

Indoor Location Tracking using Received Signal Strength Indicator

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1. Introduction

The development pace of location tracking research is highly tied up with the advancement of wireless sensor network (WSN) and wireless technologies. As sensor nodes in WSN became smaller and stronger, the ability of processing information and managing network operation also became more intelligent. This can be observed from the application of tracking from coarse-grained to fine-grained advancement.

In coarse-grained tracking such as (Zhao, et al., 2003), the location of target is just detected by two or more sensor nodes along the movement path of the target. The coordinate of the tracked target is then determined by averaging the location coordinates of those sensor nodes which are able to detect the target. Using this approach, the accuracy and resolution of location estimation is affected by the density of sensor nodes in the area.

In fine-grained tracking such as (Smith, et al., 2004), three or more sensor nodes are responsible to track the target in the area. Instead of just detection, the distances between the target and the sensor nodes are measured. The determination of distance between two entities is called "ranging". Using the measured distances, the exact location coordinate of the target can be computed by angulation or lateration techniques (Hightower, et al., 2001). Therefore, increasing the node density of the area does not really increase the accuracy of location estimation. It rather depends on the accuracy of the ranging method.

This chapter presents the authors' research investigation of developing an indoor tracking and localization system. The experimental system was tested and achieved in the laboratory of Dongseo University for supporting author's PhD studies. The thesis (Pu, 2009) provides further technical details for the design and implementation of the tracking system. For the ease of reading, this chapter was organized as follows: section 1 gives overall fundamentals of location tracking systems, from every aspect of considerations. Section 2 analyzes the nature of wireless ranging using received signal strength indicator, especially for the case of indoor signal propagation and ranging. Section 3 provides the complete flow of designing and implementing indoor location system based on received signal strength. Finally, section 4 concludes the whole work.

1.1 Classification of Location Tracking Systems

Localization of sensor nodes and location tracking applications have been an important study since WSN concept was introduced. Today, various techniques and technologies (Zhao, et al., 2004) are available for the development of off-the-shelf location systems (Hightower, et al., 2001). The selection requirement of location systems can be more specific to suit different needs and environments such as accuracy, indoor/outdoor environment, positioning techniques, ranging methods, security and privacy, device available, WSN deployment restriction, network scale, implementation cost, healthy consideration, and etc. From the technology point of view, classification of location systems can be categorized in a tree as shown in Fig. 1.

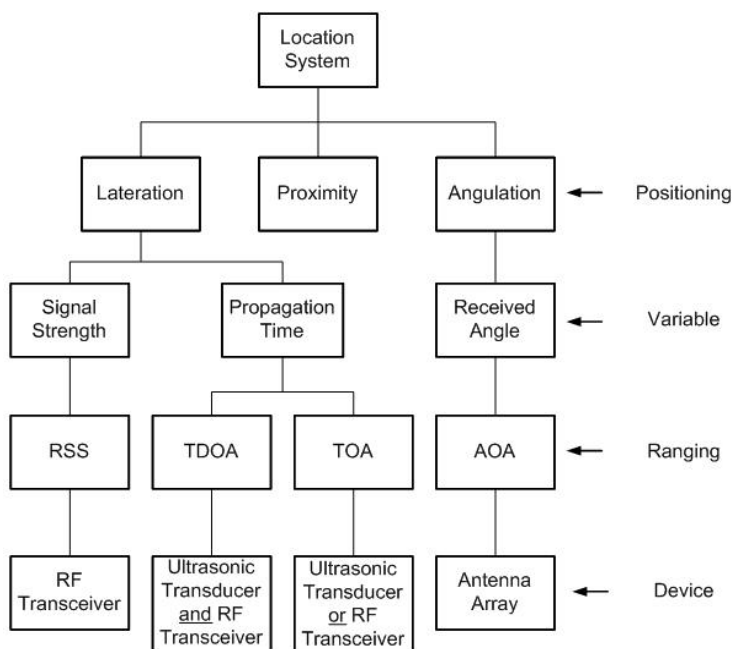


Fig. 1. Classification of Location Tracking Systems (Pu, 2009).

1.1.1 Positioning Aspect

In Fig. 1, classification is first viewed from positioning aspect, followed by variable, ranging, and device aspects. From the positioning aspect, three kinds of location estimation techniques can be used to determine location coordinate including proximity, angulation, and lateration methods (Hightower, et al., 2001).

Proximity estimation is a range-free (He, et al., 2005) or detection (Nakajima, 2007) based technique that does not compute the exact location coordinate of the tracking target. Hence, this kind of location estimation is a “coarse-grained” method. Both angulation and lateration estimations are range based technique which are able to compute the exact location coordinate of the tracking target from measured sensor data. Hence, this kind of location estimation is a “fine-grained” method. The difference between them is the way of

estimation. Angulation (Kamath, et al., 2007) computes location coordinate from the angles between target location and reference locations, whereas lateration (Rice, et al., 2005) computes location coordinate from the distances between target location and reference locations.

1.1.2 Variable Aspect

From the variable aspect of location system in Fig. 1, there are three types of variable can be used to find location-related sensor data. These variables are easy to measure from physical world: received angle, propagation time, and signal strength. Received angles between target and reference locations are the main variables measured for angulation estimation.

Propagation time is the time duration taken for a signal to travel from transmitter to receiver. Since the propagation speed of a kind of signal through a medium is constant, it is convenient to find distance between transmitter and receiver from propagation time. Signal strength can be measured at receiver when it receives the signal from transmitter. If distance is further, signal strength becomes weaker by attenuation of path. Using this relationship, it is possible to find distance by evaluating total attenuation. Both propagation time and signal strength are able to provide distance between transmitter and receiver, thus they are used in lateration estimation.

1.1.3 Ranging Aspect

From the ranging aspect of location system in Fig. 1, there are four types of distance measurement techniques. They are angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), and received signal strength (RSS). AOA (Tian, et al., 2007) is a method to measure the angle of arrival of a received signal. By comparing the direction of signal arrival with a reference orientation, received angle can be measured. The receiver may also know its own orientation for better angle measurement.

TOA (Mak, et al., 2006) is used when centralized communication is possible. This ranging method measures the arrival time between transmitter and receiver. Two approaches can be used to implement this ranging method. First approach uses a transmitter to transmit signal to many receivers. All receivers then forward their signal arrival time to a centralized system for comparison. Another approach uses many transmitters to send signals to a receiver. The receiver measures arrival time of all signals and makes comparison in the receiver system. This approach may have technical problems as all transmitters must be synchronized so that they send signal among certain time segments. In addition, signals may be lost due to multiple signals received at the same time if signal propagation time is exactly equal to the duration of time segment.

TDOA (Najar, et al., 2001) is an improved version of TOA to avoid synchronization difficulty and packet loss problems. To implement TDOA, a transmitter is required to send two different signals with different propagation speeds. When the two signals are received at the receiver, the difference of arrival times between two signals can be measured. Using the difference of arrival times, time of flight (TOF) of a signal can be found, and it is exactly equal to propagation time of a signal.

RSS (Cong, et al., 2008) is a method to find distance from attenuation of propagation path. If the transmission power is known, the total attenuation of signal propagation through the path can be calculated by subtracting the received power from transmitted power.

1.1.4 Device Aspect

From the device aspect of location system in Fig. 1, there are basically three types of distance measurement tools: antenna array, RF transceiver, ultrasonic transducer. Among them, antenna array is used to measure angle of received signal (Abdalla, et al., 2003) by comparing the phase difference of signals from different antennas. The measurement result can be used in AOA ranging.

If only RF transceiver is used, it can measure the received power and provide to RSS ranging method. In most of the RF transceiver, a dedicated register is used to store the received signal strength indicator (RSSI). Therefore, it is a low-cost and convenient way to measure distance.

If either RF transceiver or ultrasonic transducer is used, then they only can measure arrival time of signals. Thus, it can be used in TOA ranging method. If both RF transceiver and ultrasonic transducer are used (Smith, et al., 2004), then two different signals: RF and ultrasound signals are propagating through the path with different speeds. In small range applications, RF propagation time can be ignore and considered zero second whereas ultrasound takes longer time. Therefore, the time difference between two signals can be measured by starting a timer at RF signal arrival and stopping the timer at ultrasonic signal arrival.

1.2 Positioning Techniques

Positioning techniques are the first to consider in the initial state of location system design. This is because positioning techniques determine the ways of computation, and thus the methods used in distance measurement, and finally devices selection. In the previous section, three major positioning methods were mentioned. In this section, the details of location estimation using proximity, angulation, and lateration are given.

1.2.1 Proximity Estimation

Proximity estimation is usually used in localization of the wireless sensor nodes in a network. Because of the nature of information provided, exact location coordinate is not available but locations of surrounding sensor nodes can be obtained. Thus, it is not suitable to be selected for location tracking applications. However, it is good for localizing large scale sensor network (He, et al., 2005).

Many approaches to proximity estimation have been proposed. The typical and authoritative range-free location estimation schemes include centroid algorithm (Bulusu, et al., 2000), DV-hop scheme (Niculescu, et al., 2003), and area-based approximate point-in-triangulation test (APIT) algorithm (He, et al., 2005).

Centroid localization algorithm broadcasts all possible reference node's location information to all other target nodes. The target nodes use the location information (x_i, y_i) from surrounding reference nodes to estimate its location coordinate $(x_{\text{target}}, y_{\text{target}})$ as shown in the following expression (Bulusu, et al., 2000):

$$(x_{\text{target}}, y_{\text{target}}) = \left(\frac{1}{N} \sum_{i=1}^N x_i, \frac{1}{N} \sum_{i=1}^N y_i \right) \quad (1)$$

where N is the total number of surrounding reference nodes considered in the location estimation iteration.

Centroid algorithm is not considered accurate enough because of the simplicity and incompleteness. The difficulty of centroid algorithm is the number of reference nodes to be considered in the estimation. By default, it is the total number of surrounding reference nodes that the target node can detect and communicate. However, estimation result could be unacceptable if the target node is located near the edge of the whole network.

To avoid the problem of centroid algorithm, it is necessary to take into consideration of the distance between reference node and target node. More precisely, the “distance” is measured in a form of hop counting as range-free approach does not perform distance ranging task. Therefore, the number of surrounding reference nodes can be limited in first or second levels (hops) of message passing.

DV-Hop localization algorithm (Niculescu, et al., 2003) was proposed to consider hop counting for distance estimation. This work uses an approach that is similar to vector routing algorithms. At first, all sensor nodes broadcast their node ID and information to the nearest sensor nodes. These surrounding nodes receive it first-hand, thus a distance vector is stored in these nodes with reference to the source nodes as first hop. These first-hand nodes diffuse distance vector outward with hop-count values incremented at every intermediate hop. If the reference nodes receive distance vector with higher hop-count value as compared to previously received hop-count value, no action is to be taken. As a result, all sensor nodes have a distance vector of all other sensor nodes. An example of a target node A and the stored hop-count for the distance vector in all other nodes is shown in Fig. 2 (He, et al., 2005).

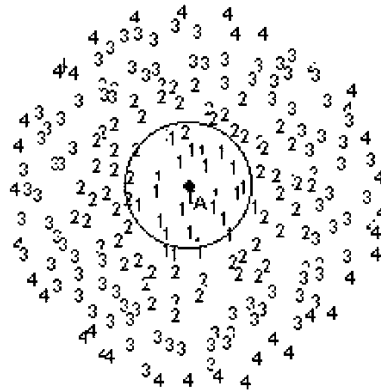


Fig. 2. Hop-count Spreading (He, et al., 2005).

After hop-count distances are obtained in every node for all other nodes, the next step of DV-Hop is to find the average distance between hops using the following expression (Niculescu, et al., 2003):

$$HopSize_i = \frac{\sum \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum h_j} \quad (2)$$

where $HopSize_i$ is the average single hop distance for sensor node i . (x_i, y_i) is the location of the node i and (x_j, y_j) is the location for all other nodes. h_j is the hop-count distance from node j to node i . If the target sensor node can hear more than three sensor nodes which are location aware, trilateration or multilateration can be used to estimate the location of target node by combining hop-count distance vector and $HopSize$.

DV-Hop performs well when the deployment of sensor nodes is regular in node density and the distances among sensor nodes. However, the estimation result may not be optimal if the radio pattern is irregular and random node deployment is used in practical. To solve this problem and have better localization result, APIT algorithm (He, et al., 2005) was proposed for area-based range-free localization solution. In APIT approach, all sensor nodes can be localized from just few GPS equipped anchors. Using the location information provided from these anchors, APIT algorithm divides the area occupied by sensor nodes into many triangular regions among beaconing nodes as shown in Fig. 3 (He, et al., 2005).

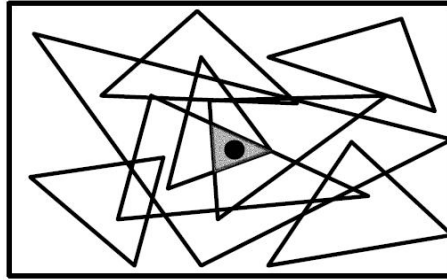


Fig. 3. Localization using APIT (He, et al., 2005).

The process of APIT algorithm first starts from localizing sensor nodes using the three GPS equipped anchors to reduce the possible area that a sensor node may be inside or outside the triangular regions. After the possible region is reduced, some sensor nodes can be anchors to further divide the area into more and smaller triangular regions in next round. This process continues until the possible region of a node can be resided small enough to obtain more accurate location estimation. This approach provide excellent accuracy when irregular radio patterns and random node placement are considered, thus it is sufficient to support location information to various scenarios of applications in sensor networks deployment.

1.2.2 Triangulation Estimation

Triangulation estimation is a trigonometric approach of determining an unknown location based on two angles and a distance between them. In sensor network, two reference nodes are required to be located on a horizontal baseline for x axis, and two sensor nodes are located on a vertical baseline for y axis. The distance d_r between the two reference nodes on the baseline can be measured in preliminary stage and stored in memory. The two angles α_1 and α_2 are measured between the baseline and the line formed by the reference node and target node as shown in Fig. 4.

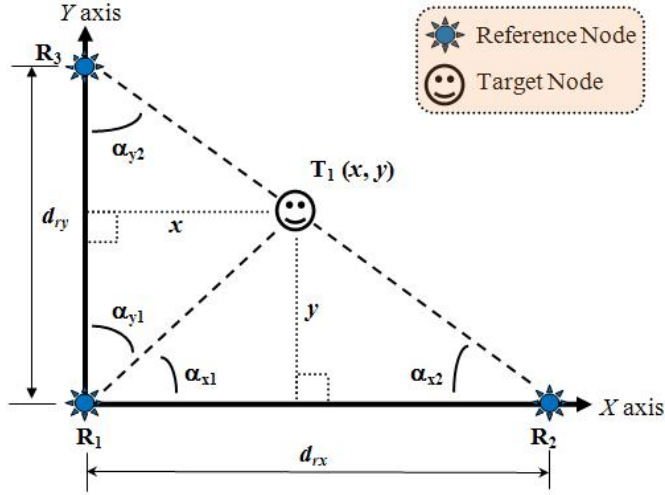


Fig. 4. Triangulation Estimation (Pu, 2009).

In Fig. 4, reference nodes R_1 and R_2 form the baseline of X-axis. Reference node R_1 can be reused to form the baseline of Y-axis together with reference node R_3 . A target node T_1 moves freely around in the area. Based on basic triangulation, the location coordinate (x, y) of T_1 can be determined by using the combination of R_1 and R_3 to find x , and the combination of R_1 and R_2 to find y (Pu, 2009):

$$x = \frac{d_{ry} \sin(\alpha_{y1}) \sin(\alpha_{y2})}{\sin(\alpha_{y1} + \alpha_{y2})} \quad (3)$$

$$y = \frac{d_{rx} \sin(\alpha_{x1}) \sin(\alpha_{x2})}{\sin(\alpha_{x1} + \alpha_{x2})}$$

Alternatively, the expressions can be reformed to a simpler way using trigonometric identity (Pu, 2009):

$$x = \frac{d_{ry}}{\tan^{-1}(\alpha_{y1}) + \tan^{-1}(\alpha_{y2})} \quad (4)$$

$$y = \frac{d_{rx}}{\tan^{-1}(\alpha_{x1}) + \tan^{-1}(\alpha_{x2})}$$

Depending on the architecture of location system, the computation of triangulation can be performed either in a centralized system that collects those angle measurements from distributed reference nodes, or in the target node itself. For the first case, the target node broadcasts a signal and the surrounding reference nodes measure the angle of received signal. The reference nodes forward the measured angles to a centralized system as shown in Fig. 5. In this case, the first reference node measures acute angle α and the second node

measures obtuse angle β . Thus, the supplementary angle of β or $(\pi - \beta)$ is the acute angle for the second node.

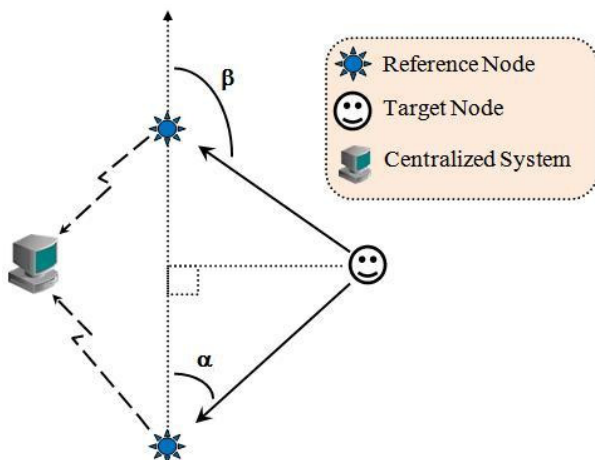


Fig. 5. Estimation in Centralized System (Pu, 2009).

For the second case, computation of triangulation can be performed inside the target node if a magnetic compass is attached to the sensor node. The magnetic compass provides orientation of the sensor node. All reference nodes broadcast signal to the target node. Hence, the target node measures the angles α , β , and γ from the received signals of the three reference nodes as shown in Fig. 6. The target sensor node computes its location coordinate using triangulation and forwards the result to centralized system for data storage or monitoring purpose.

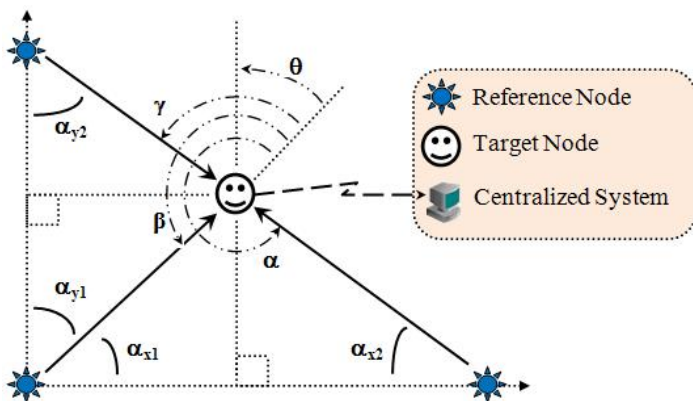


Fig. 6. Estimation in Target Node (Pu, 2009).

Using electronic magnetic compass (EMC) module attached to the sensor node, an offset angle θ can be obtained. This offset angle θ is used to justify all measurements to a reference

orientation regardless of the sensor node's orientation. Thus, all acute angles for triangulation using (3) or (4) can be found as follows (Pu, 2009):

$$\begin{aligned}
 \alpha_{x1} &= (\beta - \theta) - 0.5\pi \\
 \alpha_{x2} &= -(\alpha - \theta) + 1.5\pi \\
 \alpha_{y1} &= -(\beta - \theta) + \pi \\
 \alpha_{y2} &= (\gamma - \theta)
 \end{aligned} \tag{5}$$

Besides the mentioned basic triangulation solutions, there are more complicated and complete solutions using triangulation for different kinds of implementation and environment such as (Rao, et al., 2007). In addition, the needs of locating objects in three dimensions lead to the development of dynamic triangulation algorithm (Favre-Bulle, et al., 1998).

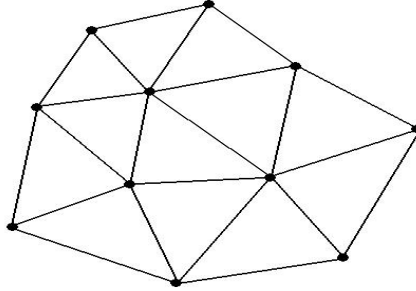


Fig. 7. Delaunay Triangulation (Pu, 2009).

With today's technology, large scale implementation is possible to achieve. Therefore, localization algorithms also must be good enough for such large scale sensor network operation. To realize this scenario as shown in Fig. 7, Delaunay triangulation (Li, et al., 2003, Satyanarayana, et al, 2008) can be used for the localization of multiple points that randomly forms complicated and connected triangles in the field. The formation of meshed triangles shape can be optimized using steepest descent method as in (He, 2008). An objective function was suggested to optimize the shape of triangle elements for the best mesh construction.

1.2.3 Trilateration Estimation

Trilateration estimation is also used to find an unknown location from several reference locations. However, the difference between trilateration and triangulation is the information provided into the process of estimation. Instead of measuring the angles among locations, trilateration uses the distances among the locations to estimate the coordinate of the unknown location. In trilateration, the distances between reference locations and the unknown location can be considered as the radii of many circles with centers at every reference location. Thus, the unknown location is the intersection of all the sphere surfaces as shown in Fig. 8.

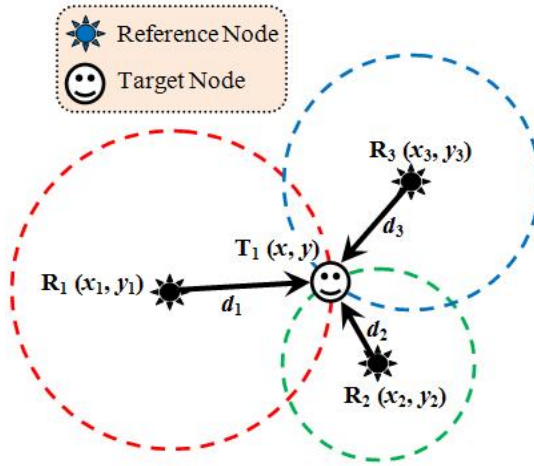


Fig. 8. Trilateration Estimation (Pu, 2009).

In Fig. 8, three reference nodes are randomly allocated. A target node is moving around the reference nodes. The target node (T_1) can be located using the coordinates of the reference nodes (R_1 , R_2 , and R_3) and the distances (d_1 , d_2 , d_3) between the reference nodes and the target node. A simple solution can be achieved using Pythagorean theorem as shown in the following expressions (Pu, 2009):

$$\begin{aligned} d_1^2 &= (x_1 - x)^2 + (y_1 - y)^2 \\ d_2^2 &= (x_2 - x)^2 + (y_2 - y)^2 \\ d_3^2 &= (x_3 - x)^2 + (y_3 - y)^2 \end{aligned} \quad (6)$$

Rearrange the equations in (6) and solve for x and y , the location coordinate of the target node can be obtained as shown in the following expressions (Pu, 2009):

$$\begin{aligned} x &= \frac{AY_{32} + BY_{13} + CY_{21}}{2(x_1Y_{32} + x_2Y_{13} + x_3Y_{21})} \\ y &= \frac{AX_{32} + BX_{13} + CX_{21}}{2(y_1X_{32} + y_2X_{13} + y_3X_{21})} \end{aligned} \quad (7)$$

where

$$\begin{aligned} A &= x_1^2 + y_1^2 - d_1^2 \\ B &= x_2^2 + y_2^2 - d_2^2 \\ C &= x_3^2 + y_3^2 - d_3^2 \end{aligned} \quad (8)$$

and

$$\begin{aligned} X_{32} &= (x_3 - x_2) \\ X_{13} &= (x_1 - x_3) \end{aligned} \quad (9)$$

$$\begin{aligned} X_{21} &= (x_2 - x_1) \\ Y_{32} &= (y_3 - y_2) \\ Y_{13} &= (y_1 - y_3) \\ Y_{21} &= (y_2 - y_1) \end{aligned} \quad (10)$$

Localization using (7) is very convenient because the distances (d_1, d_2, d_3) can be obtained from ranging, and the location coordinates of all reference nodes are previously stored in sensor nodes. In large scale sensor network, perhaps there are only several sensor nodes are equipped with GPS module. Thus, all other nodes are required to be located using these GPS equipped sensor nodes.

There are three possible scenarios that localizing a large scale sensor network could meet if only few sensor nodes among them are equipped with GPS:

1. The sensor nodes are able to reach at least three GPS-node
2. The sensor nodes are able to reach one or two GPS-nodes only
3. The sensor nodes are not able to reach any GPS-node

To use lateration techniques, at least three reference nodes are required. The second and third scenarios are not able to fulfill the requirement. For this reason, atomic and iterative multilaterations (Savvides, et al., 2001) were developed for large scale network. Atomic multilateration is used to estimate the location directly from three or more reference nodes as shown in Fig. 9(a). If all sensor nodes are able to reach at least three GPS-nodes, then atomic multilateration is used.

If sensor nodes are too far away from GPS-nodes, it is not able to fulfill the requirement of at least three reference nodes. Therefore, iterative localization may be considered to spread location to other nodes. This approach is called iterative multilateration. In this approach, sensor nodes are converted to reference nodes after localized by GPS-nodes as shown in Fig. 9(b). In next step, these reference nodes can be used to localize other nodes that are not reachable to GPS-nodes. This process continues until all sensor nodes in the network are localized.

In a large scale sensor network, atomic and iterative multilaterations can be used to localize any sensor nodes if the first scenario happens at initial state. However, the random allocation of GPS-nodes could be far to each other. Thus, no sensor node can reach at least three GPS-nodes at initial state. This leads to second and third scenarios at initial state. To solve this problem, collaborative multilateration (Savvides, et al., 2001) was proposed as shown in Fig. 9(c). In this approach, two sensor nodes are close to each other. These two sensor nodes are not able to localize themselves as each of them only can reach two GPS-nodes at initial state. Collaborative multilateration helps to determine their location by exchanging location information between the two sensor nodes.

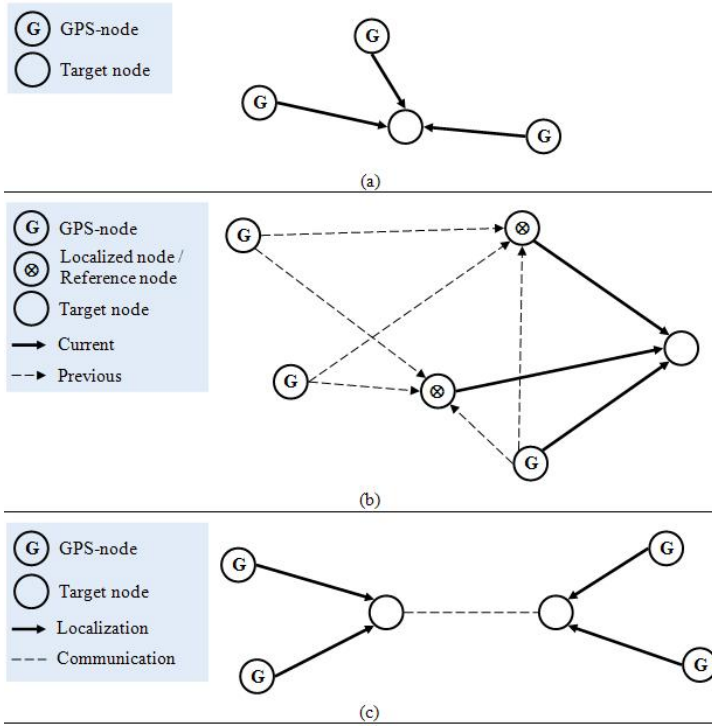


Fig. 9. Atomic, Iterative, and Collaborative Multilateration (Savvides, et al., 2001).

2. RSS Ranging in Indoor Environment

2.1 RSS Ranging

The strength of received power from a signal can be used to estimate distance because all electromagnetic waves have inverse-square relationship between received power and distance (Savvides, et al., 2001) as shown in the following expression:

$$P_r \propto \frac{1}{d^2} \quad (11)$$

where P_r is the received power at a distance d from transmitter. This expression clearly states that the distance of signal travelled can be found by comparing the difference between transmission power and received power, or it is called “path loss”.

In practical measurement, the increment of pass loss due to increment of distance may be different when it is in different environments. This leads to environmental characterization using path loss exponent n as shown in the following expression (Pu, 2009):

$$p_r = \frac{P_{(d_0)}}{(d/d_0)^n} \quad (12)$$

where $P_{(d_0)}$ is the received power measured at distance d_0 . Generally, d_0 is fixed as a constant $d_0 = 1$ m. Path loss exponent n in the expression is one of the most important parameters for environmental characterization. If the increment of path loss is more drastic when distance increases, the value of path loss exponent n would be larger as shown in Fig. 10. The solid line on top indicates the attenuation or path loss if $n = 2.0$. The dash line next to the solid line indicates the attenuation if $n = 2.5$, and so forth.

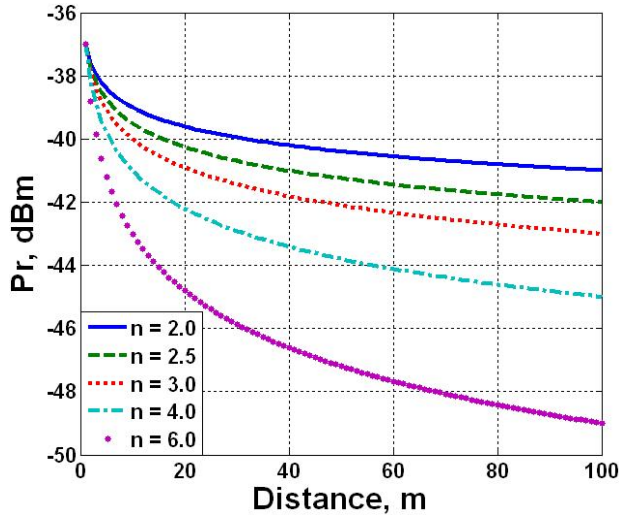


Fig. 10. Effects of Path Loss Exponent (Pu, 2009).

Another important feature that constitutes the rules of path loss in Fig. 10 is the beginning point of each curve. The starting point of all curves is fixed at -37 dBm. If this setting is smaller, then all curves would be shifted lower. In fact $P_{(d_0)} = -37$ dBm exactly. Therefore, $P_{(d_0)}$ is also one of the important parameters that characterizes environment

In most radio transceiver modules, the measurement of received power is just an auxiliary function. The measured value provided by the module may not be exactly received power in dBm. However, received signal strength indicator (RSSI) is used to represent the condition of received power level. This can be easily converted to a received power by applying offset to calibrate to the correct level.

RSSI is generally implemented in most of the wireless communication standards. The famous standards include IEEE 802.11 and IEEE 802.15.4. RSSI value can be measured in the intermediate frequency stage, which is before the intermediate frequency amplifier, or in the baseband stage of circuits. After obtaining RSSI value, the processor or microcontroller with built-in analog-to-digital converter (ADC) converts it to digital value. This value is then stored in a register of the controller for quick data acquisition.

2.2 RSSI in Indoor Environment

To use RSS ranging method effectively, we have to identify the differences between indoor and outdoor location tracking using RSSI. With RSSI adopted, the performance and implementation methods are totally different between indoor and outdoor. Therefore, if we

just consider indoor location tracking scenario, we are able to simplify system complexity and improve estimation method according to indoor environment.

After going through study and experiments, we considered the differences in design, implementation, and deployment stages. Table 1 illustrates the comparison between indoor and outdoor environment.

	Outdoor	Indoor
Path loss model	Linear	Affected by multi-path and shadowing
Accuracy	Easy to achieve but not necessary (wide space)	Difficult to achieve but important (small space)
Space	Wide and not limited	Small and mostly rectangular
Deployment	Random and ac hoc	Can be planned
Transmission power	Maximum to maintain LQI	Adjusted to avoid interference
Height of reference nodes	Ground	Ceiling
Map	Global	Local

Table 1. Comparison of Indoor and Outdoor Location Tracking (Pu, 2009).

In Table 1, path loss model (Phaiboon, 2002) is a radio signal propagation model, which is used to model the nature of signal attenuation over space. After going through environmental characterization or calibration, we are able to use this model to convert RSSI value to distance value.

In indoor environment, the signal strength is not linear as the distance linearly increased because of multi-path fading (Sklar, 1997) and indoor shadowing (Eltahir, 2007) effects. We have to study a better way to tackle this problem for better estimation accuracy.

From experiments, we knew that non-linear path loss becomes more serious as the size of indoor area (for example, a room) is small, leading to difficult accuracy achievement. However, indoor area is always smaller as compared to outdoor. Thus, the resultant location error becomes obvious as the accuracy is worst.

To calculate the absolute location coordinate, distances among sensor nodes are combined using lateration method. When the number of involved reference nodes is increased, lateration matrix size can be large causing increased computational complexity. Therefore, we can calculate absolute location coordinate by just using three reference nodes in a room (trilateration) (Thomas, et al., 2005). This helps to reduce system complexity and computational power.

In addition, the indoor area is always rectangular shape. During deployment stage, we can carefully plan the location of various reference nodes. Therefore, ac hoc deployment of sensor nodes is not suitable to be used in indoor deployment although many researchers focused on the study of ac hoc sensor network. Through location planning, we can allocate the reference nodes at strategic locations of the squared area (room). Using this kind of deployment, we can further simplify estimation formulas. Hence, in-network processing becomes possible.

Another important difference between indoor and outdoor implementation is the signal transmission power. Our experiments show that radio signal energy spread when it propagates through outdoor free area as shown in Fig. 11. **Error! Reference source not found.** This figure indicates the minimum power required to maintain link quality indicator (LQI) at 100 for various distances. Therefore, transmission power for outdoor environment must be as high as possible to maintain a safety level of LQI, thus ensuring the quality of wireless communication channel.

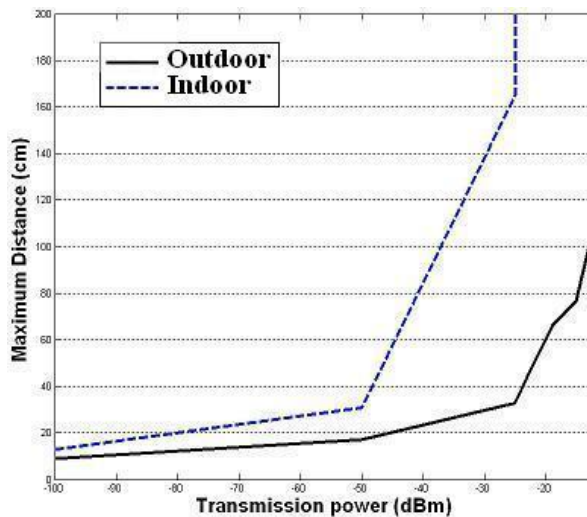


Fig. 11. Minimum Power Required for Communication (Pu, 2009).

On the other hand, signal transmission in indoor environment must be adjusted to suitable level for interference avoidance from neighbor area. It is not encouraged to use the reference sensor nodes located in neighbor area to estimate the location coordinate of the target node in current area. This is because path loss model could be seriously inaccurate and non-linear while radio signal propagates through wall with high signal attenuation. There is no worry about maintaining LQI as difficult as outdoor because the radio signal energy can be conserved within enclosed area.

For outdoor ac hoc deployment, sensor nodes are allocated randomly on ground. However, indoor deployment requires the reference nodes to be fixed beneath ceiling to avoid obstacles and must be the same height among them. This manual installation of reference nodes also needs to be planned for better strategic location. Because of the partitioned area of indoor space, it is more convenient if we display the target node's location using local axis method. In this method, every area has its own axis. To find location in the display map, areas can be differentiated by area ID.

3. Location Tracking System Design and Implementation

The design of a complete location system involves three areas of knowledge including (a) the signal and information processing to compute location information as output, (b)

realization of the system by implementing using various technologies available, and (c) acquisition of location data and store, analyze, monitor, and display in a centralized management server. In this chapter, the first two areas are the focus whereas the third area was excluded.

3.1 System Design

In general, the first task to be considered in a location system design work is the core of information handling through signal processing and data mining. This decides how the process goes through from raw signal to valuable information.

3.1.1 System Block Diagram

We need to consider how to find the location coordinate from raw RSSI data. It has to go through several processing steps as shown in Fig. 12.

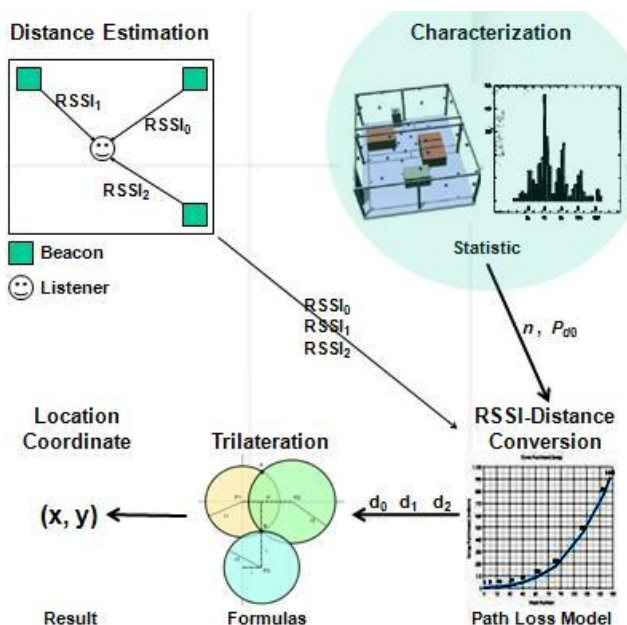


Fig. 12. The Findings of Location from Raw RSSI (Pu, 2009).

In Fig. 12, RSSI values are collected from reference nodes in distance estimation step. Using these RSSI values, we can perform environmental characterization to find suitable parameters for that area. When calibration process is over, the environmental parameters are fixed and will not be change unless large changes happen to the objects within the area. The next step is to obtain continuous RSSI values from the reference nodes in the online operation. With both RSSI values and environmental parameters ready, we can convert those RSSI values into distance using path loss model.

After RSSI-Distance conversion, we are able to obtain the distances between target sensor node and the reference nodes. By applying trilateration, it combines distances and find the

exact location coordinate of the target sensor node within the area. The overall system block diagram is shown in Fig. 13.

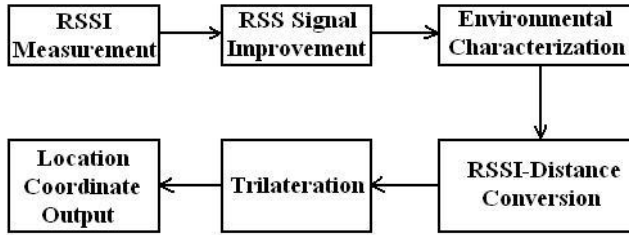


Fig. 13. Overall System Block Diagram (Pu, 2009).

3.1.2 RSSI Measurement Step

In this step, RSSI values are collected from the reference sensor nodes. Practically, RSSI value is not exactly the received power at the RF pins of the radio transceiver. Therefore, it has to be converted to the actual power values in dBm using the following expression (Pu, 2009):

$$P_i = (RSSI_i + RSSI_{\text{offset}}) \quad (13)$$

where P_i is the actual received power from beacon node i . $RSSI_i$ is the measured RSSI value for reference node i , which is stored in the RSSI register of the radio transceiver. $RSSI_{\text{offset}}$ is the offset found empirically from the front end gain and it is approximately equal to -45 dBm. This is to make sure that the actual received power value has dynamic range from -100 to 0 dBm, where -100 dBm indicates the minimum power that can receive, and 0 dBm indicates the maximum received power.

3.1.3 RSSI Signal Improvement Step

In indoor environment, raw RSSI data is highly uncertain and it is fluctuating over time. The study must go back to the investigation of radio signal propagation in indoor environment. For RSS ranging application, the analysis of the radio propagation manner is slightly different from the well-established theory for just digital communication purpose.

In digital communication, the study of received power is to avoid burst error and ensure high bit-error rate communication. The level change of RSS is not important as long as it is maintained within the safety region. However, when RSS is used in estimating distance, the estimation result is directly based on the level of RSS. Therefore, it is necessary to improve the signal quality of RSS.

From analysis, the reasons of RSSI variation in indoor environment can be well categorized for better understanding as shown in Fig. 14. Based on past research and analysis, we classified the reasons of RSSI variation in terms of both small/large scale and temporal/spatial characteristics. Fig. 14 clearly states all possible reasons of indoor RSSI variation in the two-dimensional classification diagram. In term of scale level, RSSI variation can be fluctuating slowly or quickly if it is in the temporal domain, and fluctuating narrowly or widely if it is in the spatial domain.

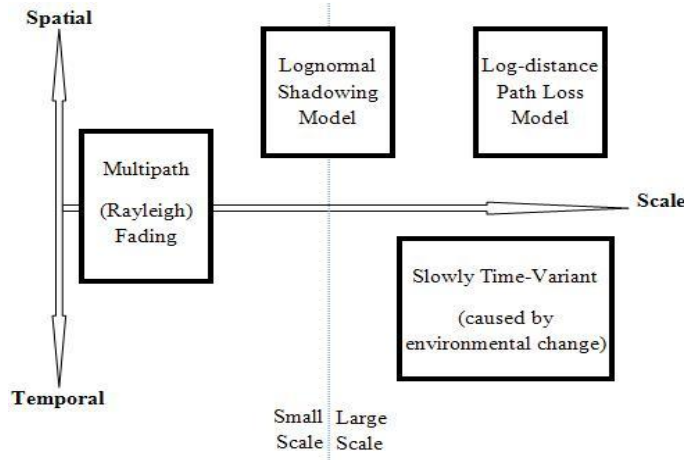


Fig. 14. Types of RSSI Variation in Indoor Environment (Pu, 2009).

Fast fading belongs to small scale variation such as multipath or Rayleigh fading, and environmental changes belongs to large scale variation as it is slowly time-variant. In the spatial domain, RSSI values do not vary in the stationary condition. RSSI values vary only when receiver moves over space or distance. Multipath or Rayleigh fading is also a spatial small scale variation. Log-distance path loss model is a large scale effect in spatial domain. Lognormal shadowing is considered as a medium size variation in the space domain.

To improve RSSI signal from both temporal and spatial variation, we can use a modified version of Kalman filter that estimates the speed of variation and use it to predict the future possible values. Based on past, current and future predicted values, RSSI variation can be reduced. With this, it is also able to cover some parts of small and large scale variation. The update of current RSSI and its variation speed can be found using the following expressions (Pu, 2009):

$$\hat{R}_{est(i)} = \hat{R}_{pred(i)} + a(R_{prev(i)} - \hat{R}_{pred(i)}) \quad (14)$$

$$\hat{V}_{est(i)} = \hat{V}_{pred(i)} + \frac{b}{T_s}(R_{prev(i)} - \hat{R}_{pred(i)}) \quad (15)$$

The prediction of the RSSI and its variation speed can be found using the following expressions (Pu, 2009):

$$\hat{R}_{pred(i+1)} = \hat{R}_{est(i)} + \hat{V}_{est(i)}T_s \quad (16)$$

$$\hat{V}_{pred(i+1)} = \hat{V}_{est(i)} \quad (17)$$

where $\hat{R}_{est(i)}$ is the i^{th} estimation value of RSSI, $\hat{R}_{pred(i)}$ is the i^{th} predicted value of RSSI, $R_{prev(i)}$ is the i^{th} previous value of RSSI, $\hat{V}_{est(i)}$ and $\hat{V}_{pred(i)}$ are the i^{th} estimation speed and i^{th} predicted speed. Parameters a and b are the gain constant, T_s is the time duration of

samples arrival. After going through this processing, highly fluctuating RSSI values are smoothed and become more stable.

3.1.4 Environmental Characterization Step

In this step, RSSI values are collected with the corresponding location of target node. Using the pair of (RSSI, Location) information to calibrate system parameters to the most appropriate level. After environmental characterization step, the distance estimation of the signal is adjusted to the minimum error state.

The important parameters used to characterize environment include path loss exponent n and the received power $P_{r(d_0)}$ measured at distance d_0 to the transmitter. For each enclosed area of indoor environment, a pair of these parameters ($n, P_{r(d_0)}$) are used to represent the conditions of the area. To characterize the area for RSS ranging, received power $P_{r(d_0)}$ is first measured by allocating a receiver d_0 apart from the transmitter. d_0 is generally fixed at 1 meter. After $P_{r(d_0)}$ is obtained, the receiver is moved to other locations to measure path loss exponent n using the following expression (Pu, 2009):

$$n = \frac{P_{r(d_0)} - P_{r(d)}}{10 \times \log_{10}(d / d_0)} \quad (18)$$

where $P_{r(d)}$ is the received power of the receiver measured at a distance d to the transmitter, which is expressed in dBm.

Theoretically, every room or area has their environmental parameters. However, the fact is that every location also has their environmental parameters although two locations are in the same room and they are neighbor. The reasons of this problem are from the RSSI variation in indoor environment especially in the medium scale spatial domain variation. Suppose we use inaccurate and uncertain RSSI source for calibration, it is impossible that we are able to obtain accurate environmental parameters from experiments. There will be different environmental parameters obtain at every location. This indeed increases the difficulty of environmental calibration works.

3.1.5 RSSI-Distance Conversion Step

If RSS ranging is used to measure the distances between reference nodes and target node, log-distance path loss model (Phaiboon, 2002) is used to express the relationship between received power and the corresponding distance as shown in the following expression (Pu, 2009):

$$P_{r(d)} = P_{r(d_0)} - 10 \times n \times \log_{10}\left(\frac{d}{d_0}\right) \quad (19)$$

After the step of environmental characterization, the two main environmental parameters n and $P_{r(d_0)}$ are obtained. Thus, the distance between transmitter and receiver can be estimated using the following expression (Pu, 2009):

$$d = d_0 \exp\left(\frac{P_{r(d_0)} - P_{r(d)}}{10n}\right) \quad (20)$$

In this expression, the estimated distance d is in centimeter if the value of d_0 provided is in centimeter such as $d_0 = 100$ cm.

3.1.6 Trilateration Step

In indoor environment, the shapes of target area are in arbitrary shape. The location coordinate of the target node can be estimated using trilateration by applying equation (7). Nevertheless, we are able to implement the reference nodes of location system in a regular way such as in a shape of rectangle or square. This helps to reduce the computation complexity of lateration. Two approaches of strategic reference node allocation can be considered as shown in Fig. 15. **Error! Reference source not found.**

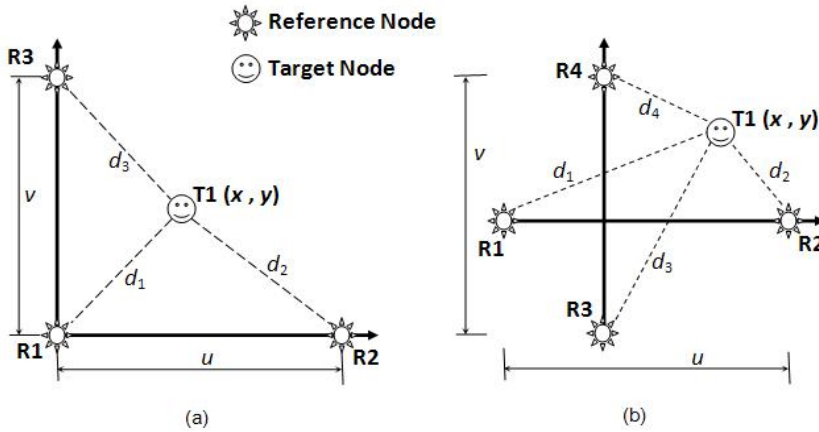


Fig. 15. Locations for Simplified Trilateration (Pu, 2009).

In Fig. 15(a), the reference sensor nodes are located at the corners of the rectangular area. This approach only requires three reference nodes for trilateration. To estimate the location coordinate, two reference sensor nodes $R1$ and $R2$ along the x-axis are sufficient to provide inputs for calculating x . Since reference node $R1$ is aligned with $R3$ along the y-axis, $R1$ also can be used together with $R3$ to provide inputs for calculating y .

In Fig. 15(b), the reference sensor nodes are located at the edges of the rectangular area. This approach requires four reference nodes for trilateration. To estimate the location coordinate of target node, two reference nodes $R1$ and $R2$ are used to provide inputs for calculating x while $R3$ and $R4$ are used to provide inputs for calculating y .

The distances among sensor nodes (d_1 , d_2 , d_3 , and d_4) are obtained using log-distance path loss model to convert RSSI values to distances. The distances (d_1 and d_2) can be used to determine x as shown in the following expression (Pu, 2009):

$$x = \frac{u^2 + (d_1^2 - d_2^2)}{2u} \quad (21)$$

In the first approach, the distances (d_1 and d_3) can be used to determine y as shown in the following expression (Pu, 2009):

$$y = \frac{v^2 + (d_1^2 - d_3^2)}{2v} \quad (22)$$

In the second approach, the distances (d_3 and d_4) can be used to determine y as shown in the following expression (Pu, 2009):

$$y = \frac{v^2 + (d_3^2 - d_4^2)}{2v} \quad (23)$$

3.2 Network Implementation

After the flow of location information processing was decided, the next step is to investigate the current technologies available and choose the most suitable solution to implement the operation network. Among many alternatives, WSN technology has the capability to perform such indoor location system works and it provides many advantages for ubiquitous implementation.

These advantages include: low power consumption, devices are not expensive, small size, software configurable and flexible, wide radio coverage, good processing ability, sufficient I/O for sensing and actuating, and etc. Most important factor is that WSN has been well established in various fields of research. Therefore, many resources and good algorithms are available from other research efforts. Hence, WSN was chosen as the main operation network to implement indoor location system.

3.2.1 Network Structure

The construction of the operation network for indoor location system based on WSN is related to the source of raw data and the sink of useful information. Thus, the characteristics of the WSN implementation for indoor location system are investigated and shown in Fig. 16 and the following points:

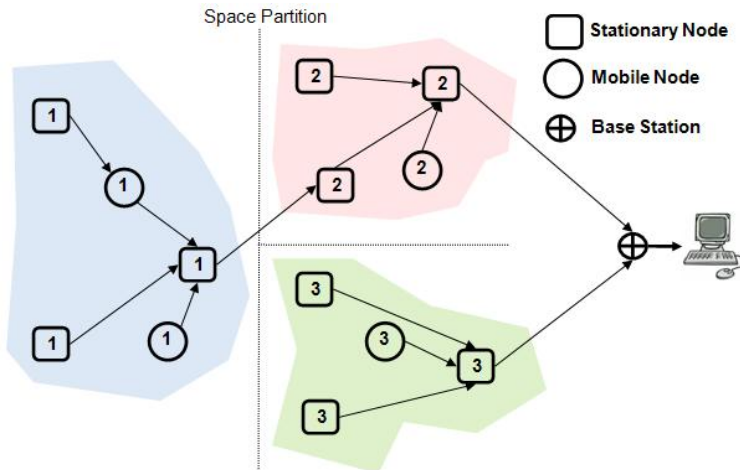


Fig. 16. Network Structure (Pu, 2009).

1. Network is constructed to support monitoring all the time, thus all sources of information send data constantly to a base station.
2. The network is multi-source single sink data network.
3. The data direction is from source to sink, thus no query service is available.
4. According to the movement status of sensor nodes, there are two types of network nodes: stationary and mobile nodes
5. All sensor nodes including stationary and mobile nodes can be an intermediate node for routing packets to base station.
6. The sensor nodes located in the same indoor area can be organized together as a cluster of the network.
7. A cluster consists of both stationary and mobile nodes. Cluster with only stationary nodes is possible but cluster with pure mobile nodes does not exist.

3.2.2 Interaction and Scheduling

For network implementation, communication signals are initiated from mobile nodes. This is to make sure that when mobile node enters a new zone, it is able to wake up all reference nodes. When a reference node cannot hear any mobile node for more than ten seconds, the reference node will be automatically switched to inactive mode. To save power consumption, an accelerometer can be installed into the sensor node. Whenever there is motion, the accelerometer is able to activate mobile node, and the mobile node activates other reference nodes. The communication paths are shown in Fig. 17.

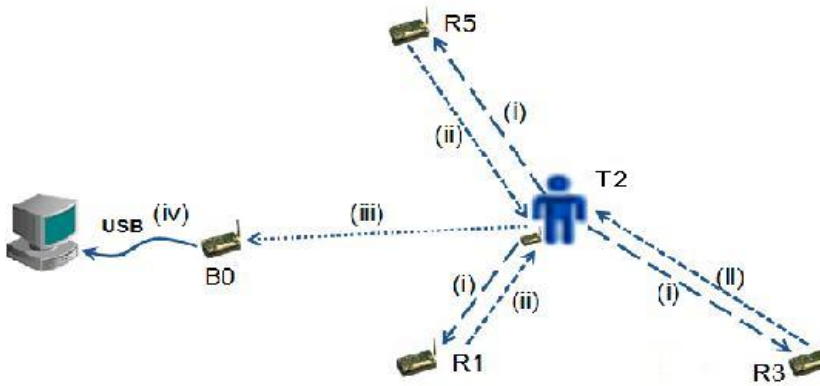


Fig. 17. Interaction and Communication Paths (Pu, 2009).

For communication path (i), target node T2 broadcasts a message to all reference nodes (R1, R3, R5). Reference nodes are awaked and reply to T2 with (ii). T2 then collects the IDs and RSSI values from all reference nodes and estimate location coordinate of the target node. The resultant location information is then forwarded to base station (B0) through path (iii). Base station forwards the data to a computer through USB (iv) for display and monitoring. To save power consumption and last the life of batteries in the sensor nodes, reference nodes are in inactive mode when there is no target node in the area. When a target node moves into the area, the movement of the target node causes motion sensor to generate activation signal. The activation signal is broadcasted to activate all reference nodes in the area.

A problem exists in this interaction among sensor nodes. When the number of reference nodes is increased, the problem becomes more serious. This problem arises because all reference nodes receive the activation signal from target node at the same time. In this case, all reference nodes are synchronized and send estimation signal for RSS ranging at the same time. Therefore, the target node receives all the estimation signals to measure RSSI at the same time. Inevitably, packet loss happens, leading to operation failure.

To solve this problem, transmission scheduling must be considered in the reference nodes. There are three kinds of transmission scheduling can be considered in indoor location tracking system implementation:

1. Use a random number generator to produce time delay t_d for the first estimation signal. The duration of delay can be obtained using the random number n_r (ranged from 0 to 1) as shown in the following expression (Pu, 2009):

$$t_d = T \times n_r \quad (24)$$

2. Use a fixed number n_{id} obtained from the node ID or address to produce time delay t_d for the first estimation signal. The duration of delay can be obtained using the following expression (Pu, 2009):

$$t_d = T \times \frac{n_{id}}{N} \quad (25)$$

3. Use a fixed number n_g obtained from the group ID to produce time delay t_d for the first estimation signal. Group ID is used to differentiate the sensor nodes within the same indoor area or cluster assigned by cluster head. Thus, the duration of delay can be obtained using the following expression (Pu, 2009):

$$t_d = T \times \frac{n_g}{G} \quad (26)$$

where T represents the transmission period of the estimation signal broadcasted from reference nodes, N is the total number of sensor nodes used in the indoor location system network, and G is the total number of member nodes in a cluster.

The first kind of transmission scheduling may still have signal collision problem as two reference nodes generate the same random number. However, the advantage is the ease of implementation. The second kind of transmission scheduling may have problem when the number of total sensor nodes is large and the transmission period T is short. This causes the divided delay time duration too short. In addition, expansion of network increases the total number of nodes, leading to unnecessary reinstallation to all sensor nodes. The third kind of transmission scheduling is a good choice, but it depends on the good clustering result of network.

3.2.3 In-network Processing

Wireless sensor network is formed by spatially distributed wireless sensor motes that are able to work independently or cooperatively with other sensor motes. Due to the size

constraint, the individual device in wireless sensor network is normally limited in processing capability, storage capacity, communication bandwidth, and battery power supply (Culler, et al., 2004). The battery life-time and the communication bandwidth usage are generally treated higher priority than the rest since in most applications, battery may not be frequently recharged or replaced. Saving bandwidth or reducing the data transmission among sensor nodes also means reducing power consumption used in communication. Therefore, various algorithms such as collaborative signal processing, adaptive system, distributed algorithm, and sensor fusion were developed for low power and bandwidth applications.

Recently, a new trend of study is focused on in-network processing and intelligent system such as (Tseng, et al., 2007) and (Yang, et al., 2007). For the applications of location tracking, (Liu, et al., 2003) develop the initial concept of collaborative in-network processing for target tracking. The focus is on vehicle tracking using acoustic and direction-of-arrival sensors. (Lin, et al., 2004, 2006) presents in-network moving object tracking. The way of tracking object is based on detection in a mass deployment of sensor nodes.

In general, the received RSSI values from reference nodes are sent to base station immediately. The based station is an interface between WSN and computer, which collects sufficient RSSI values and forwards them to the computer. In this case, location estimation task is performed and stored in the computer.

Besides the monitoring of user's activities, location information also can be used to support the needs of network routing, data sensing, information query, self-organization, task scheduling, field coverage, and etc. If the sensor nodes need the resultant location information for decision making, the computer has to send the computed location estimation result back to sensor nodes through the network. In this way, location estimation does not consume processing power in the sensor nodes but this greatly increases the wireless data transmission traffic for multi-user condition.

For a compromise, it is better to let the sensor nodes to collect all RSSI values and estimate location coordinates locally within the WSN. The estimated location information is then forwarded to a computer for monitoring or display. This approach also provides fast location update rate due to short packets used. If the location information can be updated immediately, the response and operation sensing tasks can be active, and the time taken for decision making is short. The architectures of estimating location coordinate in a computer and in sensor nodes are shown in Fig. 18.

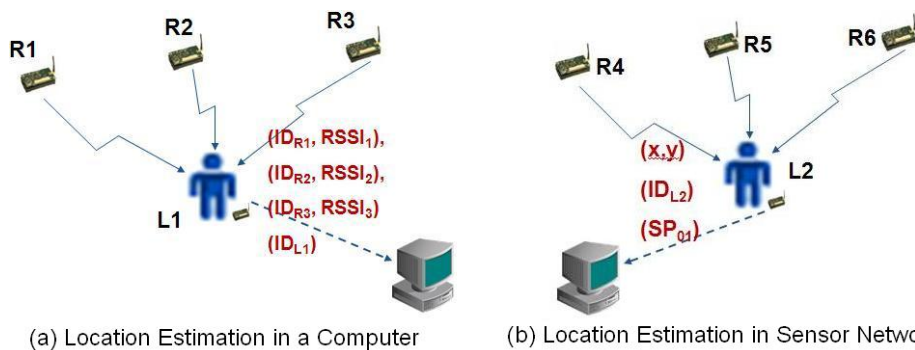


Fig. 18. Two Scenarios of Location Estimation (Pu, 2009).

In Fig. 18(a), R1 to R3 are reference nodes in the area. A mobile node L1 is hold by a user and moving around the area. L1 collects data from all reference nodes, and forwards them to a computer. The packet includes the ID of each reference nodes (ID_{R1} , ID_{R2} , ID_{R3}), RSSI values from each reference node ($RSSI_1$, $RSSI_2$, $RSSI_3$), and the ID of the mobile node (ID_{L1}). If the number of reference node increases, the packet size would be large. This largely increases network traffic and load.

In Fig. 18 (b), R4 to R6 are reference nodes in the area. A mobile node L2 is hold by user and moving around the area. L2 collects data from all reference nodes, and perform location estimation locally. The resultant packet is then forwarded to computer. Hence, the packet only includes the coordinate (x, y), space ID (SP_{01}), and the ID of the mobile node (ID_{L2}). If the number of reference node increases, the packet size does not increase but still remains small and constant because only the estimation result is forwarded to computer.

Wireless sensor network have substantial processing capability in the aggregate, but not individually. For most of the low-power mobile device such as wireless sensor motes, the processors or microcontrollers are limited in computational capability. For this reason, indoor location estimation algorithms must be simple and ease of implementation.

For ensuring light-weight processing and tool-independent programming, it is necessary to consider carefully that algorithms, mathematical calculations and processing are simple and programmable to any low-power mobile devices which have limitation and constraints. The main computational loads are in RSSI-distance conversion step and in trilateration step. Computation using trilateration can be simplified by carefully planning the locations of reference nodes at strategic locations and applying equations (21) to (23).

However, the computation of RSSI-distance conversion is not easy to be implemented in a resource and computational power limited sensor node. This is because the computation of exponential function is required in the equation (20), which generates large number if the input data is not stable. To solve this problem, Taylor series can be used to avoid exponential computation and simplify the calculation by selecting appropriate length of expression L as shown in the following expression (Pu, 2009):

$$d = d_0 \times \left(1 + \frac{x^1}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots \frac{x^L}{L!} \right) = d_0 \times \left(1 + \sum_{i=1}^L \frac{x^i}{i!} \right) \quad (27)$$

where

$$x = \ln(10) \times \left(\frac{P_{r(d0)} - P_{r(d)}}{10n} \right) \quad (28)$$

4. Conclusions

This chapter is to provide essential knowledge on the development of a location awareness system for location monitoring in ubiquitous applications. The location system must be able to estimate fine-grained location in indoor environment. Wireless sensor network was selected as the main body of the system. All data from wireless sensor network are sent to a base station for centralized operation and management.

Based on the way of ranging, location system can be time measurement or signal measurement. Time measurement can be achieved using the combination of RF and ultrasound for time difference of arrival (TDOA). Signal measurement can be achieved by converting received signal strength indicator (RSSI) to distance. Since RSSI does not need additional dedicated devices for ranging, and the power consumption is much lower than other distance measurement methods, it was selected as the ranging method in this research. With the existing technology, RSSI ranging is still not a perfect solution for fine-grained location tracking because of inaccurate and uncertain input data when it is used in indoor environment. Therefore, it is required to be improved through research studies. Three important processes of indoor location tracking can be studied to improve the performance. First, the signal quality of RSSI in indoor environment must be studied for accuracy and precision improvement. Second, the methods used for environmental characterization need to be re-investigated so that a convenient and effective calibration method or procedure can be developed to obtain accurate environmental parameters. Third, the positioning algorithm must be reconsidered to exploit an innovative way of location estimation that may provide advantages additional to traditional positioning algorithm.

5. References

- Abdalla, M.; Feeney, S. M. & Salous, S. (2003). Antenna Array and Quadrature Calibration for Angle of Arrival Estimation, SCI, Florida, July 2003.
- Bulusu, N.; Heidemann, J. & Estrin, D. (2000). GPS-less Low Cost Outdoor Localization for Very Small Devices, *IEEE Personal Communications Magazine*, vol.7, no.5, pp.28–34.
- Cong, T.-X.; Kim, E. & Koo, I. (2008). An Efficient RSS-Based Localization Scheme with Calibration in Wireless Sensor Networks, *IEICE Trans. Communications*, vol.E91-B, no.12, pp.4013–4016.
- Culler, D.; Estrin, D. & Srivastava, M. (2004). Guest Editors's Introduction: Overview of Sensor Networks, *IEEE Computer Society*, vol. 37, no. 8, pp.41–49.
- Eltahir, I. K. (2007). The Impact of Different Radio Propagation Models for Mobile Ad hoc Networks (MANET) in Urban Area Environment, *AusWireless*, pp. 30–38, Sydney, Australia, Aug 2007.
- Favre-Bulle, B.; Prenninger, J. & Eitzinger, C. (1998). Efficient Tracking of 3D-Robot Positions by Dynamic Triangulation, *MTC*, pp.446–449, St. Paul, Minnesota, May 1998.
- He, J. (2008). Optimizing 2-D Triangulations by the Steepest Descent Method, *PACIIA*, pp.939–943, Wuhan, China, December 2008.
- He, T.; Huang, C.; Blum, B. M.; Stankovic, J. A. & Abdelzaher, T. F. (2005). Range-Free Localization and Its Impact on Large Scale Sensor Networks, *ACM Trans. Embedded Computing Systems*, vol.4, no.4, November 2005, pp.877–906.
- Hightower, J. & Borriello, G. (2001). Location Systems for Ubiquitous Computing, *IEEE Computer*, vol.34, no.8, August 2001, pp.57–66.
- Kamath, S.; Meisner, E. & Isler, V. (2007). Triangulation Based Multi Target Tracking with Mobile Sensor Networks, *ICRA*, pp.3283–3288, Roma, Italy, April 2007.
- Li, X.-Y.; Calinescu, G.; Wan, P.-J. & Wang, Y. (2003). Localized Delaunay Triangulation with Application in Ad Hoc Wireless Networks, *IEEE Trans. Parallel and Distributed Systems*, vol.14, no.10, pp.1035–1047.

- Li, X.-Y.; Wang, Y. & Frieder, O. (2003). Localized Routing for Wireless Ad Hoc Networks, ICC, pp.443–447, Anchorage, Alaska, USA, May 2003.
- Lin C.-Y. & Tseng, Y.-C. (2004). Structures for In-Network Moving Object Tracking in Wireless Sensor Networks, BROADNET, pp.718–727, San Jose, California, USA, 2004.
- Lin, C.-Y.; Peng, W.-C. & Tseng, Y.-C. (2006). Efficient In-network Moving Object Tracking in Wireless Sensor Network, *IEEE Transactions on Mobile Computing*, vol.5, no.8, pp.1044–1056.
- Liu, J.; Reich, J. & Zhao, F. (2003). Collaborative In-Network Processing for Target Tracking, *EURASIP Journal on Applied Signal Processing*, vol.4, pp.378–391.
- Mak, L. C & Furukawa, T. (2006). A ToA-based Approach to NLOS Localization Using Low-Frequency Sound, ACRA, Auckland, New Zealand, December 2006.
- Najar, M. & Vidal, J. (2001). Kalman Tracking based on TDOA for UMTS Mobile Location, PIMRC, pp.B45–B49, San Diego, California, USA, September 2001.
- Nakajima, N. (2007). Indoor Wireless Network for Person Location Identification and Vital Data Collection, ISMICT, Oulu, Finland, December 2007.
- Niculescu, D. & Nath, B. (2003). DV Based Positioning in Ad hoc Networks. *Journal of Telecommunication Systems*, vol.22, no.1-4, pp.1018–4864.
- Phaiboon, S. (2002). An Empirically Based Path Loss Model for Indoor Wireless Channels in Laboratory Building, IEEE TENCON, pp.1020–1023, vol.2, October 2002.
- Pu, C.-C. (2009). *Development of a New Collaborative Ranging Algorithm for RSSI Indoor Location Tracking in WSN*, PhD Thesis, Dongseo University, South Korea.
- Rao, S.V.; Xu, X. & Sahni, S. (2007). A Computational Geometry Method for DTOA Triangulation, ICIF, pp.1–7, Quebec, Canada, July 2007.
- Rice, A & Harle, R. (2005). Evaluating Lateral-based Positioning Algorithms for Fine-grained Tracking, DIALM-POMC, pp.54–61, Cologne, Germany, September 2005.
- Satyanarayana, D. & Rao, S. V. (2008). Local Delaunay Triangulation for Mobile Nodes, ICETET, pp.282–287, Nagpur, Maharashtra, India, July 2008.
- Savvides, A.; Han, C.-C. & Mani, B. (2001). Strivastava. Dynamic Fine-Grained Localization in Ad-Hoc Networks of Sensors, MobiCom, pp.166–179, Rome, Italy, July 2001.
- Sklar, B. (1997). Rayleigh Fading Channels in Mobile Digital Communication Systems: Characterization and Mitigation, *IEEE Communications Magazine*, vol. 35, no. 7, pp. 90–109.
- Smith, A.; Balakrishnan, H.; Goraczko, M. & Priyantha, N. (2004). Tracking Moving Devices with the Cricket Location System, MobiSYS, pp.190–202, Boston, USA.
- Thomas, F. & Ros, L. (2005). Revisiting Trilateration for Robot Localization, *IEEE Robotics*, vol.21, no.1, pp.93–101.
- Tian, H.; Wang, S. & Xie, H. (2007). Localization using Cooperative AOA Approach, WiCOM, pp.2416–2419, Shanghai, China, September 2007.
- Tseng, Y.-C.; Chen, C.-C.; Lee, C. & Huang, Y.-K. (2007). Incremental In-Network RNN Search in Wireless Sensor Networks, ICPPW, pp.64–64, XiAn, China, September 2007.
- Yang, H.-Y.; Peng, W.-C. & Lo, C.-H. (2007). Optimizing Multiple In-Network Aggregate Queries in Wireless Sensor Networks, LNCS, vol.4443, pp.870–875.

- Zhao, F.; Liu, J.; Liu, J.; Guibas, L. & Reich, J. (2003). Collaborative signal and information processing: an information directed approach, *Proc. IEEE*, vol.91, no.8, pp.1199–1209.
- Zhao, F. & Guibas, L. J. (2004). *Wireless Sensor Networks: An Information Processing Approach*, Elsevier: Morgan Kaufmann Series.