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A Low-Cost Open-Source Architecture for a Digital Signage Emergency Evacuation System for Cruise Ships, Based on IoT and LTE/4G Technologies

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Abstract: During a ship evacuation, many people panic as they do not know the direction that leads to the emergency muster station. Moreover, sometimes passengers get crowded in corridors or stairs, so they cannot save their lives. This paper proposes an IoT-enabled architecture for digital signage systems that directs passengers to the muster stations of a cruise ship by following the less dangerous route. Thus, crews' and passengers' safety risks during a ship evacuation can be low, and human health hazards may be limited. The system is based on a low-cost and open-source architecture that can also be used in a variety of fields in industrial IoT applications. The proposed modular digital signage architecture utilizes Light Emitting Diode (LED) strips that are remotely managed through a private Long-Term Evolution (LTE)/Fourth Generation (4G) cellular network. Publish–subscribe communication protocols were used for the control of the digital strips and particularly through a Message Queuing Telemetry Transport (MQTT) broker who publishes/subscribes every message to specific topics of the realized IoT platform, while the overall digital signage system centralization was implemented with an appropriate dashboard supported from an open-source RESTful API.

Keywords: digital signage system; LTE cellular network; 4G cellular network; MQTT; IoT platform; IoT dashboard; Node-RED; LED strips; open air interface; software-defined radio

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1. Introduction

The fourth industrial revolution (Industry 4.0) enables suppliers and manufacturers to leverage new technological concepts to improve the Industrial IoT, Big Data, and Cloud Computing. New, low-cost products and services can be created to increase productivity and replace old procedures and services [1]. Cruise ships can be considered as isolated industrial units, and therefore security procedures and other services should be reviewed and replaced if needed.

According to the International Maritime Organization (IMO), once an abandon ship signal is given, the survival crafts should be fully launched with their complement of persons- within 30 min [2]. This timeframe only starts when all passengers have been gathered at the emergency muster station, with life jackets. Except for this timeframe, the total evacuation time also includes the time that passengers and crew need to assemble at the muster station. IMO recommends that the maximum allowable total evacuation time should not be over 60 min for ships having no more than three main vertical fire zones and not over 80 min for ships having more than three main vertical fire zones [3–5].

To properly compute the total time needed to evacuate a ship, two methods have been made. The first one is the simplified method, where the total evacuation time is calculated in comparison with an acceptable period, which depends on the vessel type and the number of Main Vertical Zones (MVZs).This total evacuation time is necessary for all persons on board to reach the muster stations and abandon ship with the survival crafts. The second method is the advanced method, where all persons on board are represented as individuals and they have particular abilities with response durations. Furthermore, there is a consideration about the layout of the ship and whether a person is a passenger or crew [6]. Both methods may lead to unwanted results if there is no central digital system, which will guide passengers to the muster station. Thus, there is a need for a new guidance system to reduce people's wrong choices and health hazards.

Health Hazards and Safety Risks during Evacuations

While an evacuation takes place, we can assume there is a great risk whatever the evacuation is. In this subsection, we specifically consider some health hazards and safety issues during an emergency evacuation. Even in the case of fire or earthquake, or in case of a public safety threat or a hazardous substance, we should consider into our evacuation procedure what equipment should be used to minimize other unrealized risks. Every evacuation poses some issues that we should have in mind. First of all, there are many physical barriers like stairs and doors, and secondly, some cultural issues such as equality and hierarchy should be kept in mind. The hierarchy of employees in a ship, for example, and their duties, should not be ignored when an evacuation takes place. To get people out of a building or dangerous area quickly and in the safest possible way, we should acknowledge several things. During a ship evacuation, people may show conformity psychology, as they are not familiar with the environment and the locations of hazard sources. Furthermore, the individual hopes that they will leave the ship faster than others, so conformity would be a difficult part of the evacuation progress. Emergency evacuation procedures of a place or a building should have been safety tested and practiced in real-life conditions. In the actual evacuation process, there may be some obstacles, objects, or even buildings that prevent the light of sight [7]. The influence of the obstruction of sight on an emergency evacuation may be crucial, and therefore the right guidance is necessary. Moreover, there are some other aspects, such as the construction conditions of the building, which make the evacuation difficult, and therefore it is necessary to study and practice the emergency evacuation procedure.

Wang et al. [8] presented research that claims a difference in the decision-making between passengers, as there is heterogeneity in their personality. The factors that affect the decision-making procedure are many, and they have been covered in many studies, including simulations [9,10], but they do not cover a digital signage system that will prevent them from making a wrong decision. However, the lack of studies that include guidance systems is still evident concerning the affecting factors, on the safe evacuation of ships, from the perspective of limiting people's health hazards. In those studies, factors such as the evacuation time, the waiting time, the exit efficiency, and health hazards are analyzed and discussed based on the numerical simulation results. The present paper aims to reduce health hazards during a ship evacuation procedure by proposing a reliable open-source IoT system that helps passengers move safely to the muster station, according to crews' guidance and ships safety procedures, and therefore we have organized it as follows. The related work of designing emergency evacuation systems is given in Section 2. The digital signage systems' design and the IoT technologies comparison are introduced in Section 3. Experimental implementation results and discussion are given in Section 4. Conclusions and future work are presented in Section 5.

2. Related Work

Nowadays, digital signage technology has developed rapidly along with IoT and mobile applications in various fields of our life, such as entertainment, education, advertisement, early warning systems, and especially in industrial IoT applications. A combination of commercial and emergency monitoring systems is developing to help people and manufacturers monitor critical facilities, such as schools, hospitals, and factories. Apart from central facilities and buildings, emergency monitor and evacuation applications and systems are developing to help people evacuate aircraft, trains, and ships. To this end, researchers focused on IoT-enabled digital signage systems, which can be combined with sensors, to gather and analyze sensitive data like dangerous gases and temperature, perform monitoring and warning functions, and direct passengers to the emergency exit and the evacuation points. Thus, as well as an improvement in emergency evacuation procedure being reached, people who live or work inside buildings, or travel by public transportation, feel safe as they know that in case of emergency, there is a well-known plan to abandon the structure or the means of travel. In this section, we present some related work on digital signage and emergency evacuation systems.

Lee et al. [11] proposed a new signage system in conjunction with an IoT platform, where the trusted information is provided through their intelligent smart signage services. Their system displays personalized and optimized content for various situations and controls the selected based on situation awareness. They have designed a trust information subsystem to support the intelligence of situation awareness and personalize features in intelligent signage services. They have modeled a trusted relationship between two things, as a six-tuple relationship that contains two trust things, one trust value, one trust scope, one trust type, and one trust validation. They also propose a system that can connect hub technology along with an IoT platform and utilize trust analysis technology between people and objects in a digital service. In our digital signage system, we have included sensors and intelligent functions that can automatically redirect passengers to a safer route in case that the initially selected is closed for some safety reasons.

Another approach is evolving digital signage while providing personalized service by adaptively changing content, as revised by Lee et al. [12]. Their digital system aimed to solve two problems. Firstly, digital signage systems have difficulty expanding their services because it is not easy to connect to additional sensing devices. Secondly, previous digital signage systems do not consider multiple signages per service. They propose a platform that provides IoT-based connectivity between the IoT platform, and multiple sensors, as a flexible service extension. They also suggest an IoT-based signage connection and centralization and service for the controlling of sensors' status. Thus, the platform can dynamically create a service group of signages, providing collaborating signages for services in wide areas. To test platforms' performance, they created a smart nursing home service, which uses a smart band to monitor users' health status and detect emergencies. The digital signage service that we propose can expand without limitation. Furthermore, sensors can publish and receive multiple messages from multiple MQTT topics that represent MVZs. We can control the services from an IoT dashboard, where we can see all installed sensors' statuses on the ship. Moreover, we cover a wide area, and passengers do not have to wear any smart band or sensor because multiple sensors on the ship detect emergencies and dynamically inform the IoT dashboard.

Zualkernan et al. [13] devised a system that, if there is a fire emergency, reduces people's congestion and speeds up the whole process by dynamically directing people to the safest exit. They used IoT technology to track the location of the fire and the location of the occupants and then direct them towards a safe exit. Their implementation used Bluetooth Low Energy (BLE) beacons, and they used occupants' mobile phones to track their location. They also used smoke and temperature sensors to track areas, and in the case of fire, the system used multiple networks, including WiFi and the Digimesh, to increase its resilience. The messages can be published or subscribed to through an MQTT broker, and the occupants can use an installed map that updates automatically on their mobile phones. This map provides the occupant's information about the dander levels to be avoided. Moreover, they have installed exit signs inside the building, which dynamically changes their status to guide people to the exit. Our implementation is for usage inside ships, and therefore passengers will change in every new voyage. Moreover, it is not legal to install a live-updated ship's map on passenger mobile phones. For these reasons, an automatic updating map of the MVZs has been installed on the IoT platform and is visible through the IoT dashboard. The control of the IoT dashboard takes place through a specially trained crew, and there are also sensors installed on the ship that can automatically update the dangerous zones or decks on the map. Dangerous MVZs are automatically avoided as the digital signage lights change their status, and occupants can follow the safest way to the muster station through digital signage.

To accomplish a real-time evacuation system in case of a fire or other emergency, Hsu et al. [14] proposed a real-time fire evacuation system. As long as buildings are tall and complex, there is a need to establish clear evacuation routes, so they used Wireless Sensors Networks (WSN) and Radio Frequency Identification (RFID) in their real-time evacuation system to achieve it. In an emergency, a digital signage system helps people by indicating the best evacuation route. They also monitor the environmental conditions to provide information about the origin of a possible fire. This digital system also provides the users' pertinent information to improve the chances of survival and supplies firefighters with real-time environment information to assure better efficiency in their operations. To accomplish the wireless transmission of the sensors in their wireless network, they used Zigbee wireless transmission technology along with RFID detection points. This implementation cannot cover large buildings or ships because Zigbee and RFRID technology do not cover large areas. Moreover, their transmission speed is lower than the transmission speed of cellular technology.

According to the aforementioned literature review, we conclude that digital signage services have become a major concern in emergencies, and their effects may lead to the minimization of health hazards. Early warning systems have largely been ignored up until now, and as the demand for fast and accurate warning systems is increasing, it is crucial to monitor dangerous areas with reliable IoT implementations. We must take appropriate measures promptly and make a meticulous design of the area to be covered, including all parameters. Motivated by the need for a new digital signage system for safe ship evacuations, we have introduced a flexible, reliable, and scalable IoT-based system to monitor and warn passengers and crew about the faster and safer direction to the muster station. We focused on the parameters that determine the safe evacuation of small and large ships, which may also be suitable for evacuations of other buildings such as schools, hospitals, homes, offices, etc. The evacuation plan should always be controlled by the crew, according to ship security procedures. Our proposal focuses on a reliable open-source IoT platform, including an IoT dashboard that uses an LTE/4G cellular sensor network, detects dangerous areas, and directs occupants to the muster station via the safest way in real-time.

3. Digital Signage Systems' Design and IoT Technologies Comparison

An IoT application enables a combination of the physical and informational world. The physical objects can share information and coordinate decisions in many domains, like healthcare, transportation, industrial automation, physical and man-made disasters, smart grids, etc. Therefore, in a real-world IoT application, we can combine networks and protocols to ensure optimal operation [15]. Before we decide on the appropriate networks and protocols for our application, we must sketch the building or the structure in which it is going to be used. In our case, we had to think about the suitable technologies for an application on a ship that is divided into MVZs. Below, we see an example of the layout of a ship's MVZ (Figure 1). This MVZ is served by two main stairwells, while the assigned muster station is located on the uppermost deck [16]. Every MVZ contains decks, and other main or auxiliary spaces, like cabins, corridors, etc.

In our example, we consider a generic large cruise ship, with a total number of 13 Decks, 962 Cabins, 10 Restaurants, 10 Bars, 1 Pool, and 10 Lifts [17]. We also take into account that there are different types of passengers on a ship, with different characteristics and behavior that will affect them during an emergency evacuation. Passengers' age, gender, walking speed and health disabilities can influence the evacuation process. Therefore, evacuation planning is one way to reduce risks and keep people safe [18]. Thus, this paper mainly analyzes the implementation of an on-premises digital signage system that will help all passengers, including those with health disabilities, to follow the evacuation process safely, combined with the guidance of the crew members and the ship's safety standards.

Our experiment takes place on the ship's deck number 8, as seen in Figure 2. We consider the "SECURE" or "NOT SECURE" passaging from a corridor named "Way 1".

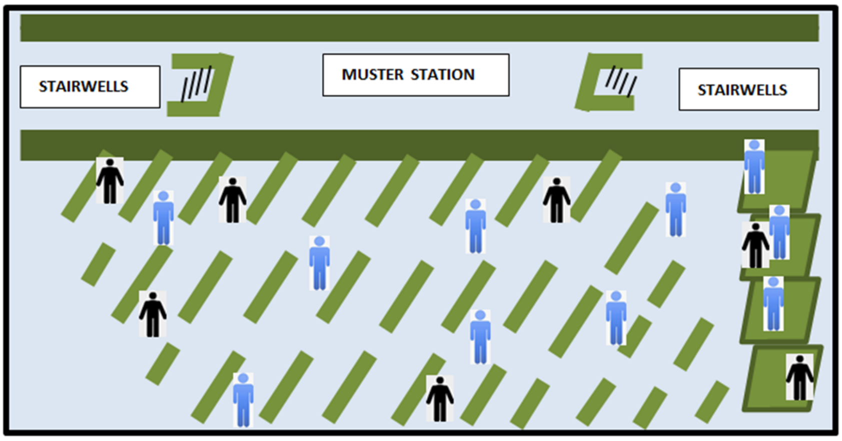

Figure 1. MVZs Layout Example.

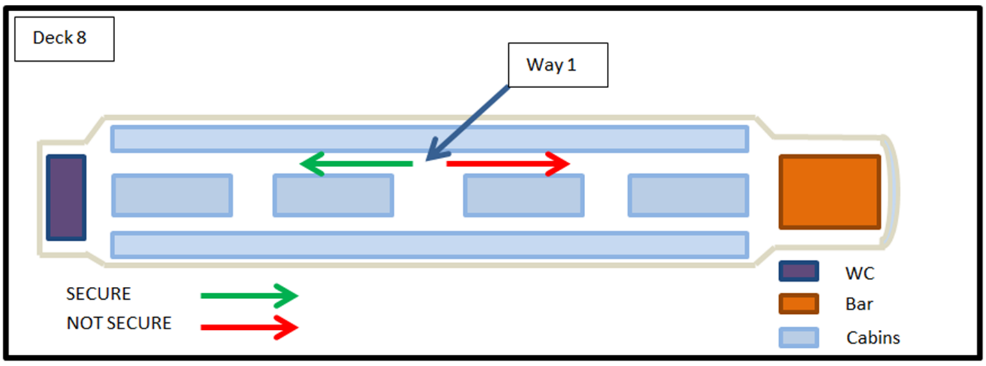

Figure 2. Evacuation simulation model.

The ship includes many corridors and directions to be signed digitally. To deploy this IoT system, we had to design a simple network that provides overall security. For those reasons, for complexity avoidance, a hybrid IoT system that combines different technologies and protocols is not suitable.

3.1. Comparison of IoT Technologies

Todays' IoT solutions require several network layers, including support from higher-level applications to lower-level media-based. To implement an Industrial IoT solution, we should first consider some characteristics such as the main application requirements, the Quality of Service (QoS), the security mechanisms, the web integration options, etc. Many wireless communication protocols standards were created to incorporate the IoT requirements in power efficiency, throughput, and reliability. Thus, there are many options to help us fulfill the requirements of wire connections, for covering area ranges from a few meters up to many hundreds, with a data rate from a few bps up to Gbps [15], as seen in Figure 3 [19].

For our application, we finally decided to use cellular networks, like 4G/LTE deployed on-premises with several base stations embedded in the ship infrastructure, while the Narrowband-IoT (NB-IoT) solution could also be suitable under certain conditions. In this subsection, we compared the options we had to implement our industrial type IoT application. In the future, we aim to build an on-premises 5G cellular network to use on isolated industrial applications and ships.

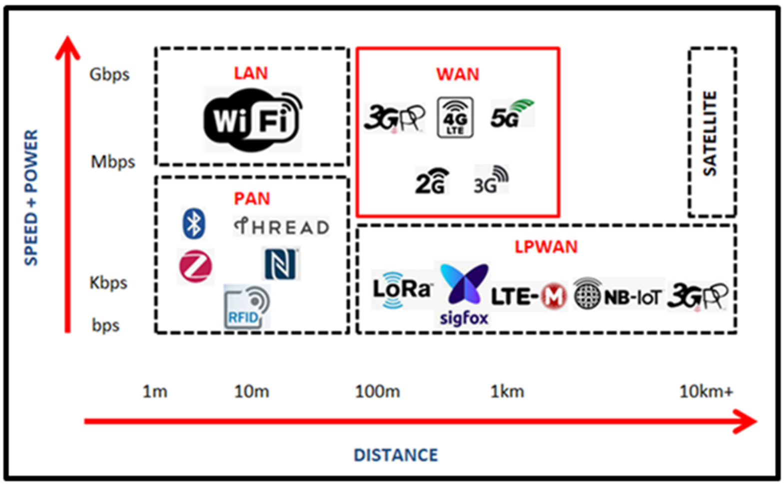

Figure 3. Comparison of IoT technologies.

3.1.1. Personal Area Network (PAN)

PAN stands for Personal Area Network, and it divides into cabled PANs and Wireless PANs (WPANs). It is a network that we use for communication among computing devices, such as mobiles, laptops, headsets, mouses, printers, etc., and other personal digital devices. We use it for low data rate monitoring and control applications. It requires little time to establish a connection and does not require much power. The most commonly used PANs methods are Bluetooth, Zigbee, and RFID. Their advantages are the low-power consumption and their built-in security method [20]. Bluetooth Low Energy (BLE) is a WPAN designed for applications in healthcare, security, home entertainment industries, etc. For example, most BLE technology in healthcare focuses on patient data monitoring, using medical devices. It is compatible with computers, micro-computers, and mobile phones. The development of BLE-based Real-Time Location Systems (RTLS), especially using wearables, is under research [21]. BLE technology can be used for RTLS in cruise ships and large industrial buildings but requires a reliable infrastructure and maintenance. While RFID has similar characteristics to BLE, and both are suitable for healthcare environments, they both cover short ranges. Moreover, RFID technology transmits low data rates and faces data droppings.

3.1.2. Local Area Network (LAN)

A LAN is a digital communication facility that carries data among a large number of computers and other IoT devices, which are located in a single building or adjacent buildings. The coverage area of LANs is a few kilometres, and they can achieve transmission rates of 1 Mb/s to 100 Mb/s, and even higher, as the LANs technology is being developed. Moreover, there are LANs that use Wi-Fi technology that are called Wireless LANs (WLANs). These networks can be used for indoor positioning due to their advantages of wide coverage, fast data transmission, and low transmission power [22]. Although LANs and WLANs can provide suitable solutions for industry implementations, they have some issues, like signal interference, interoperability, and security issues. A nice industrial approach is to combine WLANs with cellular technology.

3.1.3. Low Power Wide Area Network (LPWAN)

LPWANs are characterized by their low power and their wide networking area. They have been designed for wireless connectivity to connect battery-operated nodes to the net. They satisfy many IoT requirements, like end-to-end security, mobility, bi-directional communication, and localization services. The most common use cases of LPWAN networks are connected industries, smart cities, and isolated data measurements [19]. Even if several LPWAN solutions have emerged, LoRaWAN is the most widely used in the industry. This is happening because it is an open standard that operates in the sub-GHz industrial, scientific, and medical (ISM) radio bands, it is widely commercially available, and it can be installed almost everywhere [23]. Although they cover long ranges, up to 10 km, they transmit with a low-data rate [24], and therefore they are not suitable for our implementation. We have rejected the usage of LPWAN technology, as LPWAN devices face some crucial problems, such as duty cycle and power transmission limitations and overall policy restrictions [25], which make them unreliable for systems that affect people's lives. Among LPWANs we include the NB-IoT, which has been introduced in the 3rd Generation Partnership Project (3GPP) to provide low-power, low-cost, and wide-area cellular connectivity for IoT applications. The NB-IoT is a narrowband radio technology which has been designed especially for IoT, as it can be directly deployed in LTE or other Global System for Mobile Communications (GSM) networks, and it can reduce the deployment costs. NB-IoT provides low power consumption, low-cost, long-range, and network security. Communication industries like Huawei, Ericsson, and Nokia have shown a lot of interest in this technology as part of the 5G IoT evolution [26]. However, they also have a low-data rate, and this may be crucial for not being chosen for industrial systems that require higher data transmitting rates.

3.1.4. Satellite Communications

Satellite communications are gaining interest in industrial and other IoT applications, where other types of communications are difficult to deploy. We refer to IoT situations, where we have to collect data from sensors or RFID, and control actuators with messages. In many industrial and cruise-ship scenarios, a large number of actuators and sensors are distributed over a wide area, and sometimes they are located in remote areas where there are no networks, and therefore the use of satellite systems becomes of paramount importance. In our case scenario, to use satellite communications, we should first consider two enabling factors: the first one is the interoperability between actuators and sensors with the satellite systems, and the second is the support of IPv4 and IPv6 over satellite. Moreover, radio resource management algorithms and the deployment of heterogeneous network interoperability are required to improve the efficiency of IoT over satellite [27]. Furthermore, we should consider the time delay that occurs while a signal is transmitted by the satellite through a transmission link, considering other timing group delays (TGD) [28]. Thus, we cannot use satellite communications in our implementation.

3.1.5. Wide Area Networks (WAN)

Cellular WANs are a form of wireless networks which differ from WLANs, as they use cellular network technologies like 2G, 3G, LTE/4G, and 5G networks for transferring data. The 1G cellular technology was introduced in the 1980s to offer voice services and was called Nordic Mobile Telephone (NMT). The 2G introduced in the 1990s was digital and was called GSM. This generation provided more services, such as Short Message Services (SMS), Multimedia Messaging Services (MMS), and General Packet Radio Services (GPRS), which offer internet services to the users. The 3G cellular technologies were introduced in the 2000s to provide faster voice, SMS, and MMS services, as well as video calling and internet services. In the third generation, there was also an exponential growth of data bandwidth and throughput from which customer services improved. Nowadays, LTE/4G cellular technologies offer improved communication links, higher data rates, and better quality of service in comparison to the earlier cellular generations. They were launched in 2010, and the improvement over the third generation and other technologies was the higher bandwidth and the better data throughput. The 5G infrastructure, which is typically based on the previous generation, has been designed to offer fast and reliable communication services, secure banking transactions, and reliable industrial IoT applications. 5G coexists with 4G/LTE technologies and it is based on Code Multiple Access (CDMA) and Beam Division Multiple Access (BDMA) technology standards, hence it supports the core network for the internet [29]. In Table 1, we see a performance comparison of the most common IoT technologies that we have described [26].

Table 1. IoT technologies performance comparison.

	PAN		WLAN	LPWAN			Cellular WAN		
	BLUETOOTH	**ZIGBEE**	**WIFI**	**SIGFOX**	**LoRa**	**NB-IoT**	**GSM**	**LTE-M**	**5 G (Targets)**
Coverage Area	1–10 m	1–100 m	17–30+ m	<12 km (160 db)	<10 km (157 db)	<15 km (164 db)	<15 km (164 db)	<10 km (156 db)	<12 km (160 db)
Spectrum Band-width	2.4 GHz (802.15.1)	2.4 GHz (802.15.4)	2.4 GHz (802.11)	Unlicensed 900 MHz 100 kHz	Unlicensed 433, 868, 915 MHz <500 kHz	Licensed 7–900 MHz 200 kHz shared	Licensed 800, 900 MHz shared	Licensed 700, 900 MHz 1.4 MHz shared	Licensed 700, 900 MHz shared
Data Rate	1 Mbps	250 kbps	150 Mbps	<100 kbps	<10 kbps	<50 kbps	10 kbps	<1 Mbps	<1 Mbps
Terminal Cost	4.00 $	3.00 $	4.00 $	2.64 $	2.64 $	2–3 $	2.97 $	3.30 $	<2 $
Network Reforming	None	None	None	Large	Large	Small to moderate	Moderate (LTE reuse)	Small	Requires 5 G NWs

3.2. Comparison of IoT Protocols

Almost every Industrial IoT implementation consists of a server and IoT nodes that should be able to cooperate. In order to connect IoT nodes over the network, a client–server architecture is required so that clients can communicate with the main server. There are many connection protocols that we can use, and HTTP and MQTT are the most common. To strengthen the modularity of our nodes, there is the need for a communication protocol which provides low latency and enhances flexibility for the nodes to be remotely controlled. We have chosen to use the MQTT protocol, which, through experimental evaluation in 3G networks, is proven to provide 90 times lower latency than HTTP [30].

3.2.1. Message Queue Telemetry Transport (MQTT) Protocol

MQTT, invented by IBM, is designed to be a notably lightweight protocol at the application layer. It is therefore suited for IoT, featuring a fixed header size of only 2 bytes, and extended for Wireless Sensors Networks (WSN) and M2M communications. MQTT is based upon Publish/Subscribe, whereas the publisher and the subscriber operate as MQTT clients and MQTT devices, while the MQTT broker operates as the MQTT server. Clients publish and subscribe messages to defined topics which are stored in the broker, pictured in the MQTT Flow Diagram (Figure 4).

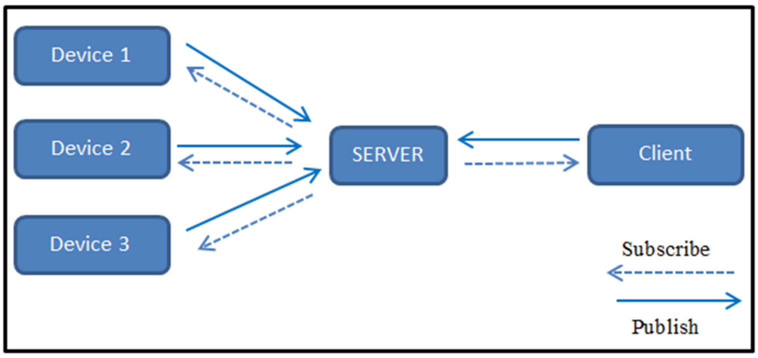

Figure 4. MQTT flow diagram.

MQTT has been designed to send messages from 0–256 Mb to one or multiple devices with low latency and is suitable for messaging over fragile networks. It is highly recommended to be used in wireless networks where we want to exchange small messages without high bandwidth demands, as bandwidth issues can induce latency. As far as security is concerned, clients and MQTT devices validate the MQTT server using an SSL/TLS certificate, stored in the server. In sequence, clients and devices provide their own certificates to the MQTT broker, which is used for authentication [30,31]. This bidirectional MQTT functionality makes the protocol favourable in industrial IoT applications, where it is commonly used.

Taking it further, MQTT features include QoS (Quality of Service), LWT (Last Will and Testament), and Retain Flag [31,32]. QoS defines the way messages are communicated between the client and the server. More specifically, with QoS 0 a message is broadcasted without guarantee of the delivery (mostly used in UDP networks), with QoS 1 the message is broadcasted until there is an acknowledgement from the receiver, and with QoS 2 the message is broadcasted precisely once until there is receiver acknowledgement [31,32]. LWT is a feature which notifies the subscribers of a sudden disconnection of the publisher like e.g., network failure [31]. With the Retain Flag, the broker stores the last retained message and broadcasts it again to update to the newly connected subscribers, a feature that proves useful in reconnecting situations. For our evacuation scenario, QoS 1 proposes that the message will be received reliably and quickly, and the passengers will be notified. LWT ensures that the clients will be notified in case the server crashes and "Retain Message" ensures that the clients will be immediately updated after a reconnection, both of which are necessary in a situation such as ship wreckage.

3.2.2. HyperText Transfer Protocol (HTTP)

HTTP is an interrelated communication protocol which also features a client–server architecture. It makes use of TCP/IP providing reliability; however, clients must first send many small packets in order to get admitted to the server. This happens via a request/response architecture, where a great amount of data can be transferred in smaller packets, often resulting in a great protocol overhead, and therefore HTTP connections can lead to serious overhead in network communication. Following this, HTTP is not suitable for IoT communication, as it may cause serious bandwidth issues. Below, we see the HTTP Flow Diagram (Figure 5).

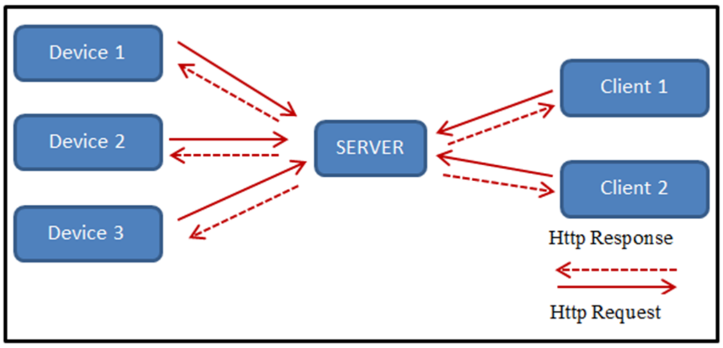

Figure 5. HTTP flow diagram.

The IoT HTTP request function includes a 9 packet TCP complex header format, which is unnecessary in most IoT cases, and thus it becomes a waste of bandwidth. HTTP protocol is more commonly used for client-triggered cases, like applications of weather reports, such as temperature and humidity reports, etc. [30].

3.3. Features and Evaluation of MQTT protocol in LTE/4G Communications

In order to evaluate the applicability of our chosen protocols, we evaluated factors which can be very critical in emergencies, and especially in our case, where every connection and reconnection should be fast and reliable. The signage modules would maintain their connection to the server no matter the situation, e.g., periodically manufacturing nodes or interference from water.

A very important factor that we should take into account in our case scenario is latency. In [33], a testbench compares the HTPP and MQTT protocols in a mobile scenario with GSM/GPRS modules, and the results show that because of the complexity accompanying the HTPP protocol, MQTT can be as much as 9.6 faster and provides a faster reconnection in the case of lost signal. This can also provide us with more robust server resources as shown in [34], where a comparison between MQTT and HTPP protocols shows that the lightweight protocol overhead of MQTT is notably better in terms of preserving network bandwidth.

Apart from HTPP, we also compared MQTT with the other candidate, Machine 2 Machine (M2M) internet application protocols. In [35], MQTT, along with CoAP and OPC UA, were evaluated and tested for their performance in different multicasting scenarios, namely “1 to many”, “many to 1”, and “many to many”. MQTT seems to outperform the other two protocols in both “1 to many” and “many to 1” scenarios, providing the lowest latency. MQTT also seems to show the best integrity when the size of the message is fixed, like in our case. In [36], MQTT, CoAP, and OPC UA are simulated in terms of latency in an LTE scenario. Both MQTT and OPC UA show greater stability than CoAP in terms of network load, and OPC UA slightly outperforms MQTT in latency, which, in the case of LTE, is not more than 20 milliseconds. However, it is noted that the protocol overhead of OPC UA is larger than MQTT and it is not taken into account in the experiment.

It is also important to evaluate our choice of MQTT features like QoS and the integration of SSL/TLS certificates. In the [32] testbed, MQTT QoS 0 and QoS 1 were compared in regard to latency for TCP connections. For the same payload, MQTT QoS 1 seems to be 30% faster than QoS 0. In [37], a testbed evaluates MQTT in regard to the delay of processing TLS and TLSMA certificates for different payloads and QoS, and the results show that the use of certificates does not significantly influence the latency of the messages (Table 2). For a QoS 1 message of 0–200 bytes, the difference is in the range of ~0.1 msec, and for a message of 1000–1200 bytes, the difference is not more than 4 msec.

Table 2. Latency for TLS and non-TLs enhanced MQQT.

Payload Size (kb)	0–200	200–400	400–600	600–800	800–1000	1000–1200
QoS 0 PT (ms)	1.9575	3.3773	4.4756	5.9152	7.1644	7.6543
QoS 0 TLS (ms)	1.9738	3.8433	5.3904	7.5574	9.9594	11.8360
QoS 0 TLSMA (ms)	1.9233	3.5789	5.4169	7.0627	9.7204	11.7716
QoS 1 PT (ms)	1.8276	2.8415	3.6975	5.1162	6.8120	7.8951
QoS 1 TLS (ms)	1.9451	3.5139	5.5778	7.9114	10.187	11.8742
QoS 1 TLSMA (ms)	1.7534	3.0070	4.4488	6.8328	9.9884	11.7456
QoS 2 PT (ms)	2.8024	3.8195	4.5763	6.1935	7.6070	8.2785
QoS 2 TLS (ms)	2.5047	3.7768	5.3041	7.9585	11.425	12.8641
QoS 2 TLSMA (ms)	2.4494	3.7117	5.2145	7.7037	10.6853	12.0606

The studies above agree with our case scenario—that we need to have fast and reliable communication for either a “many to 1” or a “1 to many” scenario with a predefined message. They show that the network capacity and stability of MQTT is needed in an otherwise unstable scenario. This shows that QoS 1 is the preferable choice for the application and that SSL/TLS security can be integrated in a costless way. We did not stand on the power consumption of the protocols, since we did not deem it necessary for this study, and the ship can provide the module and batteries can flexibly be used. However, ref. [38] shows that power consumption for MQTT can be as low as 20% as that of an HTPP application.

4. Low-Cost Experimental Implementation Using on-Premises LTE/4G Network

To implement an on-premises LTE/4G network, we used the Open Air Interface (OAI) software [39]. It is an open-source software program that runs on the Ubuntu Linux environment and is provided by University Eurecom. Its purpose is not only experimental. It actively participates in the research and development of 5G and other communication products, also used on IP Multimedia System (IMS) platforms. Figure 6 describes the implementation of the isolated LTE/4G network. Applications include the operation of E-UTRAN (OAI eNB and UE) and OAI EPC (MME, S-GW, P-GW) and the HSS database for user management. The eNB application is running on an Ubuntu Linux low-latency kernel PC (eNB PC), and the MME, HSS, and SPGW applications are running on an Ubuntu Linux generic Kernel PC (EPC PC). The program can work in real-time with Software-Defined Radio (SDR) platforms and commercial User Equipment (UE).

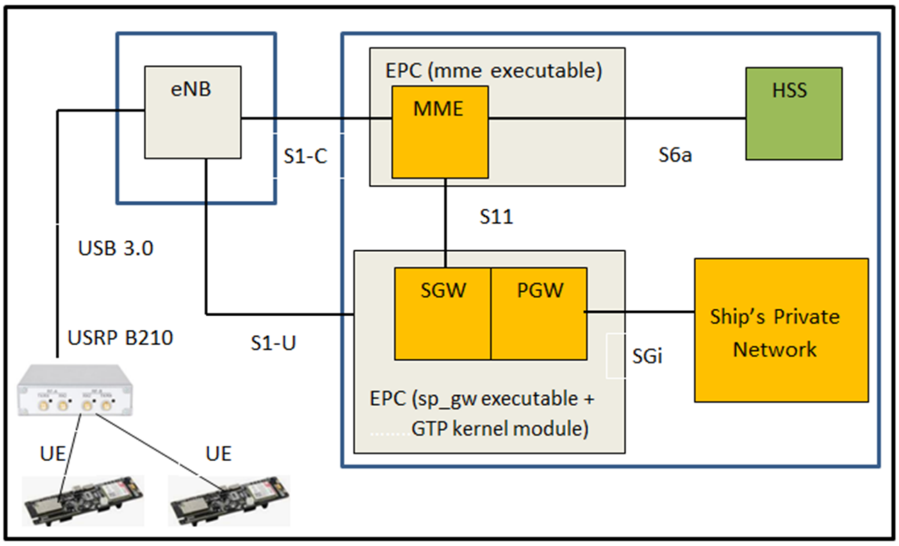

Figure 6. LTE/4G on-premises implementation—high level architecture.

In Table 3, we describe the LTE/4G abbreviations.

Table 3. 4G/LTE abbreviations.

ACRONYM	ABBREVIATION
eNB	Evolved Node B
EPC	Evolved Packet Core
EUTRAN	Evolved Terrestrial Radio Access Network
HSS	Home Subscriber Server
MME	Mobility Management Entity
OAI	Open Air Interface
PGW	Packet Data Network Gateway
SGW	Serving Gateway
UE	User Equipment
S1-C,S1-U,S11,S6a,SGi	Communication Protocols

LTE networks are covered with several standard security procedures, where all components in the system, such as UE, eNB, MME, and HSS, are involved [40]. Our 4G/LTE network is an isolated on-premises network, and therefore, external users and passengers do not have access. We should also take into consideration that the radio channel characterization is subject to an investigation because of the propagation (reflection, scattering, and diffraction). Furthermore, many obstacles whose dimensions are similar to the wavelength of the transmitted electromagnetic wave are responsible for loss due to multipath fading, electromagnetic absorption, etc. In [41], the authors reported the LTE penetration losses measurement inside a building. They observed the penetration of the radio channel at 2.6 GHz through the exterior, interior, and plasterboard walls in a building. Their result shows that penetration loss reduces the radio frequency (RF) energy inside a building. Their statistical report is very useful, and therefore, we should carefully examine the number of base stations that we should install on the ship.

Below, we describe the experimental procedure that we followed to simulate the digital signage system of the cruise ship. Our experimental setup includes a digital LED strip installed on an LTE/4G module, placed on deck number 8 on the cruise ship.

4.1. Experimental Implementation

To implement a low-cost open-source monitored Emergency Evacuation System, based on smart signage, we have built a scalable LTE/4G sensor network, which is composed of low-cost LTE/4G modules (Figure 7a) and digital LED strips (Figure 7b). The LED strips are used in the current project both as a low-cost signage tool, as well as a durable and flexible digital signage component. We use a LILYGO TTGO T-SIM7000G development board with a SIMCOM7000G (Figure 7a) modem installed, and an LTE/4G sim card (Figure 7a), which is connected to a cellular network, to control the digital LED strips.

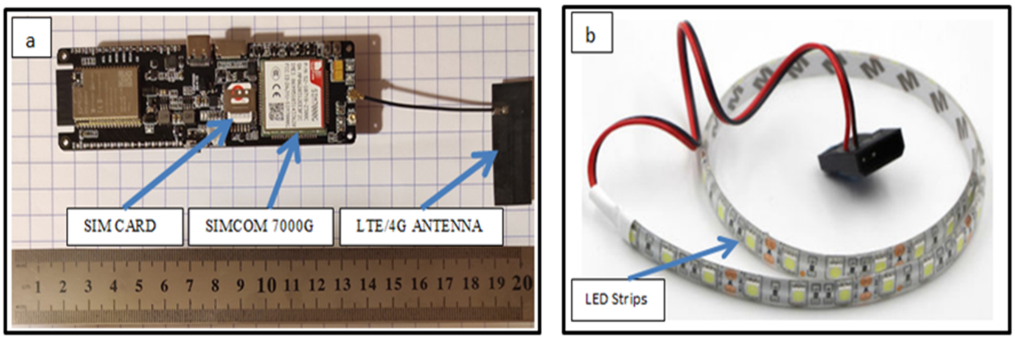

Figure 7. (**a**) Low-cost 4G/LTE module; (**b**) Digital LED strips.

We have chosen the LILYGO TTGO T-SIM7000G module, which is very compact, with a 16850 battery holder. It is also a low-power global cellular module which supports LTE CAT-M1 and NB-IoT technology. It can also be used for location tracking, as it has integrated a high-speed multi-GNSS (GPS, GLONASS, and BeiDou/Compass, Galileo, QZSS standards) chipset [42]. It can be programmed through Arduino IDE, which is a user-friendly IoT tool for node programming. With the most recent SIMCOM7000G modem, the LILYGO TTGO T-SIM7000G gives us a combination of power, friendliness, and adaptability that enables us to connect our nodes and create IoT industrial applications for energy metering, asset tracking, monitoring, digital signage, etc. In Power Save Mode (PSM) and Extended Discontinuous Receptions (eDRX), the LTE/4G modem can extend battery life up to 10 years [43].

The SIMCOM 7000G modem is powerful and expansible with many interfaces, such as UART, GPIO, PCM, and I2C. Compared to GSM modems, it provides deeper coverage enhancement. It has been designed for applications where low latency is required, along with low-throughput data communication in a variety of propagation use cases. It combines performance and security with flexibility, and therefore it suits Machine-To-Machine (M2M) applications, such as asset tracking, remote monitoring, health monitoring, digital signage, etc. [43]. Table 4 depicts SIMCOM 7000G modem details.

Industrial IoT systems have been grown rapidly, and the pervasiveness of smart nodes enables the foundation of more interactive things and users, with the hope to improve industrial procedures and system monitoring. To face the growing complexity of industrial IoT systems, where specialized resources are missing, several industrial and academic approaches have been proposed to improve the end-user experience and allow them to implement and configure their IoT applications. The most common solutions are based on Visual Programming Languages (VPLs), which have been used to develop theProgrammable Logic Controllers (PLCs) systems. Thus, many IoT implementations are created and controlled with the usage of VPLs, where Node-RED is one of the most well-known. Node-RED is an open-source software that enables the mashup of IoT devices, APIs, and third-party services, all together in a hybrid text-visual programming solution [44]. It also provides a browser-based editor that makes the connections easy. Our network uses a Node-RED IoT platform and a Node-RED IoT dashboard, which were installed along with an MQTT broker on an Ubuntu 20.04 LTS machine (Figure 8).

Table 4. SIMCOM 7000G modem details.

PRODUCT		**SIM7000G**
Form Factor		LCC, 68PIN
Dimensions (mm)		24X24X2.6
Frequency Bands	Cat-M	B1/B2/B3/B4/B5/B6/B8/B12/B13/B17/B18/B19/B20/B25/B26/B28/B39
	Cat-NB	B1/B2/B3/B4/B5/B6/B8/B12/B13/B17/B18/B19/B20/B25/B26/B28
	GSM	850/900/1800/1900MHz
Temperature GNSS		−40 °C~+85 °C optional
ELECTRICAL FEATURES		
Supply Voltage Range (V)		3.0~4.3
Power Consumption	Power Off (uA)	7
	PSM (uA)	9
	Sleep (mA)	1
	Idle (mA)	11
DATA TRANSFER		
Cat-M (Kbps)		300(DL)/375(UL)
Cat-NB (Kbps)		34(DL)/66(UL)
EGPRS (Kbps)		85.6(DL)/85.6(UL)
SOFTWARE FEATURES		
Protocol		TCP/UDP/LWM2M/COAP/MQTT/FTP/HTPP/TLS/DTLS/NTP
FOTA		•
Embedded AT		•
Firmware Upgrade		USB/FOTA
INTERFACES		
SIM Card		1.8 V/3.0 V
UART		•
USB		•
PCM		•
ADC		•
I2C		•
CERTFICATION		
Regulatory		RoHS/REACH/CCC/CE(RED)/GCF/Deutsche Telekom/FCC/IC/OCD(Anatel)
Carrier		Deutsche Telekom/ORANGE/PTCRB

We built flows to control the Digital LED strips by using palette nodes, which can be deployed to its runtime in a single click. Figure 9 represents an experimental flow that directs passengers of deck 8 to the safest direction. The Node-RED dashboard is a front-end web application that was developed to control the digital LED strips that were installed on the ship. We controlled them by publish/subscribe messages through the MQTT Broker to specific topics that represent the decks of the ship inside the MVZs. Figure 10 depicts the experimental Node-RED Dashboard, which controls the "SECURE" (Figure 10a) and "NOT SECURE" (Figure 10b) digital signage on "deck 8" into an MVZ.

In Figure 9 we see a "SWITCH" node and an "MQTT OUT" node, connected via an MQTT connection. Each change in the state of the "SWITCH" will automatically generate a message on the output with the specified digital LED strip color value (green or red). On the output is the "MQTT OUT" node, which is connected to the MQTT Broker and publishes the message. MQTT is one of the most commonly used communication protocols for IoT platforms. Whether it is from the perspective of device compatibility or resource consumption, and overall security, the MQTT protocol has certain advantages and is one of the most competitive communication protocols in the Industrial IoT [45].

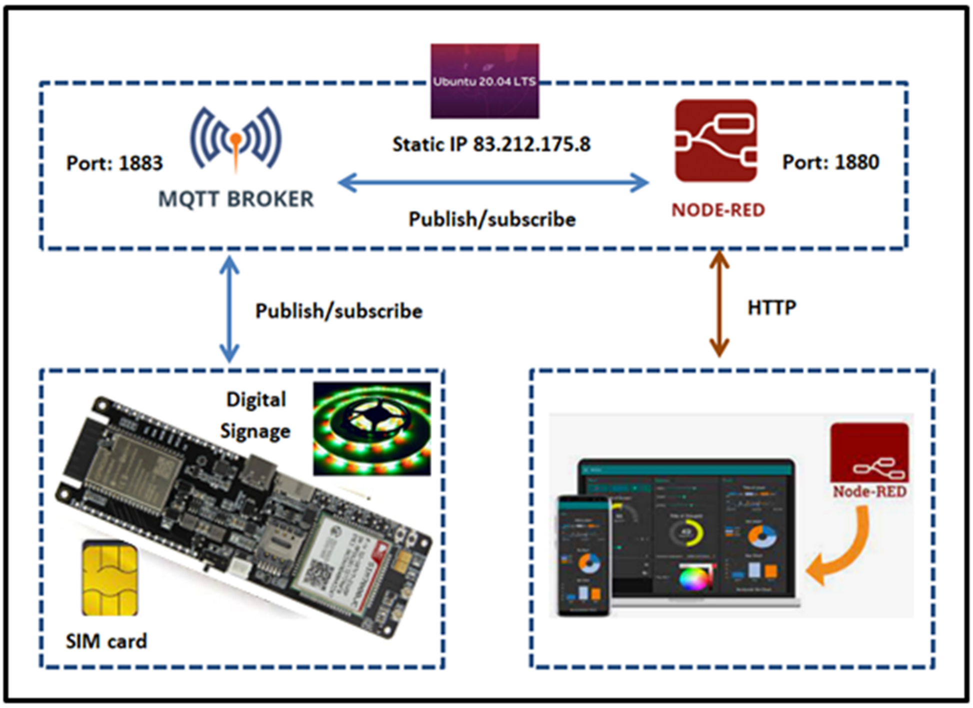

Figure 8. Experimental network architecture.

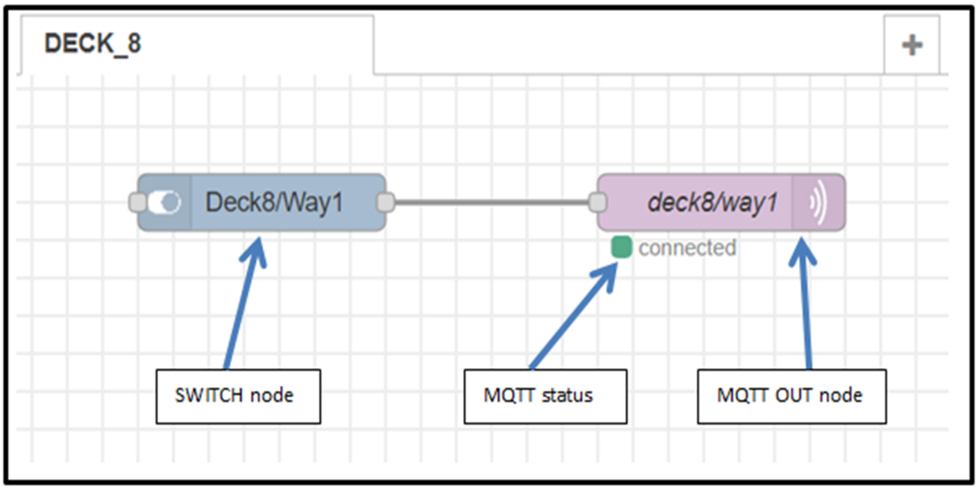

Figure 9. "Deck 8" experimental flow.

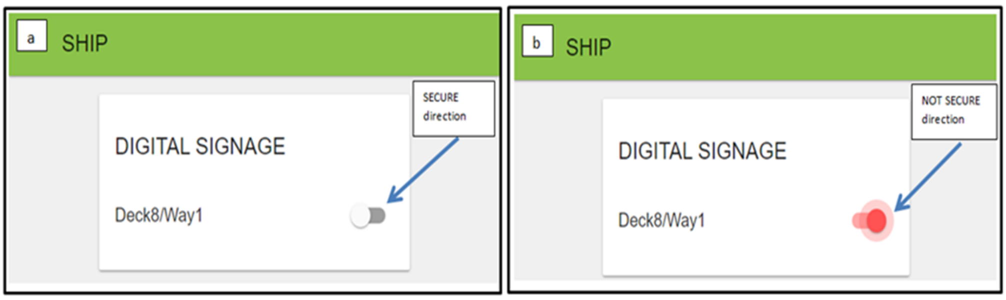

Figure 10. Experimental dashboard for controlling digital signage (**a**) SECURE; (**b**) NOT SECURE.

Figure 10 shows the two possible conditions for digital signage in "Deck 8/Way 1" that a user can control from the Node-RED dashboard. When the "SWITCH" remains in the "SECURE" direction (Figure 10a), the digital LED strip remains GREEN (Figure 11a), and when the "SWITCH" goes to "NOT SECURE" direction (Figure 10b), the digital LED strip changes to a RED color (Figure 11b). For the experiment, we used one digital LED "WS2813B, while we can connect any size (number of LEDs on the strip) we want, without permissions. WS2813B is an improved version of WS2812B, a popular LED strip for industrial projects given its low driving voltage, high brightness, and great color consistency. Each addressable LED has an integrated driver, and therefore the color and the brightness of each LED can be controlled individually. Thus, we can create any complex digital signage. The most significant advantage of WS2813B strips is their LED bypass property. If any LED in the middle of the chain burns out, then the circuit remains closed, and the remaining LEDs will still light up.

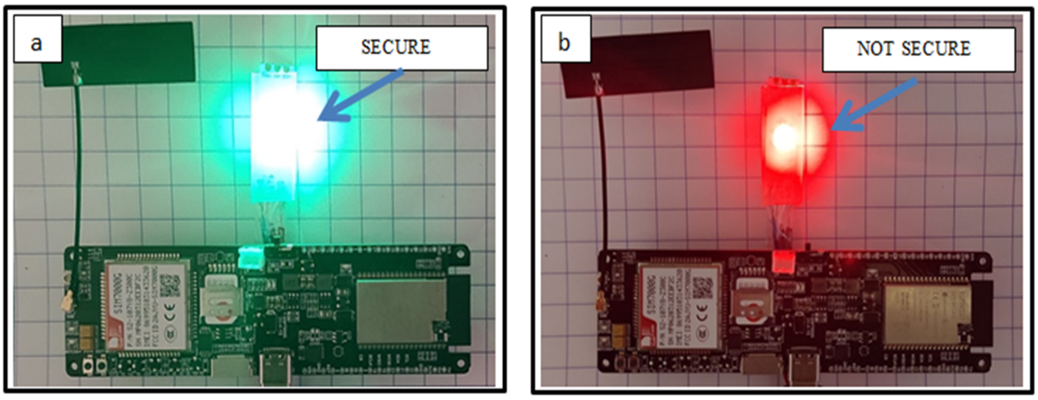

Figure 11. Experimental digital signage. (**a**) SECURE; (**b**) NOT SECURE.

Following this methodology, we can cover all ship's MVZs with low-cost open-source digital signage modules and control them centrally through a real-time IoT dashboard. Moreover, we can easily add low-cost, reliable sensors to increase the security of the evacuation procedure. For example, we can add smoke, gas, fire, or water sensors to automatically give signal alarms in emergency cases, change the digital signage, and inform the IoT dashboard at the same time. Below, we analyze an example of the digital signage system's scalability.

4.2. Digital Signage Scalability

In this subsection, we analyzed an example of how we can expand the system by controlling the outputs of the deployment boards and displaying sensor data from the deployment boards on the "Node-RED" Dashboard. The Node-RED software runs on an Ubuntu Server, and communication between the deployment board and the Node-RED software was achieved with the MQTT protocol. A smoke sensor detector was installed on the module that controls the digital signage LEDs on Deck 8 (Figure 12). Figure 12 depicts the block diagram of the publish–subscribe communication between the MQTT clients and the MQTT broker.

If the smoke sensor detects smoke, the module publishes to the Deck 8/way1 topic of the Broker a new message "Smoke detected" (1a). At the same time, the module subscribes to the Deck 8/way1 topic (1b), and the second MQTT client (Node-Red dashboard), which has already subscribed to the topic, publishes a message to the module "Digital Signage RED" (2). Therefore, when a new message is published to Deck 8/way1 topic, the module receives the "RED" or "GREEN" messages and turns the LED strips red or green. Following this method, we can add another type of safety sensor that can automatically change the state of the Led strips and inform the dashboard. Except for safety sensors, there is another option to add people count sensors, to help the crew direct the passengers to the muster station. Thus, we can tackle some people's congestion problems. In case of an emergency evacuation there are specific routines for each deck. Passengers are not allowed to inform the digital signage system for safety reasons, because the evacuation plan is guided by the crew. The digital signage dashboard can help the crew to execute the evacuation plan.

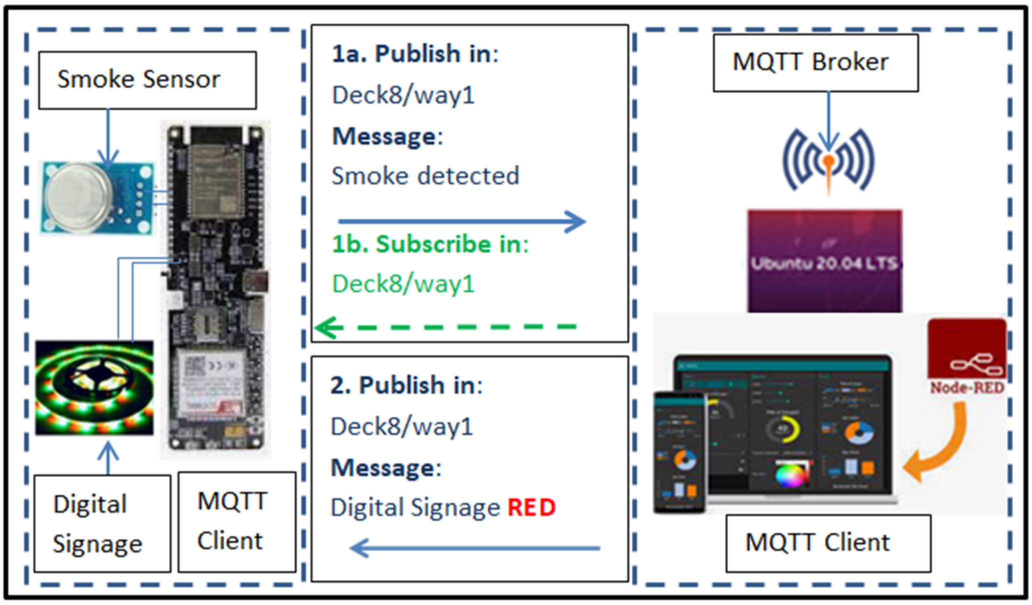

Figure 12. Digital signage scalability example.

5. Conclusions—Future Work

Our future work concentrates on four main directions. First of all, we are working on system development and improvement by adding other alarm and security sensors to make the system autonomous by collecting and monitoring as much data as possible. This will allow us to end up with accurate conclusions about intelligent Emergency Evacuation Systems on ships, and other large buildings, like schools, hospitals, and industrial structures. At the same time, simulation tools such as Matlab, Omnetpp, and Network Simulation 3 (NS3) will help us compare and improve the cellular networks by analysing the Radio Frequency (RF) propagation and the Received Signal Strength Indicator (RSSI) inside ships and buildings. Our third goal is to conduct experiments inside ships and industrial buildings. Taking into account the results, we will be able to compute the exact number and the positions of the on-premises cellular base stations needed to cover the whole ship or the building. Lastly, we aim to expand the system further by enabling 5G cellular technologies in our network architecture, including core and Radio Access Network (RAN), to achieve end-to-end latency on the order of 1ms. Latency is highly critical in Early Warning Systems and other applications like automated industrial production, control/robotics, transportation, health care, etc. [46]. 5G also introduces some new positioning methods based on multi-cell round trip time (multi-RTT) measurements and multiple antenna beam measurements for enabling the downlink angle of departure (DL-AoD) and uplink angle of arrival (UL-AoA) estimations [47]. The multi-RTT positioning method that is robust against network time synchronization errors, and the angle-based methods that are more relevant to the usage of multiple antennas in 5G networks, will improve our emergency evacuation system and industrial applications in general.

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