buildings

MDPI

Review

Building Fire Evacuation: An IoT-Aided Perspective in the 5G Era

Hongqiang Fang [1,*], Siuming Lo [1] and Jacqueline T. Y. Lo [2]

[1] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China; bcsmli@cityu.edu.hk
[2] Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, USA; tszyin@stanford.edu
* Correspondence: hqfang3-c@my.cityu.edu.hk

Abstract: Complex and tall buildings have been constructed in many cities recently. Fire safety should be a major concern of building designers, engineers, and governments. Previous fire experience has made us understand the importance of acquiring fire-ground information to facilitate firefighting operations, evacuation processes, rescues, etc. Recently, the rapid advancement in Information Technology, Data Analytics, and other detection and monitoring systems has provided the basis for fire safety researchers to re-think fire safety strategies in the built environment. Amongst all fire safety studies, evacuation in tall buildings, including elevator evacuations, has attracted much attention. IoT-aided building fire evacuation is a new concept of the building evacuation mode, which improves the building evacuation process by making decisions of escape based on the real-time fire-ground information, such as the fire environment and occupant situations. Focusing on IoT applications in building fire evacuation, this paper explores the advantages and insufficiencies of current smart building fire evacuation systems. A conceptual design of an IoT-aided building fire evacuation control system is described. The system is introduced in the sequence of information needs, information sources and data transmission, and potential services and applications. Finally, new insights into promising 5G technologies for future building fire evacuations are discussed.

Keywords: building evacuation; Internet of Things (IoT); 5G era; state of the art review; system architecture design

check for updates

Citation: Fang, H.; Lo, S.; Lo, J.T.Y. Building Fire Evacuation: An IoT-Aided Perspective in the 5G Era. *Buildings* **2021**, *11*, 643. https://doi.org/10.3390/buildings11120643

Academic Editor: Benedetto Nastasi

Received: 5 November 2021
Accepted: 7 December 2021
Published: 13 December 2021

1. Introduction

Rapid urbanization and increases in the urban population have resulted in high-density development and erection of tall buildings in cities. Large complex tall buildings can accommodate over ten thousand occupants. Their safety should be a great concern of building designers, engineers, and governments.

In June 2017, the world was all astounded by the Grenfell Tower fire in London, UK. The fire caused the entire building to burn out, causing 80 deaths and over 70 injuries [1]. Delayed building evacuation was considered to be one of the factors leading to the great loss of life in that fire [2]. In the Grenfell Tower fire, a "stay-put" policy was initially employed [3]. The "stay-put" policy suggests that residents not directly affected by the fire should remain within their flats and wait for further notice [2]. This policy was made because a fire in such a building would usually be contained within the floor of origin, and it is expected that occupants other than those living or staying near the fire origin may not need to evacuate. However, the Grenfell Tower fire spread dramatically and was soon out of control, making the "stay-put" policy totally lose its functions. The abandonment of the "stay-put" policy was made very late, when the thick toxic smoke had already spread to the single narrow stairwell in the building. As the only escape route was blocked, only a few residents successfully escaped after relinquishing the "stay-put" policy. There were indeed many people trapped in their rooms on high-level floors.

To lead to such a situation, the following possible points may be considered:

(1) Information concerning the fire-ground may be insufficient, e.g., fire development situation, first-aided and subsequent firefighting resource allocation, evacuation process, and so on.

In the Grenfell Tower fire, due to a lack of feedback on fire-ground information about fire development, trapped occupants, and evacuation progress, the incident commander (IC) may not have had sufficient information to judge if the evacuation tactics should be altered, so that the occupants may not have been alerted to escape immediately. Like the Grenfell Tower fire, currently, collections of fire-ground information of most of the other building fires can only depend on the reports by firefighters who have entered the building. This sort of information collection mechanism may delay and make it hard for ICs to obtain the full picture of the fire development situation immediately and affect the IC's decision-making process.

(2) Lack of effective communication means to alert building occupants.

The Grenfell Tower may not have been equipped with the public address (PA) system or other effective means of communication to advise the occupants of the fire situation and escape arrangement [4]. The only two ways that the IC could alert the occupants inside the building were through the physical deployment of firefighters to each floor or to notify the occupants directly from the control room using phone calls. Both approaches were time-consuming and difficult to operate. Although conditions in the stairs did not present an insurmountable hurdle at first, full evacuation of the building was not considered timely. The same situation can be suffered by any type of buildings around the world. Due to the lack of effective means of communication to alert and assist building occupants in these buildings, evacuation of the occupants can be seriously delayed.

(3) Difficulty of organizing an effective evacuation.

Even if all the occupants in the building were successfully notified to evacuate, a sudden evacuation would cause a mass gathering of people in stairwells and reduce the evacuation efficiency. For tall building evacuation, it is necessary to control the sequence and means of evacuation for each building floor in order to make the evacuation remain orderly and more efficient. However, it is not easy to carry out such an organized evacuation strategy. It requires reliable information on the building plan, fire information, and occupants' locations to help plan the evacuation strategy. It needs effective means of communication to guide the occupants during the evacuation. Therefore, it is difficult to organize a safe and effective total building evacuation in tall buildings at current stages.

The delayed evacuation in the Grenfell Tower fire indicates that building fire evacuation still faces some common difficulties and challenges. The major deficiencies include inadequate situational awareness of interior fire environments, less effective communication between occupants and rescuers, and a lack of systematic analyses of evacuation strategies. If these insufficiencies cannot be addressed, the tragedy of the Grenfell Tower fire is likely to happen again.

To successfully overcome these insufficiencies, we must have innovative approaches and new technologies for managing the facilities, such as effective detection, monitoring, tracking system, data analytics, communication systems, etc., to provide valuable support for developing an innovative building fire evacuation system. The 21st century is undergoing a fast-paced trend of digitalization with the emergence of the Internet of Things (IoT). The IoT is an integration of technologies that connects ubiquitous devices and facilities with various networks to provide efficient and secure services for all applications anytime and anywhere [5]. By facilitating the collection and exchange of data among virtually everyone and everything, the IoT is enabling the cyber and physical environments to become unprecedentedly entangled, which promotes efficiency in performance and economic benefits and minimizes the need for human involvement. At present, tall building fire evacuation insufficiencies come from the inadequate perception of fire-ground information and the lack of effective communication means between the interior and exterior of the incident premise. These insufficiencies eventually cause inappropriate decisions in evacuations. The use of IoT can provide a possible solution for building evacuation control in fire emergencies. By using the IoT to build a connection with a wide variety of sensors, actuators, and devices pre-installed or post-deployed on the fire-ground, the IC and fire control room can obtain fire-ground information in real-time. Moreover, embracing the strong analytical power of IoT to analyze a huge volume of data generated from various connected IoT sensors and devices, the IoT system can tell more available information to help ICs make more appropriate decisions during the commanding.

Another factor that makes the IoT a welcome solution for building fire evacuation control is the incentive of the fifth generation of cellular technology (5G). 5G is a new global wireless standard after 1G, 2G, 3G, and 4G networks [6]. It was proposed and started its commercial deployment in 2019 [7]. Compared to the previous 2G, 3G, and 4G Long Term Evolution (LTE), 5G operates in an additional millimeter-wave (mmWave) spectrum from 28 GHz up to 95 GHz to provide a larger band of frequencies [8]. As a result, it enables a peak throughput of 10–20 Gbps, 100 times faster than 4G LTE networks. More than increasing the speed, 5G also contains technologies enabling approximately 1 ms latency in data delivery, increased energy efficiency consumption, massive device communication, etc. [9]. These attributes make new experiences and services in IoT connectivity and applications possible [10]. Three new service areas were categorized, which are enhance mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable and low latency communication (uRLLC). The overall vision for these three broad 5G usage families and their basic service requirements are illustrated in Figure 1.

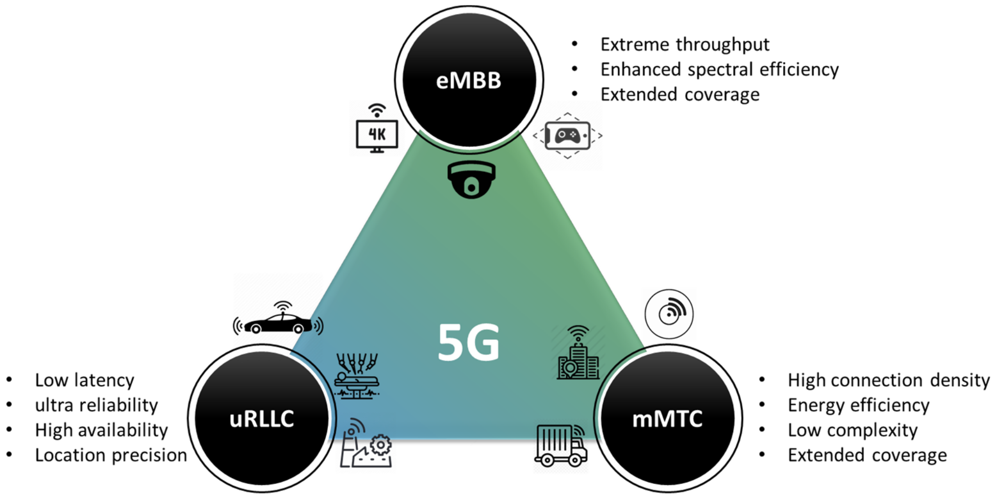


Figure 1. The overview of 5G usage scenarios and services.

With the support of 5G in communication, the utilization of IoT to support building fire evacuation will become a reality. A wide variety of IoT applications can be utilized for improving evacuation in high-rise buildings. For instance, many new mobile IoT applications that can only be supported under 5G environments, such as drones with HD cameras and augmented reality/virtual reality (AR/VR)-based evacuation guidance, can be used for the first time on the fire scene. Furthermore, due to the 5G characteristics of massive capacity and connectivity, the data collection from a wide range of sensor sources can also become possible. These data sources include temperature, smoke, states of various fire protection systems, and many other sensor sources, providing a solid basis for understanding and decision making of the building evacuation under fire emergencies. Therefore, there is no doubt that the IoT-aided building fire evacuation will truly play a role in the upcoming 5G era.

To facilitate the understanding and research of IoT-aided building fire evacuation, we conducted a literature review of the state-of-the-art smart building fire evacuation system. After that, based on the benefits and insufficiencies, the system architecture of an

IoT-aided building fire evacuation control system was designed. Finally, new insights that 5G technologies can bring to the building fire evacuation were discussed. The article is organized as follows:

- Section 2 introduces the concept of IoT in smart building applications.
- Section 3 describes a review of the state-of-the-art smart building fire evacuation system.
- Section 4 suggests a preliminary design of an IoT-aided building fire evacuation control system.
- Section 5 discusses the opportunities in the 5G era.
- Section 6 provides a discussion.
- Section 7 provides a concluding remark.

2. Overview of IoT Technology for Smart Buildings

The IoT system is an integration of technologies to provide end-to-end IoT solutions with a mix of IoT devices, IoT data, IoT platforms, and IoT applications [11]. Therefore, the design of its system architecture is the core that enables the function of an IoT system. Generally, the architecture of IoT systems can be divided into layers. An intelligent IoT system can be represented as a 5-layered architecture, which contains (1) perception layer, (2) network layer, (3) middleware, (4) service layer, and (5) application layer [12]. Figure 2 illustrates the schematic diagram of such an IoT architecture for smart buildings.

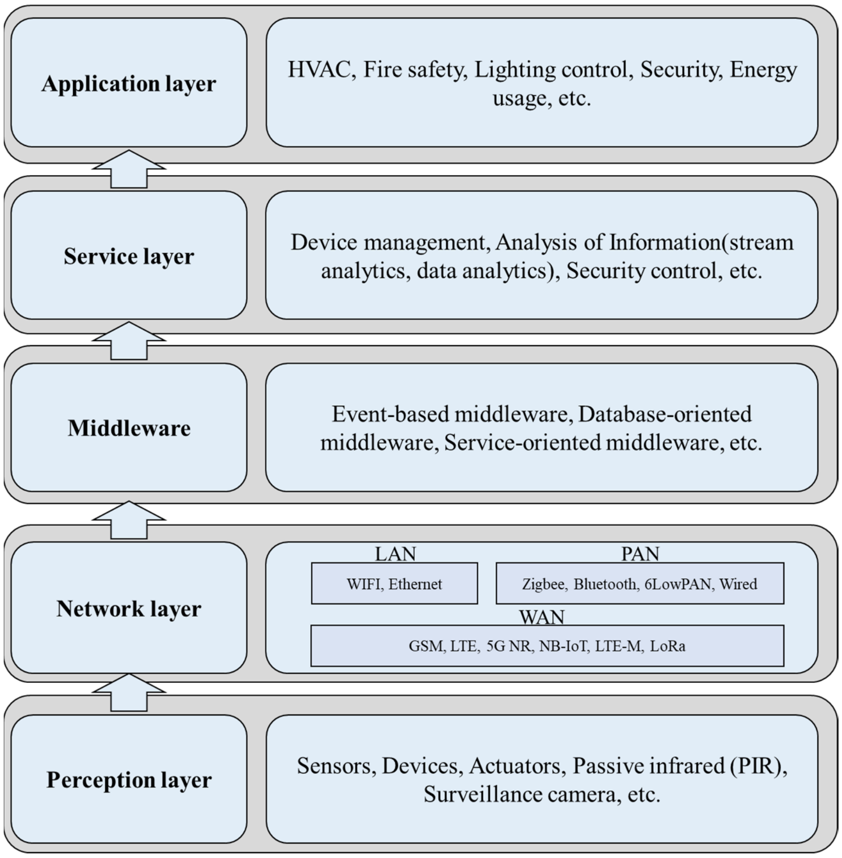


Figure 2. A five-layer IoT architecture for smart buildings.

The perception layer is located at the bottom of the IoT system architecture. It consists of various sensing and actuating devices to provide data and information collected from the physical world. In smart buildings, a large number of sensors, actuators, and devices have been used to measure the built environment conditions such as ambient status, state of facilities, occupancy rate, etc. [13–15]. The collection of this sort of information helps various smart building applications, including smart facility management, lighting control, electrical usage, HVAC control, etc.

After capturing the sensor data in the perception layer, the collected information needs to be sent to a receiver for further processing and control. As a result, the network layer is established. In building systems, structured cabling is one of the commonest methods for telecommunication [16]. With cables installed within a raised floor void or suspended ceiling reaching everywhere inside buildings, data communication among sensors can be enabled with wired connections. However, with greater demands of using various data sources to collect information needs in building systems, wired connections may not be as flexible and convenient. Therefore, a variety of wireless personal area networks (WPAN), such as Bluetooth, Zigbee, Wi-Fi, etc., is being used to connect IoT sensors and devices in buildings [17]. By enabling these WPAN to connect to the backbone network of the building through a route or gateway, wireless communication between data sources and the IoT platform can be set up. In addition to the communication based on structured cabling, cellular-based wireless networks are also becoming popular for indoor wireless communications, whether with low throughput sensors or bandwidth-hungry devices. The endpoint devices can directly connect to the Internet via cellular-based wireless networks due to their extensive indoor and outdoor coverage, so simpler local set-up and mobility can be achieved under this connection method. The most frequently used cellular-based communication technologies include NB-IoT for low-power wide-area communication [18] and LTE for high-speed communication [19]. Table 1 summarizes the main characteristics of several wireless communication technologies for indoor telecommunication.

Table 1. Specifications of mobile communication technology used for IoT.

Characteristics	NB-IoT	4G LTE	Wi-Fi 6	ZigBee 3.0	Bluetooth 5
Spectrum	Licensed	Licensed	Unlicensed	Unlicensed	Unlicensed
Range	1 km (urban), 10 km (rural)	1 km (urban), 5 km (rural)	50–100 m	10–100 m	10–100 m
Connected devices	Over 1,000,000/km^2	100,000/km^2	254/gateway	240/gateway	7/gateway
Bandwidth	200 kHz	5–20 MHz	160 MHz	2 MHz	1 MHz
Peak data rate	200 Kbps	1Gbps	9.6 Gbps	250 Kbps	2 Mbps
Battery life	>10 years	Hours	Days	>2 years	Days

Even though wireless communication technologies provide a more flexible and accessible means of data communication for IoT sensors or devices, the range and strength of radio signals may be strongly influenced in some specific indoor spaces (e.g., multiple rooms, long corridors, elevator shafts, and basements) because of the attenuation of these structures to radio signals [20]. The specifications of mobile communication technology given in Table 1 only present the performance measured in the most favorable signal propagation conditions. The performance of these mobile communication technologies may all get weakened to some extent in indoor environments. For example, through the testing of signal quality of ZigBee in rooms and corridors, it was found that the recommended distance for indoor environments is a distance not exceeding 25 m [21]. As for Wi-Fi, accuracy locating with signal strength could only be enabled within a range of 25 to 50 m for indoor environments [22]. Moreover, the penetration losses of 4G LTE signals in indoor building areas were also demonstrated by Zulkefly et al. [23] and Soliman et al. [24]. Therefore, networking devices such as access points, wireless repeaters, and routers should be applied to ensure the reliability of wireless communication in indoor environments.

Furthermore, middleware is followed to build the connection between physical and application layers. Middleware is usually described as a software system designed to be the intermediary between IoT devices and applications, so that seamless connectivity and data management for distributed applications can be enabled [12]. To realize IoT application in smart buildings, middleware based on events with database storage is gaining popularity due to the easiness of deployment and lightness of resource utilization. Message Oriented Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), and BLE (Bluetooth Low Energy) are some popular connectivity protocols explicitly designed for this aim [25].

The service layer lies at the upper level of the IoT architecture. Owing to the strong analytical power of IoT, the service layer can strongly interact with the application layer to cater to the design and demands of the application layer for providing effective utilization of the collected data. The service layer is established in smart building applications to provide various services, including device management, information analyses, and security control. Finally, with the development of user interfaces in the application layer to access various IoT-based services, monitoring and control of the smart building facilities can be enabled.

3. Review of Current Developments

To help the evacuation of occupants, many studies have tried using IoT technologies to develop smart evacuation systems in buildings. In general, a smart building fire evacuation system is composed of a detecting (or measurement) unit, a route planning solver (e.g., an algorithm), and a guiding device (e.g., exit signs, personal devices) [26]. Innovations and new technologies are fully applied in each part. Therefore, in this section, we conduct a review of the state-of-the-art smart building fire evacuation systems and try to find out what advantages and insufficiencies exist in current smart building fire evacuation systems.

3.1. Review of the State-of-the-Art Smart Building Fire Evacuation Systems

The most common design of the detecting unit in smart building fire evacuation systems is to apply sensors to perceive various environmental parameters during the fire emergency, including smoke [27–29], temperature [30,31], and other sensor sources [32,33]. The data communications of these sensors are usually built by Wi-Fi [28,29], Zigbee [32], and Bluetooth [29–31]. A comprehensive IoT-based building fire evacuation system was exemplified by Park et al. [34]. The system enabled the detection of fire occurrence places by monitoring the real-time environment data from multiple smart sensors, including gas leak detector sensors, temperature sensors, electric leak detector sensors, and multi-gas detector sensors. In addition to this, the system was also connected with various actuators, including electric breakers and gas valve breakers, to enable remote cut-off of further fire hazards in buildings. The data transmission of all these sensors was built under the ZigBee environment.

Moreover, some solutions consider detecting occupants' situations (e.g., position, flow rates, presence). These states of occupants are also important factors in building evacuations. In order to dynamically direct people to the safest exits and speed up the evacuation process, many researchers have developed smart systems tracking locations of the building occupants. With received signal strength indication (RSSI) through Bluetooth Low Energy (BLE) beacons, many researchers enabled localization of occupants via occupants' mobile phones [28–30]. In addition, a mobile RFID-based system for localization was proposed by Chittaro and Nadalutti [35]. A ZigBee-based localization module that identifies people's positions and understands whether they are evacuating was proposed by D'Orazio et al. [36]. The systems described by Jiang [37] and Atila et al. [38] both employed purposely deployed RFID beacons to collect personnel localization in buildings. Furthermore, personal localization using Global Positioning System (GPS) and Wi-Fi access points were also mentioned by Dominicis et al. [39]. In addition to tracking the locations of building occupants, some studies also consider optimizing the evacuation routes according to the personnel density or speed in the evacuation route. The crowd evacuation speed and flow rates are often detected via surveillance cameras [40,41]. The detection of occupants' presence and/or other behaviors in building areas during the evacuation process was also introduced by several authors [42–45]. The most typical approach used to count the number of people in a target area is through visual-based cameras. Finally, some studies combine BIM technologies to manage and visualize the collected fire and occupant information in a 3D model [29,30,46–49]. This BIM innovation successfully makes it easier for building managers and firefighters to be aware of the real-time fire environment and evacuation on-site.

Furthermore, focusing on intelligent route planning, researchers also propose various intelligent building route planning algorithms considering real-time environmental factors and occupants' situations during the evacuation. By giving information about fire origin, nodes of trapped occupants, and nodes of firefighters, Chou et al. [31] proposed a fire rescue path planning approach based on Dijkstra's algorithm. The approach enabled finding the optimal path of escape in a short computational time. In the work of Jiang [37], an intelligent route planning algorithm was proposed by considering the intensity of the fire. In this way, fire hazards can be considered when planning the evacuation route. In order to suggest evacuees with less crowded paths toward safety exits, a situation-aware route planning system considering evacuees' behaviors during the evacuation (e.g., running, waiting in a queue, herding) was proposed by Billhardt et al. [43]. With beacon sensors to recognize the location and movement of every occupant inside the building during the evacuation, this system successfully enables evacuees to bypass the congestion and dangerous area in advance. Moreover, Ma and Wu [49] developed a system that optimizes the evacuation route for evacuees and rescued people. By monitoring the number of people using the stairs, strategies for stair evacuation can be adjusted. However, the research on intelligent route planning focuses more on individual path-finding during the evacuation. It is rarely considered how the smart system can coordinate the total building evacuation containing a large number of occupants.

Finally, many researchers also developed various smart devices regarding evacuation guidance to make the evacuation signal and planned evacuation route successfully delivered to building occupants. One possible approach is to send signals and instructions to users' mobile phones via a pre-installed application [29,31,34,47], frequently applying Wi-Fi and cellular networks for communication. However, these networks are infrastructure-based networks that are prone to fail in critical environments. Therefore, a MANET (Mobile Ad Hoc Network)-based evacuation guidance system was developed by Ohta and Dunkel [50]. The MANET is a wireless network without a centralized server or network infrastructure, so it can be used to provide more reliable evacuation guidance to occupants. The same sort of communication approach was also used by Zualkernan et al. [28]. In addition, by considering that not everyone is necessarily equipped with a smartphone or has downloaded the application, which means that some people may not be able to receive the guidance, another approach for evacuation guidance using "smart exit signs" was proposed by several authors [28,40,51–53]. These "smart exit signs" are usually equipped with dynamic signage, which can dynamically change their directions to inform evacuees of the directions towards the shortest safe evacuation paths.

3.2. Summary of Advantages and Insufficiencies

From the state-of-the-art smart building fire evacuation systems review, some of the advantages and inefficiencies are summarized.

First, by using various devices and sensors, the smart building fire evacuation systems can successfully detect fire situations and evacuation processes on the scene. The parameters they collected include not only environmental factors but also occupants' situations. By monitoring the environmental factors, such as flame, heat, and smoke, ICs and building managers can become more aware of the current fire situation and promptly initiate the evacuation. As for the occupants' situations, monitoring of the occupants' presence or positions during the evacuation process can help understand the bottlenecks of the evacuation. The ICs and building managers can then adjust the evacuation strategy and guide the occupants to escape smoothly. Moreover, the position information also offers help to the search of trapped occupants during the rescue mission.

Furthermore, the development of various smart systems helping evacuation guidance also provides a valuable contribution. Lacking effective means of communication to guide occupants to escape is one of the major difficulties for building fire evacuation. Therefore, a "smart exit sign" can be useful when responders hardly reach the incident floor and guide the occupants to leave. In addition, the "smart exit sign" is a stationary device pre-installed inside buildings, so no other devices or software need to be used by occupants, which satisfies building evacuation scenarios with mass populations.

The major insufficiency of current smart building fire evacuation systems is that most of the systems only achieve the perception of either the information of fire environment or occupants' situations. The interpretation of these data and how they will influence the total building evacuation have been less considered. Even though some previous research has enabled smart route planning based on the information collection regarding fires or occupants' situations, the focus was more on evacuees' path finding within single floors. The systematic understating and prediction of the total building evacuation considering dynamic fire development and occupants' situations was insufficient. As a result, the current smart building fire evacuation system does not seem to be able to coordinate and organize the prompt total building evacuation under fire emergencies, which is the major difficulty faced by tall building evacuations.

With more extensive use of various wireless communications in the 5G era, the connectivity and analytical power of the IoT will increase a lot. More connectivity of various IoT sensors and fast computation of the collected data can be enabled. Therefore, a preliminary design of an IoT-aided building fire evacuation control system is proposed in view of the advantages and insufficiencies in current smart building fire evacuation systems.

4. Preliminary Design of an IoT-Aided Building Fire Evacuation Control System

In the upcoming 5G era, various sensors and devices will become available to monitor various environmental parameters and occupants' situations in buildings. Taking into full consideration the available information on facilitating a more effective and efficient fire evacuation, we analyze the information sources, means of data transmission, and potential services and applications that should be provided for building fire evacuation control. After that, an IoT architecture for an IoT-aided building fire evacuation control system is proposed.

4.1. Information Needs

Generally, two aspects of safety issues are the major concerns during the fire evacuation. At first, there is the need to ensure that occupants stay away from the thermal hazard caused by the fire. Enclosure building fires create a large volume of heat and toxic smoke inside the building, and the spread of these hazards causes a major threat to evacuees [54]. Thus, it is essential to monitor the indoor fire environment and know where the hazardous areas are in a fire. In addition, fire safety equipment, such as firewater systems and fire doors, is the active design to stop the fire spread. The condition of these facilities in fires plays an important role in building evacuation. Therefore, information of the state of various fire safety equipment should also be monitored.

Furthermore, in terms of occupants' situations during the evacuation process, chaos and disorder are also a concern [55]. Tall buildings encompass a large number of occupants working and living together. In fire emergencies, the convergence of the crowd in the stairwells may cause mass blockage and panic, so it is rather challenging to evacuate all these occupants simultaneously. Phased evacuation control has been proven more suitable for tall building fire evacuation [56]. The phased evacuation strategy conducts a controlled, area-by-area evacuation to decrease the queuing time and density of people. Still, its effectiveness must be strongly built on the timely information feedback of the overall evacuation progress [57]. Therefore, real-time occupant count data of different building areas should be collected to optimize the evacuation strategy and assist the building evacuation.

Finally, evacuation signals and the implemented evacuation strategy need to be delivered to occupants in time in a fire emergency. The existing fire emergency systems, such as fire alarm systems, fire emergency lighting systems, and PA systems serve this purpose. Therefore, it is necessary to monitor the state of these systems to avoid a malfunction in emergencies. Moreover, due to the importance of providing evacuation guidance in tall building fire evacuation, smart devices that can promptly guide the occupants to escape should be used. The most direct way to deliver clear evacuation guidance in tall buildings is through voice and visual indicators. Therefore, remote control and operation of the PA system and the "smart exit signs" need to be built.

According to the analysis above, the overall information needed for building fire evacuation control is listed in Table 2.

Table 2. Information needs for building fire evacuation control.

Information Needs			Purposes
Fire hazard monitoring (A)	Indoor fire environment (A1)	Temperature (A11)	Measure the hot gas layer (HGL) temperature at corridors to avoid thermal hazards on the evacuation routes.
		Smoke (A12)	Measure carbon monoxide level at corridors to avoid toxic smoke spreading on the evacuation routes.
	Fire protection system (A2)	Firewater system (A21)	Monitor the state of firewater systems, such as sprinkler systems, indoor fire hydrant and hose reel installation, etc., to avoid malfunction.
		Fire doors (A22)	Monitor the state of fire doors to keep the fire compartmentation intact.
People counting (B)	Building entrances (B1)	Office buildings (B11)	Count the total occupants entering and leaving the building.
		Residential and commercial buildings (B12)	Count the total number of occupants entering and leaving the building.
	Building floors (B2)	Elevator lobbies (B21)	Count the inlet and outlet of the occupants on each floor.
		Stairwell exits (B22)	Count the inlet and outlet of the occupants on each floor.
	Building areas (B3)	Corridors and common areas (B31)	Collect the occupancy information in buildings.
		Rooms and private use areas (B32)	Collect the occupancy information in buildings.
Evacuation guiding (C)	Fire emergency system (C1)	Fire alarm system (C11)	Provide visual alarms and sound alarms to evacuees.
		Emergency lighting (C12)	Provide light sources to evacuees.
	Evacuation guidance system (C2)	Exit and directional sign (C21)	Inform evacuees of the directions towards the safe evacuation paths.
		Public address system (C22)	Provide voice-based evacuation guidance to evacuees.

4.2. Information Sources and Data Transmission

To enable the collection of the information needs as mentioned above in building fire evacuation, there is the need to determine the perception devices and their means of communication, which formulate the perception and the network layers in the IoT architecture.

4.2.1. Fire Hazard Monitoring

To monitor the environmental fire information in a building, various physical sensors are mainly applied. Thermocouples are the most widely used sensor devices to enable the measurement of temperatures in an enclosure space. The range of the measurements varies from 0 to 1700 °C by type [58]. To measure the indoor carbon monoxide (CO) concentration levels, CO gas detectors can be used [59]. By installing these sensors in spaces and corridors throughout the whole building, identification of the fire origin and its affecting areas can be achieved. In addition, the state of various fire protection systems can be monitored by additional sensor sources. For example, door lock sensors can be installed to monitor fire doors' open or closed status in buildings. The state condition of firewater systems can be monitored by water flow or pressure sensors.

Due to the fact that there is a large amount of environmental and equipment state sensor sources and they are installed everywhere inside buildings, flexibility and simplicity of connectivity may be one of the major concerns. Data communication via wireless networks shows its advantages in this aspect. The transmission of these sensor data runs in a small volume of data and has low refresh rate requirements, so narrowband wireless networks for communication, such as ZigBee, NB-IoT, LTE-M, and Lora, can fit their needs. At the same time, the narrowband wireless networks also support communications among massive low throughput IoT devices at a relatively low cost and low device power consumption. However, the prerequisite of using these wireless communication networks for sensor data transmission is that they should be resistant to high temperatures and dense smoke in fire environments. Former tests carried out by Schubert and Scholz [60] showed that sensor data transmitted under 2.4 GHz signals (e.g., Wi-Fi, ZigBee, Bluetooth) might not be affected much by the dense smoke and high fire temperature within their test regime. A similar conclusion was obtained by Hofmann et al. [61], also showing that smoke and fire do not influence much the communication in the 2.4 GHz frequency band. Therefore, working in a lower frequency band with stronger penetration, these proposed narrowband networks are believed to support sensor data communication under fire conditions.

4.2.2. People Counting

To obtain the occupant count and localization information inside buildings, various occupant counting techniques can be employed. The mainly used technologies are radio frequency (RF), infrared, video cameras, or network connecting signals such as GPS, cellular data, wireless local area network (WLAN), and Bluetooth [62]. The benefits and drawbacks of these approaches were reviewed by Yang et al. [62]. In order to cause minimal influence on occupants' normal lives and privacy, multiple applicable techniques are applied to count occupants in building fire evacuation control.

First, a turning gate and swipe card system can be used at the building entrances to count the total entering and leaving occupants. The data count can be directly sent to the local server and connected to the IoT platform with a wired connection. Since the turn gate system only allows the authorized occupants to gain entry, manual recording should be kept for additional visitor entry. The building manager can record visitors' information with a web-based spreadsheet through the Wi-Fi network in buildings.

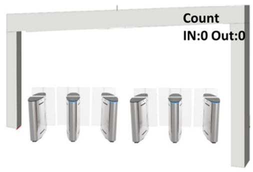
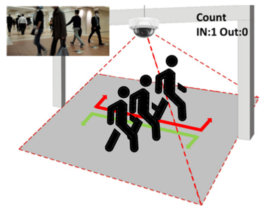
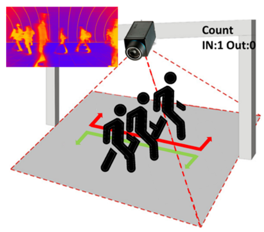
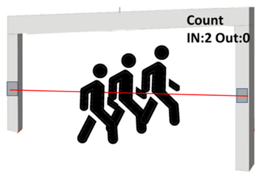
Additionally, it is considered that a turn gate system may not be suitable for people counting in residential or commercial buildings, which much affects occupants' normal life, and it hardly tells the specific number of occupants on each floor. Therefore, it is suggested to use visual-based video counters in these areas. The visual-based video counter is a video camera combined with computer vision-based algorithms to count people [63]. It can be used by direct mounting above the building/floor entrances and conducting the counting. This approach causes minimal influence on building occupants and has high recognition accuracy. Due to the high bandwidth and high reliability needs for streaming video data transmission, it is better to use wired connections for local data transmission. By connecting with the existing backbone cable of the building, the real-time local video can be directly sent to the local server and connected to the IoT service platform. An alternative approach is to link these visual-based video counters to a gateway (placed elsewhere) with cables and then connect to the IoT service platform with broadband cellular networks. The connectivity in this way not only makes it easier for the service platform to be placed on the cloud but also can ensure the reliability of streaming video data transmission in local fire environments. For the broadband cellular networks, 4G LTE and the latest 5G NR can be employed.

However, it is worth noting that people counting using visual-based video counters may fail when the building floor is full of smoke, so a thermal counter can be used at the exits of each floor as an alternative option in case the thick smoke obscures the visual-based video counters. The thermal counter is a low-resolution infrared camera combined with the people counting algorithm to enable the counting of people in low light conditions [45]. In practical usage, the thermal counter can be put inside a protective box to isolate it from the effects of fire temperature and smoke. For the data transmission of the thermal imaging data of the thermal counter, wired connections to the service platform of this IoT system are better applied.

Finally, occupant counting needs to be carried out at the room level. For corridors and public areas in buildings, the visual-based approach is applicable. However, the visual-based approach seems inappropriate for individual rooms and private use areas because privacy protection is the major concern in these places. As a result, it is recommended to use infrared beam counters. The infrared beam counter mainly consists of Passive Infra-Red (PIR) sensors and their communication modules. The PIR sensors can detect general movement by identifying infrared radiation emitted by or reflected from occupants without collecting any other personal information. They have been widely used in occupancy counting in buildings [64–67]. The major disadvantage for infrared beam counters is that when two or more persons walk side by side into the area of PIR sensor detection, the infrared beam counter may count only one, so it is not suitable for rooms with large front entrances. Fortunately, the width of the doors for most individual rooms in buildings only allows one or two persons to pass at a time. At the same time, the test by Schubert [60] also showed that fire conditions have no direct influence on infrared sensor uses. Therefore, it is applicable to use the PIR sensor for counting occupants at room level. Since the infrared beam counter transmits only the counted number of occupants, narrowband wireless networks in low power consumption can be applied for data communication between the sensors and the IoT platform, the same as those sensors and devices for fire hazard monitoring.

To better understand the solutions for people counting in building fire evacuation control, the major proposed people counting solutions are summarized in Table 3.

Table 3. Summary of the people counting solutions for fire evacuation control.

People Counting Solutions	Application Scenarios	Solution Diagrams
(a) Turn gate system	• Building entrances (office buildings)	
(b) Visual-based video counter	• Building entrances (residential and commercial buildings) • Elevator lobbies • Exits • Corridors and common areas	
(c) Thermal counter	• Exits (heavy smoke conditions)	
(d) Infrared beam counter	• Rooms and private use areas	

4.2.3. Evacuation Guiding

The evacuation guiding system needs to maintain functionality at all times. Therefore, monitoring of the state of various emergency evacuation systems and remote control of the public address system and the "smart exit signs" system is needed. Like the fire protection systems, the state monitoring of the emergency evacuation systems can be achieved by detecting the states and transmitting the data through narrowband wireless networks. For the exit and directional sign systems, narrowband wireless communications can be used to directly build the connection between the IoT devices and the system platform due to its low transmission of data. For public address and voice alarm systems, considering that voice messages or later video streaming may even be used to aid the occupants in building fire evacuation, it is suggested to use cables to build the local connectivity and then link these systems to the IoT system platform on the cloud through a route or gateway with wired or wireless broadband networks. In this way, the voice or video guidance of the evacuation can be easily delivered by ICs from the exterior of the incident premises.

As a summary, the overall information sources and means of data transmission for information needs of building fire evacuation control are given in Table 4.

Table 4. Information sources and means of data transmission of all information needs in building fire evacuation control.

Information Needs	Means of Data Collection			Data Sources	Data Transmissions	Data Integration
	Manual Check	Real-Time Monitoring	Remote Control			
A11		•		Thermocouple	ZigBee, NB-IoT, LTE-M, Lora	BIM-based fire hazard monitoring module
A12		•		Gas detector	ZigBee, NB-IoT, LTE-M, Lora	
A21	•	•		Firewater system, manual check (spreadsheet)	ZigBee, NB-IoT, LTE-M, Lora, Wi-Fi	
A22		•		Door sensors	ZigBee, NB-IoT, LTE-M, Lora	
B11	•	•		Turn gate, swipe card, manual check (spreadsheet)	wired, RFID, Wi-Fi	BIM-based occupant counting module
B12		•		Visual-based video counter	wired, LTE, 5G NR	
B21		•		Visual-based video counter	wired, LTE, 5G NR	
B22		•		Visual-based video counter, thermal counter	wired, LTE, 5G NR	
B31		•		Visual-based video counter	wired, LTE, 5G NR	
B32		•		Infrared beam counter	ZigBee, NB-IoT, LTE-M, Lora	
C11		•	•	Visual alarm and alarm sounder	ZigBee, NB-IoT, LTE-M, Lora	BIM-based evacuation guidance module
C12		•	•	Emergency lighting system	ZigBee, NB-IoT, LTE-M, Lora	
C21		•	•	Smart exit and directional sign	ZigBee, NB-IoT, LTE-M, Lora	
C22		•	•	Public address (PA) system	wired, LTE, 5G NR	

4.3. Potential Services and Applications

The proposed information sources and data transmission provide a practical means of gathering on-site information for IoT-aided building fire evacuation control. However, an IoT system is more than data collection. The utilization of the wealth of collected data for service and application is the main purpose of an IoT system. Therefore, several potential services and applications for building fire evacuation control have been designed.

4.3.1. BIM-Based Monitoring Platform

In recent years, Building Information Modeling (BIM), as well as Virtual Design and construction (VDC), has gained increasing impact in the Architecture, Engineering, and Construction (AEC) Industry. The development of BIM/VDC provides a virtual design and construction platform to facilitate the design and construction as well as the project management process. The tool permits the display of building plans in three dimensions; people can easily understand the building geometries and the added information right into the building components. Recently, there have been some research works concerning the use of BIM for building fire safety management and evacuations [29,47,49,68,69].

For the proposed IoT-aided building fire evacuation control system, it is also important to integrate the collected sensor data into a BIM model and establishing visualization for the users. Visualized information can make it easier for building managers and ICs to guide the evacuation and manage various emergency evacuation facilities and equipment. The visualized information includes both static and dynamic information. The static information contains geometries of the building and compartments, locations of various fire protection and evacuation equipment, and maintenance information. The dynamic information is data collected from the local sensors, which can contain people counts, states of various facilities, and detections of the indoor environment. By attaching the dynamic information to the corresponding equipment or spaces inside the BIM model, browsing the real-time sensor data from a 3D interface is able to be achieved. Apart from visualizing these monitoring data, the BIM model also creates a platform for exchanging data with the fire risk assessment module and evacuation decision supporting module to provide more useful services. The approaches and functions of these two modules are introduced next.

4.3.2. Fire Risk Assessment

The major function of the fire risk assessment module is to help identify the hazardous areas of the fire event so that occupants can bypass the area and evacuate smoothly. By collecting the ambient status from various environmental sensors, monitoring of the indoor fire environment is enabled. Afterwards, by comparing these monitoring data with the criteria for occupants to safely evacuate the building, such as at 2.0 m height of the enclosure space, air temperature below 100 °C, concentrations of carbon monoxide below 2800 ppm, etc. [70], the areas at risk can be identified. Finally, by linking these identified hazardous areas to the BIM platform, hazardous areas can be directly viewed on BIM models.

In addition to identifying the hazardous areas in a fire, the collected data can also be used to mine more necessary information regarding fire characteristics, such as fire origins, fire sizes, stages of fire development, etc. This sort of problem is called a fire inverse problem, which involves using the observed sensor data to infer the causal factors that produced it. Many studies have explored the inference of fire origins, fire sizes, and stages of fire development from temperature observations [71–74]. With the machine learning approach to find out the relationship between the fire characteristics and a large volume of simulated fire data, dynamic inference of the various fire characteristics from a series of on-site sensor data collection can be enabled. Understanding the characteristics of the ongoing fire provides the necessary information basis for building managers and ICs to predict the risks in the evacuation process, so it is very important for evacuation decisions.

4.3.3. Evacuation Decision Support

The evacuation decision support module works for the major purpose of evacuation control, including the planning of evacuation strategies and subsequently the evacuation guidance. For the planning of evacuation strategies, evacuation simulation provides a possible approach. Evacuation simulation is a computer-based approach to determine the total egress time based on the simulation of crowd dynamics and pedestrian motion. The existing software or modeling approach include FDS + Evac [75], SGEM [76], agent-based modeling (ABM) [77], and cellular automata (CA) [78]. By determining the input parameters, such as building geometries, initial occupants' locations, evacuation strategies, and individual behaviors and interactions, evacuation simulation can predict the evacuation process and evaluate the evacuation with some indicators, including total egress time, travel distance, door flow rate, etc. From these indicators, whether or not the evacuation strategy is acceptable can be determined. In the currently proposed system, the data collection of people counting for each floor is dynamically linked with the simulation model. In addition, the hazardous areas and characteristics of the ongoing fire analyzed in the fire risk assessment module are also connected to the evacuation model. The evacuation simulation may become more adaptable to the real fire situation on-site by considering these dynamic parameter inputs. With such dynamic evacuation modeling to assess the effectiveness of different evacuation strategies, such as evacuating occupants with different sequences, whether evacuating occupants with the help of elevators, etc., safety and effectiveness of implementing the building evacuation can be significantly improved.

As for the evacuation guidance part, it is meant to make the planned evacuation strategies come into action. With the control of the exit and directional signs, the evacuation decision support module can deliver the planned evacuation route to evacuees. Moreover, the state and condition of each exit and directional sign can be monitored and viewed in the BIM-based platform. Furthermore, considering that it may need to control the sequence of evacuation for each floor, the evacuation decision support module also enables sending voice alarms and instructions to the designated areas or floors via PA systems.

4.4. Advantages of the Proposed System

By summarizing the information sources, means of data transmission, and potential services and applications in building fire evacuation control, a preliminary design of an IoT-aided building fire evacuation control system is proposed. The system architecture is demonstrated in Figure 3. With the sensors and devices to collect various information on the fire-ground, a variety of means of data transmission are applied to build the communication between sensors and the IoT platform. In order to provide more diversified services and applications to help the building evacuation, promising technologies including BIM, fire inverse, and evacuation simulation are embraced in the system. Furthermore, considering the importance of data protection and system security, the system is also equipped with an authentication and encryption layer to protect the endpoint devices so that malicious attacks and data breaches can be avoided. In addition to protecting the security of endpoint devices, data security in the IoT platform can be enabled by firewalls and strong user authentication processes. With these measures, the proposed system can be secure and only used for its intended uses (i.e., fire-ground situational awareness, evacuation planning, or evacuation guidance).

The advantages of the proposed system are summarized as follows:

(1) Monitoring the fire environment and occupants' situations in buildings.

IoT technology provides a possible approach to link the cyber and physical environment together in building fire evacuation control. By establishing the perception layer and network layer of the proposed IoT system, the ubiquitous sensors and various communication networks can be integrated to enable the monitoring of the fire environment and occupants' situations in buildings. Compared with traditional fire evacuation, the IoT-aided fire evacuation highly improves the information collection and update on-site, ensuring safety in evacuations. Moreover, the collected people count information is also useful for building energy management in regular time. Therefore, it is applicable to implement such a system in buildings.

(2) 3D-visualization of the building information.

By exchanging the monitoring data from various sensors and devices through the Internet, IoT enables the aggregation of all the on-site information into one place. Thus, combined with BIM, the visualization and management of various evacuation equipment and facilities within the BIM model can be achieved. With the BIM model to show the locations of various evacuation facilities and hazardous areas, a direct understanding of the relationship between the building geometry and the fire situation can be built by building managers and ICs, making it easier to guide occupants' evacuations. As for the information regarding the state of various firefighting equipment and evacuation facilities, it consists of its historical data and real-time monitoring data. By attaching the state information to the specific equipment and facilities in the BIM model, browsing and control of these installations can be achieved.

(3) System-level-based evacuation strategy planning.

With the integration of IoT devices, IoT data, and IoT platforms, the IoT system enables data transfer and interoperation to support more advanced services and applications. Therefore, the fire risk assessment module and the evacuation decision support module are proposed, respectively. These modules can help the planning of evacuation strategies from a systematic level. Compared with the traditional pre-defined fire evacuation plan, the currently proposed system enables dynamic adjustment of the evacuation strategy according to the fire development and the pattern of occupants' location. As a result, more effective and efficient fire evacuation control in tall buildings can be achieved.

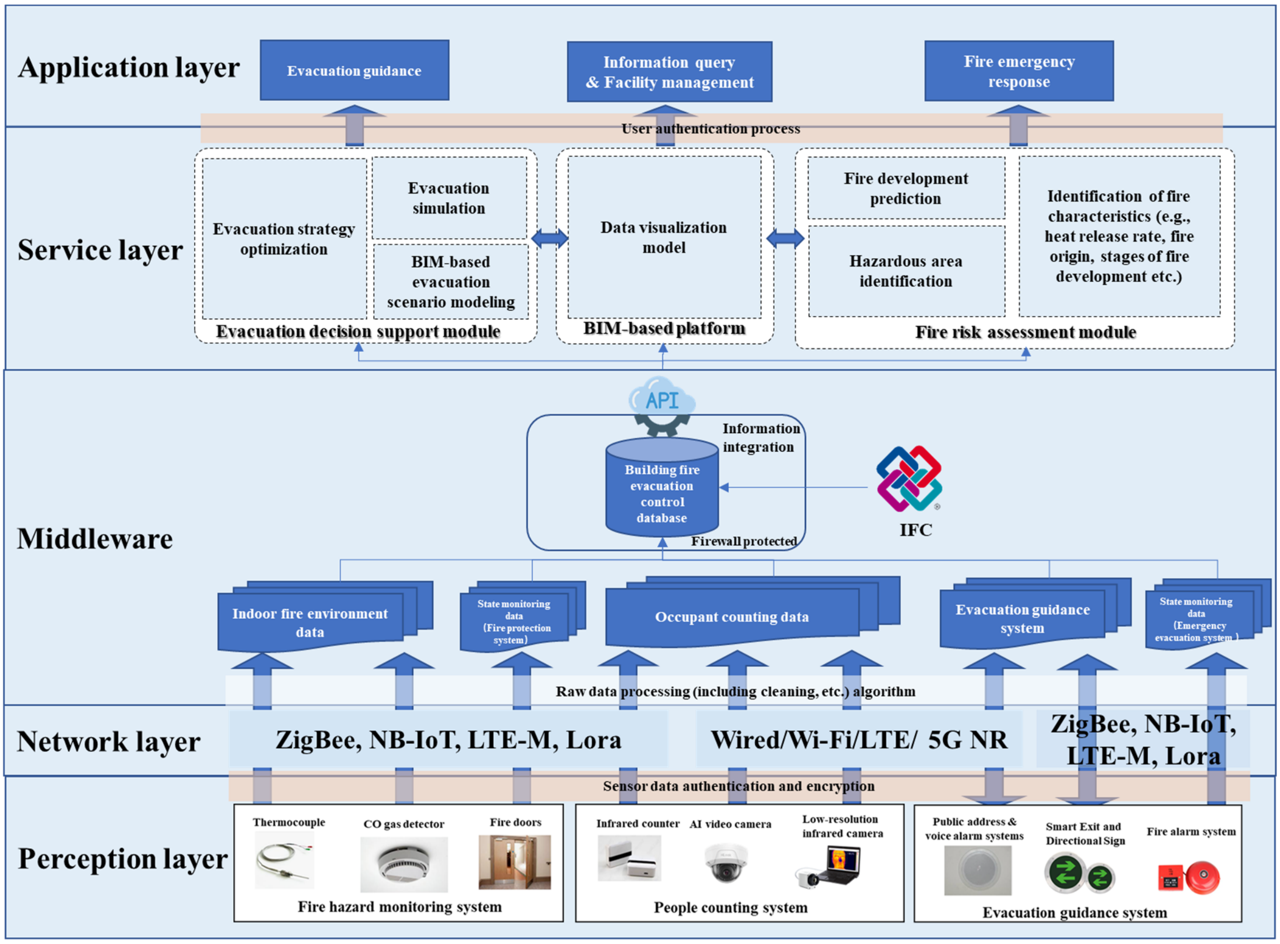


Figure 3. IoT-aided building fire evacuation control system.

5. Opportunities in the 5G Era

With the commercial deployment of 5G starting in 2019, we are stepping into the new era of mobile communications. More than improving the mobile broadband speed, 5G also fits the needs of a diverse range of speed, bandwidth, and quality of service requirements, making the nature of the 5G communications more suitable for future IoT system design requirements [79]. The major technological breakthroughs in 5G, including millimeter-wave (mmWave) spectrum, massive MIMO, network ultra-densification, network function virtualization (NFV), software-defined networking (SDN), device-to-device (D2D) communications, etc., ensure such a more diverse and reliable network connection [80]. With the continued deployment of the 5G infrastructure, there are certainly more opportunities to apply 5G technologies in building fire evacuation control in the future. Therefore, opportunities for building fire evacuation in the 5G era are introduced in this section.

5.1. Massive Machine Type Communications

From the proposed IoT-aided building fire evacuation control system, it is obvious that the major communication in the fire evacuation control system is Machine to Machine (M2M) communication. M2M transmits a small volume of data but connects a great number of devices, so it is mainly used for automated data transmission and measurement between mechanical or electronic devices, such as temperature measurement, state monitoring, infrared people counting, etc. In the 5G era, with the connection of various building systems and components to implement smart buildings, traditional IoT-enabled communication technologies, such as Zigbee, Bluetooth, GSM, etc., may become insufficient to support massive M2M communications in buildings because of their limitations in coverage and connected devices. Therefore, the low-power wide-area networks (LPWAN) are worth using. Currently, the most commonly used LPWAN in IoT is Narrow Band Internet of Things (NB-IoT).

The NB-IoT is a cellular-based LPWAN proposed in 2016, supporting a high volume of low complexity connected devices intended to transmit small data packages. Thus, it fits the need of M2M communications in IoT applications by transmitting tiny amounts of information in a long-range [18]. Due to the fact that NB-IoT meets most 5G mMTC requirements, NB-IoT will continue to play an important role in communication in the 5G era and eventually evolve into a part of 5G technologies [81]. The benefits of using the NB-IoT in fire evacuation control is summarized as follows:

(1) Extensive indoor and outdoor coverage.

NB-IoT provides improved indoor and outdoor coverage—approximately 1 km in urban areas and 10 km for rural areas [82]. Therefore, it is convenient to install the IoT sensors wirelessly in any place in a large complex building, not only the deep underground spaces but also floor gardens on top of the building.

(2) Available for massive connection.

NB-IoT allows for deployments of up to 200,000 devices in theory per cell [83]. With such great multiplexing, more sensors and devices in buildings are available to connect to the network and send their states to the building managers and/or fire services. This promotes the situational awareness abilities and management of resources on the fire-ground.

(3) Low device power consumption.

Devices with NB-IoT usually consume less power than other enabling technologies. The battery life of NB-IoT-based devices is over 10 years. This is highly valued for IoT applications because a large number of sensor nodes spread everywhere. Frequent battery replacement not only consumes a large amount of power but also increases the cost of labor.

(4) High reliability and security.

NB-IoT uses a licensed spectrum as other cellular technologies do, so the quality of service (QoS) and security can be guaranteed. Communicating in a licensed spectrum, NB-IoT avoids interference from other users located nearby. Furthermore, carefully specified by standards body 3GPP, NB-IoT also benefits from the security features of cellular networks.

(5) Low cost.

The NB-IoT scores with low module costs as well as low operation and service prices. At present, the cost of NB-IoT modules is as little as USD 6–12 each [84]. The services charge is around USD 3–6 per year per device for China Mobile in China. In addition, the extensive coverage of NB-IoT eliminates the use of nodes and gateways in buildings, so the cost of deploying the network is also reduced.

5.2. AR-Enabled Fire Evacuation

Augmented Reality (AR) is becoming one of the most promising technologies to facilitate evacuation safer, quicker, and easier. Unlike Virtual Reality (VR), AR overlays digital or computer-generated information over a real-time environment. Thus, AR supplements reality rather than completely replacing it. In building fire evacuation, with the use of a smartphone or head-up display (HUD), the virtual indicators can be superimposed onto the real objects in buildings, such as exits, stairwells, and hazardous areas. In this way, occupants can be alerted and find evacuation routes immediately.

The application of AR facilitating fire evacuation has been studied a lot. In the study of Tsai and Yau [85], AR technologies, route planning, and three-dimensional graphics technologies were integrated to provide evacuation route guidance by giving virtual indicators on the escape route in the context of a radioactive accident. An AR-based building fire evacuation system was developed by Sharma S et al. [86]. The system applied a Microsoft HoloLens augmented/mixed reality device to provide a visual representation of a building in 3D space and allowed the occupants to see where exits were in the building. Moreover, AR technologies were applied to help firefighters search and rescue in fire emergencies. The C-Thru helmet from Qwake Technologies was developed to help firefighters' fire-ground operations by showing the silhouettes of otherwise indiscernible objects and people on the fire-ground [87]. However, limited by the mobile communications previously used that possess low speed and high latency, the application of AR is not to scale. Using AR in fire evacuation is still being explored.

In the 5G era, this situation will change. The high bandwidth and ultra-low latency that the 5G network provides will bring more new experiences to AR-enabled fire evacuation. In the future, occupants can use AR to identify the risks in surroundings during the evacuation, such as falling ceilings, thick gas layers, or even collapsing walls. In this case, it is necessary to enable real-time video streaming via the 5G network because the captured video must be transmitted to a local or cloud processor for visual-based data processing in real-time due to the limitation of the computing power on the end device. Moreover, with the edge computing work with 5G, the network latency will be highly reduced by processing data closer to the end-user. Low wireless latency improves the immersion of the users, helping evacuees receive feedback from the processor more quickly and receive better information acquisition from the interaction with the environment.

5.3. Network Slicing Technology in Emergency Communication

Network slicing has emerged as one of the essential components in 5G technologies [88]. Compared with previous mobile network communications, the 5G network allows numerous users with varying requirements to operate within one network. Therefore, it is imperative to apply a technique to subdivide one network into various virtual networks and accommodate various priorities and use cases. By employing network function virtualization (NFV) and software-defined networking (SDN) to manage the dynamically changing capacity requirements, the network slicing technology will fit the needs by unlocking and orchestrating the specific resources to create network slices fitting different application scenarios [89].

In the 5G era, one of the most useful applications for network slicing is mission-critical communications [90]. Mission-critical communication is mainly used for emergency response (ER) operations where the communication needs to be reliable, available, and secure in any circumstance. In the past, mission-critical communication was mainly supported by public safety networks (PSNs), such as Terrestrial Trunked Radio (TETRA), Digital Mobile Radio (DMR), and Project 25 (P25), all of which are private networks only serving the ER services [19]. To some extent, these networks provide dedicated and reliable communication for mission-critical operations, but they are developed by narrowband communication technologies, so only voice services are supported. With the wide distribution of public cellular base stations and the demand of using faster and rich information communication to support public safety services, such as voice and video calling, internet/intranet access, high-quality imaging, and real-time video recording [91], it is inevitable to evolve PSNs from traditional radio-based networks to commercial cellular networks. However, it is dangerous to directly use commercial cellular networks for ER communication because the reliability, availability, and security of commercial networks may not be guaranteed in some circumstances. For example, in large public events, thousands of mobile users may connect to the network at once, causing the network to collapse easily. Emergency communication under the same network can be severely disturbed in such a situation. The network slicing technology provides a possible approach for solving this. Through the 5G network slicing, we can bypass the commercial consumer networks, which may already be congested or at full capacity, and create additional network capacity to support the ER information that involves transmitting significant amounts of real-time data in a reliable and uninterrupted manner.

In the building fire evacuation situation, a sharp increase of network connection by occupants and citizens may emerge at the surrounding area of the building after the fire occurrence. Therefore, it is necessary to create two slices, one of which is dedicated to emergency responders and the others to serve public users. Communicating under the network slice for ER, the IC can enable liaising with responders in the fire building without interference. As a result, the real-time evacuation progress can be reported to IC clearly and on time. Moreover, the broadband network slice will support many bandwidth-hungry applications to facilitate fire-ground situational awareness. These applications include using drones with high-resolution cameras to monitor fire development on building exteriors and setting up video channels to collect real-time fire situations from the firefighters entering the fire-ground. With the help of the 5G network slicing technology, more effective and efficient fire evacuation and ER operations can be conducted.

5.4. D2D in On-Site Information Delivering

Device-to-Device (D2D) communication, which refers to a radio technology that enables direct communication between devices (i.e., users) without data traffic going through any infrastructure node such as an access point or base stations, is recognized as one of the important technical components of the evolving 5G architecture [92]. By establishing the connection with each other directly, this type of communication can work in the absence of network operators or any central entity such as a base station [93]. Therefore, it is very useful for emergency situations where the cellular infrastructure is completely or partially dysfunctional. To help the build of emergency communication under such emergencies, many D2D applications have been proposed. One of the most important application scenarios is to help rescue missions by maintaining proximate communication among rescuers, communication between rescuers and victims, etc. [94–96]. The D2D technology can provide increased data rates and better QoS in emergency communication by building direct connections among users. In addition, the D2D communication can be used in a multi-hop manner to relay signals by connecting to other devices that reach operational base stations [97–99]. This sort of application can enable the extension of the network coverage or alternatively boost the existing network's capacity in critical conditions.

There is also a large likelihood of encountering partial or total network failure in building interiors due to fire damage or network congestion in urban tall building fire events. The lack of prompt on-site communication may cause the IC to make wrong commands and delay the escape of the building occupants. Furthermore, due to the increased reliance on wireless sensors or devices to facilitate various operations before or during the ER in the future, the collapse of the network in buildings may cause even more severe impacts to ER operations. Therefore, it is essential to maintain the robustness of the communication network in tall buildings. One possible approach is to use the network slicing technology to create additional slices for emergency communication. However, this approach is only helpful when the network infrastructure is intact. Fire incidents in tall buildings may damage the cellular infrastructure in buildings causing total network malfunction. The D2D communication successfully solves this issue by providing direct communications among users without going through any infrastructure nodes. Thus, it will surely play an important role in future building fire evacuation in tall buildings. Moreover, another application of D2D communication is to directly deliver the live information of the fire event and evacuation guidance to occupants' mobile devices. This allows the occupants to be aware of the fire event in a timely fashion and take prompt actions.

6. Discussion

The currently proposed IoT-aided building fire evacuation provided a possible approach for turning the building fire evacuation smart. By integrating the promising technologies of IoT, BIM, and 5G into fire emergency response and building evacuation, it is believed that a more effective and efficient building fire evacuation mode can be achieved, and more lives can be saved. However, to deploy such a system in practice, there may still be some difficulties. One of the important aspects is that its effectiveness and reliability may be a great concern to fire authorities. Even though 5G and other existing wireless communication networks provide a much simpler and flexible way to support various IoT use cases in built environments, there still needs to be more evidence to convince that the effectiveness and reliability of wireless sensors (e.g., fire detector, fire alarm) can be ensured and meet the requirements of current regulations of fire detection and fire alarm systems in terms of various fire situations. In addition, the interoperation of IoT devices between different vendors is also a problem. Currently, the IoT industry has no widely adopted data standards that IoT vendors can conform to, which makes it difficult to integrate the diversified sources of data in buildings into one platform. Therefore, in terms of the legislation control for IoT-aided building fire evacuation in the future, specific information needs, means of data transmission, and data interoperability should be stipulated by authorities. Furthermore, the stipulation of the construction of IoT-aided building fire evacuation systems should run through its whole life cycle, including the system design along with the building design in the design phase, implementation of the system in the building construction stage, and specific system operation and data management requirements in the operation phase.

In addition to acquiring the fire hazard information and occupants' situations on the fire-ground inside buildings, the currently proposed IoT-aided building fire evacuation also expects to employ the collected information to assist occupant evacuation with a dynamic adjustment of evacuation strategies via various modern information and communication technologies (ICT). Therefore, people's responses in such critical situations in connection to modern ICT or their adaptability to real-time evacuation guidance may play important roles in the successful operation of the system. Previous research conducted under an international survey and a full-scale evacuation trial [100,101] demonstrated that the active dynamic direction-changing signage systems indeed have their effectiveness in real evacuation scenarios. In addition, the effectiveness of public displays providing dynamic directions for crowd evacuation was also convinced in a large-scale football stadium scenario with simulations [102]. As for the usability of smartphones in providing dynamic evacuation strategy notification to evacuees, a study by Amores et al. [103] showed that people might have limited cognitive capacity when using mobile phones under stress. However, most of the experimental participants believed that the mobile phone is somewhat useful to their evacuations. From the previous research, it is believed that occupants can be adapted to the evacuation mode proposed by the IoT-aided building fire evacuation system, and the IoT-aided building fire evacuation has the potential to become a game-changer in future building fire emergency response and evacuation.

7. Concluding Remarks

From the tragedy of the Grenfell Tower fire, we can see room for improving the current emergency response and building fire evacuation, with the ongoing trend that all engineering fields are actively improving their efficiency and effectiveness with the aid of IoT-based systems. As one of the important aspects of building and fire safety, building fire evacuation should also not fall behind this progress. The IoT-aided building fire evacuation is a new concept of building evacuation mode which enhances the building fire evacuation, including the elevator evacuation process, by making the most appropriate evacuation strategies based on the real-time fire-ground information, such as fire environment and occupants' situations. With the maturity of IoT technologies and the appearance of more IoT application scenarios in the 5G era, the IoT-aided building fire evacuation will no longer be only a concept. It has great potential to be used in practice and play more important roles in future emergency response. Therefore, by focusing on IoT applications in building fire evacuation, this paper investigated the advantages and insufficiencies of current smart building fire evacuation systems. After that, a preliminary design of an IoT-aided building fire evacuation control system was proposed. The proposed IoT system was designed in the sequence of information needs, information sources and data transmission, and potential services and applications, which corresponds to the architecture of an IoT system. In addition, the advantages of the proposed system were also concluded. The proposed system could enable (1) monitoring of the fire environment and occupants' situations in buildings; (2) 3D-visualization of the building information; and (3) system-level-based evacuation strategy planning. With the help of the proposed IoT system, safe and more efficient building fire evacuation will surely be enabled.

The 5G era will be characterized as the age of boundless connectivity for all and intelligent automation, which enriches people's lives and improves the efficiency of all engineering fields. In building fire evacuation, 5G combined with IoT, BIM, and various data analytics technologies also presents vast amounts of possibilities and opportunities to overcome the challenges ahead of information perception, data management, and intelligent decision making. The wonderful things that 5G brings to building fire evacuation are not only allowing for more IoT use cases to transmit their data in a wireless approach, but also bring various communication services with different performance requirements, whether they are massive machine type communications, bandwidth-hungry applications (e.g., HD video streaming, AR applications), or critical emergency using scenarios, so that information needs related to indoor environments, states of various building facilities, and occupants' status can be systematically integrated and freely worked together in actual fire emergency scenes. However, to deploy such a system in practice, there may still be difficulties. Aspects include system reliability, legislation control, and acceptance of the public, which still need to be improved. Only in this way can IoT-aided building fire evacuation truly fulfill its functions in the 5G era.

Author Contributions: The following are categorizations of individual contributions to this paper: conceptualization of research idea, H.F.; research methodology, H.F.; writing—original draft preparation, H.F.; writing—review and editing, S.L. and J.T.Y.L.; supervision, S.L.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the grants No. 7005046 and No. CityU 11217319.

Acknowledgments: The authors gratefully acknowledge the grants Nos. 7005046 and CityU 11217319 for supporting this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. BBC. Grenfell Tower: What Happened. Available online: https://www.bbc.com/news/uk-40301289 (accessed on 29 October 2019).
2. Arewa, A.O.; Ahmed, A.; Edwards, D.J.; Nwankwo, C. Fire Safety in High-Rise Buildings: Is the Stay-Put Tactic a Misjudgement or Magnificent Strategy? *Buildings* **2021**, *11*, 339. [CrossRef]
3. Preston, J. The Grenfell Tower Fire: 'Stay Put' and Eliminationism. In *Grenfell Tower: Preparedness, Race and Disaster Capitalism*; Springer International Publishing: Cham, Germany, 2019; pp. 31–53.
4. GTI. *Grenfell Tower Inquiry: Phase 3 Report-1. Report of the Public Inquiry into the Fire at Grenfell Tower on 14 June 2017*; APS Group on behalf of the Controller of Her Majesty's Stationery Office: London, UK, 2019; pp. 602–607.
5. Athreya, A.P.; Tague, P. Network self-organization in the Internet of Things. In Proceedings of the 2013 IEEE International Workshop of Internet-of-Things Networking and Control (IoT-NC), New Orleans, LA, USA, 24 June 2013; pp. 25–33.
6. Wang, C.-X.; Haider, F.; Gao, X.; You, X.-H.; Yang, Y.; Yuan, D.; Aggoune, H.M.; Haas, H.; Fletcher, S.; Hepsaydir, E. Cellular architecture and key technologies for 5G wireless communication networks. *IEEE Commun. Mag.* **2014**, *52*, 122–130. [CrossRef]
7. Harrison, V. 5G: World's First Commercial Services Promise 'Great Leap'. Available online: https://www.bbc.com/news/business-47796528 (accessed on 5 April 2019).
8. Al-Falahy, N.; Alani, O.Y. Technologies for 5G networks: Challenges and opportunities. *IT Prof.* **2017**, *19*, 12–20. [CrossRef]

9. Zaidi, A.A.; Baldemair, R.; Andersson, M.; Faxér, S.; Molés-Cases, V.; Wang, Z. Designing for the future: The 5G NR physical layer. *Ericsson Technol. Rev* **2017**, 1–13. Available online: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/designing-for-the-future-the-5g-nr-physical-layer (accessed on 15 October 2021).
10. Ejaz, W.; Anpalagan, A.; Imran, M.A.; Jo, M.; Naeem, M.; Qaisar, S.B.; Wang, W. Internet of Things (IoT) in 5G Wireless Communications. *IEEE Access* **2016**, *4*, 10310–10314. [CrossRef]
11. Gartner. IoT Integration. Available online: https://www.gartner.com/en/information-technology/glossary/iot-integration. (accessed on 15 October 2021).
12. Sembroiz, D.; Ricciardi, S.; Careglio, D. Chapter 10—A Novel Cloud-Based IoT Architecture for Smart Building Automation. In *Security and Resilience in Intelligent Data-Centric Systems and Communication Networks*; Ficco, M., Palmieri, F., Eds.; Academic Press: Cambridge, MA, USA, 2018; pp. 215–233.
13. Agarwal, Y.; Balaji, B.; Gupta, R.; Lyles, J.; Wei, M.; Weng, T. Occupancy-driven energy management for smart building automation. In Proceedings of the 2nd ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Building, Zurich, Switzerland, 2 November 2010; pp. 1–6.
14. Dong, B.; Prakash, V.; Feng, F.; O'Neill, Z. A review of smart building sensing system for better indoor environment control. *Energy Build.* **2019**, *199*, 29–46. [CrossRef]
15. Jia, M.; Srinivasan, R.S. Occupant behavior modeling for smart buildings: A critical review of data acquisition technologies and modeling methodologies. In Proceedings of the 2015 Winter Simulation Conference (WSC), Huntington Beach, CA, USA, 6–9 December 2015; pp. 3345–3355.
16. Jew, A. Data Center Telecommunications Cabling and TIA Standards. In *Data Center Handbook: Plan, Design, Build, and Operations of a Smart Data Center*; John and Wiley and Sons: Hoboken, NJ, USA, 2021; pp. 193–210.
17. Havard, N.; McGrath, S.; Flanagan, C.; MacNamee, C. Smart Building Based on Internet of Things Technology. In Proceedings of the 12th International Conference on Sensing Technology (ICST), Limerick, Ireland, 4–6 December 2018; pp. 278–281.
18. Sinha, R.S.; Wei, Y.; Hwang, S.-H. A survey on LPWA technology: LoRa and NB-IoT. *ICT Express* **2017**, *3*, 14–21. [CrossRef]
19. Jarwan, A.; Sabbah, A.; Ibnkahla, M.; Issa, O. LTE-Based Public Safety Networks: A Survey. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 1165–1187. [CrossRef]
20. Diago-Mosquera, M.E.; Aragón-Zavala, A.; Castañón, G. Bringing It Indoors: A Review of Narrowband Radio Propagation Modeling for Enclosed Spaces. *IEEE Access* **2020**, *8*, 103875–103899. [CrossRef]
21. Kuzminykh, I.; Snihurov, A.; Carlsson, A. Testing of communication range in ZigBee technology. In Proceedings of the 2017 14th International Conference The Experience of Designing and Application of CAD Systems in Microelectronics (CADSM), Lviv, Ukraine, 21–25 February 2017; pp. 133–136.
22. Smailagic, A.; Kogan, D. Location sensing and privacy in a context-aware computing environment. *IEEE Wirel. Commun.* **2002**, *9*, 10–17. [CrossRef]
23. Zulkefly, N.R.; Rahman, T.A.; Al-Samman, A.M.; Mataria, A.M.S.; Leow, C.Y. 4G channel characterization for indoor environment at 2.6 GHz. In Proceedings of the 2015 IEEE 11th International Colloquium on Signal Processing & Its Applications (CSPA), Kuala Lumpur, Malaysia, 6–8 March 2015; pp. 63–65.
24. Soliman, M.M.; Sabbir, M.M.H.; Alkaeed, M.; Ahmed, M.R.; Rafi, I.A.; Mahfuz, M.M.H. Investigation of Signal Penetration Loss Variation on Different Building Components and Disparity of Receiver Location on 3G/4G Network in the Context of Bangladesh. In Proceedings of the 2020 11th IEEE Control and System Graduate Research Colloquium (ICSGRC), Shah Alam, Malaysia, 8 August 2020; pp. 53–58.
25. Ngu, A.H.; Gutierrez, M.; Metsis, V.; Nepal, S.; Sheng, Q.Z. IoT middleware: A survey on issues and enabling technologies. *IEEE Internet Things J.* **2016**, *4*, 1–20. [CrossRef]
26. Ibrahim, A.M.; Venkat, I.; Subramanian, K.G.; Khader, A.T.; Wilde, P.D. Intelligent Evacuation Management Systems: A Review. *ACM Trans. Intell. Syst. Technol.* **2016**, *7*, 1–27. [CrossRef]
27. Balboa, A.; González-Villa, J.; Cuesta, A.; Abreu, O.; Alvear, D. Testing a real-time intelligent evacuation guiding system for complex buildings. *Saf. Sci.* **2020**, *132*, 104970. [CrossRef]
28. Zualkernan, I.A.; Aloul, F.A.; Sakkia, V.; Noman, H.A.; Sowdagar, S.; Hammadi, O.A. An IoT-based Emergency Evacuation System. In Proceedings of the 2019 IEEE International Conference on Internet of Things and Intelligence System (IoTaIS), Bali, Indonesia, 5–7 November 2019; pp. 62–66.
29. Cheng, M.-Y.; Chiu, K.-C.; Hsieh, Y.-M.; Yang, I.T.; Chou, J.-S.; Wu, Y.-W. BIM integrated smart monitoring technique for building fire prevention and disaster relief. *Autom. Constr.* **2017**, *84*, 14–30. [CrossRef]
30. Zhang, J.; Guo, J.; Xiong, H.; Liu, X.; Zhang, D. A Framework for an Intelligent and Personalized Fire Evacuation Management System. *Sensors* **2019**, *19*, 3128. [CrossRef]
31. Chou, J.-S.; Cheng, M.-Y.; Hsieh, Y.-M.; Yang, I.T.; Hsu, H.-T. Optimal path planning in real time for dynamic building fire rescue operations using wireless sensors and visual guidance. *Autom. Constr.* **2019**, *99*, 1–17. [CrossRef]
32. Saeed, F.; Paul, A.; Rehman, A.; Hong, W.; Seo, H. IoT-based intelligent modeling of smart home environment for fire prevention and safety. *J. Sens. Actuator Netw.* **2018**, *7*, 11. [CrossRef]
33. Sarwar, B.; Bajwa, I.S.; Jamil, N.; Ramzan, S.; Sarwar, N. An Intelligent Fire Warning Application Using IoT and an Adaptive Neuro-Fuzzy Inference System. *Sensors* **2019**, *19*, 3150. [CrossRef] [PubMed]

34. Park, S.; Park, S.H.; Park, L.W.; Park, S.; Lee, S.; Lee, T.; Lee, S.H.; Jang, H.; Kim, S.M.; Chang, H.; et al. Design and Implementation of a Smart IoT Based Building and Town Disaster Management System in Smart City Infrastructure. *Appl. Sci.* **2018**, *8*, 2239. [CrossRef]
35. Chittaro, L.; Nadalutti, D. A Mobile RFID-Based System for Supporting Evacuation of Buildings. In *Mobile Response, Proceedings of the the Second International Workshop on Mobile Information Technology for Emergency Response, Bonn, Germany, 29–30 May 2008*; Springer: Berlin/Heidelberg, Germany, 2008.
36. D'Orazio, M.; Longhi, S.; Olivetti, P.; Bernardini, G. Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire. *Autom. Constr.* **2015**, *52*, 16–28. [CrossRef]
37. Jiang, H. Mobile Fire Evacuation System for Large Public Buildings Based on Artificial Intelligence and IoT. *IEEE Access* **2019**, *7*, 64101–64109. [CrossRef]
38. Atila, U.; Ortakci, Y.; Ozacar, K.; Demiral, E.; Karas, I.R. SmartEscape: A Mobile Smart Individual Fire Evacuation System Based on 3D Spatial Model. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 223. [CrossRef]
39. Dominicis, C.M.D.; Depari, A.; Flammini, A.; Rinaldi, S.; Sisinni, E. Smartphone based localization solution for construction site management. In Proceedings of the 2013 IEEE Sensors Applications Symposium Proceedings, Galveston, TX, USA, 19–21 February 2013; pp. 43–48.
40. Ran, H.; Sun, L.; Gao, X. Influences of intelligent evacuation guidance system on crowd evacuation in building fire. *Autom. Constr.* **2014**, *41*, 78–82. [CrossRef]
41. Rinne, T.; Hostikka, S.; Paloposki, T.; Korhonen, T.; Saari, J.; Heliövaara, S. Application of RFID and video imaging on evacuation observations in offices and public buildings. *Fire Saf. Sci.* **2008**, *9*, 329–340. [CrossRef]
42. Yu, K.; Yu, C.; Lien, C.; Cheng, S.; Lei, M.; Hsu, H.; Tsai, N. Intelligent evacuation system integrated with image recognition technology. In Proceedings of the 2015 8th International Conference on Ubi-Media Computing (UMEDIA), Colombo, Sri Lanka, 24–26 August 2015; pp. 23–28.
43. Billhardt, H.; Dunkel, J.; Lujak, M.; Fernández, A.; Hermoso, R.; Ossowski, S. An Architecture for Situation-Aware Evacuation Guidance in Smart Buildings. In Proceedings of the AmILP@ECAI, The Hague, The Netherlands, 29 August 2016.
44. Cheng, J.C.P.; Chen, K.; Wong, P.K.-Y.; Chen, W.; Li, C.T. Graph-based network generation and CCTV processing techniques for fire evacuation. *Build. Res. Inf.* **2021**, *49*, 179–196. [CrossRef]
45. Amin, I.J.; Taylor, A.J.; Junejo, F.; Al-Habaibeh, A.; Parkin, R.M. Automated people-counting by using low-resolution infrared and visual cameras. *Measurement* **2008**, *41*, 589–599. [CrossRef]
46. Chen, X.-S.; Liu, C.-C.; Wu, I.-C. A BIM-based visualization and warning system for fire rescue. *Adv. Eng. Inform.* **2018**, *37*, 42–53. [CrossRef]
47. Wang, S.-H.; Wang, W.-C.; Wang, K.-C.; Shih, S.-Y. Applying building information modeling to support fire safety management. *Autom. Constr.* **2015**, *59*, 158–167. [CrossRef]
48. Wang, B.; Li, H.; Rezgui, Y.; Bradley, A.; Ong, H.N. BIM Based Virtual Environment for Fire Emergency Evacuation. *Sci. World J.* **2014**, *2014*, 589016. [CrossRef]
49. Ma, G.; Wu, Z. BIM-based building fire emergency management: Combining building users' behavior decisions. *Autom. Constr.* **2020**, *109*, 102975. [CrossRef]
50. Ohta, T.; Dunkel, J. Simulation of Evacuation Route Guidance in MANET-based Building Evacuation System. In Proceedings of the 12th EAI International Conference on Performance Evaluation Methodologies and Tools, Palma, Spain, 12–15 March 2019; pp. 195–196.
51. Ferraro, V.; Settino, J. Evacuation and Smart Exit Sign System. In *The Internet of Things for Smart Urban Ecosystems*; Cicirelli, F., Guerrieri, A., Mastroianni, C., Spezzano, G., Vinci, A., Eds.; Springer International Publishing: Cham, Germany, 2019; pp. 363–383.
52. Jia, Q.-S.; Zhang, Y.; Zhao, Q. Controlling the Internet of Things—From Energy Saving to Fast Evacuation in Smart Buildings. In *Intelligent Building Control Systems: A Survey of Modern Building Control and Sensing Strategies*; Wen, J.T., Mishra, S., Eds.; Springer International Publishing: Cham, Germany, 2018; pp. 293–310.
53. Cho, J.; Lee, G.; Lee, S. An automated direction setting algorithm for a smart exit sign. *Autom. Constr.* **2015**, *59*, 139–148. [CrossRef]
54. Purser, D.A.; McAllister, J.L. Assessment of hazards to occupants from smoke, toxic gases, and heat. In *SFPE Handbook of Fire Protection Engineering*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 2308–2428.
55. Wang, J.; Zhang, L.; Shi, Q.; Yang, P.; Hu, X. Modeling and simulating for congestion pedestrian evacuation with panic. *Phys. A Stat. Mech. Its Appl.* **2015**, *428*, 396–409. [CrossRef]
56. Ronchi, E.; Nilsson, D. Fire evacuation in high-rise buildings: A review of human behaviour and modelling research. *Fire Sci. Rev.* **2013**, *2*, 1–21. [CrossRef]
57. Wong, K.H.; Luo, M. Total building evacuation strategy for high rise buildings. In *Tall Buildings: From Engineering to Sustainability*; World Scientific: Singapore, 2005; pp. 1113–1120.
58. Mohammed, I.; Talib, A.A.; Sultan, M.; Saadon, S. Temperature and heat flux measurement techniques for aeroengine fire test: A review. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Kuala Lumpur, Malaysia, 8–9 November 2016; pp. 12–36.
59. Nandy, T.; Coutu, R.A.; Ababei, C. Carbon monoxide sensing technologies for next-generation cyber-physical systems. *Sensors* **2018**, *18*, 3443. [CrossRef] [PubMed]

60. Schubert, E.; Scholz, M. Evaluation of wireless sensor technologies in a firefighting environment. In Proceedings of the 2010 Seventh International Conference on Networked Sensing Systems (INSS), Kassel, Germany, 15–18 June 2010; pp. 157–160.
61. Hofmann, P.; Kuladinithi, K.; Timm-Giel, A.; Görg, C.; Bettstetter, C.; Capman, F.; Toulsaly, C. Are IEEE 802 wireless technologies suited for fire fighters? In Proceedings of the 12th European Wireless Conference 2006—Enabling Technologies for Wireless Multimedia Communications, Athens, Greece, 2–5 April 2006; pp. 1–5.
62. Yang, J.; Santamouris, M.; Lee, S.E. Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings. *Energy Build.* **2016**, *121*, 344–349. [CrossRef]
63. Akkaya, K.; Guvenc, I.; Aygun, R.; Pala, N.; Kadri, A. IoT-based Occupancy Monitoring Techniques for Energy-Efficient Smart Buildings. In Proceedings of the Wireless Communications & Networking Conference Workshops, New Orleans, LA, USA, 9–12 March 2015.
64. Andrews, J.; Kowsika, M.; Vakil, A.; Li, J. A motion induced passive infrared (PIR) sensor for stationary human occupancy detection. In Proceedings of the 2020 IEEE/ION Position, Location and Navigation Symposium (PLANS), Portland, OR, USA, 20–23 April 2020; pp. 1295–1304.
65. Mathur, S.; Subramanian, B.; Jain, S.; Choudhary, K.; Prabha, D.R. Human detector and counter using raspberry Pi microcontroller. In Proceedings of the 2017 Innovations in Power and Advanced Computing Technologies (i-PACT), Vellore, India, 21–22 April 2017; pp. 1–7.
66. Raykov, Y.P.; Ozer, E.; Dasika, G.; Boukouvalas, A.; Little, M.A. Predicting room occupancy with a single passive infrared (PIR) sensor through behavior extraction. In Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Heidelberg, Germany, 12–16 September 2016; pp. 1016–1027.
67. Sheikh Khan, D.; Kolarik, J.; Anker Hviid, C.; Weitzmann, P. Method for long-term mapping of occupancy patterns in open-plan and single office spaces by using passive-infrared (PIR) sensors mounted below desks. *Energy Build.* **2021**, *230*, 110534. [CrossRef]
68. Rüppel, U.; Schatz, K. Designing a BIM-based serious game for fire safety evacuation simulations. *Adv. Eng. Inform.* **2011**, *25*, 600–611. [CrossRef]
69. Mirahadi, F.; McCabe, B.; Shahi, A. IFC-centric performance-based evaluation of building evacuations using fire dynamics simulation and agent-based modeling. *Autom. Constr.* **2019**, *101*, 1–16. [CrossRef]
70. Weng, Poh. Tenability criteria for design of smoke hazard management systems. *Ecolibrium.* **2011**, *8*, 32–37.
71. Overholt, K.J.; Ezekoye, O.A. Characterizing Heat Release Rates Using an Inverse Fire Modeling Technique. *Fire Technol.* **2012**, *48*, 893–909. [CrossRef]
72. Kou, L.; Wang, X.; Guo, X.; Zhu, J.; Zhang, H. Deep learning based inverse model for building fire source location and intensity estimation. *Fire Saf. J.* **2021**, *121*, 103310. [CrossRef]
73. Buffington, T.; Cabrera, J.-M.; Kurzawski, A.; Ezekoye, O.A. Deep-Learning Emulators of Transient Compartment Fire Simulations for Inverse Problems and Room-Scale Calorimetry. *Fire Technol.* **2021**, *57*, 2859–2885. [CrossRef]
74. Fang, H.; Lo, S.M.; Zhang, Y.; Shen, Y. Development of a machine-learning approach for identifying the stages of fire development in residential room fires. *Fire Saf. J.* **2021**, *126*, 103469. [CrossRef]
75. Korhonen, T.; Hostikka, S.; Heliövaara, S.; Ehtamo, H. FDS+ Evac: An agent based fire evacuation model. In *Pedestrian and Evacuation Dynamics 2008*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 109–120.
76. Lo, S.M.; Fang, Z.; Zhi, G.S. An Evacuation Model: The SGEM Package. *Fire Saf. J.* **2004**, *39*, 169–190. [CrossRef]
77. Liu, S.B.; Lo, S.M.; Ma, J.; Wang, W.L. An Agent-Based Microscopic Pedestrian Flow Simulation Model for Pedestrian Traffic Problems. *IEEE Trans. Intell. Transp. Syst.* **2014**, *15*, 992–1001. [CrossRef]
78. Huang, D.Y.; Lo, S.M.; Chen, J.; Fu, Z.; Zheng, Y.; Luo, L.; Zhuang, Y.; Cheng, H.; Yang, L.Z. Mapping fire risk of passenger-carried fire load in metro system via floor field cellular automaton. *Autom. Constr.* **2019**, *100*, 61–72. [CrossRef]
79. Akpakwu, G.A.; Silva, B.J.; Hancke, G.P.; Abu-Mahfouz, A.M. A Survey on 5G Networks for the Internet of Things: Communication Technologies and Challenges. *IEEE Access* **2018**, *6*, 3619–3647. [CrossRef]
80. Akyildiz, I.F.; Nie, S.; Lin, S.-C.; Chandrasekaran, M. 5G roadmap: 10 key enabling technologies. *Comput. Netw.* **2016**, *106*, 17–48. [CrossRef]
81. Ericsson, RP-180581, Interim Conclusions for IoT in REL-16, document 3GPP. In Proceedings of the TSG RAN meeting 79, Chennai, India, 19–22 March 2018.
82. Mekki, K.; Bajic, E.; Chaxel, F.; Meyer, F. A comparative study of LPWAN technologies for large-scale IoT deployment. *ICT Express* **2019**, *5*, 1–7. [CrossRef]
83. Lea, P. *Internet of Things for Architects: Architecting IoT Solutions by Implementing Sensors, Communication Infrastructure, Edge Computing, Analytics, and Security*; Packt Publishing: Birmingham, UK, 2018; pp. 252–258.
84. Pelaez, A. LoRaWAN vs. NB-IoT: A Comparison between IoT Trend-Setters. Available online: https://ubidots.com/blog/lorawan-vs-nb-iot/ (accessed on 4 February 2020).
85. Tsai, M.-K.; Yau, N.-J. Enhancing usability of augmented-reality-based mobile escape guidelines for radioactive accidents. *J. Environ. Radioact.* **2013**, *118*, 15–20. [CrossRef]
86. Sharma, S.; Bodempudi, S.T.; Scribner, D.; Grynovicki, J.; Grazaitis, P. Emergency Response Using HoloLens for Building Evacuation. In *International Conference on Human-Computer Interaction*; Springer: Cham, Germany, 2019; pp. 299–311.
87. Vince, J. Prototype Fire Helmet Mount Provides 'Iron Man' View. Available online: https://www.firehouse.com/tech-comm/news/21227185/prototype-fire-helmet-mount-provides-iron-man-view (accessed on 17 June 2021).

88. Porambage, P.; Okwuibe, J.; Liyanage, M.; Ylianttila, M.; Taleb, T. Survey on multi-access edge computing for internet of things realization. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2961–2991. [CrossRef]
89. Rodriguez, J. *Fundamentals of 5G Mobile Networks, 1 ed.*; John and Wiley and Sons: Hoboken, NJ, USA, 2015; pp. 167–190.
90. Li, X.; Samaka, M.; Chan, H.A.; Bhamare, D.; Gupta, L.; Guo, C.; Jain, R. Network Slicing for 5G: Challenges and Opportunities. *IEEE Internet Comput.* **2017**, *21*, 20–27. [CrossRef]
91. Analysis Mason. Report for the TETRA Association: Public Safety Mobile Broadband and Spectrum Needs, Report No. 16395-94, 8 March 2010. Available online: https://www.pc.gov.au/__data/assets/pdf_file/0003/189840/sub004-public-safety-mobile-broadband-attachment7.pdf (accessed on 15 October 2021).
92. Li, Z.; Sanchez Moya, F.; Gabor, F.; Da Silva, J.M.B., Jr.; Koufos, K. Device-to-device (D2D) communications. In *5G Mobile and Wireless Communications Technology*; Osseiran, A., Monserrat, J.F., Marsch, P., Eds.; Cambridge University Press: Cambridge, UK, 2016; pp. 107–136.
93. Jameel, F.; Hamid, Z.; Jabeen, F.; Zeadally, S.; Javed, M.A. A Survey of Device-to-Device Communications: Research Issues and Challenges. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2133–2168. [CrossRef]
94. Wu, S.; Shin, O.-S.; Shin, Y. Proximate device discovery with delayed responses in LTE public safety networks. In Proceedings of the 2016 International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea, 19–21 October 2016; pp. 849–851.
95. Usman, M.; Gebremariam, A.A.; Raza, U.; Granelli, F. A Software-Defined Device-to-Device Communication Architecture for Public Safety Applications in 5G Networks. *IEEE Access* **2015**, *3*, 1649–1654. [CrossRef]
96. Castel, T.; Lemey, S.; Agneessens, S.; van Torre, P.; Rogier, H.; Oestges, C. LTE as a potential standard for public safety indoor body-to-body networks. In Proceedings of the 2015 IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT), Luxembourg, 24–25 November 2015; pp. 1–6.
97. 3GPP. Delivering Public Safety Communications with LTE-3GPP White Paper. Available online: https://www.3gpp.org/IMG/pdf/121218_lte_for_public_safety_rev3_-_cl.pdf (accessed on 15 October 2021).
98. Fodor, G.; Parkvall, S.; Sorrentino, S.; Wallentin, P.; Lu, Q.; Brahmi, N. Device-to-Device Communications for National Security and Public Safety. *IEEE Access* **2014**, *2*, 1510–1520. [CrossRef]
99. Ali, K.; Nguyen, H.X.; Shah, P.; Vien, Q.; Bhuvanasundaram, N. Architecture for public safety network using D2D communication. In Proceedings of the 2016 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Doha, Qatar, 3–6 April 2016; pp. 206–211.
100. Galea, E.R.; Xie, H.; Lawrence, P.J. Experimental and survey studies on the effectiveness of dynamic signage systems. *Fire Saf. Sci.* **2014**, *11*, 1129–1143. [CrossRef]
101. Galea, E.; Xie, H.; Deere, S.; Cooney, D.; Filippidis, L. An international survey and full-scale evacuation trial demonstrating the effectiveness of the active dynamic signage system concept. *Fire Mater.* **2017**, *41*, 493–513. [CrossRef]
102. Langner, N.; Kray, C. Assessing the Impact of Dynamic Public Signage on Mass Evacuation. In Proceedings of the International Symposium on Pervasive Displays, Copenhagen, Denmark, 3–4 June 2014; pp. 136–141.
103. Amores, D.; Vasardani, M.; Tanin, E. Smartphone usability for emergency evacuation applications. In Proceedings of the Leibniz International Proceedings in Informatics, LIPIcs, 142, LIPIcs, Regensburg, Germany, 9–13 September 2019. [CrossRef]