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LoRaWAN Range Extension for Environments with High Attenuation

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Abstract: The deployment of widespread LPWAN sensor networks, such as LoRaWAN, in high attenuation environments like forests and mines, faces a significant challenge due to the considerable reduction in communication range. LoRaWAN gateways are typically deployed to expand network coverage. These gateways require internet connectivity, often realized using cellular networks. However, in such deployment areas, cellular coverage may be limited or entirely unavailable. The use of LoRaWAN range extenders to extend coverage is inevitable. However, current LoRaWAN range extenders provide only limited coverage extension as they lack multi-hop support, necessitating the presence of online gateways. In this work, a new approach for LoRaWAN range extenders, named the LoRaWAN GW2ED Range Extender, is presented. Briefly explained, the new solution combines a LoRaWAN gateway, a local middleware, and an LoRaWAN end-device without the need for internet access by the range extender. The new approach is compared to other range extender solutions. The implementation of the concept is illustrated by architecture and sequence diagrams. In field tests within a dense forest, each PoC LoRaWAN GW2ED Range Extender extended the LoRaWAN range by an additional kilometer. This new approach is fully compatible with the LoRaWAN specifications as well as with LoRaWAN Commercial Off-The-Shelf (COTS) end-devices.

1 Introduction

LoRaWAN (Long-Range Wide Area Network) is a well-established LPWAN (Low-Power Wide-Area Network) technology for (I)IoT (Industrial Internet of Things) applications, providing considerable coverage within an unlicensed radio spectrum. However, in areas with high attenuation, the range of LoRaWAN is significantly reduced, as opposed to line-of-sight conditions where distances of over 10 km can be achieved. Environments such as forests, mines, or industrial production halls exemplify scenarios with notable attenuation challenges. For environments with sufficient cellular network coverage, LoRaWAN coverage can be increased by deploying more LoRaWAN gateways with cellular network backend connectivity, i.e., reducing the distances to LoRaWAN sensors. However, there are environments where sufficient cellular network coverage is not given, and the extension of LoRaWAN range is inevitable for the operation of widespread sensor networks, as illustrated in Figure 1.

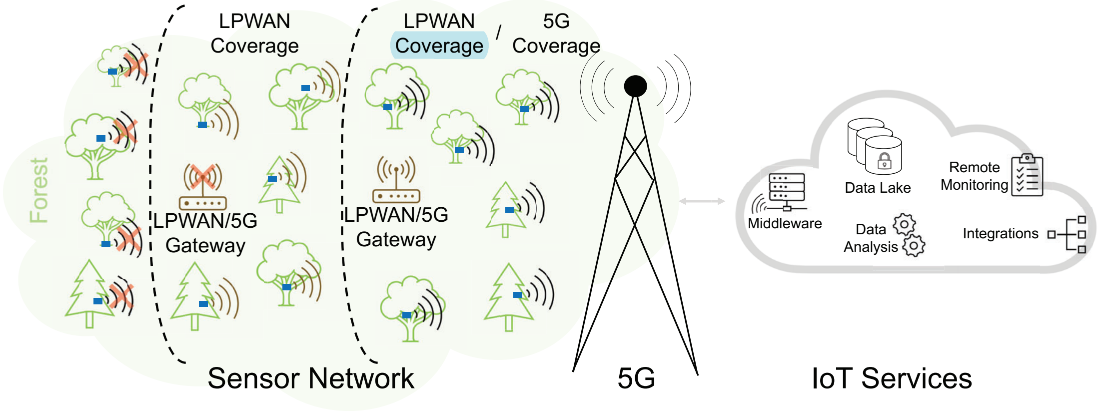

Figure 1: LPWAN forest sensor network for e.g., forest health monitoring challenged by high attenuation and off-cellular-network-coverage.

Within this work, known alternatives for extending the LoRaWAN range are investigated, including LoRaWAN Relays [2] und LoRa Relays [3]. Moreover, a new solution, named LoRaWAN GW2ED (Gateway to End-Device) range extender is presented, which overcomes significant disadvantages of the solutions known so far. Briefly explained, the LoRaWAN GW2ED solution combines a gateway and an end-device, attached back-to-back. This paper provides an exploration of the architecture and mechanisms of the new LoRaWAN GW2ED solution. Mechanisms implementing a LoRaWAN GW2ED solution, such as sensor data relaying, downlink message forwarding, and remote management functionalities, are illustrated in comprehensive diagrams. Additionally, the new solution is compared to alternative range extender solutions. The paper also presents the evaluation results obtained from a PoC (Proof-of-Concept) implementation of a LoRaWAN GW2ED Range Extender. An important aspect of this work is, that the new solution is compatible with existing COTS (Commercial Off-The-Shelf) LoRaWAN end-devices.

This work is structured as follows: Section 2 addresses challenges associated with operating sensor networks in high-attenuation environments and discusses solutions for extending the LoRaWAN range, including an overview of related work. Next, in Section 3, the new solution for extending the LoRaWAN range, called LoRaWAN GW2ED, is introduced, along with architecture and sequence diagrams. The implementation of a LoRaWAN GW2ED range extender is presented in Section 4. Section 5 focuses on the evaluation of the PoC implementation, which was tested within a forest environment. This evaluation includes a comparison of the new solution with alternative range extenders. Finally, Section 6 concludes this paper and presents future work.

2 LoraWAN Range Extender Concepts

Problem Statement

The deployment of sensor networks in environments with high attenuation, such as forests, mines, and industrial production halls, faces a critical challenge due to the significantly reduction in communication range. For instance, in a study conducted by Villarim et al. [VL19], the communication range of LoRa technology was evaluated in both urban and forest settings. In urban environments, they achieved a maximum range of 2.1 km, while in forest areas, the range dramatically decreased to 800 m and 232 m. Expanding LoRaWAN coverage typically involves the deployment of additional LoRaWAN gateways, which rely on active internet connectivity. However, in high attenuation environments, sufficient cellular coverage may not be given. This underscores the necessity for a solution that operates independently of cellular internet connectivity. Therefore, this paper explores solutions for extending LoRaWAN coverage through the use of range extenders.

LoRaWAN Basics

Further, relevant information about LoRaWAN important for paper is given. LoRaWAN is a well-established LPWAN technology that operates within an unlicensed radio spectrum, such as the 868Mhz band in the EU. LoRaWAN's coverage can be extended by deploying additional LoRaWAN gateways, making it particularly advantageous for environments with high attenuation, where the signal strength is reduced. In contrast, NB-IoT, another LPWAN technology, relies on cellular licensed communications bands, and its coverage extension is dependent on the services provided by mobile network operators. LoRaWAN benefits from a robust market, offering a diverse range of COTS smart sensors, which are sensor device equipped with built-in LPWAN functionality, as well as a wide range of COTS LoRaWAN gateways.

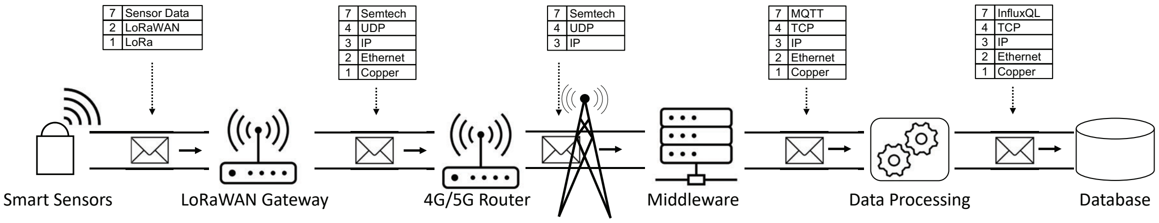

Figure 2: Data flow from smart sensor to a database exemplified with LoRaWAN, the Semtech UDP Packet Forwarder, MQTT and InfluxDB.

Furthermore, some key technical aspects of LoRaWAN are described. Figure 2 shows the data flow from a smart sensor to a database, including each entity involved in the process as well as network protocols utilized in the process. Smart sensors utilize the LoRa communication protocol to transmit their data. LoRaWAN gateways receive these LoRa messages and typically relay them over the internet to a middleware, using protocols like the Semtech UDP Packet Forwarder (P.F.). The middleware, often hosted within a cloud-based environment, comprises multiple software modules. The LoRaWAN network server manages the LoRaWAN layer for end-devices, performing functions such as deduplication handling of uplink message (detect when multiple gateways forward the same uplink message), downlink queueing, interaction with the application server, and join server. The application server handles the payload of the end-device, including payload decryption. The decrypted payload is then made accessible for further processing, often by publishing it on an MQTT broker. The join server manages the OTAA (Over-The-Air Activation) process for end-devices, including the exchange of session keys. Widely used middleware solutions include The Things Stack and the open-source Chirpstack [CS23]. Subsequently, from the MQTT broker, a service can store the sensor data within a database, such as the time-series database InfluxDB, for further utilization. Figure 3 provides an uplink message from an end-device, such as a sensor's temperature value, in the LoRaWAN architecture. Within the radio range of ED$_1$, two LoRaWAN gateways are present, forwarding the message over the internet to the middleware, where the deduplicated message is processed. In LoRaWAN, all devices belong to the same middleware.

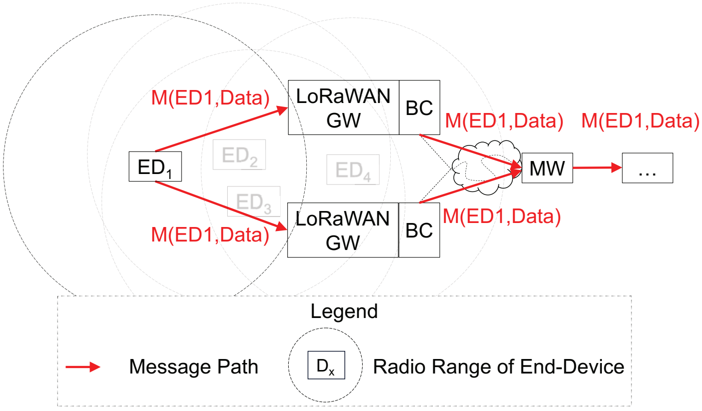

Figure 3: Uplink consideration for the LoRaWAN architecture (GW = gateway; MW = middleware such as Chirpstack or The Things Network; ED = end-device; BC = backend connectivity; M(x,y) = message with sender device ID x and payload y).

The LoRaWAN specification describes three distinct classes of devices. In Class A, end-devices transmit data by sending uplink messages at any time. Following the uplink transmission, there are two short downlink windows available for receiving data. Class A end-devices are commonly used for environmental monitoring and are typically configured to transmit their measured data at predefined intervals or in response to alarm triggers, such as reaching a sensor threshold. These end-devices are often powered by batteries with lifespans up to 10 years. Class B involves gateways transmitting time-synchronization beacons to schedule downlink messages to end-devices. This class introduces a structured downlink communication schedule for devices. Class C devices are typically mains-powered and maintain a continuous receive windows, allowing them to be in a constant listening mode for incoming data.

As previously mentioned, extending the coverage of LoRaWAN is typically accomplished by deploying additional gateways. However, in regions characterized by limited internet accessibility, such as areas with inadequate cellular network coverage, the expansion of the LoRaWAN range becomes essential for the successful operation of an extensive sensor network. Further, two existing solutions for range extenders are presented.

LoRaWAN Relays

In September 2022, the LoRa Alliance introduced a LoRaWAN Relay specification [TS22]. This specification describes the deployment of relay devices positioned between LoRaWAN end-devices and a LoRaWAN gateway, as illustrated in Figure 4.

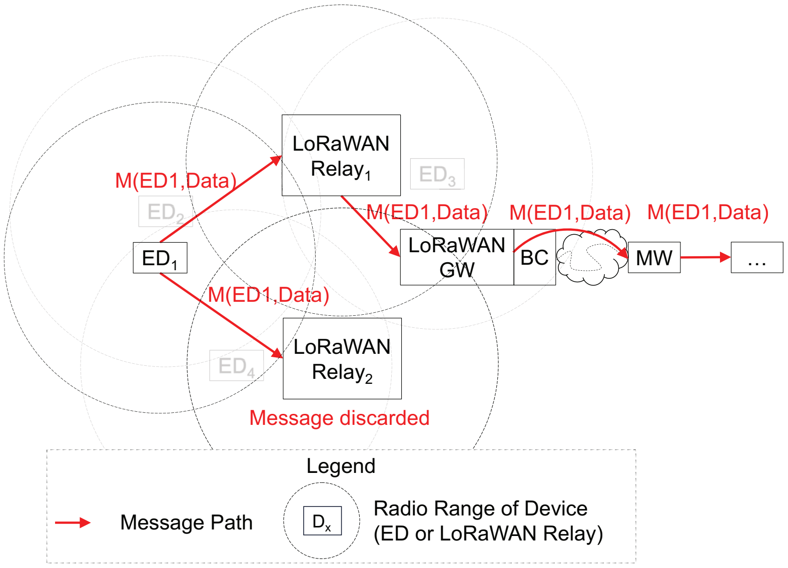

Figure 4: Uplink consideration for LoRaWAN Relay scenario (GW = gateway; MW = middleware; ED = end-device; BC = backend connectivity, M(x,y) = message with sender device ID x and payload y).

The LoRaWAN relay specification employs Wake On Radio (WOR) technology. When an end-station initiates an uplink message, a WOR frame is transmitted, activating the relaying station to await the impending uplink transmission. Afterwards, the received uplink data from the end-station is forwarded to the gateway. As both end-stations and relay devices typically operate in sleep mode, waking up only for data transfer, relay devices can also be powered by batteries. Additionally, to accommodate the increased delay introduced by the relaying mechanism, a third receive window for end-stations has been introduced. The visualization of this relaying mechanism is depicted in Figure 5.

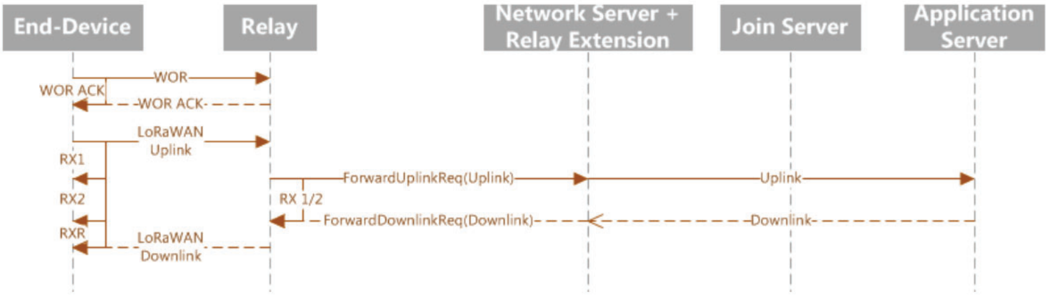

Figure 5: Sequence diagram of a LoRaWAN end-device join request using a LoRaWAN relay [TS22].

Currently, LoRaWAN relays have been designed to support a maximum of 16 different end-devices [SE23]. An end-device must be registered at a LoRaWAN relay while also remaining registered at the same middleware. Messages received at a relay from an end-device that does not belong to that LoRaWAN relay are discarded, as visualized in Figure 4. However, uplink message can only received when a relay is ready (awake) for data reception. It's important to note that relays cannot be cascaded, meaning that the relay devices cannot be daisy-chained. End-devices must implement the necessary functionality, implying that existing devices from manufacturers require firmware updates to enable this functionality. Additionally, commercially available LoRaWAN relays are not yet accessible in the market.

LoRa Relays

On the other hand, LoRa Relays offer the capability to relay LoRa frames, as illustrated in Figure 6. Mamour et al. proposed a LoRa relay that can be integrated into an existing LoRa network [MC19]. Their approach involved storing downlink messages at the relay and forwarding them after the next uplink transmission, thus enabling downlink functionality. Typically, a relay requires some form of configuration to determine which devices' data it should relay, as indiscriminate relaying of all received LoRa data could potentially violate duty cycle regulations. Their solution sidesteps the need for a management protocol by introducing an observation phase, eliminating the necessity for control messages between end-devices, gateways, and relay devices. During this phase, triggered by a device restart, the system logs all devices that transmit within a specific timeframe. Only messages from the learned devices are subsequently relayed. Furthermore, during this phase, transmission intervals of the smart sensors are observed to put the range extender to sleep to lower its power consumption when no messages are expected to be received. However, this mechanism limits the operation of the range extender to interval-based transmissions, making it unsuitable for applications like fire detection that require alarm-based operation. Changing the transmission interval of a smart sensor also necessitates a new observation phase. For a large-scale deployment, a management protocol is essential; otherwise, all relay stations would need to be manually restarted for the observation phase.

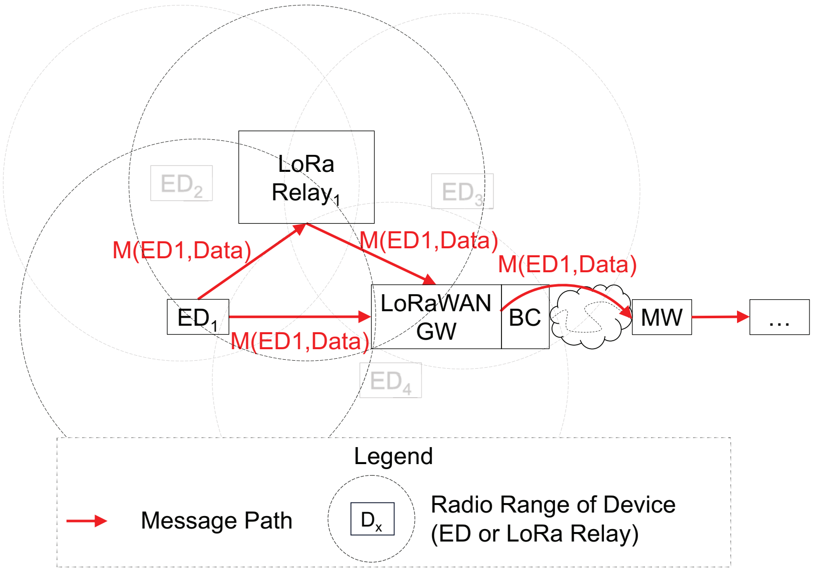

Figure 6: Uplink consideration for LoRa Relay scenario (GW = gateway; MW = middleware; ED = end-device; BC = backend connectivity; M(x,y) = message with sender device ID x and payload y).

An end-device’s message can be received by both a LoRaWAN gateway and a LoRa relay simultaneously, with the relay forwarding the same message to the same LoRaWAN gateway, as illustrated in Figure 6. End-devices remain registered with the middleware. Unlike end-device, LoRa relays are not registered with a middleware. Additionally, LoRa relays cannot be cascaded, which imposes limitations on their operational range.

Satellite-based internet access, as exemplified with Starlink, offers the potential for deploying sensor networks independent of cellular coverage. Depending on the use case, the utilization of satellite-based internet can be advantageous. However, for environments like mines, such a system does not work. In forestry applications, the use of such technology is feasible, but several considerations must be taken into account. Firstly, the power consumption of such a system is significantly higher compared to a mobile network router, particularly complicating autonomous operation using e.g., a photovoltaics system. Secondly, a predominantly unobstructed view of the sky is required, which is hindered, in particular, by forest canopy. In environments where conventional mobile network coverage is absent for extended distances, this solution can be employed for the gateway with internet connectivity, thereby increasing LPWAN coverage through the use of range extenders.

The previously introduced range extenders are primarily engineered for low-power operation, limiting their capacity to support only a small number of smart sensors per extender. These solutions are not well-suited for network scenarios involving a higher number of end-devices. Additionally, these extender solutions lack the capability to be cascaded, necessitating the deployment of additional LoRaWAN gateways with internet access. Nevertheless, it's worth noting that cellular coverage is frequently unavailable in high attenuation environments. Consequently, there is a need for a range extender solution that can address these limitations.

In the upcoming section, a novel approach called LoRaWAN GW2ED range extender is introduced. The range extender solutions presented in this section will later be compared to this innovative approach.

3 LoRaWAN GW2ED Range Extender Solution

This section presents a novel approach for extending LoRaWAN coverage, called LoRaWAN GW2ED Range Extender. Compared to known range extenders so far, this solution is capable of operating in network scenarios with a higher number of end-devices. It is fully compatible with all existing LoRaWAN COTS smart sensors. In contrast to LoRaWAN relays, which require a firmware update that may not be offered from vendors, the new range extender solution offers seamless compatibility. Furthermore, these range extenders can be cascaded, resulting in extensive coverage, which can be achieved with just one LoRaWAN gateway with internet access.

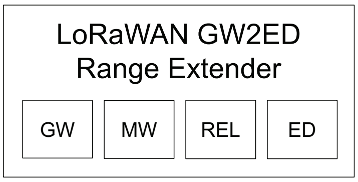

Figure 7: Internal architecture of a LoRaWAN GW2ED Range Extender (GW = gateway; MW = middleware such as Chirpstack; REL = range extender logic; ED = end-device).

The new approach, LoRaWAN GW2ED, consists of four primary components, as depicted in Figure 7. The first component is a LoRaWAN gateway, providing both uplink and downlink capabilities for connected devices. The second component is an offline middleware connected to the gateway. The third component is the range extender (RE) logic, and the last component is a LoRaWAN end-device responsible for relaying data received from the RE logic to the next LoRaWAN GW2ED range extender or LoRaWAN gateway with backend connectivity. Additionally, the end-device can also receive downlink messages, which are then forwarded to the RE logic. The RE logic acts as an intermediary between the middleware and the range extender's end-devices, managing uplink and downlink messages from end-devices and handling remote management tasks, including device registration and error message forwarding. It encapsulates other end-devices' message payloads and device information for later mapping of payload data to the respective end-device.

Device Registration and Encrypted Communication

In this solution, end-devices are registered within the middleware of the nearby range extender. This registration can be performed remotely with the help of a management protocol. The remote registration process includes the exchange of a device-specific Application Keys, which are necessary for OTAA. As a result, communication between end-devices and the middleware is encrypted. The device registration process, including the encrypted segments, is illustrated in Figure 8.

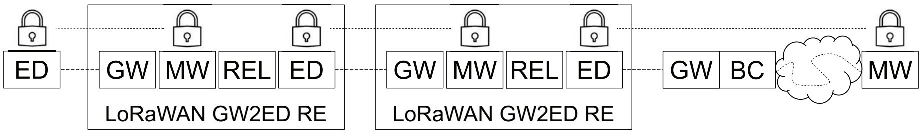

Figure 8: Device registrations within LoRaWAN GW2ED Range Extender scenario (GW = gateway; MW = middleware; REL = range extender logic; ED = end-device; BC = backend connectivity).

In LoRaWAN, each end-device can only be registered with one middleware. Messages originating from end-devices, which might be received by multiple range extenders, are exclusively processed by the specific range extender where the end-device is registered. An uplink message scenario is visualized in Figure 9. In this scenario, the end-device ED_1 sends an uplink message, like a temperature reading. Both GW2ED range extenders, RE_2 and RE_3, receive the message as they are within the radio range of ED_1. However, ED_1 is registered in the middleware of RE_3. Therefore, RE_2 discards the message, and the message is encapsulated in RE3 before being relayed further. In this case, the message is received by RE_1 and RE_2. Once again, RE_2 discards the message, as the end-device registered in RE_3 is unknown to RE_2. RE_1 then forwards the same encapsulated message to the LoRaWAN gateway. After reaching the (cloud-based) middleware, a decapsulation entity extracts the message to retrieve the source end-device information and the payload of ED_1.

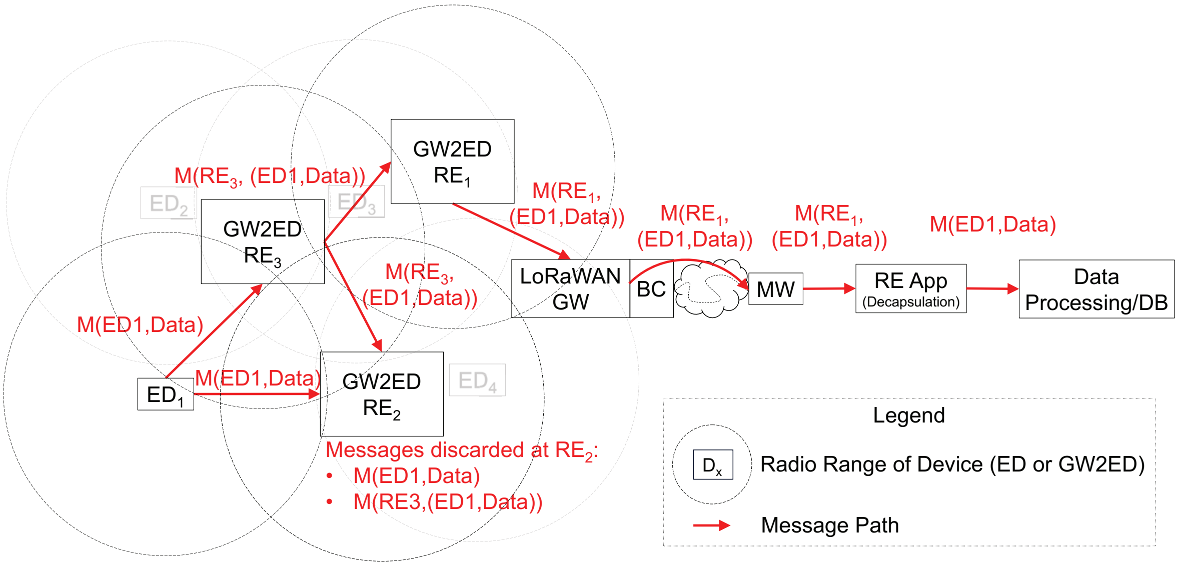

Figure 9: Uplink consideration for LoRaWAN GW2ED Range Extender scenario. (GW = gateway; MW = middleware; ED = end-device; RE = range extender; BC = backend connectivity; M(x,y) = message with sender device ID x and payload y; M(x,(y_1,y_2)) = message with sender device ID x, source device id y_1 and payload y_2).

Uplink Messages

Next, consider the example sequence diagram, which elucidates the sequence of events for an uplink message from a LoRaWAN end-device, as depicted in Figure 10. In this scenario, an end-device is already registered with the middleware of the adjacent LoRaWAN GW2ED range extender. It is assumed that a successful Join procedure, encompassing key exchange, has been previously completed.

1. The end-device transmits its uplink data using LoRa.
2. The LoRaWAN gateway of the range extender receives the message and forwards it to the middleware, possibly employing the Semtech UDP Packet Forwarder.
3. The middleware receives the message and passes it to a data integration service, which may publish the message on an MQTT broker.
4. The range extender logic component receives the message, encapsulates it by adding information related to the original end-device to the original payload, and forwards the message to the range extender's end-device. The end-device sends the encapsulated message using LoRa.
5. If there are additional range extenders, it's recognized that the message has already been relayed. Therefore, no further information regarding the uplink message is added.
6. Through the last gateway in the series, which likely has internet connectivity, the received data is sent to the cloud-based middleware.
7. The message is decapsulated to extract the source end-device information and the payload of ED_1.

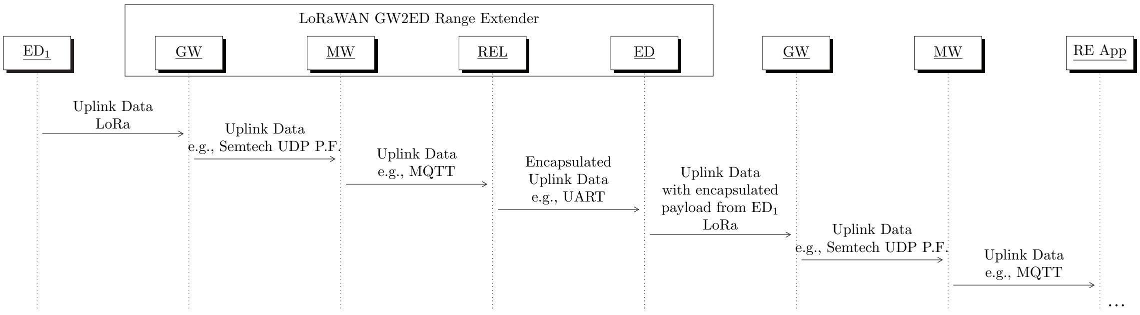

Figure 10: Sequence diagram of an end-device's uplink message when utilizing a LoRaWAN GW2ED Range Extender. (GW = gateway; MW = middleware; ED = end-device; RE = range extender; REL = range extender logic).

Downlink Messages

Downlink messages are also supported by the LoRaWAN GW2ED Range Extender. In this process, downlink messages from the cloud-based middleware for a specific end-device are relayed to the end-device through one or more range extenders. The sequence diagram in Figure 11 illustrates the flow of a downlink message. In this example, the end-device of the range extender is a LoRaWAN Class C device, ensuring constant accessibility.

1. A range extender application creates a downlink for the end-device of the range extender with an encapsulated downlink payload for ED_1 and passes it to the middleware.
2. The cloud-based middleware (on the right) forwards the downlink message to the gateway, which then relays the message to the end-device of the range extender via LoRa.
3. The range extender logic component decapsulates the payload and queues a new downlink message for ED_1 at the range extender's middleware.
4. In this example, the target end-device is a LoRaWAN Class A device, which means it must wait for an uplink message to open a downlink window. Once this occurs, the middleware of the range extender forwards the downlink message through the gateway to the target end-device.

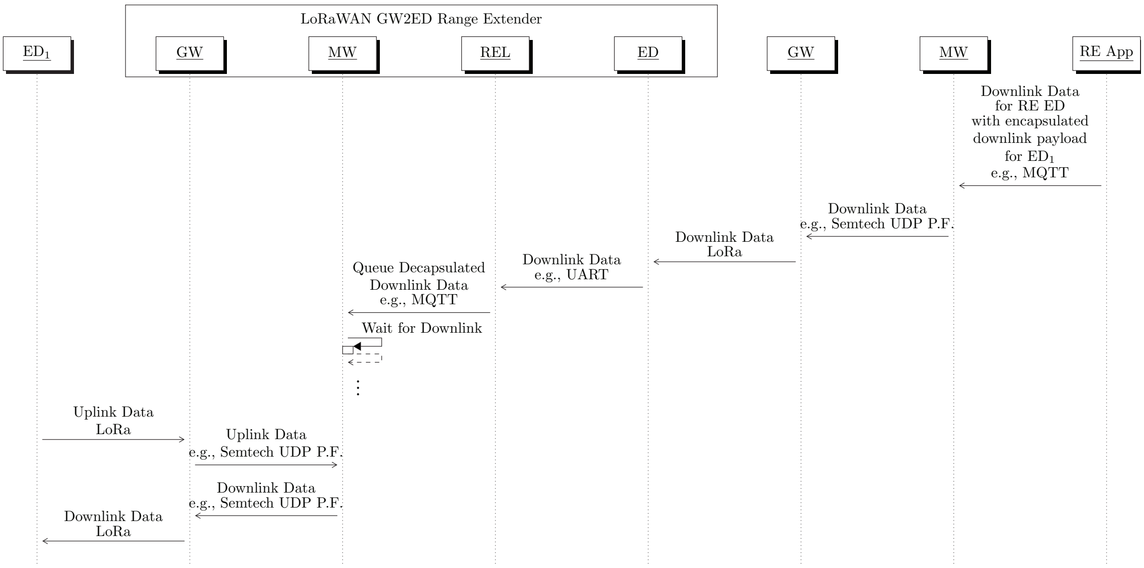

Figure 11: Sequence diagram of a downlink message to an end-device in a LoRaWAN GW2ED Range Extender scenario. (GW = gateway; MW = middleware; ED = end-device; RE = range extender; REL = range extender logic).

Remote Management

The range extender can only be accessed remotely through LoRa messages, requiring a remote management protocol for configuration changes. This protocol encompasses tasks like adding new end-devices to a range extender and modifying the network's topology, which determines the connections between different range extenders. To establish these connections, the end-device of one range extender must be registered with the middleware of the next range extender, as previously illustrated in Figure 8.

The process of adding a new end-device to a range extender is visualized in the sequence diagram in Figure 12. Here, the range extender application generates a downlink message to initiate the addition of a new device. This message includes information specifying the target range extender, as well as details about the new end-device, including the DevEUI (64-bit) and the AppKey (128-bit).

1. The range extender application generates the downlink message, which is then sent through the middleware via the gateway to the end-device of the range extender. If the message is intended for another range extender, it is relayed through a series of downlink messages until it reaches the relevant range extender.
2. Within the range extender, the range extender logic component registers the new device using the middleware's API.
3. At a later point in time, the target end-device can initiate an OTAA Join procedure at the middleware of the respective range extender.

4. Upon the successful completion of the standardized Join Accept response, the end-device becomes operational and ready to communicate.

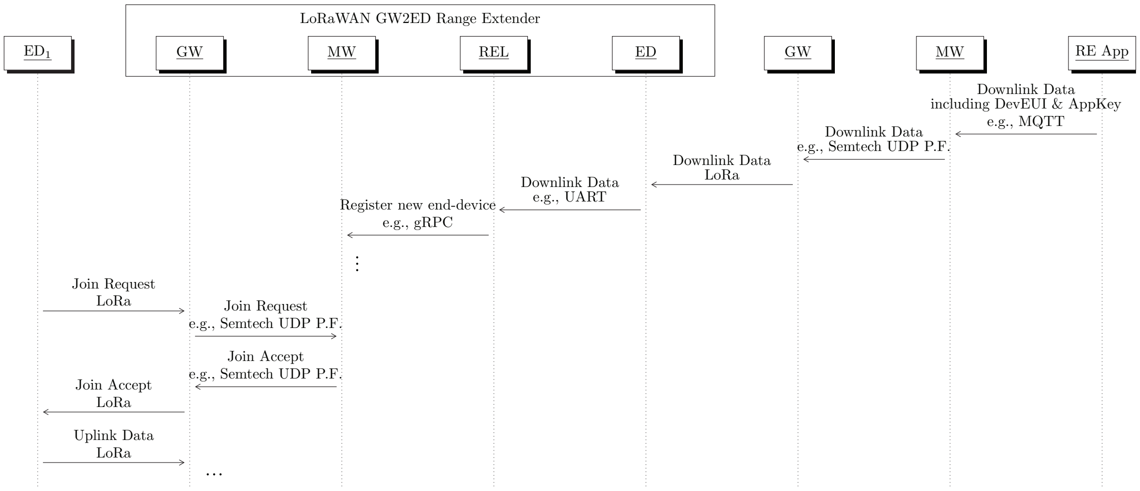

Figure 12: Sequence diagram of the end-device registration process for a LoRaWAN GW2ED Range Extender scenario as part of the remote management procedure. (GW = gateway; MW = middleware; ED = end-device; RE = range extender; REL = range extender logic).

4 Implementation of LoRaWAN GW2ED Range Extender

This section describes the PoC implementation of the LoRaWAN GW2ED Range Extender with the following components and configurations:

- **Gateway:** The Dragino DLOS8N served as the gateway in this implementation. It utilized the Semtech UDP Packet Forwarder for data forwarding, directing data to the local middleware.
- **Middleware**: Chirpstack, an open-source middleware, was chosen for this setup. It was run in Docker containers on a Raspberry PI 3B operating Raspberry PI OS. Additionally, an MQTT Broker, specifically Mosquitto, was deployed as a Docker container.
- **End-Device:** The LoRaWAN USB Adapter LA66 by Dragino was employed as the end-device in this implementation. It was connected to the Raspberry PI and configured as part of the LoRaWAN network. This end-device was registered with the cloud-based middleware, which was also Chirpstack. A second end-device from a second range extender with an identical setup was registered with the middleware of the first range extender.
- **Range Extender Logic:** The range extender logic, responsible for managing communication and data relay, was developed using the Python programming language. This Python application included an MQTT subscription to receive data from the middleware. The received data was then forwarded to the LoRaWAN USB Adapter end-device using a serial connection. This allowed the end-device to send uplink messages to the next LoRaWAN gateway or range extender. Furthermore, the range extender logic processed downlink data received at the range extender's end-device. It analyzed the payload to determine the target of the message. The downlink message could be intended for the same range extender, another range extender, an end-device registered with the local middleware, or an end-device registered with another range extender. For tasks such as new device registration, the script utilized a gRPC API interface to register the device with its local middleware. To transmit downlink messages to another range extender, the range extender logic scheduled the downlink message by publishing it at the MQTT Broker, addressing the end-device of the next range extender.

Regrettably, it was found that the LoRaWAN USB Adapter could operate solely as a LoRaWAN Class A device. As a result, downlink messages were only accessible to the range extender when a downlink window was activated following an uplink message. An adapted sequence diagram for this situation is depicted in Figure 13.

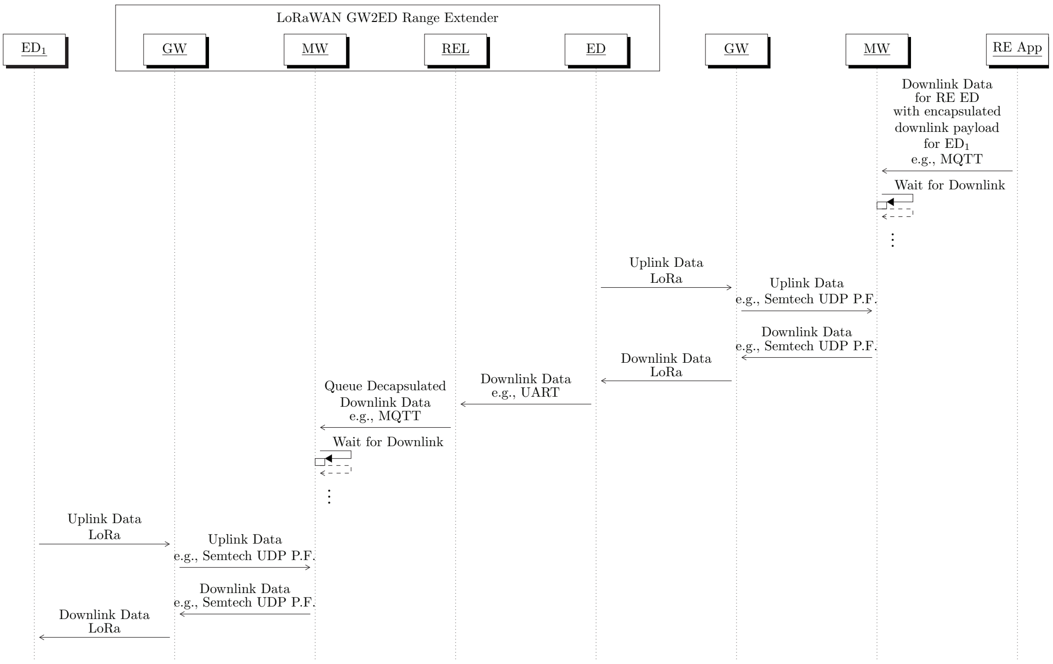

Figure 13: Sequence diagram of a downlink message in the PoC implementation of the LoRaWAN GW2ED Range Extender scenario (GW = gateway; MW = middleware; ED = end-device; RE = range extender; REL = range extender logic).

5 Evaluation

This section evaluates the approach of the LoRaWAN GW2ED range extender. The PoC implementation is tested for functionality and range in a high attenuation environment. Following this, the new solution is compared with other range extender solutions.

Evaluation of PoC Implementation

Two PoC range extenders were tested within a forested area, which represents a high attenuation environment. Figure 14 shows an outdoor, solar-powered LoRaWAN gateway with internet access, while the other images portray the range extender enclosed in a case and affixed to a tree. All antennas and gateways were positioned at approximately 4 meters in height. The LoRaWAN field tester from Adeunis has been used as an end-device, which was registered with the second range extender's middleware. To access the performance, debugging messages transmitted from the range extender to the cloud-based middleware were used to determine the RSSI and spreading factor of each range extender.

Without the range extender, the field tester, registered at the cloud-based middleware, achieved a range of approximately 700 meters using Spreading Factor 7 and around 1000 meters when using Spreading Factor 12. Remarkably, similar results were obtained with the range extender, signifying that each range extender effectively extended the range by approximately 1 kilometer.

Figure 14: Solar-powered LoRaWAN gateway with internet access and the LoRaWAN GW2ED Range Extender located in a forest in Wolfenbüttel, Germany.

Comparison of the LoRaWAN GW2ED Range Extender with other LoRaWAN range extender solutions

Table 1 offers a comprehensive comparison between the developed solution presented in this work and other range extender solutions introduced in Section 2. The comparison covers various aspects, each of which will further be elaborated while discussing several of these aspects.

	LoRaWAN Relays	**LoRa Relays**	**LoRaWAN GW2ED**
Extendibility by multi-hop	No	No	Yes
Commercial availability	No	No	No
Remote management	Yes	No	Yes
Maximum number of supported end-devices	16	Low	High
Downlink capabilities	Yes	Yes	Yes
Power consumption	Low	Low	Higher
Support of COTS end-devices	(Yes)	Yes	Yes

Table 1: Comparison of LoRaWAN GW2ED Range Extender solution with other range extender solutions.

Following the discussion of the aspects of the comparison:

Extendibility by multi-hop: This aspect is about the support for cascading multiple range extenders. Only the new solution (LoRaWAN GW2ED Range Extender) provides this feature. Cascading range extenders is inevitable for operating sensor networks in high attenuation environments with inadequate cellular network coverage.

Commercial availability: Currently, none of the presented range extender concepts are currently commercially available, even though LoRaWAN Relays are already standardized in Version 1.0.

Remote management: Remote management includes features like remote device registrations or modifying the range extender topology. It is supported by both LoRaWAN Relays and LoRaWAN GW2ED Range Extender. However, LoRa Relays, as presented, do not currently support remote management, which limits their suitability for larger deployments.

Maximum number of supported end-devices: The LoRaWAN Relays specification limits the number of end-devices per relay to 16. The number of supported end-devices for the LoRa Relay is not explicitly defined, but it's estimated to be low due to the relay having to wake up for each uplink message. In contrast, the LoRaWAN GW2ED solution supports scenarios with a higher number of end-devices, limited only by the compliance to the duty cycle regulations.

Downlink capabilities: All solutions support the use of downlink mechanisms.

Power consumption: LoRaWAN Relays and LoRa Relays are designed for a battery-powered operation and have low power consumption. The current LoRaWAN GW2ED concept is not optimized for low power consumption, resulting in a higher power consumption compared to the other range extender solutions. Additionally, the PoC implementation of the LoRaWAN GW2ED solution is also not optimized for low power consumption. To reduce energy consumption of the LoRaWAN GW2ED solution, an interval-based operation is possible, as described in Reference [BW23]. In this approach, the sending interval of end-devices is synchronized with the on-time of gateways using downlink messages, allowing gateways (or in this case, the range extender) to be turned off during off-time intervals, significantly reducing power consumption. It is important to note that all range extender solution are currently available as PoC implementations, making it challenging to compare their power consumption accurately.

Support for Commercial Off-The-Shelf (COTS) end-devices: Support of COTS end-devices is available for all solutions. However, COTS end-devices using LoRaWAN Relays require firmware updates in order to support the new relaying specification.

6 Conclusion & Future Work

The deployment of LoRaWAN in high attenuation environments presents significant challenges for establishing efficient sensor networks due to the considerable reduction in the LoRaWAN range. Recognizing this need for LoRaWAN range extension, as evidenced by the recent LoRaWAN relay specification, this work has proposed a new approach for a LoRaWAN range extender, the LoRaWAN GW2ED Range Extender, which operates independently of internet connectivity. Existing specified range extender solutions have limitations, such as the absence of cascading mechanisms. The LoRaWAN GW2ED Range Extender is unique in providng extendibility through multi-hop capability.

The results demonstrate that each range extender effectively extends the LoRaWAN range by a distance comparable to that of a standard LoRaWAN gateway. In the tested scenario within a forest environment, an initial LoRaWAN range of approximately 1 km was extended by an additional 1 km for each added range extender. Importantly, this solution is fully compatible with existing LoRaWAN COTS end-devices and does not require any firmware modifications on these devices. Furthermore, the solution supports both uplink and downlink capabilities and can be used in network scenarios with a higher number of end-devices. It adheres to existing LoRaWAN procedures and protocols without any alterations.

In the future, the integration of all components into a single device to reduce power consumption will be considered. Further refinement of the management protocol is essential to support additional features, such as error message handling within range extenders, including frame counter violations of end-devices. Features like multi-path routing are feasible but require changes to existing mechanisms as presented in this work. In multi-path routing scenarios, ensuring that downlink messages are not sent redundantly to end-devices is crucial.

Additionally, for areas lacking internet connectivity and aiming to extend LoRaWAN coverage, exploring a LoRaWAN gateway that utilizes satellite-based LoRa for uplink communication could be considered as an alternative approach [AB22].

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