Rural Environmental Monitoring via ultra wide-ARea networKs And distriButed federated LEarning

Coverage capabilities and limitations of existing LP-WAN technologies

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1. Abstract

One of the main objectives of REMARKABLE's WP2 is to establish the limits of existing Low-Power Wide-Area Networks (LP-WAN) technologies for wide-area IoT. LP-WANs, such as LoRaWAN, Sigfox, and NB-IoT, offer substantial benefits for wide-area IoT deployments, but they also have several limitations including Coverage and Scalability, Device Power Consumption, Interference vulnerability and Standardization and Interoperability.

This document presents the plan and related activities foreseen to understand the limits of existing LP-WANs and to develop possible solutions to overcome them: in particular, in this deliverable LoRaWAN Range Extender and AlLoRa are presented and analysed as possible solutions.

The actions reported in the current document contribute to the existing literature by identifying IoT cases where the REMARKABLE solutions could play an important role.

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2. Introduction

Low-Power Wide-Area Networks (LP-WAN) technologies, such as LoRaWAN, Sigfox, and NB-IoT, offer substantial benefits for wide-area IoT deployments but also have several limitations.

Firstly, LP-WAN technologies generally support low data rates, ranging from a few bytes per message to hundreds of kilobits per second. While this is sufficient for many IoT applications, it is unsuitable for those requiring high throughput. Additionally, these networks often experience high latency, which can be a significant limitation for applications demanding real-time or low-latency communication. Another notable issue is scalability. Although LP-WANs provide extensive coverage, they may struggle in densely populated areas due to interference and limited channel availability. This results in a restricted capacity to support a high number of devices in a small area. Moreover, despite being designed for low power consumption, some use cases may demand more power than the devices can support over long periods, especially in scenarios requiring frequent communication.

Operating in the unlicensed spectrum, as in the case of LoRaWAN and Sigfox, LP-WANs are susceptible to interference from other devices using the same frequency bands. This can impact reliability, scalability, and performance. Furthermore, the security mechanisms in LP-WAN technologies, while effective, are often less robust compared to traditional cellular networks, posing potential vulnerabilities in encryption, authentication, and data integrity. Additionally, many LP-WAN technologies have asymmetric uplink and downlink capabilities, with more robust uplink channels than downlink. This asymmetry can limit bidirectional communication. The lack of uniform standards and interoperability between LP-WAN technologies further complicates widespread adoption and integration into diverse IoT ecosystems.

On the other hand, traditional cellular technologies are power-hungry and ill-suited for many IoT applications. Newer cellular solutions aimed at IoT, like NB-IoT and LTE-M, offer improved power efficiency but still need to be widely available in many countries.

Understanding these limitations is crucial for selecting and designing appropriate IoT solutions that align with specific application requirements and constraints.

The aim of our work is to:

1) Investigate the coverage limits of existing LP WAN technologies,
2) Identify improvements at device and network side providing extreme coverage of main LP WAN technologies,
3) Identify rural IoT use cases in REMARKABLE that could be addressed using existing direct single-hop LP WAN communication

In these first 18 months we have focused on points 1) and 2), developing some technologies that could assist overcoming some of the limitations listed above.

2.1. Definitions

IoT (Internet of Things): IoT refers to the network of physical objects—devices, vehicles, appliances, and other items—embedded with sensors, software, and connectivity to exchange data with other devices and systems over the internet. It enables automation, monitoring, and control in various applications, from smart homes to industrial automation.

LP-WAN (Low-Power Wide-Area Network): LP-WAN is a type of wireless communication network designed for long-range connectivity and low power consumption. It is optimized for battery-powered devices, enabling cost-effective and extended-duration operations in wide-area IoT applications. Ambient energy scavenging can increase battery lifetime.

LoRaWAN (Long Range Wide Area Network): LoRaWAN is an LP-WAN protocol built on LoRa (Long Range) modulation technology that employs chirp spread spectrum. It provides secure, bi-directional communication for IoT devices over long distances, using unlicensed radio spectrum, with features like adaptive data rates and low power consumption. It is standardized as Recommendation ITU-T Y.4480 "Low power protocol for wide area wireless networks", of the International Telecommunications Union, and can be self-deployed by small organizations.

Sigfox: Sigfox is a proprietary LP-WAN technology that offers ultra-narrowband communication. It is designed for low data rate applications, providing extensive coverage and minimal power usage by transmitting small packets of data over long distances using unlicensed ISM bands.

NB-IoT (Narrowband IoT): NB-IoT is a cellular LP-WAN standard developed by the 3rd Generation Partnership Project (3GPP). It operates within the licensed LTE spectrum, offering robust indoor coverage, low power consumption, high connection density, and long battery life for IoT devices. The throughput is higher than that of LoRa and Sigfox, at the cost of higher power consumption.

- Applicable Reference Material

[1] Grant Agreement Number: 101086387 — REMARKABLE — HORIZON-MSCA-2021-SE-01.

[2] Making the Most of Your H2020 Project - Boosting the impact of your project through effective communication, dissemination and exploitation, The European IPR Helpdesk, available at: https://op.europa.eu/en/publication-detail/-/publication/3bb7278e-ebf3-11e9-9c4e-01aa75ed71a1/language-en/format-PDF/source-164620962

2.2. List of Acronyms

Acronym	Definition
AI	Artificial Intelligence
CN	Communications and Networking
FL	Federated Learning
HAP	High-altitude Platform
IoT	Internet of Things
ICT	Information and Communication Technologies
ISM	Industrial, Scientific and Medical (frequency bands)
LoRa	Long Range
LoRaWAN	LoRa Wide Area Network
ML	Machine Learning

NB	Narrow Band
NB-IoT	Narrow Band Internet of Things
LEO	Low-Earth Orbit
NSS	Networked Sensing Systems
LP-WAN	Low-power Wide-area Network
LR-UWAN	Low-power Ultra-wide-area Network
LR-PAN	Low-rate Personal Area Network
RSSI	Received Signal Strength Indicator
TinyML	A kind of embedded ML
UAV	Unmanned Aerial Vehicle
UC	Use Case

Table 1. List of acronyms.

3. Project Introduction

3.1. The REMARKABLE project

Internet of Things (IoT) technology combined with complementary support for data analytics is the cornerstone of today's digital transformation. The societal and economic impact of IoT/machine learning (ML) systems in urban and suburban areas significantly outpaces the one in rural areas due to a limited reach of connectivity infrastructure. IoT technologies have a huge potential for improving the economy and quality of life in rural areas, both in developed and developing countries. For instance, about 30.6% of the EU population lives in rural areas, which cover over 83% of the total EU area. Nonetheless, the average GDP per capita in rural EU areas is only 75% of the EU average [5]. Moreover, even though mobile networks cover more than 99% of the population in some European countries (such as the UK), they cover only about 79% of their landmass, thus leaving more than 20% of deep rural country areas without signal coverage [6]. To reverse further widening of the urban-rural gap, one needs to bring efficient and affordable IoT/ML solutions to deep rural areas, reaching out to applications and use cases ranging from wildlife management, rural tourism, livestock monitoring, water and air pollution control, and others.

REMARKABLE is an interdisciplinary project comprising experts from computer science, communication engineering, life sciences, environment and management. These experts come from diverse organisations in the UK, Europe and Africa. The project's vision is to bring IoT/ML systems a step closer to seamless, energy efficient and secure deployment targeting use cases in deep rural areas. This will be done by identifying main gaps in connectivity and affordable data analytics and through interleaved research, development and validation in a real-world setting. The project is centred on an IoT/ML-based technological platform that will be adapted and demonstrated in the context of use cases applied in environmental monitoring, management, and conservation.

In short, the REMARKABLE project emphasises a necessity of bringing rural areas into the reach of IoT/ML technologies. Its ultimate goal is to facilitate a reduction of urban-rural gap which is currently increasing. Making advanced information and communication technologies (ICT) such as IoT/ML systems a rural commodity will play a crucial role in reversing the rural depopulation trends due to an expanded range of economic opportunities through empowering and modernising traditional rural ecosystems. The added value of deploying IoT/ML in deep rural areas is in reaching out to new streams of data sources that could prove invaluable in tackling and better understanding the growing environmental concerns, ranging from local and regional (such as pollution monitoring) to global ones (such as climate change).

REMARKABLE considers several objectives in terms of research and innovation that will also have a large environmental and societal impact, summarised in Table 2.

	Objective	Outcome	WP-M	Deliverable	Respons. Partner
Research and Innovation Objectives	Secure and Trustworthy Sensing, Localisation and Digital Twins	Design of robust, secure, trustworthy, and traceable IoT platform suitable for deep rural applications	M44	D.1.1-D.1.4	ULHT
	Connecting the Unconnected – Ultra Wide-Area IoT Networks	Provide a solution for connectivity of IoT devices deployed in deep rural areas beyond the reach of current wireless cellular network infrastructure	M44	D.2.1-D.2.4	UNS-FTN
	Secure and Frugal Distributed Data Analytics for Rural IoT	Develop a novel data analytics platform based on privacy-preserving distributed ML methods that are frugal secure and scalable	M44	D.3.1-D.3.4	MMU
	Demonstration, Validation and Assessment	Demonstrate, validate, and assess developed solutions in uses cases in real-life conditions, across European and African countries	M48	D.4.1-D.4.4	UA
Environmental and Societal Impact	Health and vitality monitoring of livestock in real-time	Enable quick animal treatment and prevent spreading illness, increase food production, track animals, identify grazing patterns, prevent desertification			
	Wildlife monitoring	Support tracking of endangered animals, reduce their poaching, improve tourist experiences in wildlife parks and reservations			
	Soil and agronomic management	Support automated irrigation and increase all-season production of food products			
	River pollution and air quality monitoring	Prevent health risk to humans, protect aquatic ecosystems from collapse and prevent the proliferation of phytoplankton			

Table 2. Summary of REMARKABLE project objectives.

3.2. Project key messages

REMARKABLE offers at least four main high-level messages that are foreseen for the principal findings produced by the projects, which are focused on the following concepts:

- The REMARKABLE project is centred on developing an IoT/ML-based technological platform that will be adapted and demonstrated in the context of use cases applied to environmental monitoring, management, and conservation.
- REMARKABLE uses and assesses innovative methodologies based on statistical data processing and decentralised federated learning methods specifically designed for different use case implementations and demonstrations.
- The REMARKABLE project places a specific focus on rural environments and, in particular, on the African continent due to the huge potential of the number of IoT applications in Africa and the lack of traditional connectivity options.
- REMARKABLE strives at developing various added-value services ranging from wildlife management, rural tourism, livestock monitoring, water and air pollution control and others.

3.3. Keywords

IoT, LoRaWAN, Long Range, LoRa

4. LoRa and LoRaWAN limitations in remote regions

LoRa and LoRaWAN face several issues when deployed in remote regions. The most important ones are:

- The lack of existing communication infrastructure makes it difficult to deploy sufficient gateways to ensure comprehensive coverage.
- Extreme environments, such as dense forests, can attenuate LoRa signals, reducing effective range and coverage.
- Remote areas often lack reliable power sources, making it challenging to maintain continuous operation of gateways and nodes. Solar power may be insufficient during extended periods of cloud cover. LoRa gateways rely on cellular base stations for their Internet connectivity, which are often powered by gasoline generators. Fuel supply is often disrupted in remote areas.
- Remote and extreme environments often have limited accessibility, making regular maintenance and troubleshooting of deployed nodes and gateways difficult and costly.
- Devices deployed in remote or extreme locations are more susceptible to tampering or theft, requiring robust physical security measures.

To overcome some of these issues, we have worked on two technical solutions that allow for the deployment of LoRaWAN and LoRa networks in such challenging environments: a LoRaWAN Range Extender and the AlLoRa communication protocol.

5. LoRaWAN Range Extender

The traditional LoRaWAN architecture is based on several end-nodes (ENs) equipped with sensors and wireless transceivers. These ENs communicate using the LoRaWAN protocol with one or multiple gateways. The gateways are responsible for receiving data frames from the ENs and transmitting them to a Network server utilizing TCP/IP connectivity, often provided by a cellular operator. The Network server is then linked to the corresponding Application server, which processes the data and makes them accessible through a web server interface.

Although cellular coverage is ubiquitous in cities and along main roads, it tends to be absent in sparsely populated or remote areas. An example is presented in Figure 1, where cellular network coverage in Kyrgyzstan (areas in pink colour) shows that rural areas with low population density and remote areas are not served. This data is gathered from https://www.gsma.com/coverage/1038 Operator Alfa Telecom, accessed on 6 June 2024.

Figure 1. Cellular coverage in Kyrgyzstan shown as pink coloured areas

The cost of servicing these areas outweighs the potential revenues attainable from a sparse customer base, making them economically unviable. For example, it precludes collecting hydrological and meteorological data in isolated areas, crucial for disaster prevention and mitigation, which is increasingly significant in face of climate change.

In the framework of making IoT accessible in remote areas, we designed a Range Extender (RE) to expand the coverage area of existing LoRaWAN gateways to regions lacking cellular coverage. This is critical for transmitting packets from the gateway to the network and application servers, in order to make the application data available online. A Range Extender Application Scenario is shown in Figure 2. The cellular tower coverage is represented by the orange dashed line circle. The coverage of the LoRaWAN gateway is depicted by the dashed green circle. A water level sensor located outside the cellular coverage area is reachable only from the RE.

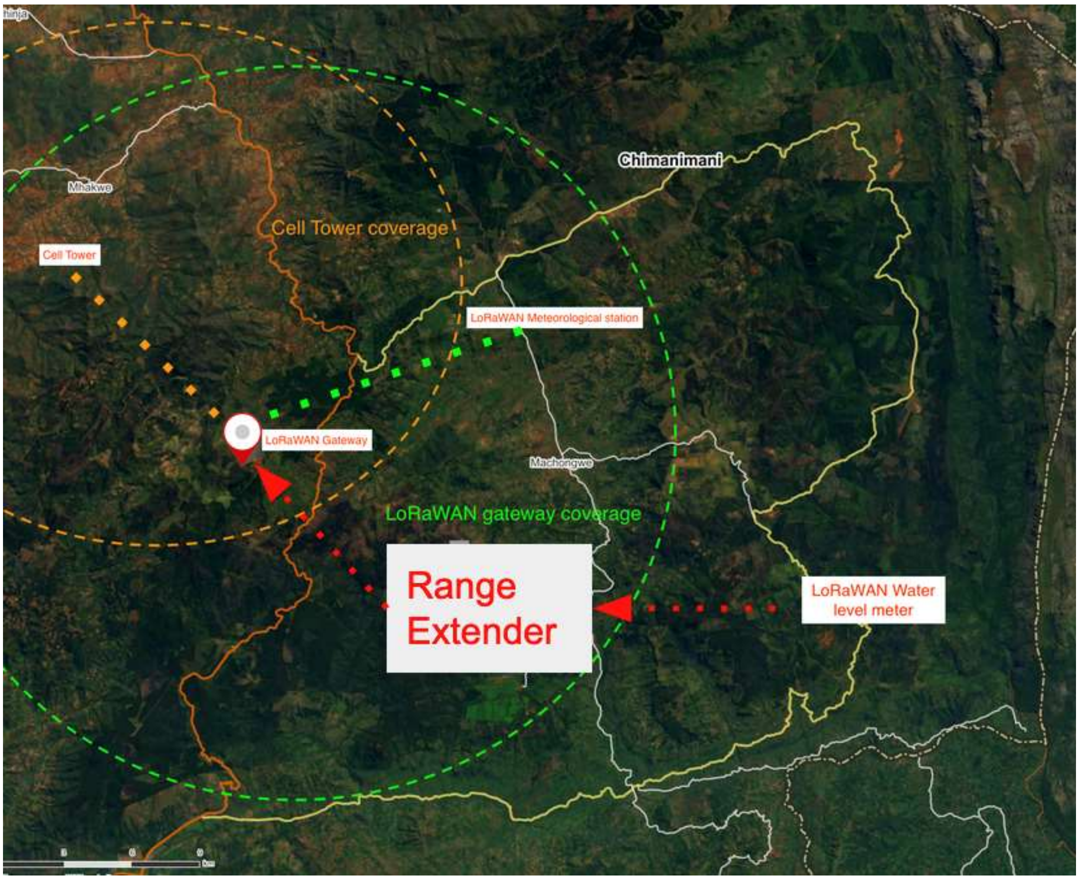

Figure 2. Increasing the coverage of a LoRaWAN gateway by means of a Range Extender, located at the edge of the coverage of the gateway and outside the coverage of the cellular base station

Our LoRaWAN Range Extender operates by receiving packets from one or multiple ENs, dismantling the frame, and assembling a new one transmitted to any existing LoRaWAN gateway as if it were originating from an EN. Consequently, the RE functions as a gateway for any EN, while it behaves like an EN to any gateway. The RE can be set promiscuously, where every received LoRaWAN frame will be retransmitted, or in selective mode, where only end nodes with specific device addresses (those on an allowlist) will be served. The latter option offers benefits such as enhanced security, energy saving, and reduced spectrum usage, a key consideration in ISM bands. This mode can be advantageous in conserving the resources of the RE, particularly power consumption, since, unlike a conventional gateway, the RE often operates on a battery and may not be equipped with a solar panel. Avoiding unnecessary packet transmissions also aid in adhering to duty cycle restrictions by reducing spectrum occupancy.

5.1. Published papers

ICTP and UPV researchers have published two papers on the Range Extender and have submitted a third one:

1. M. Altayeb, M. Zennaro, E. Pietrosemoli and P. Manzoni, "Optimizing the Performance of LoRaWAN Range Extenders in Sparse and Unconventional Contexts," 2023 IEEE Globecom

Workshops (GC Wkshps), Kuala Lumpur, Malaysia, 2023, pp. 714-719, doi: 10.1109/GCWkshps58843.2023.10464980.
2. M. Altayeb, M. Zennaro, E. Pietrosemoli, P. Manzoni and R. Nordin, "A LoRaWAN Uplink Range-Extender (LURE) for Extended and Energy-Efficient Wireless IoT Communications," ICC 2023 - IEEE International Conference on Communications, Rome, Italy, 2023, pp. 6151-6156, doi: 10.1109/ICC45041.2023.10279021.
3. M. Altayeb, M. Zennaro, E. Pietrosemoli, “Optimizing Battery Life for LoRaWAN Range Extenders: Techniques and Strategies”, submitted to ACM Good IT, Bremen (Germany), September 2024

ICTP researchers have also worked on using AI/ML on FPGAs as this architecture offers many advantages compared to traditional IoT devices. Being able to process data on the Edge would alleviate the need for data transmission.

- Romina Molina, Ivan Morales, Maria Liz Crespo, Veronica Gil Costa, Sergio Carrato, Giovanni Ramponi (2024) An end-to-end workflow to efficiently compress and deploy DNN classifiers on SoC/FPGA. IEEE Embedded Systems Letters (Early Access). DOI: 10.1109/LES.2023.3343030
- R. Molina, V. Carrer, M. Ballina, M. Liz Crespo, L. Bollati, D. Sequeiro, S. Marsi, G. Ramponi (2023). ML-based classifier for precision agriculture on embedded systems. In: Berta, R., De Gloria, A. (eds) Applications in Electronics Pervading Industry, Environment and Society. Lecture Notes in Electrical Engineering book series, vol 1036, pp. 117-124, Springer, Cham. https://doi.org/10.1007/978-3-031-30333-3_15

6. AlLoRa

UPV researchers have proposed AlLoRa (Advanced Layer LoRa), a modular, low-power, long-range communication protocol based on LoRa, that allows monitoring of remote natural areas. The protocol's design prioritizes energy efficiency and long-range capabilities to ensure sustainable operation and extensive coverage. Its adaptability to various hardware configurations and support for mesh networking further facilitates the deployment of expansive sensor networks in ecologically sensitive areas.

AlLoRa has been evaluated and tested in an operational oceanographic buoy that has been deployed to address the specific environmental crisis of the Mar Menor lagoon in southeastern Spain. The results reveal that AlLoRa offers good performance regarding transfer time, power consumption, and range. The throughput ranged from around 2 kbps with SF7 to approximately 300 bps with SF11; the power consumption per kilobyte transmitted varied from 395 uWh to 428 uWh, depending on the specific device used. Figure 3 shows a range test in Mar Menor done using a Source Node sending a small message simply containing the Received Signal Strength Indicator (RSSI) of each request received.

The gateway was installed on the roof of the IEO (Spanish Institute of Oceanography, Murcia, Spain) at a height of approximately 25 m. The Source Node was moving in a boat toward the predetermined buoy coordinates. UPV researchers registered the GPS position of the Source Node to confront the received signal strength indication (RSSI) at the Gateway with the distance, reaching a maximum of 11.69 km. The scenario for this experiment is presented in Figure 3.

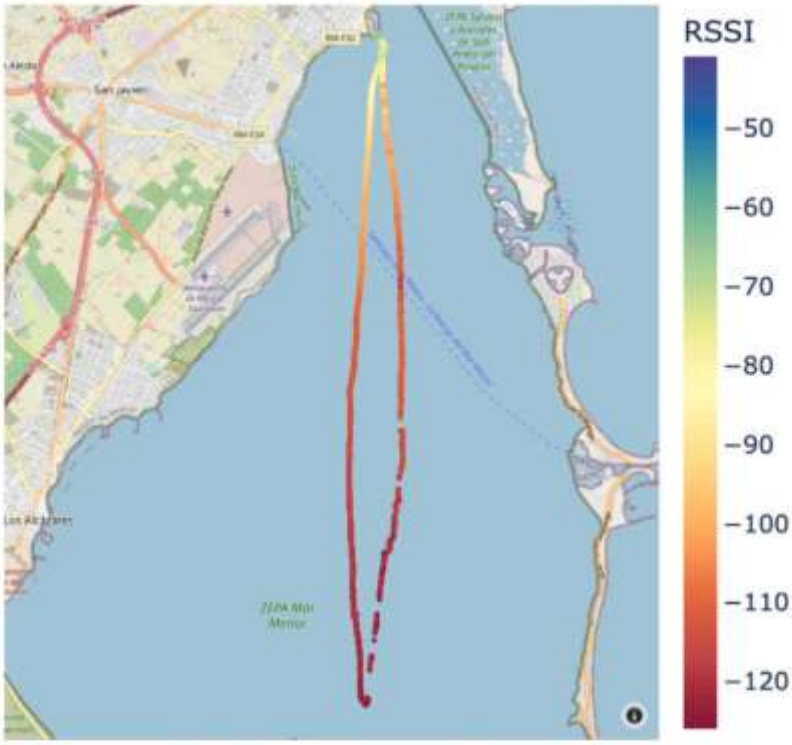

Figure 3. AlLoRa range experiment in Mar Menor lagoon. Gateway location at the top. When the boat containing the source node was close, the received signal was stronger (yellow colour). At the bottom of the figure the signal is weaker (red colour), reaching val

AlLoRa is a half-duplex protocol based on a classical stop-and-wait ARQ scheme, where one or various Source Nodes wait for commands from a Requester/Gateway Node and answer with the requested data. It offers two operation modes, i.e. point-to-point and mesh modes. The latter extends the former by increasing the coverage area using intermediary nodes to forward packets until reaching the destination node. The mesh mode is activated if the Source node does not respond after a certain number of queries specified by the user. AlLoRa was developed using a series of interchangeable modules to simplify its deployment on a wide range of devices, giving access to the content transfer protocol and its combined capabilities. AlLoRa packets transport the content transmitted by the Source Node, which is split into chunks (blocks of bytes) that are sent using the protocol. The AlLoRa Mesh mode tested successfully in the field, maintaining communication between nodes at distances of 20.33 km.

6.1. Published papers

UPV researchers have published two papers on the AlLoRa:

1. Arratia, B., García-Guillamón, P., Calafate, C. T., Cano, J. C., Cecilia, J. M., & Manzoni, P. (2023, January). A modular and mesh-capable LoRa based Content Transfer Protocol for Environmental Sensing. In 2023 IEEE 20th Consumer Communications & Networking Conference (CCNC) (pp. 378-383). IEEE.

2. Arratia, B., Rosas, E., Calafate, C. T., Cano, J. C., Cecilia, J. M., & Manzoni, P. (2024). AlLoRa: Empowering environmental intelligence through an advanced LoRa-based IoT solution. Computer Communications.

6.2. Secondments

ICTP has hosted three network members to work on this research line:

- Vukan NINKOVIC, from University Novi Sad (FTN-UNS), working on coding schemes to optimize data throughput
- Benjamin ARRATIA, from University of Valentia (UPV), working on ML techniques to optimize the AlLoRa communication protocol
- Brena LIMA, from COFAC Cooperativa de Formacao e Animacao Cultural crl (ULHT), working on optimization techniques to optimize data throughput

7. Conclusions

In the first 18 months we have worked on two possible solutions to foster the use of IoT in rural and extreme environments. By developing a Range Extender, we have shown that End Nodes can be placed outside the reach of GSM coverage and applications in remote environments can be developed. With the AlLoRa protocol, we have developed a suitable solution for environmental monitoring that includes mesh capabilities in addition to long distance one-hop links.