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Emergency Communication System Based on Wireless LPWAN and SD-WAN Technologies: A Hybrid Approach

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Abstract: Emergency Communication Systems (ECS) are network-based systems that may enable people to exchange information during crises and physical disasters when basic communication options have collapsed. They may be used to restore communication in off-grid areas or even when normal telecommunication networks have failed. These systems may use technologies such as Low-Power Wide-Area(LPWAN) and Software-Defined Wide Area Networks (SD-WAN), which can be specialized as software applications and Internet of Things (IoT) platforms. In this article, we present a comprehensive discussion of the existing ECS use cases and current research directions regarding the use of unconventional and hybrid methods for establishing communication between a specific site and the outside world. The ECS system proposed and simulated in this article consists of an autonomous wireless 4G/LTE base station and a LoRa network utilizing a hybrid IoT communication platform combining LPWAN and SD-WAN technologies. The LoRa-based wireless network was simulated using Network Simulator 3 (NS3), referring basically to firm and sufficient data transfer between an appropriate gateway and LP-WAN sensor nodes to provide trustworthy communications. The proposed scheme provided efficient data transfer posing low data losses by optimizing the installation of the gateway within the premises, while the SD-WAN scheme that was simulated using the MATLAB simulator and LTE Toolbox in conjunction with an ADALM PLUTO SDR device proved to be an outstanding alternative communication solution as well. Its performance was measured after recombining all received data blocks, leading to a beneficial proposal to researchers and practitioners regarding the benefits of using an on-premises IoT communication platform.

Keywords: emergency communication systems; off-grid areas; critical infrastructures; LPWAN; SD-WAN; IoT platform; MATLAB; NS3

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1. Introduction

Autonomous communication-wide networks are vital in controlling emergencies or unexpected crises when public networks malfunction, and for establishing new communication networks among people in off-grid areas. In emergencies, wired communication methods may suffer from damage, and may be unavailable in isolated and off-grid areas. In comparison to wired communication networks, wireless networks are more efficient as they offer many advantages, such as availability, cost savings, flexibility, efficiency, and fewer installation issues. Therefore, our research focuses on wireless and wide-area communication protocols.

On the one hand, due to latency, reduced coverage, and a low level of reliability brought on by the loss of data packets, wireless technologies such as Wi-Fi, Thread, Z-Wave, ZigBee, and 6LoWPAN [1] are unable to meet the needs of IoT-based ECS. To employ satellite communications, we should consider IPv4 and IPv6 support over satellite, as well as actuator and sensor interoperability with the satellite systems. To increase the effectiveness of IoT over satellites, heterogeneous network interoperability, and radio resource management must be deployed [2,3]. Together with the time delay that happens when a signal is relayed by the satellite through a transmission, we should also consider other timing group delays [3,4].

On the other hand, LPWANs are a promising technology for wireless communication networks. Widespread technologies such as LoRaWAN, Sigfox, NB-Fi, and mioty have developed rapidly, and many LPWAN networks have been deployed in various countries. Although LoRaWAN, Sigfox NB-Fi, and mioty were designed for similar applications, they use different approaches. A typical LPWAN network has a star-of-stars topology consisting of end devices (nodes), gateways, and a server. In the considered LPWANs, gateways communicate with the server through a broadband link. The end devices communicate with the server via wirelessly connected gateways, while the gateways act in a similar way to transparent retransmitters between the sensors and the server. LPWAN networks impose limitations on the emitted power as they operate on unlicensed ISM radio bands [5]. They can enable low-cost applications over large areas, while LPWAN devices can cover distances of more than 10 km with typical transmission powers of 10 mW. This feature is achieved by transmitting very low payload bit-rates of a few kBit/s between the nodes and the highly exposed gateway antennas placed on top of high buildings or broadcast towers [6]. Moreover, LPWAN technology is suitable for dense or thick locations for long-term monitoring applications and is the best technology that can send small packets of data over long distances for a long time as it supports long battery life [7].

One of the most promising LPWAN technologies for sensor networks is Long-Range (LoRa) technology. It provides a novel wireless communication protocol that compromises data rate and time-on-air to achieve low power consumption and long-distance transmissions. LoRa is appropriate for spare transfer applications with relatively small payloads because of its limited transmission bandwidth. This method is particularly suited for metering applications of non-critical parameters, such as weather meters, air quality or other environmental meters, smart agriculture, connected farms, as well as in-person, animal, and vehicle tracking [8]. As a result, ECSs may exchange messages, measure health sensor data, and track people or cars using LoRaWAN in combination with other LPWAN technologies.

Operation scenarios and emergencies set strict requirements for long-distance data transmission, driving researchers to design highly prospective wide-area networks. SD-WAN technology provides a promising architecture for those wide-area networks [9]. It is regarded as a pioneering architecture of next-generation WANs, as it provides network operators with a new tool to build networks in off-grid areas. SD-WANs are applied to software-defined techniques in networking connections to cover a wide geographical area, and they can be combined with LPWAN technologies to build hybrid emergency networks. They also simplify the connection core and management between users and providers and allow the necessary monitoring, flexibility, and centralized control with lower costs.

Compared with the public WAN, SD-WAN has two suitable superiorities for developing autonomous communication systems. First of all, it offers a user-friendly programmatic framework for hosting and controlling IoT applications that are created in a centralized manner while taking into account the IoT application-level needs to ensure the quality of experience for users (QoE). Second, it enables centrally defined network policies and network traffic management without needing manual configuration of user equipment [9,10]. Based on network functionality, virtual modules can be added to overlay network combinations and edge gateways as part of the SD-WAN operating principle.

In this article, we provide an overview of the state of research in the field of ECSs based on LPWAN and SD-WAN technologies. First, we introduce the evolution of current IoT implementations, then we present the basic features of these networks, and finally, we quote a simulation and a hybrid IoT application in the area of ECSs, before concluding with the targets of our future research.

2. Related Work

LPWAN and SD-WAN technologies have attracted too much attention in the literature. There are many surveys for the evaluation and comparison of nominal performance indices of these network technologies based on their specifications [5]. Apart from this approach, researchers have focused on IoT-enabled ECSs, which sometimes can provide phone or video calls, and may be combined with sensors to gather and analyze sensitive data (e.g., health data), perform monitoring and warning functions, and enable live tracking. In this section, we present these IoT applications and platforms for ECSs, based on these networks.

During a disaster, rescue team personnel are exposed to danger. To avoid risking the lives of these personnel, Manuel et al. [11] have integrated a Search and Rescue (SAR) robot into rescue operations. The heavily damaged infrastructure of disaster areas presents the biggest obstacle to using robots in rescue operations. A working communication system allows the robot and base station to share real-time information in the rescue environment. They suggest innovative communication architecture for search-and-rescue missions based on LoRaWAN and a SAR robot in situations where there is limited coverage or no communication system in severely damaged catastrophe sites. The SAR robot can operate in worst-case disaster scenarios where the entire communication infrastructure is destroyed since it is monitored and controlled from a remote base station. The functions of this SAR robot have been tested in a Gazebo simulated environment, while an actual test setup inside the lab facilities has shown great promise. The RoboMaC communication device, a unique full-duplex LoRa-based transceiver device capable of transmitting control commands from the base station to the SAR robot while returning the robot's geolocation data to the base station, has been installed on the SAR robot. By using this technique, the rescue team can locate and assist injured patients while reporting their whereabouts to the base station while tracking and controlling the SAR robot from a distance or standoff position. This eliminates the need for the presence of conventional communication networks. The RoboMaC devices were able to attain a signal range of 1.6 miles.

To manage the sporadic and rare events linked with emergencies in wireless Internet-of-Things (IoT) scenarios, Sisinni et al. [12] proposed a method to increase the performance of emergency communication when LPWANs are the backbone of the IoT. They created an innovative message replication technique (LoRa-REP), which is fully compliant with the LoRaWAN requirements to get around several LoRaWAN limitations. A private LoRaWAN network with a local backend and a public LoRaWAN infrastructure with a cloud-based backend were the two operating paradigms that were taken into consideration and tested. They also offered two examples of real-world applications to demonstrate the viability of their suggested strategy. The outcomes of the real-world use cases demonstrated the effectiveness of the suggested approach, which lowered the loss of emergency messages by at least two times. Moreover, the average transaction time was decreased by 200 ms in the worst-case situation.

Macaraeg et al. [13] developed a low-power, robust, and decentralized emergency communication network to coordinate emergency response and relief efforts when infrastructure damages have been caused by natural calamities. Based on LoRa technology, they suggested a workable emergency communication device for mesh networks. To enable mesh networking in LoRa, they implemented a modified Ad Hoc On-demand Distance Vector (AODV) routing protocol. This change routes the metric using the Received Signal Strength Indicator (RSSI). This method's effectiveness was assessed using the Packet Delivery Ratio (PDR). As a result, they created a method to send text messages between mobile phones using a mesh LoRa network. The outcomes of this implementation demonstrated that a higher spreading factor enhances PDR performance, extending the range of the transceivers. Moreover, they showed that transceiver PDR performance deteriorates when increasing the hop count. Thus, a point-to-point transmission is preferable.

To reduce the material cost and loss of lives caused by fires, Roque et al. [14] proposed an ECS for instant fire detection through smoke or gas sensing. They have implemented an outdoor Sigfox-based communication system, as Sigfox among LPWAN is a provider that commercializes IoT solutions through partnerships including various network operators. An outdoor application requires long-range connectivity and low power consumption, so they used devices that allow a longer battery life. Their system manages a sleep mode option for energy-saving and data processing. A solar panel charges the system's battery while providing energy on cloudy days. Two sensors are responsible for sensing temperature and smoke, and an Arduino board, an MP3 shield, and a GSM shield are taking over the automated mobile call implementation. Therefore, a Sigfox backend system, away from the monitoring area, will be generated by an emergency alert. In general, this solution is a valid proposal for any researcher who wants to develop an easily-integrated low-budget IoT solution.

Besides the LoRaWAN applications, SD-WAN networks can give solutions to a wide range of critical and emergency events. Prasanna et al. [15] worked on instructions about developing an earthquake early warning system. They conducted some experiments to assess the system latencies and compare the decentralized earthquake early warning (EEW) design concerning a centralized EEW approach. These scenarios included several hypothetical earthquakes. The results of sixty simulations demonstrated that the ideal alerting conditions are produced with an SD-WAN-based hole-punching architecture enabled by a Transmission Control Protocol (TCP). The outcomes also clearly demonstrated that the decentralized EEW system architecture performs better than the central EEW system architecture, saving crucial seconds.

O'Raw et al. [16] approach SD-WAN from the perspective of whether they can offer security in an Industrial Internet of Things (IIoT). For IIoT devices, remote attacks pose a serious concern, particularly in critical infrastructures. SD-WANs create such secure dedicated networks that there is a reduction in the attack surface of organization devices. Additionally, enabling SD-WANs in the Cloud can reduce the risk of an attacker being able to see the IP addresses of the source and destination nodes as packets pass through the network routers.

Wang et al. [17] researched SD-WAN usage during an emergency lack of power communication resources. An emergency communication network is essential to sustain the network (electrical grid) power functionality. Optical fiber networks have many benefits, such as sufficient bandwidth, high reliability, easy maintenance, and anti-electromagnetic interference, and they are preferred for communication networks. However, in case of a disaster, optical cables may not work properly, so there is a significant impact on the reliable operation of a communication network, making the requirement for an immediate emergency network (the SD-WAN) essential. The study concludes that optical fiber utilization efficiency may increase significantly when using an SD-WAN implementation. If an optical cable is damaged, SD-WAN can be used as an emergency link to quickly restore communications services and ensure the uninterrupted operation of a power network.

We should mention that big companies such as Nokia, Juniper Networks, Silver Peak, and even Cisco [18] have approached SD-WAN technologies and invested in them. Cisco SD-WAN [18,19] is a software-defined wide-area network solution offered by Cisco Systems. It simplifies the deployment and management of WAN networks while improving network performance and security. For critical infrastructures or emergencies, Cisco SD-WAN can provide uninterrupted communication services, efficient data transmission, and enhanced security. It enables organizations to prioritize critical traffic and dynamically select the optimal path based on real-time network conditions. Cisco SD-WAN can also detect and respond to threats, ensuring the safety and integrity of data transmission. Overall, Cisco SD-WAN can help organizations to provide efficient and reliable communication services during crises.

The authors of [3] offer a dependable, adaptable, and scalable IoT-based system that monitors and alerts passengers and crew to the safest route to muster stations during an emergency evacuation. They also examine the factors that determine a ship's safe evacuation, which could be helpful for other kinds of structures, including schools, homes, and hospitals. This proposal offers an IoT dashboard using a private LTE/4G cellular sensor network and a dependable open-source IoT platform. The suggested architecture recognizes not-safe locations and instantly guides passengers in the safest path to the muster station.

Except for implementation approaches, some researchers are focusing on existing network improvement. In case the traditional electric emergency communication system cannot fulfil the requirements of emergency communications, Zhang et al. [20] have proposed network architecture for rapidly deploying wireless networks based on Long Term Evolution (LTE) technology. Its design enables the communication between portable terminals, UAVs, data terminals, and dependable users in the field of the cluster coverage area. It is a self-organizing LTE private network for quickly constructing wireless networks. This architecture has multiple LTE mini-base stations covering a communication network area. The nearby base stations can communicate with one another. Building a wireless multi-hop self-organizing network for information sharing requires a wireless channel between the base stations. Once a base station receives pieces of information, it forwards them to neighbor base stations. If one base station fails, neighbor base stations forward the information. This LTE ad hoc network is capable of swiftly deploying a self-organized communication network and effectively avoiding communication breakdowns. A UAV carries the LTE terminal equipment, a camera, and a processing module for data analysis to get around the limitations of current communication networks. The camera collects video data. After the processing and data analysis, the data package is transmitted from the video device to the command and dispatch desk for monitoring analysis, and further commands.

Shah [21] proposed a network case for disasters and emergencies composed of small UAVs instead of a single large UAV for Flying Ad Hoc Networks (FANETs) implementation. The UAVs are highly beneficial in 5G and 6G networks due to their low-cost communication capabilities and flexibility. He introduced a new cluster-size-based back-off mechanism for performance optimization. UAVs join a cluster once deployed in a specific area while the clusters are formed by grouping adjacent UAVs. In every cluster, a Cluster Head (CH) is connected to an Emergency Communication Vehicle (ECV).To explore the performance of this mechanism, a Markov-chain analytical study is presented that takes into account the Nakagami-m fading channels. However, high FANET node mobility can result in rapid topology changes and frequent link breakage, with unstable communications that result in packet losses and collisions. To avoid this issue, the networks can divide into smaller clusters or groups for the efficient control of their topology and channel contention reduction. The performance metrics, influencing parameters, and other relationships among them are taken into consideration while analytical simulation results verify this study. A quantitative comparison of the known cluster-based methods shows that the proposed architecture is superior to all.

In [22], the authors propose a heterogeneous communication architecture that communicates between moving agents in harsh conditions and uses a Ubiquitous Sensor Network (USN) consisting of Drone-Based Wireless Mesh Networks and Near Vertical Incidence Skywave technologies, able to reconnect the relocating agents that constitute it and spanning a large-scale area. Before their proposal, they first survey the emergency communications challenges, then they analyze the existing technologies for emergencies, and finally, they conduct an extensive review of the most common technologies for ECSs. They conclude that ECSs share many similarities with the USNs and that a dynamic set of actuators and heterogeneous sensors can be deployed into a large-scale area to address the adverse communication circumstances.

Table 1 summarizes the most relevant surveys on ECSs described in this section compared to our proposed system. Each study contributes to a specific field and can be improved to be highly beneficial in its scientific area.

Table 1. ECSs Comparison.

Survey	Communication Technologies	Contribution	Evaluation
[3]	LTE/4G, SD-WAN	Emergency Evacuation System for Cruise Ships	Implementation
[11]	LPWAN, LoRa	Search and Rescue (SAR) Robot	Implementation
[12]	LPWAN, LoRa	Emergency Communication System in IoT	Implementation
[13]	LoRa, Bluetooth	Off-grid Emergency Communications	Simulation Implementation
[14]	LPWAN, Sigfox, GSM	IoT Surveillance System for Outdoor Fire Detection	Implementation
[15]	SD-WAN	Low-Cost Earthquake Early Warning System	Simulation Implementation
[16]	SDN, SD-WAN	Securing the Industrial IoT for Critical Infrastructure	Case study
[17]	SD-WAN, 4G	SD-WAN Technology in Power Communication Scenarios	Case study
[20]	4G/LTE	Electric Power Emergency Communication Design	Case study
[21]	UAV, 5G and Beyond	Emergency Communication Systems in case of Disasters	Simulation Case study
[22]	USN	Communication Technologies in Emergency Situations	Case study
Proposed ECS	LTE/4G, SD-WAN LPWAN, LoRa	Emergency Communication System in case of Disasters	Simulation Implementation

3. An Overview of LoRaWAN and SD-WAN Technologies

3.1. LoRaWAN Technology

According to the LoRa Alliance technology group, which is supported by over 500 members being operational since the end of March 2015 [23], a considerable number of devices anticipated for the Internet of Things are expected to be supported by Low-Power, Wide-Area Networks (LPWAN) (IoT) [24].

Among these alliance members, technology leaders such as IBM, Cisco, HP, Foxconn, Semtech, and Sagemcom, as well as companies such as Schneider, Bosch, Diehl, and Mueller, and many small and medium-sized enterprises (SMEs) and startup companies cooperate to consolidate on the LoRaWAN® standard for optimizing LPWANs battery life, capacity, range, and cost. A Low Power Wide Area (LPWA) networking protocol named LoRaWAN is used to wirelessly link battery-powered "things" to the internet in local, national, or global networks. The LoRaWAN [25] protocol criteria that focus on the IoT are bi-directional communication, mobility, end-to-end security, and localization services. LoRaWAN is an open and standardized low-power wireless network (LPWAN). Table 2 shows a performance comparison between the most popular LPWAN technologies [3,26].

Table 2. LPWAN Comparison Performance.

Feature	SIGFOX	LoRa	NBIoT
Coverage Area	<12 km (160 dB)	<10 km (157 dB)	<15 km (164 dB)
Frequency	Unlicensed 900 MHz	Unlicensed 433, 868, 915 MHz	Licensed 7–900 MHz
Bandwidth	100 kHz	<500 kHz	200 kHz shared
Data Rate	<100 kbps	<10 kbps	<50 kbps
Network Reforming	Large	Large	Small to moderate

The underlying physical layer or the wireless modulation utilized to create the long-range communication link is LoRa [24,27], or Frequency Shift Keying (FSK), a chirp spread spectrum-based proprietary modulation scheme (CSS). FSK modulation is frequently used in wireless systems because it is a very effective modulation for low-power achievement. Chirp spread spectrum modulation, the foundation of LoRa, keeps the low-power properties of FSK modulation while greatly extending the communication range. Because of the great reached communication distances and robustness to interference, the chirp spread spectrum has been used in military and space communication for decades; nonetheless, LoRa is the first low-cost implementation for commercial use that offers the benefit of long-range capability. Entire cities or even areas covering hundreds of square kilometers may be covered by merely one gateway or base station offering a high link budget, although the range highly depends on the environment or obstructions in a given location. The link budget, typically given in decibels (dB), is the primary factor in determining the range in a given environment. Scalable bandwidth, constant envelope, low power, a quite robust scheme, multipath, fading resistance, Doppler resistance, long-range capability, enhanced network capacity, and geolocation capabilities are some of the key properties of this modulation.

Cycleo created the LoRa modulation technology, which Semtech eventually purchased. According to Semtech, the main characteristics of this technology are the suppressed cost of end devices, operating expenses, and infrastructure investments. Furthermore, standardization, low power consumption that allows a usable battery life of up to 20 years, and long-range penetration even in dense urban or even indoor applications and rural areas are eminently outstanding characteristics while providing low power GNSS-free geolocation, security (end-to-end AES Advanced Encryption Standard,) and high capacity (support of many devices per LoRaWAN gateway according to the RF emission restrictions applied from legislation).

LoRaWAN employs a star topology [25,27] in which devices are linked directly to gateways which are then linked to a network server via a backhaul (e.g., Ethernet). LoRaWAN, unlike other IoT technologies, does not employ a mesh network architecture, although mesh networking may be useful for increasing communication range due to an impact on device battery life owing to message forwarding.

LoRaWAN enables bidirectional communications between end devices, though they are asymmetric because uplink transmissions (from end devices to gateways) are strongly favored. LoRa technology transmits in ISM free-use frequency bands shared with other wireless technologies. Therefore, it must comply with defined usage rules, particularly concerning the duty cycle, transmission power, and bandwidth. The most common use cases of LPWAN networks are isolated data measurements, industry applications, and Smart Cities [8,28].

Security Options

Regarding terms of security in LoRa Wide Area Networks, LoRaWAN employs a cryptographic mechanism based on AES-128 [29] that operates in counter mode (CTR) while based on a pre-shared key from which two additional keys for session security are derived. End devices must be activated before the initialization of the derivation process to connect to a specific LoRaWAN network otherwise; the network server silently discards the transmitted frames. To be considered activated, an end device must have a valid copy of the following data:

- application session key—AppSKey,
- end-device address—DevAddr, and
- network session key—NwkSKey.

The LoRaWAN specification 1.0 provides two methods for establishing keys [30] leading to two types of joining schemes used, depending on data being either stored manually in the device or acquired via the radio link, i.e.,:

- Personalization Activation (PA)
- Activation Over-the-Air strategy

In the case of Personalization Activation (PA), the device includes hard-coded authentication data before initializing communication with the network so requiring no join procedure, while binding the end device to a specific LoRaWAN network because they include the device's LoRaWAN network identifier (NwkId), network address (NwkAddr), and cryptographic session keys.

As a result, the end device is permitted to communicate with specific LoRaWAN networks while keeping these values constant. The preshared AppKey within the end device is used to generate the AppSKey and NwkSKey keys. While utilizing the activation strategy referred to as ABP, all parameters such as the network session key (NwkSKey), the device address (DevAddr), and the application session key (AppSKey) are configured at production time. The AppKey is an AES-128 key that is used in the subsequent session key derivation process. As a first step, the end device sends a join-request message containing the AppEUI, DevEUI, and DevNonce. Replay attacks are prevented by using a DevNonce value, although the join-request message is not encrypted. Finally, following a successful procedure, the network server sends a join-accept message to conclude the transaction and confirm the end-to-device authentication, keeping in mind that AppKey has already been used to encrypt the message.

On the other hand, by using the Activation Over-the-Air strategy, each end device performs a join procedure explicitly defined to securely connect to a specific network after obtaining all necessary cryptographic material. The joining procedure is initiated by the end device whilst providing the following information:

- application identifier—AppEUI,
- end-device identifier—DevEUI and
- application key—AppKey.

The DevEUI identifies an end device, whereas the AppEUI identifies an entity capable of processing the end-join request of the devices.

The OTAA scheme is considered to be more secure than ABP [30], a fact that led us to opt for our LoRaWAN implementation.

3.2. WAN and SD-WAN Technologies

Due to the constant development of technology and the need for a better quality of service both in data transfer and real-time communication, we need to increase the development of new technologies while upgrading existing ones. With the current known WAN technology, companies have managed over time to obtain reliable communication between the central points and their branches without any problems [31]. As computer and telecommunication networks size up devices such as routers and switches through interconnections, many organizations, and businesses are turning to SD-WANs as a solution [32].

WAN technology was a widely distributed technology approximately 30 years ago. The term "Data Centers" was an unknown concept, and network administrators had to manipulate servers manually, wherever they were, as these devices needed to be configured on-site one by one [33]. WAN networks had two disadvantages, as they were expensive and rigid. At the first point, WAN network equipment was costly because of the specialization scope that had to be completed. Secondly, these devices had the necessary information for the local system's network and were not responsible for the global network. Overall, due to their low flexibility, any new deployments for adding new WAN extensions and capabilities were not easy to perform [34]. Table 3 depicts a performance comparison of the most common WAN technologies [3,26].

Table 3. WAN Comparison Performance.

Feature	**GSM**	**LTE-M**	**5G (Targets)**
Coverage Area	<15 km (164 dB)	<10 km (156 dB)	<12 km (160 dB)
Frequency	Licensed 800, 900 MHz shared	Licensed 700, 900, 1.4 MHz shared	Licensed 700, 900 MHz shared
Data Rate	10 kbps	<1 Mbps	<1 Mbps
Network Reforming	Moderate (LTE reuse)	Small	Requires 5G NWs

SDN technology was the most recognized subject in the previous decade in the network world because of the solution that promised to provide for large scaled networks. Centralized monitor control using software plans can increase network speed and provide a better quality of service, both in voice and data transmission [35,36]. Compared to classic networks, SDN can provide improved network architecture of three layers under the same infrastructure. The "application" layer is responsible for monitoring and load balancing, the "control" layer regards network topology, and the "data plane" layer is responsible for the network equipment's physical connections [37].

3.2.1. SD-WAN Technology Definition

SD-WAN is a new technological deployment that works as an alternative to today's WAN communication technology. An SD-WAN network provides suitable automotive procedures for better data tracing from point to point (p2p). These automated actions can evolve SD-WAN into a productive, stable, and reliable solution for an organization [38]. The term SD-WAN comes from the words Software, Defined, Wide Area, and Network, and is part of a new era of implemented SDN that drives rooting packets between data centers and headquarters to a WAN with higher speeds. Before this implementation, companies and organizations were obliged to use specific network equipment and discrete leased circuits at any monetary cost. SD-WAN can provide balanced loaded data traffic by using multiple WANs and increased bandwidth [32]. Using the SDN benefits the private network as it separates into two layers, the "control" layer and the "data" layer. The "control" layer is managed over the cloud, or by using on-premises infrastructure. A software management implementation is responsible for managing how "data" will be transferred over the network, as they can be driven by separated paths depending on the network traffic and the pre-planned plan [39].

3.2.2. SD-WAN Architecture and Security Options

SD-WAN was developed to replace the classic WAN. The core job of SD-WAN is to simplify all the functions of a WAN to provide flexibility and scalability over the traditional WAN. The architectural structure of SD-WAN includes three layers [40]. The "data" layer consists of hardware and software devices with similar functionalities close to IP networks which can virtualize bandwidth by forwarding data, i.e., to 4G/LTE mobile networks. Sometimes routers are also considered virtual cloud services, such as Iaas. The "control" layer is responsible for network improvement, energy traffic monitoring, and providing a better quality of service for all the transmitted data. It can also perform many managed implementations for debugging, collecting information about the network topology and its status, and managing the number of real-time connected devices. The "application" layer allows network administrators and application developers to configure the requirements for an efficient network with a low energy cost and high availability [32,33,40,41].

The SD-WAN provides secure connections from edge to edge, allowing users to create a new complicated network infrastructure between MPLS and LTE to increase their critical connection experience. The SD-WAN can be traffic manageable by providing priority to specific nodes. Many hardware devices are no longer needed due to the virtualizing of services, and therefore lower costs and better performance, either to bandwidth or to the network, are achieved. Available scalability and agility are flexible services to add any new sites. The QoS for data transition is higher due to load balancing because the network is centralized and controlled [32,42]. It also provides end-to-end encrypted traffic within the network over the internet. All components are fully certified and safe, and the "certified keys" exchanging procedure gives SD-WAN the possibility of seamless communication between headquarters and data centers, as this communication is always safely controlled since it is encrypted [43].

4. A Hybrid Approach to Emergency Communication Systems

An ECS is a communication mechanism that deals with emergencies where communication facilities are damaged or the area is out of the communication grid. Its purpose is to use unconventional and hybrid methods for establishing communication between a specific site and the outside world [44]. Therefore, a smooth communication system should be ready to report disasters and implement rescues or to connect off-grid areas and critical infrastructures with a communication network.

4.1. High-Level Architecture

In this section, we propose our hybrid approach to an ECS based on SD-WAN and LoRaWAN technologies. The combination of open-source protocol and 5G technology creates several difficulties for SDWAN-based virtualization and slicing management [45]. Thus, the proposed system consists of an autonomous wireless 4G/LTE base station and a LoRa network. To implement the on-premises LTE/4G network, we used the Open Air Interface (OAI) open-source software. OAI is available from University Eurecom and runs on Ubuntu Linux, and its purpose is not only experimental, as it actively participates in the research and development of 5G and other communication networks and is also used on IP Multimedia System (IMS) platforms [3]. We also deployed a private star-of-stars topology LoRaWAN network, in which gateways relay messages between the end devices and a LoRa network server [8]. The gateways transmit data to the LoRa network server installed on a Linux environment in our isolated 4G/LTE network. Figure 1 describes the implementation of this hybrid approach, while Table 4 defines the ECSs abbreviations.

The 4G/LTE implementation uses the HSS database, OAI EPC (MME, S-GW, and P-GW), and E-UTRAN (OAI eNB and UE). The MME, HSS, and SPGW apps operate on an Ubuntu Linux generic Kernel PC, while the eNB application runs on an Ubuntu Linux low-latency Kernel PC (eNB PC) (EPC PC). Using Software-Defined Radio (SDR) platforms and commercial user equipment, the 4G/LTE network operates in real-time (UE) [3]. The UE can be a 4G/LTE commercial mobile phone or commercial 4G/LTE module, subscribed in the private 4G/LTE network via a registered sim card. Users holding mobile phones can use Voice over Internet Protocol (VoIP) applications, while 4G/LTE modules send geolocation and other data (e.g., health data, environmental data) to an IoT platform. VoIP is a beneficial innovation based on contemporary business and industry needs, as it offers the technology of transporting voices in the environment of a data network. The software implementation and internet connectivity have offered this service incredible flexibility when voice communication systems are to be deployed. It also provides real-time transmission of voice signals through the Internet Protocol (IP) across a private data network or the public Internet [46]. Figure 2 shows our experimental 4G/LTE base station.

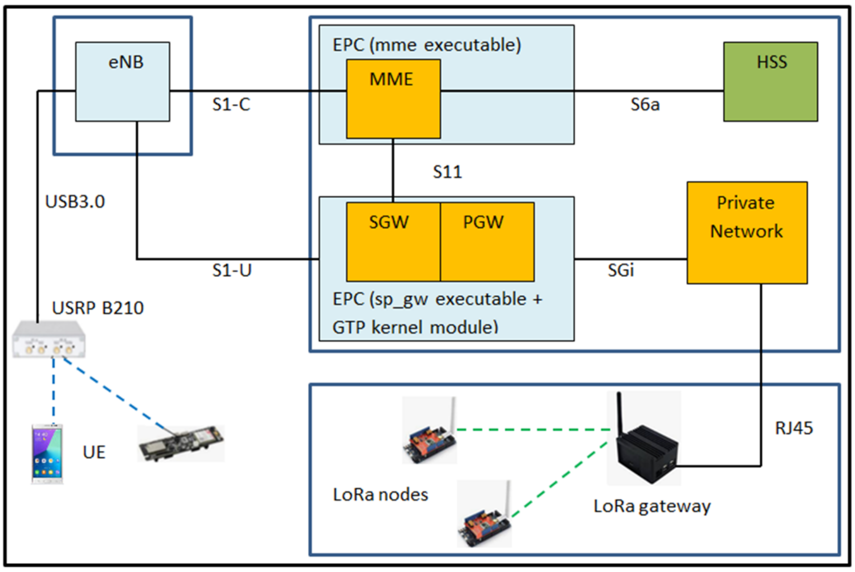


Figure 1. ECS Hybrid Approach—High-Level Architecture.

Table 4. ECS 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	Mobile User Equipment
S1-C, S1-U, S11, S6a, SGi, RJ45, USB3.0	Communication Protocols
USRP B210	Software Defined Radio Device
LoRa gateway	LoRaWAN Gateway
LoRa nodes	LoRa User Equipment

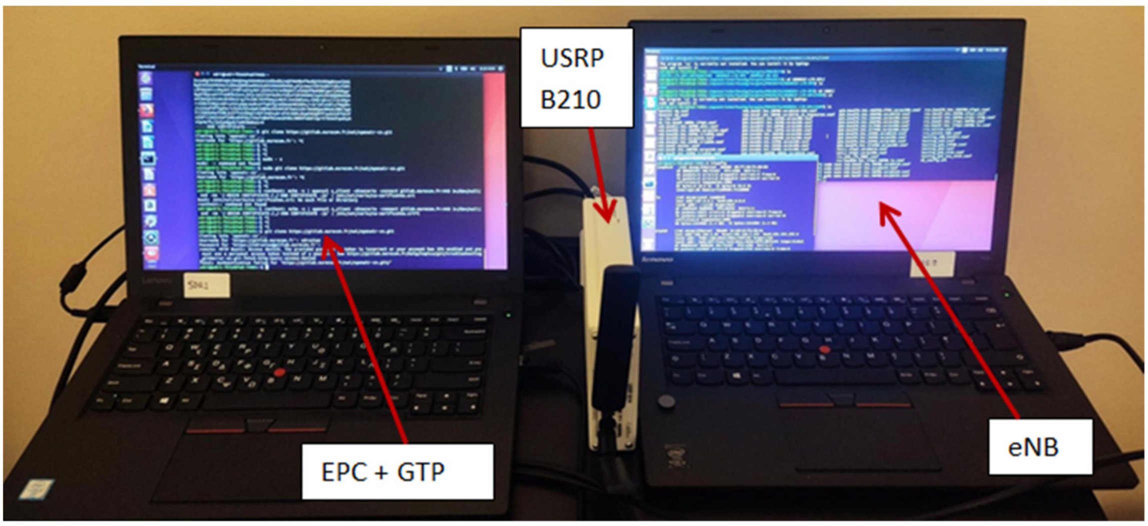
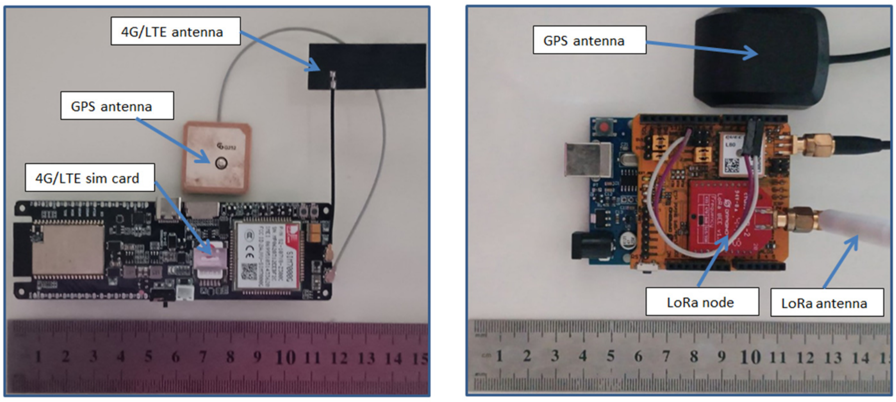


Figure 2. 4G/LTE Base Station Setup.

As far as the LoRaWAN is concerned, we have implemented a firm, low-power consumption, and scalable wireless sensor network composed of a LoRaWAN gateway, LoRaWAN nodes, and GPS sensors. We use GPS sensors for geolocation tracking, while users can exchange another type of information (e.g., health data, environmental data) with the IoT platform.

4.2. Experimental Open-Source IoT Platform

For the evaluation of our Emergency Communication System, we have built a hybrid LoRaWAN/WAN sensor network composed of LoRa and LTE/4G modules (Figure 3). The modules integrate a GPS receiver and are used in the current project as a tracking tool as they transmit their coordinates to the IoT platform through the hybrid network. We decided to use some of the most well-liked tools, primarily open-source software solutions. We chose "Grafana" software for user interfaces and data visualization and "Influx DB" for web database development. Because "Python" is a hardware-independent programming language, we used it to develop the 4G/LTE base station's low-level programming. The Message Queuing Telemetry Transport (MQTT) "Mosquitto" broker was installed to transfer messages between the UE modules (4G/LTE nodes) and the IoT platform. The "Chirpstack" LoRa Server, a free-to-use and open-source tool, was used for the LoRaWAN Network Server. Arduino IDE software and the "C++" language were adopted to program the LoRa nodes and the LTE/4G modules.



(**a**) (**b**)

Figure 3. (**a**) 4G/LTE module; (**b**) LoRa node.

Figure 4 depicts a scheme of the network topology with the various hierarchical layers from the hybrid IoT modules, the gateway, the base station, the LoRa server, and the application server.

Data from the sensor was saved in InfluxDB and connected with a front-end application and Grafana server, allowing data visualization through this server. We utilized the Grafana server because it has an integrated Graphite query parser that enabled us to query, view, alert on, and comprehend sensor metrics regardless of where they are stored [8]. In this illustration, InfluxDB is used to store GPS coordinates, while Grafana Map is used to display them in real-time.

Figure 5 shows the real-time positioning of two outdoor modules, a LoRa node (blue color) and a 4G/LTE node (green color). The experimental scenario was tested in an outdoor rural environment, while other indoor and hybrid (indoor-outdoor) environment use cases were also examined without any problems. Furthermore, standardized messages and other sensor data (e.g., health data) can be sent between users and the IoT platform through the MQTT broker.

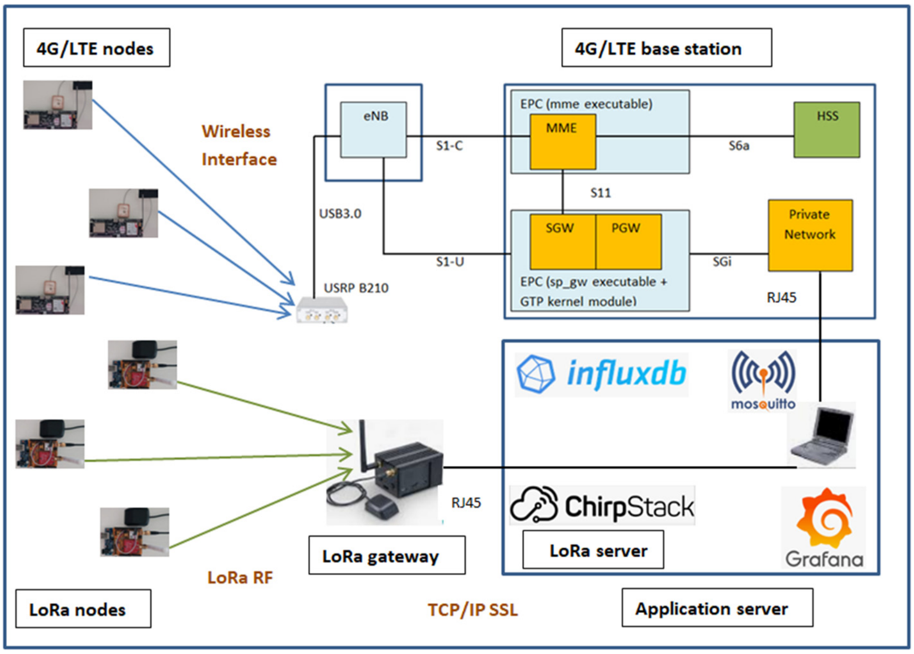


Figure 4. ECS utilized architecture and network topology.

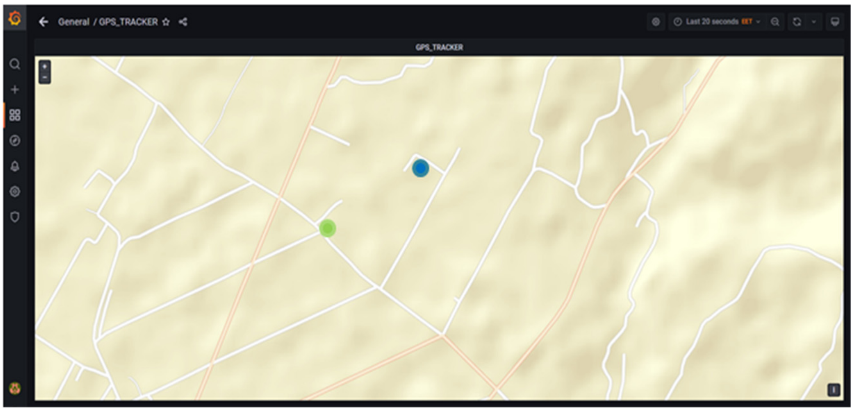


Figure 5. Real-time Sensors: Data Visualization.

To make use of VoIP calls, we deployed a private VoIP application based on open-source software and a low-cost computing platform. Thus, to enable a VoIP network between the UEs, an Asterisk server is going to be installed. Asterisk is a software implementation of a Private Branch Exchange (PBX) that manages the phone calls between VoIP clients [47].

5. Scenario and Simulation Report

Simulation tools are essential to determine whether it would be feasible to use one or more LoRa gateway, and one or more 4G/LTE base stations, to efficiently address all nodes in an off-grid area. To study our network performance, we built two different simulation scenarios, an indoor LPWAN, and an outdoor SD-WAN approach.

5.1. Scenario 1: LPWAN Simulation

To simulate the LoRa-based wireless network, we considered a scenario that requires real-time end-node tracking by measuring the 3-axis sensor position. The measurements are simulated on the Network Simulator 3 (NS3) using the LoRaWAN open-source module for the NS3 tool. The Packet Delivery Ratio (PDR) simulation results are shown below, along with the first deployed scenario. We used a two-story concrete building as the foundation for our hypothetical situation. The structure's measurements were 10 m by 20 m by 6 m, with each story standing 3 m tall. We took into account the fact that each floor had four rooms and that all outside walls had windows.

This could represent a small industrial building where the employees carry the end nodes in their bags to use in emergencies. There are twenty nodes randomly installed inside the building, and a LoRa gateway on the second floor. For this case scenario, we did not consider any plastic or metal installations or other obstacles within the building. Figure 6 shows the 3D dimensions of the building's LoRaWAN topology. We used a Python script to accurately draw the nodes and gateway inside the building [48]. Table 5 contains the NS3 used 3-axes coordinates of the LoRa elements

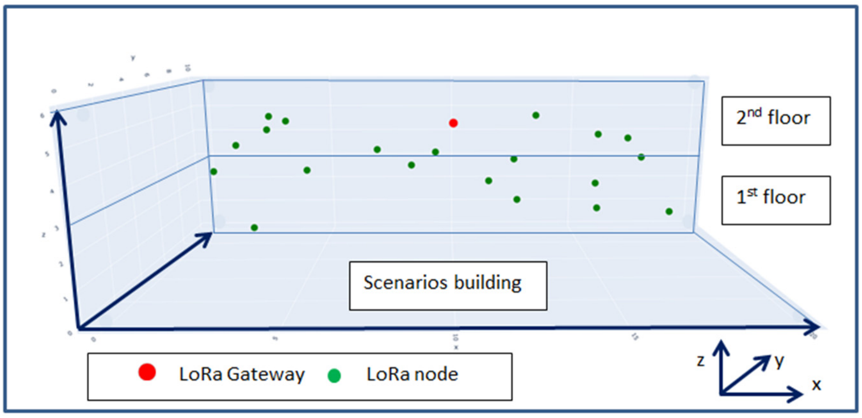


Figure 6. LoRaWAN 3D Topology Inside Building.

Table 5. LoRa Elements 3-axes Position.

LoRa Element	X Position (m)	Y Position (m)	Z Position (m)
gateway	10.0	5.0	5.0
node 1	15.8	4.2	4.6
node 2	3.1	7.7	4.9
node 3	2.9	3.7	4.5
node 4	16.3	4.5	3.9
node 5	15.3	6.7	2.5
node 6	4.2	5.6	4.9
node 7	2.8	8.2	4.3
node 8	16.9	2.9	2.4
node 9	11.9	2.6	2.9
node 10	9.3	7.8	3.45
node 11	8.6	3.4	3.8
node 12	14.6	3.6	4.8
node 13	13.0	7.1	4.9
node 14	15.0	4.9	2.0
node 15	12.5	9.0	2.9
node 16	7.7	1.8	4.2
node 17	5.7	1.0	4.6
node 18	1.4	5.9	3.1
node 19	11.4	8.1	2.3
node 20	4.3	0.5	2.6

Each LoRa node was programmed to sample a 3-axe sensor every 5 min for 24 h. A 20-byte-long message containing the five-digit decimal precision position of the node was harvested from each sensor and used as the node's payload. LoRa modulation has six spreading factors (SF) from SF7 to SF12. SF influences time-on-air, data rate, battery life, and receiver sensitivity. Compared to a higher SF, for fixed bandwidth and coding rate, a lower SF provides a higher bit rate. In our simulation, we used SF7. The propagation loss model we used was the Log-Distance Path Loss model, in which the path loss exponent was empirically set to 1.7 as the simulation is taking place indoors. The simulation also considers losses due to shadowing.

The simulation provides information on the total number of packets sent throughout the network from each node to the gateway, the number of packets interfered with, the number of packets successfully re-received, the number of packets lost because there were not enough receiving nodes available to communicate with the gateway, the number of packets lost from the gateway because the signals were weak and below receiver sensitivity, and the number of packets lost by a busy transmitting gateway. The Packet Delivery Ratio (PDR) is calculated by dividing the total number of packets sent by the number of successful packets. A PDR of 96.7% (1) was attained for this example scenario with the gateway located at the building's geometric center. On the other hand, the Lost Packet Ratio (LPR) was 3.3% (2), but no packet was lost because of a bad connection between the nodes and the gateway. There were no low sensitivity losses or losses due to a busy gateway. Other experimental results have shown that LoRa technology may be considered stable in the worst fading case scenarios, where packet loss is 18% [49]. Additional research has demonstrated that the channel condition and packet collision can both have varying effects on LPR. The primary causes of LPR are the distance of transmitted data and the traffic patterns of the end devices. A summary of these findings and their implications provides crucial direction for future large-scale LoRaWAN network deployments [50]. In general, in LoRaWAN applications, an LPR between 2–10% is acceptable.

$$\text{PDR} = \frac{\text{PACKETS RECEIVED}}{\text{PACKETS SENT}} 100\% = \frac{5570}{5760} 100\% = 96.7\% \tag{1}$$

$$\text{LPR} = \frac{\text{INTERFERED FAILURE}}{\text{PACKETS SENT}} 100\% = \frac{190}{5760} 100\% = 3.3\% \tag{2}$$

Figure 7 visually compares the results to emphasize the simulation output. A sufficient firm data transfer with the fewest possible losses is offered with the gateway installed in the middle of the simulation field. Consequently, every single LoRa node in this instance is completely covered. As a result, it is possible to address all 3-axes sensors while the resulting data are successfully received from the network server.

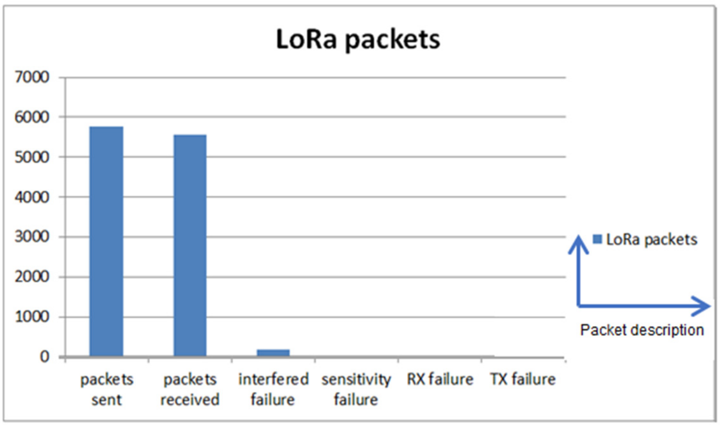


Figure 7. LoRa Packets.

Other indoor and outdoor simulation scenarios can be held to simulate real-life environments. Therefore, we can determine the number of gateways needed, and their exact position, to reduce deployment costs.

5.2. Scenario 2: SD-WAN Simulation

To simulate the SD-WAN, we considered a scenario that requires the transmission of a photograph by a mobile UE. This one-base station case study is simulated on the

MATLAB simulator using the LTE Toolbox and an ADALM PLUTO SDR device. Planning, constructing, and assessing the performance of radio communication networks (including cellular networks) depends on a thorough understanding of radio signal propagation Path Loss (PL). To organize, create, and assess the performance of wireless systems, PL models are created and tuned by the examined environment. Thus, we adopted the Log-Distance Path Loss (LDPL) model. LDPL is a radio propagation model that predicts the path loss a signal encounters inside a building or densely populated areas over a distance [51]. We consider a portable—private LTE/4G base station deployed in an off-grid small rural area without obstacles. Therefore, we examine a clear line-of-sight (LOS) scenario between the base station and a UE. The 4G/LTE technology uses Orthogonal Frequency Division Multiplexing (OFDM) a multicarrier modulation technique that uses the Discrete Fourier Transform (DFT) and the Inverse Discrete Fourier Transform (IDFT) to convert the frequency selective channel into the flat fading channel [52].

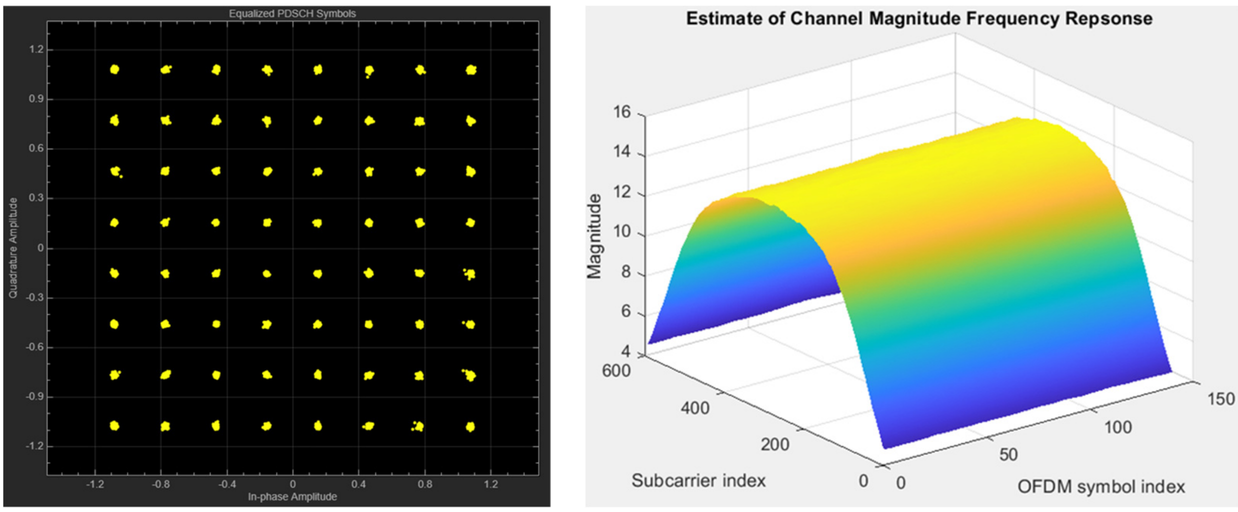
For simultaneous broadcast and reception on the ADALM PLUTO SDR platform, the simulation procedure outputs a single antenna LTE waveform. The algorithm packs and encodes the chosen image into radio frames during waveform synthesis. The application then extracts the received image from the LTE waveform after the reception. The simulator uses a baseband Reference Measurement Channel (RMC) waveform created by the LTE Toolbox to create numerous radio frames from an imported picture file. It produces a continuous RF LTE waveform by using the repeated transmission feature of the SDR. This feature transfers the baseband RMC waveform to the ADALM PLUTO SDR's hardware memory and transmits the waveform over the air continuously and without breaks.

The first frame acquired by the receiver is not always the first transmitted because the LTE waveform is traveling over the air in a loop and the frames are decoded out of order. The frame number determination helps to recombine the received frames accurately. The current system frame number is revealed in the Master Information Block (MIB) and is also decoded. The simulator decodes the Physical Downlink Control Channel (PDSCH) and the Downlink Shared Channel (DL-SCH) after determining the frame number and showing the equalized PDSCH symbols. Subframe number 5 is not required for data transmission, so the subframe-captured data is not considered during decoding [53]. When the LTE frames are successfully decoded, the simulator shows the detected frame number for each frame (Table 6) and the equalized PDSCH symbol constellation for each subframe (Figure 8a). In LTE networks, the PDSCH is the upper data-carriage downlink channel. Based on the LTE standards, such as DCI format and bandwidth, the PDSCH provides Downlink Control Information (DCI) code words with varying lengths [54]. The simulation of the PDSCH transmission is vital, as it incorporates procedures of scrambling, modulation, layer mapping, precoding, and data mapping to resource elements. The simulator also computes the bit error rate (BER), error vector magnitude peak (EVM peak), and round mean square (EVM RMS) values for every frame, and analyzes an approximation of the channel magnitude frequency response between the cell reference point 0 and the receive antenna (Figure 8b).

To determine the quality of the received data, we first initialize our SD-WAN variables to let the simulator calculate the BER between the transmitted and received data of our scenario. The BER is the ratio of the bit's error number and the number of bits transmitted, while a high BER causes a packet loss which increases delay and reduces throughput [55]. Since there are no obstacles or objects between the transmitter and receiver causing path losses in our case, the BER was zero. In [51] the authors examine various PL mobile propagation LOS and non-LOS (NLOS) case studies, taking into account other effects such as the seasonal effect. They conclude that fixed wireless networks provide easy network connectivity in rural areas.

Table 6. Decoding Procedure.

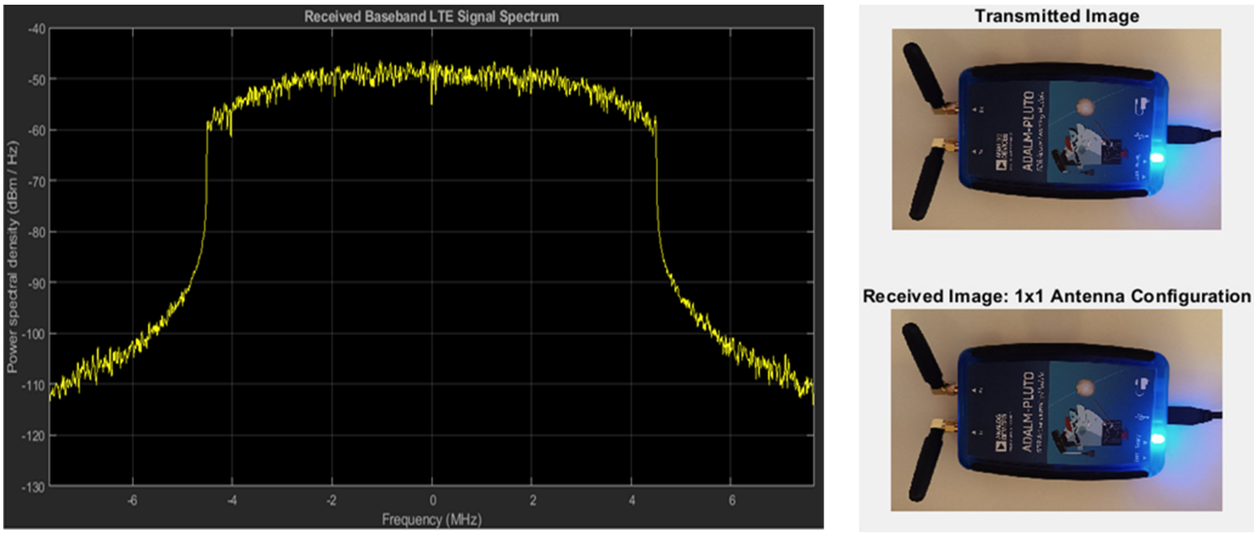
Decoding Procedure	Result
Generating LTE transmit waveform: Packing image data into 30 frame(s).	Setting channel map to '1'.
SDR hardware sampling rate configured to capture 50 LTE RBs.	Starting a new RF capture.
Establishing connection to hardware.	Corrected a frequency offset of 2.666334×10^{-1} Hz. Detected a cell identity of 88. Corrected a timing offset of 29,371 samples.
Performing DL-SCH Decode for frame 1 of 30 in burst:	Successful MIB Decode. Frame number: 713. Retrieving decoded transport block data.
Performing DL-SCH Decode for frame 2 of 30 in burst:	Successful MIB Decode. Frame number: 714. Retrieving decoded transport block data.
… … … … .	… … … … .
Performing DL-SCH Decode for frame 29 of 30 in burst:	Successful MIB Decode. Frame number: 711. Retrieving decoded transport block data.
Performing DL-SCH Decode for frame 30 of 30 in burst:	Successful MIB Decode. Frame number: 712. Retrieving decoded transport block data.
Recombining received data blocks:	EVM peak = 12.543% EVM RMS = 1.060% BER = 0.00000. Number of bit errors = 0. Number of transmitted bits = 8,084,832.
Constructing image from received data.	



(**a**) (**b**)

Figure 8. (**a**) Equalized PDSCH Symbols; (**b**) Channel Magnitude Frequency Response.

The received data are reformed into an image, as seen in Figure 9b. In LTE networks, the physical layer baseband processing has strict real-time deadlines [56], so basebands signal spectrum analysis is an essential part of a simulation. Figure 9a depicts the Received Baseband LTE Signal Spectrum.



(**a**) (**b**)

Figure 9. (**a**) Received Baseband LTE Signal Spectrum; (**b**) Transmitted and Received Image.

EVM is a well-liked system-level performance metric specified as a compliance test in various communication standards, including mobile communications (4G LTE, 5G). It is a valuable system-level indicator that quantifies the overall effect of all potential wireless system impairments through a single value [57]. Actually, it is the difference between the expected value of a symbol represented by a demodulated complex voltage and the value of the received symbol [58]. The results of the simulated scenario showed that the EVM RMS = 1.060% and the EVM peak = 12.543%. Furthermore, 8084832 bits were transmitted without error (BER = 0.00000 (Number of bits in Error/Total number of bits transmitted)). The simulation tool showed that a one-base station SD-WAN architecture manages data transmission without errors in LOS conditions. Other (LOS and NLOS) BER simulation analysis for OFDM systems tested with various modulation methods has shown that the OFDM method gives almost a perfect performance, as the BER varies from 0.0002 to 0.2051 in the worst scenario [52].

Since the 1960s, researchers have studied the issue of simulating packet loss in networks. Given that packets might be lost due to many factors, including signal attenuation and refraction, multipathing, noise (including thermal noise), competition for media access, and other buffer problems, modeling packet loss in wireless networks is difficult. Numerous simulation models mentioned in [59] are compatible with wireless networks, including LPWAN and LTE. The authors of this study have demonstrated the utility of using PL models to simulate wireless system performance and to create novel strategies and algorithms. Physical and medium access losses are two categories of packet loss sources. Physical losses can be caused by signal degradation, coexistence with other technologies, and interference from other networks or devices. Buffer overflows and collisions brought on by competition in the medium or hidden terminals might result in medium access losses. Therefore, every ECS should be examined and simulated as a unique scenario.

As mentioned, ECSs are network-based systems that help people exchange information during crises and physical disasters and are able to restore communication when telecommunication networks fail and in off-grid areas. Therefore, in our simulation scenarios, we mostly assume LOS 4G/LTE and LPWAN networks. For VoIP applications, other simulation scenarios must be made. To summarize, the simulation reports, combined with the results from the experimental scenario, prove that the proposed low-cost and open-source architecture can be used for an easy-to-deploy hybrid ECS that is able to send and receive data in emergencies. Moreover, it can be valuable for the command and control in off-grid industrial buildings and critical infrastructures.

6. Conclusions—Future Work

A significant variety of IoT-focused novel wireless communication technologies have been recently applied in communications. Investment in these technologies for the year 2027 is projected to reach the amount of 1463 billion dollars, reflecting their rapid increase in terms of investment. The number of linked IoT devices worldwide is predicted to reach 75 billion by 2025 [60].

Thus, an Emergency Communication System (ECS) as a network-based system that enables people to exchange information during crises or physical disasters when basic communication options may have collapsed proved to be a quite promising and feasible option. By implementing an autonomous wireless 4G/LTE base station and a LoRa network the purpose of using unconventional and hybrid methods for establishing communication between a specific site and the outside world is achieved as the combination of communication technologies can allow researchers to improve and develop open-source ECS over conventional architectures. As the LoRa-based wireless network was simulated on the Network Simulator 3 (NS3) using the LoRaWAN open-source module for the NS3, the simulation outcome following the practical implementation allowed firm and sufficient data transfer, providing trustful communications between LPWAN sensor nodes and a LoRa gateway. The proposed scheme provided low data losses by optimizing the installation of the gateway within the premises, while on the other hand the SD-WAN scheme that was simulated on the MATLAB simulator and the LTE Toolbox, in conjunction with an ADALM PLUTO SDR device, proved as well to be an outstanding alternative communication solution with no bit errors measured after recombining all received data blocks. With a zero BER, the simulation tool showed that a LOS one-base station SD-WAN architecture manages data transmission without any errors, thus providing a reliable and robust communication network alternative beyond well-established normal telecommunication networks.

In the future, we are going to focus on ECS development. We will continue working on systems improvement by adding more base stations and testing a private VoIP application. This methodology will allow us to make accurate conclusions about ECSs for emergencies and off-grid industrial and critical infrastructures. At the same time, we will continue using simulation tools such as NS3, Omnet++, and MATLAB to compare and improve cellular networks by analyzing the RF propagation and the RSSI of our case studies. The next goal is to conduct experiments inside industrial buildings and large infrastructures. Considering the outcomes, we will compute the exact specific number and the positions of the on-premises cellular base stations needed to cover a functional ECS for VoIP applications. Finally, as soon as we overcome some virtualization and slicing management challenges [45], we aim to enable 5G technologies in our architecture to achieve end-to-end latency on the order of 1 ms. After the VoIP application evaluation [46,47], and the 5G implementation, we will be ready to present a cost-effective solution that employs VoIP communication in embedded systems. As a safe, secure, and easy-to-deploy communication network, it could be used as an ECS in emergencies, in industry, and by the army.

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