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RESEARCH ARTICLE

IoT-Based School Building Evacuation Guidance System with Audible Sound Wave Backup Communication

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ABSTRACT: Various IoT-based systems have been developed to guide people to evacuate buildings during emergencies like fires. However, research on environments where the internet is disrupted or the radio wave conditions are poor is insufficient. This study proposes an IoT-based system for guiding safe evacuations, utilizing both internet-based communication and a fallback audible sound wave mode for disruptions. This study presents an IoT-based evacuation guidance system that operates via MQTT and switches to sound-based communication when the internet fails. It receives digitally encoded emergency data through the internet or building sound broadcast systems and minimizes transmission by storing the building layout and calculating optimal evacuation paths using Dijkstra's algorithm. The system utilizes 18 kHz and 19 kHz audio frequencies with FFT (Fast Fourier Transform) and BFSK (Binary Frequency Shift Keying) modulation for sound wave communication. The test was conducted in a simulated school environment, where the system successfully guided users to exits during emergencies, including scenarios with network disruptions. Additionally, a noise interference test was performed to assess the robustness of sound wave communication. Results indicate that the proposed system effectively guides evacuation with minimal data transmission and maintains functionality during internet disruptions, showcasing its potential for enhanced emergency response systems.

KEYWORDS: Embedded Systems, Internet of Things, Networking and Data Communications, Evacuation Guidance System, Sound Wave Communication.

Introduction

In emergencies such as fires, safely and quickly evacuating a building is crucial to minimizing casualties. To facilitate this, all buildings above a certain size are required to display evacuation floor plans, guiding people to evacuate safely. However, this approach has limitations, as it cannot identify the exact location of hazards in real time. As a result, it may inadvertently direct people toward danger, causing confusion and potentially leading to more hazardous situations. This risk increases in complex buildings or for unfamiliar visitors, highlighting the need for a system that can intelligently guide individuals to optimal escape routes in real time.

Various methods utilizing IoT technology have been studied to assist in building evacuations during disaster situations.[1-4,7,10] Among these, certain studies utilize various sensors and LED guide lights to guide evacuees using pre-identified escape route data, demonstrating similarities to this study.[1,2] However, both rely on network connectivity for real-time information exchange between system entities, which means IoT devices may fail to function if the network is disrupted. Similarly, another study proposes a system that assists evacuation during fires using smartphone communication and frequency-based technology, but it also depends on Wi-Fi communication.[3] Despite these advancements, most IoT-based evacuation systems remain heavily reliant on internet communication. In disasters such as fires, where Wi-Fi may become inoperative or in areas with poor signal conditions, these systems risk becoming non-functional.

Therefore, research is needed on a system that can transmit emergency information to evacuation guidance devices even when the IoT-based network is disabled, assisting people in escaping safely. Additionally, by minimizing changes to existing building systems, this approach can reduce costs while also limiting communication between IoT devices, thereby reducing dependence on a central server that holds critical information.

To address these challenges, this study proposes an IoT-based evacuation guidance system that remains operational even in network-disrupted environments. The system is primarily based on the MQTT[6] (Message Queuing Telemetry Transport) protocol, which operates over TCP/IP. When the network is unavailable, it utilizes the alternative communication method on audible sound waves. Under normal conditions, evacuation guidance devices installed along passageways operate via MQTT. However, in emergencies where internet connectivity is lost, the system leverages existing building broadcast systems to receive situation codes and hazard location data. This information is then used to activate direction-indicating lamps, guiding people safely and efficiently toward proper exits.

DOI: 10.36838/v7i7.5

■ Methods

A. System Design:

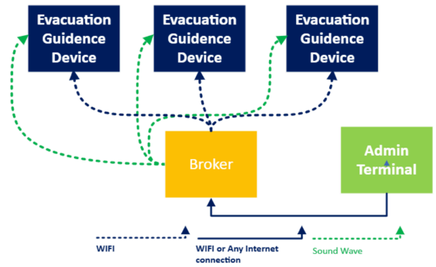

Figure 1: This figure illustrates the overall system architecture for the IoT system, including the interactions between the Admin Terminal, the Broker, and the Evacuation Guidance Devices.

The Evacuation Guidance Device is implemented on a Raspberry Pi and installed in each corridor of the building. This IoT device guides evacuees via escape route indicator lamps and is equipped with both a TCP/IP connection and an audio-band communication receiver. The Broker functions as a standard MQTT[6] broker, facilitating message transmission between the MQTT Publisher (Admin Terminal) and the Subscriber (Evacuation Guidance Device). Additionally, it converts the payload of messages published to specific topics into broadcast data suitable for the audio-band channel, which is then transmitted via speakers. The Admin Terminal is an IoT application installed on the administrator's system for managing and responding to emergencies. It publishes predefined disaster-related data to the broker, ensuring that the information is reliably disseminated to all Evacuation Guidance Devices (Figure 1).

Under normal conditions, the Evacuation Guidance Device receives emergency information through TCP/IP-based MQTT communication and periodically receives status signals from the voice band channel to verify communication connectivity. In an emergency, as long as the internet is operational, information for emergency escape route guidance is received via the internet-based MQTT protocol. If the internet is disconnected, information about the hazardous situation and location within the building is received from the Broker through the voice-band channel. Based on this information, the optimal escape route is calculated, and directional lamps are activated according to the user's current installation location.

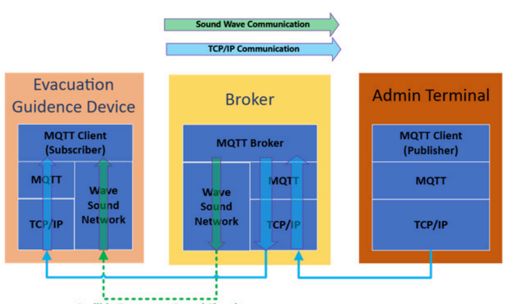

Figure 2: This figure illustrates the layered structure of the communication protocol between the Evacuation Guidance Device, Broker, and Admin Terminal.

The Evacuation Guidance Device is equipped with both TCP/IP-based MQTT protocol communication and data reception via audible frequency sound waves. In the event of a disaster where the network is unavailable, it utilizes the information transmitted through the sound wave-based communication channel. The Broker is responsible for relaying messages from the Admin Terminal to the Evacuation Guidance Device and transmitting published data through both communication channels: TCP/IP-based and sound waves. The Admin Terminal publishes information about disaster situations occurring in the building to Evacuation Guidance Devices by transmitting critical disaster information to the Broker via the TCP/IP-based MQTT protocol, which then forwards the messages to the devices through both communication channels (Figure 2).

B. Digital Data Transmission over Sound Wave:

In the system designed in this study, the sound wave-based communication process is carried out as follows. On the transmission side, digital data is converted into a bitstream and then modulated into sine wave tones at two carrier frequencies (18 kHz and 18.5 kHz). These tones are broadcast through a speaker. On the receiving side, a microphone captures the sound and processes it using the Fast Fourier Transform (FFT) to convert the signal into the frequency domain. The system employs Binary Frequency Shift Keying (BFSK) 5 digital modulation, where each of the two transmission frequencies represents a binary value: one frequency for '0' and the other for '1'.

Figure 3 illustrates this process, showing how the bitstream is transmitted from the sender to the receiver. The sender converts the digital bitstream into sound wave signals at the two designated frequencies, which are then broadcast via a speaker. The receiver's microphone captures these signals, undergoes the demodulation process, and reconstructs the original bitstream.

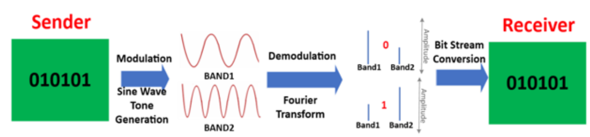

Figure 3: This figure illustrates the process of digital data transmission using Binary Frequency Shift Keying (BFSK) over sound waves.

C. Sound Wave Data Transmission Packet Format:

In the sound wave communication system implemented in this study, one synchronization channel (19 kHz) and one data channel (using two carrier frequencies) are utilized. Figure 4 shows the sound wave communication packet structure. Before data is transmitted in the data channel, a signal filled with '1's is first sent through the synchronization channel. Each synchronization channel's one frame consists of 40 bits. Data transmission through the data channel occurs while the sync channel is activated as '1' and is fixed at a length of 24 bits. A single data frame transmitted through the data channel consists of Preamble bits (4 bits), Data (16 bits), and Checksum (4 bits) for error detection.

In the experiment, each data bit has a duration of 0.1 seconds in the data channel and the sync channel. That is, the bit transmission rate of the data channel, including all overhead while the data channel is active, is 10 bits per second.

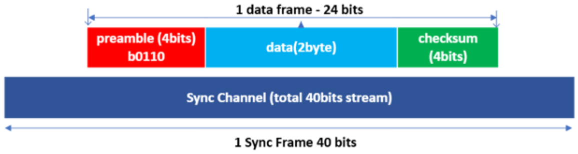

Figure 4: This figure illustrates the sound wave communication packet structure.

While one sync frame, as described in Figure 4, is active, one data frame is transmitted. There is a 1-second gap between each sync frame. As a result, one data packet frame is transmitted every 5 seconds (Figure 5).

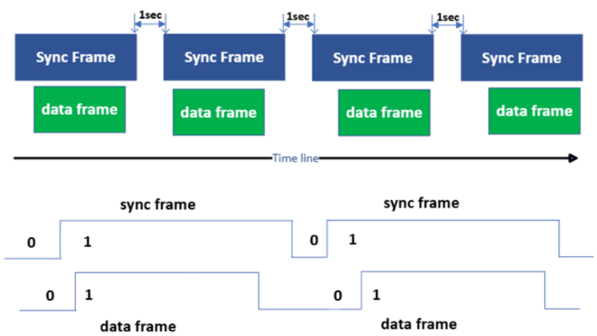

Figure 5: This figure illustrates the timing between the sync channel and the data channel in data transmission over the sound wave channel. The data frame, consisting of 24 bits, is transmitted during the 40-bit duration in which the sync frame signal remains at logic '1'.

D. Protocol:

Figure 6 illustrates the emergency evacuation guidance system protocol between the Admin Terminal, Broker, and Evacuation Guidance Devices. In normal (non-emergency) situations, the Broker periodically transmits a check message via the sound wave channel to indicate that the channel is active. When emergency-related information is published by the Admin Terminal, the data is transmitted through both the general IoT channel (TCP/IP) and the sound wave channel.

For emergency evacuation guidance, the messages transmitted via both the general IoT channel (TCP/IP) and the sound wave channel consist of a 1-byte status code and a 1-byte status parameter.

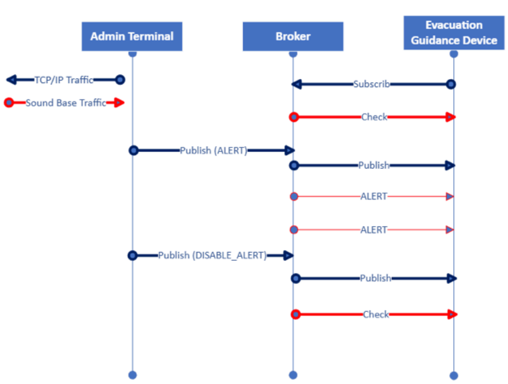

Figure 6: This figure illustrates the protocol between the Admin Terminal, Broker, and Evacuation Guidance Devices.

Table 1 provides examples of status codes and parameters used in ALERT or Check messages in Figure 6. For example, in a normal situation with no emergency, the Check Message transmits a 2-byte Emergency Code (Status code, region code): [0x00, 0x00]. When a fire drill is issued, the status code 0x01 is sent along with a region code indicating the risk area. For instance, [0x01, 0x04] indicates that a fire drill is in progress and the fire is in region 0x04.

Table 1: This table shows examples of status codes and parameters for emergency evacuation guidance.

	Status Code (1byte)	Parameter (region code, 1byte)
Normal	0x00	0
Fire Drill	0x01	0 ~ 255
Shooting Drill	0x02	0 ~ 255
Fire	0x80	0 ~ 255
Shooting	0x81	0 ~ 255

E. Simulated School Building Environment:

To test the operation of the system developed in this study, a school building layout like a real school environment was simulated. Figure 7 depicts a map of a virtual school building. Figure 7 (Left) shows the floor plan of the school building, and Figure 7 (Right) represents it as a graph, where each location is modeled as a vertex, and the movement cost between connected locations is represented as edges. Table 2 provides the data representation of the graph in Figure 7.

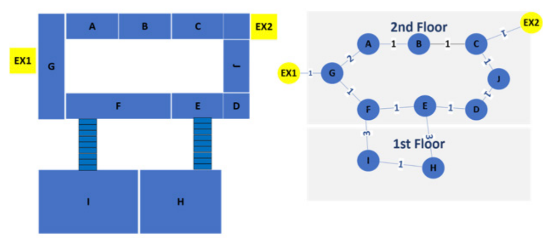

Figure 7: Left: Virtual school building floor plan, Right: graph data structure.

Under normal conditions, when no emergency has occurred, the evacuation guide device installed in region D determines the shortest evacuation route as D-J-C-EX2 using Dijkstra's algorithm8 (Figure 8).

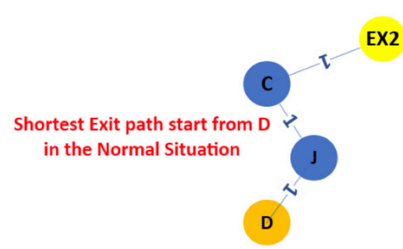

Figure 8: This figure shows the shortest path to the EX2 in a normal situation, starting from location D.

Each evacuation guidance device maintains a table that represents the cost of moving between vertices to calculate the optimal escape route from its location. Table 2 shows this

DOI: 10.36838/v7i7.5

vertex cost table based on the building structure illustrated in Figure 7. The intersection of each row and column indicates the cost of moving between two vertices, where a value of ‘0’ denotes either an inaccessible path or the same vertex.

Table 2: This is the vertex data table that contains the cost of moving from every vertex to every other vertex in the building structure graph shown in Figure 7.

	A	B	C	D	E	F	G	H	I	J	EX1	EX2
A	0	1	0	0	0	0	1	0	0	0	0	0
B	1	0	1	0	0	0	0	0	0	0	0	0
C	0	1	0	0	0	0	0	0	0	1	0	1
D	0	0	0	0	1	0	0	0	0	1	0	0
E	0	0	0	1	0	1	0	3	0	0	0	0
F	0	0	0	0	1	0	1	0	1	0	0	0
G	2	0	0	0	0	1	0	0	0	0	1	0
H	0	0	0	0	3	0	0	0	1	0	0	0
I	0	0	0	0	0	3	0	1	0	0	0	0
J	0	0	1	1	0	0	0	0	0	0	0	0
EX1	0	0	0	0	0	0	1	0	0	0	0	0
EX2	0	0	1	0	0	0	0	0	0	0	0	0

F. System Testing:

To test the system developed in this study, a virtual school building layout defined in Figure 7 was used, and the following test scenario was configured:

- Two locations (A and D) were assumed to be equipped with evacuation guidance devices (Raspberry Pi[9]).
- The status codes and hazard area codes defined in Table 1 were transmitted via the MQTT channel and the Sound Wave Communication channel, respectively.
- Each of the two evacuation guidance devices calculated the expected evacuation route and was monitored to verify whether the guidance lamps were activated in the correct direction.
- The hazard status codes were changed sequentially (0x8003, 0x8006, 0x8007) and transmitted during the test.
- During the test, the internet connection was intentionally disconnected, and random noise was played to verify whether the Sound Wave Communication functioned correctly under such conditions.

Here, each region code ‘A’ to ‘J’, ‘EX1’, and ‘EX2’ from Figure 7 is mapped to numbers 1 to 10, 128, and 129.

Results and Discussion

A. Testing in Normal Situation:

To test the system developed in this study, the Evacuation Guide Device was implemented on a Raspberry Pi. Emergency codes were broadcast via sound waves using a regular speaker, along with background noise, and the system was designed to recognize these signals. A spectrum analyzer app and a noise level meter app on a smartphone were used to measure the frequency and noise levels. Figure 9 shows the test environment for this system.

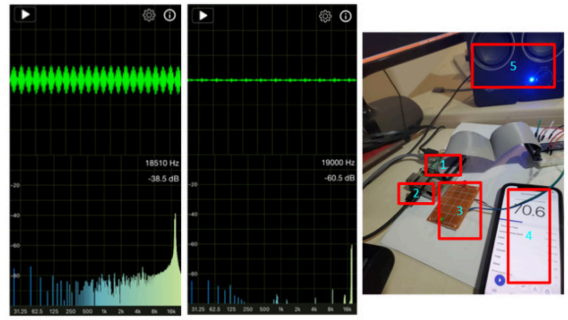

Figure 9: System testing environment: Left- 18.5 kHz, Center- 19 kHz sound wave signal measurement, Right–system testing picture (1: Raspberry Pi, 2: microphone, 3: evacuation direction lamp, 4: noise level measurement, 5: broadcasting speaker for sound wave).

The status code and hazard location were transmitted via MQTT or sound wave to the Evacuation Guidance Device, and the system's response was recorded. Each scenario used a status code of 0x80 (Fire), with hazard locations designated as 0x03, 0x06, and 0x07, respectively. Table 3 presents the results of executing the evacuation guidance devices that are installed at two different locations of the building (A and D) when fire emergencies occur at three different locations.

Table 3: Test results of scenarios 1, 2, and 3 from locations A and D.

	Emergency alert packet Data (MQTT or Sound Wave)	Device at D Shortest Evacutation Path	Device at A Shortest Evacuation Path
Scenario 1	0x8003	D->E->F->G->EX1	A->G->EX1
Scenario 2	0x8006	D->J->C->EX2	A->G->EX1
Scenario 3	0x8007	D->J->C->EX2	A->B->C->EX2

Table 4 shows the updated Vertex Table according to the Emergency Scenarios in Table 3. When an Emergency Packet with a status code of 0x80 is transmitted, the Evacuation Guidance Device interprets the second byte of the payload (0x03, 0x06, and 0x07) as the hazardous area. It then updates the Vertex Table, setting the movement cost to or from the affected area to 99, effectively marking it as highly restricted.

Table 4: Vertex table updated by scenario 1(Left), scenario 2(Center), and scenario 3(Right).

Status Code : 0x8003

	A	B	C	D	E	F	G	H	I	J	EX1	EX2
A	0	1	0	0	0	0	1	0	0	0	0	0
B	1	0	99	0	0	0	0	0	0	0	0	0
C	0	99	0	0	0	0	0	0	0	99	0	1
D	0	0	0	0	1	0	0	0	0	1	0	0
E	0	0	0	1	0	1	0	3	0	0	0	0
F	0	0	0	0	1	0	1	0	1	0	0	0
G	2	0	0	0	0	1	0	0	0	0	1	0
H	0	0	0	0	3	0	0	0	1	0	0	0
I	0	0	0	0	0	3	0	1	0	0	0	0
J	0	0	99	1	0	0	0	0	0	0	0	0
EX1	0	0	0	0	0	0	1	0	0	0	0	0
EX2	0	0	1	0	0	0	0	0	0	0	0	0

Status Code : 0x8006

	A	B	C	D	E	F	G	H	I	J	EX1	EX2
A	0	1	0	0	0	0	1	0	0	0	0	0
B	1	0	1	0	0	0	0	0	0	0	0	0
C	0	1	0	0	0	0	0	0	0	1	0	1
D	0	0	0	0	1	0	0	0	0	1	0	0
E	0	0	0	1	0	99	0	3	0	0	0	0
F	0	0	0	0	99	0	99	0	99	0	0	0
G	2	0	0	0	0	99	0	0	0	0	1	0
H	0	0	0	0	3	0	0	0	1	0	0	0
I	0	0	0	0	0	99	0	1	0	0	0	0
J	0	0	1	1	0	0	0	0	0	0	0	0
EX1	0	0	0	0	0	0	1	0	0	0	0	0
EX2	0	0	1	0	0	0	0	0	0	0	0	0

Status Code : 0x8007

	A	B	C	D	E	F	G	H	I	J	EX1	EX2
A	0	1	0	0	0	0	99	0	0	0	0	0
B	1	0	1	0	0	0	0	0	0	0	0	0
C	0	1	0	0	0	0	0	0	0	1	0	1
D	0	0	0	0	1	0	0	0	0	1	0	0
E	0	0	0	1	0	0	0	3	0	0	0	0
F	0	0	0	0	1	0	99	0	3	0	0	0
G	99	0	0	0	0	99	0	0	0	0	1	0
H	0	0	0	0	3	0	0	0	1	0	0	0
I	0	0	0	0	0	3	0	1	0	0	0	0
J	0	0	1	1	0	0	0	0	0	0	0	0
EX1	0	0	0	0	0	0	1	0	0	0	0	0
EX2	0	0	1	0	0	0	0	0	0	0	0	0

As a result, the system generated different escape routes for each case based on location (A and D) and displayed directional guidance lamps accordingly (Table 3).

B. System Testing by Noise and Network Disruption Stress:

The test was conducted over approximately 30 minutes, alternating between Scenarios 1, 2, and 3, while applying random noise and intermittent internet disconnection to simulate stress conditions. To evaluate sound wave communication under noisy conditions, continuous ambient noise ranging from 50 dB(A) to 80 dB(A) was introduced during testing. Additionally, the internet connection was intentionally interrupted five times during the test. As a result, a total of 300 sound wave sync frames and data frame transmissions were made over the 30 minutes. Among them, there were 2 instances where the sync frame failed due to the inability to maintain a continuous sequence of '1's for 40 bits. Additionally, there were 4 instances where the data frame had a checksum error, requiring a wait until the next transmission.

Conclusion

This study proposes a guidance system designed to ensure the safe evacuation of individuals from a school building in the event of a disaster. The system is based on IoT technology and operates using the MQTT protocol. Even in situations where the TCP/IP network is unavailable, it can guide people to the shortest evacuation route by broadcasting encoded emergency information via sound waves through the building's public address system.

When a disaster, such as a fire, occurs, the emergency code and the location of the hazard within the building, published by the management system via the MQTT IoT protocol, are transmitted to evacuation guidance devices installed throughout the building. Each device then activates a guidance light to indicate the nearest escape route based on its current location.

In this study, a virtual school building structure was created, and evacuation guidance tests were conducted under simulated emergency conditions. During testing, stress factors such as random noise and network disconnections were introduced to evaluate the system's stability. The results showed that the system generally operated reliably and demonstrated its potential to assist in the safe evacuation of school buildings during disasters.

In scenarios involving network disconnection, several synchronization and data transmission errors were observed in the sound wave channel, or data frame transmission errors occurred, requiring a wait for the next transmission. In the current implementation, the low transmission rate of 10 bps results in each data reception taking 5 seconds. If an error occurs during a transmission, the system must wait for the next attempt, causing a delay of up to 10 seconds. Therefore, improving transmission efficiency remains an area for future research.

Acknowledgments

I truly thank my parents for their constant support during this research. I also appreciate Mr. Yoon for his helpful advice throughout the project, and my brother Kevin for always encouraging me and sharing his ideas.

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Author

Geonhyeong Lee is a student at Bergen Catholic High School with a strong interest in IoT systems and emergency communication technologies. Through the development of an evacuation guidance system using sound-based backup communication, he explored the practical applications of engineering. He plans to major in computer engineering in college.

DOI: 10.36838/v7i7.5