Experimental Study of Wireless Sensor Networks for Indoor Construction Operations

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Abstract -

Emerging wireless sensor networks (WSN) technology offers a great potential in supporting current project management practices. Deploying wireless sensor networks on construction sites can lead to significant time and cost savings by providing accurate and near-real-time data to project management personnel. Continuous monitoring of labor usage, materials placement and equipment performance provides valuable data for assessing progress of construction operations and assists in improving safety and security on job sites. Construction activities take place in outdoor and indoor environments, while Global Positioning System (GPS) is ideal solution for tracking outdoor activities; it is not applicable for indoor application due to the lack of line-of-sight to satellites signals. Therefore, GPS-less means of tracking is required in indoor environments. While several research efforts had been attempted to develop indoor positioning systems utilizing various wireless technologies, there is no clear understanding of which wireless technology performs better in indoor construction environment. This research aims to experiment and test wireless technologies to aid the selection of wireless sensor networks configuration in support of current practice of progress tracking at construction on job sites. This paper describes experimental study conducted to determine the effectiveness of wireless technologies for dynamic indoor resource position tracking. The experiments investigate the challenges of wireless technologies applications in indoor environments, in particular, Wireless Local Area Networks (WLAN), Bluetooth, Zigbee and Synapse SNAP. A total of 21 experiments were carried out and 1752 data sets were analyzed. The results showed that Synapse SNAP out-performed all other technologies. The findings of this study are expected to provide a reference for future research on selection of indoor positioning technologies.

Keywords - Wireless Sensor Networks; Progress tracking; Indoor positioning

1 Introduction

Accurate and frequent project progress tracking is critical for effective project control and on-time project delivery. Presently, GPS has been widely used for tracking of outdoor construction operations. Its theory of operation is based on measuring times of arrival (TOA) of radio signals travelling between orbiting satellites and a mobile GPS unit. The GPS location is then calculated using a triangulation algorithm based on measured times and satellites position. The major advantages of the GPS are its reliability, availability and practical accuracy, however it is not suitable for indoor applications due to the lack of signal coverage particular inside buildings. [1].

Indoor localization research has been going on for decades in the robotics field [2,3]. The fact that indoor localization research is to date a very active research area indicates that there are still many challenges left to resolve. The challenges depend on the required accuracy and reliability dictated by the application. The fundamental challenge indoors is that the radio frequency environment is characterized by limited coverage, severe multipath signal fading and non line of sight (NLOS) conditions, which severely impact wireless signals propagation. This paper is dedicated to experiment and investigate the challenges of wireless radio signals propagation in indoor environments.

2 Literature Review

Manually monitoring progress of construction projects is not only expensive, subject to human error, and approximate but also is delivered with a time lag. Field supervisory personnel on construction site spend between 30-50% of their time recording and analyzing field data [4] and 2% of the work on construction sites is devoted to manual tracking and recording of progress data [5]. In addition, since most data items are not captured digitally, data transfer from a site to a field office requires additional time. When the required data is not captured accurately or completely, extra communication is needed between the site office and field personnel [6].

The construction industry lags behind other industries in adopting innovative new technologies. The need to accelerate the rate of technological adoption in the construction industry has been well documented in the literature [7]. The rapid advances in sensing technologies motivated researchers to study the feasibility of using such technologies to automate and integrate individual technologies for tracking and monitoring in the construction industry.

Recent research demonstrated that, data collection technologies and sensors coupled with mobile computers can provide cost-effective, scalable, and easy-to-implement progress tracking at construction sites [8,9,10,11,12,13,14]. Several data collection technologies had been utilized for tracking of construction activities, such as 3D imaging, Global Positioning System (GPS), Radio Frequency Identification (RFID), Ultra Wide Band (UWB), hand-held computers, voice recognition and wireless technologies.

Cavanaugh [15] presented a system that uses radio frequency and radar technology to locate, in three dimensions, workers indoors. Another study by Teizer et al. [16] demonstrated that the use of remote sensing and actuating technologies such as RF, Ultra Wideband (UWB), and imaging technologies can improve construction safety by warning or alerting workers on foot and/or equipment operators in real-time when a too-close proximity to unknown or other construction recourses can cause hazards. The studies by Teizer [16] have shown promising results in outdoor construction experiences as well as potential for indoor safety improvement. In this respect, Zhang et al. [17] used a multi-agent system to detect possible collisions or conflicts associated with operations of equipment on construction sites.

Due to limitations of the previously discussed technologies, the usage of WSN has been expanding in recent construction research efforts. A WSN is a self-organizing network composed of a large number of sensor nodes, closely interacting with the physical world. It features low-cost nodes, extensive network capability allowing deployment of large quantities of nodes so as to increase the network coverage, stability and reliability in wireless communication.

A new tracking architecture was implemented using wireless sensor modules by combining radio frequency signals and Ultrasound; the results showed accurate position estimations with enhanced net-work flexibility [18]. However, traditional ultrasound positioning has some disadvantages including line-of-sight transmission, multipath, high cost and power consumption which may hinder the possible applications in complicated construction environments [19]. Various combinations of RFID and Zigbee-based sensor networks have also been applied for materials tracking and supply chain management [20,21]. RFID tags were used to identify various kinds of construction materials, and the ZigBee communication technology was used to wirelessly transfer this information. These studies confirmed that WSN can improve the wireless communication and network flexibility but their primary use was only data transmission, and not positioning.

The construction environment is characterized as a spatially expansive, object-cluttered, fast-changing, and harsh environment. The adoption of data acquisition technologies for progress tracking on construction sites would require simultaneous tracking of items under challenging conditions. These conditions characterized by the presence of moving resources and by metallic environments and extreme weather events, which could impact the communications, which largely depend on the surroundings [22]. Thus, the operational ability of a technology-based tracking solution must be enhanced to survive in such environment. Recent advances in computing and communication have caused a significant shift in wireless data acquisition research. However, its deployment in buildings construction sites is still challenging, due to poor signal propagation in indoor environment. Wireless network connectivity is limited indoors by physical obstacles and structural barriers such as walls, and by interference in the frequency spectrum. This research was motivated by the increasing need for understanding the behavior of various wireless networks in indoor construction environment.

3 Indoor RF Propagation

The electromagnetic theories define radio wave propagation in free space, however predicting radio wave propagation in complex jobsites is very difficult due to the effects of wave reflection and scattering. These effects lead to multiple waves traveling through varies paths, which is known as multipath propagation. The resultant interface can be constructive of destructive in respect to the received power [23].

Received signal strength (RSSI) is used by wireless networking community to measure signal strength. The signal path-loss model is used to convert the measured RSSI into distance between a transmitter and a receiver. However the RSSI value is highly dependent on the multipath and shadow fading interferences as shown in Figure 1. The signal propagation depends heavily on surrounding environment. The difference in signal propagation can be noticed through comparison presented in figure 1(a) & (b). If a mobile node communicates in corridor environment the link characteristics will differ from an anechoic chamber environment with pronounced multipath fading. The anechoic chamber is a room designed to minimize reflections of radio waves and to shield an experiment from external interference [24].

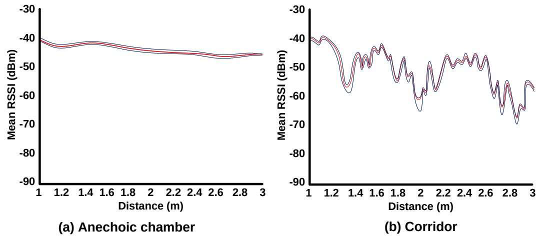

Figure 1. Signal propagation in different environments [24]

Several localization techniques had been proposed in literature, but most of them are based on ideal radio signal propagation. However in real construction environment and in the presence of shadow fading and multipath problems, such localization techniques are not applicable and produce huge errors. In the following sections, real signal propagation scenarios are analyzed in order to provide solutions for WSN deployment in indoor construction environment.

4 Test Bed Setup

In order to experiment and investigate indoor propagation of different wireless networks, 21 experiments are conducted and 1752 data sets are recorded for more than 876 minutes (grand total of all experiments). The experiments took place in laboratory environment at Building Engineering department at Concordia University. Two areas were used for testing, a 25 meter long corridor for the straight line testing and 20 m x 20 m open area for the grid test. All these experiments are performed in different scenarios either in terms of number of nodes, distance between the nodes, line of sight and finally, in terms of topology i.e. straight-line/grid (Figure 2).

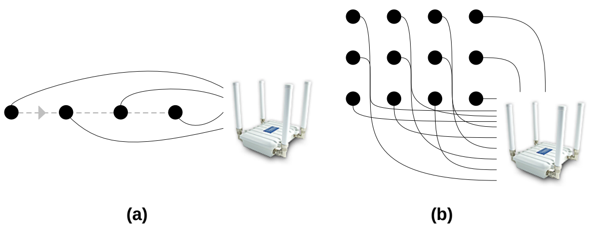

Figure 2. Straight Line (a) and Grid (b) deployment

A Waspmote platform is used to build the mobile nodes for the experimentations, which includes a microcontroller operating at 14MHz, 128Kof ROM, 8K of RAM, a wireless transceiver interface socket, and a USB interface for device programming and logging. Each device operates on rechargeable batteries. Its wireless interface socket is compatible with different communication protocols (WLAN, Bluetooth, Zigbee and Synapse SNAP) and frequencies (2.4GHz, 868MHz, 900MHz) as shown in figure 3.

Figure 3. Waspmote platform mobile nodes

Four wireless technologies are used in the experiments, in particular, Wireless Local Area Networks (WLAN), Bluetooth, Zigbee and Synapse SNAP. Their technical details with respect to frequency, output power, range, sensitivity and cost are summarized in Table 1.

Table 1 Wireless networks hardware

Wireless Network	Blue-tooth	Zigbee	WLAN	Synapse
Hardware Module	Roving Network (RN-41)	Xbee 802.15.4	Roving Network (RN-171)	RF300
Freq	2.4 GHz	2.4 GHz	2.4 GHz	915 MHz
Data Rate Kbps	3x1024	250	921	150
Power dBm	15	0	10	20
Range m	100	90	100	250
Sensitivity dBm	-80	-92	-83	-99
Tx current mA	65	35	120	85
Rx current mA	35	50	38	18.5
Cost	$24.95	$22.95	$29.95	$34.64

All experiments are summarized in table 2. The setup for straight line experiments is shown in Figure 4. The path is 20 m long, straight track with 20 waypoints with a distance of 1 m between two consecutive waypoints. Two stationary (transmitter) sensor nodes are placed next to the track at 0 m and 21 m. A mobile unit (receiver) is placed at the 1 meter mark and recorded the RSSI from each of the transmitters for 5 mins. Then the mobile unit was advanced to the next waypoint. Each experiment is repeated for each of the four wireless networks (WLAN, Bluetooth, Zigbee and Synapse SNAP).

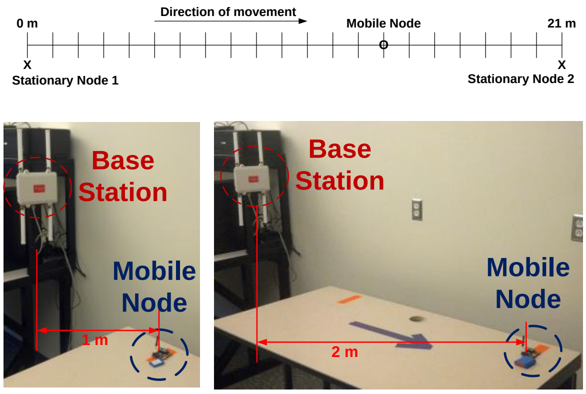

Figure 4. Experimental setup for evaluation of wireless networks in a straight line setting

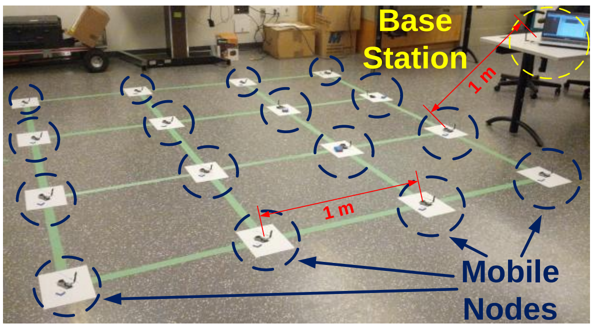

Figure 5. Experimental setup for grid setting

The setup for grid setting experiments is shown in figure 5. The mobile nodes are set as transmitters, and the station unit is set as receiver. Then the setup was reversed, the mobile nodes where receivers while the station unit was transmitter. This grid test is used to explore the effect of multiple broadcasting on the same bandwidth and frequency, in order to understand the effect on the RSSI. The grid size changes from 3m x 3m to 6m x 6m, with a distance of 1 m between two consecutive nodes. One stationary sensor nodes is placed next to the grid at 1 m and center of the grid. Each experiment is repeated for each of the four wireless networks (WLAN, Bluetooth, Zigbee and Synapse SNAP).

RSSI of data packets received by the mobile node is measured using a program written using C++ and installed on the fixed node. In this program, a stationary node sends a PING packet to the mobile node and the mobile node responds with another data packet that contains the RSSI value with which the PING packet was received. The two stationary nodes send PING packets in a strict round-robin fashion to avoid packet collisions. Each node sends 3 packets per second, which results in 3 RSSI samples per second per link.

Table 2 Experiments Scenarios

Exp. #	Nodes #	Dist. (m)	TX Level	LOS	Topology
1	3	1-20	0	Y	S.L
2	3	1-20	0	N	S.L
3	3	1-20	1	Y	S.L
4	3	1-20	1	N	S.L
5	3	1-20	2	Y	S.L
6	3	1-20	2	N	S.L
7	3	1-20	3	Y	S.L
8	3	1-20	3	N	S.L
9	3	1-20	4	Y	S.L
10	3	1-20	4	N	S.L
11	3	1-20	5	Y	S.L
12	3	1-20	5	N	S.L
13	3	1-20	6	Y	S.L
14	3	1-20	6	N	S.L
15	4×4	3	6	Y	Grid
16	4×4	6	6	Y	Grid
17	6×6	3	6	Y	Grid
18	6×6	6	6	Y	Grid
19	3×4	3	6	Y	Grid
20	3×6	3	6	Y	Grid
21	4×6	3	6	Y	Grid

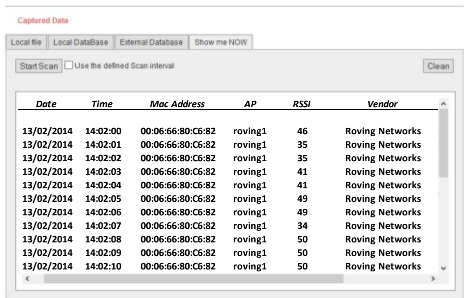

Figure 6. RSSI measurement program interface

5 Results analysis

The received signal strength (RSSI) of a given wireless network is dynamic, which is affected by the periodic/random changes in the physical properties of the surrounding environment or even a group of people passing around the transmitter or receiver. To make an overall comparison between the RSSI measurements, the raw RSSI data from real-time measurements is filtered to remove the small oscillations using a moving average with a window size of 10 samples and an even sample weight as shown in figure 7.

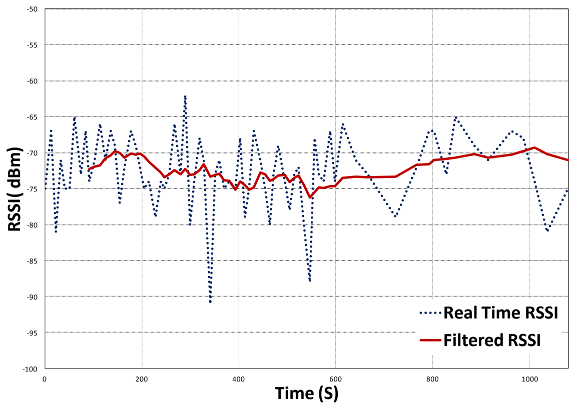

Figure 7. Real-Time RSSI VS Filtered RSSI

5.1 Impact of base station distance

The collected data presented in figure 8, clearly show that the received signal strength at each point is declining as expected. Even though, the declining rate is inconsistent with all wireless technologies. For example the node at 4 meters receives a weaker signal on the incoming packets with Bluetooth and WLAN than the node at 5 meters. Also the node at 7 meters receives a weaker signal on the incoming packets with Zigbee than the node at 8 meters. In all measurements Synapse hardware showed more consistency in returning RSSI values in declining order.

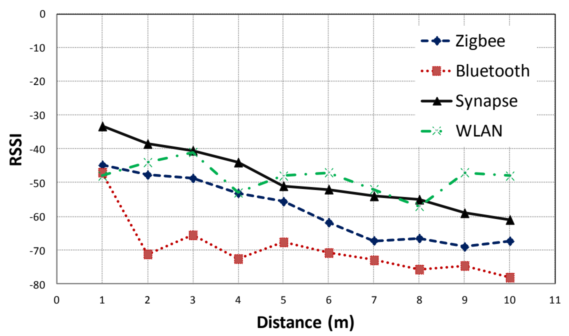

Figure 8. RSSI measurement straight line formation

A major source of error when measuring RSSI is due to multipath effects caused by objects in the environment. In the office environment, where the tests were performed, the radio environment is likely to change between every measurement point as the room contains quite many things that could cause multipath effects.

5.2 Impact of multipath

The multipath results for signal reflection from objects and such as walls, ceilings in indoor environment. The received signal arrives as multiple reflections or direct signal as shown in figure 9. The measured RSSI is directly affected in a constructive or destructive way with respect to the original transmitted signal.

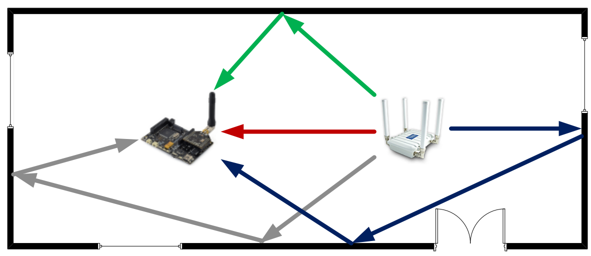

Figure 9. Multipath interference

The multipath interference can have many forms such as reflection, scattering, refraction or diffraction. Signal Reflection occurs when the signal is reflected back towards the transmitter. Signal scattering creates multiple new signals after striking an object. Signal refraction occurs when the signal is bent while it is passing through an object and signal diffraction is the change in the signal direction when it passes around and object.

5.3 Impact of Attenuation

As a radio signal propagates from the transmitter to the receiver, the signal attenuation takes place. This is mainly due to the transmission medium properties. The Path loss describes this attenuation as a function of the wavelength of the carrier frequency and the distance between the transmitter and receiver. Path loss is derived from the Friis transmission equation (Eq, 1) and is defined as:

$$Path\ Loss = 20\ log\left(\frac{4\times\pi\times r}{\lambda}\right)\ d \qquad \text{Eq. 1}$$

Where r is the distance between the transmitter and receiver, and λ is the wavelength.

The signal attenuation is directly related to the frequency of the RF signal and the transmission medium materials type and density. The lower the Signal frequency the higher distance the signal will travel through air and through objects. Using frequencies below 900 MHz significantly improves the connectivity in indoor environments, as shown in figure 10.

Each material has a different attenuation coefficient, which is used to quantify the amount of signal strength reduction for each material type. Drywalls have a relatively low attenuation, about 2 db, while concrete and brick walls have higher attenuation levels. The number of walls that a RF signal has to pass through also affects the signal strength and must be taken into consideration when designing indoor wireless system.

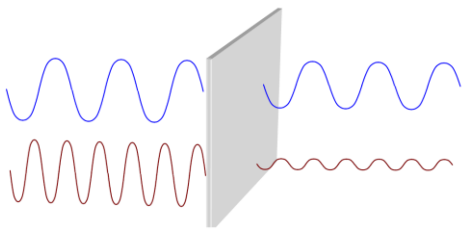

Figure 10. Attenuation interference

5.4 Impact of Antenna Orientation

The transmitter and receiver nodes antenna orientation can affect the radio signal strength due to that fact that the antenna radiation pattern is not uniform. In order to measure the impact of the antenna orientation impact a standard procedure is applied to measure the average RSSI at 24 different degrees with a fixed receiver node and a rotating transmitter node at a 1m distance. This test was performed using Waspmote microcontroller and the output power of the radio signal was set to -10dBm in a relatively obstacle-free environment.

As shown in figure 11(a), the radiation pattern of the Synapse antenna is unsymmetrical and suffers for distortion with a difference in the measured RSSI of up to 10dBm. Figure 11(b) illustrates the coverage range, which is calculated based on the radiation pattern. Synapse has shown a wider and higher coverage range than the other three wireless technologies.

6 Conclusion

This paper described experimental study conducted to determine the effectiveness of wireless technologies for dynamic indoor tracking of construction operations. The challenges in RF-based localization technologies were analyzed by conducting a total of 21 experiments. Four wireless technologies were investigated, in particular, Wireless Local Area Networks (WLAN), Bluetooth, Zigbee and Synapse SNAP. The results showed that Synapse SNAP out-performed all other technologies. The findings of this study can be summarized as following:

- The RSSI fluctuation is a phenomenon which is caused by multipath interference and signal reflections. A weighted average filter can be used to elevate this problem and smooth the raw data.

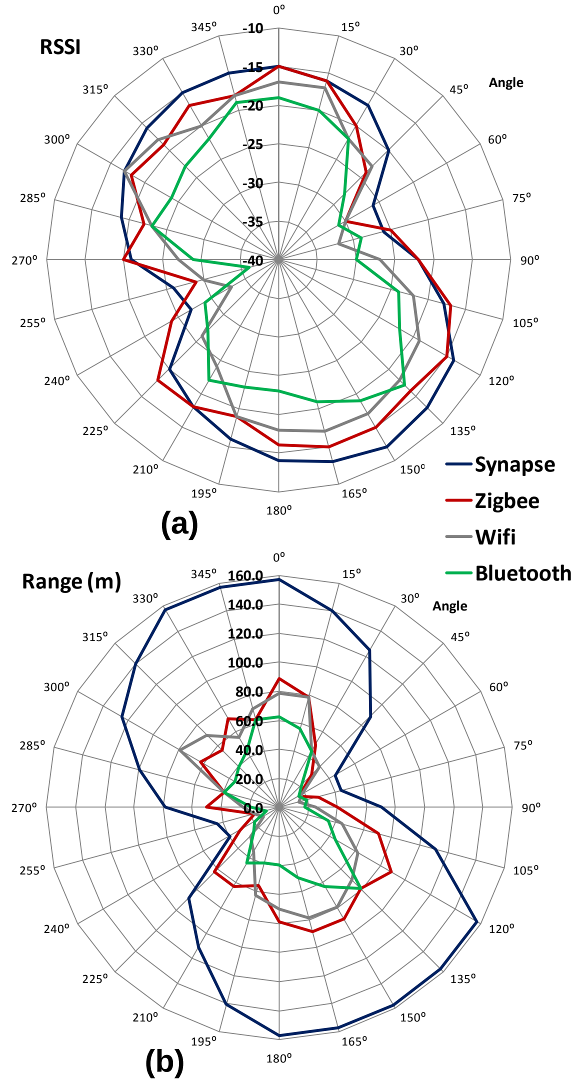

Figure 11. Antenna orientation and range

- Heavy congested environment suffers from higher multipath interference, which can be reduced by continually calibrate the pass loss model parameters.

- The field measurements confirmed the Faiis equation that signal attenuation is directly proportional with the operating frequency. The RF 900 MHz frequency has better performance in indoor environment than 2.4 GHz.

- The antenna radiation pattern is not uniform and there for the antenna orientation impacts the received signal strength and reduce coverage range. It had been confirmed during these experiments that WSN hardware had electromagnetic effect, and by leaving a vertical distance between the hardware and the antenna, this effect was reduced.

- The commonly used empirical model for indoor propagation cannot be fixed, and it needs continuous calibration to reflect the continually changing surrounding environment.

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