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# A WIRELESS NETWORK SYSTEM FOR AUTOMATED TRACKING OF CONSTRUCTION MATERIALS ON PROJECT SITES

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**Abstract**. This paper presents a new prototype framework of automated tracking and monitoring system for construction materials. Previous technologies such as RFID and GPS deployed in construction material tracking have been reviewed and signal strength-based localisation has been examined. As an emerging network standard for industrial applications, brief specifications of ZigBee™ protocol have been described. We introduce a ZigBee-based tracking system architecture using hybrid 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

Typical construction processes require large budgets and resources to be committed within a constrained project time. However, inefficiencies associated with current practices of manually tracking materials, equipment and workers in construction field often cause 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, procurement, just in time (JIT) deliveries and asset information tracking. Furthermore, current practices of data 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 analysing field data, and 2 % of construction work is categorised as manual tracking and controlling of material handling (Cheok *et al.* 2000; McCullouch 1997). Even though many construction firms well notice the importance of effective materials tracking, today's practice in materials management decisions still tend to be ad hoc and intuitive not based on the data. Thus, manual handling and controlling of materials causes errors due to personal judgments and writing skills, and lack of systemic understanding of communication protocols often results in process delays. As a result, it becomes more critical to provide real-time method of identifying, registering, collecting and communicating information about the status of construction materials.

Advanced computing and sensor network technologies provide potential for advanced data acquisition and communication for automation and improvement in process performance – such as RFID and GPS (Jaselskis, El-Misalami 2003; Peyret *et al.* 2000). During last several years, applications of radio frequency identification (RFID) technology had already taken place as a prototype in construction industry for identifying and tracking products. Jaselskis and El-Misalami (2003) 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. The research 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 (Song *et al.* 2006). 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 (Goodrum *et al.* 2006). Utilising 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 older technologies, eg 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 localisation 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 readers cost from $2,500 to $3,000 depending

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**Table 1.** Characteristics of different RSSI-based localisation techniques (Lymberopoulos *et al.* 2006)

| Technique | Design Approach | Technology | Testbed Dimensions | Location Error |
|---|---|---|---|---|
| Ecolocation | Ordered sequence of raw RSSI data | MICA2 | 26×49(ft) (Indoor) | 10 ft |
| Probability grid | RSSI-based probabilistic | MICA2 | 410×410(ft) (Outdoor) | 66 ft |
| Radar | RSSI fingerprint map | 802.11b | 42.9×21.8(m) | 15 ft |
| Mote track | RSSI fingerprint map | MICA2 | 18751 $ft^2$ | 13 ft |
| LEASE | Online fingerprinting and signal propagation modelling | 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 with respect to the location-detection performance | N/A | N/A | N/A |
| Monte Carlo localisation | Learning based with signal strength map | 802.11b | N/A | 7.2 ft |
| Nibble | Bayesian networks | 802.11b | 224×96(ft) (Indoor) | 20 ft |

on various features in the device (ABI Research… 2005). Thus it is prohibitively expensive for practical application to 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 (Goodrum *et al.* 2006). 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, localisation 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 (Lu *et al.* 2004). Thus it is unreliable to achieve the accurate localisation for material tracking and monitoring in a highly dense environment such as construction sites.

We present a new prototype framework of automated tracking and monitoring system that will address the needed shift from the time-and-labour-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 hybrid 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 strategy for construction applications.

## 2. Localisation techniques

For the achieving tracking, monitoring, controlling, and geometric-based routing, localisation is a primary task for a higher level of sensor network functions such as tracking, monitoring, controlling, and geometric-based routing (Elnahrawy, Martin 2004). Many of the localisation techniques found in previous researches are based on the received radio strength indicator (RSSI) due to its wide availability to wireless radio signal communication (Lymberopoulos *et al.* 2006). Especially RSSI-based localisation has an advantage that utilisation of the same radio hardware for both communication and localisation would make it possible to provide efficiency in simple design framework over a specific localisation infrastructure – such as ones using directional antennas or the same transmission signal, and separate design of ultrasound or infrared (Elnahrawy, Martin 2004). Table 1 summarises the characteristics of different RSSI-based localisation techniques.

However, RSSI-based localisation has a critical limitation that has been observed in the physical characteristics of radio signal propagation. Since raw RSSI does not provide enough accuracy for localising the mobile objects to be used in practical application, the distance prediction requires additional investigation into the probability method or learning-based localisation algorithm (Lymberopoulos *et al.* 2006). 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 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 localisation error observed in the RSSI-based techniques shown in Table 1 illustrates that most errors range from 10 ft to 20 ft for indoor system (Lymberopoulos *et al.* 2006). While construction site is considered 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. Consequently, the motivation toward a reliable localisation and communication calls for a different framework of technique to provide the acceptable accuracy to be deployed in construction processes.

## 3. ZigBee™

As an emerging wireless communication standard, ZigBee provides a capability of realising the ubiquitous environment to satisfy such requirements. ZigBee supports the industrial network standards as a superset of IEEE 802.15.4 standard, and many industrial applications, including construction automation, structural health monitoring, 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 on 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 (ZigBee Alliance…2005)

| 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)

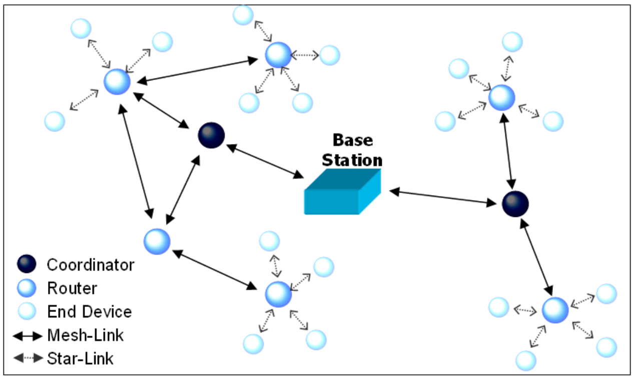



**Fig. 1.** ZigBee network (Skibniewski, Jang 2006)

A ZigBee network consists of ZigBee coordinators, ZigBee routers and ZigBee end-devices, as is shown in Fig. 1 (Skibniewski, Jang 2006). 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 to sensing and network-based data communication in construction industry.

## 4. Methodology

For a reliable localisation, elimination of undesirable multipath components and fading is an important issue in the RF-based wireless network such as ZigBee. Even though 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 on construction site.

### 4.1. Coordinating scheme

Coordinating is an initial task for 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. The sensor nodes with ZigBee protocol transmit the radio signal with 2.4 GHz 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 localisation 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 localisation 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 Fig. 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.

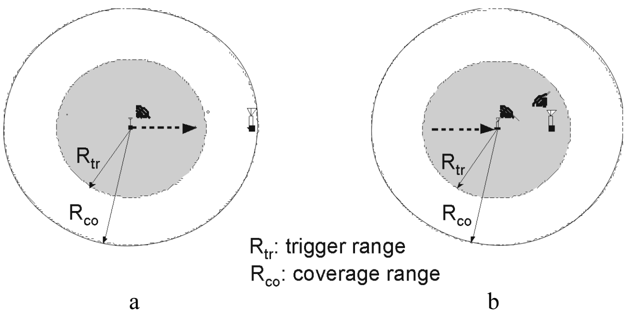



**Fig. 2.** Coordinating scheme to trigger the query pulse for measuring the distance between ZigBee router and sensor device: a – sensor is out of trigger range and b – sensor is within trigger range

$$I_{tr} = \frac{SS_{tr}}{SS_{co}}, \tag{1}$$

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

### 4.2. Time-of-flight method

This paper introduces a hybrid of RF signal and ultrasound based on time-of-flight method. While localisation method based on a received signal strength index (RSSI) simplifies the device design in most cases, the fluctuation of RSSI due to multipath and fading of the radio signal propagation often results in a poor accuracy. By using a hybrid technique, it is possible to eliminate the multipath property of signal propagation with an increased localisation accuracy. When a ZigBee router confirms the RFI by coordinating scheme, it emits a query pulse to measure the distance between a remote sensor and a router. After a transceiver in the remote sensor detects the RF query pulse, it sends the response pulse back to the ZigBee router again, and the travelling 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 250 kbs at 2.4 GHz frequency band illustrated in Fig. 3, immediately it checks in the query pulse that comes from the router.

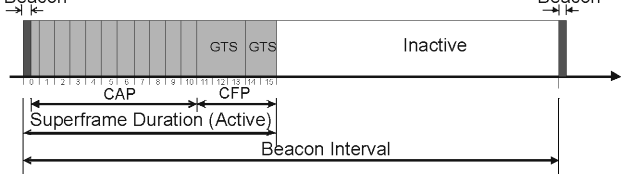



**Fig. 3.** Superframe structure of the RF signal packet (Zheng, Lee 2004)

Two alternative approaches have been examined for estimating the distance of an object from the ZigBee router based on time-of-flight: one includes the use of generic RF signal as a response pulse; and the other scheme uses the ultrasound signal as a response pulse (Fig. 4). The packet structure 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 remote sensor receives the original RF query pulse transmitted directly from the router, it transmits as the RF response pulse to the ZigBee router. Based on the first-arrival signal detecting scheme using time-stamp approach, the remote sensor's distance can be measured by time-of-flight ensuring the elimination of multipath property of the radio signal without interference. Once the router recognises the remote sensor's ID (by RF) and distance (by response pulse), the geographic coordination of the remote sensor can be obtained by trilateration technique that uses two or more ZigBee routers to determine the coordination of the tags.

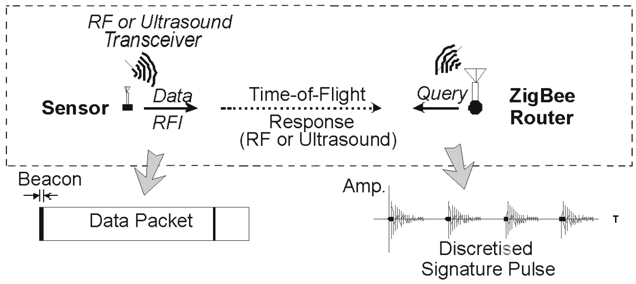



**Fig. 4.** Description of combination of signature pulse: two alternative approaches (RF and ultrasound)

## 5. Feasibility analysis

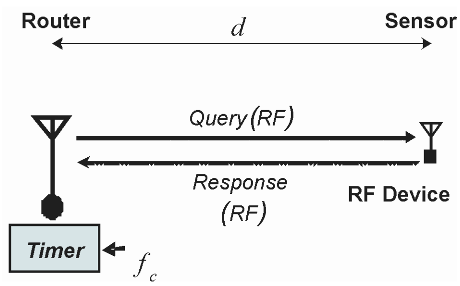
In this section we study feasibility of location estimation of the objects by using a router and a ZigBee enabled sensor or a smart tag. We consider two scenarios in our feasibility analysis: measurement of the distance by RF signal, and measuring of the distance by combination of RF and ultrasound. It should be noted that multipath effect can be removed by timestaming method in which sensor turns off ADC after the first-arrived signal is detected (Jang 2007).

### 5.1. Localisation by RF signal

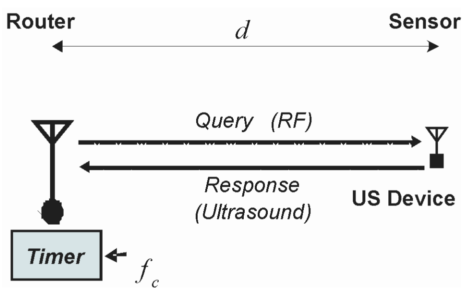
Let's suppose that it is desired to estimate the distance from the router with accuracy of 1 meter, and also assume that the maximum distance of objects from the router is about 200 m. As shown in Fig. 5(a), we assume that the timer is implemented by a counter that counts up with a fixed clock frequency $f_c$. The required resolution of 1 m 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 m is possible if $1/f_c$ is smaller than the round trip time of the RF signal for an object in distance of 1 m. This will lead us to the following equation:

$$f_c \geq \frac{3\times10^8 \text{ m/s}}{2\times1 \text{ m}} = 150 \text{ MHz}. \quad (2)$$

The calculation in (2) shows that an increment of $1/f_c = 6.6$ 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 an increased error in distance measurement. 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 (MICA2DOT…2006). For example, if the clock frequency of the microprocessor module of a sensor is $f_p = 50$ MHz, this means that the sensor can have the worst case delay of $1/f_p = 20$ ns in responding the query of the router after receiving it. This is because the fact that if the micorprocessor'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 distance measuring.




a




b

**Fig. 5.** The schema 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

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

### 5.2. Localisation by combination of RF and ultrasound signals

In this scheme, we introduce a second signalling mode based on ultrasound for a more accurate measurement of distance, shown in Fig. 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 a timer starts. 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 schedulling a sensor node do not cause an error in estimation of distance. The second 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 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.

Under similar assumption of measurement of distance up to 200 m 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 that 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 schedulling delay at the sensor. Therefore the dominant component of the round trip delay of the signal is the time of travelling the ultrasound signal form the sensor to the source.

It is useful to note that in this case, an 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 processing and schedulling delays at the microprocessor of sensor node. 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. This means that relatively slow speed of ultrasound travel time is not sensitive to the selection of microprocessor's instruction cycle; thus the accuracy is solely dependent on the travel time of ultrasound signal.

### 5.3. Simulation result

For accuracy simulation, three fixed beacons are placed at each vertex point of a triangle, and remote node is set to move along with the square-shape path of 70-by-70 meters. Three clock frequencies of microprocessor, eg

8, 25 and 50 MHz, are selected, and travel speed is set at $3 \times 10^8$ m/s for radio signal propagation and 340 m/s for ultrasound signal propagation. A mobile sensor moves along the square path at the speed of 1 m/s, and the sampling cycle of estimating each position is set at 500 ms. The hybrid scheme using radio and ultrasound signal presented in this paper results in relatively high accuracy ranges in the order of few tens centimeters. However, if a RF-only scheme is considered, 75 percentile errors measured at 8 MHz clock frequency increase about 20 meters. It is interesting to mention that the root-mean-square (RMS) values often provide a good reference in the situation where the variants are marked positive and negative from the exact values. Thus randomly varying quantities in position estimation can be expressed in terms of positive magnitude, providing more inclusive representation of variance than arithmetic means. In Fig. 6, RMS values measured from the combination of RF and US indicates 58.6 cm in all range of clock frequencies. However, a RF-only scheme results in 2.8, 5.8, and 17.4 meters at 50, 25, and 8 MHz clock frequencies, respectively. If the clock frequency decreases to several hundreds of KHz, one cannot justify the rationale of deploying the RF-only scheme in distance and position estimation.

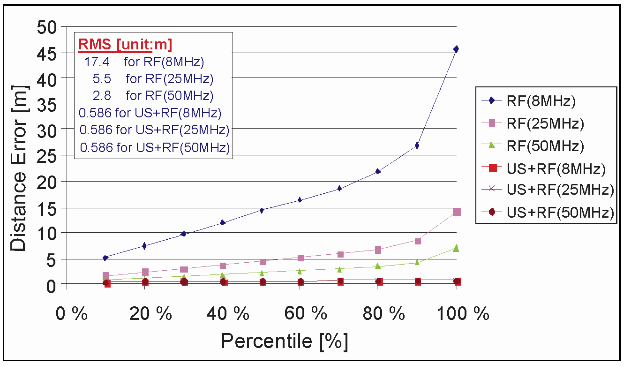



**Fig. 6.** Percentile of position error

## 6. Scenario application on construction site

This paper envisions the possible scenario utilising the ZigBee protocol on construction site illustrated in Fig. 7. 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, ie field office, along with the *ad hoc* path. Different smart tags are categorised, 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 hardening or corroding caused by water in a 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 a high temperature especially in a 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 a practical way of wireless monitoring on the construction site.

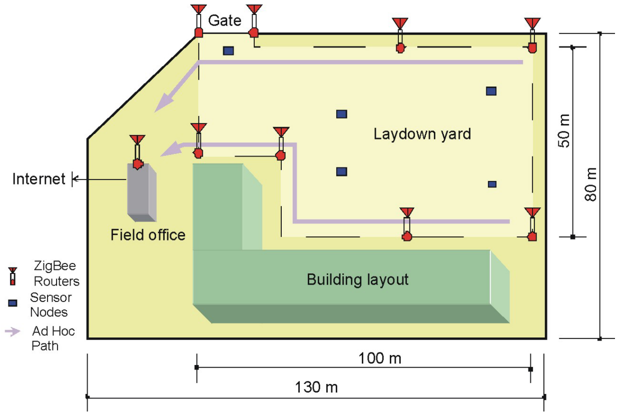



**Fig. 7.** Possible application scenario for the material tracking and monitoring system on construction site

Further application can be identified with the framework of real-time information collection in which construction activities associated with the information about material, workers, and equipment could be updated and collaborated with project management systems – such as web-based project management system (PMS), 4D visualisation software, project scheduling package, or enterprise resource planning (ERP). The information flow diagram, illustrated in Fig. 8 envisions the potential of information system for the future 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 utilising the advanced technologies of sensor and network.

## 7. Deployment challenges

Challenges for the prototype applications of material tracking and monitoring system on construction site can be categorised into the following four practical issues: 1) line of sight; 2) battery life cycle; 3) device size and cost; and 4) signal interference.

### 7.1. Line of sight

Typically, the radio frequency signal does not 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 localisation technique utilising the ultrasound response pulse may incur the limitation due to LOS issue because the time of flight requires an open space for measuring the distance in order to assure the absence of obstacles. Hence it is necessary to configure the

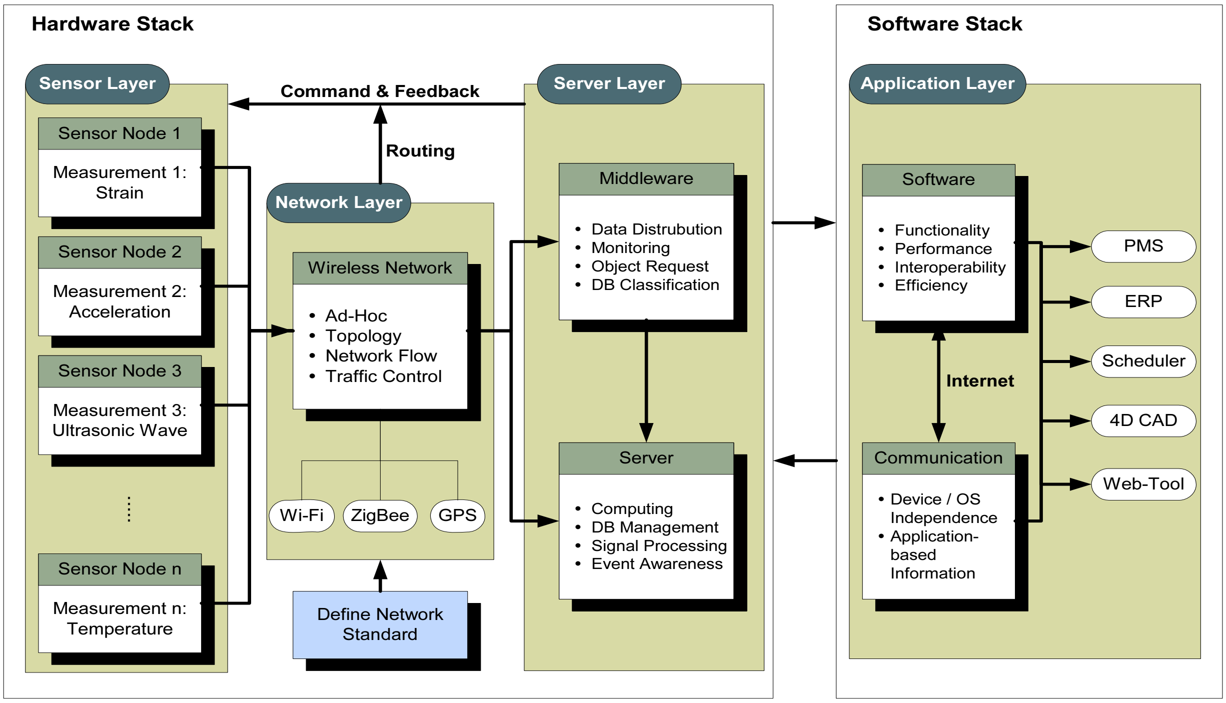



**Fig. 8.** Information flow diagram for possible collaboration with project management systems

different setup of sensor placement for the practical use of this technique a higher location, such as ones installed on top of construction light pole, might overcome the LOS problem for the tracking system of the structural 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.

### 7.2. Battery life cycle

Battery life cycle 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 a possible subject for our future research activities.

### 7.3. Device size and cost

With the development of microelectromagnetic system (MEMS), it is possible to design a very tiny sensor device to be used in 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 technology development, 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.

### 7.4. Signal interference

The specification of radio signal recommended by ZigBee Alliance utilises 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 (IEEE Standards…2003). 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 with 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.

## 8. Conclusions

ZigBee is an emerging network technology capable of realising the ubiquitous computing environment in many industrial areas. It is expected that ZigBee can support many industrial applications including construction automation, structural health monitoring, and automated control and operation. Using flexible and scalable networking features, ZigBee has a potential to explore a flexible mesh network, wide range of applications, and interoperability.

By deploying the ZigBee networks, this paper introduced a system architecture of automated materials tracking for construction process, in which bulk materials such as precast concrete, steel girders, PVC pipes etc could be a possible target for the proposed tracking application. To overcome the limitations of previous RFID- and GPS-based technologies observed in current construction practices, a new localisation technique with combination of radio frequency and ultrasound was presented for a 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. Further investigation indicated that automated field data acquisition on construction site can benefit from the development of this system in respect of the future collaboration mechanism with several project management platforms.

Based on the associated components of network specifications and tracking method described in the paper, further investigation will continue to develop the advanced algorithm for localisation and ad hoc scheduling 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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**BEVIELIO TINKLO SISTEMA AUTOMATIŠKAI STATYBINĖMS MEDŽIAGOMS STEBĖTI STATYBVIETĖSE**

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Santrauka

Straipsnyje aprašomas naujas automatizuotos statybinių medžiagų stebėsenos sistemos modelis. Apžvelgiamos tokios technologijos, kaip RFID ir GPS, anksčiau naudotos stebint statybines medžiagas, ir nagrinėjamas signalo stiprumu pagrįstas lokalizavimas. Aprašoma tinklo standarto ZigBee™ protokolo, naudojamo pramonėje, specifikacija. Pateikiama ZigBee tipo stebėjimo sistema, naudojanti RF ir ultragarso technologiją, skirtą pozicionavimo tikslumui gerinti ir jo kainai mažinti. Be to, pateikiama sistemos galimybių analizė ir taikymo sistema, nagrinėjanti galimą šios sistemos naudojimą statyboje.

**Reikšminiai žodžiai**: ZigBee, daviklių tinklas, stebėjimas, kontrolė, statybinės medžiagos, lokalizavimo technika.

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