中央研究院
資訊科學研究所
Institute of Information Science, Academia Sinica • Taipei, Taiwan, ROC

TR-IIS-18-002

Building/environment Data/information System for Fine-Scale Indoor Location Specific Services

C.C. Li, H. Wang, J. W. S. Liu, C. J. Wu, E. T. H. Chu

Mar. 1, 2018 || Technical Report No. TR-IIS-18-002

http://www.iis.sinica.edu.tw/page/library/TechReport/tr2018/tr18.html

Institute of Information Science, Academia Sinica
Technical Report TR-IIS-18-002

Building/environment Data/information System for Fine-Scale Indoor Location Specific Services

C.C. Li, H. Wang, J. W. S. Liu
Institute of Information Science
Academia Sinica
Taipei, Taiwan

C. J. Wu
Department of Computer Science
National Tsing-Hua Univ.
Hsin Chu, Taiwan

E. T. H. Chu
Dept of Comp. Sc. & Inf. Eng.
Nat. Yunlin Univ. of Sc. & Tech
Yunlin, Taiwan

Abstract and Keywords

This report describes a building/environment data and information system, called BeDIS for short. It is designed to support fine-scale, location specific services by smart devices and mobile applications for people in large smart buildings. Structured as a fog/mist, the system is scalable and responsive under overload; can function without Internet, WiFi and cell connections; and degrades gracefully when parts of it are damaged. During normal times, it enables hundreds and thousands of people to locate themselves sufficiently accurately and navigate amidst dense crowd and moving objects in the building via their mobile phones. When triggered by a disaster/emergency alert from responsible government agencies or the building safety system, BeDIS functions as a system of micro data servers for delivering location- and situation-specific emergency response instructions to people and attributes of the building, interior layout and objects in their immediate vicinities to support the choices of response actions of active devices and applications within fractions of a second to seconds. This paper describes its fog/mist structure, design and implementation.

Keywords –Location specificity, Data mist, Indoor positioning and navigation, Location beacon, Active emergency response

An 8-page version of this report will appear in Proc. of the 2nd IEEE Int.Conf. on Edge and Fog Computing (ICFEC 18)
May 1-3, 2018 in Washington DC

Building/environment Data/information System for Fine-Scale Indoor Location Specific Services

C.C. Li
Institute of Information Science
Academia Sinica
Taipei, Taiwan
jakelee@iis.sinica.edu.tw

C. J. Wu
Department of Computer ScienceNational Tsing-Hua Univ.
Hsin Chu, Taiwan
philwu576@gmail.com

H. Wang
Institute of Information Scienc
Academia Sinica
Taipei, Taiwan
hollywang@iis.sinica.edu.tw

E. T. H. Chu
Dept of Comp. Sc. & Inf. Eng.
Nat. Yunlin Univ. of Sc. & Tech
Yunlin, Taiwan
Edwardchu@yuntech.edu.tw

J. W. S. Liu
Institute of Information Science
Academia Sinica
Taipei, Taiwan
janeliu@iis.sinica.edu.tw

***Abstract*—This paper describes a building/environment data and information system, called BeDIS for short. It is designed to support fine-scale, location specific services by smart devices and mobile applications for people in large smart buildings. Structured as a fog/mist, the system is scalable and responsive under overload; can function without Internet, WiFi and cell connections; and degrades gracefully when parts of it are damaged. During normal times, it enables hundreds and thousands of people to locate themselves sufficiently accurately and navigate amidst dense crowd and moving objects in the building via their mobile phones. When triggered by a disaster/emergency alert from responsible government agencies or the building safety system, BeDIS functions as a system of micro data servers for delivering location- and situation-specific emergency response instructions to people and attributes of the building, interior layout and objects in their immediate vicinities to support the choices of response actions of active devices and applications within fractions of a second to seconds. This paper describes its fog/mist structure, design and implementation.**

Keywords—Location specificity, Data mist, Indoor positioning and navigation, Location beacon, Active emergency response

I. Introduction

In recent years, increasing adoption of technologies in areas such as Internet of Things (IoT), sensor networks, and home and building automation has made our buildings and cities much smarter than a decade ago. As examples, automatic lighting and smart heating/cooling controls are now common place in modern buildings, and surveillance cameras, fire/smoke detectors and toxic air alarms in building security and safety systems have made our living environment safer.

Nevertheless, many essential indoor location-based services are still not available today. As an example, today, a typical person spends a considerable amount of time in large public buildings including transport hubs, large department stores and major hospitals. During rush hours and on special occasions, such buildings are likely to be crowded, and people and objects may block views of pathways, direction signs and exits. Scalable and responsive indoor positioning services (IPS) that can help people locate/navigate themselves and find friends within a few meters in crowds can significantly improve their experiences in such buildings. Yet, with rare exception, even the most modern large public buildings still do not offer such services. More seriously, when one makes an emergency call indoors using a mobile phone, the location accuracy timeline published by USA FCC says that until year 2020, the error in his/her horizontal location can be as large as 50 meters [1]. That is half a football field long [1]!

This work was supported in part by Taiwan, Academia Sinica, Sustainability Science Research Program Project DRBoaST (Disaster Resilience through Big Open Data and Smart Things).

A. *Design Goals and Functionalities*

This observation motivated the building/environment data and information (BeDI) system [2]. Called BeDIS for short hereafter, the system intends to be a part of information technology (IT) infrastructure needed to support indoor location specific decisions and actions of smart devices, mobile applications and people in general and in large public buildings in particular. This is illustrated by Fig. 1, which shows the structure of BeDIS, its relationship with sources that provide it with data and information, and examples of services and applications it is designed to support.

As one can see from Fig. 1, the system has two major components: *BeDIPS* and *BeDI Mist*. The former is a BeDI-based indoor positioning system [2][3] for large public buildings. It is designed to deliver to Bluetooth enabled devices the 3-D coordinates and a brief textual description of its own location. The vertical location is in terms of the floor/level on which the receiving device is, and is error free. Horizontal location accuracy can be configured to range from 3-5 meters to 6-10 meters, or at room-level. This accuracy is sufficient when the coordinates provided by the system at selected locations are used as waypoints in navigation graphs used by navigators exemplified by the one shown in bottom left of the Fig. 1; Section IV will describe such a navigator. When the location data are used for waypoints on routes of automatic guided vehicles (e.g., delivery robots), however, on-board control, guidance, navigation and object avoidance capabilities are needed for improved accuracy.

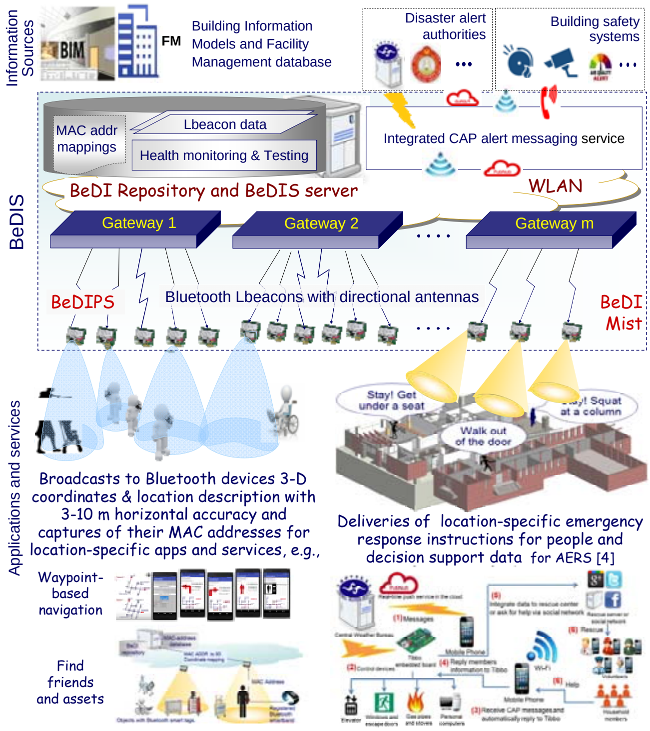

Fig. 1. Architecture, components and functionalities of BeDIS

The primary function of the BeDI mist is to deliver fine-scale (e.g., 3-10 m), location-specific data on attributes of the building, interior layouts, facilities and objects of interest to active, smart devices and mobile applications pervasively deployed in the building. Active smart devices and applications [4] are also called iGaDs (intelligent guards against disasters) [5]. They can automatically process disaster alerts encoded in the international standard CAP (Common Alert Protocol [6]) format and disseminated by authorized senders and then in response, take risk reduction actions. (For example, in response to an alert of an observed strong earthquake, they shut the gas valves and heating equipment, bring elevators to the nearest floor and open access-controlled doors before the ground shaking starts. Active mobile applications deliver location-specific instructions to users to help them stay out of harm's way at their locations as illustrated by Fig. 1.)

iGaDS and active emergency response systems (AERS) [4] [5] containing them were proposed as a means to enhance disaster preparedness of our homes, workplaces and living environment. To be effective, when choosing whether to respond to an alert and what action(s) to take in response, each iGaD must take into account not only parameters (e.g., severity) of the disaster specified by the alert, but also attributes of the building and interior and characteristics and conditions of the facilities and other objects in its immediate vicinity. Structured as a fog/mist [7][8], BeDI mist is designed to deliver such location-specific decision support data and information needed by iGaDs when triggered by a CAP alert from an authorized sender or building safety system. The relative deadline (i.e., the allowed response time) for delivery of the data depend on the type of the emergency, ranging from fractions of a second to seconds in case of earthquake and fire alerts, tens of seconds to minutes in case of flash flood and tsunamis, and tens of minutes in case of tornados and typhoons.

B. Location beacons (Lbeacons)

As Fig. 1 shows, both BeDIPS and BeDI mist use *location beacons* (or *Lbeacons* for short) to deliver data. Lbeacons are low-cost Bluetooth smart ready devices [9] pervasively installed throughout the building. Lbeacons in each area of the building are connected via one or more Zigbee star networks for set up, initialization, and health monitoring purposes, They in turn are connected via gateways to the wireless local-area networks and Internet within the building and the BeDIS server. After initialization, each Lbeacon stores locally the 3-D coordinates and a brief description of its own location, as well as other location-specific data it is responsible for delivery. Consequently, it can operate independently during runtime.

One can see from Fig. 1 that BeDIS is so named because of its reliance on data in the Building Information Model (BIM) and facility management (FM) database of the building [10][11]. BIM are files that give a complete digital representation of functional, physical and geometrical characteristics and relevant attributes of the building and objects of interest in it. BIM/FM database integrates dynamic information on facilities and equipments with BIM to provide the necessary support for facility management and building operation and maintenance [12-14]. In recent years, BIM and lightweight data exchange standards (e.g., [15]) have been adopted by AEC (Architecture, Engineering, and Construction) industries in an increasingly larger part of the world [16]. Buildings constructed before the wide adoption of BIM are documented by blueprints. Our experience through case studies reported in [17] show that with the help of modern software tools such as Autodesk Revit [18], blueprints can be translated into BIM at an acceptably low cost.

For these reasons, BeDIS is built on the assumption that every public building of some specified size or larger has a BIM/FM database. The building and environment data and information (BeDI) repository in Fig. 1 is a physical or virtual repository that provides access to datasets selected from the BIM/FM database. The selected datasets contain at least 2D-3D geometric models of the building components (including stairwells, corridors, and so on) and objects such as ceilings, walls, etc. on which hardware components of BeDIS (e.g., Lbeacons and gateways) are installed.

C. Contributions and Organization

This paper is an extension of our previous paper [2]. Its contribution includes the fog computing architecture and network structure of the proposed BeDI mist. As mentioned earlier, some or all Lbeacons can function as micro data servers. When commanded to do so in response to CAP alerts and during emergencies, 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 in response. This paper describes the functionalities of the micro data servers, smart gateways and the BeDIS server that turns BeDI repository from a cloud into a fog or a mist for sake of scalability and responsiveness.

Other contributions of this paper include waypoint-based indoor navigation for Bluetooth Low-Energy (BLE) enabled mobile devices. In a building served by a BeDIPS, waypoints [19] in navigation graphs [20] are marked by Lbeacons. As Section IV will show, navigation graphs can be incrementally downloaded. Given the fact that there is yet no widely adopted indoor positioning standard, it would be good if one's navigator can work with multiple indoor positioning systems. Waypoint navigation is a way to accomplish this goal.

Bottom left part of Fig. 1 illustrates the use of BeDIPS for locating and tracking MAC addresses of Bluetooth devices under its coverage. This capability can be exploited for services such as tracking people with special needs wearing smart bracelets, finding family members and friends in crowds, locating equipment with Bluetooth tags and estimating crowd sizes during exhibitions, etc. The BeDIS components for these purposes are also contribution of this work.

Following this introduction, Section II presents related work. To make the paper more self contained, the section also presents briefly the requirements of BeDIS for large public buildings and reasons for the inabilities of IPS based on state-of-the-art technologies to meet the requirements. Section III describes the structure and implementation of Lbeacons. Section IV describes the design and implementation of waypoint-based system for navigation anywhere in general and a navigator for use in buildings with Lbeacons. Section V describes the fog/mist architecture of BeDIS, specifically, the design and structure of micro data servers and smart gateways and their collaborations with BeDIS server in command generation. Section VI discusses the work by Lbeacons and gateways during configuration and initialization and health monitoring and self testing of the system. Section VI summarizes the paper and presents future work.

II. Background and Related Work

For years now, indoor positioning and navigation has been a highly contested arena filled with big companies and startups [21]-[23] aiming to be leaders. It has also been an active research area with results on hardware, methods and tools reported by numerous surveys and comparative studies (e.g., [24] - [29]) and technical articles (e.g., [30]-[45]). Still, none of the existing technologies have become widely accepted standards, and there are few if any large scale deployments of IPS servicing general public in large buildings even in technologically advanced regions of the world. Similarly, location specific mobile services down to scales of a meter to a few meters indoors are still scarce.

Such slow progress is likely due to the fact that any IPS for large public buildings must have all the attributes described below as a requirement. This section first presents the required attributes and then a brief overview of state-of-the-art indoor positioning technologies and why systems built on these technologies cannot meet the requirement. In contrast, both BeDIPS and BeDI mist have these attributes as it will become evident shortly in this and subsequent sections.

A. Requirements of IPS and BeDI mist

First of all, any system must have acceptable performance. The performance of an IPS is usually measured in terms of location accuracy. According to USA government, horizontal accuracy of civilian GPS is 3-7.8 m with 95% confidence. For general public indoors, horizontal error within 3-5 m is considered highly accurate, and 6-10 m is acceptable [21], but the system must never misinform the user which floor he/she is on. The performance of a BeDI mist is measured in terms of the relative deadline (i.e., the maximum response time), which ranges from a fraction of a second to minutes for delivery of location specific data to mobile and embedded devices.

Second, the system must be scalable, responsive and resilient: Even when the number and density of people (and hence the workload) surge by orders of magnitude, as it will surely happen everyday and on special occasions in buildings of the types considered here, performance deterioration of the system must remain tolerably small. Except for during setup, initialization and periodic self-testing, the system can operate without the help of Internet, WiFi and cell connections. When parts of the system are damaged, the remaining part can continue to deliver location data. Moreover, the system should be able to assess its own health automatically during operation.

Third, the system must be easy to configure, customize, install and maintain. During remodeling and renovation, updates of the system can be made systematically and easily. In case of BeDIS, the development environment described in [2] eases the tasks of deciding where to place Lbeacons and installing them at their chosen locations. The exact location of each Lbeacon given by its 3-D coordinates is maintained in the BeDI repository. Every beacon is surely mounted on an object that is characterized by data in some datasets in the BIM. Its coordinates are kept up to date during remodeling, renovation and maintenance processes as the BIM datasets on the model of the object are updated during the processes.

Lastly and most importantly, user device capabilities required to access the system are minimal: BeDIPS can serve not only Bluetooth Low Energy (BLE) enabled smart phones but also feature phones equipped with only Bluetooth BR/EDR protocol stack [9] and OBEX (OBject Exchange) protocol [46]. They all can receive from the system the coordinates and text description of the user's location. Indoor maps while desirable are not necessary. The navigator described in Section IV is made to be platform independent as much as possible and does not require an indoor map.

B. Indoor Positioning Technologies

Many techniques proposed in recent years can provide location accuracy significantly better 3-10 meters. Examples include some of the winners of Microsoft Indoor Location Competitions in years 2015-2017 [29]. Some of them use non-standard signal(s), and others use sophisticated measurements, however. The requirement that the service can be accessed via common mobile devices prevents their use in large public buildings. Clearly, systems that use light signals (e.g., [30]) do not work during fire emergencies.

1) Range-based and fingerprint-based systems

Today, the majority of indoor positioning systems in use are range based, or fingerprint based, or both using WiFi, FM and Bluetooth signals. The required 3 to 10 meter horizontal accuracy is achievable by pure range-based, triangulation systems. Such systems require only an application computing triangulations on smart mobile devices the location of the device based on received signal strength (RSS) 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 and measuring additional parameters of the signals (e.g., time of arrival as reported in [30]). A serious disadvantage of such systems is that 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 and create blind spots in coverage. This is why their location accuracy is more likely to be in 20 meter range [47] in large public buildings full of people, and their room accuracy can be less than 50% [28].

Fingerprinting is another commonly used approach to indoor positioning. A fingerprint is a set of location-specific values of received signal strengths (i.e. a signal pattern). Types of fingerprints used for indoor positioning include patterns of WiFi and Bluetooth 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 [33] - [41]. A fingerprint-based IPS has a server which maintains a database of fingerprint-to-location mappings. A common way for a mobile device to determine its own location is to send the fingerprint captured by it at its location to the server and rely on the server to find the location(s) with a matching fingerprint. Better location accuracy is an advantage of fingerprint-based systems compared with range-based systems. (According the evaluation study of IPS in healthcare environments reported in [28], room level accuracy of WiFi and Bluetooth fingerprint-based systems are 96 and 76 %, respectively, while the accuracies of corresponding triangulation systems are 47 and 61 %.) Because of their reliance on Internet and the fingerprint server, such systems have longer response time, do not scale, and do not degrade gracefully.

An alternative way is to have mobile devices download the fingerprint-location mappings so that they can determine their own locations. The obvious disadvantage is the space required to store the mappings and energy consumed to search the mappings locally. Requiring user devices capable of capturing and storing fingerprints is another disadvantage of such IPS. Fingerprint-to-location mappings are captured at different locations in the building during setup and maintenance times, leading to high setup and maintenance cost.

2) Proximity-Based Systems

Based on available performance data (e.g., data from [28]], proximity detection systems offer a good solution for indoor positioning in large public buildings. In addition to being less expensive to deploy 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).

As stated in Section I, BeDIS uses Lbeacons to deliver data to Bluetooth enabled devices. Each Lbeacon broadcasts to devices coming within its coverage area, which by design is made small. Hence, BeDIPS is similar to proximity detection systems (e.g., [45]): Existing IPS based on proximity detection may use of radio tags and Bluetooth low-energy beacons such as iBeacons [48] from Apple Inc. and Eddystone [49] from Google. iBeacon, Eddystones and other Bluetooth proximity marketing products (e.g., [50][51]) 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 its own 3-D coordinates and location descriptions.

C. Fog Computing

BeDIS is a system of smart things that is a structured as a fog [7], [8]. As it will become evident from the discussions in the later sections, the processing, storage and communication demands of BeDIS are relatively low compared with resource demands of many Internet of Things and cyber-physical systems for smart homes, buildings and environment.

The major challenges of BeDIS arise from the fact that it needs to deliver to a vast number of embedded and mobile devices, time-critical location specific data. The geometric scale can be as small as few square meters, and the relative deadlines can be as short as fractions of a second to seconds. These requirements are met most naturally by adopting fog computing architecture. Indeed, many IoT applications, from smart lighting to smart traffic lights to power restoration of smart grid, require low latency, location awareness and use of wireless access.

Since fog and mist computing was introduced by Cisco, consensus on benefits and challenges of fog as an architecture for diverse IoT applications has grown increasingly wider (e.g., [52]-[54]). Efforts by OpenFog Consortium and similar groups (e.g., Open Connectivity Foundation) are now molding system level fog architecture (e.g., [55]), identifying security risks and requirements of fogs and proposing approaches to address them (e.g., [56]), and developing testbed framework [57] and regional testbeds (e.g., [58]) to support experimentation, assessment and validation of fog platform and applications in general and individual aspects (e.g., security) specifically. We will leverage the results of these efforts to address some of our critical problems. Examples include security of BeDIS and interfaces among its components and with external smart environment and building safety systems.

III. Structure of Lbeacons

Fig. 2 shows the structure of Lbeacons. The data delivered by each Lbeacon are downloaded during initialization and configuration and stored locally afterwards. During normal times, it continuously broadcasts the 3-D coordinates and description of its own location. During emergencies, it can be commanded by its local gateway to broadcast location-specific emergency response instructions or building and environment data in addition to (or instead of) location data. The Lbeacon logs all errors and exceptions during its operation. The content of the log will be used for system health monitoring purposes in ways to be described in Section V.

The primary users of BeDIPS part of the system are people in buildings. The devices they use to access the IPS are mobile phones. Even today, over 45% of phones in use are feature phones and the percentage will still be around 25% in 2020 [55]. To serve these phones as well as smart phones, Lbeacons send location data via both BLE and BR/EDR protocol paths. The vertical coordinate provided to a user is the floor/level where the user is. That is, the vertical coordinate are expressed as B8, G, 1, 2 …, 101 and so on. The horizontal coordinates broadcast by every Lbeacon is its own latitude and longitude relative to the southwest corner of the building. So, the horizontal coordinates of any point within a building down to centimeter accuracy can be specified using 8 bytes each. Lbeacons deliver their location data to phones via the EDR/BR data path according to OBEX protocol [46], with packet size more than sufficient to accommodate location data and description. The protocol being widely supported, most phones can display the brief textual descriptions such as "Level 8, RM 807". 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. An alternative is to broadcast data using connectable advertising with 62 bytes of payload. This option is used by micro data server to send decision support data.

Except for rare exceptions, Lbeacons are installed on ceilings. The required location accuracy is achieved by providing them with directional antennas and adjusting their ranges and beam widths, thus, the shapes of their coverage areas. Typically, a complex building requires several types of beacons. All Lbeacons have directional antennas with conical beams, but different types differ in ranges and angles. For example, Lbeacons with 3 meters range and 60-degree radiation pattern can achieve 3-5 meter horizontal accuracy in a typical room. Zero vertical error is achieved by making the range of all beacons in the room less than the ceiling height. Beacons with larger ranges for places with tall ceilings need to use antennas with narrower (e.g., 30 degree) radiation patterns to achieve the same accuracy.

In the process of pushing data to mobile devices as they pass through its coverage area, each Lbeacon acquires the MAC addresses of the devices that are in discoverable mode and tags each acquired address with time stamps marking the start and end of each time interval during which the device with that MAC address stays under the Lbeacon. Time-stamped MAC addresses are saved locally. The Lbeacon uploads this data to the BeDIS server when it is polled. This data enables BeDIS to support location-based and personalized services as illustrated by Fig. 3.

Fig. 4 shows a picture of the current version of Lbeacon and its interior. It has been used for demos and assessment purposes. This type is for areas with 3-6 m ceilings. It has four 60 degree antennas and dongle pairs. (For illustration purpose, the dotted square in the left part of the picture is the outline of two 30 degree antennas.) In the performance study reported in [2], two dongles were used for pushing location data to Bluetooth BR/EDR devices and one dongle for broadcast to BLE devices. One dongle was used for health monitoring.

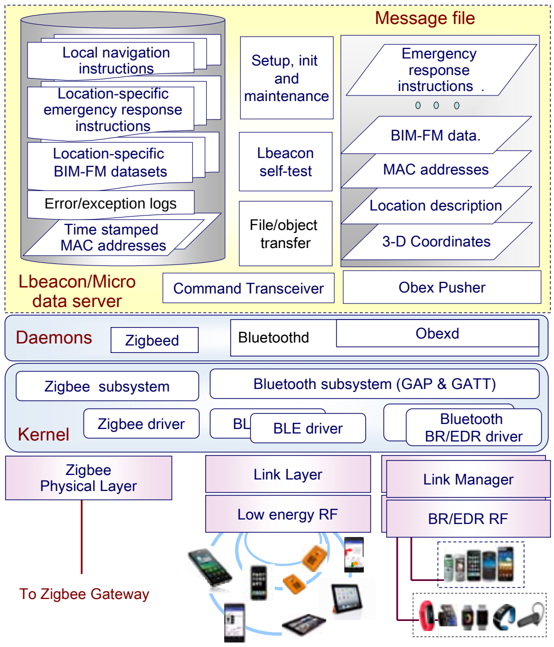

Fig. 2. Structure of Lbeacons

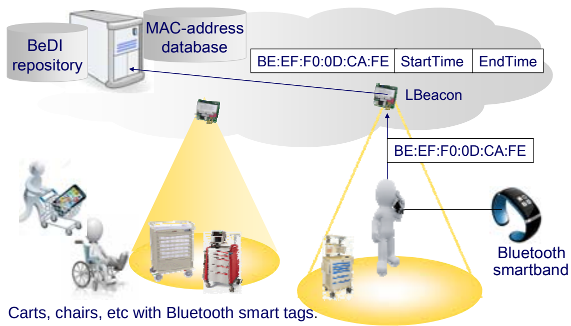

Fig. 3. Infrastructure for tracking applications

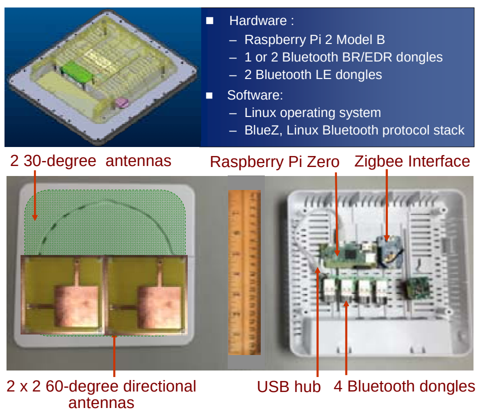

Fig. 4. Picture of a Lbeacon with 4 60-degree antennas

IV. Waypoint-Based Navigation with Lbeacons

According to Webster dictionary, a *waypoint* is an intermediate point at a known location on a route of travel. Oxford dictionary further emphasizes that the coordinates of waypoints have been generated by a computer. The routes from any source and destination used by a *waypoint-based navigator* are made up of segments connected by waypoints.

A. *Navigation and Region Graphs*

More formally, the nodes in the *navigation graph* used by indoor waypoint-based navigators for people are waypoints at selected locations in the building. As pointed out in [20], the nodes, and hence waypoints, reflect functions and locations of human navigation process: Each node is located at a possible source or destination, or a place where a human is likely to require a decision or assurance, and so on. Edges between two waypoints are possible paths from one node to the other traversable by people on foot, on wheelchair, etc. As examples, each path between two waypoints may be along a corridor, in the middle of an open space, via an escalator or elevator, and so on. Ideally, the path is along the line of sight between the waypoints at the ends of the path.

When given by the user a source and destination pair, constraints and preferences (e.g., use stairs and easy-to-follow route), a typical navigator selects a route based on the given navigation graph and then guide the user step by step as he/she traverses the route. When the navigator is waypoint based, it provides directives and/assurances at each waypoint. In a building serviced by a BeDIS, there is a Lbeacon at each waypoint. It broadcast the UID and coordinates of the waypoint to navigators as they pass by. Such waypoints are said to be *active.* Active waypoints make the implementation of navigators simpler as there is no need for the application to monitor their own positions. In contrast, navigators relying on triangulation and fingerprint-based systems must look up or compute its own position during travel to determine whether it has reached the next waypoint. So, waypoints supported by such systems are said to be *passive.*

Fig. 5 shows an example. The graph is that of a corner of a building of a university hospital. The corner houses the registration, the pharmacy, several labs (e.g., the lab for blood test) and physicians' offices. The figure lists the meanings of common types of nodes in the graph. One can see that in addition to nodes that represent possible sources and destinations of travel, the graph also has nodes for use by the navigator to generate and deliver directions (e.g., "turn left here") and assurances (e.g., "continue in this direction for 7 meters" and "you should see the stairs at this point") to the user.

To facilitate incremental download of the navigation graph by navigators, the entire area of the building is partitioned conceptually into disjoint regions, and the navigation graph is partitioned into subgraphs accordingly: Here, the term *region* refers to an area on a single floor. The navigation graph is structured hierarchically with two levels. At the lower level, each region has a navigation subgraph representing the waypoints in the region and possible paths linking them, as illustrated by Fig. 5. The top level graph is called the *region graph.* Nodes in it are regions. The attributes of each region node include the list of all possible sources and destinations in the region, their access information (e.g., whether accessible by general public) and other data a navigator needs to compute routes for different users. Edges connecting two region nodes represent possible ways to go between them. In the example in Fig. 5, the region subgraph containing nodes Region 1 and Region 2 should have two edges: They represent the Stair 2 and Elevator 10.

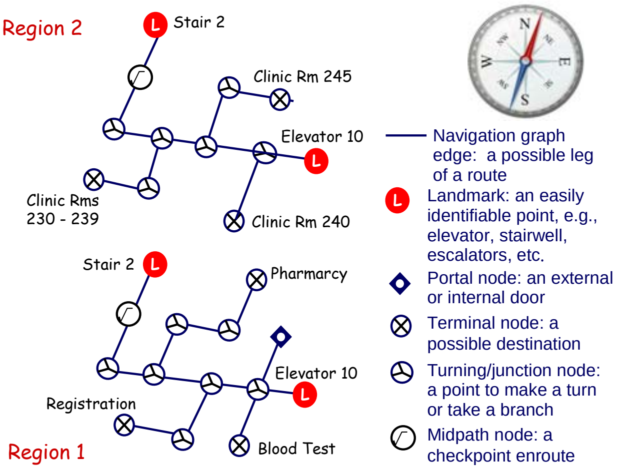

Fig. 5. An example of navigation graph

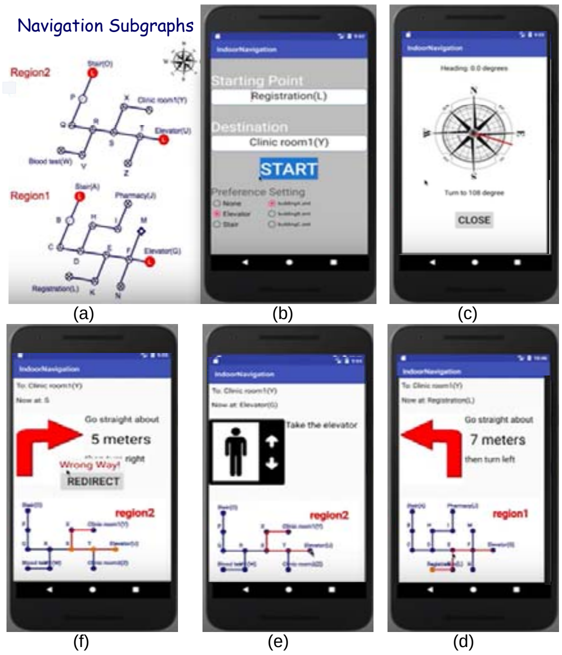

Fig. 6. Screen shots of waypoint-based navigator

B. *A Waypoint-Based Navigator*

Fig. 6 shows the screen shots of a waypoint-based navigator that run with the support of BeDIPS. The application runs on Android phones and is implemented in Java. The use scenario assumes that a new user can download the navigation graph of the building upon entering the building. In the first step, only the region graph is downloaded, thus enabling the user to select his/her source and destination and reducing the time the navigator needs to plan a route. Then the navigation subgraph of the region containing the source node is downloaded followed by that of the next region on the route, and so on.

Again, there is a Lbeacon at each waypoint. The source and destination selected by the user are in Region 1 and Region 2, and the user prefers to use stairs as shown part (b). So, immediately after the user's selection, the navigation subgraphs of the regions are downloaded to user's phone, as shown in part (a). At the start and each time when the user may not be facing the right direction, the navigator displays the compass as shown in (c) and instructs the user to turn to the right direction. Subsequently, the navigator presents directions from waypoint to waypoint using a style similar to the style of navigators using heads-up display for drivers. As parts (d)-(f) show, the navigator also presents a part of the navigation graph for users who want to view their progress during travel. The application also provides audio instructions for users who prefer voice directives and users who do not want to look at their phones while they are walking.

V. FOG STRUCTURE OF BEDIS

From Fig. 1 in Section I, one can see that the major components of BeDIS are connected by three levels of star networks. The BeDIS server is at the root of the star network of gateways. Each gateway in turn contains the root of a Zigbee star network that connects Lbeacons in an area of the building. Thus connected, the server, gateways and Lbeacons collaboratively manage the system, including configuration and initialization and self-testing and health monitoring. During emergencies, they collaboratively help people, devices and applications to response to each alert and warning in a fine-scale location specific way.

A. *Micro Building/environment Data Servers*

As stated in Section III and IV, under normal condition, each Lbeacon functions as an active waypoint: It deliver its 3-D coordinates and location description continuously to Bluetooth devices under their coverage and collect the MAC addresses of the devices in discoverable mode. This was illustrated by the lower left part of Fig. 1. The Lbeacon switches to emergency mode when commanded to do so by the local gateway. It stays in the emergency mode until it receives a B2N (Back to Normal) command from the gateway, While in the emergency mode, its functions as a micro BeDI server: This is illustrated by the lower right part of Fig. 1.

Similar to location data and description, each micro BeDI server also stores locally, emergency response instructions to be broadcast. As Fig. 2 shows, the micro server 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. The instructions were written by emergency response experts during preparedness phase. They were downloaded to the micro server during initiation and maintenance times. Each instruction is tens of bytes in length, there are tens of instructions for the area covered by each beacon, and there are in order of tens of different emergency scenarios calling for different sets of instructions. So, 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 beacons. Storing the instruction locally enables each micro server to deliver data independent of the rest of the system. Thus, the system is made more disaster resilient and responsive.

Fig. 2 also shows that each micro data server also stores location-specific subsets of building/environment and facility management data. During emergencies, each micro data server can be commanded to broadcast to devices and applications the data to the devices under its coverage to support their decisions on risk reduction actions (e.g., shut the gas valves and open access controlled doors). In this way, the BeDIS can meet the timing requirements ranging from a fraction of a second to minutes for the data delivery.

B. *Structure of Smart Gateways*

Fig. 7 depicts the structure of a gateway and its connections with Lbeacons, as well as information sources and systems serving the building. In particular, the BeDIS server and gateways subscribe to a messaging service that forwards to them emergency/disaster alerts from government authorities and from building safety systems. All messages are in XML-based CAP format [6] and hence are referred to as CAP alerts.

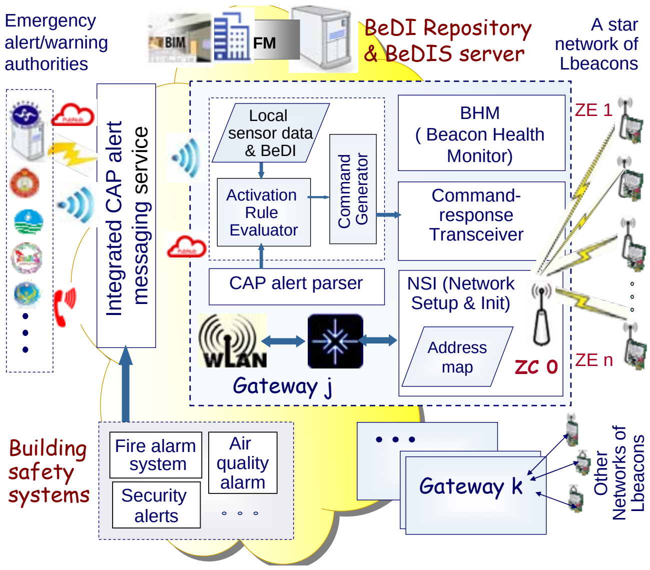

Fig. 7. Structure of smart gateway

Like typical gateways, each BeDIS gateway facilitates the communication of Lbeacons in a Zigbee networks to and from the BeDIS server via the WLAN of the building. The gateway is smart because it has the capability of parsing CAP alerts and evaluating activation rule(s) defined for the gateway. The results generated by the CAP alert parser from an alert include the type, severity and other parameters of the emergency warned by the alert. In general, the activation rule [5] of an active device is an executable specification of whether and what actions the device is to take in response to a CAP alert.

The parser, rule engine and response action activation rules are key elements of active devices and applications; details on them can be found in [6, 56].

The activation rule of a gateway is expressed in terms of the emergency parameters extracted from the CAP message and local sensor and building/environment data on the area containing the gateway and Lbeacons connected to it. The rule specifies the conditions under which the gateway is to broadcast command(s) to Lbeacons and the selection of the command(s) to broadcast. Each command specifies a message which is either an emergency response instruction for people or a BIM-FM data object for decision support of devices and applications. Upon receiving a command, the micro server broadcasts the message specified by the command.

By providing each gateway with a rule engine to evaluate the rules customized for the geographical area containing the gateway, the decisions on how to respond to each CAP alert are distributed among the BeDIS server and the gateways. With rare exception, the decision made by the server is confined to whether to forward the current CAP alert to all the gateways: The alert is forwarded only when the affected area(s) specified within the alert include the location of building and when response actions are required at some locations in the building. In other words, location specific choices of the commands to Lbeacons are left to the individual gateways. Finer scale than the general area of the gateway is achieved by customizing the instructions and data to be delivered by each micro data server to take into account the attributes of the coverage area of the server.

VI. Distributed System Management

Again, BeDIS is managed collaboratively by the server, gateways and Lbeacons. This section describes their interactions during set up initialization and self-testing.

A. *Set up and Initialization*

Each gateway has a network setup and initialization (NSI) module as shown in Fig. 7. When the system is powered up, the module powers on the coordinator node (ZC) of a Zigbee star network and gets it ready to accept join requests of Lbeacons in the immediate area. Also as a part of initialization, the module creates *an address map*. It will use the map to hold the mappings of 16-bit network addresses of Lbeacons and their 3-D coordinates and UIDs during operation.

During initialization, each Lbeacon within line of sight and range of the coordinator sends to the coordinator (i.e., network address 0) a join request (i.e., an association request frame). In response, the coordinator assigns a 16-bit network address to the Lbeacon and sends the address to the Lbeacon. The Lbeacon then sends to the coordinator its own 3-D coordinates and UID and location description. After initialization, the coordinator can address the Lbeacons in the star network individually and identify the senders of packets from them.

B. *Health Monitoring by Lbeacons and Gateways*

A requirement of an IPS for a large building listed in Section II is that the health of the system can be assessed during runtime. The BHM (beacon health monitor) module in each gateway is for this purpose. Fig. 8 shows the interaction among the BeDIS server, gateways and Lbeacons during routine health assessment. The goal is to generate a repair list containing Lbeacons UIDs to be replaced if any.

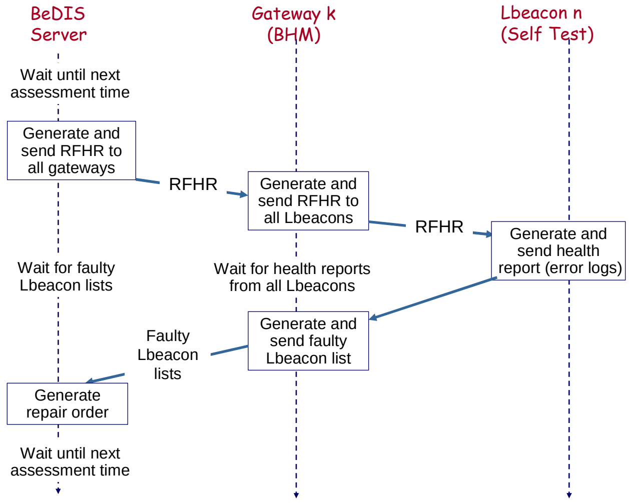

Fig. 8. Collaborative health assessment

Typically, the health of every Lbeacon is tested 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 Lbeacon is capable of testing for its own health and report the result to the BHM. After receiving reports from all Lbeacons on the network, the BHM generates and sends to the BeDIS server a global health report, listing the UID and location of every defective or failed Lbeacon thus identified. The report is used as input to facility management (FM) system on Lbeacons to be repaired or replaced.

The RFHR command from the gateway is received and responded by the self-test component of each Lbeacon. In the alpha version, the component generates the health report solely on the basis of the error/exception log maintained by the Lbeacon. The log holds all error messages generated by exception and error handlers whenever any part of object push operation encounters error or throws an exception. The health report packet of the Lbeacon contains the messages in the log generated since the previous health report was sent, together with a control code and the 3-D coordinates of the Lbeacon. Some error/exception message indicate failure of some important functions (e.g., device scanning) while others are about recoverable errors. The assessment on the seriousness of error conditions are now left to the BHM of the gateway.

Clearly, the reliability of health assessment of the system depends on capability of self-test component, and 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 will be done via receiver emulation. As Fig. 2 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 end-to-end self test, the receive dongle is set to scannable mode. 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. (In Lbeacons with only two dongle-antenna pairs, the dongles will 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 Lbeacon must stop to broadcast either BLE or BR/EDR packets. The duration of the test being in order of minutes, the degradation in service is tolerable especially when the test is scheduled at night.)

VII. Summary and Future Work

The previous sections described the Building/environment Data and Information System (BeDIS) as an infrastructure for location specific services within large buildings and building complexes visited by thousands of people daily. During normal times, indoor positioning, navigation and object tracking are its primary functions. Unlike similar indoor positioning system built on advanced technologies, the system can serve devices enabled by Bluetooth 2.0 or higher, is scalable and responsive, does not require Internet to function, degrades gracefully, and can automatically assess its own health on a regular basis. During emergencies, BeDIS can provide fine-scale, location specific decision support data to hundreds and thousands active devices and mobile applications designed to process disaster and 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 emergencies.

These design objectives are accomplished by structuring the system as fog/mist [7] [8] [52] [53]: The system uses pervasively deployed location beacons and common user devices to deliver and consume location specific data, smart gateways to process alerts/warnings and make decisions on whether and how to respond to the alerts with the help of location beacons. The work done by BeDIS server in the cloud is confined primarily to managing the system.

The other challenge arises from the design, configuration and deployment of BeDIS. It would not be feasible to decide where to place thousands of Lbeacons and install them at correction locations without the development tools described in [2]. The tools exploit the data in the BeDI repository to support the selection of types and locations of location beacons for good coverage and pinning down their locations physically during installation. Currently, the navigation graph containing waypoints marked by Lbeacons are constructed manually from the BeDI of the building. A next step to exploit the data for automatic generation of navigation graphs. We will experiment with the ways proposed in [20].

Our work to date has focused primarily on proving the concept of BeDIS. Lbeacons now run on Raspberry Pi W and Linux operating system, and BlueZ [57]. An alpha version of BeDIPS containing a small number of Lbeacons have been demonstrated within the Institute of Information Science Building during the annual open house in the past three years when the building was filled by hundreds to visitors. This year, a waypoint-based navigator [58] implemented on an Android smart phone demonstrated convincingly that the system and the navigator work well in crowded and complex space.

We have started to pursue pilot studies for assessing usability and effectiveness of BeDIPS in real-life operating conditions in large public buildings heavily used by the general public. Likely test sites include a large and complex building in a teaching hospital and part of a city government building. (The navigation graph in Fig. 5 is that of the test site in the hospital.) For the purpose of these studies, the work of generating BIM and BeDI of the test sites have demonstrated without doubt that BeDI can be generated from blueprints with acceptably low cost. In the process of these studies, we will complete the specification of a beta version of the system and navigators. The next step is to develop the beta version and make it ready for wide deployment.

The development of an alpha version of micro BeDI data server and smart gateway are now underway. Like Lbeacons, smart gateways will also run in Raspberry Pi W and Linux operating system. We have yet to decide whether to use MQTT-SN [59], the version of MQTT (MQ Telemetry Transport) protocol for wireless sensor networks, for communications to and from gateways. Work to be done as soon as possible also include thorough experimentation to assess their responsiveness, as well as the development of standard format(s) for BeDI sent from micro servers to active mobile applications and a tool for extracting location specific BeDI from the repository for specified areas.

BeDIS is a mission-critical system of smart things. Dependability is of critical importance [60]. Among attributes of dependability, BeDIS was designed with maintainability, availability and reliability in mind. Security and safety issues are yet to be addressed, however. Structured as a fog, the system has some of the security risks mentioned in [54]. Among them, physical exposure is the most obvious one. Lbeacons and gateways are numerous and pervasive. Keeping them physically secure is essential. They all store and broadcast critically important messages. Security of data in motion and at rest must be assured. We will take the approaches proposed by OpenFog Consortium and adopt solutions as they become available. In addition to security, safety is also important.

Another thrust of our current work is on safety of BeDIS and AERS (active emergency response system) supported by the infrastructure. A common definition of safety is the absence of dangerous conditions that can cause serious harm death, injury, damage to property and economical loss [28]. BeDIS and the AERS of a large building supported by the infrastructure contain vast numbers of active devices, mobile applications and local sensors. Even when all of them function correctly, the combinations of their actions and actions of people they serve may lead to catastrophic consequences. Our future work also includes the development and use of the AERS simulation framework [62] for assessment of safety of the systems.

ACKNOWLEDGMENT

The authors wish to thank Dr. I. Ru Liu of Accton Technology for the design and construction of directional antennas used in Lbeacons. The implementation and experimentation and of Lbeacons were done with the help of many graduate students, undergraduate part time workers and summer interns. The authors thank them sincerely.

REFERENCES

[1] Indoor location accuracy benchmark, FCC, https://www.fcc.gov/public-safety-and-homeland-security/policy-and-licensing-division/911-services/general/location-accuracy-indoor-benchmarks, Last retrieved: September 2017

[2] C. C. Li, J. Su, E. T.-H. Chu and J. W. S. Liu, "Building/environment Data/information Enabled Location Specificity and Indoor Positioning," *IEEE Internet of Things Journal*, 2017.

[3] J. W. S. Liu, L. J. Chen, J. Su, C. C. Li and E. T.H. Chu, "A Building/environment Data Based Indoor Positioning Service," 2015 *IEEE International Conference on Data Science and Data Intensive Systems* (DSDIS), December 2015

[4] C. Y. Lin, E. T.-H. Chu, L. W. Ku, and J. W. S. Liu, "Active Disaster Response System for Smart Buildings," *Sensors*, volume 14, number 9, pp. 17451-17470, September 2014.

[5] J. W. S. Liu, E. T. H. Chu and C. S. Shih, "Cyber-Physical Element of Disaster Prepared Smart Environment," *IEEE Computer*, Vol. 46, No. 2, pp. 69 – 75, February 2013

[6] Common Alert Protocol (CAP), v1.2. Available: http://docs.oasis-open.org/emergency/cap/v1.2/CAP-v1.2-os.html, last retrieved: October 2017

[7] "OpenFog Reference Architecture", OpenFog Consortium, Technical Report v.1.0, February 2017. Available at: https://www.openfogconsortium.org/ra/: Last retrieved: October 2017

[8] A. D. Dharshana, K. Ramaya and N. Kanimozhi, "Fog Computing - an overview," International Journal of Research and Development, Vol 4, No. 1. Jan-Feb. 2017, pp. 462-464.

[9] Bluetooth Core Specification. https://www.bluetooth.org/en-us/specification/adopted-specifications, Last retrieved: October 2017.

[10] BIM, Building Information Models/Modeling. Available: http://en.wikipedia.org/wiki/Building_information_modeling, Last retrieved : October 2017

[11] FM (Facility Management), https://en.wikipedia.org/wiki/Facility_management: Last retrieved: October 2017

[12] Paul Teicholz, Ed. (2013), *BIM for Facility Managers*, Wiley.

[13] "Using BIM for Operations and Facility Management," http://auworkshop.autodesk.com/library/bim-curriculum-construction/using-bim-operations-and-facilities-management, Last retrieved: October 2017

[14] J. Zhang, B.-C. Seet and T. T. Lie, "Building Information Modeling for Smart Built Environments," *Buildings*, 2015, 5, 100-115; doi:10.3390/buildings501010

[15] T. Liebich and M. Weise, "ifcXML4 Specification Methodology," http://www.buildingsmart-tech.org/downloads/ifcxml/ifcxml4/ifcxml4_specification_methodology_v1-1.pdf, Last retrieved: October 2017

[16] W. Jung and G. Lee, "The status of BIM adoption on six continents," I*nt. Jr. of Civil, Environmental, Structural, Construction and Architectural Engineering* Vol.9, No.5, 2015, pp. 444-448.

[17] F. T. Lin, et al., "Data requirements of indoor emergency evacuation systems," Technical Report No. TR-IIS-16-001, Institute of Information Science, Academia Sinica, January 2016.

[18] Autodesk Revit, https://en.wikipedia.org/wiki/Autodesk_Revit and http://www.autodesk.com/education/free-software/revit, last retrieved: October 2017

[19] Waypoint, https://en.wikipedia.org/wiki/Waypoint: Last retrieved: October 2017

[20] L. Yang and M. F. Worboys, "Generation of navigation graph for indoor space," *International Journal of Geographical Information Science*, 17:16, May 2015, pp. 1737-1756.

[21] D. Dodge. (June 2013). Indoor location startups innovating indoor positioning. Available: http://dondodge.typepad.com/the_next_big_thing/2013/06/indoor-location-startups-innovating-indoor-positioning.html

[22] D. Schneider, "New indoor navigation technologies work where GPS can't," *IEEE Spectrum*, November 2013.

[23] Indoor positioning startups. Available: https://angel.co/indoor-positioning, Last retrieved: October 2017

[24] R. F. Brena, J. P. García-Vázquez, et al., "Evolution of indoor positioning technologies: A survey," *Journal of Sensors*, Volume 2017 (2017), Article ID 2630413, 21 pages.

[25] S. Doiphode, J.W. Bakal, and M. Gedam, " Survey of indoor positioning measurements, methods and techniques," *International Journal of Computer Applications* Vol. 140, No.7, April 2016, pp. 0975 – 8887

[26] M A. Al-Ammar, S. Alhadhrami, et al., " Comparative survey of indoor positioning technologies, techniques, and algorithms," *Proceedings of International Conf. Cyberworlds* (CW), October 2014.

[27] Z. Farid, R. Nordin, and M. Ismail, "Recent advances in wireless indoor localization techniques and systems," *Journal of Computer Networks and Communications*, Volume 2013, 12 pages, 2013.

[28] T. Van Haute, E. De Poorter, et al., " Performance analysis of multiple Indoor Positioning Systems in a healthcare environment," *Int. Jr. of Health Geographics*, Vol 15, No. 7, 2016, 15 pages

[29] Microsoft Indoor Location Competitions, 2015, 2016 and 2017, http://research.microsoft.com/en-us/events/indoorloccompetition2015/, http://research.microsoft.com/en-us/events/msindoorloccompetition2016, https://www.microsoft.com/en-us/research/event/microsoft-indoor-localization-competition-ipsn-2017/ last retrieved October 2017.

[30] T. Q. Wang, Y. A. Sekercioglu, A. Neild, and J. Armstrong (October 2013) "Position accuracy of time-of-arrival based ranging using visible light with application in indoor localization systems," *IEEE Jr. of Lightwave Technology*, Vol. 31, No.20, 2013, pp. 3302-3308.

[31] "An indoor positioning system based on echolocation," *MIT Tech. Review*, Emerging Technology From the arXiv, July 25, 2014.

[32] S. P. Tarzia, P. A. Dinda, R. P. Dick, and G. Memik, "Indoor localization without infrastructure using the acoustic background spectrum," in *Proc, of ACM MobiSys*, 2011, pp. 155-168.

[33] J. Chung, M. Donahoe, C. Schmandt, I.-J. Kim, et al., "Indoor location sensing using geo-magnetism," in *Proc. of MobSys*, 2011, pp. 141-154.

[34] D. Takahashi. "Indoor Atlas uses magnetic sensors for finding places in the great indoor," November 2013. Available: http://venturebeat.com/2013/11/15/indoor-atlas-uses-magnetic-sensors-to-the-great-indoors/

[35] P. Bahl and V. Padmanabhan, "RADAR: an in-building RF-based user location and tracking system," in *Proc. of IEEE INFOCOM*, 2000, pp. 775—784.

[36] A. Farshad, J. Li, M. K. Marina and F. J. Garcia "A microscopic look at WiFi fingerprinting for indoor mobile phone localization in diverse environments," In *Proc. of IPIN* , 2013.

[37] S. Sen, B. Radunovic, R. R. Choudhury, and T. Minka, "You are facing the Mona Lisa: spot localization using PHY layer information," *in Proc. of ACM MobiSys*, 2012, pp. 183-196.

[38] K. Wu, J. Xiao, Y. Yi, M. Gao, and L. M. Ni, "FILA: fine-grained indoor localization," in *Proc. of IEEE INFOCOM*, 2012, pp. 2210 – 2218.

[39] Y. Chen, D. Lymberopoulos, J. Liu, and B. Priyantha, "FM-based indoor localization," in *Proc. of ACM MobiSys*, 2012, pp. 169-182.

[40] A. Popleteev, "Indoor Positioning Using FM Radio Signals," PhD Dissertation. University of Trento, Italy, 2011.

[41] A. Matic, A. Papliatseyeu, V. Osmani, and O. Mayora-Ibarra, "Tuning to your position: FM radio based indoor localization with spontaneous recalibration," in *Proc. of PerCom2010*, 2010, pp. 153 – 161.

[42] A. Varshavsky, E. Lara, J. Hightower, A. LaMarca, and V. Otsason, "GSM indoor localization," *Pervasive and Mobile Computing*, Vol. 3, No. 6, 2007, pp. 698–720.

[43] X. Hu, L. Cheng, and G. Zhang, "A Zigbee-based localization algorithm for indoor environments," in *Proc. of ICCSN*T '11, 2011, pp. 1776 – 1781.

[44] S.-H. Fang and T.-N. Lin., "Cooperative multi-radio localization in heterogeneous wireless networks," *IEEE Trans. Wireless Comm*. Vol.9, No. 5, 2010, pp. 1536-1276

[45] P. Wawrzyniak, P. Korbel, P. Skulimowski, and P. Poryzala, "Mixed-mode wireless indoor positioning system using proximity detection and database correlation," in *Proc. of FedCSIS*. 2014, pp. 1035 – 1042.

[46] OBject EXchange (OBEX)/ Available: https://en.wikipedia.org/wiki/OBject_EXchange, Last retrieved: October 2017

[47] Skyhook Wireless. Available: http://www.skyhookwireless.com/about-skyhook

[48] iBeacon. Available: http://en.wikipedia.org/wiki/IBeacon

[49] Eddystone, https://developers.google.com/beacons/eddystone

[50] Proximity marketing. Available: http://en.wikipedia.org/wiki/Proximity_marketing

[51] J. Lindh, "Bluetooth Low Energy beacons," Texas Instruments, Application Report SWRA475, January 2015.

[52] J. McKendrick "Fog Computing: a New IoT Architecture?", https://www.rtinsights.com/what-is-fog-computing-open-consortium/, last retrived: November 2017

[53] J. S. Preden, K. Tammemäe, A. Jantsch, M. Leier, A. Riid, and E. Calis. "The benefits of self-awareness and attention in fog and mist Computing," IEEE Computer, Vol. 48, No. 7, pp. 37-45, July 2015.

[54] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, " Fog computing and its role in the Internet of Things," *Proceedings of Mobile Cloud Computing*, ACM SIGCOMM 2012, pp. 13-15.

[55] "OpenFog architecture Overview," OpenFog Consortium Architecture Working Group, http://www.OpenFogConsortium.org, Feb. 2016

[56] B. A. Martin, *et al.*, "OpenFog security requirements and approaches," invited paper, Fog World Congress 2017.

[57] OpenFog Testbed Frame work version 3, Feb. 8, 2017, https://www/openfogconsortium.org/get/406

[58] H. Y. Huang, et al., "Trustworthy OpenFog Computing Testbeds Developed in the Greater China Region,"

[59] "Feature phone and smart phone shipment worldwide from 2008 to 2020," https://www.statista.com/statistics/225321/global-feature-phone-and-smartphone-shipment-forecast/ Last retrieved: November 2017.

[60] BlueZ. Available: http://www.bluez.org/about/, last retrieved November 2017

[61] A demo of waypoint based indoor navigation with support of BeDIPS, https://www.youtube.com/watch?v=6oaXx0XrJ-A&feature=youtu.be, last retrieved in November 2017

[62] A. Stanford-Clark and H. L. Truong, "MQTT for Sensor Networks (MQTT-SN) Protocol Specification, Version 1.2, November 2014.

[63] "No dependability, no Internet of Things," 2004. https://ec.europa.eu/digital-agenda/en/news/no-dependability-no-internet-things, retrieved: November 2017

[64] J. W. S. Liu and E. T. H. Chu, "Dependability of Active Emergency Response Systems," in Proc. of DEPEND 2015. 2015. pp. 33-37.