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Hybrid solution for smart rural applications in areas without internet coverage

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Abstract: Agriculture and livestock farming are one of the main economic bases of rural areas in Southern Europe, with many classified as "sparsely populated". This article proposes and tests a technical solution to support different applications that require a large range of coverage and tracking assets, as can be found for instance in smart farming, or environmental monitoring. LoRaWAN, which provides several kilometres of coverage, low battery consumption and robust communications, is selected as the solution to overcome the lack of cellular network connectivity in those areas. Then, the design of a hybrid solution for rural areas, that requires the use of a LoRaWAN mobile gateway to extend the range of LoRaWAN coverage, is presented. In addition, to ensure quality of service (QoS) and avoid data loss, a 5G Internet connection is used to provide connectivity to the LoRaWAN gateway, combined with the store & forward communications mechanism to avoid data loss in areas without internet connection.

Keywords: LoRaWAN, 5G, store&forward, smart agriculture, smart livestock, mobile gateway LoRaWAN.

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1. Introduction

Nowadays, we are at the beginning of the "Decade of Action" proclaimed by the United Nations for achieving the goals and targets set out in the 2030 Agenda for Sustainable Development. Due to the rise of the digital world, information, and communication technologies (ICTs) play a key role as development enablers that can facilitate people capabilities to reach all the goals set out in the 2030 Agenda. As evidenced by the COVID-19 pandemic, digital connectivity is essential to be connected to the rest of the world and these is being a nexus between economic resilience and social growth [1].

The agriculture and livestock sector, covering crops, farming, fisheries, and forests, is the world’s biggest employer and one of the most important at the economic level. Therefore, these are sectors that have exciting potential for the use of ICTs as they would revitalize the rural labour force, thus meeting some of the SDGs (Sustainable Development Goals).

This project focuses on the digitization of different applications in rural areas, which occupies 84% of the territory, within the framework of the Spanish Government's strategy to encourage the use of innovative technologies in rural areas to helping young people to see the rural environment as an attractive place to live and work [2].

Among the LPWAN (Low Power Wide Area Network) technologies, LoRaWAN is a good candidate because it has clear advantages over other technologies such as greater range of coverage, low battery consumption or good reception of information below noise level and does not depend on public infrastructure to connect thousands of devices. On the other hand, it cannot be used for applications demanding high throughput and bandwidth but is still enough to fulfil telemetry and simple sensor data requirements. Currently, LoRaWAN devices are cheap and robust, thus reducing deployment cost. In addition, its use is very simple, so its adoption has grown exponentially in the last decade.

The goal and contribution of this work is the design of a solution for rural areas that requires the use of a LoRaWAN mobile gateway to extend the reach of the LoRaWAN coverage. In addition, 5G Internet connection is used to provide connectivity to the LoRaWAN mobile gateway, combined with the store&forward (S&F) communications mechanism since many of these areas lack of cellular network connectivity. This hybrid implementation, that combines two connectivity solutions such as LoRaWAN and 5G, working at together at the same time, allows maintaining the quality of service (QoS) and avoiding data loss in areas without Internet connection.

The use of a LoRaWAN mobile gateway makes sense when dealing with a specific type of application, such as locating lost animals or people, or environmental monitoring, where the search range is very wide. Although LoRaWAN presents great communication robustness in different environments, as presented in other projects, they are affected by weather conditions or orography. Therefore, one of the improvements presented in this article is the use of a mobile gateway located on top of an off-road vehicle, since it provides the advantages of a LoRaWAN network, but it is limited to the mobility of the vehicle since it can only move on roads or forest tracks.

Thanks to this technical solution, if the point of interest is outside the LoRaWAN coverage, the mobile installation can be moved to the last GPS position received by the gateway, and from that location, given the range of this technology, recovering node’s signal is much more probable.

From network architecture point of view, the LoRaWAN infrastructure is then connected to the internet, and with data analysis and visualization platforms via a cellular connection. 5G is the most suitable option (where available, falling back to 4G if needed). In this way, the resulting monitoring solution can benefit even further from 5G technologies such as network slicing, allowing different services with different speed, latency and reliability requirements coexisting in the same network. Depending on the use case, network slices can respond to requirements such as low latency, or high bandwidth, or even ultra-reliability for a critical IoT use cases such as IoV (Internet of Vehicles) security systems. The network slice profile fitting the proposed solution in this work is the one for higher latency and lower bandwidth for a massive IoT use cases, such as tracking extensive livestock in remote areas.

The scenario selected for the LoRaWAN mobile network covers areas with and without Internet connectivity. Therefore, for the areas without Internet connectivity, the store&forward communication mechanism, implemented in the LoRaWAN mobile gateway, automatically activates to avoid data loss. While the LoRaWAN mobile gateway is in areas without Internet connection, messages are stored using the FIFO (First-In, First-Out) method of data storage, but when the mobile gateway returns to an area with Internet connection, it sends the stored information packets to the display platform, ThingSpeak [3]. Data received is timestamped when generated, so even when receiving it in non-real time it is still valid for traceability and analysis. The data received by the LoRaWAN gateway are the RSSI (received signal strength indicator), the SNR (signal-to-noise ratio), timestamp, and the GPS coordinates of the node’s location, and subsequently, the PDR (packet delivery ratio) is calculated for each of the nodes in the different experiments performed as a comparative table.

The area for the study of the tests has been selected in a mountainous region with the necessary environmental characteristics for applications such as extensive livestock monitoring, irrigation automation in remote areas or tracking moving assets. These are located around the small town of Rubielos de Mora in Spain. The locations of the nodes have been chosen strategically as they allow different types of environments to be studied at the same time. The different environments range from deep ravines with high vegetation to high areas without forest cover. Once the behaviour of the nodes in each of their locations has been observed, the aim is to design a hybrid solution implementing the use of a LoRaWAN mobile gateway using an Internet connection through the 5G network. For this purpose, the behaviour of the LoRaWAN mobile network is analysed in different areas with and without cellular network coverage.

The rest of the paper is organized as follows. Section 2 presents Related Work on other tracking and monitoring systems and LoRaWAN simulations to contrast theory results with the results obtained to experimental rural applications. On the other hand, an introduction to LoRaWAN is made in section 3. In section 4 the described system and scenario is presented. Test results, to evaluate technology feasibility in these scenarios, are shown in section 5. Finally, considerations on applications, along with conclusions and future work, are presented in section 6.

2. Related work

This section presents different studies and implementations related to the work presented, covering different aspects of interest. The first part introduces articles analysing and the use of LoRa and LoRaWAN technologies in different scenarios, applications, and environments similar to the one selected in the scope of this article, but are limited to fixed gateway positions, as it is the common implementation in real use cases [4-12]. Then works covering the topic of gateway mobility are introduced, focusing more on the solution presented [13-14]. Finally, the combined use of 5G with LoRaWAN for similar applications in related works is shown as the last related topic [15-16].

There are many performances of LoRa networks in distinct types of environments such as urban or rural environments [4 - 5]. Experiments have shown that for fixed installations with fixed nodes in LoRa has a coverage between 2 - 5 km while for rural the coverage can reach between 10 to 30 km depending on the rural area if there are optimal conditions (direct line of sight, maximum signal power and data rate configured). Furthermore, environmental factors, such as temperature and vegetation, have negative impact the communication ranges [5 - 7]. These projects either focus on characterizing the LoRa physical channel (LoRaWAN is not evaluated), only use one gateway in the network deployment, or only consider static devices, which limits the extrapolation of these results to the proposed use case.

A LoRaWAN network is presented in [8] which is used for fire prevention and monitoring of fires in rural Spain. In this project, nodes are installed to measure temperature, humidity, wind speed, as well as the amount of CO2 in the environment for preventive fire detection. The system design is based on the distribution of many fixed LoRa nodes located in the treetops, while the gateway is fixed in the centre of the forest connected to TTS (The Things Stack). To visualize data, they use a web application in which they show heat maps that are established according to the values of the sensors. Furthermore, maps given the orography of the location of choice, but both nodes and gateways do not move in this application. Authors in [9 - 10] present installations related to the field of agriculture, consisting of a fixed gateway and several fixed nodes measuring parameters such as temperature, humidity, atmospheric pressure, or wind speed. In addition, they present different sensors, which send the information to TTS and visualize the data obtained, as well as the battery consumption per LoRaWAN message using the ThingsBoard platform.

In [11] authors evaluate the performance of a LoRaWAN network related to the monitoring of wild animals in a forest area. To characterize this network, they use typical values such as RSSI, SNR and PDR. The results show that they reach a maximum length of 860 m in dense forest while in areas with less dense forest mass they reach distances of more than 2050 m. On the other hand, the PDR results are lower than expected may be due to different loss effects when using a large packet payload, using less emission power than allowed or simply the location of the gateway.

Other projects such as [12] the authors perform tests in scenarios with fixed gateway and mobile nodes with speeds higher than 20km/h to study and evaluate the LoRaWAN network at different speed ranges. Although interesting, those tests do not fit in this work because those speeds are hardly achieved on forest roads in remote areas. On the other hand, the authors use a fixed gateway and mobile nodes to evaluate the LoRaWAN network, while this work aims to characterize the advantages of a mobile gateway LoRaWAN network. Finally, authors demonstrate experimentally that speed does not have a large impact on the efficiency (PDR) of the devices, but rather the efficiency is determined by the location of the LoRaWAN infrastructure, vegetation, buildings, etc.

The previous articles have a common feature, the LoRaWAN gateway is fixed in one location while the nodes are either fixed or mobile. As this article focuses on the mobility of the LoRaWAN gateway, the previous articles are not of great interest since they do not evaluate the behaviour of a mobile network.

In [13], authors present an application dedicated to rural cow monitoring using a mobile LoRa gateway. Their study based on the data obtained from the simulation performed with LoRaSim in which two simulation scenarios are presented. Firstly, different fixed gateways (1 - 8) and, secondly, a mobile gateway. To do the simulation of the gateway and mobile nodes they do a static simulation in three parts with LoRaSim. First, they do a static simulation with the fixed nodes when the gateway is approaching. Secondly, they do a simulation when the gateway is in a central area together with the simulated nodes and finally, they do a last static simulation when the gateway is far away from the area where the nodes are located. In addition, the number of nodes used in the simulation varies between 100 and 1500 randomly located along the path of the mobile gateway. Moreover, the configuration of the nodes is fully dynamic, i.e., the values of SF (Spreading Factor), CR (Coding Ratio) and BW (Bandwidth) vary dynamically depending on the position where the node is located. It should be noted that the packet size is twenty bytes, which is sent every one hundred seconds (1 min. 30 sec.) for one thousand seconds (17 min. approx.). The graphs show the values of DER and NEC related to the number of nodes in the simulation. Finally, they compare these experiments and conclude that use of a mobile gateway, which stops at two or more points, is much more efficient than use of multiple fixed gateways reducing deployment costs.

Other application in [14] use a mobile gateway to read electricity meters in residential areas. In this article, a use case simulated with LoRaSim is presented in which over (100 - 200) nodes are located at the electricity meter of each house while the mobile gateway will be installed on a motorcycle which will cross the residential area. Different experiments are performed on the same scenario by changing configuration parameters, as well as choosing a random data rate or using an optimal configuration per node in relation to the gateway distance. In these experiments, the same type of simulation is performed as in the project [11] since they perform a static simulation in three parts as explained in the previous work. In addition, for such experiments they obtain the values of DER and NEC, depending on the number of nodes in the simulations. Furthermore, calculate of packet collisions for each experiment to comparing them with each other and define which one is the optimal. They conclude for this application that the choice of the mobile gateway would not be an optimal solution because there are many collisions since many nodes transmit at the same time with the same configuration, since then, nodes would have to send the information when the number of collisions is not too high.

As detailed in the two previous articles, it focuses on characterizing a LoRa mobile network for two different applications. These articles are of great interest although they are only simulations and not experimental results as detailed in this article.

In this article [15], the authors present a multi-RAT solution with 5G network partitioning techniques for IoV (Internet of Vehicles) use cases. In it, they implement an integration of heterogeneous radio technologies with IoT communications by creating network partitioning without risks for the scalability of the core 5G network. To validate their results, they implement a device that selects, depending on the traffic characteristics of the application, between two radio technologies, firstly, 4G for areas with mobile coverage and LoRaWAN for long range areas. In addition, they perform an experimental test of the device in the Espinardo campus of the University of Murcia in which they represent through a predefined route, the accesses made by the device to one and the other radio technology. Finally, they perform through simulations a deeper study on the scalability of the system response by measuring parameters such as RTT (Round Trip Time), the capabilities of the system using three different slicing, etc.

In [16], as in project [15], the authors present a device capable of choosing between two different radio technologies, 5G and LoRa, but finally they do not present experimental tests since they focus on the mathematical implementation of ML (Machine Learning) for the police functions that determine the RAT through which the transmission of information has to be performed. Their device is capable of connecting to a 5G cellular network or to a LoRaWAN network depending on the traffic characteristics of the application whereas, this article uses the 5G cellular network to provide Internet connectivity to the LoRaWAN gateway.

In conclusion, there are many articles, deployments, and application related to LPWAN technology. This present work has detected the need to characterize, analyse and evaluate the behaviour of the mobile LoRaWAN network to the requirements of different applications and scenarios to increase the digitization of rural areas, solving real problems and improving working conditions of rural inhabitants, thus encouraging young people to see this environment as an attractive place to live, train and work.

3. Technology overview

This section gives a detailed overview of the technology. It covers the LoRa physical layer as well as the LoRaWAN MAC layer open standard. Then the implementation of the proposed Store & Forward mechanism is described. Finally, an overview of the 5G technology is provided, in order to cover all the elements of the proposed solution.

3.1. LoRa and LoRaWAN

The LoRa physical layer has been patented by Semtech in 2014 [17]. Its modulation is based on CSS (Chirp Spread Spectrum), using linear frequency modulation chirp pulses with high bandwidth to encode information. Chirp pulses are sinusoidal signals with time-varying frequency, determining symbols representing the information.

To further improve the robustness against noise and burst interference, LoRa uses diagonal interleaving as well as forward error correction (FEC) codes with code rates from 4/5 to 4/8, using in the following tests the 4/5 rate. The data rate and symbol rate depend on the SF and the bandwidth used. The symbol rate (R_S) that can be used is given by the following formula [18]:

$$R_S = \text{SF} \cdot \left(\frac{\text{BW}}{2^{SF}}\right) = SF \cdot \left(\frac{1}{T_S}\right) \quad (1)$$

In (1), SF is the spreading factor and BW is the bandwidth in Hz. From the first equation, it is seen that the symbol time is increased by increasing the SF, decreasing the symbol rate. The calculation of the data rate (R_b) is given by the following formula:

$$R_b = SF \cdot \frac{4BW}{(4+CR)\cdot 2^{SF}} \quad (2)$$

In (2), CR is the code rate and BW is the bandwidth in KHz. The data rate in this formula is expressed in bps. From the second equation, it can be noticed that by increasing the SF, less bits per symbol will be encoded, decreasing the data rate. The LoRa physical layer operates in three different frequency bands depending on the country where the tests are performed. The frequency bands are 433, 868 or 915 MHz, which correspond to the ISM frequency bands used in different countries, e.g., in Europe, only the 868 and 433 MHz bands can be used, while in the USA, the 915MHz band is used. In this article uses the 868 MHz band which has a total of eight 125 kHz channels that can be optionally used for LoRa communication. In Europe, due to transmission regulations [19], each transmission in any of the 868 MHz and 867 MHz sub bands must comply with a 1% radio duty cycle or implement a listen-before-talk or adaptive frequency agility mechanism. When the duty cycle regulation is met, it means that, if the radio transmitted for 1 s, it cannot transmit for the next 99 s. Depending on the application to use and the frequency, the value of duty cycle is limited between 0,1% and 10% as shown in Table 1. In this paper use the band frequency G1 (868,0-868,6 MHz) with a maximum EIRP of 25mW (14 dBm) and less than 1% of duty cycle. This choice allows that end nodes can use 8 different channels to improve resiliency to noise.

Table 1: Restrictions on EU bands

Name	Band (MHz)	Limitations
G	863,0-868,0 MHz	EIRP < 25mW – duty cycle < 1%
G1	868,0-868,6 MHz	EIRP < 25mW – duty cycle < 1%
G2	868,7-869,2 MHz	EIRP < 25mW – duty cycle < 0.1%
G3	869,4-869,65 MHz	EIRP < 500mW – duty cycle < 10%
G4	869,7-870,0 MHz	EIRP < 25mW – duty cycle < 1%

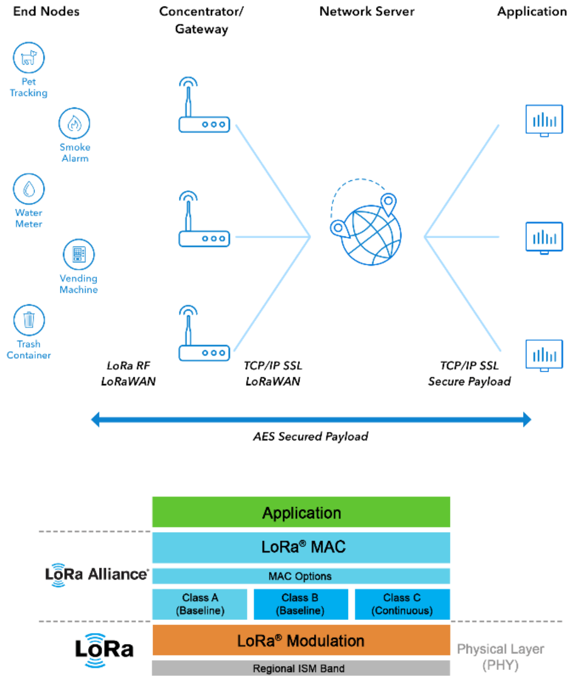

Figure 1 LoRaWAN architecture (up) and layers (down) [19]

LoRaWAN is a network protocol for LPWAN applications, which are characterized by low power consumption and long range, working over LoRa technology. LoRaWAN supports a central network server in its architecture, which is responsible for orchestrating all devices (gateways and end nodes) in the network (selecting the best gateway for each node). The LoRaWAN architecture has a star topology, where the end nodes can only communicate with the gateways and not directly with each other. In addition, many gateways can connect to the same network server as shown in Figure 1. LoRaWAN gateways are connected to the network server through the TCP/IP SSL network, while the end devices use LoRa to communicate with one or more gateways. In addition, many gateways can connect to the same network server as shown in Figure 1. LoRaWAN gateways are connected to the network server through the TCP/IP SSL network. The LoRaWAN network standard defines three different classes of end nodes, classes A-C. Features of class A nodes are a set of basic options that every node needs to implement to join a LoRaWAN network. To enable bidirectional communication, each uplink transmission of a class A node is followed by two short downlink receive windows during which the end node will listen for possible downlink traffic as shown in Figure 2. The first and second downlink receive windows start 1 and 2 seconds, respectively, after the end of the uplink transmission.

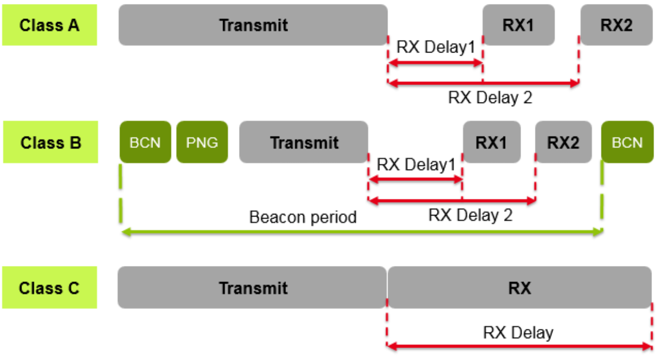

Figure 2 LoRaWAN Classes windows mode [20]

In addition, the LoRaWAN standard specifies the activation methods that each end node can use to join to the network. These methods depend on whether the node is activated over the air (OTAA) or by personalization (ABP).

Several keys and identifiers that are needed to achieve node activation and communication over time such as AppKey, DevEUI, DevAddr, etc. In this paper, OTAA activation has been used for device activation since its implementation is efficient and unproblematic since nodes do activate automatically over the air.

3.2. Store & forward mechanism

The implementation of the store & forward mechanism in this article has been done by using a Python script running on the gateway, which hosts a Linux SO. In this way, the LoRaWAN private network and application servers run on a Docker container on the gateway as well as the script, so the entire LoRaWAN infrastructure is mobile. The script subscribes to the different MQTT message queues of the LoRaWAN private network and stores these messages in files depending on the node name, since it is a unique identifier. Meanwhile, every few seconds the script oversees checking the Internet connection and sending the information through a POST request to the IoT platform from where the node data is monitored. Figure 3 shows the pseudo code for the script implementation.

```
def on_message (client, userdata, message):
    global messages_buffer
    messages_buffer.append (message)
    return

while True:
    if (connection_to_Internet ( )):
        if (length(messages_buffer) == 0):
        else:
            for i in messages_buffer:
                message_to_json = json.loads (message)
            if (deviceName == ‘name of the node’):
                file = open (‘name of the node’)
                file.write (message)
                messageCount = messageCount + 1
                url = url_api_key_post
                answer = requests.post (url +”&field1=”+value)
                ……………………………………
            messages_buffer = []
    else:
        client.loop ( )
        time.sleep (time_in_seconds)
```

Figure 3 Store & Forward mechanism pseudo-code

3.3. 5G

The fifth generation or 5G technology arose as an evolution of its precursor, 4G technology, in response to technological requirements to reduce costs and production times. Along with these advances go the evolution of different wireless communication technologies such as LoRaWAN, SigFox, NB-IoT, etc. However, there are many industrial use cases that require a much more demanding technology in terms of reliability, latency, and speed in these scenarios, hence the emergence of 5G.

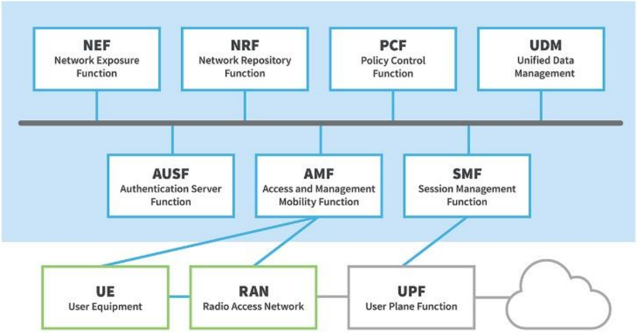

Figure 4 5G network architecture [21]

This technology is divided into two equally important systems; on the one hand, the Core system, which oversees controlling communications, so that data transmitted in any direction can be processed, in addition to registering users and security tasks, and on the other hand, the Radio system, which oversees sending and receiving information using the air. Some of the improvements in 5G communications, in both systems, compared to its predecessor is the subdivision into smaller segments called "minislots". More information can be transmitted simultaneously, increasing transfer speeds. The automatic allocation of radio resources, without the need for the connected device to request an amount of resources, allows a significant reduction in round-trip latency, and the transmission of information at different frequencies depending on the use case and the density of devices. In addition, there is a substantial change in the system architecture since the components are connected through a common bus, allowing the integration of future components in a more simplified way as shown in Figure 4.

Finally, another advantage is so-called "slicing" of the network, since it is the ability to provide different services to each user profile previously created in the Core system depending on their needs. Figure 5 provides an architectural view showing a network divided into multiple instances called network slicing, where each is optimized for a specific application or service requirement.

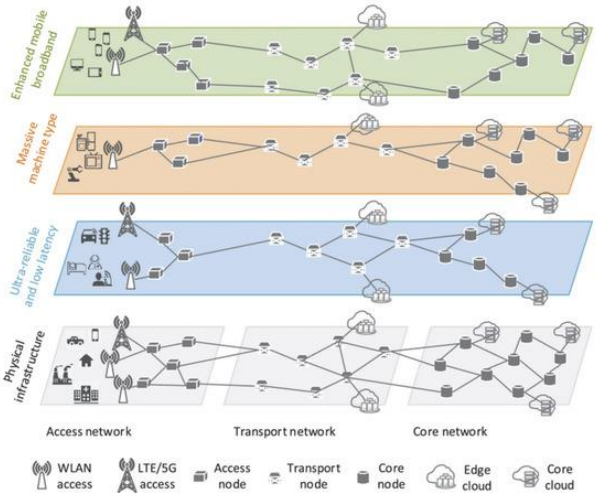

Figure 5 An architectural view of the 5G network slicing [22]

As shown in the figure 5, slicing allows multiple virtual networks to be deployed on a physical infrastructure, enabling resource isolation and customized network operations, depending on the traffic profile. As new 5G services have varying requirements depending on the scope of application such as Agriculture 4.0 or Smart Farming, network slices in remote areas must combine a set of network resources as well as the implementation of LPWAN technologies to efficiently serve the people living in these areas by improving the quality of service they currently have with the different technologies deployed.

4. Testbed and scenario

The scenario chosen to deploy the testbed is the area nearby the town of Rubielos de Mora, in the province of Teruel in Spain. Figure 6 shows the map with the position of the nodes and the route followed by the mobile gateway decided prior to the experiment.

LoRaWAN nodes have been placed in different locations depending on the topography of the terrain since the behaviour of the network is studied in different environments typical of rural areas. The devices will be monitored by a mobile gateway which will follow the route traced in blue as shown in Figure 6. Firstly, it should be noted that each of the fixed node locations has different topographical characteristics from deep valleys with forest mass to large peaks without vegetation. These features include different altitudes as well as different densities of obstacles, and different types of vegetation.

The experiments have been carried out under standard weather conditions, with a temperature between 10-20 degrees Celsius and approximately 60% relative humidity, no rain. As mentioned in the related work, the articles [5-7] explain how weather factors can have a negative impact on communications. Secondly, the mobile gateway is in the off-road car that will follow the route in blue at an average speed between 15-18 km/h simulating the usual speed on a forestry road.

In Figure 6, the areas with cellular Internet connection are coloured, while the uncoloured areas are without connection. The testbed includes the study of the LoRaWAN mobile network behaviour at the beginning and end of the route as if it were a fixed installation and the mobile network following the route with and without the implementation of the store&forward mechanism. Table 2 shows the distances between the fixed gateway positions and the nodes, for reference.

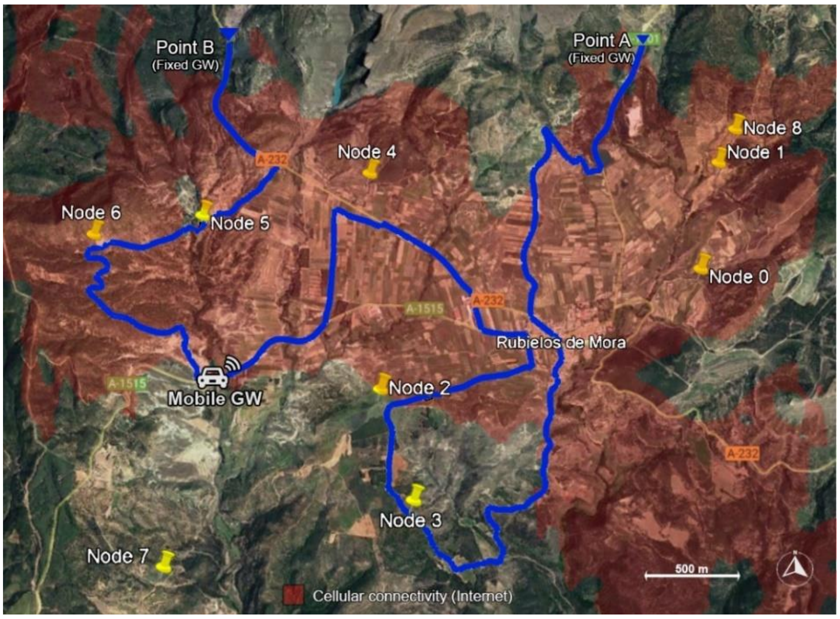

Figure 6 Scenario with nodes location, start/end point, route, and cellular coverage.

Table 2: Link distances between nodes and GW positions

Node	Distance to Point A (Km)	Distance to Point B (Km)
0	2.43	4.99
1	1.5	4.81
2	4.4	3.77
3	5.06	4.8
4	3.09	1.96
5	4.68	1.85
6	5.67	2.38
7	6.81	5.08
8	1.27	4.96

It should be noted that, depending on the type of smart application, the number or devices required to deploy can vary greatly. For example, in emergency applications, such as locating lost people or animals, each of them needs to carry a device either as a smart bracelet or a collar in case of animals. Regarding the characterization of the traffic in the network to provide the required service, the message is transmitted in a packet of 44 bytes of payload, enough to contain the GPS coordinates and other relevant data, depending on the application.

Each device sends between 184 (SF8) and 13 (SF12) messages per day, depending on the configuration of the private network. These values have been calculated based on the duty-cycle limited transmission regulations defined by the European Telecommunications Standards Institute (ETSI) for the 863-870 MHz band in the EU. Unlike public platforms, when testing on a private network with ChirpStack, we only must comply with the European regulations since we do not use public infrastructure.

The selection of the SF (Spreading Factor) determines the message airtime, which means that a higher SF limits the message rate per day but allows connections over longer distances and therefore extends the range of LoRaWAN coverage. On the other hand, the SF must be carefully selected according to the requirements of each application. It should be considered that, although LoRaWAN has an ADR (Adaptive Data Rate) mechanism to dynamically select the FS, it is not recommended to activate it for nodes in motion since it increases the usual energy consumption of the node. On the other hand, activating ADR would mean configuring the devices with an SF optimized for the obsolete RSSI and SNR conditions of the previous node locations, since the SF is chosen based on the SNR values of a certain number of previously transmitted messages [23].

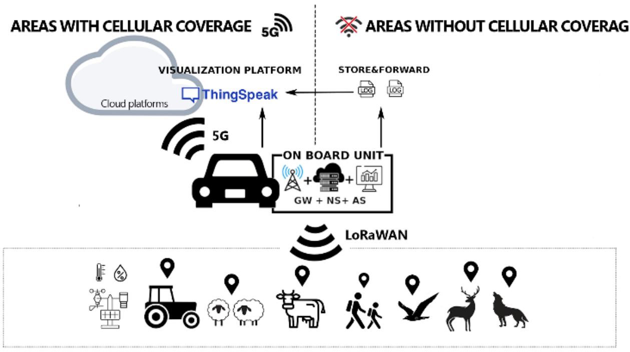

Figure 7 Architecture of the hybrid solution proposed

Since ChirpStack allows using all SF values, the presented tests have been performed with two very distant SFs, SF8 and SF12, in order to profile applications with different range and data rate requirements.

The hardware used in the tests consists of 9 end devices and 1 mobile gateway, which is going to follow the route in blue as shown in Figure 6. The end devices are based on the LilyGO TTGO T-BEAM v1.1 hardware, which pack the popular ESP32 microcontroller, with Semtech's LoRa SX1276 chip, and the NEO-6M GPS sensor to obtain the location coordinates. This device is encapsulated with a dedicated 3D printed encapsulation to provide a collar form factor that can be used on animals and powered by a 9800mAh battery. As for the gateway, it consists of a Raspberry Pi 4 with RAK831 LPWAN Gateway Concentrator Module, with a 6.5 dBi omnidirectional antenna in the 824 - 960 MHz band. This gateway connects to the network server and from there to the application server of the ChirpStack private network, which is created from a Docker image on a local machine. Then the application server injects the information from the nodes to the ThingSpeak visualization platform where the data from the different nodes is displayed in real time. Figure 7 shows the architecture of the monitoring platform described above.

The whole LoRaWAN network infrastructure, with the GW, the network server (NS) and the application server (AS) is located on the top of an off-road vehicle, in what is called the On-board unit, as shown in Figure 8.

Figure 8 LoRaWAN mobile gateway installation

In this case, the only limitation is the displacement of the vehicle as it can only go on roads or forest tracks.

The experiments have been performed 5 each. As shown in Figure 6, the location of the nodes is fixed for simplicity in deploying and collecting the nodes, but this solution is designed so that the user can benefit from the advantages of having a LoRaWAN mobile network since, by having a LoRaWAN mobile gateway you can locate animals or people outside the coverage range of the fixed gateway stations.

5. Results and discussion

To validate the network performance and the feasibility of using this solution in remote environments, several metrics have been obtained during the experiments. These results are SNR (signal-to-noise ratio) and RSSI (received signal strength indicator), linked to the receiving GW, timestamp, and sequence number to calculate the packet delivery ratio (PDR), and response time to locate a moving object (connection time when entering/leaving the coverage area). The number of packets lost during periods of non-cellular connectivity is also registered, in order to compare the benefits of the store&forward mechanism.

Focusing on the nodes located at the different geographical locations, as shown in Figure 6, Table 3 shows in detail the comparison of the PDR using two different SFs and placing the mobile gateway at different point along the route. The left part of the table compares, for the different SF tested, the PDR achieved at each node on a fixed gateway either at points A or B, which are the starting and ending points of the route. The right part shows the PDR obtained by each node when the LoRaWAN mobile gateway has followed the route with or without enabling the proposed store&forward mechanism.

As shown in Table 3, when the GW is at the start or end points of the route, we have areas with no LoRaWAN coverage since the PDR of the nodes is null, while if a LoRaWAN mobile gateway is used, we receive information from all nodes. The last row shows the average of the values for each experiment. It can be seen that, employing fixed GWs, either at the start or at the end of the route, is not efficient since it shows no LoRaWAN coverage for several nodes. Crossing Table 2 and 3, it can be seen that for SF8 the maximum distance covered in this scenario is around 3km for point A, while point B only stablishes a stable connection with node 2 at 3.77 km, while closer nodes do not connect at all. SF12 achieves further distances as expected (more nodes are reached), although there are still 3 nodes left out of the network.

This is because apart from distance, the most important limitations are obstacles along the link. Which is another motivation to use mobile gateways that can palliate this by moving to more convenient locations depending on the position of nodes. Even if it seems that mean PDR values are lower for the mobile gateway, it can at least collect data from nodes that were completely off-coverage before. By using a mobile GW without the store&forward mechanism, information is obtained from all devices although it is observed that most PDRs do not reach 30%.

Table 3: Link metrics obtained for fix and mobile gateway

Fixed GW					Mobile GW **without** S&F		Mobile GW **with** S&F	
	POINT A		POINT B					
Nodes	SF8 PDR (%)	SF12 PDR (%)	SF8 PDR (%)	SF12 PDR (%)	SF8 PDR (%)	SF12 PDR (%)	SF8 PDR (%)	SF12 PDR (%)
0	97,82	75	0	0	15,85	27,78	23,17	44,45
1	45,65	58,33	0	0	20,73	22,22	31,71	33,33
2	30,43	83,33	65	83,33	32,92	38,89	48,78	66,67
3	0	0	0	33,33	12,19	16,67	43,9	44,45
4	0	83,33	0	33,33	10,97	38,89	21,95	72,22
5	0	0	10	83,33	8,54	11,11	24,39	16,67
6	0	91,67	0	58,33	28,05	33,33	41,46	50
7	0	0	0	50	0	27,78	0	44,45
8	28,26	83,33	0	0	17,07	33,33	30,48	50
MEAN	22,46	52,78	8,33	37,96	16,26	27,78	29,54	46,92

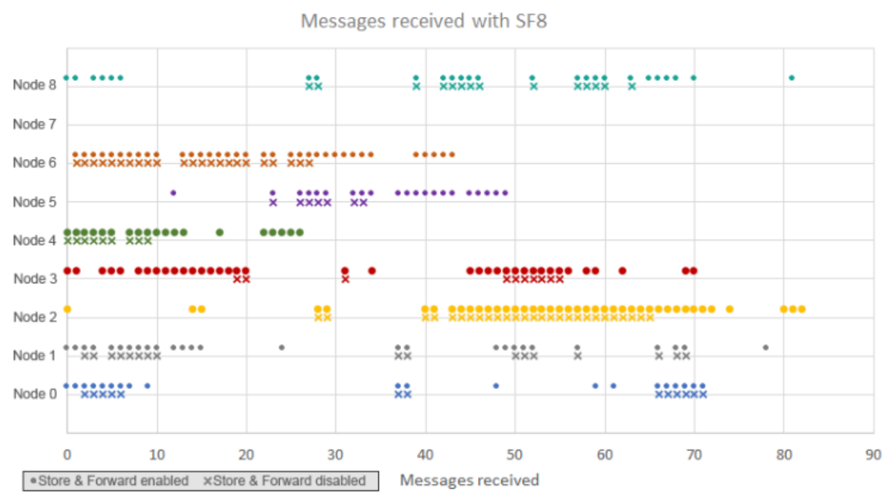

Figure 9 Messages received with/without S&F (SF8)

Figure 10 Messages received with/without S&F (SF12)

However, with the use of the store&forward technique, PDR improves by 13.28% using SF8, and 19.14% using SF12. Therefore, the implementation of the store&forward mechanism is essential when dealing with applications in remote areas where the Internet connection is not stable. Looking at these results, the design of this solution is recommended for those applications that require the use of a LoRaWAN mobile gateway to extend its coverage range, for example, tracking moving assets in smart farming, environmental monitoring, etc.

Figures 9 and 10 show the messages received with each of the SFs used, with or without enabling the store&forward mechanism as indicated in the legend at the bottom of the figures. First, the missing points are the messages that were not received due to the coverage of the LoRaWAN network. As shown in the figures, depending on the location of the nodes and the route followed by the mobile gateway, the LoRaWAN coverage range will be modified. On the other hand, there are two areas where there is no Internet connection since only dots are observed, this is due to the two areas without cellular network coverage shown in Figure 6.

The first area without cellular coverage is where node 3 is located and the second area is at the end of the route. In addition, it is observed that the route goes through areas where it is very likely to fail the Internet connection because it is very close to those areas without cellular network coverage that are uncoloured in Figure 6. For these reasons, in Figures 9 and 10, there are times that when performing the experimental tests, we are in these border areas and as seen in these figures, only data from certain nodes are sent to the visualization platform. Therefore, in these graphs it is clear the need to implement the store&forward because, if not implemented, information that may be useful or necessary, depending on the requirements of the application, would be lost.

Regarding power consumption aspects, one of the energy limitations when using a mobile installation is the power supplies of such mobile devices. In [24], they use a LoRaWAN mobile gateway mounted on a drone and its main limitation is the power supply of the drone, since being a small battery reduces the flight time of the drone to 10 or 15 minutes. Therefore, after observing the results of the authors and knowing about this limitation, in this article we have used an 18000mAh power bank that acts as a power source for the LoRaWAN gateway and the router that gives Internet connectivity. After checking the battery consumption in the gateway during each test, it is concluded that the power bank lasts for 8 hours in full operation. This factor can be established as an energy limiting factor, but nevertheless, it is possible to power the gateway via USB or automobile auxiliary power outlet. Power consumption on the nodes' side has been widely analysed previously [25] and is out of the scope of this work, which focused on the mobile gateway operation.

6. Conclusion and future work

Following the results obtained in the previous section, implementing the hybrid solution proposed in Figure 7 provides a simple design to improve the quality of rural services or applications in remote and mountainous areas with poor network coverage (either from cellular or fixed LoRaWAN networks). The architecture designed in this article differs from other proposals in the implementation of a mobile LoRaWAN GW with the store&forward mechanism for areas without cellular coverage.

Results will depend on the position of nodes and the possible paths for the moving GW. Nevertheless, the solution suggested, providing mobility to the LoRaWAN GW, and including S&F tools, has proven to fill the gaps for connection issues either in LoRaWAN or cellular(5G) coverage. For the selected representative scenario, it has been possible to reach every node in SF12 with the moving GW, while only a maximum of 66% of the nodes were reached with fixed GW. Also, the S&F mechanism has proved to enhance by nearly 20% the PDR for the moving GW when cellular coverage is lost.

Data obtained in these areas could not be visualized in the ThingSpeak (or any other) platform, since, not having an active Internet connection causes the packets to be discarded. It is worth mentioning the incorporation of LoRa technology to 5G, which can use the Massive Machine Type traffic profile to increase network efficiency and maintaining required QoS.

As for future work, an open research point looking to introduce the store&forward also on the nodes can increase even more the PDR on the mobile GW for critical applications but requires careful tunning due to the increased power consumption it would require. On the other hand, we intend to study the difference in terms of PDR, distances reached and installation costs of the use of a fixed GW, a terrestrial mobile GW, such as a car, and an aerial mobile GW, such as a drone, considering the different applications that may arise when implementing any of these types of installations. Finally, in relation to 5G functions, it is intended to incorporate the N3IWF (non-3GPP Interworking Function) module function to the GW LoRaWAN to enable a secure connection to the core of the 5G system.

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