QiLoc: A Qi Wireless Charging Based System for Robust User-Initiated Indoor Location Services

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***Abstract*—This paper presents the design and implementation of a novel user-initiated indoor localization system called QiLoc. QiLoc is a simple yet effective way to accurately locate and identify occupants of Qi-compatible devices inside buildings. The system is composed of *QiLoc Stations* and a *QiLoc Server*. A QiLoc Station is usually embedded inside or under a desk/table. By using the Qi wireless charging protocol, it can extract the unique ID of a charging device, thus locating the occupant. The QiLoc Server maintains the location information of all occupants, and provides a set of APIs via standard web services such as location, ad hoc group membership, and authentication. Using these primitives, QiLoc enables various smart home applications. We have deployed QiLoc in an office building and implemented a number of applications, including a smartphone app that identifies people in the same physical space, and a Windows-based notification system that provides live updates of colleagues' locations. We also demonstrate how QiLoc can enhance human interaction and productivity by integrating with industrial solutions like calendar, instant messaging, and email systems.**

I. Introduction

A plethora of smart building and intelligent space scenarios have been envisioned by academia and industry over the past few decades. In social networking, we have imagined that strangers close-by or in the same physical space can discover and interact with the ones having common interests; in workspace, colleagues sitting in the same meeting room may easily form ad hoc groups and share documents with each other; at home, rooms can know where and who we are, adjusting the lighting and temperature conditions to our preferences automatically; and in commercial spaces, stores can detect our location and identity, pushing targeted advertisements to us. While some of the above scenarios have been realized in demos, most of them are still restricted to academic exercises and proof-of-concepts. Therefore, we have yet to see these applications benefit our everyday lives.

Although a large amount of research efforts have explored indoor localization and occupancy identification, all of them have their drawbacks. The approaches based on signal strength (e.g., ultrasound [1], [2] and visible light communication [3]) and fingerprinting (e.g., WiFi [4], [5] and Bluetooth [6], [7]) suffer from accuracy problem to various degrees. Since radio signals can be easily attenuated by reflection, diffusion and multi-path effects, these systems are often unreliable in practical indoor environments. Moreover, the approaches relying on RFID and NFC are ill-suited due to the cost, ease-of-use, and scalability issues.

In this paper, we present *QiLoc*, a system that provides user-initiated indoor localization services based on Qi wireless charging protocol [8]. Qi is a widely adopted wireless charging standard that realizes wireless power transfer through electromagnetic induction. A standard Qi wireless charging system comprises of a power transmission pad and a Qi-compatible device (e.g., a smartphone with a Qi adapter/casing). In the Qi specification, there exists a unique ID in the charge controller of the device, and it is transmitted to the charger upon insertion. Currently, there are around 62 Qi-compatible smartphones [9]; many new smartphones coming out will also be compatible. Smartphones that are not directly compatible with Qi can be easily integrated with adapters/cases, including iPhone [10]. As Qi is becoming more mainstream, many Qi hot spots are starting to appear in public places such as coffee shops and airports [8]. Note that our approach is also not restricted to the Qi wireless standard, but general to all wireless charging protocols including Qi's competitor PMA (Power Matters Alliance) [11].

Fig. 1. The service concept of QiLoc system. A QiLoc Station, usually embedded inside a desk, not only enables wireless charging for smartphones, but also extracts their unique IDs, providing user-initiated location information.

The QiLoc system comprises two major components, i.e., *QiLoc Station* and *QiLoc Server*. A QiLoc Station is equipped with a charging board that enables Qi wireless charging through electromagnetic induction. It is usually embedded inside or under desk and table. Figure 1 shows a QiLoc-enabled desk, where a QiLoc Station is installed underneath. Moreover, the charging board is custom-designed so that it can extract the unique ID of the charging device, since the existing charging board do not expose this ID. Once the ID is obtained, the QiLoc Server communicates with this QiLoc Station and locates the device occupant by the stored location of the QiLoc Station. The QiLoc Server maintains the location information of occupants and provides a set of

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APIs via standard web services such as location, ad hoc group membership, and authentication. Different from the traditional coordinate-based location interpretation, QiLoc represents a new robust and scalable location primitive that delivers precise desk-level indoor location and identification. It features the following desirable properties:

- Accurate, reliable, and effort-free localization.
- Privacy preserving and non-intrusive.
- Requiring no additional hardware from the user.

The key idea of QiLoc is that users can actively share their exact locations when sitting down and putting their phones on a Qi wireless charger, e.g., the QiLoc-enabled desk in Figure 1. This is a behavior that most people are already used to. Then the system will learn about the location of the occupant while charging her phone. Such an approach does not need any additional actions from the user such as opening an app or enabling some functions on the phone. Based on this primitive, we build a number of applications and show that they are effective in improving our everyday lives.

In this paper, we make the following contributions:

1) We design and implement the QiLoc hardware, i.e., QiLoc Station, which can be embedded inside or under desks/tables. By utilizing the Qi wireless charging protocol, a QiLoc Station is able to extract the unique IDs from phones placed on the desk, thus providing the precise desk-level indoor location.
2) We design and implement the QiLoc Server that communicates with QiLoc Stations, maintains location information of occupants, and provides a set of APIs via standard web services. These services include location, ad hoc group membership, and authentication.
3) We implement a number of representative applications based on QiLoc, including a smartphone app that locates others in the same logical space (e.g., the same room) and provides several interaction methods; a desktop notification system that gives live updates of colleagues' locations and automatically logs the user in when sitting in front of her computer.
4) We show how QiLoc can be leveraged to greatly enhance human interaction and productivity by integrating precise and live location information with calendar, instant messaging, and email systems.

II. Related Work

Many positioning systems have been developed over the years for indoor localization. With the proliferation of wireless networks, the approaches leveraging radio frequency technologies, such as WiFi, Bluetooth, and RFID, have attracted broad research interest. The WiFi-based solution falls into two basic categories, i.e., *triangulation*, e.g., [12]–[14], and *fingerprinting*, e.g., [4], [5], [15]. The former method, guided by the received signal strength indicator (RSSI), suffers from accuracy problem. Because of the fluctuation of wireless signal, RSSI does not necessarily reflect the actual distance between the transmitter and receiver. The latter method needs to generate a signal strength map for all possible locations through a wardriving process, which usually incurs heavy computation overhead.

Secondly, the Bluetooth-based solution, e.g., [6], [7], mainly relies on RSSI triangulation to estimate the location. This method can only achieve high localization accuracy under the dense deployment of nodes, making it cost prohibitive. iBeacon [16], a representative Bluetooth-based localization system, has performance that is subject to signal reflection, diffusion, and dynamic beacon transmit power. Lastly, the RFID-based solution, e.g., [17], leverages RFID tags to locate a target object. Of particular note is the LANDMARC system [17], which uses reference tags to reduce the needed RFID readers. However, the reference tags, which are always in the active mode, result in higher computation overhead than passive tags. Nevertheless, the accuracy of LANDMARC is susceptible to the placement and deployment density of the reference tags.

Using ultrasound signal [1], [2] is another way for location estimation. These approaches typically estimate the location based on the time-difference-of-arrival of acoustic signal. However, the existing ultrasound-based indoor localization systems usually require additional infrastructure, e.g., base stations that can transmit ultrasonic signals periodically. Moreover, to achieve high localization accuracy, the ultrasonic receivers have to be carefully calibrated.

NFC, an exciting technology that emerged recently, has been used for indoor localization. For example, the authors in [18] propose to use NFC tags containing the URL of indoor map for localization. However, the NFC-based localization systems have several limitations. First, the NFC interface is typically switched off when the screen of smartphone is locked, making it impossible for automatic localization without the assistance of user. Moreover, NFC has not been widely deployed in workplace.

In addition to the aforementioned approaches, other indoor localization systems have exploited infrared [19] and visible light communication [3]. However, their localization performance is highly variable due to the dependence on environments.

In summary, the existing indoor localization systems are largely based on a passive scheme, where the location of user is automatically determined. Although this is desirable for many applications, it often faces significant challenges to achieve high accuracy. To address this issue, QiLoc employs user-initiated localization scheme, which yields high accuracy and robustness.

III. System Overview

Figure 2 shows the system architecture of QiLoc. Specifically, QiLoc is composed of several QiLoc Stations and a QiLoc Server, and supports various upper-layer applications. **QiLoc Station**s, typically embedded inside or under desks and tables, have fixed desk-level locations that are pre-known to the system. Each QiLoc Station has a sensing area that is outlined by its charging board, as shown in Figure 1. While charging a Qi-compatible device, the QiLoc Station will extract its unique ID from the wireless charging signal, thus accurately locating the occupant. On the cloud side, a **QiLoc Server** communicates with QiLoc Stations in real-time, maintains the occupant's location information, and provides a set of APIs via standard web services such as location, ad-hoc group membership, and authentication. Different from

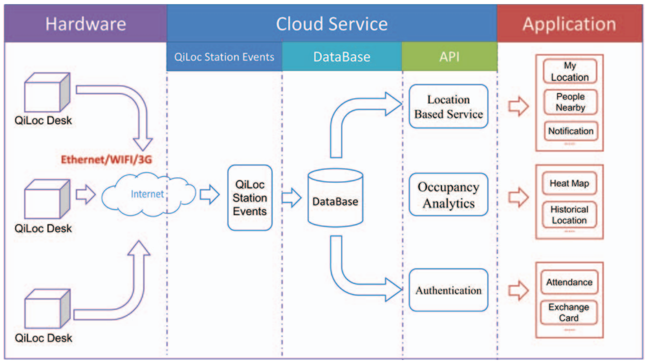


Fig. 2. The system architecture of QiLoc. The QiLoc Station charges and identifies the Qi-compatible device placed on its sensing area. A "place" or "remove" event is sent to the QiLoc Server, which then pushes the occupant's real-time location information to her subscribers.

the existing indoor localization systems that merely focus on positioning accuracy, QiLoc takes the accurate desk-level indoor location as a primitive and enables a wide range of smart home **applications** on top of it.

QiLoc Station. QiLoc Stations are the front-ends of QiLoc system. Figure 3 shows a prototype of QiLoc Station and its internal components. Upon detecting a Qi-compatible device, a QiLoc Station will not only initiate Qi wireless charging automatically, but also retrieve the device's identity, thus supporting the upper-layer applications with desk-level occupant's location information. Specifically, a QiLoc Station consists of the following three major modules.

Power Module: This component provides reliable and sufficient power supply for a QiLoc Station. In order to obtain low-noise power supply, we design a novel regulated power structure for noise reduction. Such a structure is implemented using low dropout regulators (LDO). Moreover, the power module employs switch-mode to supply sufficient current. By rectification and filtering, it yields a charging current up to 10 A, which satisfactorily meets the need of Qi wireless charging.

Sensing and Charging Module: The power transmission pad serves as the sensing module of a QiLoc Station and extracts the unique ID from a charging smartphone. Specifically, the power transmitter communicates with the power receiver through backscatter modulated power signal, in which the phone's unique ID is encapsulated with a constant header. Therefore, the sensing module can retrieve the ID information by measuring the modulated power signal. We have designed and implemented a special charging board as the sensing module that transmits power as well as extracts ID. Although the latest Qi wireless charging protocol enables to use a (pseudo) random number generator to dynamically generate part of the Basic Device Identifier, a Power Receiver manufacturer should ensure that the combination of Basic Device Identifier and Manufacturer ID is sufficiently unique [8]. So the unique ID can be extracted from current charging devices.

Network Module: A QiLoc Station is designed to be cloud-enabled. It can use a wide range of wireless protocols such as Ethernet, WiFi, cellular (3G/4G), and even ZigBee. For large-scale deployment, a relay station can be used to connect QiLoc Stations in a certain area to the cloud. The network module mainly contains a micro-controller unit and a TCP/IP protocol stack. At runtime, it receives the extracted phone's ID from the sensing module and then updates the cloud.

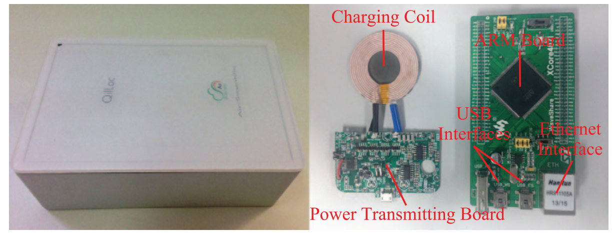


Fig. 3. A prototype of QiLoc Station and its internal components.

QiLoc Server. The QiLoc Server is responsible for data storage and real-time communication with QiLoc Stations. It mainly consists of a *data storage module* and a *service module*. The data storage module maintains the location information of all QiLoc users. In particular, we use the sMAP for data stream achieving, thus enabling efficient saving and searching of time series data. Based on the location database, the QiLoc Server supports a wide range of services such as location-based service, authentication service, and occupancy analytics. Specifically, the location-based service responds the location queries such as the user's present location and locations of people of interest. Relying on the mapping between a user and her phone's ID, the authentication service verifies the users' legitimacy. The occupancy analytics records a user's routine and thus identifies the "hot spots" that she frequently visits. All these services are provided through standard RESTful APIs [20]. Therefore, third-party developers can easily integrate QiLoc with their own applications to enrich functionality.

Applications. With the provided web services and RESTful APIs, QiLoc opens up ample opportunities for various indoor location services. QiLoc can be and has been deployed in a wide range of scenarios, providing rich location information. Such information, available at the QiLoc Server through standard APIs, can be leveraged to build or integrated with various applications. For example, a user can query her present and historical locations from her phone, and subscribe to certain people of interest to obtain live location information on a desktop. The authentication service can enhance workplace productivity by enabling practical applications such as live attendance monitoring and convenient file exchanging. We will present several representative applications that we have implemented based on QiLoc in Section VII.

IV. QiLoc Station

In this section, we present the design and implementation of a QiLoc Station, which is the front-end of QiLoc.

A. Qi Wireless Charging Protocol

A typical Qi wireless charging system consists of two major components, i.e., a power transmitter and a power receiver. The transmitter (equipped in a QiLoc Station) conducts wireless power transfer to the receiver (attached to a Qi-compatible device). To ensure the regulated power signal meets the requirements of power receiver, the power transmitter communicates with the receiver following the Qi wireless charging protocol. Specifically, such communication is one-way from the receiver to the transmitter, and employs backscat-

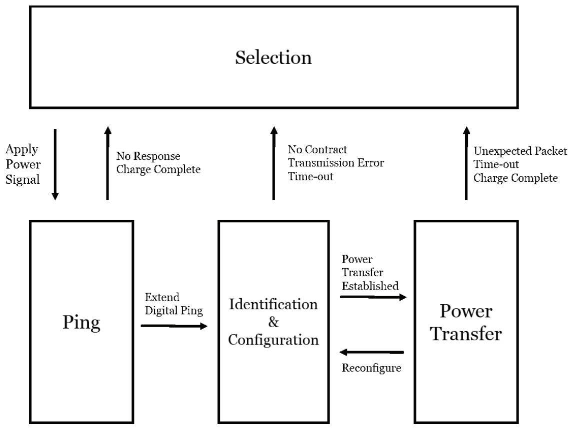


Fig. 4. The wireless power transfer phases.

ter modulation. The power receiver adopts a differential bi-phase encoding scheme to modulate data bits into the power signal. It uses an 11-bit asynchronous serial format to transmit a data byte to the charging board, where a byte consists of a start bit, 8 data bits, a parity bit, and a stop bit. Since the receiver modulates the amplitude of the charging power, the transmitter can extract the encoded data stream by measuring the current and voltage of the power signal.

The Qi wireless charging mainly compromises four phases, i.e., the *Selection*, *Ping*, *Identification and Configuration*, and *Power Transfer* phases, as shown in Figure 4. If no Qi-compatible device is detected by the power transmitter, the system will remain in the *Selection* phase. Moreover, the Qi wireless charging system can return to the *Selection* phase immediately if a device is taken away from the table. In the *Selection* phase, the power transmitter monitors the sensing area for the placement and removal events of Qi-compatible devices. If the charging board discovers one or more devices in the sensing area, it will identify and locate them. In particular, it differentiates between the Qi-compatible devices from other objects such as coins and keys. In the *Ping* phase, the power transmitter gives a digital ping and waits for the response from the power receiver. If the charging board discovers a Qi-compatible device, it will enter the next phase to identify the detected device. In the *Identification and Configuration* phase, the power transmitter identifies the detected device and receives packets from the power receiver. The packet contains the power transferring information such as the maximum amount of power that the charging device allows.

B. Station Architecture

We now present an architecture overview of a QiLoc Station. A QiLoc Station can be divided into four modules, i.e., *central controller*, *power transmitter* (*charging board*), *power supply*, and *network* modules. When a Qi-compatible device is placed on the sensing area, the charging board will detect it, extract its ID, and then communicate with the central controller using USART. The central controller is responsible for processing the data stream extracted from the charging board and packing the JSON format packets [21], which contain the location information and unique ID of the charging device. In this paper, we adopt an STM32F407 based on ARM Cortex-M4 [22] as the central controller for raw data processing and communication control, as shown in It has decent performance

	b_7	b_6	b_5	b_4	b_3	b_2	b_1	b_0
B_0	Major Version				Minor Version			
B_1	(msb) Manufacturer Code							
B_2								(lsb)
B_3	Ext	(msb) Basic Device Identifier						
⋮								
B_6								(lsb)

Fig. 5. The structure of the packet.

in data processing and communication while running at the speed of 168 MHz. The network module receives the extracted ID information from the power transmitter module through an I2C bus and then communicates with the cloud using JSON format packets.

C. Power Supply

It is challenging to generate qualified power supply for Qi wireless charging. First, the wireless power signal between coils can be rather feeble provided that the power supply is insufficient, making a QiLoc Station incapable of detecting the existence of a charging device. To supply sufficient power, the QiLoc Station is designed to adopt the switching power module. After rectification and filtering, the 220 V alternating current is converted to 24 V digital current. A DC-DC converter of switching power further converts the input voltage to 7 V. Such a switch-mode power design can provide charging current up to 10 A, which satisfactorily meets the need for Qi wireless charging. Moreover, the QiLoc Station employs regulated power for noise reduction as the Qi wireless charging circuit requires low-noise power supply. The high ripples in power supply may affect the communication between the charging device and power transmitter, making the QiLoc Station incapable of identifying the charging device. Given this, we design a novel power supply structure to reduce the noise. Specifically, this structure is implemented using low dropout regulator (LDR). We adopt the LM1084 LDR for voltage regulation, providing an output voltage of 5 V at the maximum load current of 5 A. The root mean square for noise of LM1084 is only 0.003% for output voltage when working in the frequency range from 10 Hz to 10 kHz. Therefore, the dual-level LDR structure can achieve a power supply fluctuation as low as 10 μV.

D. ID Extraction

The power transmitter communicates with the power receiver through backscatter modulated power signal. Specifically, in the *Identification and Configuration* phase, the power receiver sends an identification packet to the power transmitter. Figure 5 shows the structure of this identification packet. In particular, the unique ID of a device is encapsulated with a header of `0x71`. As a result, the device's ID can be retrieved from the modulated power signal. However, traditional power transmitters based on IC scheme cannot expose information from an packet. In this paper, we design a special charging circuit board as the power transmitter of a QiLoc Station. It uses a programmable microcontroller to obtain the data stream, copy it to ARM, and further extract the device's ID.

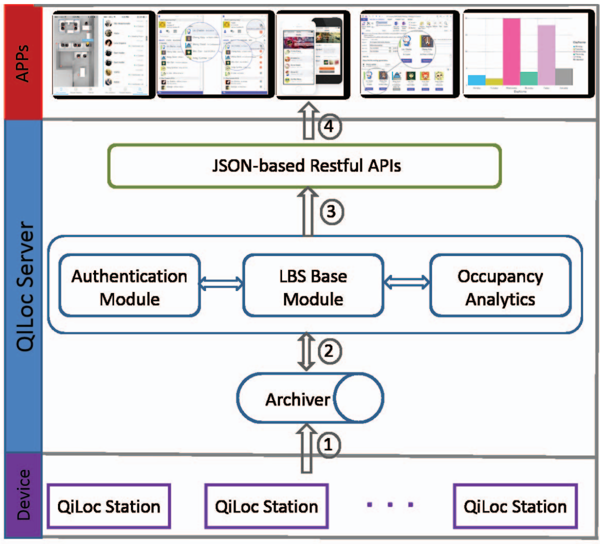


Fig. 6. The QiLoc data exchange framework.

E. Data Communication

The QiLoc Station can adopt a wide range of wireless communication protocols, such as WiFi, Ethernet, and cellular, to communicate with the cloud. In this paper, we choose LwIP, a lightweight TCP/IP protocol stack as the network protocol stack. LwIP (lightweight IP) is a widely used open source TCP/IP stack designed for various embedded systems. Moreover, experiments show that the lwIP protocol stack can run on ARM Cortex-M4 very efficiently, costing 10 KB RAM on average. The QiLoc Station uses DM9000 as the MAC driver for MAC layer communication. For better extension of system, we use JSON [21] format for data exchange between a QiLoc Station and a QiLoc Server. At runtime, the network module receives the extracted device's ID from the sensing module through an I2C bus and then communicates with the cloud using JSON format packets.

V. QiLoc Server

QiLoc Server provides services and RESTful APIs for developers. The APIs can help developers to implement many useful applications. To store and query the data efficiently, we use sMAP to define the data format and store the data. In the following subsections, we will first describe the data format and the archiver system, then follows the web services we provided.

A. Data Format and Storage

Figure 6 shows the QiLoc data exchange framework, To store and query the data efficiently, we use sMAP to define the data format and as the archiver.

sMAP is a a simple RESTful web service which allows instruments and other producers of physical information to directly publish their data. It enables the simple and efficient exchange of sensor data. It is a specification for transmitting physical data and describing its contents, which also provides tools for building, organizing, and querying large repositories of physical data. sMAP allows instruments and other producers of physical information to directly publish their data, and it

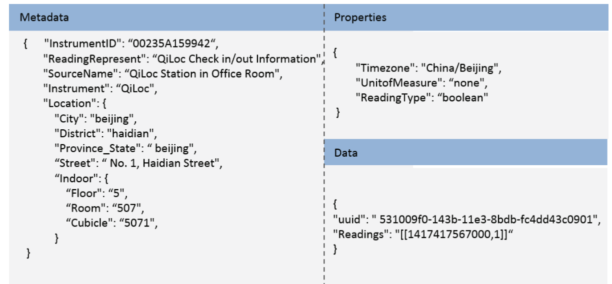


Fig. 7. The QiLoc Station data format.

provides powerful RESTful service to get the data from sMAP archiver. All the above features make it an ideal choice for our system.

QiLoc Station is our main data sources, we have to include both the location information and the real-time occupancy reading information at the same time, so we define the source data format, as shown in Figure 7. We add detailed and hierarchical metadata, such as instrument ID and location, to make it easier and natural to retrieve data in the future. The detailed location information also provide information to the backend algorithm and the visualization service. In the data section, each UUID is mapping to a unique PhoneID, while the boolean 1/0 stands for check in/out status of the phone.

B. Web Services

Three different modules are used to deal with the occupancy status data uploaded by QiLoc stations, the implementation details and provided services are described as follows.

LBS Based Module: The module will deal with the raw occupancy status data and provide the basic services and APIs, such as what is the current location of the user, Who are in a specific zone, etc.

Authentication Module: By mapping the user and her phone's unique ID, QiLoc enables authentication service such as attendance.

Occupancy Analytics Module: The module conducts analytics on the users' occupancy data to mining interesting patterns. It will provide various services, such as where is the hot spot of the office room, what is the favourite place of one user, etc.

VI. Discussion

In previous sections, we present the design and implementation of QiLoc. In particular, the QiLoc Station utilizes a specially designed charging board that can extract the charging device's ID while wirelessly charging it. In this section, we describe an alternate implementation of QiLoc. Nowadays, wireless power transmitters have been deployed in various public places such as McDonald's and Starbucks [23]. A key difference between such a power transmitter from our designed QiLoc Station (see Section IV) is that this charger uses IC for power transfer control, making it incapable of extracting information from the charging devices (see Section IV-D). In order to leverage these existing infrastructure and reduce the deployment cost, we explore an alternate implementation of QiLoc. Specifically, we develop an accessary that can be placed on top of an IC-based charging board and realize the functions

```
{
  "_id": ObjectId("53b16ba242653f6db827273c"),
  "Status": "checkin",
  "UID": "01",
  "Floor": "05",
  "Timestamp": NumberInt(1404136354),
  "PID": "711000100050D740B6",
  "AID": "AirScientific",
  "Cubicle": "509"
}
```


Fig. 8. The data representation of extracted location information.

of a QiLoc Station. This accessary can measure the power signal by using a secondary coil based on electromagnetic induction, as well as extract the identification packet by decoding. It is placed between the power receiver (i.e., the charging device) and the existing power transmitter (i.e., the charging board). We note that such an accessary should be assigned a unique ID and placed in a fixed location.

VII. Applications and Evaluation

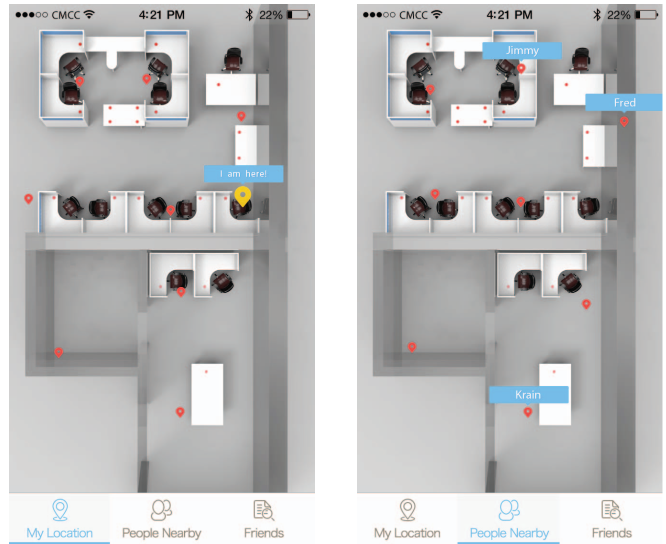
A contribution of QiLoc is that it utilizes the accurate desk-level location information as a primitive and enables a wide range of smart home applications such as location-based services, authentication-based services, and human interaction analytics. In this section, we present the design and implementation of several representative applications.

A. *Location Based Applications*

With recent advances in mobile technologies, smartphone enjoys drastic dropping in price and has proliferated into everyone's daily life. Each phone is associated with a unique ID that can be extracted by a QiLoc Station during wireless charging. Once the ID is tied with the phone's user, we can accurately locate a person of interest by positioning her phone. Owing to such a mapping feature, various location-based applications can be built on top of QiLoc.

1) Live Location Feed: A straightforward application based on QiLoc is to provide real-time location feed. Imagine that, when a smartphone user enters an unfamiliar office building, it would be very helpful to know her real-time position with respect to her destination and the floor plan. Another interesting usage is to learn the identities/positions of certain peopler of interest. For example, an absent-minded user may want to be reminded of the identities of people that sit next to her during a meeting, and a boss would like to know if her staff have spent too much time in the rest area. With QiLoc, such location-based information can be easily obtained while the phone is charging. A sample of the extracted location information is shown in Figure 8.

We have implemented a QiLoc app on iOS. It can provide the user's current location, position certain people of interest, and remind identities of people in the same physical area. As discussed in Section IV-D, when a smartphone is placed on the charging board, the QiLoc Station will automatically extract the phone's ID and transmit it to the QiLoc Server to update the cloud database. The smartphone app can then query the database about its own location and display it on the screen, as shown in Figure 9(a). Moreover, the database also stores the locations, timestamps, and status of other occupants, thus enabling a user to retrieve information about other people of interest. Figure 9(b) shows the screenshot of our app for finding friends' locations.



(a) User's own location. (b) Friends' locations.

Fig. 9. Screenshots of QiLoc app on iOS. It provides accurate real-time location information of people of interest.

In addition to the smartphone app, we also designed a desktop notification gadget. The gadget is written in C#. By using the real-time location feed of QiLoc, such a notification tool is particularly useful in an office scenario where people are interested in knowing the location of their colleagues. For example, there is often a need to locate and gather a team of people for an ad-hoc meeting. In our desktop notification gadget, one can subscribe the location updates of certain people of interest. When the target person places/removes her phone on/from a charging board, QiLoc will automatically sense the event and push the corresponding location information to the subscriber(s), resulting in a desktop balloon tip as shown in Figure 10.

2) Industrial Solution Supplement: We then explore the feasibility of integrating QiLoc with existing industrial communication/collaboration solutions such as Microsoft Lync [24]. Specifically, Lync is a widely-adopted platform for unified communications in enterprise workplace. It provides a real-time view of other colleagues' current availability status, i.e., whether they are available, away, offline, or busy. This type of information is very helpful for workplace communication and collaboration. However, Lync can still be enhanced by

Fig. 10. A balloon tip from QiLoc desktop notification, enabling timely location updates of people that the user has subscribed to.

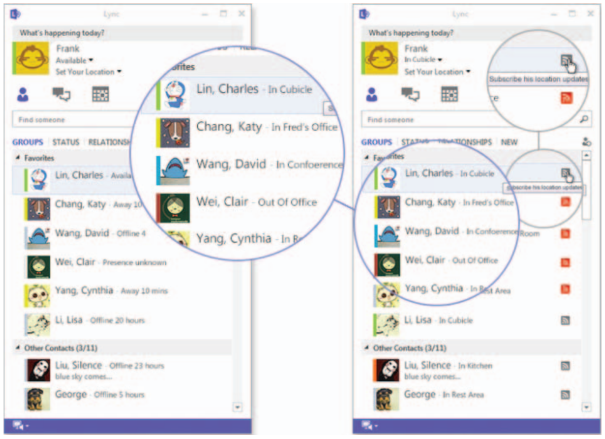


Fig. 11. Concept UIs of Lync before and after integrating with QiLoc. In QiLoc-integrated Lync, a user can easily subscribe to QiLoc location updates of her contacts and receive timely notification.

providing additional information. For example, a user may want to know not only the basic availability of her colleagues, but also their accurate locations at this moment, which are not supported by Lync. Moreover, a user may be interested in someone's recent location updates, which are not provided by either. By integrating QiLoc with Lync, we can easily obtain these detailed and fine-grained location information. While we cannot implement Lync with Qiloc since Lync is closed-source, we show that the integration is simple since the location-based services of QiLoc are provided through standard RESTful APIs to facilitate such integration. Figure 11 compares the user interfaces (UIs) of Lync before and after integrating with QiLoc. Specifically, the left figure is the original UI where only the availability information is present, and the right figure shows the QiLoc-integrated UI where fine-grained location information is provided, e.g., whether a certain colleague is in her own cubicle or in the conference room.

Similar to Lync, we also integrate Microsoft Outlook [25] with QiLoc to ease the meeting notification process. Based on the real-time location information provided by QiLoc, the organizer can directly obtain each participator's status and location within Outlook. If someone is away, the organizer can send a reminder email timely. Figure 12 shows the UI of Outlook Meeting Workspace after integrating with QiLoc.

3) Social Networking Catalyst: We envision another promising scenario that can benefit from the user-initiated location information provided by QiLoc is social networking software (SNS). Being able to discover and interact with people that are close-by and share common interests is a thrilling feature of SNS. Current SNSs generally realize this by using checking services such as Foursquare [26], which, however, suffers two major drawbacks. First, it requires localization service that relies on GPS, which works extremely well for an openair localization, but does not perform effectively in indoor environments due to the disability of GPS signals to penetrate in-building materials. Second, the user needs to manually select the correct localization result, causing unnecessary inconvenience. With the user-initiated location information provided by QiLoc, a SNS can automatically retrieve the accurate desk-level location of the user, greatly facilitating the social networking activity. We note that, similarly to the improvement to SNS, the precise and live location information provided by QiLoc can also enhance many other applications such as mobile advertisements and building energy footpringting.

B. Authentication Based Applications

By mapping the user and her phone's unique ID, QiLoc enables authentication service such as attendance. For example, a user, e.g., Alice, reaches her QiLoc-enabled office. Initially, QiLoc does not know if Alice has arrived or not, and thus maintain her status as "check out". As soon as Alice places her phone on the charging board, the QiLoc Station will extract the phone's ID, which is then sent to the QiLoc Server to determine if it matches the record. Once a positive match is detected, QiLoc will update the attendance database on the cloud and set Alice's status as "check in". Moreover, QiLoc periodically checks the presence of phone's ID and will mark the user as "check out" in the absence of her phone's ID. Similar schemes can be applied to enable automatic sign-in for meetings. In practice, QiLoc can run as a background system service without user's awareness.

C. Human Interaction Analytics

By mining almost half one year of location information stored at the QiLoc Server, we can conduct various trajectory-based analytics. In this section, we present two simple but useful applications – similar users discovery and individual anomaly behaviors detection. Both of these applications are based on sub-trajectory clustering algorithm. The trajectories of a certain user can be split into a series of sub-trajectories that reflect her daily routines. Therefore, users who share more common sub-trajectories tend to maintain stronger interaction. Moreover, the anomaly events can be detected when the trajectory of a user largely deviates from the historical observations.

A number of clustering algorithms have been proposed in machine learning society over the past few decades, such as K-means, DBSCAN, OPTICS, and STING, for various purposes. It is shown that the density-based clustering algorithms are more suitable for line segments due to its ability to discover

Fig. 12. Concept UI of Outlook Meeting Workspace after integrating with QiLoc. A meeting organizer can directly obtain each participator's status and location within Outlook.

arbitrary shape and filter out noise. However, since QiLoc is designed for indoor location services, the points on a trajectory represent the sites such as a conference room instead of the exact GPS coordinates, making it unnecessary to resort to these dedicated trajectory clustering algorithms. Therefore, we employ one of the most widely adopted clustering algorithms – K-means because of its simplicity and effectiveness. We demonstrate the procedures in Algorithm 1 and Algorithm 2. Algorithm 1 aims to find similar users by exploring their common sub-trajectories. We feed the algorithm with a collection of historical trajectories $\{U_1, U_2, \ldots, U_N\}$ (U_i represents the historical trajectories of QiLoc user i). Then, the algorithm will expose the latent routine patterns by clustering the similar sub-trajectories into groups. Finally, K matrices are generated with each matrix indicates the similarities between users in one latent pattern. Specifically, $M_{ij}^{(k)}$ denotes the amount of common sub-trajectory shared between user i and user j. We note that a large value of $M_{ij}^{(k)}$ implies user i and user j are more similar under the latent pattern k. Algorithm 2 aims to detect an abnormal sub-trajectory which largely deviates from all the latent patterns. We note that one cluster k can be treated as a normal latent pattern only when it has sufficient amount of points, thus we remove the clusters with too few points. We then calculate the distance between sub-trajectory S and the center point of each normal cluster. The sub-trajectory S is considered to be abnormal when it deviates away from all the normal clusters.

We now clarify several points about the proposed algorithms. Both the procedures involve *split* a trajectory into a group of sub-trajectories and the distance metric between two sub-trajectories. The key objective of splitting a trajectory is to extract the basic behavior patterns. There are various metrics having been proposed, such as the cosine distance, norm distance, and especially those designed for line segment clustering including the perpendicular distance, the parallel distance, and the angle distance. However, as we discussed earlier, the QiLoc system is mainly developed for indoor users and the trajectories recorded by QiLoc are just a collection of symbols or more precisely it can be deemed as string. Therefore, we adopt the string edit distance which is widely used in bio-informatics to quantify the similarity of DNA sequences as our metric. Let us denote two strings $s = s_1 \ldots s_m$, $t = t_1 \ldots t_n$ with length m and n, respectively, and their edit distance d_{mn} is defined recursively by:

$$d_{i0} = \sum_{k=1}^{i} w_{del}(t_k), \quad \text{for } 1 \le i \le m$$

$$d_{0j} = \sum_{k=1}^{j} w_{ins}(s_k), \quad \text{for } 1 \le j \le n$$

$$d_{ij} = \begin{cases} d_{i-1,j-1}, & s_i = t_j \\ min \begin{cases} d_{i-1,j} + w_{del}(t_i) \\ d_{i,j-1} + w_{ins}(s_j), \\ d_{i-1,j-1} + w_{sub}(s_j, t_i) \end{cases} & s_i \ne t_j \end{cases}$$

where $w_{del}, w_{ins}, w_{sub}$ represents the cost of performing delete, insert, and substitute operations respectively. The computation complexity of edit distance can be reduced to $O(mn)$ by using the dynamic programming. We note that to train the K-means using the EM algorithm and its running time depends on the iterative times. Assume the iterative times is T and M points exist in both the two procedures, then the time complexity of Algorithm 1 and Algorithm 2 is $O(TM + N^2K)$ and $O(TM + cK)$, respectively, where c is the constant. Once we have learned the K clusters the complexity of Algorithm 2 will be $O(cK)$.

We evaluate our proposed algorithms using the data collected by QiLoc over six months. In Algorithm 1, we set K to 3 to discover the hidden structure of the data. Figures 13 and 14 show the similarity matrices of the two clusters with points more than four hundreds. It can be easily observed that the user$_1$, user$_2$, user$_3$, and user$_4$ share more common sub-trajectories under cluster one while user$_5$, user$_6$, user$_7$ have more under cluster two, which implies that the user$_1$, user$_2$, user$_3$, and user$_4$ are more similar to each other under the latent behavior pattern one. It is true to user$_5$, user$_6$, user$_7$ under the hidden behavior pattern two. This indicates that these users belong to two different departments in their

Input: A collection of trajectory $\{U_1, U_2, \ldots, U_N\}$
Output: K-Similarity Matrices $M^{(1)}, \ldots, M^{(K)}$
for $i = 1$ *to* N **do**
  $P \leftarrow P \cup \{\text{Split } U_i \text{ into sub-trajectory points}\}$
end
$cluster_1, \ldots, cluster_K \leftarrow$ running K-means over P
for $k = 1$ *to* K **do**
  $c_{ki} \leftarrow$ The times user$_i$ occurs in $cluster_k$
  for $i = 1$ *to* N **do**
    for $j = 1$ *to* N **do**
      $M_{ij}^{(k)} \leftarrow min\{c_{ki}, c_{kj}\}$
    end
  end
end
return $M^{(1)}, M^{(2)}, \ldots, M^{(K)}$
end

Algorithm 1: Similar Users Discovery

Input: A collection of trajectory $\{U_1, U_2, \ldots, U_N\}$;
  A piece of of sub-trajectory S;
  Threshold ϵ
Output: Boolean $anomaly$
for $i = 1$ *to* N **do**
  $P \leftarrow P \cup \{\text{Split } U_i \text{ into sub-trajectory points}\}$
end
$cluster_1, \ldots, cluster_K \leftarrow$ running K-means over P
$NormalCluster \leftarrow \emptyset$
for $k = 1$ *to* K **do**
  if $length(cluster_k) \ge \epsilon$ **then**
    $push(NormalCluster, cluser_k)$
  end
end
for $k = 0 : length(NormalCluster)$ **do**
  $ClusterRadius_k \leftarrow$ radius of $NormalCluster_k$
  $center_k \leftarrow$ center point of $NormalCluster_k$
end
for $k = 0 : length(ClusterRadius)$ **do**
  if $Distance(S, center_k) \le ClusterRadius_k$ **then**
    return false
  end
end
return true
end

Algorithm 2: Anomaly Behaviors Detection

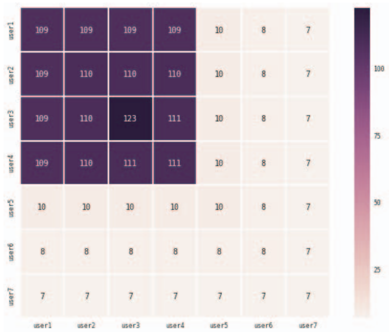


Fig. 13. Similarity matrix of cluster one.

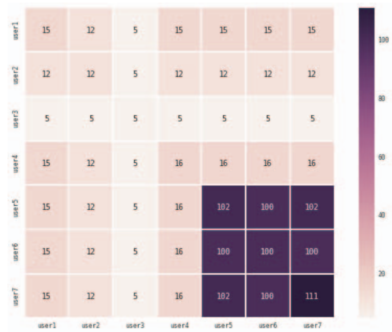


Fig. 14. Similarity matrix of cluster two.

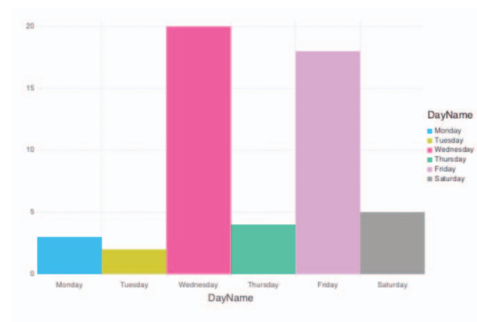


Fig. 15. The histogram of abnormal points.

physical community. We verify Algorithm 2 by calculating the number of abnormal sub-trajectories of QiLoc users. Figure 15 demonstrates the number of abnormal points of each day and it reveals that there are much more anomaly behaviors in Wednesday and Friday, and this phenomenon coincides with the fact that the company normally holds its weekly meeting on Wednesday and Friday afternoons.

VIII. Conclusion

In this paper, we present the design and implementation of a novel user-initiated indoor location system called QiLoc. QiLoc is a simple yet effective way to accurately locate and identify occupants inside buildings. QiLoc is composed of QiLoc Stations and QiLoc Server. QiLoc Stations are embedded inside or under desks/tables. By utilizing the Qi wireless charging protocol, a QiLoc Station is able to extract the unique IDs from phones placed on the desk, and therefore locating the user. QiLoc Server communicates with QiLoc Stations, maintains location information of occupants, and provides a set of APIs via standard web services. These services include location, ad hoc group membership, and authentication. Using these primitives, QiLoc enables a wide range of smart-building applications. We have implemented a number of applications based on QiLoc, including a smartphone app that locates others in the same logical space (e.g., in the same room) and provides several interaction methods; a Microsoft Windows-based notification system that gives live updates of colleagues' locations and automatically logs the user in when sitting in front of her computer. We also show how QiLoc can be leveraged to greatly enhance human interaction and productivity by integrating precise and live location information with calendar, instant messaging, and email systems.

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