

WIRELESS NETWORK-BASED TRACKING AND MONITORING ON PROJECT SITES OF CONSTRUCTION MATERIALS

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Abstract. This paper presents a new prototype framework of automated tracking and monitoring system for construction materials. RFID and GPS technologies used in construction material tracking have been reviewed, and signal strength based localization has been examined. As an emerging network standard for industrial applications, brief specifications of ZigBee™ protocol have been described. We introduce a ZigBee-based system architecture using combination techniques of RF and ultrasound to improve positioning accuracy and cost benefit. Finally, feasibility analysis and application scenario have been examined to present the possible deployment framework in construction area.

Keywords: ZigBee, sensor network, tracking, monitoring, construction materials, localization technique

1. Introduction

In general, construction processes require large budgets and resources to be committed within a constrained project time duration. However, inefficient processes associated with current practices of manually tracking materials, equipment and workers in construction field often causes problems with successful completion of a construction project. Due to the size and complexity of many construction projects, it has become more difficult to manage supply chains, just in time (JIT) deliveries and asset information tracking. In addition, current practices of data collection and acquisition in the construction field are also struggling with the development of improved information management systems. Previous observations on construction sites indicate that the field supervisory personnel spends 30-50% of work time on recording and analyzing field data and 2% of construction work is categorized as manual tracking and controlling of material handling [2, 9]. By manual processes, the accuracy of collected data relies on the judgments and writing skills of the people collecting the data. Furthermore, the time-consuming process of transforming the field data into digital formats contributes to delays in the construction projects.

Today, computing and sensor network technologies provide potential for data acquisition and communication for automation and improvement in process performance – such as RFID and GPS [6, 11]. During last several years, applications of radio frequency identification (RFID) technology had already taken place in construction industry for identifying and tracking

products. Jaselskis and El-Misalami demonstrated two pilot tests using RFID conducted in power plant project in Mississippi and the construction of a catalytic cracking unit in a Texas refinery [6]. The tests showed that RFID tags reduced the time required to download data into a company's material tracking system, and RFID can be a beneficial technology to the receiving process of construction material. In response to the need to track identified materials through the supply chain, Song et al. conducted field tests of current RFID technology to examine its technical feasibility for automatically identifying and tracking individual pipe spools in laydown yards and under shipping portals [13]. Goodrum et al. conducted the experimental test for tool tracking system using active RFID tags with 32 Kb memory, 3.6 V battery, and antennae operating at 915 MHz [4]. Utilizing a PDA, a prototype system was developed to track tools in a mobile environment and to inventory hand tools located in either mobile gang boxes or truck boxes.

While RFIDs provide an advanced materials tracking method when compared with previous technology, e.g. bar code, several limitations have been observed when applied to construction practices. The basic functionality of RFID is to present remote identification and tracking of distributed RFID tags. Because of the fact that RFID was originally designed to replace the bar code technology, broader applications to wireless monitoring and localization are quite limited. A recent survey conducted by RFID Journal showed that the cost of RFID tags vary from 20 cents to 6 dollars based on the tag's specification. However, most of the RFID

Table 1. Characteristics of different RSSI-based localization techniques [8]

Technique	Design Approach	Technology	Testbed Dimensions	Location Error
Ecolocation	Constrained based approach applied on the ordered sequence of raw RSSI data	MICA2	26 × 49(ft) (Indoor)	10 ft
Probability Grid	Probabilistic. RSSI values are used to estimate the one-hop distance in a grid	MICA2	410 × 410(ft) (Outdoor)	66 ft
Radar	RSSI fingerprint map	802.11b	42.9 × 21.8(m)	15 ft
MoteTrack	RSSI fingerprint map	MICA2	18751 ft ²	13 ft
LEASE	Online Fingerprinting and signal propagation modeling	802.11b	225 × 144(ft)	15 ft
Bayesian Indoor Positioning System	Learning Based	802.11b	225 × 144(ft)	20 ft
Stochastic Indoor Location System	Optimal positioning of a given number of clusterheads with respect to the location-detection performance	N/A	N/A	N/A
Monte Carlo Localization	Learning based with signal strength map	802.11b	N/A	7.2 ft
Nibble	Bayesian networks	802.11b	224 × 96(ft) (Indoor)	20 ft

readers cost from \$2,500 to \$3,000 depending on the various features in the device [1]. Thus, it is prohibitively expensive to practically cover the large scale of construction site because the coverage range of communication for even active RFID tags is within 15 m that is not enough reading range for practical use [4]. Even though the global positioning system (GPS) can provide somewhat improved accuracy for locating the tags' position by combining them with RFID, GPS receivers are still expensive to track and monitor a large amount of materials in a typical construction project. In addition to high cost, localization systems based on GPS alone also suffer from the multipath and signal masking in highly dense areas. Due to these limitations, significantly large positioning error, greater than 20 m over 40 % of points and greater than 100 m over 9 % of points, have been found with the use of stand-alone global positioning system applied in construction-vehicle tracking systems [7]. Thus, it is unreliable to depend on the accurate localization data for material tracking and monitoring in a highly dense environment such as construction site.

We present a new prototype framework of automated tracking and monitoring system that will address the needed shift from the time- and labor-intensive legacy systems into sensor- and network-based tracking and monitoring systems for construction materials. The paper is describing the design of tracking and monitoring system architecture based on ZigBee™ networks, named as Automated Material TRACKing (AMTRACK). As an emerging technology introduced for industrial monitoring and controlling, brief specifications of ZigBee™ protocol have been described for possible tracking and monitoring tools in construction processes. To implement the ZigBee™-based tracking and monitoring system, we proposed the combination techniques of radio frequency signal and ultrasound to improve positioning accuracy and cost benefits. In addition, feasibility analysis and application scenario

have been examined to present the possible deployment framework in construction.

2. Related work

2.1. Localization techniques

Localization is a primary task for higher level of sensor network functions such as tracking, monitoring, and geometric-based routing [3]. Most of the localization techniques are based on the received radio strength indicator (RSSI) due to its widely availability in wireless radio signal communication [8]. Especially, RSSI-based localization has an advantage that utilization of the same radio hardware for both communication and localization would make it possible to provide efficiency in simple design framework over a specific localization infrastructure – such as ones using directional antennas or same transmission signal, and separate design of ultrasound or infrared [3]. Table 1 summarizes the characteristics of different RSSI-based localization techniques.

However, RSSI-based localization has a critical limitation that has been observed in the characteristics of radio signal propagation. Since raw RSSI does not provide enough accuracy of localizing the mobile objects to be used in practical application, the distance prediction requires additional investigation on the probability method or learning-based localization algorithm [8]. The main factors associated with the inaccuracy are identified as the multipath propagation and signal fading. Multipath is the propagation phenomenon that results in two or more propagation paths between sensor and receiving antenna. Fading induces the rapid fluctuations of amplitudes, phases, or multipath delays of a radio signal over a short period of time or travel distance. The level of inaccuracy inherited from the physical properties of radio signal increases as the chance of reflections or scatterings of signal from unwanted obstacles becomes

higher, such as indoor environments where signals travel with much obstruction. The localization error observed in the RSSI-based techniques shown in table 1 illustrates that most of the errors range from 15 ft to 25 ft for indoor system. While construction site is considered as an outdoor system where the chaotic properties of signal propagation can be much lessened than indoor due to little obstruction, there still exists physical limitation of multipath and fading in signal propagation because of the complicated layouts of construction sites. As a consequence, the motivation toward reliable localization and communication calls for a different framework of technique to provide the acceptable accuracy to be deployed in construction processes.

2.2. ZigBee™

ZigBee is emerging network technology and a wireless communication standard capable of realizing the ubiquitous environment to satisfy such requirements. As a superset of IEEE 802.15.4 standard, ZigBee supports the industrial network standards, so that many industrial applications including construction automation, structural health monitoring, and automated control and operation can benefit from the advantages of the technology. ZigBee specification takes advantage of the IEEE 802.15.4 wireless protocols as communications method, and expands on this with a flexible mesh network, wide range of applications, and interoperability. The ZigBee specification has been released publicly in June 2005, and products supporting the ZigBee standard are widely available in the market. Specified frequency allocations and physical layer recommended by IEEE 802.15.4 is listed in table 2.

Table 2. Frequency allocations and physical layer in IEEE 802.15.4 [15]

Frequency band	2.4 GHz	915 MHz	868 MHz
Number of channels	16	10	1
Bandwidth (kHz)	5,000	2,000	600
Data rate (kbps)	250	40	20
Symbol rate (ksps)	62.5	40	20
Modulation method	O-QPSK*	BPSK**	BPSK
Diffusion method	DSSS***	DSSS	DSSS
Available regions	Worldwide	USA	Europe

O-QPSK* (Offset Quadrature Phase Shift Keying)
 BPSK** (Binary Phase Shift Keying)
 DSSS*** (Direct Sequence Spread Spectrum)

A ZigBee network, shown in figure 1, consists of ZigBee coordinators, ZigBee routers and ZigBee end devices [12]. The coordinator and routers are able to form a star network configuration using PAN coordinator functions, and it is possible to form a multi-hop network by simultaneously configuring the mesh network between the coordinator and routers. On the other hand, the end devices take part in the network communication by

linking to the coordinator and routers through star-link networks. The end devices conduct multi-hop communications via connected routers to communicate with other devices connected to the networks. Using the advantages associated with the flexible ad hoc networking, the promise of ZigBee application can be found in robust and reliable, self-configuring and self-healing networks that provide a simple, cost-effective and battery-efficient approach for sensing and network based data communication in construction industry.

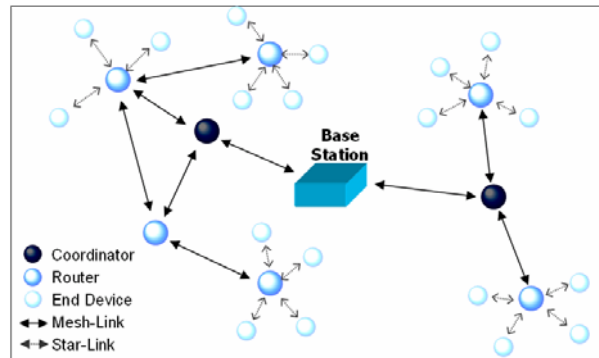


Fig 1. ZigBee network [12]

3. Location identification technique

In the RF-based wireless sensor network such as ZigBee, elimination of undesirable multipath components and fading is an important issue to achieve the localization of the distributed objects. While a construction site is considered as an outdoor environment where severe multipath of radio signal propagation is somewhat reduced compared to an indoor environments, there are still major concerns about complicated properties of signal propagation due to the reflection from ground, buildings, equipment, and materials. Our research focuses on the new methodology to mitigate the unwanted components of signal propagation for accurate and reliable measurement of the location of distributed sensor devices. Additionally, it also proposes a new approach to a potential deployment of ZigBee network to the automated tracking and monitoring system in construction site.

3.1. Coordinating

Coordinating is one of the most important tasks in wireless communication networks. To select the paths and to advertise the identity of a smart tag (or sensor), different coordinating algorithms impose over communication overheads. In the ZigBee networks, the sensor nodes transmit the radio signal with 2.4GHz frequency and 250 kbps data rate within the coverage range of 10-100 m, and this specification of transmission determines the level of power and network topology to be communicated between sensor nodes and ZigBee router. Particularly, our investigation approach includes the localization of construction components in a large scale

outdoor environment, so the allowable coverage range and power consumption rate would be the main issue for the reliable localization technique.

One approach to address this issue is to use the concept of radio frequency indicator (RFI) that advertises the identity of smart tag by transmitting the device ID and null data packet to the fixed ZigBee router. The schematic of the system is shown in figure 2. When a router receives a radio signal from a smart tag, it switches to a ready mode (power save mode includes both ready mode and inactive mode) to trigger a query pulse for measuring the distance of the smart tag. In order to discard the unwanted low-strength signals that exit around the router, a level of threshold, trigger index (I_{tr}), needs to be determined with the ratio of SS_{tr} and SS_{co} , so it is assured that a level of signal strength for reliable communication can be obtained with increased duration of power save mode.

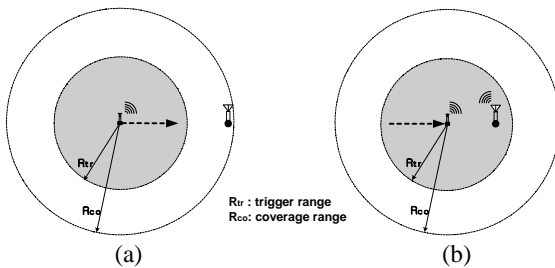


Fig 2. Coordinating scheme to trigger the query pulse for measuring the distance between ZigBee router and sensor device: (a) sensor is out of trigger range and (b) sensor is within trigger range

$$I_{tr} = \frac{SS_{tr}}{SS_{co}} \quad (1)$$

Where, SS_{tr} and SS_{co} are the received signal strength within trigger range and coverage range, respectively.

3.2. Query and response pulse based on TOF

This paper introduces a combination of RF signal and query pulse on a different channel. While localization method based on a received signal strength index (RSSI) simplifies the device design in most case, the fluctuation of RSSI due to multipath and fading of the radio signal propagation often results in a poor accuracy. By using a combination technique, it is possible to eliminate the multipath property of signal propagation with increased localization accuracy. When a ZigBee router confirms the RFI by coordinating scheme, it emits a query pulse to calculate the distance of the smart tag by time-of-flight method. After a transceiver attached in the tag detects the first arrival of the query pulse, it sends the original pulse back to the ZigBee router again, and the traveling time of the round trip pulse enables to measure the distance of the sensor device with eliminating the undesirable multipath property of the signal. At the same time, sensor starts to transmit the sensory data to ZigBee

router through radio signal packet recommended by IEEE 802.15.4 with 250kbs at 2.4 GHz frequency band illustrated in figure 3, immediately it checks in the query pulse that comes from the router.

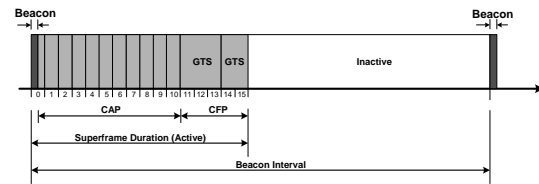


Fig 3. Superframe structure of the RF signal packet [14]

This paper propose two alternative approaches for estimating the distance of an object from the ZigBee router based on time-of-flight: one includes the use of discretized signature pulse of radio frequency signal; and the other scheme uses the ultrasound pulse as a response pulse (see figure 4). The discretized signature pulse of radio signal is designed to identify the unique characteristics of the original pulse, and an indicator located in front part of the radio pulse accounts for the measuring point in time-of-flight method. Once the RF transceiver in the tag receives the original signature pulse transmitted directly from the router, it transmits as the same RF response pulse as the original one to the ZigBee router. Since frequency and signature shape will not be changed or distorted unless it is reflected or refracted, the tag's distance can be measured by time-of-flight ensuring the elimination of multipath property of the radio signal without interference. On the other hand, ultrasound query pulse attached to smart tag with omni-directional antenna is used for measuring the distance between them. First arrival of the ultrasound response pulse to the router is then used as unique pulse ID for measuring the distance with eliminating the unwanted waves that are reflected or refracted from the obstacles. Once the router recognizes the smart tag's ID (by RFI) and distance (by query pulse), the geographic coordination of the smart tags will be obtained by multilateration technique that uses two or more ZigBee routers to determine the coordination of the tags.

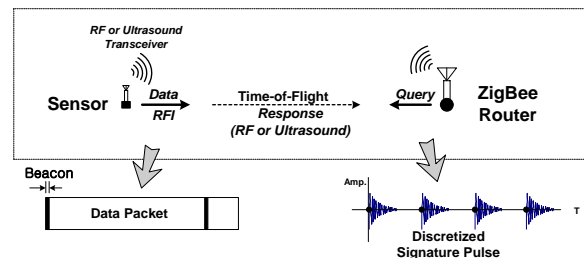


Fig 4. Description of combination of signature pulse: two alternative approaches (RF and ultrasound)

4. Feasibility analysis

In this section we study feasibility of location estimation of the objects by using a router and a ZigBee

enabled sensor or a smart tag. We consider two scenarios in our feasibility analysis: Measurement of the distance by RF signal; and measuring of the distance by combination of RF and ultrasound.

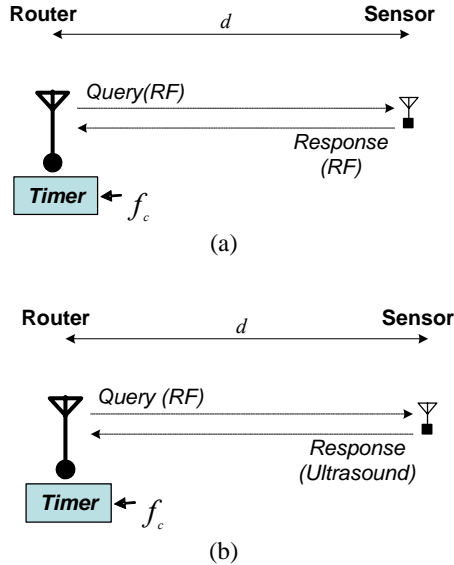


Fig 5. The schematic of the distance estimation from the router based on (a) the round trip time of the RF signal and (b) combination of RF signal and ultrasound signals

4.1. Measurement of the distance by RF signal

In order to make a more detailed performance study of the system, assume that it is desired to estimate the distance from the router with accuracy of 1 meter, and also assume that the maximum distance of objects from the router is about 200 meters. As shown in figure 5(a), we assume that the timer is implemented by a counter that counts up with a fixed clock frequency f_c . The required resolution of 1 meter means that the timer needs to have the resolution of 200 divisions, which means that it needs to have at least 8 bits. On the other hand, each increment happens in time $1/f_c$ and accuracy of 1 meter is possible if $1/f_c$ is smaller than the round trip time of the RF signal for an object in distance of 1 meter. This will lead us to the following equation:

$$f_c \geq \frac{3 \times 10^8 \text{ m/s}}{2 \times 1 \text{ m}} = 150 \text{ MHz} \quad (2)$$

The calculation in (2) shows that an increment of $1/f_c = 6.6 \text{ ns}$ causes a 1 meter error in estimation of the distance from the router. One possible shortcoming is that if the undesirable errors and processing delays happen in scheduling of the sensors, it will cause increased error in measurement of the distance. All operations of a sensor are performed according to an on-board oscillator that generates timing of the internal processor of the sensor. The frequency of such an oscillator is typically 10-100 MHz for current sensor technologies [10]. For example, if the clock frequency of

the microprocessor module of a sensor is $f_p = 50 \text{ MHz}$, then this means that the sensor can have the worst case delay of $1/f_p = 20 \text{ ns}$ in responding the query of the router after receiving it. This is because the fact that if the microprocessor's operations can only be triggered on the rising and falling edges of the digital clock generated based on the oscillator frequency. A delay of 20 ns can generate up to 3 meters error in measurement of distance.

The error in estimation of distance of an object from the router based on the measurements of RF round trip time delay is a result of very fast traveling speed of RF signals in the space. In order to resolve this issue, we study a second scenario, in which an alternative ultrasound signaling is used to measure distance of sensors to the router.

4.2. Measurement of the distance by combination of RF ultrasound signals

In this scheme, we use a method similar to the method introduced in section 4.1; however, we introduce a second signaling mode based on ultrasound for a more accurate measurement of distance, shown in figure 5(b). In this case, estimation of the distance is similar to the previous case. The router sends a query with the tag of an object of interest and at the same time starts a timer. Among all the sensors that receive the query of the router, only the one that matches the tag on the query responds by sending an ultrasound response back. There are two major differences in this case with the previous one: the first difference is that the speed of ultrasound signals is in the about 340 m/s which is significantly smaller than the speed of light, therefore, small delays introduced by scheduling of a sensor node do not cause an error in estimation of distance. The second difference from the scheme in section 4.1 is that here the ultrasound signal does not carry in digital information, and it does not have any form of modulation. Note that in this case, a sensor needs to send an ultrasound signal within a short period of time after observing a query of the router containing its tag, and no digital information is needed to be exchanged in the backward direction from the sensor to the router.

In order to perform similar calculation to those in section 4.1, and under similar assumption of measurement of distance up to 200 meters with the accuracy of 1 meter, we need the timer to be an 8 bit timer with the following clock frequency:

$$f_c \geq \frac{340 \text{ m/s}}{1 \text{ m}} = 340 \text{ Hz} \quad (3)$$

Note that in this case the signal travels with the speed of light in the forward direction and with the speed of ultrasound in the backward direction. Since the speed of light is about one million times faster than the speed of ultrasound, we ignore the component of the delay introduced by the propagation delay of RF signal in the forward direction, or the small processing or scheduling delay at the sensor. Therefore the dominant component of the round trip delay of the signal is the time of

traveling the ultrasound signal from the sensor to the source.

It is useful to note that in this case, a 1 meter increase in the distance of the object from the router results about 3 ms increment in the value of round trip time. This increment is significantly larger than the typical travel time of RF between the router and the sensor (about 1.3 μs for maximum distance of 200 meters), or the typical processing and scheduling delays at the microprocessor of sensor node (typically in order of 10-100 ns). Therefore, we predict that the estimation of error based on combination of RF and ultrasound waves to give a high performance and a very small error in estimation of the distance of sensors from the router.

A final issue in regard to the system based on combination of RF and ultrasound signals is dependence of the speed of ultrasound signals to the ambient parameters such as temperature and pressure. Such dependences can be taken into consideration by integrating proper sensors that are integrated to the router and make compensation for the changes in the environmental parameters.

5. Application scenario in construction site

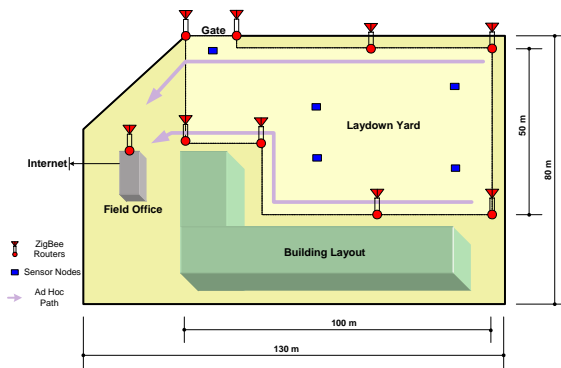


Fig 6. Possible application scenario for the material tracking and monitoring system in construction site

This paper envisions the possible scenario utilizing the ZigBee protocol in construction site illustrated in figure 6. ZigBee routers are placed at the location that can cover the entire laydown yard within their trigger ranges (R_{tr}) to detect the events associated with the movement of distributed smart tags. In this network topology, sensing data collected to each of the routers is transmitted to the base station, i.e. field office, along with the ad hoc path. Different smart tags are categorized, identified, and attached to the construction materials according to the characteristics of material property and measurement type within the geometry of construction site. For example, humidity sensor can be attached to the bulk of a cement bag or a steel beam to sense the level of humidity in order to avoid the hardening or corrosion caused by water in the humid environment. Other examples can be demonstrated in the PVC pipe where a temperature sensor is placed to detect the temperature variance to avoid melting or any defect caused by the

high temperature especially in the hot summer, allowing a field manager with the next step of preparedness to mitigate the observed phenomenon. Deployment benefit of this possible scenario is expected to provide not only the method of tracking the construction components but also practical way of wireless monitoring in the construction site.

Further application can be identified to the framework of real-time information collection in which construction activities associated with the information about material, workers, and equipment could be updated to and collaborated with project management systems – such as web-based project management system (PMS), 4D visualization, project scheduling package, or enterprise resource planning (EPR). The information flow diagram illustrated in figure 7 envisions the possible information system for the collaboration with the project management tools based on the identification of the functional dependencies of each event associated with the construction activities. The future research will investigate the detailed design and suggestion on the sensor, server and application layer to provide a motivation of automated construction environment utilizing the advanced technologies of sensor and network.

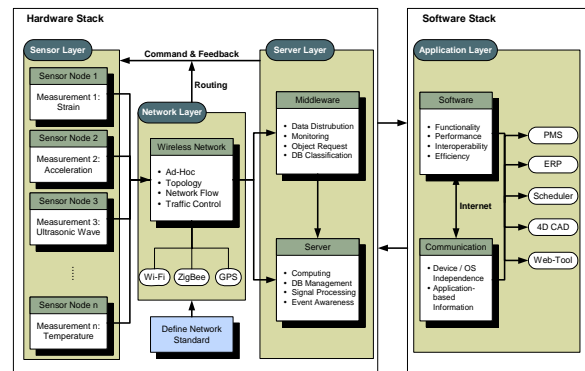


Fig 7. Information flow diagram for possible collaboration with project management systems

6. Deployment challenges

Challenges for applying the material tracking and monitoring system in construction site can be categorized into the following four practical issues: 1) signal interference; 2) line of sight for signal propagation; 3) device size and cost; and 4) battery management.

6.1. Signal interference

The specification of radio signal recommended by ZigBee Alliance utilizes 2.4 GHz frequency with low transmission power of up to 1 W, which is allowed by FCC regulations. Low power transmission scheme with low duty cycles (under 1%) provides the reduced interference by other devices and systems practically in-network systems [5]. Also, other type of radio signals that use similar frequency range, such as 2.4 GHz

cordless phone and 2.4 GHz Wi-Fi communication, etc, would not interfere the signal of IEEE 802.15.4 because different scheme of band structure is used to prevent the possible interference between them. In a highly dense network, however, signal collision problem could arise especially when several nodes try to transmit data simultaneously. Future research will identify the factors that might cause the possible signal interference or collision in the practical applications. This issue is widely studied in the area of communication theory, and the recommended Media Access Control (MAC) schemes for IEEE 802.15.4 is equipped with state-of-the-art collision avoidance techniques, which enable it to operate efficiently in a high interference environment with dense deployment of sensor nodes.

6.2. Line of sight for signal propagation

In general, the radio frequency signal doesn't require the line of sight (LOS) issue to be communicated with the distributed sensor nodes, hence it is widely accepted that the radio signal is a good candidate for wireless monitoring systems. However, our localization technique utilizing the query pulse may incur the limitation due to LOS issue because the time of flight requires the open space for measuring the distance in order to assure the absence of obstacles. Hence, it is necessary to configure the different setup of sensor placement for the practical use of this technique. For practical example, ZigBee routers placed in higher location, such as ones installed on top of construction light pole, might overcome the LOS problem for the tracking system of the construction materials that are laid in the complicated arrays of laydown. Further research will be focused on the topological analysis to improve the practical deployment strategy and possible application framework.

6.3. Device size and cost

With the development of micro electromagnetic system (MEMS), it is possible to design a very tiny sensor device to be used in the industrial applications. However, practical design of sensor device varies according to the deployment strategy and protocol specification, and detailed categories and attributes related to the measurement characteristics that define the sensor types and network specifications must be identified in order to satisfy the needs and requirements. In addition to the size of the sensor device, the economics associated with the device cost plays a critical role to the decision maker in the management point of view. It is believed that the size and cost of the sensor device will gradually fall down with the development of the technology, thus MEMS based sensor platform will provide a good applicability to large scale of construction project as a cost- and performance-effective tool for the framework of advanced information systems.

6.4. Battery management

Battery management is also a fundamental challenge to the application of wireless sensor network for long-term deployment framework. While power efficient technique, such as sleep mode, can provide possible solution to better performance of battery's life-cycle, more fundamental scheme of battery management needs to be examined and developed to overcome the limitations related to the life-cycle of the battery. Our next research objectives will include the investigation of the different platform that provides an advanced architecture for a reliable and long-term power source applicable to wireless sensor framework. Photovoltaic battery or radiation empowered sensor network will be possible subject for our future research activities.

7. Summary and future perspectives

ZigBee is emerging network technology and a wireless communication standard capable of realizing the ubiquitous computing environment in many industrial areas. As a superset of IEEE 802.15.4 standard, ZigBee supports the industrial network standards, so that many industrial applications including construction automation, structural health monitoring, and automated control and operation can benefit from the advantages of the technology. ZigBee specification takes advantage of the IEEE 802.15.4 wireless protocols as communications method, and expands on this with a flexible mesh network, wide range of applications, and interoperability.

By deploying the ZigBee networks, this paper introduced system architecture of automated materials tracking for construction process. To overcome the limitations of previous RFID- and GPS-based technologies observed in current construction practices, a new localization technique with combination of radio frequency and ultrasound was presented for more accurate positioning performance. A feasibility analysis showed that combination of radio frequency and ultrasound will provide a better performance in measurement accuracy than the one that uses only RF. Using different channel allocation supported by ZigBee standards, various sensor-based devices can be embedded into this system capable of providing versatile monitoring capacities for different purposes. Further investigation indicated that automated field data acquisition in construction site can benefit from the development of this system with respect to the future collaboration mechanism with several project management platforms.

Based on the associated components of network specifications and tracking method described in the paper, we plan to continue our investigation related to the development of advanced algorithm for localization and ad hoc networking strategy. In addition, we will implement the device design for practical application to construction sites for cost- and performance-effectiveness. As the continuous research activities relating to ubiquitous computing in civil infrastructure systems, the interface design for multi-communication protocols, middleware platform, and network topology formulation will be created in the future.

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