Chapter

Hybrid Architectures to Improve Coverage in Remote Areas and Incorporate Long-Range LPWAN Multi-Hop IoT Strategies

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Abstract

At the height of M2M communications, there are many alternatives and architectures that present solutions for each case and each environment. The interoperability strategy or the combination of different solutions with adequate flexibility can be solutions to maintain a capacity for easy incorporation of new sensor nodes depending on the coverage or not of operators. In addition to interoperability strategies, this chapter presents some alternatives that include multi-hop techniques, combining different technologies. Special emphasis will be placed on low-power wide area networks systems (LoRa, Narrow Band IoT, LTE, etc.) applied in remote environments, such as nature reserves and ocean or fluvial ecosystems. An estate of art of these areas will be presented, as well as results of different development of our group.

Keywords: wireless sensors networks, IoT, LPWAN, multi-routing, interoperability, IoT protocols

1. Introduction

The number of sensors/actuators implemented in the real world today in various kinds of applications (agriculture, weather observation, marine observation, monitoring of seismic movements, medicine, or industrial applications, for example) is immense. In the world of Internet of Things, almost all of these sensor's nodes have the same requirements in terms of the need for low power, self-configurability, low cost, moderate data rate, and wireless communication capability. Traditionally, the wireless networks used for communication between the nodes and the gateway that connects the things networks with the IP network was of the star type. However, at present, the rapid mass introduction of new elements in networks of this type (Massive Machine to Machine Networks) demands greater flexibility in the topologies and architectures used, as well as the ability to interoperability between the various existing technologies in a transparent way to the end users of the system. In addition, this interoperability allows to extend the coverage of the network if the appropriate protocols and architectures are used that allow, in turn, the adaptation to the conditions of each medium.

In urban and suburban areas, it is easier to resort to cloud connection techniques such as NB-IoT or LTE-M, where 4G or 5G coverage is required to reach the final network, meeting the requirements of data rate, consumption, and low cost. However, many of the possible applications mentioned above are developed in environments, where internet connectivity is very limited or nonexistent, but it is necessary to cover large areas where the sensors are located. These can be large agricultural, livestock farms, or marine or river environments. It is in these cases where hybrid strategies and architectures that combine different technologies and require adequate interoperability between different technologies acquire their importance. In short, to achieve greater coverage there are two main strategies: Development of multi-hop topologies using the appropriate routing protocols of mobile nodes in each case, and on the other hand, the combination of different wireless communication technologies depending on the characteristics of the environment. In the case of remote areas, where there is no cellular network coverage, the immediate thing is to think about LPWAN technologies that use unlicensed bands (LoRa, LoRaWAN, Sixfox, and Weightless). Typically, these techniques employ star technology with a high range. In the case of LoRaWAN, it uses the physical layer of LoRa, based on Chirp spread spectrum, integrating, in addition, the network layer. Where it is necessary to increase coverage, this technology could be implemented by developing clusters of clusters around a gateway that intercommunicates with another until reaching the final destination [1, 2]. This chapter will emphasize networks that allow the rapid incorporation of new mobile nodes, so this structure does not seem the most appropriate in principle. The following are the two strategies mentioned above (Multi-hop and Combination of technologies).

2. Multi-hop strategies

Using the physical layer of LoRa, the payload of the data packet can be used to implement different protocols used by mobile wireless sensor networks (WMSNs). This allows the approach of tree or mesh topologies using these protocols. Keep in mind that, in the case of this chapter, mobile nodes can act as repeaters and end nodes in all cases and that they can appear and disappear from the network at any time. For this reason, the most appropriate protocols are the proactive ones that require the routing table to be constantly updated. Another important dilemma, in these cases, is the parameter used to choose the appropriate route to the destination. On the one hand, minimizing the Time on Air (ToA) of the data packets may be a priority to minimize system latency, or depending on the type of data, the rate of packets received can be used. As is known, in the case of LoRa, several communication parameters can be varied such as the bit rate (BR), the spreading factor (SF), or the transmitted power (Pt). The main challenge is that the system adjusts to the requirements of latency, reliability, or QoS minimizing the energy consumption of the different nodes. For this, there are several works developed on different technologies.

Figure 1 shows an example case of the compromise between the different priorities in a multi-hop topology in the case of LoRa technology. If the end node has direct access to the gateway in both cases if the RSSI route is taken as a parameter to choose the route, in case a) a better response will be obtained, and that route would

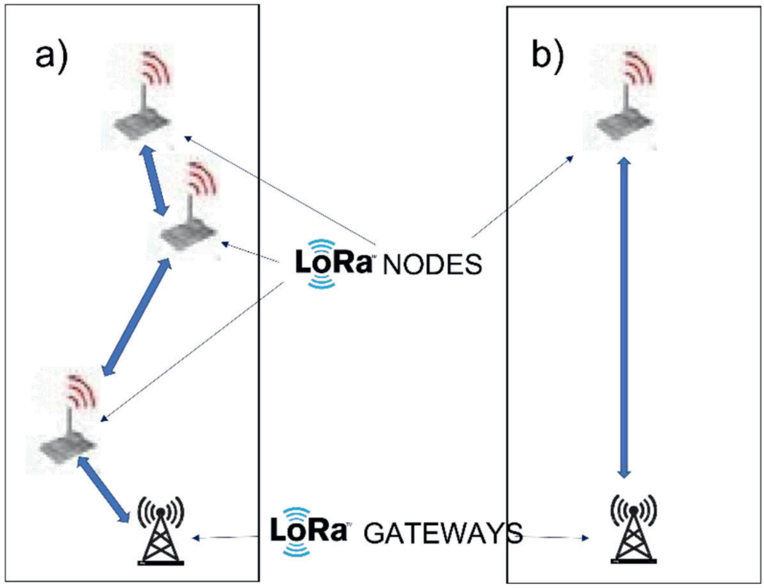

Figure 1.
Two communication cases: a) using multi-hop, b) direct communication with the gateway.

be chosen. The consequence is that it is not necessary to increase the transmission power or the SF achieving a better BR. However, the total ToA would be higher due to the processing of the intermediate nodes, and in addition, they are forced to consume more energy. In case b), it would probably be necessary to increase the transmit power or increase the SF to obtain an adequate Packet Error Rate (PER), although the TOF of the packets would be lower. It is, therefore, important to determine the priority of the parameters to be minimized when choosing the appropriate route depending on the type of data packets, the required latency, or the need to reduce consumption. For this reason, the knowledge of the nature of the entire network is needed and not just find the nearest neighbor. This knowledge must be constantly updated due to the presence of mobile nodes, which impose proactive protocols [3]. In [4], an assessment of the energy efficiency of the network is highlighted according to the network topology and the number of hops. For example, for a given LoRa transceiver, measurements of the energy consumed in a meshed network, such as the one shown in **Figure 2**, are obtained as a function of the range, the number of hops, and the distance between the repeater nodes. Where D is the end-to-end distance (i.e., between the sender and sink node), and d is the distance between each intermediate node.

2.1 Routing protocols

There are multiple routing protocols for the different mobile node network topologies deployed [5]. When selecting one of them for the case of LoRa technology, it is important to consider whether the rapid discovery of new routes or the number of total nodes in the network is critical. In the case of reactive protocols, such as Ad-hoc On-Demand Distance Vector Routing [6], the network is not saturated with route update packets, although in the case of the incorporation of mobile nodes, the use of

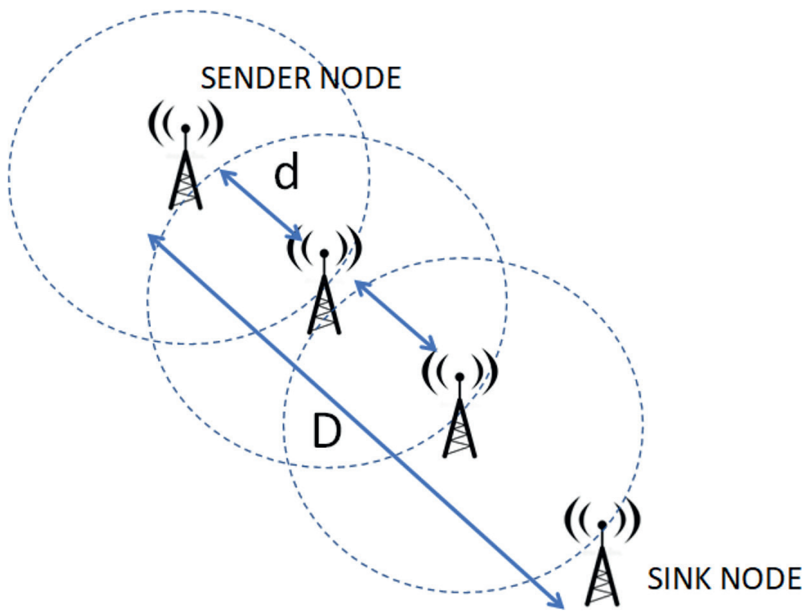

Figure 2.
Mesh topology [4].

these protocols may not be the most appropriate, depending on the time they remain in the network. Others are based on clustering of nodes within the total network (clustering) for large networks, as is the case of LEACH [7], where all nodes can become the central node of a cluster with equal probability. It is a proactive protocol that can be mono-hop or multi-hop [8], both based on extending the life of the network. In the case of the mobile sink-based routing protocol (MSRP) [9], the life of the network is extended avoiding the effect that the nodes closest to the sink of each cluster transmit a greater number of data packets than those that are farther away. For this, the sink nodes become mobile nodes that collect information from several clusters of the total network.

A mixed solution for these mobile node networks, also based on node zone grouping, is the zone routing protocol (ZRP) [10], which groups nodes according to the number of hops required. It is based on the coexistence of two protocols: one intra-zone of proactive type that allows the constant search of the neighboring nodes and another inter-zone of reactive type, thus avoiding the saturation of the network.

For the case of LoRaWAN systems, also based on grouping LoRaWAN nodes around a cluster gateway is the proposal in [11]. This paper proposes a star of stars architecture, where devices or end nodes are connected to one or more gateways using the physical layer of LoRa. Each end device transmitted data to the cluster gateway, and the cluster gateway concatenated data from all the devices in an array and transmitted it to the central gateway. The authors demonstrate that a better energy efficiency is achieved in this star of stars topology.

There are many other applications such as those of large farms, the monitoring of seismic movements, or networks of marine buoys with sensors, where the mobility of the nodes is reduced, although there is still the fact that there are nodes that fall due to lack of battery or new ones are incorporated. This chapter focuses primarily on these cases.

Optimized Link State Routing protocol (OLSR) [12] is a proactive protocol that adapts link state routing for use in mobile ad-hoc networks. It allows multipoint relays. Each node selects a set of its single-hop neighbors to act as relays this information is shared between nodes making this protocol well-suited to large and dense networks with random and sporadic traffic. Destination-sequenced distance vector routing protocol (DSDV) [13] incorporates a sequence number to their routing tables and only refreshes the routing tables when receiving a DSDV packet with a higher sequence number than the node already has. This makes this protocol suitable for fixed node networks or with low-mobility nodes. Another reactive protocol used in these kinds of networks and maybe the most appropriate for the case above explained is Ad-hoc On-Demand Distance Vector Routing (AODV) [14], where each node initializes the routing discovering through a route request packet answered by all network neighbors and during the network recognition process a reverse path is created. Dynamic source routing (DSR) supposes an evolution of this protocol, where a list of hops from source to destination is collected in the RREQ packet as it travels through the network. This list allows implementing a total cost parameter of the route if information about SF, BR, and power required is added. This could be a solution for the problem described in **Figure 1**.

An IoT-oriented protocol is Pv6 routing protocol for low power and Lossy Networks (RPL) proposed by The IETF routing over low-power and Lossy Networks working group [15] RPL]. RPL is a gradient routing technique [16] that considers a WSN as a direct acyclic graph (DAG) rooted at the sink. The goal of RPL is to minimize the costs to reach any sink (from any sensor) by means of an objective function. This function can be defined in many ways adapting it to the operating scenario. Some authors [17] have developed a LoRa network RPL based. In this case, the optimal per-link spreading factor (SF) is one of the RPL objective functions (OF0) in order to compute rank, using the selected LoRa SF as routing metric.

Other approaches try to minimize the energy consumption of the LoRa nodes in a multi-hope network by minimizing the distance to the best neighbor taking into account the node state (busy or free). This is the energy-efficient multi-hop communication solution (e2McH) proposed in [18]. A more complex solution to improve coverage an energy consumption is presented in [19], using variable neighborhood search (VNS) and a minimum-cost spanning tree algorithm employing LoRaWAN end nodes and LoRa nodes as repeaters. In this work, the initial solution approach to find the multi-hop route to the final gateway is based in the PRIM algorithm [20] to find minimal spanning tree, storing the values of SF, BW, and Pt for each node. After that, variable neighborhood search (VNS) is employed to change node characteristics. The authors propose a stochastic algorithm that changes neighborhood structures to find local minimal solutions using a function objective based in the energy per useful bit transmitted. This proposal is designed for a three-level network: Level 1: gateway, level 2: repeaters, and level 3: sensors.

In summary, all these works seek the choice of appropriate protocols to minimize, mainly, the energy consumed, and the Time on Air (ToA) parameters of the packets transmitted along multi-hop networks. Some proposals are based on the location of the nodes, and others are based on the suitability of the configurable parameters of the LoRa nodes (SF, Pt, or BW). In certain use cases, it is also possible to extend the network coverage by combining different wireless communication technologies depending on the environmental conditions. The latter gives greater flexibility to the design of the final network adding more dynamic adaptability to the environment. In the next section, different use cases that develop this type of strategy are presented.

3. Interoperability strategies

There are currently many radio technologies (RAT) available when thinking about the interconnection of sensor networks. Depending on the coverage radius, BR, QoS, or consumption of these devices one or the other can be selected. To obtain greater flexibility in the design of networks that adapt to different scenarios, it may be interesting to combine several of them. The options to achieve interoperability between the different technologies can be very varied, both in a software way or in a hardware way. The IoT network designer is often faced with this dilemma when it comes to choosing one technique or another. Many manufacturers already develop, for example, configurable chipsets that can integrate different radio access technologies (RAT's) [21–23], usually using different transceivers interconnected with a microcontroller unit (MCU) through SPI or UART interfaces. Through these combinations, it is not only intended to expand the coverage of the sensor network, but also to be able to reach areas where a single specific technology cannot do due to environmental conditions (obstacles, indoor/outdoor scenarios, density of nodes, etc.).

Another interesting alternative is the one proposed by [24] in which interoperability between different technologies is achieved through software defined networking (SDN). The objective is the coexistence between different radio access technologies in terms of protocols, coding, or signaling in a transparent way to the final application in the IP network. The architecture is organized into six levels, and the interoperability is classified into: device level, syntactic level, semantic level, network level, and platform level. Each technology has its own modulation, coding scheme, protocols, routing methods, or end-to-end applications communications. The proposed architecture is based on the implementation of software defined radio (SDR), network function virtualization (NFV), and SDN to solve the interoperability problem.

This chapter presents cases of hardware interoperability between two LPWAN technologies or between LPWAN and PAN technologies. A classification could be made into two types of interoperability from the Hardware point of view:

1. Inter-network interoperability: Implementing central nodes that act as a gateway between the two technologies that are separated in the network. In this case, a hierarchical structure of the network would be obtained, and the "translation" point would be only one.

2. Distributed Interoperability: Developing end nodes, routers, or central nodes that implement the two technologies and can choose between one and the other, or even redundant communications using both. This case gives greater flexibility to the network and allows automatic adaptation to the environment of the nodes of the same.

Figure 3 shows the two interoperability models mentioned.

3.1 Inter-network interoperability

This philosophy is applicable, mainly if the conditions of the environment set the radio access technology to be used in different areas of the total network, or to separate the traffic of one network from another implementing a topology contemplating subnets. It is possible, for example, that in cases of long extensions of land or marine or river environments, there are areas, where 4G or 5G coverage is available, such as

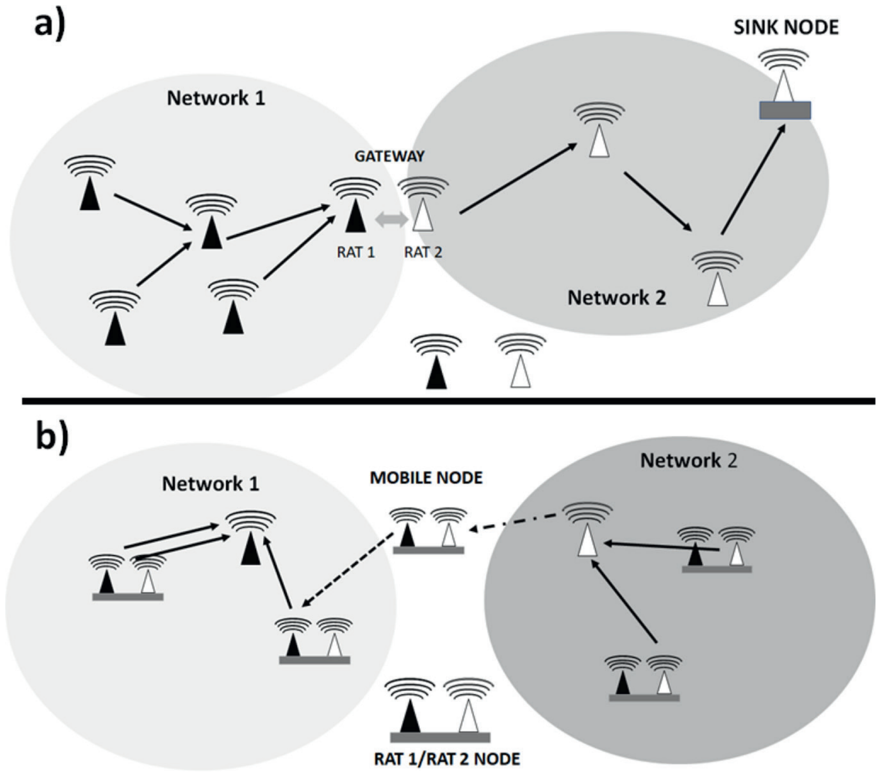

Figure 3.
Two kinds of interoperability possibilities including multi-hop: a) inter-network, b) distributed.

urban or suburban environments and others without this type of network deployed. In the case of long-range technologies, we would choose options such as NB-IoT or LoRa, for example. Another possibility is to interconnect a cellular network already deployed with a network of sensors located at long distances and indoors, as would be the case of greenhouses or fish farms. In these cases, the philosophy used would be to create gateway nodes between the different RAT's. Its function is to adapt protocols, contents of the payloads, and control of access to the medium. In addition, this separation enables the possibility of existence of pre-processing before communication between networks, reducing the traffic load between subnetworks and in the entire network (Edge Computing) [25]. The latency in cases of Sensor/Actuator interaction can also be reduced with this arrangement since the data does not have to be sent to the rest of the network in the event that they are on the same subnet. Examples of this philosophy are presented below.

3.1.1 LoRa-ZigBee interoperability

As seen in previous sections, one of the biggest challenges of this type of network is the reduction of power consumption. ZigBee technology, based on the 802.15.4 [26] standard, is widespread in sensor communications networks. It allows flexible network configuration, moderate ranges (10–100 meters), low-power consumption, and data transmission rates from 40 to 250 Kbps depending on the band of use (915 MHz or 2.4 GHz). It is more susceptible to be used indoors and in the absence of obstacles.

In the comparison between LoRa and ZigBee, the latter is characterized by its lower cost, as well as its lower power consumption and a higher BR, to consist of a shorter range. The combination, therefore, of both technologies can mean energy and economic savings in some cases. In the case of smart buildings, for example, there are performance comparisons of both [27] that ratify the above in addition to the fact that LoRa technology provides greater penetrability through walls or cement walls. In these cases, it would be possible to implement a network that follows the philosophy of **Figure 3a**, where the ZigBee nodes would be forming a subnet within the same enclosure without wall obstacles and are interconnected by LoRa links, longer range and more robust to obstacles. Within the same smart buildings ecosystem, there are other proposals such as [28], where the inverse strategy is presented, that is, the interconnection with the end nodes is formed by LoRa links, while the ZigBee links implement the connection with the central data collector and the IP network. In this way, the BR of the ZigBee technology is used in the final stretch of the network, as well as its greater security thanks to the AES 128 [29] encryption algorithm.

Another environment, where interoperability is applicable, is that of remote natural parks or crops, where greenhouses appear scattered over a large area. In these cases, it is essential to sensorize them. ZigBee is a very suitable technology for this, case, but, if it is necessary to cover large areas, LPWAN technologies result more suitable to implement the backbone of the complete system. This is the philosophy that this research group has followed in [30], adding VLC communications systems [31]. The overall architecture of the system is shown in **Figure 4**, where interoperability between the different technologies (LoRaWAN, ZigBee, and VLC) is implemented in each of the access points of the ZigBee subnets.

In case that there is communication between nodes of the same ZigBee subnet, it is forwarded directly by each access point, avoiding the increase in latency in a possible sensor-actuator communication or in the case of alarm action. When making the gateway between the two RAT's it is necessary to take into account the size of the payloads of both. In this case, the Waspmote [23] hardware platform of Libelium has been used, which contains an ATmega1281 microcontroller with a series of connected sensors and allows two simultaneous communication modules connected *via* SPI bus. The microcontroller is responsible for storing the messages from each node of the network and retransmission by the necessary technology. In the case of ZigBee-LoRaWAN, a fragmentation of the data packets is necessary as shown in **Figure 5**.

In addition, the use of VLC is proposed for the transmission to a mobile device [32] of contents stored in the memory of the access point or transmitted through LoRaWAN from the central gateway of the network. The goal was to create a cellular network, where ZigBee and VLC coverage were given to each cell.

3.1.2 Lora-NB-IoT

Another contribution within the strategies reflected in **Figure 4**. a is based on LoRa and NG-IoT technologies [33] where a network of LoRa-NB-IoT gateways is implemented between areas where there is 4G or 5G coverage, and those where there is not. NB-IoT operates in the licensed bands associated with mobile operators and allows communications with low consumption and with BR from 120 to 160 Kbps. In addition, it has a low latency of the order of 1 to 10 sec. This can be an inconvenience, but for sensor networks, it is not a critical aspect. In this case of hybrid network, the

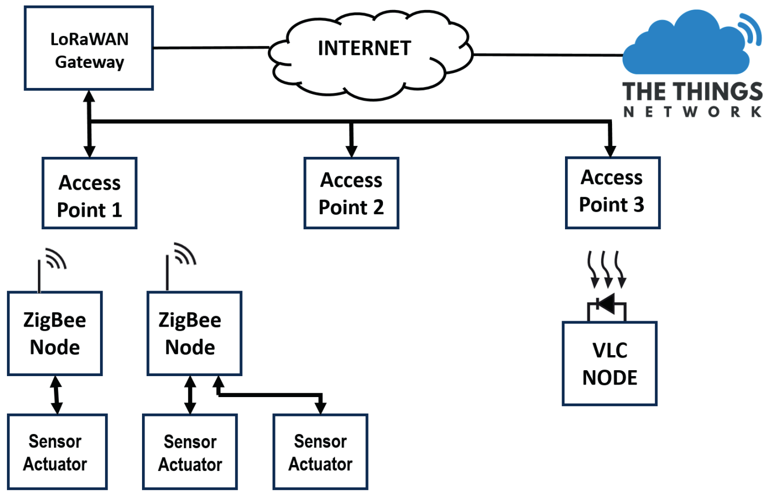

Figure 4.
Global network architecture [30].

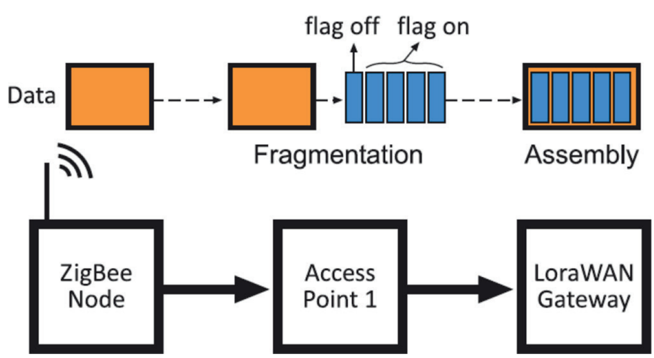

Figure 5.
Fragmentation in a ZigBee-to-LoraWAN communication.

LoRaWAN subnet is responsible for communications that require greater immediacy, and the NB-IoT network forms the gateway to the IP network of all sensor data. The architecture used is based on three layers: sensor nodes layer, forwarding layer, and cloud layer. The end-to-end communication of the network is carried out using the MQTT messaging protocol [34], based on the publish/subscribe philosophy, which is supported by all nodes in the network.

3.2 Distributed interoperability

An example of the philosophy presented in **Figure 3**. b of distributed interoperability is presented in [35], where a multi-RAT architecture is proposed for each node using two LPWA technologies: LoRa and NB-IoT. The latter allows greater BR, in addition to direct connection to IP technology through the mobile network. Therefore, the use of this technology implies the existence of coverage by a mobile operator to be able to implement the network. In the uplink, the use of NB-IoT may require higher power consumption due to the need to implement the entire IP protocol stack. In this case, the use of LoRa may be less energetically costly. The authors propose a series of possible functionalities thanks to these multi-RAT nodes, such as:

- “a security or malfunction detection system with heartbeat status messages over LoRaWAN and emergency alarm traffic over either NB-IoT or both technologies,
- an assisted living wearable with low priority traffic over LoRaWAN and emergency traffic over NB-IoT,
- actuators with heartbeats or status reports over LoRaWAN and direct control loop traffic over NB-IoT,
- a shipment tracking system using NB-IoT whenever available and private LoRaWAN in remote areas (in warehouses, on ships in the sea, etc.).”

Precisely on this last point is based the use case proposed in the next section of this chapter.

4. Proposed use case

In coastal maritime environments, there is a need to monitor parameters such as currents, salinity, winds, temperature, water oxygenation, etc. The sensors responsible for these measurements can be assembled in buoys or, in some cases, in ships that usually sail on certain routes in the area. These ships can act as mobile nodes of the network collecting information from their own sensors or those of fixed buoys at a point and act as repeaters. An appropriate LPWAN technology for the interconnection of these nodes to the gateway could be LoRa, which also has great advantages due to its characteristics in this environment. There are multiple studies analyzing the propagation of radium in this ecosystem [36, 37].

On the other hand, in many archipelagos, there are certain areas in which there is mobile network coverage since operators provide it on routes transited by habitual maritime traffic, such as car and passenger ferries. These vessels are likely to be used as mobile nodes that would act as a gateway between technology, such as LoRa and NB-IoT. The use of nodes that combine these two technologies as proposed in the previous section is very useful giving greater versatility to the network and choosing one or the other always depending on the conditions. Not only offering a path to the cloud through land but also using the vessels themselves as mobile sink nodes agglutinating a cluster of sensor nodes in their route. **Figure 6** shows this use case.

The implementation of hybrid LoRa/NB-IoT nodes allows the right technology to be chosen in each case to reach the final application in the cloud. The nodes have a memory that stores data from sensors that could not be sent during times of absence of connection. In this particular case, non-proactive protocols could be contemplated because the appearance and disappearance of nodes in the network are not so fast, so the updating of routes does not have to be so continuous and the number of nodes in the network at each moment is not as large as in urban or suburban environments.

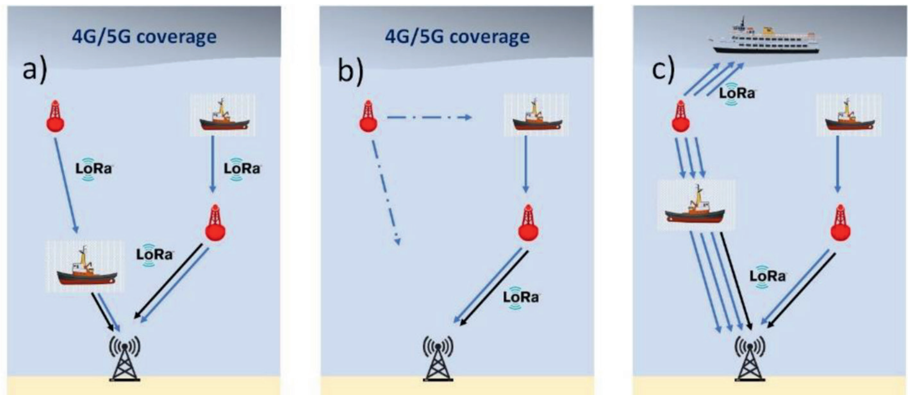

Figure 6.
Proposed use case. a) LoRa multi-hop network with a central gateway, b) connection loss, and c) recovered path and retransmission of the saved data. Incorporation of mobile sink node with 4G/5G connection and interoperability.

DATA	Flags	Hop Count	Destination Address	Source Address	Seq. Number	Sensors Data	Power Level

Figure 7.
Main frame structure.

Destination Address	Sequence number	Hop Count	Next Hop	Pointer to a list of prec.

Figure 8.
Routing table entry.

The protocol used by our group in this case, for the multi-hop LoRa network is based on the Ad-hoc On-Demand Distance Vector (AODV), with some small variations that allow the forwarding of sensor data accumulated in the queues implemented by the nodes. In addition, a field appears in the routing tables of each node that contains a pointer to a list of precursors to store the path of the packet to reach the node in question. So far, its operation has been proven in different types of links (aquatic and suburban). It is currently at the stage of action. **Figure 7** shows the format of the data package used, and **Figure 8** shows the routing table entry.

Figure 9 shows the pseudocode of the main algorithm responsible for finding a route to the gateway directly or through another node to transmit sensor data and the level of power used. That allows the measurements to be carried out in the end.

Simulations have been carried out with Matlab using the Longley-Rice model. This has been done to see the behavior in the marine environment from real points between the gateway on land and an isolated node. **Figure 10** shows the results obtained on a sea route between the islands of Gran Canaria and Tenerife.

The system has been implemented using Libelium Waspmote with a LoRa communications module based on Semantech's SX1272. Depending on the manufacturer and depending on the SF and BW, it has different operating modes. The worst sensitivity for the lower SF case is −114 dBm and − 134 dBm for the maximum SF (12).

```
Algorithm 2: sendSensorsInfo function

Result: Creates a sensor info message and sends it directly if a route to LoRa Gateway (LGW)
available or looks for a route to LGW in other case.
Input:  destiny_address = LoRa Gateway Address;
        flags = 101;
        timeout = timeout specified in loop function


route = searchTableEntry(destiny_address);
if(route == NULL) then
        route = discoverRoute(destiny_address, flags);

        if(route == NULL then
                return -1;
        end

end

powerLevel = route.powerLevel;

createPayload();

for(i = 0; i < MAX_DATA_RETRIES; i++) do
        r = sendMsg(route.nextHop, payload, payloadLength, DATA, timeout);

        if(r == 0) then
                return 0;
        else
                increasePower();
        end
end

processRERR();

deleteTableEntry();

return -1;
```

Figure 9.
Main algorithm pseudocode.

Figure 11 shows the RSSI measurements in a coastal environment with a gateway and in different locations of a mixed coastal environment.

5. Conclusions

This chapter has carried out a review of the options currently available to improve coverage in sensor networks, especially those covering large areas in remote areas (LPWAN). A classification of two strategies has been proposed to obtain greater coverage and flexibility based on interoperability between existing technologies. In addition to the state of the art, a contribution made by our research group has been presented in which multi-hop and interoperability strategies are combined by adding new techniques, such as VLC and OCC. Finally, a use case is presented in which all the techniques seen can be accommodated helping to solve a specific particular problem using a low-cost solution. This prototype is in the measurement period, although the results obtained show good performance in terms of TOA and latency. A very flexible and adaptive architecture is achieved that avoids the loss of data due to the fall of a route or a node. As a future line, a node with NB-IoT / LoRa connectivity is incorporated into the cellular network.

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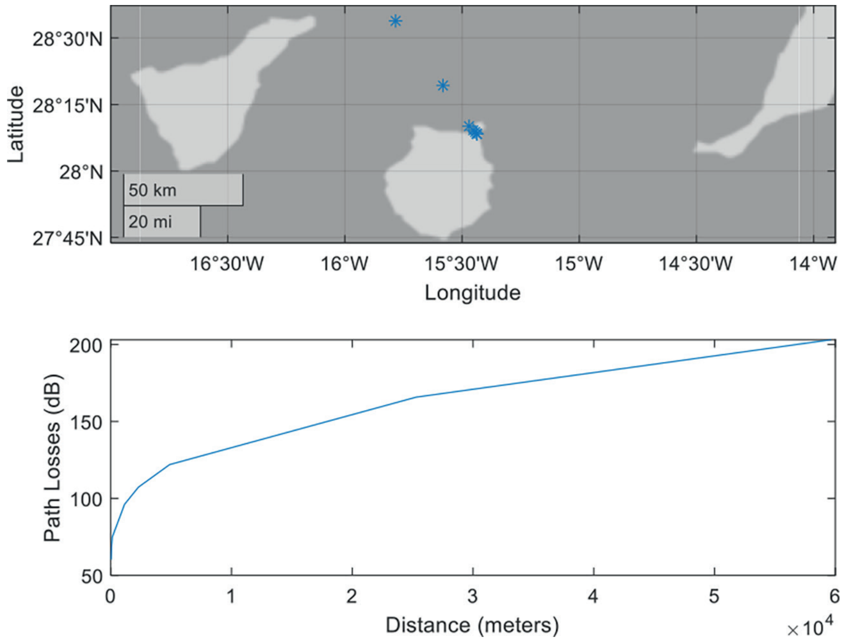

Figure 10.
Path losses versus distance.

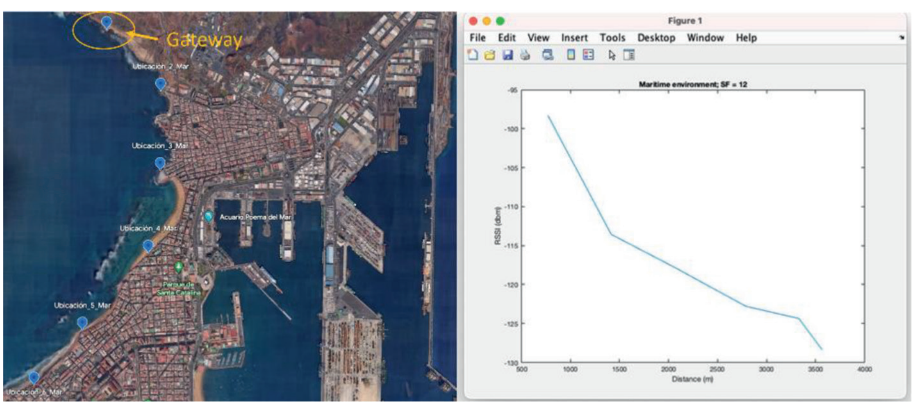

Figure 11.
Measured RSSI versus distance.

Conflict of interest

The authors declare no conflict of interest.

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