehicles, which estimates AoA by means of a set of optical sources and a rotating optical sensor. The system is not suitable for outdoor sensor networks due to its cost and complexity. Ref. [30] first transforms TDoA measurements into AoA information, then applies triangulation for location estimates. It requires three base stations with synchronized rotating directional antennae.

2.2.2 Range-free Localization

Range-free localization requires no measurement on distance or angle among nodes. They can be further classified as local techniques and hop-counting techniques [19].

- Local Techniques. A simple centroid algorithm is proposed in [3], in which each sensor estimates its position as the centroid of the locations of the neighboring beacons. The computation error can be reduced by a density adaptive algorithm (HEAP) if beacons are well-positioned [5]. However, this is unfeasible for ad hoc deployment. Later, He *et al.* propose the APIT method [16], which divides the environment into triangular regions between beacon nodes. Each sensor determines its relative position with the triangles, and estimates its own location as the center of gravity of the intersection of all the triangles that the node may reside in. However, APIT requires long-range beacon stations, which requires expensive high-power transmitters.

- Hop-Counting Techniques. In DV-hop [31, 32], base stations flood their positions to all nodes in the network. Sensors compute the minimum distance in hops to several base stations. Base stations compute an average distance per hop to other base stations, which will be flooded to the whole network to facilitate sensors to calculate their positions. Ref. [35] refines location estimates computed by DV-hop by using neighboring sensor positions and distance estimates to help convergence to a better solution. Similarly, Amorphous positioning scheme [29] also uses flooding to inform sensors of their hop-count distances to each beacon. The difference is that Amorphous localization method improves the location estimates through an offline hop-distance computation and neighbor information exchange. The hop-counting method excludes the requirement for densely-distributed beacons. However, the multi-hop flooding involves a large amount of communication overhead, and relies on a network with dense and uniformly-distributed sensors.

2.3 Secure Localization Schemes

Most of the current location discovery schemes assume a benign environment where sensors can get correct reference information from beacons. However, the actual sensor networks may be deployed in hostile environments. Beacons can be compromised, then inject false positioning information into the network. Sensors can be misled and then claim that they are at positions that are far away from their actual locations. In some cases, such false reports may incur disastrous results. For example, in sensor networks designed for military tracking and reconnaissance surveillance, nodes are misled and report themselves in faraway places. The false information may result in a fatal decision-making, when sensors report that they are in a safe region [12]. Hence, it is important to assure that the received beaconing information is true, or the resolved location is correct.

Sastry*et al.* [34] make the first attempt to solve the secure localization problem in wireless sensor networks. A distance bounding protocol, ECHO, is proposed to use both RF and ultrasound signals for secure location verification. However, such scheme only works for in-region verification, which means that ECHO only verifies whether or not a node is within a region of interest. Besides, ECHO relies on the availability of both RF and ultrasound signals.

Lazos and Poovendran propose a range-independent secure positioning scheme, SeRLoc, in [23]. Using directional antennas, each beacon node transmits different beacon signal at each antenna sector. Thus, if a sensor receives a beacon from a specified antenna sector, the sensor must reside within that sector. Based on the information received about the sector boundary lines and the positions of the beacons, a sensor can identify the overlapping region of all the sectors that it hears and estimate its location as the center of gravity (CoG) of the region. SeRLoc can tolerate the wormhole attack, the sybil attack and compromised sensors. However, SeRLoc does not work well if beacons are compromised.

A novel localization anomaly detection scheme, namely LAD, is proposed by Du *et al.* [12], which works for detecting location estimation anomaly at sensor nodes. LAD assumes *a prior* knowledge of the deployment distribution and the group memberships of node neighbors, and enables sensors to detect localization anomalies. By verify the inconsistency between the derived locations and the node observations, LAD can determine if an anomaly happens. LAD works effectively against localization anomalies, but requires the availability of the deployment distribution which is hard for many sensor network applications.

Capkun and Hubaux [6] analyze the resistance of positioning techniques to position and distance spoofing attacks, and propose the Verifiable Multilateration mechanism for secure computation and verification of node positions. A secure positioning scheme, SPINE, is also proposed, which can resist against distance modification attacks from a large number of attackers.

2.4 TPS, iTPS, and TPSS

TPS [9] and iTPS [40] rely on the transmission of RF signals from beacon stations for location discovery. Such schemes require no time synchronization in the network and minimal extra hardware in sensor construction. No connectivity knowledge is needed, thus they can scale well to large networks. Since sensors just listen passively to beacon signals, no extra communication overhead is introduced. With only local measurements, TPS and iTPS retain the fine-grained computation of range-based schemes, but exclude the necessity of time synchronization among beacon nodes. As the location detection algorithm involves only some simple algebraic operations, the computation overhead is also low.

TPSS retains all the above nice features of TPS and iTPS, but requires no powerful long-range beacons to cover the entire network. With only a few short-range beacons deployed, sensors can compute their positions easily. TPSS can be applied to large-scale sensor networks where the deployment of powerful long-range beacons are too expensive or not practical.

3 Network Model

In this chapter, we consider a sensor network deployed over a two-dimensional monitored area. Actually, our TPSS scheme can be easily extended to higher-dimensional space. In this model, each sensor has limited resources (battery, CPU, etc.), and is equipped with an omni-directional antenna. Some sensors, called *beacons*, have the ability to position themselves. They are deployed together with typical sensors whose positions are to be computed with the TPSS. An example scenario is plotted in Fig. 1. The beacon nodes will broadcast beacon signals periodically to assist other sensors with location discovery. Note that the only difference between a beacon and a sensor is whether the location is known. Whenever a sensor gets localized using the TPSS algorithm, it will broadcast its own location and help other sensors for position detection. In other words, it can work as a beacon node.

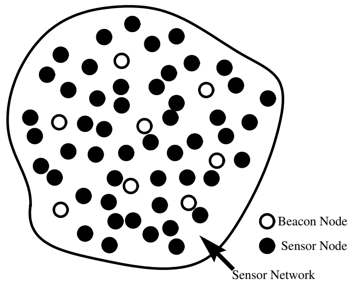


Figure 1: An Example Sensor Network

4 TPSS: A Time-Based Positioning Scheme with Short Range Beacons

In this section, we propose TPSS, a time-based positioning scheme for sensor networks with short range beacons. TPSS consists of three steps. In the first step, a sensor collects all the signals from the neighboring beacons, and groups them according to the sources of the signals. The next two steps work on the signals belonging to the same group: the range differences from beacon nodes to the sensor are computed and then the coordinates are resolved.

4.1 Step 1: Signal Collection

Assume each beacon node initiates a beacon signal once every T seconds. This signal contains the beacon's location and a TTL (Time To Live) field with a initial value ≥ 3. The format of the message is demonstrated in Fig. 2. A beacon node hearing a beacon signal with $TTL > 0$ will broadcast it again after decreasing the TTL value by 1 and after attaching both its own location and the time difference between when the signal is received and when it is re-broadcasted. This is indicated by the *relay* and *delay* fields in the message format shown in Fig. 2. Each sensor with unknown location listens passively for the beacon signals and group them according to the initiators of the messages. If a sensor receives the same signal (originated from the same beacon) at least three times, the location of the sensor can be readily determined by the following two steps.

src	*TTL*	$relay_1$	$delay_1$	$relay_2$	$delay_2$	......

src: location of the node generating the message
TTL: time to live
$relay_i$: location of the *i*-th node relaying the message
$delay_i$: time bw. when the msg is received and when it is re-broadcasted by the *i*-th relay

Figure 2: Format of the Message Transferred

4.2 Step 2: Range Detection

We only consider groups containing at least three messages originated from the same beacon node. In each group, select three where the involved beacons are *non-collinear*.

We first assume the beacon signal is relayed without loss, that is, the signal from the initiator as well as from all the intermediate relay nodes can successively reach the sensor S. Fig. 3 shows one such example. Beacon A starts a message $M = (A, 3, -, -)$ which arrives S and beacon B at time t_1 and t_b, respectively. B modifies M as $M^{'} = (A, 2, B, \Delta t_b)$ and re-broadcasts it at time $t_b^{'}$, where $t_b^{'} = t_b + \Delta t_b$. $M^{'}$ arrives at S and beacon C at time t_2 and t_c, respectively. C modifies $M^{'}$ as $M^{"} = (A, 1, B, \Delta t_b, C, \Delta t_c)$ and broadcasts $M^{"}$ at time $t_c^{'}$, where $t_c^{'} = t_c + \Delta t_c$. Finally, $M^{"}$ arrives at S at time t_3. Assume all the nodes transfer the signals at the same speed v. Let d_{sa}, d_{sb}, d_{sc} represent the distances from the sensor S to beacons A, B, C, respectively. Let d_{ab}, d_{ac} denote the distance between beacons A and B, A and C, respectively.

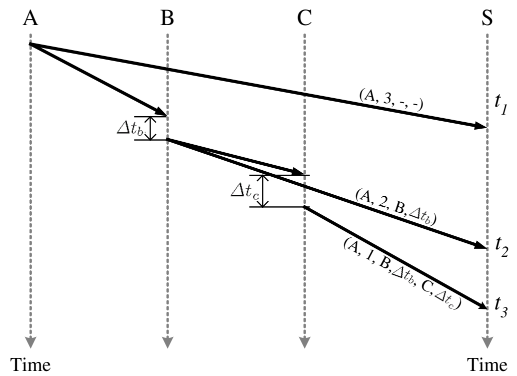


Figure 3: Range Detection: Signal is Relayed Without Loss

We have

$$\frac{d_{ab}}{v} + \Delta t_b + \frac{d_{sb}}{v} - \frac{d_{sa}}{v} = t_2 - t_1 \quad (1)$$

$$\frac{d_{bc}}{v} + \Delta t_c + \frac{d_{sc}}{v} - \frac{d_{sb}}{v} = t_3 - t_2 \quad (2)$$

which gives

$$d_{sa} = d_{sb} + k_1, \quad \text{where} \quad k_1 = d_{ab} - v \cdot (t_2 - t_1 - \Delta t_b) \quad (3)$$
$$d_{sc} = d_{sb} + k_2, \quad \text{where} \quad k_2 = -d_{bc} + v \cdot (t_3 - t_2 - \Delta t_c) \quad (4)$$

Eqs. (3)(4) show that k_1, k_2 can be obtained by measuring t_1, t_2, t_3 with S's local timer, learning the positions of A, B, C and time differences $\Delta t_b, \Delta t_c$ from the beacon signals. We are going to apply trilateration with k_1, k_2 to compute coordinates (x, y) for sensor S in Step 3.

Note that TPSS can still work if some beacon signals get lost during the transmission from the initiator or any intermediate relay nodes. As long as a sensor S receives one signal from three different relay beacons, S's location can be computed with TPSS. For example (Fig. 4), M is a beacon signal travelling along beacons 1, 2, 3, 4 and 5. The messages relayed by beacons 1 and 4 are lost or destroyed during the transmission. S receives M only from beacons 2, 3, 5 at time t_0, t_1, t_2, respectively. Let $d_{ij}(d_{sj})$ denote the distance between node $i(s)$ and j, and Δt_i be the time difference information conveyed by beacon node i. We have:

$$\frac{d_{23}}{v} + \Delta t_3 + \frac{d_{s3}}{v} - \frac{d_{s2}}{v} = t_1 - t_0 \quad (5)$$
$$\frac{d_{34}}{v} + \Delta t_4 + \frac{d_{45}}{v} + \Delta t_5 + \frac{d_{s5}}{v} - \frac{d_{s3}}{v} = t_2 - t_1 \quad (6)$$

It follows that,

$$d_{s2} = d_{s3} + k_1, \quad \text{where} \quad k_1 = d_{23} - v \cdot (t_1 - t_0 - \Delta t_3) \quad (7)$$
$$d_{s5} = d_{s3} + k_2, \quad \text{where} \quad k_2 = -(d_{34} + d_{45}) + v \cdot (t_2 - t_1 - \Delta t_4 - \Delta t_5) \quad (8)$$

In this case, k_1, k_2 can be known when S receives three messages among all that has been relayed after the same initiator.

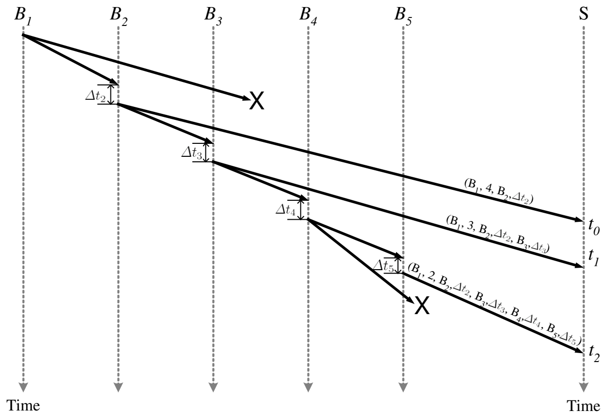


Figure 4: Range Detection: Signal is Relayed With Loss

Comparing Eqs. (3)(4) with (7)(8), we can summarize the result of range detection as following:

$$d_{SA} = d_{SB} + k_1 \tag{9}$$

$$d_{SC} = d_{SB} + k_2 \tag{10}$$

where, A, B, C are the three relay nodes in the same group that convey messages originated from the same source and are sorted according to the sequence they relay the signal.

Remarks:
(i) All times are estimated locally. For example, the arrival times of the signals (t_1, t_2, etc.) are measured at sensor S's local timer; the time differences at relay nodes ($\Delta t_b, \Delta t_c$, etc.) are computed based on the beacon's local timer.
(ii) For each sensor S, range detection is conducted on

each group that contains messages from the same initiator. Corresponding location computation is taken in the next step. Averaging all the results computed for S, the final result is taken as the coordinates of node S.
(iii) For each group, there may exist multiple methods to select the three messages. Consider a signal travelling along beacons 1 to 4, and assume all the relayed signals arrive at S finally. We have $d_{s,i} = d_{s,i-1} + k_{i-1}$, where $k_i = v \cdot (t_{i+1} - t_i - \Delta t_{i+1}) - d_{i,i+1}$, $d_{ij}(d_{sj})$ is the distance between node $i(s)$ and j, Δt_i is the time difference at the relay node i, and t_i is the time S receives the message from beacon i, for $i = 2, 3$, and 4. The three equations can be divided into two overlapping groups. Group I contains $d_{s2} = d_{s1} + k_1$, $d_{s3} = d_{s2} + k_2$; while group II contains $d_{s3} = d_{s2} + k_2$, $d_{s4} = d_{s3} + k_3$. Each group can be used to compute S's coordinates in the next step independently.

4.3 Step 3: Location Computation

From Eqs. (9)(10), $d_{SA} = d_{SB} + k_1$, $d_{SC} = d_{SB} + k_2$, we get the following three equations with three unknowns x, y and d_{SB} based on trilateration:

$$(x - x_b)^2 + (y - y_b)^2 = d_{sb}^2 \quad (11)$$
$$(x - x_a)^2 + (y - y_a)^2 = (d_{sb} + k_1)^2 \quad (12)$$
$$(x - x_c)^2 + (y - y_c)^2 = (d_{sb} + k_2)^2 \quad (13)$$

As proposed in [9], we can solve these equations in two steps: First, transform the coordinates into a system where A, B, C reside at (x_1,0), (0,0) and (x_2, y_2), respectively; Second, solve the equations with the efficient method proposed in [9]. Since the positions at the original coordinate system can always be obtained through rotation and translation, the solution provided by [9] can be treated as a general one:

$$
\begin{aligned}
x &= \frac{-2k_1 d_{sb} - k_1^2 + x_1^2}{2x_1} && (14)\\
y &= \frac{(2k_1x_2 - 2k_2x_1)d_{sb}}{2x_1y_2} + \frac{k_1^2x_2 - k_2^2x_1 + x_2^2x_1 + y_2^2x_1 - x_1^2x_2}{2x_1y_2} && (15)
\end{aligned}
$$

where d_{sb} is the root of $\alpha d_{sb}^2 + \beta d_{sb} + \gamma = 0$, with

$$
\begin{aligned}
\alpha &= 4[k_1^2y_2^2 + (k_1x_2 - k_2x_1)^2 - x_1^2y_2^2], && (16)\\
\beta &= 4[k_1(k_1^2 - x_1^2)y_2^2 + \\
&\quad (k_1x_2 - k_2x_1)(k_1^2x_2 - k_2^2x_1 + x_2^2x_1 + y_2^2x_1 - x_1^2x_2)], && (17)\\
\gamma &= (k_1^2 - x_1^2)^2y_2^2 + (k_1^2x_2 - k_2^2x_1 + x_2^2x_1 + y_2^2x_1 - x_1^2x_2)^2. && (18)
\end{aligned}
$$

Remarks:
Steps 2 and 3 are repeated once per epoch on all triple messages within each group and all valid groups that can help S estimate its position. The final coordinates (x, y) are obtained by averaging all the results. Once S's position is known, it will become a beacon and help other sensors on location estimation. The iteration of such process can help more and more sensors get localized, as shown by our simulation results in Section 5.

5 Performance Evaluation

We consider a sensor network deployed over a field of 100 by 100. The transmission range of sensors and beacons is fixed to 10. We assume each sensor can correctly receive from all the beacons within its transmission range. Each beacon initiates a beacon signal once per epoch. A sensor becomes a beacon node after its position is resolved. Since

MATLAB provides procedures to randomly deploy sensors and beacons, it is selected to perform all the simulations.

According to Eqs. (3)(4) and (7)(8), the coordinates (x, y) are obtained from the measurements of t_i's, Δt_i's. The accuracy of t_i's depends on the local timers of the sensor nodes, whose measuring error is affected by the TDoA timer drift, the signal arrival time correlation error, and the reception delays, etc. In the beacon node, Δt_i is computed based on the beacon's local timer and the known system delays, whose inaccuracy is determined by the reception and transmission delays, the time-stamping inaccuracies, and the turn-around delay measurement errors, etc. In our simulation study, we only consider the inaccuracy of the TDoA measurement at the sensors (t_i's), since Δt_i's play the same role. Such inaccuracy is modeled as a normal distribution in the simulation.

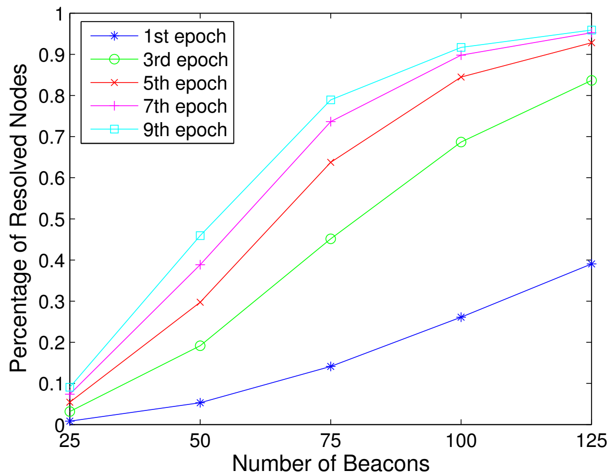


Figure 5: Percentage of resolved nodes vs. the number of the initial beacons: the first 9 epochs.

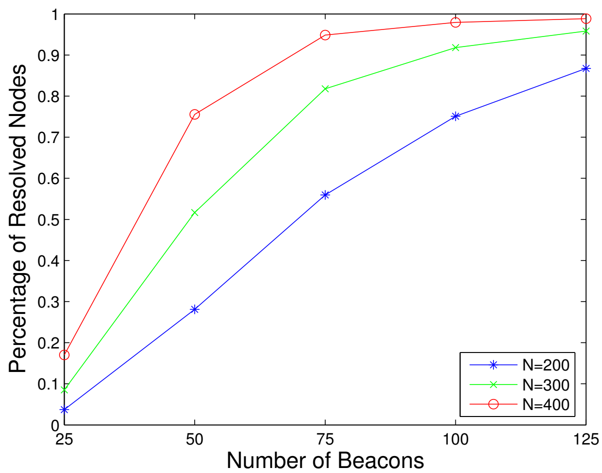


Figure 6: Percentage of resolved nodes vs. the number of the initial beacons: with different network density.

We will evaluate the effectiveness of TPSS. First, we want to study the percentage of sensors whose locations can be resolved while varying the number of initial beacons. We consider a network with 300 nodes. Fig. 5 reports the results for the first 9 epochs. We can tell that the percentage of resolved nodes increases as the number of the initial beacons increases. This also holds true as the number of epochs increases. Another observation is that the more the initial beacons are deployed, the less epochs TPSS will require to achieve a high percentage of the resolved nodes in the network. Second, we test the impact of network density on the localization process. Fig. 6 illustrates the percentage of resolved sensors when the number of initial beacons varies under different network density. The number of epochs is set to 10. It shows that as the network density increases, more and more sensors get localized. This is reasonable. Given a fixed number of beacons deployed in a fixed-sized network, the more sensors within the network, the more nodes can be covered by a three-beacon group. Therefore the increase of the number of sensors will not require the number of beacons to be increased as well, as long as the existent beacons can cover most of the network. All the results are the average over 100 runs.

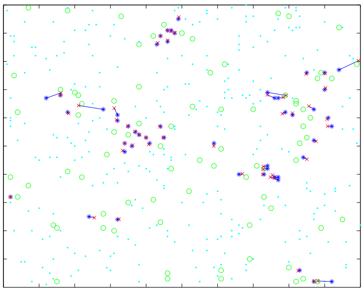
We obtain two observations from Fig. 5 and 6. First, the more number of beacons deployed, the more number of sensors get localized. Second, once more and more sensors resolve their positions, more and more sensors get localized. Thus we can expect that with only a small number of short-range beacons deployed, many sensors can be localized using our TPSS scheme. Intuitively, these two results are reasonable since the number of beacons increases. We can give a brief statistical analysis about why the increase of the number of beacons can result in a better performance. Assume a network contains N nodes randomly deployed over an area of size L by L, in which q percent of the nodes are beacons. The transmission range of a node is R. Whether a sensor can determine its position depends on whether it has enough beacons in the neighborhood. We will not consider the case when three beacons are colinear, since the possibility is quite low. Thus we have:

$$
\begin{aligned}
P(S \text{ is resolved}) &\approx P(S \text{ can be reached by at least three beacons}) \\
&= \sum_{d=3}^{Nq} P(S \text{ can be reached by } d \text{ beacons}) \\
&= \sum_{d=3}^{Nq} \binom{Nq}{d} p^d (1-p)^{Nq-d}, \text{ where } p = \frac{\pi R^2}{L^2} \\
&\to \sum_{d=3}^{Nq} \frac{\lambda^d}{d!} \cdot e^{-\lambda}, \text{ as } N \to \infty, \text{ where } \lambda = Nqp, p = \frac{\pi R^2}{L^2} \\
&= 1 - e^{-\lambda}(1 + \lambda + \lambda^2/2) = f(\lambda)
\end{aligned}
$$

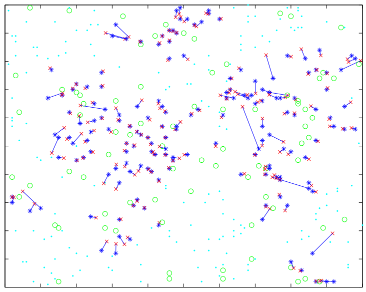
Since $\lambda = Npq > 0$, $f'(\lambda) = \lambda^2 e^{-\lambda}/2 > 0$, which indicates that $f(\lambda)$ will increase as λ increases. Therefore the more number of beacons (Nq), the higher probability that a sensor gets localized using our TPSS scheme.

Next we study the impact of the inaccuracy of TDoA measurements on the localization errors. The first result is reported in Fig.7 for a network of 400 nodes with 20% of initial beacons. For each sensor that has been resolved, the estimated location is linked with the corresponding real position. We observe that as the epoch increases, the position error tends to increase. This trend can also be observed in a further study given on the impact of different epochs and measurement errors on position errors. The result is given in Fig. 8, which shows the computation errors (averaged over 100 tests) after 1 or 3 epochs for different network density with the same initial beacon percentage 25%.

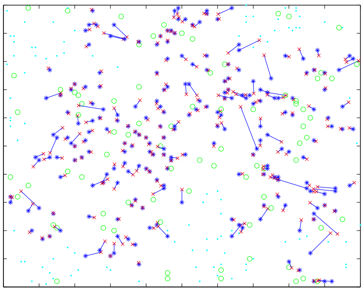
The increasing of positioning errors along with epochs shows the effect of cumulative errors. Recall that once a sensor gets localized, it will use its computed position to help other sensors on position estimation. Considering the



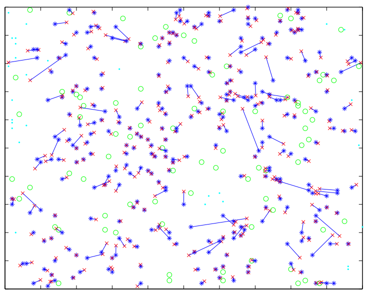
(a) epoch=1, 15.94% resolved



(b) epoch=3, 51.56% resolved

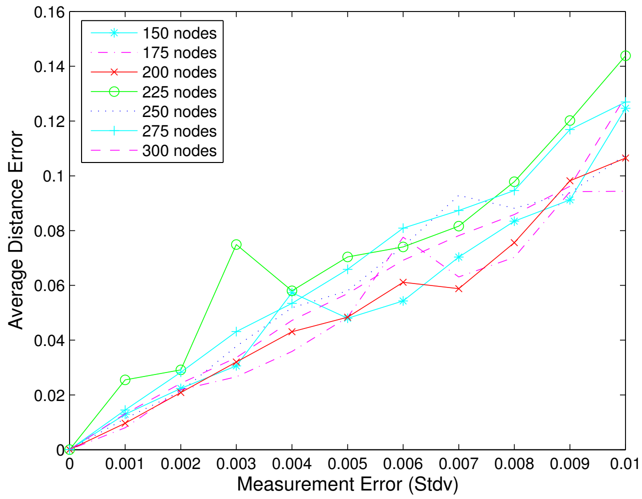


(c) epoch=5, 69.69% resolved

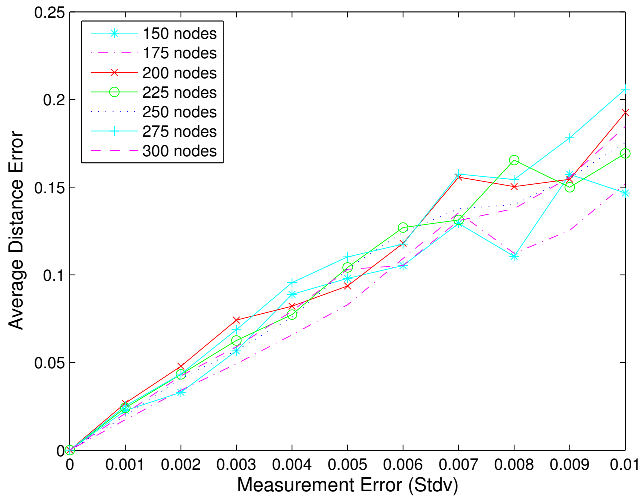


(d) epoch=10, 91.25% resolved

Figure 7: Illustration of TPSS in terms of variant epochs and resolved percentage. The measuring errors are assumed normally distributed w.r.t. N(0, 0.05). In each figure, "o" represents a beacon, "x" represents the estimated location of a sensor which is linked to the real position (denoted by *), and "·" represents a node whose location is not resolved yet.



(a) epoch=1



(b) epoch=3

Figure 8: Illustration of Position Errors in terms of Different Epochs and Measurement Errors: with Different Network Density.

unavoidable measuring errors, such a process makes it possible to "pass" computation errors from resolved sensors to the others, though it does help in reducing the number of beacons necessary for location discovery. As more and more sensors get localized, more and more computation errors are introduced, that is, the inaccuracy gets cumulated. However, Figs. 7-8 show that such an error cumulation is quite slowly in TPSS. For most of the resolved sensors, the localization error is still tolerable comparing with the transmission range. Another observation from Fig. 8 is that the computation errors increase along with the TDoA measurement errors. This trend shows the impact of measurement errors in local timers at sensors, which can be easily understood from Eqs. (3)(4) and (7)(8). Thus the larger the TDoA measuring error, the larger the position error.

6 Conclusion

In this chapter, we present TPSS, a time-based localization scheme which uses only short-range beacons. While retaining most of the benefits that TPS, iTPS have, TPSS releases the strict requirement that the beacon stations should be able to reach all the sensor nodes in the network. Simulation results show that TPSS is a simple, effective and practical location discovery scheme that can be used in sensor networks.

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