# Building/environment Data/information Enabled Location Specificity and Indoor Positioning

C. C. Li, J. Su, E. T.-H. Chu, *Member, IEEE*, and J. W. S. Liu, *Life Fellow, IEEE*

***Abstract*—The building/environment data and information system (BeDIS) described here is a part of infrastructure needed to support location-specific, active emergency preparedness and responses within large buildings. BeDIPS (Building/environment Data and information based Indoor Positioning System) is one of its components. BeDIPS can provide people in large buildings with sufficiently accurate location data. It is scalable, disaster resilient and is easy to configure, deploy and maintain. BeDIPS works without Internet and serves both smart phones and most legacy Bluetooth devices. The other component of BeDIS is BeDi mist, a virtual repository of data and information on the building, interior layouts and facilities. The mist uses micro data servers and smart gateways to deliver fine-scale, location-specific decision support data on a timely basis to hundreds and thousands of active devices and mobile applications**

***Index Terms*—Active disaster preparedness and response, Data mist, Indoor positioning, Location beacons, Location specificity**

## I. Introduction

In recent years, technological and infrastructure advances have enabled responsible authorities in developed regions to generate accurate early alerts of common types of natural disasters, encode the alerts in a standard machine readable format, and disseminate them via all communication pathways. A common practice is to send the alerts to emergency alert systems/services (EAS) and let them translate the alerts into textual, audio and visual warnings and then broadcast the warnings to people. Typical warnings provide individuals with no specific instructions on how to respond at their locations. This fact and limitation in human reaction time limit the effectiveness of early warnings.

A better alternative is to send alerts from authorized senders directly to smart devices and applications that can process the alerts and automatically take location-specific risk reduction actions to reduce chance of injury and property damages. Examples of such devices include smart valves and switches, elevator controllers, door controller, etc. In response to an early alert of an observed strong earthquake of a severity exceeding the thresholds indicated by the code and shock tolerances of the building and facilities in it, the smart devices shut the gas valves and electric appliances, bring elevators to the nearest floor, open access-controlled doors, and so on. Mobile applications deliver to their users not only the warning of imminent ground moments, but also location-specific instructions, e.g., telling people near load-bearing structures to stay where they are and people in hazardous areas to go to specified safe locations. Hereafter, by *active devices and applications,* we mean specifically smart devices and mobile applications for emergency/disaster preparedness and response. The term *location specificity* refers to the ability of an active device to select its action(s) in response to each emergency alert based on not only the type and parameters of the alert but also on characteristics of the building, interior layout and objects around the location of the device. Location specificity also means that preparedness and response instructions delivered to their users by active mobile applications are customized according to the attributes of their locations.

The *Building/environment Data and Information* (BeDI) System (or *BeDIS*) described here is a part of the information technology (IT) infrastructure that supports location-specific, active emergency preparedness and response within large public buildings (e.g., transport hubs, major hospitals, and large department stores). A critical piece of the infrastructure is an indoor positioning system (IPS) that can reliably help people locate themselves. The *building/environment data and information based indoor positioning system* (BeDIPS) described in our iThings2015 paper [1] is for this purpose. The other major component of BeDIS is a virtual repository of data and information on the building, interior layouts and facilities. The repository, referred to hereafter as *BeDI mist*, is structured according to the approaches of fog and mist computing [2, 3]. It aims to support fine-scale location-specific decisions and operations of active devices and applications.

### A. High-Level Requirements and Architecture

Upon receiving and processing an emergency alert targeting the geographical area of a building, hundreds and thousands of embedded and mobile devices running active applications in the building need data on attributes of the building and environment around their locations to decide whether and how to respond to the alert. The required response time of the mist is a fraction of second to a few seconds in case of earthquake alerts, a few seconds to minutes in case of tornado, flash flood and landslide alerts, and minutes to tens of minutes in case of severe storms and typhoons warnings.

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C. C. Li and S. Su are with the Institute of Information Science, Academia Sinica, Taipei, Taiwan. (e-mail: {jakelee, johnsonsu}@iis.sinica.edu.tw).

E. T.-H. Chu is with Department of Computer Science and Information Engineering, National Yunlin University of Science and Technology, Yunlin, Taiwan. (e-mail:edwardchu@ yuntech.edu.tw).

J. W. S. Liu is with the Institute of Information Science and Research Center for Information Technology Innovation, Academia Sinica, Taipei, Taiwan. (e-mail: janeliu@iis.sinica.edu.tw).

Similarly, BeDIPS is designed to have the following attributes required of IPS for large public buildings:

- *Sufficiently accurate*: The vertical location provided by the system is error-free, meaning that the user is never misinformed of the floor on which he/she is. The system can be configured to provide high (i.e., 3-5 meters) or medium (i.e., 6-10 meters) horizontal accuracy, or room-level accuracy.
- *Scalable:* During orders of magnitude surges in crowd density, degradation in location accuracy and response time remains tolerable.
- *Disaster resilient*: The system can function without Internet, WiFi and cellular network coverage and degrades gracefully when parts of it are damaged.
- *Easy to configure, deploy and maintain*: The required updates due to changes in layouts and characteristics of the building can be made systematically and easily, and the health of the system can be assessed during operation.
- *Minimal required capabilities of end-user devices:* The capabilities required of user devices to access the service should be minimal. Specifically, the majority of cell phones can receive from the system the coordinates and text description of the user's location.

Fig. 1 shows the overall structure and major components of BeDIS. As the upper half of the figure shows, the workhorse of both BeDIPS and BeDI mist are *location beacons*, hereafter referred to as *Lbeacons* (or simply beacons). Lbeacons are installed pervasively throughout the building. For the purposes of configuration, initialization, and monitoring and testing, Lbeacons in each area of the building are connected via one or more Zigbee star networks. They in turn are connected via gateways to the local-area network and Internet within the building and the BeDIS server.

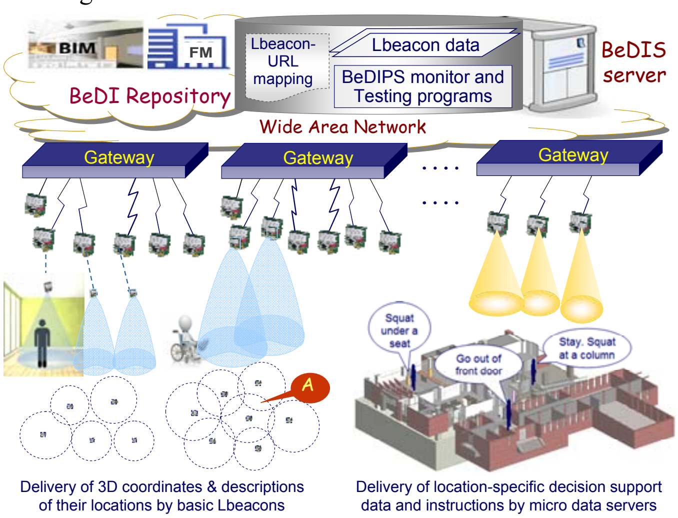



Fig. 1 Architecture, major components and functionalities of BeDIS

### B. Contributions

Most of existing IPS require Internet, WiFi, and/or cellular coverage to work, and can service only modern smart phones. Indeed, no indoor positioning system based on existing IPS technologies (e.g., [4-34]) can meet all the above listed requirements of IPS for large public building. In contract, BeDIPS can, To justify this claim, we note that as the lower half of Fig. 1 illustrates, BeDIPS uses Lbeacons to deliver data: Each beacon stores the 3D coordinates and a textual description of its own location. It uses a Bluetooth Smart Ready module [35] to deliver data on its location to Bluetooth devices in its coverage area, including smart phones, feature phones and many legacy Bluetooth devices. The required location accuracy is achieved by providing Lbeacons with directional antennas and adjusting their ranges and beam widths, thus, the diameters of their coverage areas. This is why BeDIPS works without Internet: It remains scalable and responsive, capable of delivering sufficiently accurate location data even when network connections in the building are disrupted and parts of the system are damaged.

In addition to BeDIPS, the BeDI mist is another contribution of the paper. The virtual repository uses *enhanced Lbeacons* as *micro* (*data*) *servers*. When commanded to do so by gateways and the BeDIS server, these near-user edge devices deliver fine scale, location specific decision support data to the vast number of active devices and mobile applications in the building within the short time from the receipt of an alert to the time when actions must be taken by devices and people. As Section VI will describe, together with smart gateways with capabilities to process and respond to CAP alerts, micro data servers turn the BeDI repository from a cloud to a mist.

The unique combination of features of BeDIPS and BeDI mist is made feasible through innovative use of building information models (BIM) and facility management (FM) data [36, 37]: Like modern smoke detectors, Lbeacons are AC powered. The selection, configuration, placement and installation of all Lbeacons needed for BeDIPS and BeDI mist to provide the desired coverage in a large building would not be feasible without the open source tools provided by the BeDIPS development environment (BDE) to be described in Section III. The tools are also contributions of this work.

Following this introduction, Section II presents background, motivation and related work. In particular, the section will present measured performance data on IPS based on common IPS technologies to explain why BeDIPS does not use the technologies. It also justifies the assumption on the availability of BIM/FM data on large public buildings. Section III presents the assumptions and design rationales of BeDIPS, together with the BIM-based development environment mentioned above. Section IV presents an overview of BeDIPS followed by the structure of the basic version of Lbeacons, experiments set up to measure the response time of the device as a function of the number of receivers in its coverage area, and performance data obtained from the experiments. Section V presents the structure of gateways connecting Lbeacons to the BeDIS server and the health monitoring and self test performed collaboratively by beacons and gateways. Section VI describes the structures of gateways and micro data servers. Section VII summarizes the paper and presents future work.

## II. Background and Related Work

This section first presents an overview of existing indoor positioning technologies and performance data on limitations of systems based on them. It then presents advances that have enabled active smart devices and mobile applications and made building/environment data and information (BeDI) available.

### *A. Indoor Positioning Technologies*

Despite years of efforts worldwide on indoor positioning technologies and many big players and over ninety startups racing to be leaders in the growing market of indoor positioning services/systems (IPS), there is still no clear winner, no large scale deployments and widely adopted standards today [4-10]. In fact, no existing system can meet all the requirements of IPS for large public buildings. This is the reason behind the very pessimistic location accuracy guideline/timeline, "50 meters by year 2020", for indoor wireless E911 calls published by USA FCC in 2015 [34].

#### *1) Range-based and fingerprint-based systems*

Today, the majority of indoor positioning systems are range based, or fingerprint based, or both. Roughly, location accuracy in order of 3-10 meters is achievable by pure range-based systems [4-6]. An example of such systems is WiFi-based Skyhook Wireless [15]. An advantage of such systems is that they require only an application computing triangulations on off-the-shelf smart phones, tablets, or laptops the location of the device based on received signal strength (RSS), or time of arrival, time difference of arrival, frequency difference of arrival, etc. of signals from anchor nodes (i.e., signal emitters with known locations). The accuracy can be improved by using more and better placed anchor nodes. This type of IPS can be expensive to maintain when the number and locations of anchor nodes change frequently, however. More seriously, their location accuracy degrades when variations in number, densities and movements of people and objects in the operating environment perturb propagation paths and cause unpredictable fluctuations in received signal strengths.

Systems aiming to provide significantly better location accuracy (e.g., down to centimeters) often use non-standard signal(s), including low frequency (e.g., 1 MHz) signals, ultra-wideband (e.g., 500 MHz) signals, visible light (e.g., LED) signals, pulsating signals, acoustic signals, and magnetic fields, and/or make sophisticated measurements (e.g., measurements of phase differences of electric and magnetic fields of received signals and near field of low frequency signals) [9-14, 16-21]. Disadvantages of these approaches include that special user devices are required. Clearly, systems that use light signals do not work during fire emergencies.

Fingerprinting, either used alone or in combination with range-based techniques, offers another way to improve location accuracy. A fingerprint is a set of location-specific values of signal strength (i.e. a signal pattern). Types of fingerprints used for indoor positioning include patterns of WiFi signals from known access points, FM signals from multiple radio stations, acoustic echo patterns and background spectrum, magnetic signatures of the building and multiple types of signals [22 - 32]. A fingerprint-based IPS has a fingerprint server supported by a database of fingerprint-to-location mappings that are captured at different locations in the building during setup and maintenance times. To determine its own location, a mobile device sends the fingerprint captured by it at its location to the server and relies on the server to find the location(s) with a matching fingerprint. Because of their reliance on Internet and the fingerprint database server, fingerprint-based systems do not scale and do not degrade gracefully. Other disadvantages include the high setup and maintenance cost of the fingerprint database. Requiring user devices capable of capturing fingerprints is another disadvantage of such IPS.

Table 1 lists representative data on range-based and fingerprint based IPS from an evaluation study of IPS in healthcare environments [32]. The area where measurements were captured consists of three large rooms connected by a corridor in a hospital ward where patients come for surgical operations in the morning and leave at the end of the day. The figures of merit used to compare IPS based on alternative technologies are point location accuracy, room accuracy, latency, and installation cost. As the top half of Table 1 shows, the fingerprint-based system has better location accuracy, but worst response time (i.e., latency). What the data does not show is the high installation, setup and maintenance cost of fingerprint-based systems. The bottom half of Table 1 depicts variations in location accuracy achieved by range-based approach. Even in the relatively simple and static test site, location accuracy cannot be controlled in general and is unacceptable specifically in terms of room-level accuracy. One expects that the location accuracy of such systems to be worse when used in buildings with more dynamic and complex operating environment (e.g., in transport hubs during rush hours and in large department stores during special sales).

TABLE 1
DATA ON LOCATION ACCURACY FOR DIFFERENT IPS TECHNOLOGIES [32]

| Technology | Point accuracy (m) | Room accuracy (%) | Latency (sec) |
|---|---|---|---|
| Fingerprint-based | | | |
| WIFI | 1.21 | 96 | 5.4 |
| BLE (iBeacon) | 2.31 | 76 | 3.06 |
| RSSI/MLAT | | | |
| WIFI | 3.65 | 47 | 3.0 |
| BLE (iBeacon) | 3.85 | 61 | 2.5 |

| RSSI/MLAT | Point accuracy (m) | | | Room accuracy (%) |
|---|---|---|---|---|
| | Minimum | Average | Maximum | |
| WIFI MLAT | 0.52 | 2.68 | 5.98 | 46.58 |
| BLE (iBeacon) | 0.94 | 3.12 | 9.09 | 61.64 |

#### *2) Proximity-Based Systems*

In BeDIPS, each Lbeacon broadcasts its coordinates and location description to devices coming within its coverage area. In this respect, BeDIPS is similar to proximity detection systems (e.g., [33]). Based on available performance data, including the data from [32], one can say that such systems offer a good solution for indoor positioning in large public buildings. In addition to being less expensive and easier to maintain than fingerprint-based systems, a proximity-based system can provide acceptable accuracy for people to locate themselves and their objects (e.g., near 100% room-level accuracy and horizontal accuracy of 1.5 to a few meters).

Existing IPS based on proximity detection may use of radio tags and iBeacons [38] from Apple Inc., sometimes with fingerprints. iBeacon and other Bluetooth proximity marketing products (e.g., [39, 40]) are designed to notify nearby smart devices of their own UUIDs or URLs, based on which the devices can look up their approximate locations. In contrast, each Lbeacon works alone to deliver location data.

### B. Active Emergency Preparedness and Response

Active smart devices and mobile applications, called *intelligent guards against disasters* (*iGaDs*) in [41], aim to improve significantly our ability and effectiveness in disaster preparedness and response. iGaDs were motivated by the fact that modern sensors, modeling and analysis technologies have significantly improved the accuracy, specificity and timeliness of warnings of common types of disasters in recent years [42]. For example, early earthquake alerts systems (e.g., [43, 44]) can provide receivers in affected areas with location-specific warnings of observed strong earthquakes a fraction of a second or more before ground motion starts. This lead time, while too short for human actions, is long enough for most iGaDs to take risk reduction actions.

An enabler of iGaDs is the Common Alert Protocol (CAP) [45] for encoding of disaster alert messages. The OASIS international standard is now widely adopted worldwide. We assume that emergency/disaster alerts are in CAP format and say that active devices and applications (i.e., iGaDs) are CAP-aware [41]. Infrastructure advances that have enabled iGaDs also include platforms for receiving and authenticating CAP-compliant alerts from alerting authorities and trusted systems and then disseminating them via multiple communication pathways. Examples include Integrated Public Alert and Warning System (IPAWS) - OPEN [46] in USA and similar platforms deployed by other countries.

Our prior work [41, 47] has demonstrated that easy to configure and customize iGaDs for diverse purposes can be built on a common architectural framework from reusable components. The prototype asynchronous message delivery service [48] demonstrated that CAP alerts can be pushed asynchronously over the Internet and that the service can meet the delay requirements of time-critical alerts and throughput demands of all authorized senders in likely scenarios.

A prototype active emergency response system (AERS) [49, 50] was built to demonstrate the effectiveness of such systems in smart homes and buildings. A typical AERS contain diverse iGaDs as well as component systems that leverage existing surveillance cameras for damage assessment, use existing embedded devices to establish temporary networks when Internet and phone connections are disrupted, and so on to support response operations during emergencies. In a field trial carried out in a multi-story office building, AERS shut off natural gas valves, opened escape doors, brought elevators to the nearest floor, and turned off electric appliance in response to a simulated strong earthquake alert. Measured data show that people took at least 15 seconds to carry out these operations. By having AERS perform them, people were given sufficient time to get under sturdy furniture, or to evacuate from the third floor to the first floor, or to run 100 meters.

### C. Data and Information for Location Specificity

Location specificity of active devices and applications within buildings would not be possible without *Building Information Model* (*BIM*) and facility management (FM) data [36, 37]. BIM of a building refers to files containing data on the building and objects of interest in it (e.g., windows, doors, elevators, electric outlets and, for a building with a BeDIS, Lbeacons). Together, the files give a complete digital representation of physical, functional and spatial characteristics and relevant attributes of the building and the objects. BIM can also incorporate dynamic information needed to support facility management and building operation and maintenance [36, 51-53]. Furthermore, XML-based data exchange standards (e.g., [54]) enables lightweight retrieval and deliveries of subsets of BIM/FM data.

In recent years, open BIM and data exchange standards have been adopted by AEC (Architecture, Engineering, and Construction) industries in an increasingly larger part of the world [55]. An important trend is the mandated use of BIM during the lifecycle of government buildings and construction projects. Buildings constructed before the wide adoption of BIM are documented by blueprints. Our experience through case studies reported in [56] show that with the help of modern software tools such as Autodesk Revit [57], blueprints can be translated into BIM at an acceptably low cost.

These facts justify our assumption that now and in the near future, every public building/facility of some specified size or larger in developed countries is served by a virtual or physical building and environment data and information (BeDI) repository. The repository provides access to datasets selected from the BIM/FM database of the building, including datasets containing 2D-3D geometric models of the building components and objects of interest in the building.

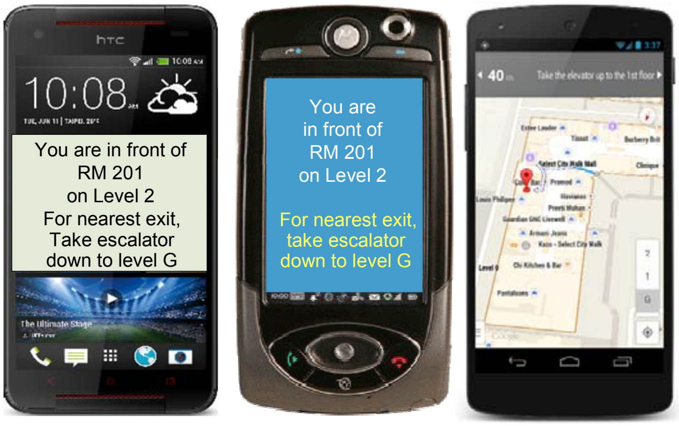
## III. Assumptions and Rationales

As stated in Section I, BeDIPS uses Lbeacons to deliver data on their locations via both Bluetooth low energy (BLE) and classic basic rate/enhanced data rate (BR/EDR) protocol paths [35]. The data are stored locally on the beacons. During runtime, the beacons operate independently. The load on each beacon is limited by the maximum number of users within its coverage area, and the beacons are designed to produce an acceptable response time under maximum load. This is why the system is scalable and degrades gracefully.

### A. Assumptions on User Devices

The primary users of BeDIPS are people in buildings. For sake of concreteness, we assume hereafter that the devices they use to access BeDIPS are mobile phones. Each phone may support Bluetooth BR/EDR, or BLE, or both. To serve phones with no indoor map and no location-navigation applications, including feature phones and other legacy devices, each Lbeacon broadcasts not only its 3D coordinates, but also a short textual description of its location (e.g., Level 2, RM 201 and Lobby, south-west corner) and optionally a one-step navigation instruction to the nearest exit. The data are sent asynchronously in vMessage format according to Bluetooth OBEX (OBject Exchange) protocol [58]. OPP (Object Push Profile) and OTP (Object Transfer Profile) [59] being widely supported, most phones can display the location description shown in Fig. 2(a).

Using 3D coordinates broadcast by Lbeacons as input, indoor location and navigation applications capable of displaying the location as illustrated by Fig. 2(b) [60] can be implemented straightforwardly on smart phones with indoor maps. Similarly, longitude/latitude coordinates from Lbeacons can be used as waypoints on routes of autonomous devices (e.g., delivery robots) in the building, but the devices need to have on-board applications for purposes such as control and guidance and navigation and object avoidance.




(a) Displays on phones without indoor maps and HereUAre application

(b) Display of location data by HereUAre [60]

Fig. 2 Location data displayed on smart phones and a feature phone.

Specifically, the vertical coordinate provided by BeDIPS to a user is the floor/level where the user is. In other words, the vertical coordinate are expressed as B8, G, 1, 2 …, 101 or -8, 0, 1, 2 and so on. The horizontal coordinates broadcast by every Lbeacon is its own latitude and longitude relative to the southwest corner of the building. Each degree of latitude is approximately 111 kilometers, and each degree of longitude is approximately 111.321 kilometers apart. So, the horizontal coordinates of any point within a building down to centimeter accuracy can be specified by using 8 bytes each. Lbeacons deliver their location data to phones via the EDR/BR data path according to OBEX protocol [58], which imposes no limit on the size of location data. Each Lbeacon broadcasts its location data as advertising data to smart phones via the BLE path. In this case, only 26 bytes are available, constraining us to encode 3D coordinates using only 12 bytes [36]. An alternative is to broadcast location data using connectable advertising, which provides 62 bytes of payload. A tradeoff is possible degradation in response time as the beacon needs to respond to scan requests from smart phones in its coverage area.

### B. Virtual BeDI Repository

By design, BeDIPS is built on state-of-the-art information and communication technologies. Nevertheless, practical challenges in configuration, deployment and maintenance of such systems can easily prevent them from being viable and feasible. To illustrate, we consider Frankfurt Airport as an example [61]: The transport hub has approximately 50,000 smoke detectors. It will need two or three times more Lbeacons to achieve 3-5 meter horizontal location accuracy. The tasks of selecting a right location of each beacon, determining the coordinates of the location and installing the beacon at the coordinates would be prohibitive without the tools provided by the BeDIPS Development Environment (BDE) illustrated by Fig. 3. With the tools, however, the tasks are only slightly more demanding than the tasks of deploying RFID tagged and smoke detectors throughout the building.

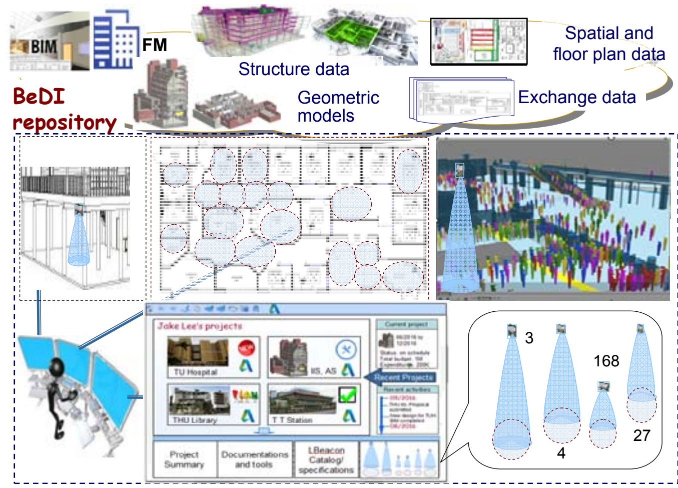



Fig. 3 BeDIPS development environment

Before describing how the BDE tools can support the design, configuration, installation and maintenance of the IPS for individual buildings, we note that BDE has three parts. The first part is the Building/environment Data and Information (BeDI) repository illustrated by the top part of Fig 3: The repository of a building is built on the BIM/FM database that was created and maintained for purposes from design, architect and construction of the building to managing the building and its facilities. We assume that every large public building has a BIM/FM database for reasons stated in Section II(C). The virtual BeDI repository provides access to selected datasets within the BIM/FM database and supports digital exchange standards (e.g., [54]) for retrieving the data.

We will return in Section VI to describe how components of BeDIPS are used to turn the repository from a cloud into a BeDI mist. From the perspective of BeDIPS, it suffices that the BeDI repository provides exact 3D coordinates of every Lbeacon. The beacon is surely mounted on an object (e.g., a ceiling, a wall or next to a light) that is characterized by data in some datasets in the BIM. The coordinates are kept up to date during remodeling, renovation and maintenance since the BIM datasets on the model and characteristics of the object are updated during the BIM processes.

### C. Tools from BeDIPS Development Environment

The second part of BDE is a project management system illustrated by the bottom part of Fig. 3. Through a dashboard, the system presents to the developer an overview of his/her projects. The developer can find here documentations and specifications. In particular, a catalog of Lbeacons provides everything he/she needs to know about them.

With rare exception, Lbeacons are installed on the ceilings. Different types of Lbeacons differ in their ranges and antenna radiation patterns. The lower right corner of Fig. 3 shows four types as examples. Each dashed circle or oval provides a rough view of the coverage area of a beacon. A complex building is likely to require several types. While Lbeacons with range around 3 meters are suitable for typical rooms, beacons with range 20 meters or more may be needed for multi-level halls. All of them have directional antennas with conical beams. Beacons with 3-meter range and 60-degree radiation pattern can provide 1.5-3 meter horizontal accuracy. Beacons with larger ranges need to have antennas with narrower (e.g., 30 degree) radiation patterns to achieve the same accuracy.

The third part of BDE is a plugin of the widely used BIM software Autodesk Revit [57], which the developer can access from his/her dashboard. According to its Wikipedia definition, Revit enables users to design a building and building components in 3D, annotate the 3D models with textual and diagrammatic drafting elements, and maintain the design in the building's BIM database. Revit rendering engine enables the user to visualize the stored models as 2D and 3D images.

The middle part of Fig. 3 illustrates a typical use scenario of BDE: The developer accesses the BDE Revit plugin by clicking the Autodesk button in the panel for his/her current project. In response, the plugin presents to the developer with 2D and 3D images of parts of the building selected by the developer.

### D. Design and Deployment

The process of design and deployment of a positioning system in a building starts from getting Revit plugin to display the floor plan and 2D-3D images of each area (e.g., office area, a corridor, and a large hall) to be covered by Lbeacons. Graphical and visualization tools built on the 2D-3D geometric models such as the ones illustrated by the middle part of the Fig. 3 can help the developer select the right type of Lbeacon for each location, experiment with the placements and orientations of the selected beacons, and visualize and assess the coverage provided by them. In the example scenario shown in Fig. 3, the developer is working on the selections and placements of Lbeacons in an office area. The floor plan in the middle shows a partially completed layout of beacons for the area. Except for the corridors, where the desired accuracy is around 1.5 to 3 meters, the desired accuracy is room level. This is indicated by the developer's choices of using beacons with small coverage area in corridors and beacons with large coverage in rooms.

Upon finding a satisfactory design for the area, the developer has the plugin generate, for each beacon to be installed in the area, its 2D barcode (i.e., its UID), type and coordinates. In addition, the plugin also generates the coordinates of a reference point for the area. The reference point is a location in the area that can be easily pinpointed by the installer. Examples include the south-west corner of the room and the left inside frame of a specified door. The coordinates of the reference point is used during installation as described below. The data generated by the Revit plugin for each area of the building when the design process completes are stored in the BeDI repository and managed by the BeDIS server.

To make Lbeacons for each area ready for installation, the installer fixes the barcode and loads the coordinates and location description of each Lbeacon on the beacon using the user interface and tools provided by the BeDIS server. The installation is carried out with the help of an installation tool that has a barcode scanner, a servomotor controlled laser pointer and network connection to BeDIS server. To install Lbeacons in an area, the installer places the tool at the reference point of the area and uses the tool to retrieve from the server the coordinates of the reference point and the barcode ids of all the Lbeacons for the area. To install a Lbeacon, he/she has the barcode of the beacon scanned by the tool. After verifying that the Lbeacon is for the area, the tool reads the coordinates of the beacon and based on the coordinates of the reference point and the beacon, directs the laser pointer to point to the spot on the ceiling where the beacon should be placed. In this way, the tool enables the installer to easily locate the point on the ceiling with the beacon's coordinates. Fig. 4 shows a photo of the installation tool and illustrates this scenario: Here, the installation tool points to the location on the ceiling where the beacon on the right should be installed.

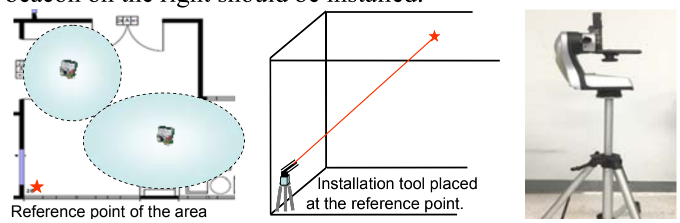



Fig. 4 Laser pointer: a BeDIPS installation tool

## IV. Basic Lbeacon Structure and Performance

Returning to Fig. 1 which shows the structure of BeDIS, we note that the most numerous components in BeDIS are Lbeacons. Once installed and initialized, each Lbeacon broadcasts its locally stored coordinates and location descriptions to Bluetooth devices under its coverage.

### A. Location Error Versus Lbeacon Density

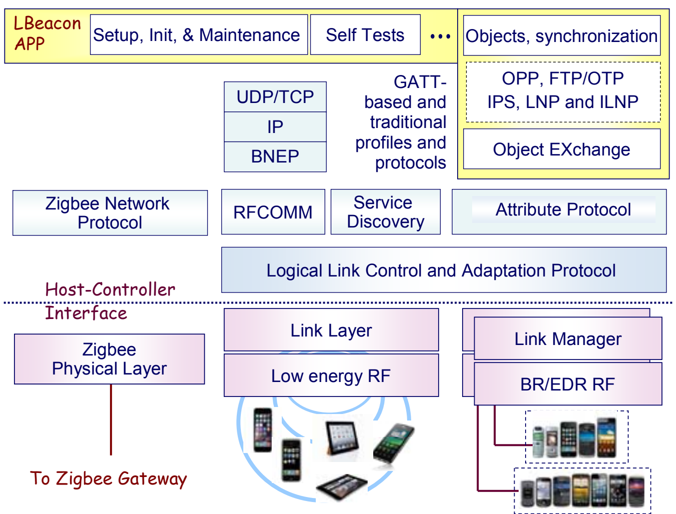
As stated earlier, the beacons are installed typically on ceilings. Their antennas point downward to the floor. The range of every beacon being less than the ceiling height, no device below the floor can hear it. This is a way to ensure zero error in the vertical position and eliminate multipath due to reflection from the floor. The bottom left part of Fig. 1 shows examples of possible placements of Lbeacons for good coverage and small location errors. Incomplete coverage patterns are often acceptable in some parts of the building, e.g., in an office area. By accepting blind spots in coverage and larger horizontal error, the required number of Lbeacons can be reduced.

At some locations (e.g., in a big exhibition hall), Lbeacons may have overlapping coverage in patterns similar to the one shown in the bottom middle part of Fig. 1. In this case, the horizontal position error is bounded by the diameter D of the beacon beam (e.g., 3 or 5-10 meters). It is possible to reduce the errors to a fraction of D if devices in areas covered by multiple beacons (e.g., the area A in Fig. 1) can estimate their own locations from the coordinates received from the beacons. In general, one can tradeoff between the total number of Lbeacons required to achieve a specified horizontal accuracy and the capabilities required of the user device. Our design choice has been to minimize the capabilities required of the user devices and HereUAre application at the expense of Lbeacon density.

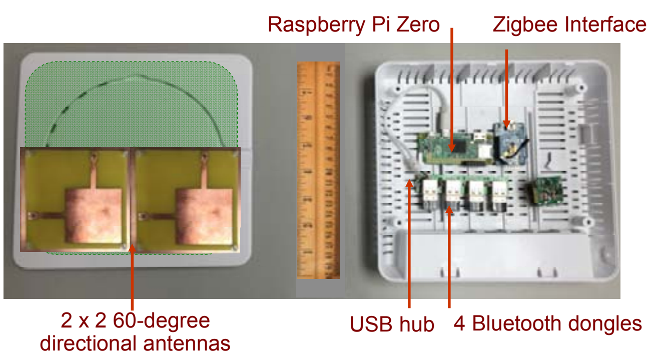
### B. *Structure of Basic Lbeacon*

Thus far, we have confined our attention to *basic Lbeacons.* Their sole function is to broadcast data on their own locations. Section V will present an extended version that is designed to be used as micro BeDI servers for timely delivery of fine-scale, location-specific data to mobile devices.

Fig 5(a) shows the block diagram of a basic Lbeacon. The device has a dual-mode Bluetooth module, a Zigbee network module, and applications that work with the BeDIS server for setup, initialization, maintenance and health monitoring purposes. Fig. 5(b) shows a photo of the current prototype. The platform is a Raspberry Pi Zero [62] running Linux operating system. The prototype has 4 Bluetooth dongles and four 60-degee antennas. It is intended for use in places where the ceiling is in the 3 to 5 meter range. The dashed rectangle in the left part of the photo represents two 30-degree antennas, which would be used if the beacon are used at places with tall ceilings (e.g., 20+ meters).




(a) Basic location beacons with dual-mode Bluetooth module




(b) A picture of basic location beacon prototype

Fig. 5 Location beacons with dual-mode Bluetooth module

The primary function of Lbeacon is provided by the Bluetooth Smart Ready (i.e., dual mode) module shown in the middle and right parts of Fig. 5. The prototype Lbeacons assumed only features of Bluetooth 4.0 [37], specifically, the coexistence of Bluetooth Lower-Energy (LE) and classic Bluetooth basic rate/enhanced data rate (BR/EDR) protocol stacks. Bluetooth LE is ideally suited for sending tens of bytes of data by the server (i.e., Lbeacons) to clients (i.e., mobile phones). As Fig. 5(a) shows, one pair of dongle and antenna is used for this purpose. Bluetooth LE only mode suffices for devices such as iBeacon [38] that do not aim to serve legacy devices. Today, a large number of feature phones and legacy Bluetooth devices remain in use, however. Being required to serve them as well, Lbeacon also has the BR/EDR protocol path shown in the bottom-right of Fig. 5(a). Two pairs of dongle and antenna are used in this protocol path. The remaining dongle and antenna pair is used for monitoring the health of the beacon. The next section will provide details on this capability.

As shown in Fig. 5, both LE transport and BR/EDR transport start from generic attribute and traditional profiles. The current Lbeacon prototype supports OPP (Object Push Profile), OTP (Object Transfer Profile), and OBEX (OBject EXchange) protocol [58, 59]. They enable the beacons to push location data illustrated by Fig. 1 to Bluetooth devices that also support these profiles. Future versions of Lbeacon will support profiles for positioning, location and navigation applications. The upper-right corner of the block diagram shows examples: As its name indicates, IPS (Indoor Positioning Service) enables the exposure of location information of mobile devices via advertising, and LNP (Location and Navigation Profile) enables the exposure of location and navigation-related sensor data by outdoor activity applications [59]. ILNP (Indoor Location and Navigation Profile) resembles LNP (Location and Navigation Profile), but is for indoor activity applications. It remains to be defined.

Before moving one, we note that the BeDIPS can be easily extended to support proximity marketing and other location based services. To illustrate this point, Fig. 4(a) shows that BeDIS server stores a mapping which associates each beacon with one or more URLs. A use scenario is that the server provides stores, offices, building managers, etc. with a tool using which they can enter URLs of web pages containing information (e.g., advertisements and announcements) specific to locations in 胡歌 the neighborhoods around the selected beacons. At initialization and update times, the URL's mapped to each beacon are also downloaded to the beacon. The URLs are also broadcast to users by the beacon along with its coordinates.

### C. *Response Time Assessment*

We note that each Bluetooth BR/EDR dongle can support connections to at most 7 clients simultaneously and that there may be 10 or more users in the area of approximately 15 square meters covered by a beacon offering 3-5 meter accuracy. So, multiple dongles are needed. The decision of using 2 dongles for the BR/EDR path is based on the measurement data from [63] on limitation of Bluetooth BR/EDR for pushing messages to devices discovered on the fly: The number of simultaneous connections reached is 7 for 1 dongle, 13 (out of 14 possible) for 2 dongles and 14 (out of 21 possible) for 3 dongles. In short, the gain from the third dongle is too small to warrants its use.

Rather than repeating measurements of the number of reachable Bluetooth Classic phones (i.e., feature phones) per dongle, we measured the delay (response time) experienced by users of feature phones in their effort to locate themselves as a function of the number of users under the coverage of a Lbeacon. The prototype Lbeacon used for the experiment is described in the top part of Fig. 6: It runs on a Raspberry Pi 2 under Linux operating system with BlueZ, the Linux Bluetooth protocol stack [64].

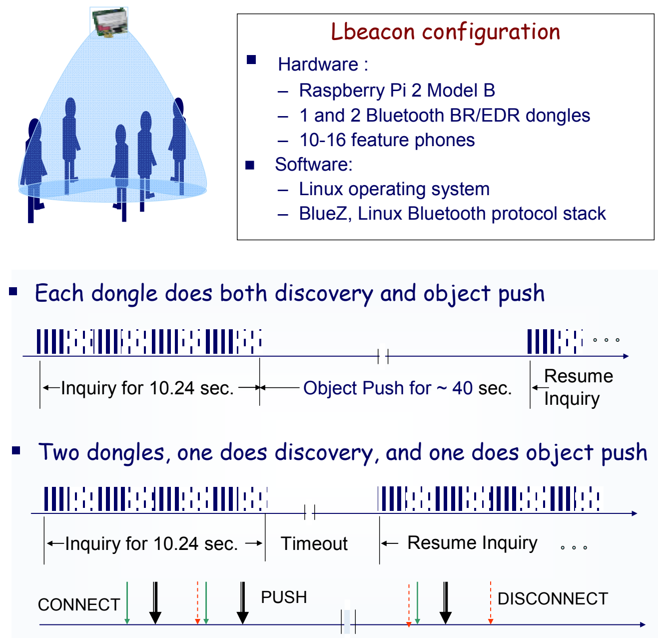



Fig. 6 Set ups for response time measurement

Fig. 6 also describes the two set ups:

- Functional identical dongles: Each BR/EDR dongle does both device discovery and object push as illustrated by the top timeline in Fig. 6. This is the configuration used in [63]. Once a connection with a client is established, the beacon may wait indefinitely until the client disconnects or moves out of the coverage area. Alternatively, the beacon maintains each connection for at most a specified length of time. It disconnects at the end of the interval, freeing it to connect with a new client. We refer the alternatives as no-timeout case and with-timeout case, respectively. The timeout interval is 20 seconds.
- Dedicated device discovery dongle: In this configuration of Lbeacon with multiple dongles, one of the dongles is dedicated to do device discovery. It does inquiry for 10.24 seconds, times out and resumes inquiry, and so on. The FHS (Frequent Hop Synchronization) packets of discovered devices are queued in a buffer. The second dongle (and other dongles if there are more than 2 dongles) uses the packets to connect to the devices and push location data. The activities of the dongles are illustrated by the two timelines in the bottom part of Fig. 6.

Fig. 7 plots the response time as a function of number of Bluetooth classic phones. By response time, we mean the delay in seconds experienced by a user of a feature phone from the instant when he/she turns on Bluetooth (or from when user with a Bluetooth enabled phone enters the beacon's coverage area) to the instant when the data pushed by the beacon is received by the phone. The small box in the upper left depicts the variation in response times among 10 phones used in the experiment when only one of them is under cover of the beacon at a time.

The solid line labeled A in Fig. 7 shows how the average response time increases with the number of phones in the coverage area when the Lbeacon used only one dongle for both device discovery and object push and there is no timeout: The average response time increases from less than 2 seconds to approximately 12 seconds as the number of phones increases to 7. As the number of phones in the coverage area continues to increase, the average response time eventually becomes longer than 40 seconds. As the upper time line in Fig. 6 shows, this is the length of time the dongle is used for object push. In other words, some of the phones have to wait for longer than a inquiry-push cycle before receiving data from the beacon.

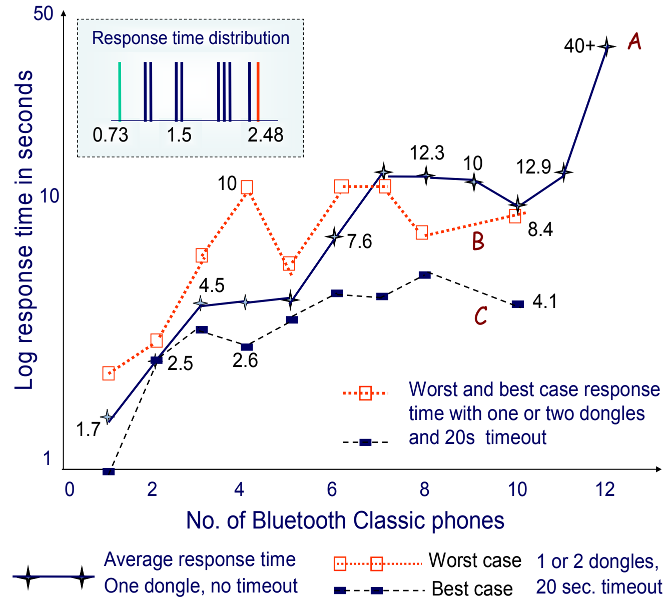



Fig. 7. Response time versus number of devices

The dotted and dashed lines labeled B and C in Fig. 7 depict the worst-case and best case response times, respectively, as a function of number of phones in the coverage area when two dongles are used, each for both inquiry and object push. Moreover, the beacon maintains each connection for at most 20 seconds. We expect that in this way, the average response can be kept under 12 seconds for 12 or fewer phones. This is the configuration used in the current Lbeacon prototype.

We also experimented with the configuration that uses one of the dongles to do nothing but device inquiry as illustrated by the bottom time line in Fig. 6. In an Lbeacon with 3 or more dongles, this configuration appears to be advantageous in reducing interferences among dongles. However, the measurement data show that dividing the work in device discovery and object push between two dongles this way offer no noticeable advantage in response time.

## V. Network Structure and Health Monitoring

Again, as Fig. 1 shows, Lbeacons serving each area in the building are connected by one or more Zigbee star networks. All the Zigbee networks are connected via gateways to the wireless local-area network (WLAN) and Internet within the building and the BeDIS server.

## A. Smart Gateways

Fig. 8 depicts the structure of BeDIS within a building and provides further details on Zigbee networks and gateways. As indicated by the left part of the figure, the system is connected to a messaging service that forwards emergency/disaster alerts from government alert/warning authorities and building safety systems. The next section will discuss components of the system, such as the CAP alert parsers and command generators within gateways, for location-specific responses to the alerts.

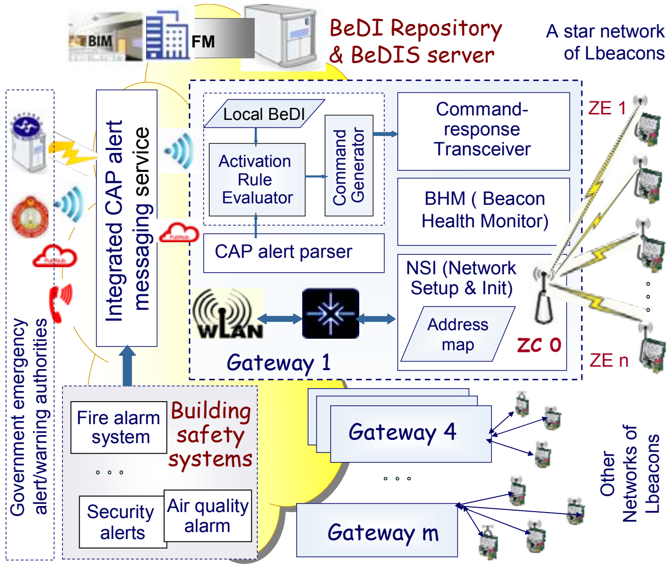



Fig. 8 Structure of BeDIS

The large rectangle in upper right half part of Fig. 8 encloses the components of a typical gateway: The network setup and initialization (NSI) module of the gateway contains the coordinator node (ZC) of a Zigbee star network. During initialization, the NSI module creates an address map. Each Lbeacon within line of sight and range of the coordinator sends to the coordinator (i.e., network address 0) a join request containing its 3D coordinates. In response, the coordinator assigns a 16-bit network address to the beacon and sends the address to the beacon. The NSI module then creates an entry in the address table, associating the address with the coordinates of the beacon. The module may get from the BeDIS server the barcode and location description of the each Lbeacon and maintain the information in the address map as the Lbeacon node joins the network. Lbeacons and gateways never sleep; so, this work is done only when the system powers up.

After initialization, the coordinator can address Lbeacons in the star network individually and identify the senders of packets from them. The former capability enables the gateway to support occasional transfers of data from the BeDIS server to individual beacons; we will return to discuss this function shortly. The latter enables the gateway to play a key role in health monitoring and self testing of the system.

## B. Self Test

One of the requirements of an IPS for a large building listed in Section I is that the health of the system can be assessed during runtime on a regular basis. In BeDIPS, this requirement is met collaboratively by Lbeacons and gateways. The health monitor and self test module in each gateway is for this purpose. Typically, the health of every Lbeacon is assessed once to few times a day. Each time, the test is initiated by a request for health report (RFHR) command broadcast by the BeDIS server to the beacon health monitor (BHM) of every gateway. Upon receiving the request, the BHM broadcasts its own request-for-health-report (RFHR) command to Lbeacons on the local star network. Every beacon is capable of testing for its own health (as shown in Fig. 5) and report the result to the BHM. After receiving reports from all beacons on the network, the BHM generates and sends to the BeDIS server a global health report, listing the ID and location of every defective or failed beacon thus identified. (The absence of a report from the Lbeacon within the timeout interval signals to the gateway that the beacon warrants attention.) The report is used as input on beacons needing repair by the facility management (FM) system of the building.

Within each Lbeacon, the RFHR command from the gateway triggers the self-test module into action: In the alpha version of Lbeacon, the self-test module generates its report based on whether any exception has been raised during execution of the object push code path since the previous report: For this purpose, the self-test module maintains an error message buffer to hold error messages generated by the exception and error handlers whenever any part of object push operation encounters error or throws an exception. When the self test module finds the error message buffer nonempty, it sends to the BHM of the gateway a health report packet containing the error type(s) (one byte) of messages found in the buffer, together with a control code (one byte) and beacon's 3D coordinates. The fact that the buffer is empty indicates that the Lbeacon has been and is in good health; the error type is NULL in that case. The self-test module empties the buffer, moving messages in it to a log file, and thus gets ready for the next RFHR from the gateway.

Clearly, the self test described above is not reliable, in particular, the health of send dongles is not assessed. In the beta version of Lbeacons, self test by 60-degree Lbeacons is done via receiver emulation. As Fig. 5(b) shows, such a beacon has four dongle/antenna pairs. Three pairs are used for broadcasting location data. The fourth dongle is used to emulate a receiver in the coverage area: During self test, the receive dongle is set to scannable. If its OBEX profile is not opened by one of the EDR senders (i.e., dongles in the BR/EDR path) within a timeout interval (presently set at 3 minutes), the senders are considered to have failed. The receive dongle is then set to receive from the BLE sender. The sender is considered healthy if it responds within 1 minute; it is considered to have failed otherwise.

Each 30-degree Lbeacon has only two dongle-antenna pairs and they are used for sending BLE and BR/EDR packets. The dongles can be dynamically configured in turn to emulate a receive dongle in order to determine the health of the other dongle. During the test, however, the beacon stops to broadcast either BLE or BR/EDR packets. We plan to assess the scheme experimentally and will use of the test in future versions if experimental data shows that the length of dead time (i.e., the length of time the beacon stops serving either BLE or BR/EDR devices) during the test is acceptably small. For now, complete end-to-end self tests of long-range, 30-degree Lbeacons can only be done manually by human testers.

## VI. BEDI MIST

As stated in Section I, BeDIS system can use Lbeacons to deliver to individual users instructions on emergency response at their locations. As examples, Fig. 9 shows instructions delivered to people at different places on the first floor of the Institute of Information Science (IIS) Building in response to an early earthquake alert. (The building is where this work is done, and the 3D model was generated from the BIM of the building.)

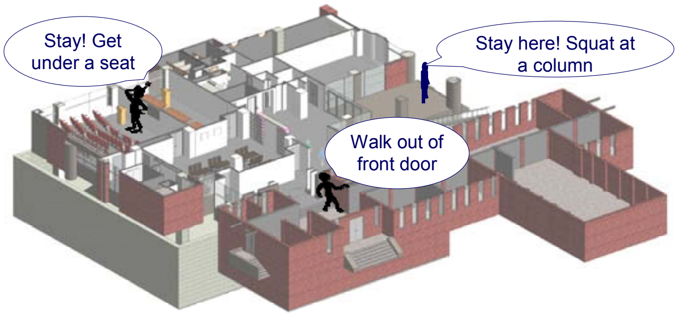



Fig. 9 Location-specific instructions in preparedness for a strong earthquake

### *A. Micro BeDI servers*

Fig. 10 shows the structure of an enhanced Lbeacon that is used as a micro server. Under the normal condition (i.e., when there is no emergency), it functions as a basic location beacon: It broadcasts its 3D coordinates and location description continuously, and tests itself on a regular basis. It switches to emergency mode when commanded to do so. In the emergency mode, it broadcasts via both LE and BR/EDR paths emergency response instructions and location descriptions alternately.

Similar to location description of each Lbeacon, emergency response instructions are also stored locally. As Fig.10 shows, the beacon holds multiple sets of instructions, one or more set for each types of emergency managed by the active emergency response system (AERS) of the building. During an emergency, which instruction(s) to broadcast and how often to broadcast the instruction(s) by each beacon are specified by the commands received by the beacon. Providing people instructions written by emergency response experts during preparedness phase is a way to ensure the quality of the instructions. Storing them locally ensures their timely delivery and reduce the reliance on the network. Each instruction is tens of bytes in length, there are tens of instructions for the area covered by each beacon, and there are order of tens of different emergency scenarios calling for different sets of instructions. The total memory space required for all possible instructions is in order of mega bytes to 10's of mega bytes. Such space demand can be easily met on modern platforms for beacon.

Another function of BeDIS is to provide active mobile devices and applications with data on the building and environment in the vicinities of the devices to support their decisions on risk reduction actions (e.g., shut the gas valves and open access controlled doors) in response to early alerts. The time available for delivery of the data ranges from a fraction of a second to minutes depending on the type of the emergency. This requirement dictates that the BeDI for the building be partitioned into subsets each for a small area covered by a few beacons and have the subsets stored on the beacons. Fig. 10 shows such location-specific subsets are stored on micro BeDI servers. The current prototype does not yet have this capability. Work remain to be done include the development of standard format for micro BeDI, since existing digital exchange standards (e.g., ifcXML[54]) are unsuitable for this purpose

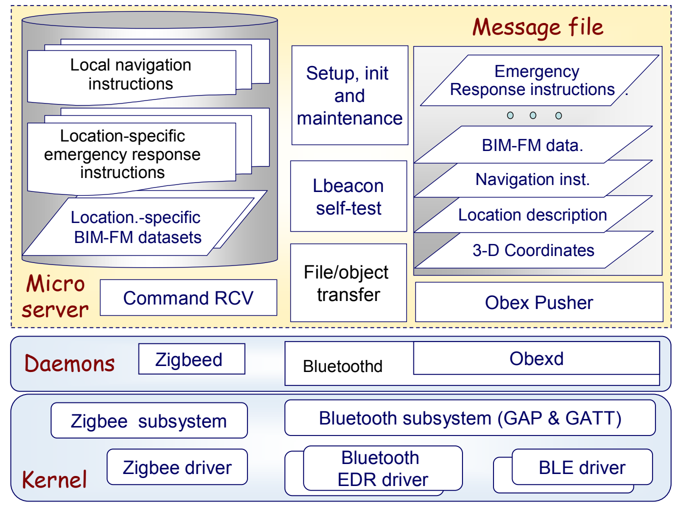



Fig. 10 Structure of Micro BeDI server

### *B. Distributed Command Generation*

Rather than relying on BeDIS server solely to command all the micro servers during emergencies, the decision on what emergency instructions and BeDI to broadcast and when to broadcast them is off loaded to smart gateways. Fig. 8 shows the components used to support such decisions.

As one can see, alert messages are pushed by the messaging service of the AERS to all the gateways, as well as active embedded devices (e.g., elevator controller, gas valves) in the system. Each gateway is equipped with a CAP message parser. Upon receiving an alert message, the parser extract from it the emergency event type, the severity of the event, affected area, and so on [43]. A rule engine, called activation rule evaluator in Fig. 8, determines from the alert parameters and local BeDI whether and what response actions should be taken. The command generator issues commands to all Lbeacons in the area according to the result of evaluation. The parser, rule engine and response action activation rules are key elements of all iGaDs; details on them can be found in [41, 47].

## VII. SUMMARY AND FUTURE WORK

The previous sections described two components of the IT infrastructure that supports location-specific decisions of active devices and applications. These devices and applications can process early disaster/emergency alerts in CAP format from authorized senders and automatically choose and take timely, location-specific actions (or instruct their human users to do so) to reduce the risks of injuries and damages during disasters.

The infrastructure components are BeDIPS and BeDI mist. BeDIPS, an indoor positioning system. Its distinguishing features of BeDIPS include that it remains scalable in the presence of massive surges in crowd density, does not require Internet, degrades gracefully, and can automatically assess its own health on a regular basis. BeDIPS uses location beacons (Lbeacons) to deliver their own 3D coordinates and location descriptions via both BLE and BR/EDR paths to common smart and classic Bluetooth devices. The inclusion of the textual description of each beacon's location eliminates the need for having a pre-installed application and indoor maps on user devices. The accuracy of the 3D coordinate from each beacon is determined by the largest width of its coverage area, typically, in order of 3-5 meter or 5-10 meters. It is sufficiently accurate to be used as input to location/navigation applications running on smart phones. Also, the longitude and latitude data can be used to define waypoints in routes of autonomous devices that move in the building under control of onboard navigation and object avoidance applications.

The design and installation of BeDIPS would not be feasible without the building/environment data and information (BeDI) repository and the open source development tools. The repository holds a subset of data in the BIM/FM database of the building, and tools exploit the data to support the selection of beacon locations for good coverage and pinning down their locations physically during installation.

Location specificity of active devices and applications requires fine-scale, location-specific BeDI on the relevant attributes of the building and objects in the immediate vicinities of the devices. Depending on the type of disaster/emergency, the available time for delivering the data to thousands of devices ranges from a fraction of a second to minutes. The BeDI Mist achieves the scalability and responsiveness of data delivery by making use of micro (BeDI) servers and smart gateways. Micro servers are enhanced Lbeacons with space for storing locally fine-scale location-specific subsets of BeDI and emergency response instructions, and the capability of responding to commands from smart gateways to broadcast BeDI and emergency response instructions.

Our work to date has been concerned primarily with proving the concept of BeDIPS and BeDI mist. Prototype BeDIPS containing a small number of location beacons have been demonstrated within the Institute of Information Science Building during the annual open house in the past two years when the building was filled by hundreds to visitors. The next step is to assess the usability and effectiveness of the system in real-life operating conditions in large public buildings heavily used by the general public. In this effort, we collaborate with several organizations that operate and manage large public buildings, including a security company that provides FM and surveillance services and a major university hospital. The work of generating BIM and BeDI of many of their buildings have demonstrated without doubt that BeDI can be generated from blueprints with acceptably low cost even for buildings

Proof-of-concept prototypes of micro BeDI server and smart gateway are now available. Thorough experimentation to assess their responsiveness remains to be done. A substantial part of the work for proving the concept of BeDI mist also remains to be done, including the development of standard format(s) for BeDI sent from micro servers to active mobile applications.

BeDIS is a system of smart things: The statement "no dependability, no IoTs" [64] applies to it. In particular, security and safety are of critical importance. Our future work in this direction includes the development and use of the AERS simulation framework [65] for assessment of safety of the system. Providing the system with the capability to operating in the secure mode will also be a major thrust of our effort.

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**Jake C.C. Li** received his B.S. degree in 2014 and M.S. degree in 2016, both in computer science from Tunghai University in Taiwan. Since 2016, he has been a Research Assistant in Institute of Information Science, Academia Sinica, Taiwan. His research interests includes the sensor networks, Internet of Things, embedded systems and computer security

**Johnson Su** received the B. S. degree in information management in 2010 and M. S. degree in electronic commerce from Taipei City University of Science and Technology. Since 2016, he is a Research Assistant in the Institute of Information Science, Academia Sinica, Taiwan, where he worked on smart devices and mobile applications for disaster preparedness and responses. His research interests include network systems and services.

**E. T.-H. Chu (M'11)** received his Ph.D. degree in computer science in 2010 from the Department of Computer Science at National Tsing Hua University,Hsinchu, Taiwan. He has more than 4 years work experience in the industry, where he worked on embedded software and owns a Chinese patent. He was a visiting scholar at Purdue University in 2009. He joined the Department of Electronic and Computer Science Information Engineering at National Yunlin University of Science and Technology, Taiwan, as an assistant professor in 2010.The areas of his research interests include low-power embedded systems and real-time operating systems.

**J. W. S. Liu (F'95)** received her B.S. degree in electrical engineering from Cleveland State University in 1959 and her Sc.D. in electrical engineering in 1968 from Massachusetts Institute of Technology. She is a distinguished visiting research fellow at the Institute of Information Science, Academia Sinica, Taiwan. She was an architect in the OS Base Core Technology Group of Microsoft Corporation from 2000 to 2004. Before joining Microsoft, she was a faculty member of the Computer Science Department at the University of Illinois at Urbana-Champaign from 1972 to 2000. Her research interests include real-time and embedded systems, technologies for building user-centric automation and assistive devices and ICT technologies for disaster preparedness and response.