Real-Time Locating Systems Using Active RFID for Internet of Things

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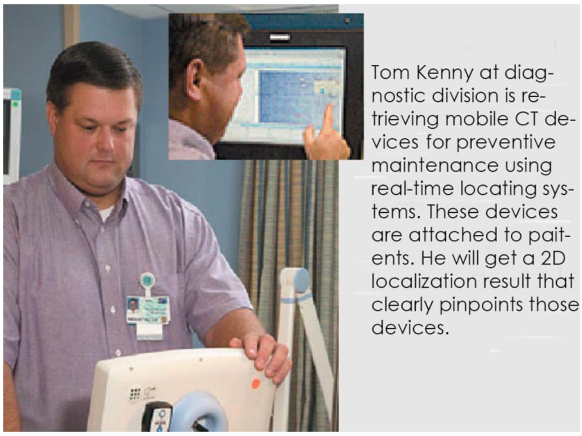
***Abstract*—The proliferation of the Internet of Things (IoT) has fostered growing attention to real-time locating systems (RTLSs) using radio frequency identification (RFID) for asset management, which can automatically identify and track physical objects within indoor or confined environments. Various RFID indoor locating systems have been proposed. However, most of them are inappropriate for large-scale IoT applications owing to severe radio multipath, diffraction, and reflection. In this paper, we propose a newly fashioned RTLS using active RFID for the IoT, i.e., iLocate, which locates objects at high levels of accuracy up to 30 cm with ultralong distance transmission. To achieve fine-grained localization accuracy, iLocate presents the concept of virtual reference tags. To overcome signal multipath, iLocate employs a frequency-hopping technique to schedule RFID communication. To support large-scale RFID networks, iLocate leverages the ZigBee. We implement all hardware using 2.45-GHz RFID chips so that each active tag can communicate with readers that are around 1000 m away in a free space. Our empirical study and real project deployment show the superiority of the proposed system with respect to the localization accuracy and the data transmission rate for large-scale active RFID networks.**

***Index Terms*—Frequency hopping, Internet of Things (IoT), radio-frequency identification (RFID), real-time locating systems (RTLSs), tag–tag communication.**



Tom Kenny at diagnostic division is retrieving mobile CT devices for preventive maintenance using real-time locating systems. These devices are attached to paitents. He will get a 2D localization result that clearly pinpoints those devices.

Fig. 1. Locating equipment in hospitals. Knowing the whereabouts of sensitive devices is a necessity because equipment is constantly in need of rinsing, calibrating, and maintenance. In a matter of seconds, RTLSs can identify the location of all tagged devices, even underneath operation tables or inside another room several miles away.

I. INTRODUCTION

THE Internet of Things (IoT) is emerging as a new computing paradigm that connects uniquely identifiable objects to an Internetlike network [1]. It enables objects to be intelligent for interacting and cooperating with each other anytime and anyplace. The IoT might significantly change the manner we perform daily activities by real-time locating systems (RTLSs) as it opens up tremendous opportunities for economies and individuals. RTLSs can automatically identify, track, and visualize objects that are usually within indoor or confined environments mainly using RF identification (RFID). Typical RTLS instances involve varying asset management such as positioning pallets of merchandise, tracking assets through a process, and clinical-level locating for healthcare capacity management. Fig. 1 illustrates an example using RTLSs for asset tracking in hospitals, in which doctors can accurately localize medical devices for potential schedule and maintenance.

RFID is a wireless communication means using RF electromagnetic fields to identify and track tags attached to objects [2]. An RFID system involves tags, readers, and antennas. RFID tags can be passive, active, or battery-assisted passive tags [3]. An active tag has an onboard battery and periodically transmits its ID signal and stored information. An active reader's working range can be adjusted from 1 m to tens of meters, allowing flexibility in applications such as asset supervision and management. Owing to its multiobject recognition, nonline of sight, and high cost-effectiveness, RFID has been widely used for indoor localization to spur IoT real-time locating applications [4]–[6]. Note that Global Positioning System satellite signals are severely attenuated and scattered by buildings, trees, and other obstructions in confined environments.

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A variety of RFID localization schemes have been proposed during the past several years [7]–[10]. In general, existing schemes can be classified into three types, i.e., distance estimation, fingerprinting, and proximity [11]. The first type of schemes leverages various distance measurement techniques to calculate location information. These techniques include the angle of arrival [12], the time of arrival (TOA) [13], the time difference of arrival (TDOA) [14], the received signal strength indicator (RSSI) [15], and the received signal phase (RSP) [16]. The second type of schemes chiefly takes advantage of the k-nearest neighbors and probabilistic techniques to locate objects by comparing the measurements of active tags with the environment fingerprints, e.g., RSSI reading sequences [17], [18]. The third type of schemes turns to the dense deployment of antennas [19] and regards that the location of the target tag is the same as the antenna that detects it. Current efforts can locate whether an object is within a radio range but cannot pinpoint its exact location. Many applications, however, require fine-grained location information. For example, readers in libraries would like to know the specific locations of the books they would borrow. Moreover, existing works emphasize on localization accuracy or the sensing distance. To the best of our knowledge, we do not find any work that takes the tag working area and the localization accuracy into the holistic design of locating systems.

To this end, we propose in this paper an RTLS using active RFID called iLocate for asset management, which can accurately locate objects with remote sensing distance. iLocate supports large-scale organizations using a radio portfolio in indoor environments. It incorporates virtual RFID reference tags, tag–tag communication, coordinators, and a frequency-hopping technique into the design. The virtual reference tags are fictitious tags deduced from real adjacent reference tags, which are for high-level localization. The tag–tag communication is the communication means between two tags within the same coordinator's working range, where the coordinator acts as the mediator. We redesign the structure of the active tags and the readers in the secondary development by incorporating a frequency-hopping spread spectrum. We also introduce reference tags whose locations are known and RFID coordinators that are lite RFID readers to improve the location estimation accuracy. Finally, we apply the proposed system to real projects. To summarize, the contributions of this paper are twofold.

1) It proposes iLocate, i.e., a real-time locating system using active RFID suits for asset management that introduces virtual reference tags to boost the localization accuracy and eliminate the RFID RSSI noise using a frequency-hopping spectrum. A virtual reference tag refers to "a tag" at a spatial place between two real adjacent reference tags. By interpolation, iLocate generates RSSI sequences for the virtual reference tags. By recognizing RSSI fingerprints, iLocate locates the objects at high levels of accuracy up to 30 cm, with ultralong distance data transmission.
2) It introduces the RFID coordinators and then comes up with a tag–tag communication protocol. The RFID coordinators are lite RFID readers that act as a local center to manage nearby tags using the tag–tag communication protocol. iLocate significantly improves the tag identification process in large-scale RTLSs.

The rest of this paper is organized as follows. Section II gives the preliminary knowledge of our design. Section III overviews the works that are close to this paper. Section IV introduces the proposed system in detail. Section V reports our implementation and empirical study. Section VI concludes this paper and looks forward to future works that we hope to accomplish.

II. BACKGROUND

An active RFID tag has an inbuilt power source and a microprocessor to continuously power its RF communication circuitry and to perform tasks. Active RFID tags can transmit a stronger signal than passive RFID tags, and active readers can access entire populations of the active tags at a longer distance than its counterparts.

An RTLS using active RFID employ "beacon" tags that periodically broadcast their status using encoded radio transmission. Active readers can be permanently installed in strategic locations, such as offices, exits, and roofs, to monitor the presence and statuses of all tags that are in their RF coverage. The readers are compatible with wired and wireless networks for integration into existing information technology infrastructures. Overlapping readers and signal strength analysis are used to determine objects' location.

Three points about the active RFID communication are particularly relevant to the real-time locating problem in asset management.

1) Active RFID tags are robust and tamper evident [20]. In some circumstances, they may become damaged or unreadable. However, a tag will issue a "tamper" warning when its operational status is changed. For the sake of simplicity, we assume that all tags are safe. Additionally, active tags can keep broadcasting signals or can remain dormant until they come in the range of an RFID receiver [21].
2) The communication range of the active RFID is from several meters to tens of meters, i.e., up to 1000 m [22]. The active RFID operates at high frequencies, i.e., 433–455 MHz and 2.4–2.5 GHz or 5.8 GHz. With the advancement of large-scale RF integrated circuits, the reading range of the active RFID will continue growing in the coming years. It is significant for an RTLS that provides high levels of accuracy together with a larger working range.
3) There is a carrier frequency offset between the active RFID readers and tags [23]. This is because the active tags not only receive low-level signals from the readers but also emit high-level signals back to the readers. Consequently, not all signal channels are available to RTLSs.

III. RELATED WORKS

Location information is fundamental to IoT applications such as location-based advertising [8] and assisting healthcare systems [10]. In tandem with the widespread adoption of the IoT, an RTLS using RFID has drawn increasing attention, which is mainly evaluated by localization techniques.

There are many indoor localization schemes using various indoor localization techniques, such as infrared [24], Bluetooth [25], ultrasonic [26], and computer vision [27]. In comparison, RFID-based localization is promising, which is characterized by nonline of sight, a low cost, and automatic identification and tracking.

A. *RFID Localization*

The core localization technique for RFID localization falls into three categories, i.e., distance estimation, fingerprinting, and proximity [11], [28]. The first family of localization systems converts RF signals as the distance using distance estimation techniques, such as the TOA [13], [29], the TDOA [14], [30], the RSP [16], [31], and two-way ranging [32]. These systems can achieve high levels of accuracy, but they suffer from a couple of problems. First, existing systems usually require clock synchronization among all the tags, interrogators, and readers in the presence of object movement. Second, they need specialized hardware to validate signal measurement. To this end, new distance estimation schemes have been exploited based on the RSSI [15], [33]. Because RSSI measurement capabilities are ubiquitously integrated into wireless receivers for automatic gain and power control, they have a low cost and are easy to use. However, the RSSI is severely affected by multipath fading and shadowing. The fingerprinting also refers to the scene analysis that locates the location of the target object by recognizing real-time RSSI sequences (i.e., fingerprints) with the closest fingerprints saved beforehand [34]. In contrast, proximity-based schemes that depend on the dense deployment of antennas provide symbolic relative localization information. When the target object is detected by a single antenna, its location is associated with the antenna. When it is in an overlapping region of multiple antennas, its location will be collocated with the antenna that receives the strongest signal.

Note that some novel localization schemes for wireless sensor networks have been investigated recently, in which the localization techniques are also valid for RFID. In [35] and [36], we get examples of using compressive sensing to assist wireless networks in localization, which exploit the signal sparseness to efficiently acquire and reconstruct signals.

B. *RTLSs*

There are some works very close to this paper, such as the Ekahau RTLS [37] and the AeroScout Solution [30]. All of them introduce reference tags whose locations are already known to provide the area coverage. However, previous efforts are heavily limited by error-prone RSSI readings that are easily interfered and diffracted, and by the reference tag density. When the tag density is very high, it leads to serious multipath, whereas when it is very low, it results in low-level localization accuracy. In addition, existing efforts do not deliberately account for anticollision.

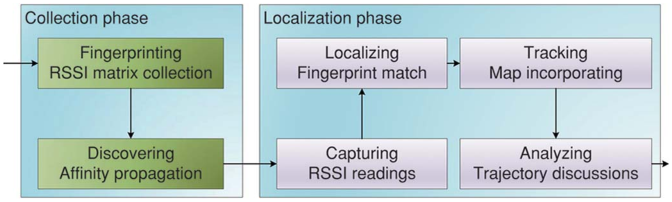

Fig. 2. Architecture of the proposed system.

In summary, RTLSs are highly desirable for certain applications of the IoT. Although indoor localization has been intensively investigated, RTLSs still remain open.

IV. RTLSs FOR IoT

In this section, we propose a real-time locating system for the IoT, i.e., iLocate, which is a fine-grained RTLS using the active RFID. iLocate can offer high levels of localization accuracy, up to the centimeter level, which is much smaller than the read range of the active RFID. The proposed hardware and software together create powerful business intelligence for decision makers.

A. *System Overview*

iLocate employs RFID tags and readers, and ZigBee to build local and large-scale RFID networks, respectively. At the beginning, iLocate deploys a set of low-cost reference tags in indoor environments. For example, reference tags can be installed on the shelves of each rack in hospitals. Then, iLocate attaches objects with RFID mobile tags and records such association between each object and its RFID. It presents RFID coordinators that refer to simplified RFID readers with a large memory space. Each RFID coordinator is only in charge of the RFID tags within its communication range, and each reports its information to RFID readers. Then, iLocate employs ZigBee to ensure long-distance data transmission. iLocate builds a lightweight RFID network, which dramatically reduces the number of RFID readers that is deployed to fully cover the studied indoor environments.

The goal of the iLocate system is to accurately and quickly locate objects in large-scale networks. To locate an object, it goes through the following steps at a high level.

1) iLocate retrieves the RFID tag attached to the object on demand.
2) iLocate acquires the RSSI readings of this tag and then locates the location range by RSSI fingerprinting. As a result, iLocate also identifies the nearest neighbors of the tracked tag.
3) According to the positions of nearest neighbors, iLocate estimates the specific position of the tag.

Fig. 2 illustrates the architecture of the proposed system comprising two phases, i.e., the collection phase and the localization phase. In the former phase, active tags are used to collect the RSSI readings, and reference tags are deployed on a map of interest. By leveraging the preprocess techniques [4], [38], iLocate discovers the missing RSSI readings. After preprocessing, iLocate stores the RSSI readings into the fingerprint database, which is known as the RSSI database. To be specific, iLocate builds a distributed RSSI database and stores the RSSI sequences in the RFID coordinators' memory space. Each coordinator is assigned to be in charge of the reference tags that are in its communication range. A coordinator will update its memory space once a reference tag loses efficacy or newly joins. Thus, the RSSI fingerprinting matrix is built in an offline manner. When iLocate captures a new RSSI fingerprinting sequence of a tag, it will compare the sequence with the fingerprint matrix that is stored in its coordinator in real time. Note that an RFID coordinator is in charge of storing local fingerprints, and each coordinator can maintain about 500 tags. When the number of tags handled by a coordinator becomes more, we will introduce more coordinators to avoid a potential bottleneck at the coordinator end.

In addition, we find that the orientation of an antenna inside the tag considerably affects its RSSI readings. Therefore, iLocate keeps track of the orientation of each tag when aggregating its RSSI readings. To be simple, iLocate associates the RSSI readings with four orientations, i.e., north, south, east, and west, which are represented by 0°, 180°, 90°, and 270°, respectively. In practice, we introduce the clustering step for the RSSI readings owing to two reasons. One is to alleviate the influence of noisy RSSI readings, and the other is to improve the query scalability. IoT applications are characterized by a large number of sensors and RFID tags, generating extremely large-scale readings so that it is time-consuming to query them all. For instance, in university libraries, tens of thousands of RFID active tags are ubiquitously used, generating tens of millions of tag readings.

Consequently, iLocate independently clusters reference tags according to their averaged RSSI sequences from each direction. It takes advantage of the affinity propagation to cluster reference tags and generates exemplars that represent the clusters to which they belong. Because the reference tags are clustered at each direction, the generated clusters may be different with respect to the number and scale of clusters. To improve the localization accuracy, we introduce virtual reference tags that are deployed every 30 cm between two adjacent reference tags. Given a virtual reference tag, its neighboring reference tags are known. By employing a linear interpolation algorithm [39], we can generate its RSSI sequences. As the large or small distance intervals would generate high false-positive and true-negative errors, we set the distance interval as 30 cm.

In the latter phase, iLocate will locate the object in two steps. Once a query request is received, iLocate identifies the active tag and immediately collects its RSSI readings. Then, it locates the range of the tag that is being tracked by using the generated clusters. The reference tags locating in the identified range are regarded as the nearest neighbors. Common tags would never be the nearest neighbors. In view of the RSSI-based distance estimation, iLocate gets the fine-grained location of the active tag and responds to the request.

Note that there are some challenges owing to the error-prone RSSI readings and severe signal interference. In the collection phase, iLocate employs the frequency-hopping technique for the communication schedule to avoid the signal interference. Moreover, it incorporates the virtual reference tags [39] into the design and "collects" their RSSI sequences by interpolation. In the localization phase, iLocate leverages the RSSI fingerprinting matrix to locate objects. To be scalable and feasible, iLocate uses the coordinator-assisted tag–tag communication for local communication.

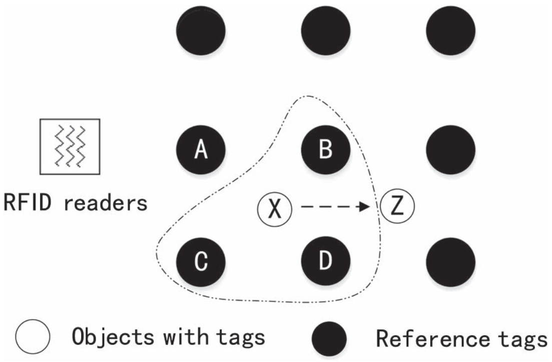

Fig. 3. RFID reference tags are deployed in a gridlike structure, where the horizontal distance of two neighboring tags might not be the same as the vertical distance. According to the indoor environment topology, together with the designed RF planning tool, iLocate places the reference tags reasonably.

B. Accurate Localization

iLocate designs a two-level step for accurate localization. To get fine-grained accuracy, it presents the virtual reference tags and employs the RSSI fingerprint technique. To remove the RSSI noise, iLocate leverages the frequency-hopping technique.

1) Fine-Grained Localization: Given an area, iLocate deploys the reference tags at a known location in an array style. The distance between the neighboring tags within a row or a column is fixed, e.g., 1 m. The RFID-tagged objects randomly cross the array. Fig. 3 gives an example of iLocate deployment, in which the reference tags retain a fixed arrangement. To cover a given area, previous work proposes some free tools such as the Aerohive Wi-Fi Planning Tool [40] and the Ekahau HeatMapper [41]. For a smooth integration with iLocate, we develop a similar module for scene planning. As it is out of the scope of this paper, we omit the detailed introduction. In this paper, iLocate can only focus on the object tracking regardless of various obstructions in indoor environments.

When iLocate receives the query about an object, it will identify the tag attached to the object based on the provided information from the query, such as the owner and properties of the objects. Then, iLocate will collect its RSSI readings about the tag. By using the clustered results, iLocate knows the range that the tag might belong to. Obviously, such location information is coarse grained. Moreover, we cannot deploy a denser tag array to get a higher level of accuracy [4]. In Fig. 3, we infer the neighboring reference tags (i.e., tags B, C, and D) to the active tag (i.e., tag X) from the closest clusters. The distance between these reference tags and the active tag is not that far, usually less than 3 m. iLocate designs a local tag communication protocol so that the reference tags emit signals at a specific frequency to communicate with the active tags. In this case, tags B, C, and D broadcast their localization requests to their neighbors at a certain power level. Tag X will only reply

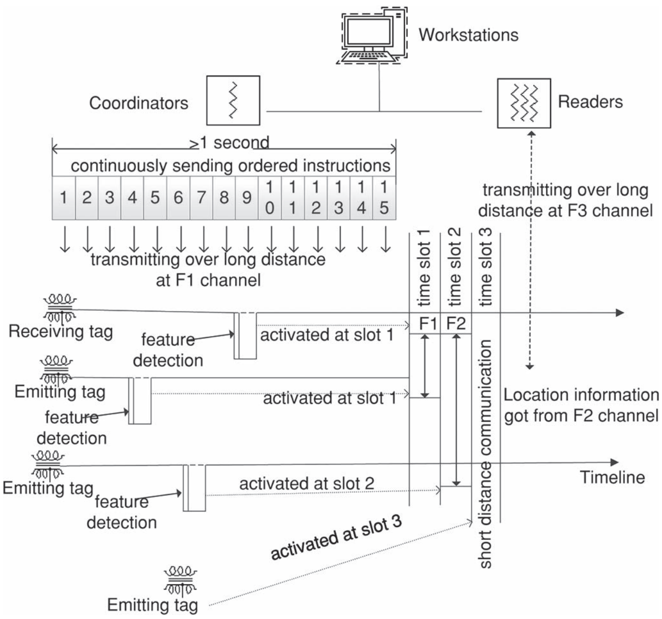

Fig. 4. Frequency-hopping technique and tag–tag communication for accurate localization. The frequency-hopping technique assists iLocate in avoiding the noise in the RSSI readings as much as possible, whereas the tag–tag communication aims to find objects within a short distance.

to the first localization request with its location information. It will omit the other same requests. Intuitively, at the same power level, the reference tag is the closest to the active tag whose localization request firstly arrives at the active tag. Therefore, the RFID coordinators can easily detect the nearest neighbor to the tag to be tracked.

To further improve the localization accuracy, iLocate presents the concept of virtual reference tags. iLocate generates a virtual reference tag between two real adjacent reference tags every 30 cm. Then, it shares the scheme in [39] to generate the RSSI reading sequences for the virtual reference tags. When an object is queried, iLocate will compare its RSSI fingerprint with the collected fingerprints of both virtual and real reference tags. Thus, iLocate achieves a higher level of accuracy up to 30 cm. As the virtual tags cannot directly communicate with the RFID tags, the coordinators, and the readers, iLocate uses its nearest real reference tag to communicate.

2) Purifying RSSI Readings: However, there are some problems that degrade the accuracy of the iLocate system. These problems consist of noisy RSSI readings and signal interference. To this end, iLocate exploits the frequency-hopping technique, as shown in Fig. 4. It introduces RFID coordinators by only enabling the function of message sending and receiving. Thus, RFID applications would save a lot regarding device costs as RFID coordinators are much cheaper than readers. The RFID coordinators continuously emit ordered instructions to their neighbors. The coordinators embed a special signal feature for ordered instructions that can identify their affiliation and neighbors and then emit the signal at the F1 channel. The tag will be activated if its feature is consistent with the signal feature. The signal feature refers to a 6-b identifier implanted to the RFID signals. From an overall viewpoint, iLocate will match the fingerprint database with the collected RSSI readings, and it will get the nearby real reference tags and virtual reference tags. As the virtual reference tags are virtual, iLocate designates the nearest reference tags to communicate with the tags being localized by the tag–tag communication at the F2 channel. The tag–tag communication is a communication means for two tags within the same coordinator's working range, in which two tags can communicate with the coordinator acting as the mediator. Finally, the moving tags report their location and affiliation to the reader at the F3 channel after getting a positive reply from the nearest reference tags.

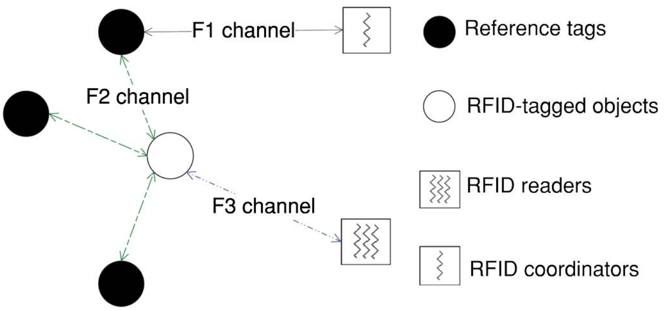

Fig. 5. Using an RTLS in real scenarios without laying the reference tags as rectangular shapes.

Using the frequency-hopping technique, the signal interference and multipath are dramatically avoided. In Fig. 3, tag X moves to Z, and tag B would like to communicate with X. Tag B finds tag X using near-field discovery, and it plans to communicate with tag X. Tag B sends the communication request to its coordinator, which schedules all communication processes. To avoid signal collision, the coordinator exploits the slotted Aloha protocol that is the fundamental protocol based on the time-division multiplexing. Note that, in real scenarios, we can deploy RFID reference tags in an *ad hoc* manner. Thus, in preliminary work, we have to detect the network topology. Fig. 5 gives the *ad hoc* deployment of the reference tags in practice, where the frequency-hopping technique is adopted.

Additionally, iLocate preprocesses the RSSI readings to ensure data reliability. To reduce the system costs, iLocate replaces most RFID readers with coordinators that only retain the communication function of the readers. To summarize, iLocate accurately finds the objects in a low-cost and efficient manner.

C. Remote Working Area

The International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 18000-7 [20] Standard and the ISO/IEC 24730-2 [42] Standard define the air interface for an RTLS, but they only define a single-hop RFID network. It is challenging to apply the single-hop network to large-scale networks owing to a limited radio communication range and indoor obstacles. To break through the barrier, iLocate presents a large-scale RTLS for the IoT that supports multiple hops, even up to tens of kilometers. The basic idea is to use RFID for short-distance transmission and ZigBee for long-distance transmission.

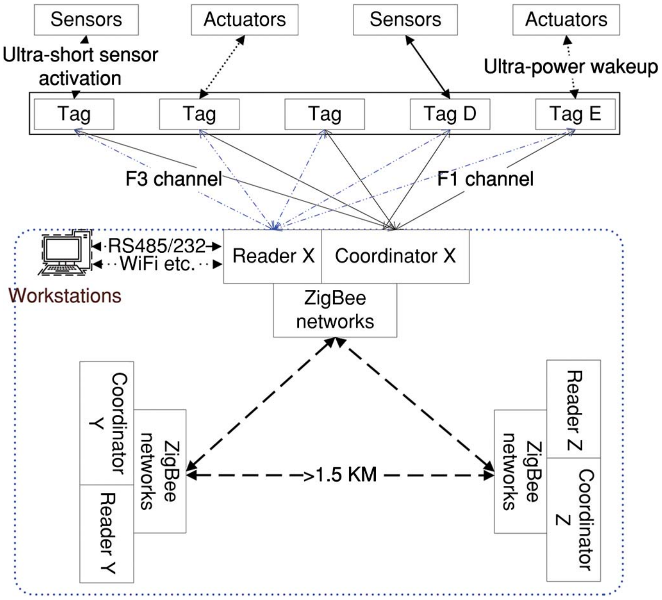

Fig. 6. Large-scale RTLS for the IoT using ZigBee that extends the one-hop RFID network coverage to tens of kilometers.

Fig. 6 illustrates the topology structure using ZigBee for large-scale IoT applications. The system consists of workstations, coordinators, readers, tags, and ZigBee networks. Users commit requests, e.g., query requests from workstations by wired or wireless communication protocols. The RFID readers will check whether they can respond upon the local one-hop tags. If not, they will schedule coordinators that encapsulate the requests and broadcast them by virtue of the ZigBee networks.

To achieve efficient communication in large-scale RFID networks, iLocate is supposed to handle the following problems, i.e., the topology construction, multiple reads, and the request broadcast. To create a network structure for RFID networks, iLocate leverages a breadth-first traversal technique that is a simple yet powerful topology building artifact. Its space complexity is $O(|N|)$, where $|N|$ is the cardinality of the set of vertices in RFID networks. Its time complexity is $O(|N| + |E|)$, where $|E|$ is the cardinality of the set of edges in RFID networks. In the worst case, iLocate visits every vertex and every edge. Note that we find that the work in [43] can build the network topology for wireless sensor networks. We will investigate it in our incoming work.

Multiple reads refer to the phenomenon in which RFID readers collide when their coverage areas are overlapped. RFID reader collision involves the signal interference among multiple readers and the interference among multiple readers of the same tag [44]. To eliminate multiple reads, iLocate employs the frequency-hopping technique to schedule the reader behaviors. Then, it uses the slotted Aloha protocol to control the tag–tag communication and the tag–reader communication. Finally, it encapsulates an identifier for each message to identify the sender and the task. When an active tag receives a request, it will check the identifier to determine whether this required behavior has been committed for a short term. The tag will omit the same request.

Fig. 7. Basic set of RTLS hardware for the iLocate system, which consists of a reader, two reference tags, six active tags, two antennas, and one universal serial bus, together with documents. An enriched toolbox contains RFID coordinators and an RFID deployment tool.

V. EXPERIMENTS

In order to evaluate iLocate, a series of experiments were conducted, and a prototype was implemented. In particular, we plan to answer the following.

1) What is the localization accuracy? Does it perform better than the existing systems?
2) How far does it cover? What is the data transmission rate for large-scale RTLS networks?
3) How does the proposed system make an inventory of all tags, i.e., the inventory performance?

iLocate implemented the RFID readers by adopting 0.18-μm CMOS integrated circuits owing to its ultralow power consumption and robustness to high-risk scenarios such as gas stations and mines. The RFID readers were configured with several omnidirectional antennas. Both the RFID readers and tags were implanted with a module of the direct frequency-hopping spectrum spread. The RFID coordinators were made by extracting the communication and simple instruction processing capabilities. The RFID coordinators were in charge of waking up and activating the active tags. To build large-scale RFID networks, iLocate employed the commercial off-the-shelf ZigBee transmission module. Fig. 7 shows the majority of the hardware we used in the iLocate system.

The experiment was run in a 40 m × 30 m area, in which there were no obstructions. The experiment area was divided into two parts, i.e., deploying two RFID coordinators in the center of each area and deploying one RFID reader in the center of the area. Two systems, i.e., Dash7 (http://www.dash7.org/) and ZigBee (http://www.open-zb.net/), were implemented. Dash7 is *de facto* for the active RFID networking that operates in the 433-MHz band, and the latter system is an open-source implementation of ZigBee based on TinyOS. The root mean error was chosen as the metric that was the absolute difference between the actual coordinates and the calculated coordinates.

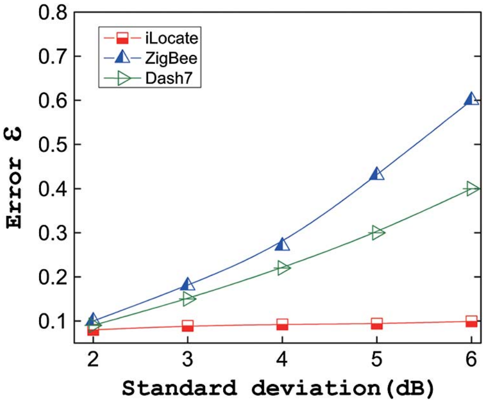

Fig. 8. Overall performance of the iLocate system when the distance between two neighboring reference tags is 1 m.

Every experiment was run ten times to get an average root mean error. The metric is computed as

$$\varepsilon = \sum_{i=1}^{10} \frac{\sqrt{(x_r - x_c)^2 + (y_r - y_c)^2}}{10} \tag{1}$$

where x_r and y_r are the real coordinates of the objects, and x_c and y_c are the computed coordinates. Evidently, the smaller ε is, the better performance the proposed system achieves.

A. Localization Accuracy

An experiment was carried out to evaluate the localization accuracy of the iLocate system when the reference tags were placed every 0.5 m both in the horizontal and vertical directions, i.e., the tag density was 0.5 m. When the tag density is bigger than 2 m, the RSSI readings become unreliable owing to signal attenuation. When the density is lower than 0.5 m, the RSSI readings also become error prone due to severe signal multipath and multiple reads. Therefore, the reference tag density was set as 0.5 m.

Fig. 8 illustrates the localization accuracy of the proposed system when the standard deviation (STD) of the RSSI varied from 3 to 8 dB. With the STD variation of the RSSI, the iLocate system showed a slow uptrend, whereas both Dash7 and ZigBee exhibited a fast uptrend. Moreover, the maximum of the mean localization error of the iLocate system was less than 0.2, indicating that iLocate achieved higher levels of localization accuracy compared with previous efforts. The reason is that iLocate considerably eliminated the RFID RSSI noise by scheduling communication using coordinators, and it obtained the fine-grained localization accuracy by introducing virtual reference tags. In addition, a prototype project was implemented in a carton packing factory, where each paper pillar was over 2500 kg and was bigger than 3 m × 1.5 m × 2.5 m. The pillars were placed in a layered manner. Fig. 9 illustrates the real deployment of using the iLocate system (see Fig. 10 for the snapshot of using the iLocate system for indoor positioning). Both Alien 9900+ passive readers and Impinj R420 passive readers, together with ultrahigh frequency tags with omnidirectional antennas, have been tested. However, their recognition rates were quite low. The Ekahau RTLS system has been also tested, whose recognition rate was about 35%. On the contrary, the recognition rate of the iLocate system was 99.15%, and its localization accuracy was higher than 98.08%. In fact, iLocate can achieve a very high level of accuracy up to 30 cm when the density of the virtual reference tags is set as 0.3 m.

Fig. 9. Using the iLocate system in a carton packing plant that is 400 m × 300 m × 3 m. In this case, we have tested various passive RFID hardware, including Alien 9900+ readers and Impinj R420 readers. Their identification rates are less than 2% due to the severe signal shielding by many large paper pillars.

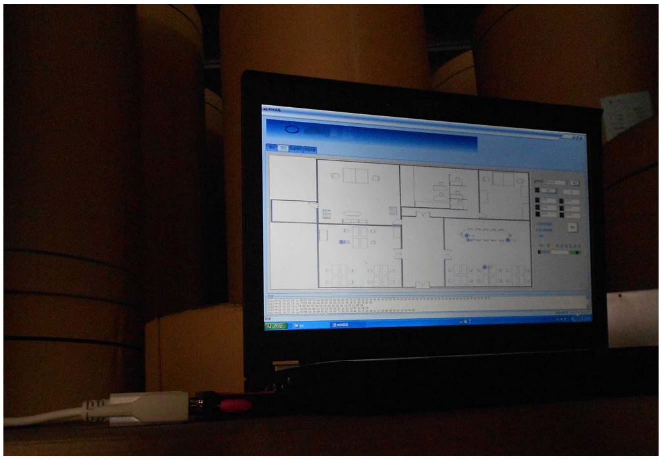

Fig. 10. Snapshot of using the iLocate system for indoor positioning, in which iLocate marks the object being tracked at the indoor ichnography.

iLocate was characterized by the large working range of each active tag operating in 2.45 GHz around 1000 m in a free space. By the long-distance direct tag–tag communication, iLocate performs in a simple manner that it does not require many RFID readers. In most cases, iLocate only required a few readers. Therefore, we omit the experimental analysis of the system behavior with the variation in the number of RFID readers. As for a coordinator, its cost is about one-tenth of a reader, indicating that our solution is competitive in the indoor localization field owing to a low cost.

B. Working Range

The iLocate system is operated in the 2.45-GHz band so that the read range between a reader and a tag is from 1 to 1000 m. To support large-scale networks that cover more than thousands of meters, iLocate extended its working range using ZigBee based on the IEEE Standard 802.15.

TABLE I
500-m WORKING RANGE OF THE PROPOSED SYSTEM

500 meters	IEEE 802.15.4	ZigBee	Dash7	iLocate
No. of hop requests	>14	6-7	1	1
No. of hop response	>14	6-7	1	1
No. of nodes involved	200	100	2	2

TABLE II
DATA TRANSMISSION

500 meters	Unslotted ZigBee	Slotted ZigBee	Dash7	iLocate
Frequency	2.45 GHz	2.45 GHz	433 MHz	2.45 GHz
BaseDataRate	250 kbps	250 kbps	28 kbps	2450 kbps
PacketTime	2 ms	2 ms	16 ms	2 ms
Hop latency	15 ms	50000 ms	N/A	N/A
Active time	102 ms	44 ms	32 ms	4 ms
Active Energy	7.2 mj	3.2 mj	0.6 mj	0.075 mj
Ave DataRate	5 kbps	1.8 kbps	14 kbps	125 kbps

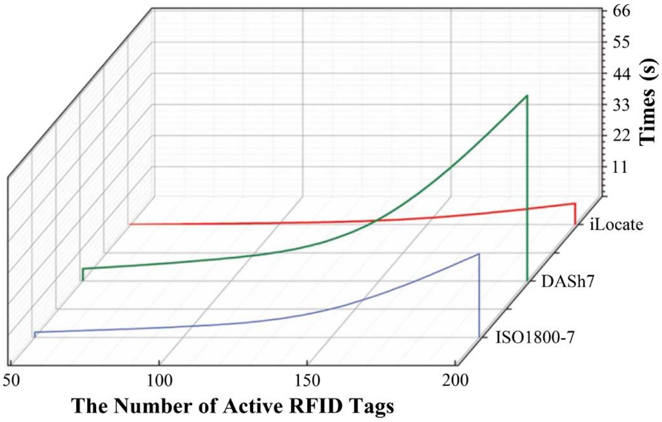

Fig. 11. Inventory performance of the proposed system.

Table I shows the 500-m working range of the iLocate system. iLocate could directly transmit information to a tag that is 500 m away. As a matter of fact, its tag working range is quite large, which is up to 1000 m in a free space, owing to the frequency-hopping module. Even in the signal shielding area, such as in Fig. 1, iLocate's tag working range was still far, up to 700 m. By virtue of the ZigBee technology, iLocate can support a larger range up to tens of miles. With few devices involved, it dramatically decreases the device costs and the maintenance costs.

C. Data Transmission

To evaluate the data transmission of the proposed scheme, several experiments were designed. The packet delivery time and the average data rate were selected as metrics.

Table II illustrates the performance of the iLocate system regarding the data transmission. Among all systems, iLocate's data transmission rate was the farthest. By employing the coordinators, iLocate efficiently coped with the data packets with short latency and a short packet time. Meanwhile, owing to the schedule of the RFID tags and readers, iLocate consumed less energy than existing systems.

D. Inventory Performance

We use "inventory" to denote an action in which an RFID system counts all tags. In order to evaluate its inventory performance, a couple of experiments were conducted. DASH7 and ISO18000-7 were selected as two primary schemes. DASH7 operates in the 433-MHz band so that its data transmission bandwidth is less than the active RFID chip sets operating in the 2.45-GHz band. To be fair, the data rate is limited to 125 kb/s.

Fig. 11 illustrates the inventory performance of the iLocate system. Compared with the DASH7 and ISO18000-7 systems, iLocate counted all tags in a very fast speed, which is about one-fourth of ISO18000-7 and one-eighth of DASH7. This is because of the tag–tag communication protocol so that RFID coordinators can order their reference tags to enumerate tags.

VI. CONCLUSION

In this paper, we have proposed a newly fashioned real-time locating system using active RFID for asset management in indoor environments, i.e., the iLocate system, for the IoT. To eliminate the RFID RSSI noise, iLocate employed the frequency-hopping technique. To achieve the fine-grained localization accuracy, it took advantage of the virtual reference tags and the tag–tag communication protocol. To support a large-scale RFID network, iLocate used ZigBee. Both our experimental results and the real project have shown the superiority of the proposed system.

However, iLocate could be further improved. In a large-scale network structure for RFID networks, the computation overhead for building the fingerprint matrix and topology is significantly heavy. We will look for some approaches to reduce the computation and the complexity, e.g., singular value decomposition. We will study new algorithms to generate RSSI sequences for virtual reference tags. We also plan to extend iLocate for location-based business industrial applications and services.

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