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On Robustness of Centralized-based Location Determination using WSN

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***Abstract*-A study on robustness of location determination techniques using wireless sensor network (WSN) is presented in this manuscript. The location estimation technique used by the wireless sensor network is based on location fingerprinting technique. Theoretically, the robustness of the location estimation depends on the availability of the number of sensor nodes in the system. The degradation of location precision performance is proportional to the decrement of number of nodes in the WSN. The analysis of this study is derived from the real deployment and measurement of a test bed in a building that is deployed with TelosB mote based wireless sensor network. The preliminary results suggest that an outage of a large number of sensor nodes has detrimental effect on the performance of the location determination system. In our case, the WSN with 17 nodes yields 82% of locations accurately estimated within 4 meters. After the outage occurred in the network and the number of sensor nodes was reduced to 9 nodes, the location precision was reduced to 35% of those. This shows a dramatically decreasing in precision performance by 47%. Thus, the number of sensors nodes is one of the significant factors that contribute to the performance of any location systems.**

Keywords: Indoor Location Determination System, Location Fingerprint, WSN, MoteTrack, Centralized, Robustness

I. INTRODUCTION

In the near future, a smart building could be embedded with array of wireless sensor nodes that can control and sense different parts of the building. Wireless sensor nodes could be built into all electrical devices of the building in order to remotely and efficiently control energy usage of these devices. For instance, all hallway lightings could be controlled by wireless sensor networks (WSNs) in order to sense a presence of a person with a passive infrared sensor and automatically control the switching of the lighting system. If the designer of the smart building plans ahead of time to provide location determination system on top of the wireless sensor infrastructure, a variety of new location-based applications could be provided to the users. For instance, patients or important health-care servicing devices could be quickly located within a smart hospital building. An alternative scenario is the use of location determination system to help firefighters quickly locate people in the building when there is a fire breakout in the building assuming the WSN can operate on its own without main power.

The vision of using wireless sensor networks to determine location is not too far fetched because today there are commercial-of-the-shelf (COTS) devices based on IEEE 802.15.4 or Zigbee standard that is equipped with a location engine [1]. With the advance in integrated circuit manufacturing the cost of such devices will be driven down and a smart building equipped with WSNs and the location engine will become feasible in the near future.

Based on the vision of the smart building described above, this research investigated on the scenario that a building could be equipped with a WSN to provide an indoor location determination system. The indoor location determination system focused in this study is based on the use of radio frequency (RF) transmitted and received by wireless sensor nodes to estimate locations. The main motivation is to investigate the robustness of the location determination performance when there is a random outage of wireless sensor nodes or the beacon nodes in the system. The integrity of the location determination system is very important in an emergency case.

The organization of this paper is as follows. First in Section II, we begin our discussion with background of indoor location determination systems based on WSNs. Then in Section III, the system setup and experiment environment are described in details. Then in Section IV, we report and analyze the performance results of our experiments. The location determination performance of the WSN systems is compared between two scenarios: before and after sensor node outage. Finally, we conclude our finding and suggest our plan on the future work in Section V.

II. BACKGROUND OF LOCATION DETERMINATION

An approach suitable for RF signals in indoor environment is to use RF patterns to determine locations [2]. The basic concept of this approach is to exploit the relationship between patterns of received signal strength (RSS) from signal source(s) and locations of objects. This approach does not require at least three signal sources to determine location as in a typical triangulation technique. It also eliminates the inaccuracy in estimating the correct distances and angles from the reference points as used by the angle-of-arrival (AOA) or the time-of-arrival (TOA) technique. The RF patterns can be formed in two manners by collecting RSS from multiple signal sources at a location or collecting RF signal emitted from single source from the location at different RF sensor locations around that location. The signal sources and RF sensors can be mobile devices equipped with wireless sensor nodes. We refer to the technique that uses only the pattern of RSS to determine a location of an object as location fingerprinting technique [3]. This technique will be the focus of this paper because WSNs are easily enhanced to support location determination. The formation of RSS patterns used in this study is based on collecting the signal from multiple signal sources at each location.

Generally, the deployment of location fingerprinting based location determination systems can be divided into two phases [3]. First, in the off-line phase, the location fingerprints are collected by performing a site survey of RSSs from multiple signal sources at different positions. The distance between two closest physical positions during the survey period is called grid spacing which is usually reported in meters or feet. The RSSs from all signal sources that can be received on a position is measured with enough statistics to create a database of RSS patterns called a radio map. The vector of RSS values at a position on the grid is called the location fingerprint. This off-line phase can be very time-consuming if there is no survey plan with a clear performance objective, and the size of indoor area is very large.

Second, in the on-line phase, a mobile station (MS) reports a sample measured vector of RSSs from different signal sources to a position location server (or a group of RF sensors collects the RSS sample from a MS and sends it to the server). Then, the server uses a pattern classification technique to estimate the location of the MS and reports the estimate back to the MS (or an application running on another station that requests for position information). The most common algorithms used to estimate the location are to compute the Euclidean distance or to calculate the likelihood probability based on Bayesian algorithm between the measured RSS vector and each fingerprint in the radio map. In the next subsection, we will discuss the use of WSN to enable location determination.

A. Wireless Sensor Network for Location Determination

Wireless sensor network is a network of small-sized and low-powered nodes that can be used to detect phenomenon in the environment. Each sensor node normally consists of a microcontroller, a RF transceiver, sensing devices such as temperature and light sensors, and a battery. A modern low-powered and low-cost RF transceiver has ability to determine received signal strength (RSS) or other forms of received signal quality or link quality indicator (LQI) which allows a sensor node to act as a RF sensor device. This feature of the transceiver can be applied to location determination as discussed in this work. Recently in 2007 Texas Instruments has unveiled a new RF transceiver with a location engine which suggests an increasing trend in applying WSN in location determination [5].

In the market, there are many commercially available wireless sensor network platforms, such as Mica or Telos [6]. Telos (Revision B) nodes are used in this study. The Telos platform is one of the most advanced wireless sensor platforms today originally developed by researchers at University of California at Berkeley. Although the price of the Telos's sensor node is expensive in 2008, we expect that there will be other wireless sensor platforms that can gain an economy of scale and can be deployed in the smart building in the near future. Telos Rev. B sensor node is based on the Texas Instruments' ultra low-power MSP430F1611 microcontroller [7]. It also equips with a low-power RF transceiver, Texas Instruments' CC2420 chipset [8] and operates at 2.4 GHz frequency range. Note that the CC2420 chip also complies with Zigbee or IEEE 802.15.4 standard [9].

Beside the hardware platform, we also need embedded software and an operating system to run on the top of the WSN. The Telos platform supports the open source TinyOS [10] which is one of the widely adopted event based operating environment for WSNs. TinyOS software allows system developers to create a variety of applications for WSN networks including the location determination system.

MoteTrack system [5] is an example of wireless sensor system used for tracking wireless sensor nodes in indoor area. The MoteTrack was developed by Harvard University which is an open source software based on TinyOS. There are currently two versions of the MoteTrack system available. The study in this paper is based on MoteTrack version 2.1. MoteTrack system supports different wireless sensor platforms such as Mica and Telos. Since there are Telos Rev. B nodes in our test bed, we can easily deploy the sensor nodes for our study.

MoteTrack can be implemented in two models [11] centralized or decentralized models. In the centralized model, a mobile node stores a reference signature database (a form of radio map or RSS pattern described earlier) and performs location estimation by itself. On the other hand in the decentralized model, the reference signature data are stored in beacon nodes (which are immobile) and location estimation is performed by the beacon nodes. However, each beacon node stores only a subset of an entire reference signature database. Therefore, the MoteTrack operated in the decentralized model is more scalable than the centralized model. In this study, we only implemented the centralized model because its source code was available for us to study. We installed MoteTrack software for sensor nodes based on TinyOS and configured the MoteTrack nodes through the Cygwin command line interface [12].

The MoteTrack system itself can be experimented in three modes: (a) the simulation mode without real motes, (b) the simulation mode with real motes, and (c) the normal mode for actual deployment. In this study, we focused on the measurement experiment thus we only used the normal mode.

Deployment of the MoteTrack system also follows two phases as in the location fingerprinting technique described in Section II. Based on the CC2420 chipset, radio frequency of the mote's transceiver can be set from 2.405 GHz to 2.480 GHz with the channel spacing of 5 MHz. The transmission power level can be selected from the minimum of -25 dBm to the maximum of 0 dBm.

The location determination performance of MoteTrack depends on the location estimation algorithm, the number of signal sources, the grid spacing which is the distance between two points that have location fingerprints in the database, the number of frequency channels, the number of transmission power and the number of collected samples that forms RSS pattern at each location as studied in [4].

III. System and Setup

A. Test bed Environments

In this research, we selected a test area on the third floor of a building in our Engineering Department at King Mongkut's University of Technology at North Bangkok as shown in Fig. 1. It is a section in a hallway and offices of the building. The building has four floors. In this area, we deployed a group of 18 wireless sensor nodes based on Telos Rev. B to enable location determination or tracking of nodes based on MoteTrack system [5]. The total of 17 sensor nodes was placed as beacon nodes on this floor as shown in Fig. 1. The 18th node was connected to our laptop for use as a mobile node. The measurement laptop for collecting WSN signals in our experiment was a Compaq Presario V2427AU running Windows XP operating system.

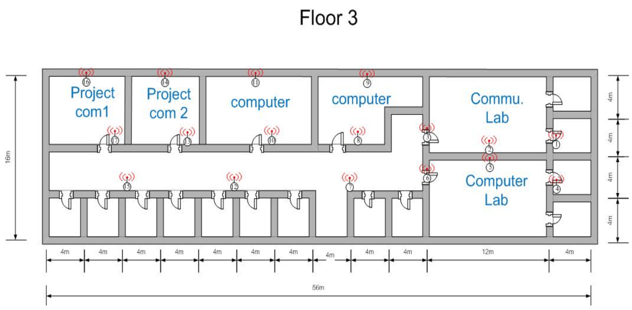

Figure 1.The third floor of our Engineering building.

The MoteTrack software consists of two parts: the embedded software based on TinyOS that runs on nodes and the Java-based software that runs on laptop. The embedded software was installed on every sensor node and the configuration of the first 17 nodes was set to act as beacon nodes and the 18th node was set to act as a centralized node. All 17 beacon nodes were installed at the 3-meter height on the pillars of the solid wall. The locations of sensor nodes were distributed to cover the third floor as denoted by small signal sources in Fig. 1. Messages from each beacon node contain the address of that beacon node, its radio frequency channel, and its transmitted power level. The mobile node then reports these three parameters, received signal strength indicator (RSSI), and link quality indicator (LQI) to the software running on the laptop via USB interface. During the off-line phase, all of information will be recorded for each location of mobile nodes and form reference signatures for each location.

B. Experimental Setup

This subsection describes the experimental setup of our study. The goal of our experiment is to compare the performance of MoteTrack system on WSN in two cases to study the random outage of beacon nodes within the network. The first scenario is called the network before outage and the second scenario is called the network after outage.

Before the measurement of location determination performance for both scenarios, the location fingerprint patterns must be collected by using MoteTrack's graphical user interface to gather all RSSs from different beacon nodes. Since the whole off-line phase for MoteTrack is not automatic, the user has to create the final radio map for the deployed WSN by using a separated command-line interface program. In this study, we collected the RSS patterns from 43 grid points which is shown by small dots in the hallway and in the middle of the rooms of Fig. 2.

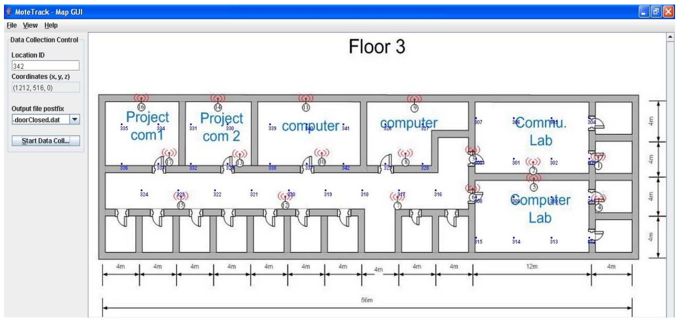

Figure 2.Example of MoteTrack system's user interface

The system's parameters for all experiments were set as follows. The 17 beacon nodes used 4 different RF channels which were 2.405, 2.425, 2.445, and 2.465 GHz. MoteTrack's manual recommends this number of channels because it can increase accuracy of the system. The transmitted power level of all beacon nodes was set to 0 dBm. The radio map was also set with grid spacing of 4 meters. Note that the grid spacing is the distance between two closest locations which we take the measurement for samples of location fingerprint patterns. The 17 beacon nodes were assigned with ID number 1 to 17. The number of collected samples in the system was approximately 500 samples at each location for the construction of WSN's radio map.

During the on-line phase of the first scenario or the network before outage, we used the graphical user interface of the MoteTrack program to issue a location estimation command. At each of the 43 positions, we performed random measurements of 100 times from 43 locations. We calculated the distance error between the estimated position returned by the program and the actual position by using Euclidean distance equation as shown in (1). Note that the MoteTrack program does not automatically calculate the distance error. We denote x_1 and y_1 as the coordinate of an actual location while x_2 and y_2 are the coordinate of the estimated location returned from the program. The returned location from the software in MoteTrack can be any coordinates or a real number in between the grid positions, which is not a discrete value. The MoteTrack system provides more fine location accuracy than other types of indoor location determination system such as the NIST location system [13].

$$\text{Distance Error} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \qquad (1)$$

Finally, in the second experiment or in the scenario of the network after outage, we used 9 beacon nodes by randomly disabling 8 beacon nodes. We ran the same test again to see the effect of the location determination performance. Note that we used the same radio map from the previous experiment which implies that the system was originally intended for 17 beacon nodes but later was degraded by the outage of some beacon nodes. In both experiments, the tested locations were directly on the grid point.

IV. Results and Analysis

The performance analysis of any positioning system can be based on two common metrics: the accuracy and the precision. The location accuracy is usually reported as the distance error deviated from the actual position, while the location precision is reported in percentages of position information that are within the distance of accuracy. These two performance metrics can be reported in a single plot between distance error or accuracy versus cumulative distribution function (CDF) or precision.

The robustness of the location system is also considered. The robustness of the system is determined when the location determination system can still operate to provide sufficient accuracy and precision under node failure. The system that has a high degree of robustness can tolerate the failure. In this study, we investigated the robustness of decentralized based location determination system when an approximate of 50% of nodes in the network was failed. It is typical for wireless sensor networks to have some failed nodes due to the depletion of energy or power supply of that particular node or due to damage to the nodes.

Fig. 3 reports the results of the first experiment or the scenario of the network before outage by showing the CDF of the distance error. The precision at the 4 meters of distance error (or accuracy) is approximately 82%, which means the location determination system will return locations within 4 meters of the real location 82 times out of every 100 times. If we look at 90% precision in Fig. 3, the system return the distance error within 5 meters. Additionally, we observe that the distance error never exceed 8 meters. This overall performance result of the system before outage is quite sufficient for most location-based applications.

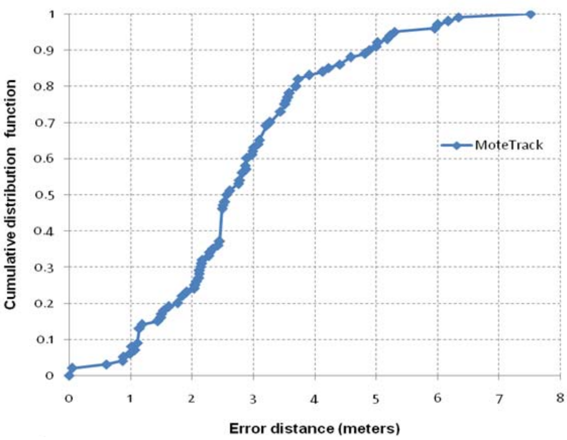

Figure 3. The distance error distribution of indoor location determination system on WSN before the outage with 17 beacon nodes

In the second experiment or the network after outage, there were 8 beacon nodes that were failed (through manually disabled). The location determination performance in this case is shown in Fig. 4. The result of the precision at the distance error of 4 meters (accuracy) is 35%. When we compared the correct estimate results with the first experiment, which used 17 beacon nodes, the system after outage has worse performance that is dropped significantly. At the 90% of precision, the system after outage experiment yields the distance error of 23 meters.

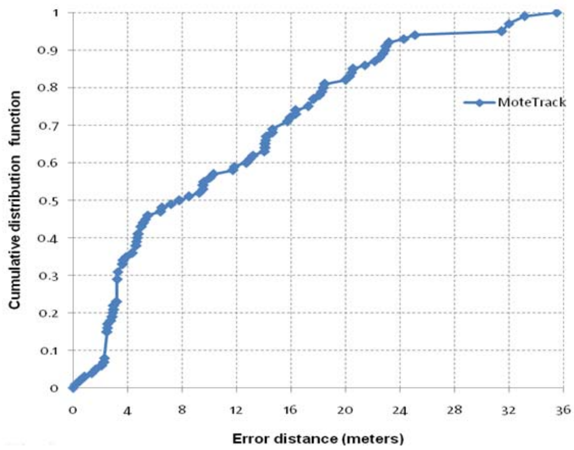

Figure 4. The distance error distribution of indoor positioning system on WSN in case 9 beacon nodes

The maximum distance error of the system after failure has greatly increased. When compared with the first experiment, the maximum distance error was increased from 8 meters to 36 meters, i.e. by 28 meters.

Table I shows the degradation of the performance from 17 beacon nodes to 9 beacon nodes in case of node failure. It shows the increasing of the probability of having distance error more than the specified accuracy. At the high accuracy, the probability of having distance error is not much different that both networks have worse performance. At the low accuracy (6 m), the network with 17 beacons performance much better than that with 9 beacons. This shows that the node failure could cause the penalty of the accuracy of the system. In other words, the fingerprint database was built with 17 beacons, but only half of them were active during the location finding; thus, the accuracy of the network with failed nodes was significantly degraded. This finding is also confirmed by our theoretical study in [4] that the degraded is non-linear.

TABLE I
Probability of Having Distance Error More Than Specified Accuracy

Accuracy	With 17 beacon nodes	With 9 beacon nodes
1 m	0.94	0.96
2 m	0.77	0.93
3 m	0.37	0.78
4 m	0.18	0.66
5 m	0.09	0.57
6 m	0.02	0.55

The steep degradation should be expected when there were a lot of failure nodes in the network. We are planning to conduct more measurement experiments to confirm this idea. We also expect that beside the number of nodes there are other factors such as the location of the beacon nodes that may influence the location performance of the system. This point will be proved in our future work.

V. CONCLUSION AND FUTURE WORK

The location determination system for indoor areas was achieved by using a location fingerprinting technique. For this technique, the number of beacon nodes is important to the performance of the system. More deployed beacon nodes can increase the system position accuracy. The failure of the existing nodes in the system can also significantly reduce the system performance. In our experiments of using MoteTrack in a centralized mode with 17 beacon nodes and one mobile node, we showed the possibility of its potential. The results showed the 82% of the time, the system could locate the mobile node within 4 meters of error. Under the node failure scenarios, our experiment results showed that with about 50% of failed nodes in the system, the location accuracy could be dropped significantly by about 10% to 50%.

The important features of an indoor location determination system are not only the performance, but also the integrity of the system. The indoor location determination system may be used to provide locations of firemen in a fire rescue, and a failed system could jeopardize the life of firemen. To increase the integrity of the system, more beacon nodes are needed for installation based on the results of our experiments or a new algorithm that is robust to node failure is required. For the future work, we would install more beacon nodes to investigate the overall accuracy and the integrity of the system. More nodes would require much effort of the installation. The optimal number of deployed beacon nodes per area could be determined.

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