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Wireless Sensor Networks for Resources Tracking at Building Construction Sites*

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Abstract: We evaluate the technical feasibility of applying emerging wireless network technologies for resources tracking at building construction sites. We first identify practical constraints in solving resource-tracking problems in an enclosed or partially covered environment. We then compare pros and cons of available localization principles and examine the latest wireless communication technologies, including Wi-Fi, Bluetooth, Ultra-Wideband (UWB) and ZigBee. We find that the ZigBee-based wireless sensor network and the received signal strength indicator (RSSI) localization method are most promising to tackle on-site tracking of construction resources. Finally, we anticipate some application challenges associated with deploying wireless sensor networks for resources tracking in the practical context.

Key words: wireless sensor network; ZigBee; tracking; signal strength; building construction site

Introduction

With rapid development and innovation of the construction industry in past decades, operations at a construction jobsite become more complex and dynamic due to increasing amounts of resources involved, which include a diversity of labor, materials, equipments and tools. Consequently, there has been a growing awareness that effective resource management plays a crucial role to the success of construction projects[1]. In particular, operations management at construction sites could benefit from resources tracking with improved situation awareness, which spans applications in (1) productivity assessment; (2) waste reduction; and (3) safety and accident prevention.

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Research into construction resources tracking and automated data collection (ADC) has advanced along with the growing power of information technologies in recent years. Radio frequency identification (RFID) and global positioning system (GPS) outweigh other technologies and have seen numerous applications in connection with tracking various resources at construction sites. On the other hand, it is noteworthy that previous efforts into construction resource tracking mainly focused on relatively open environments, such as material storages, earth-moving or road construction sites. When applied at enclosed or partially covered building sites, RFID tags suffer from sharp decrease in communication distance with the existence of metals in their vicinity (e.g., reinforcement mesh, steel scaffold, shoring, or shutter, metal door, and hoardings)[2,3]; While the performance of GPS positioning can be severely degraded due to blockage, deflection and distortion of satellite signals[3,4]. Therefore, research investigations and off-the-shelf solutions relating to tracking resources at building construction sites have been rare so far. Current field practices at building sites still rely on traditional manual methods for resource tracking, which are labor-intensive, costly, and error-prone[5] (such as time cards).

In this paper, we intend to evaluate the technical feasibility of applying emerging wireless network technologies for resources tracking at building construction sites. Based on critical reviews of available localization methods and state-of-the-art wireless communication technologies, we identify that the ZigBee-based wireless sensor network and the received signal strength indicator (RSSI) method are most promising for solving on-site resources tracking problems.

The reminder of this paper is organized as follows: First, we analyze some basic localization principles commonly used for wireless positioning, followed by assessment of four wireless network technologies, namely Wi-Fi, Bluetooth, Ultra-Wideband (UWB), and ZigBee. We then evaluate the feasibility of using those technologies and methodologies for resources tracking at building construction sites. Next presented are some deployment challenges as we foresee. Conclusions are drawn and future research recommendations made in the end.

1 Localization Principles

In order to locate objects in wireless networks, four different measurement principles are commonly adopted: angle of arrival (AOA), RSSI, time of arrival (TOA), and time difference of arrival (TDOA), as shown in Fig. 1.

In AOA, at least two base stations (BS1 and BS2 in Fig. 1a) are required to locate the mobile unit (MU). Directional antennas or antenna arrays are used to measure the direction of the transmitted signal (α_1 and α_2). The location of the MU can then be determined at the intersection of the two angled directional lines. AOA is capable of locating the object with only two stations. Nonetheless, the accuracy of this approach is limited by signal shadowing, or by multipath reflections yielding misleading directions[6]. Another disadvantage of AOA is the relatively high investment of infrastructure, such as directional antennas or antenna arrays.

Positioning with RSSI is based on propagation-loss equations[6]. The distance between a base station and a mobile unit (L_1 and L_2 in Fig. 1b) can be estimated by calculating the attenuation of the emitted signal strength being received. Currently, most of indoor positioning approaches are based on RSSI, because it is convenient to be implemented and usually requires software modifications without extending existing infrastructure[7]. On the downside, due to high nonlinear features of the radio signal strength in indoor environments or built-up areas, the strength is severely susceptible to environmental conditions.

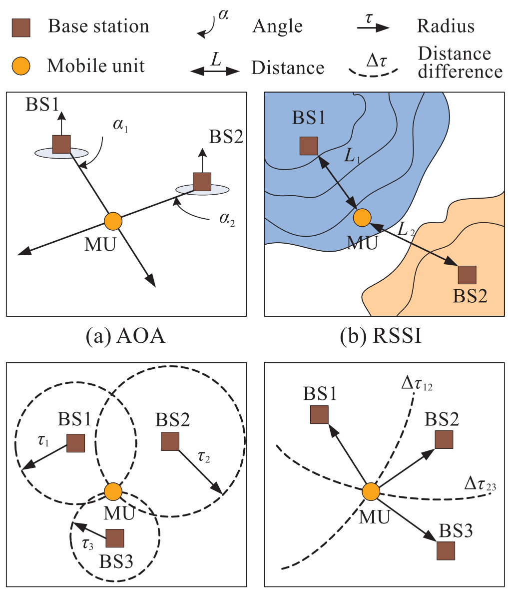

Fig. 1 Principles of location measurement

In a TOA system, the time-of-flight of a signal traveling between a mobile unit and a specific base station is measured for calculating the distance (τ_1, τ_2, and τ_3 in Fig. 1c). Once the transmission radii are measured, the location of the mobile unit can be determined using geometrical triangulation methods (intersection of three distance circles). TOA solutions provide accurate positioning given the availability of extremely precise time-keeping devices. GPS with atomic clocks is one of the most famous and successful application of TOA.

Similar to TOA, TDOA measures the time-difference of arrival of the signal transmitted from two base stations (Fig. 1d). However, both TOA and TDOA demand accurate source clocks and clock synchronization. In addition, multipath fading and shadowing degrade the accuracy of TOA and TDOA measurements significantly.

2 Enabling Wireless Network Technologies

With improvements in wireless network technologies in recent years, there is a growing research interest to explore whether those emerging technologies could find practical applications in resources tracking at building construction sites. In this section, the pros and cons of state-of-the-art IEEE wireless network technologies are discussed, including 802.11x wireless local networks (WLAN) (Wi-Fi) and 802.15.x wireless personal area networks (WPAN) (Bluetooth, UWB and ZigBee). An overview of the relevant, representative IEEE standards is presented in Fig. 2.

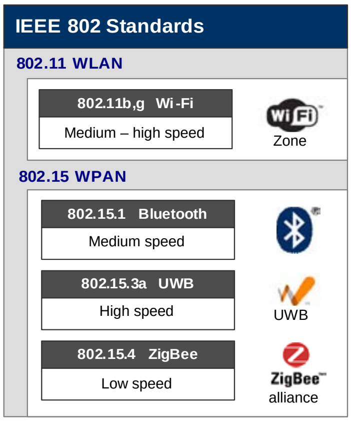

Fig. 2 Overview of state-of-the-art IEEE 802 wireless network standards

2.1 Wi-Fi

Currently, the most prominent specification for IEEE 802.11 WLAN standards is Wi-Fi alliance. Wi-Fi operates in the license-free 2.4 GHz industrial, scientific, and medical (ISM) band. It provides wired LAN extension or replacement in a range of market areas, e.g., enterprise, home, and hot spots. There are some distinct advantages of Wi-Fi, including (1) economical solution; (2) wide coverage and easy availability; and (3) stability and robustness.

Localization based on Wi-Fi has been seen as a cost-effective solution for indoor environments. RSSI is widely adopted, and the accuracy of typical Wi-Fi positioning systems is approximately 3 - 30 m, with an update rate in the range of a few seconds[6]. The most well-known solution by far is the RADAR system developed by Microsoft in 2000[8], and the commercial software-based Ekahau system[9]. On the downside, many studies ascribed low accuracy of Wi-Fi localization to multipath errors encountered in complex environments. As for the application of WLAN in construction, less research is published except for Khoury and Kamat's approach[10]. They developed a dynamic user-viewpoint tracking scheme that can allow identification of construction entities visible in a user's field of view. GPS and magnetic orientation sensors are implemented to track user's outdoor location and viewpoint. For indoor enclosed environments where GPS becomes unavailable, their ongoing research investigates applicability of WLAN for dynamic user tracking.

2.2 Bluetooth

The Bluetooth technology is originally designed as a short-range wireless connectivity solution for personal, portable, and handheld electronic devices. The Bluetooth radio also operates on the 2.4 GHz ISM band. Notably, Bluetooth employs a fast, frequency-hopping spread spectrum (FHSS) technology to avoid the interference in the ISM band and ensure the reliability of data communication.

With extensive applications of Bluetooth for wireless data communication in hand-held devices and wireless computing, researchers also have drawn on Bluetooth for local positioning. Similar to Wi-Fi, Bluetooth can provide several meters of localization accuracy based on the popular RSSI methodology. Strong multipath interference is identified as one of the key factors that affect positioning accuracy. With respect to the utilization of Bluetooth in construction engineering, Lu et al.[3] embedded Bluetooth technology into roadside beacons for positioning construction vehicles at building sites. In their field trials, it was found that the communication range of Bluetooth module reduced from the nominal 100 m to 20 m due to complex site conditions.

2.3 UWB

UWB technologies can transmit extremely short and low power electro-magnetic pulses. The radios use frequencies from 3.1 GHz to 10.6 GHz, with the radio spectrum spreading over a very wide bandwidth. There are some distinctive advantages of short-range high-bandwidth UWB: (1) high immunity to interference from other radio systems; (2) high multipath immunity; (3) high data rate, and (4) fine range-resolution capability[11].

Investigations of UWB dated to more than three decades ago, and early applications included precision radar imaging and localization[12]. However, due to strict regulation by the Federal Communications Commission (FCC) under the U.S. government, the commercial use of UWB had not been allowed until 2003. By far, as one of the earliest civilian applications of UWB, Fontana et al.[13] utilized UWB for accurate assets localization. TOA measurement was adopted to achieve the position accuracy of better than one foot.

2.4 ZigBee

ZigBee is a global standard for wireless mesh network technology that addresses remote monitoring and control applications. The technology defines the physical and medium access control (MAC) layers for low cost and low rate WPAN. Important features of ZigBee are: (1) low data rate; (2) extremely low power consumption; (3) low complexity; and (4) high reliability and security.

As an emerging wireless network technology, ZigBee-based wireless sensor networks are regarded a promising solution to a multitude of location-dependent applications, such as wildlife monitoring, instruction detection and war field surveillance and so on[14]. Notably, Jang, and Skibniewski[15] proposed ZigBee-based wireless sensor network for object tracking and monitoring in construction processes. They applied ultrasound and TOA for localization of construction materials. The ranging data were collected simultaneously for centralized computing via a ZigBee network. However, disadvantages associated with traditional ultrasound positioning may hamper the potential applications in complicated construction environments, for instance, lack of line-of-sight transmission, multipath, high cost and power consumption.

Each IEEE wireless network technology well serves special purposes and is particularly suitable for certain applications. In order to provide a clear picture of technical differences, comparisons among proposed four wireless network technologies are given in Table 1.

Table 1 Comparison of four wireless network technologies

	Wi-Fi	Bluetooth	UWB	ZigBee
Standard	IEEE 802.11b,g	IEEE 802.15.1	IEEE 802.15.3a	IEEE 802.15.4
Frequency band	2.4 GHz	2.4 GHz	3.1 GHz-10.6 GHz	868/915 MHz, 2.4 GHz
Data rate	Up to 22 Mb/s	1 Mb/s	40-600 Mb/s	20/40/250 kb/s
Network topology	32 active nodes	8 active nodes	N/A	255 active nodes
Range	100 m	10 /100 m	30 m	10/100 m
Battery life	h	Days	h	Years
Cost	Relatively high	Relatively low	Highest	Lowest
Applications	Wireless internet access	Data and voice access, Ad-hoc networking	High speed wireless communication, radar	Remote monitoring and control

3 ZigBee-Based Resource Tracking Network

Evaluation of available localization methods and emerging wireless network technologies entails a comprehensive understanding of their strengths and limitations. We then identify that the ZigBee-based wireless sensor network and the RSSI localization principle are most promising for tracking various resources at building construction sites.

3.1 ZigBee wireless sensor network

Comparison of four wireless network technologies indicates that most of these standards operate in the similar frequency band, namely unlicensed ISM 2.4 GHz. Different technical protocols are specially developed to meet a variety of application requirements, for example, high data rate, low interference or long battery life. For resources tracking at building sites, ZigBee provides a relatively ideal technology over other candidates thanks to following advantages: (1) the low cost of ZigBee nodes and its extensible network capacity enable deployment of large numbers of nodes, which increases system coverage and communication reliability; (2) low power consumption eases operation and maintenance of the system; (3) ad-hoc network architecture supports flexible deployment and adjustment of the network; (4) high reliability and security of ZigBee wireless data communication enhance its performance at construction sites. In addition, the low data rate is acceptable for data communication of tracking and locating resources at a construction site.

When deployed at building construction sites, ZigBee nodes can be divided into two categories: static nodes and mobile nodes. Static nodes with well-defined coordinates are scattered in a building site and constitute a customized ad-hoc network for resource tracking and wireless data communication. Mobile devices, on the other hand, are attached to the resources being tracked, such as labor, material, equipment or tool etc. While a mobile device falls in the signal coverage of a specific static node, they communicate with each other by making wireless links. Meanwhile, the IDs of both devices together with time data are collected and transferred to the control center for further calculation.

3.2 RSSI for range estimation and localization

In terms of location measurement, AOA, TOA, and TDOA methods depend heavily on line-of-sight transmission and require expensive infrastructure. Meanwhile, those methods suffer from severe shadowing or blocking due to complicated surrounding settings and the presence of a variety of materials, equipments, and building structures at construction sites. In addition, accurate measurements of time-of-flight for both TOA and TDOA methods are even more challenging, since radio frequency travels as fast as light and 10 ns time delay causes nearly 3 m of ranging error. As such, RSSI is considered to be straightforward and more suitable for localization applications at building construction sites.

In ZigBee wireless sensor networks, distance between two ZigBee nodes could be estimated from received signal strength with the aid of signal propagation models. Once the ranges are determined in relation to three different nodes, the location of the tracking node can be calculated by use of geometrical triangulation algorithms.

4 Implementation Challenges

In contrast with successful and widespread applications of resources tracking in open areas, it is more challenging to devise effective solutions for building construction sites. Key challenges, along with some unique constraints encountered at building construction sites, are identified and discussed in regard to (1) accuracy; (2) robustness; (3) flexibility; and (4) cost.

4.1 Accuracy

Accuracy is one of the most important requirements for resources tracking at construction sites. Accuracy of “arm’s length” (i.e., 1-2 m) is considered to be appropriate for tracking resources effectively[3]. Such accuracy seems to be difficult to achieve based on RSSI at construction sites in light of the highly nonlinear fashion of radio signal propagation and severe multipath fading or shadowing effects. In addition, unstable and fast-changing surroundings at building sites may further degrade the performance of RSSI localization. Therefore, accurate models of signal propagation are expected to be established by extensive site tests and using nonlinear statistical models.

4.2 Robustness

Given a relatively harsh environment of construction sites (e.g., noise, dust, rain, impact, and strong light), the robustness of the technology to be deployed is a crucial issue that deserves to be considered carefully. The problem is expected to be addressed by increasing numbers of ZigBee nodes and optimizing the topology of wireless sensor networks.

4.3 Flexibility

The resources tracking system at a building construction site should be flexible for deployment, configuration, and maintenance, due to changing characteristics of building sites and different tracking requirements. Fortunately, this may not be an obstacle for ZigBee wireless sensor networks, because the ad-hoc network architecture enables flexible implementation and adjustment of the network.

4.4 Cost

Cost of the system is always one of the most concerned factors, especially for application oriented research. Beyond the low price of a single ZigBee node, consideration of the operation and maintenance costs of the entire tracking sensor network is also significant.

5 Conclusions and Future Work

With rapid development and innovation of the construction industry, the needs for better resource management grow considerably. Resources tracking can effectively facilitate resource management, and therefore spawns more and more research interests. However, limited by the unique constraints in construction building site, few off-the-shelf systems are capable to provide technically feasible and economical solutions to resource tracking so far. Meanwhile, emerging wireless network technologies afford potential opportunities for resource tracking applications at building sites.

The purpose of this research is to evaluate the technical feasibility of applying state-of-the-art wireless network technologies for solving resource tracking problems at building construction sites. Based on evaluation of pros and cons of available localization methods and emerging technologies, we identify that the ZigBee-based wireless sensor network and the RSSI localization method are most promising for resource tracking application at building construction sites. Deployment challenges of wireless tracking networks in the practical context are anticipated in terms of accuracy, robustness, flexibility, and cost. With the further development and improvement of the ZigBee-based wireless sensor network, the system is expected to be capable of (1) continuously tracking various construction resources at a building construction site; (2) low-cost, real-time, and reliable wireless data communications; and (3) flexible deployment and adjustment of the wireless network. In the near future, we will carry out extensive site tests to assess the exact performance of ZigBee-based wireless sensor networks and RSSI enabled localization under realistic site constraints.

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