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# A Green and Energy-Efficient LoRaWAN Communication Framework for Advanced Metering Infrastructure*

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## Abstract

This article presents a comprehensive approach to designing and implementing an energy-efficient Advanced Metering Infrastructure (AMI) system based on LoRaWAN technology. The project focuses on optimizing energy consumption, minimizing network congestion, and enhancing sustainability through green communication mechanisms. A dedicated LoRaWAN network simulator and prototype deployment were used to evaluate transmission parameters, gateway placement, and adaptive data rate strategies. Results demonstrate that LoRaWAN can provide reliable and low-power communication for smart metering applications, with minimal infrastructure costs and measurable energy efficiency gains. The presented research combines simulation-based modeling with real-world validation, bridging the gap between theoretical optimization and practical deployment in urban AMI environments.

**Keywords:** LoRaWAN, Smart Metering, Energy Management, Green Communication, AMI, IoT, LPWAN.

## Introduction

In recent years, smart cities and intelligent infrastructures have become the focus of governments and industries seeking to enhance energy efficiency, environmental sustainability, and citizens' quality of life according to Dell'Isola et al. (2019). As part of this transformation, Internet of Things (IoT) technologies play a central role by connecting devices, sensors, and systems into large-scale, data-driven environments. Global energy transition and the growing emphasis on sustainability have encouraged the development of green communication infrastructures for smart cities and intelligent grids. According to Silva et al. (2018), cities are embedding smart sensors, communication modules, and analytics into their infrastructures to automate management processes and optimize resource use. The overarching goal is to enable urban operations with minimal human intervention, where information is continuously collected, analyzed, and acted upon to improve services and sustainability, as presented by Abbas et al. (2020).

The rise of the IoT ecosystem, supported by the rapid development of artificial intelligence (AI), is often described as the next major technological revolution. Together, these domains are reshaping how data are exchanged, how protocols are designed, and how network services are delivered. With billions of devices expected to operate simultaneously, designers of IoT systems must carefully evaluate the scalability, resilience, and interoperability of available communication technologies. This challenge is particularly significant for networks functioning in unlicensed ISM (*Industrial, Scientific and Medical*) frequency bands, where coexistence, congestion, and regulatory limits must be accounted for.

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Among the most dynamic areas of IoT development is the energy sector, where operators and service providers increasingly rely on remote measurement and automation. The decarbonization of power systems amplifies the role of telemetry for grid observability, demand management and customer engagement. Electricity utilities are actively deploying systems capable of remote data acquisition, monitoring, and analysis of energy consumption. Modern smart meters measure and record parameters such as voltage, current, and power factor, transmitting them at regular intervals for both operational and billing purposes. These data streams are vital not only for utilities, enabling system monitoring, grid balancing, and fault detection, but also for consumers, who can track their energy use in near real time to make informed decisions and manage costs.

This evolution has led to the emergence of *Advanced Metering Infrastructure* (AMI) – an integrated ecosystem of smart meters, communication networks and data management platforms. AMI enables two-way data exchange between energy suppliers and consumers, unlocking capabilities that traditional *Automatic Meter Reading* (AMR) systems could not provide. Through AMI, utilities can remotely connect or disconnect services, detect tampering or outages, and monitor voltage quality without on-site visits. When combined with consumer-facing technologies, such as in-home displays or programmable communication thermostats, AMI also serves as a behavioral feedback mechanism, encouraging peak demand reduction and energy conservation. It enables periodic readings, event alarms, and control signals, forming the nervous system of modern utilities.

Communication between metering devices and the network can be carried out using a variety of wired and wireless technologies. The native wired communication method offered by most suppliers is, undoubtedly, *Power Line Communication* (PLC). In contrast, common wireless communication solutions encompass a broader range of options, including cellular mobile networks, Wi-Fi, ZigBee, Wi-SUN (*Smart Utility Networks*), wireless ad-hoc networks over Wi-Fi, wireless mesh networks, and finally, *Low-Power Wide Area Networks* (LPWANs) – Peruzzi et al. (2022), Leonardi et al. (2023), Noreen et al. (2017).

This article generally concerns the development of prototype of an advanced metering system (AMI) for electricity measurement, utilizing low-emission radio transmission based on LoRaWAN technology. This study discusses a project that was carried out for one of the leading providers of technological solutions for the largest Polish energy companies in the field of software development related to electricity distribution. The research introduces several innovative areas of investigation that have not been previously explored in this context.

The first area focuses on assessing the feasibility of using LoRaWAN technology for two-way communication with electricity meters within an AMI-class system – a solution that has not been implemented for this purpose before. The second research objective involves examining the adaptability of LoRaWAN to meet the specific technical and operational requirements imposed by AMI systems.

Another key contribution of the article is the development of a set of best practices and operational mechanisms that can be applied in the construction of data acquisition systems based on LoRaWAN networks. Their implementation will ensure optimal utilization of available bandwidth, minimize the risk of data loss, and optimize retransmission processes to enhance communication reliability.

Finally, it encompasses the design and implementation of prototype LoRaWAN interfaces for integration with existing electricity meters, enabling their seamless incorporation into AMI-class systems and thus supporting the transition toward modern, energy-efficient metering infrastructures.

## Research Gap and Objectives

Despite the growing popularity of low-power wide area networks (LPWANs) in the *Internet of Things* (IoT) domain, the application of LoRaWAN in *Advanced Metering Infrastructure* (AMI) systems remains relatively unexplored. Most existing studies have focused on generic IoT use cases, environmental sensing, or agricultural monitoring, rather than on energy-critical and bidirectional metering environments. Moreover, previous research has often analyzed LoRaWAN through simulation-only approaches or small-scale laboratory tests, without validating the technology in real urban deployment conditions that reflect the complexity of AMI communication.

Another observed gap lies in the limited quantitative assessment of LoRaWAN's energy efficiency in comparison to its reliability and scalability. While many works highlight LoRaWAN's low-power characteristics, few provide measurable indicators, such as the *Data Extraction Rate* (DER), *Packet Delivery Ratio* (PDR), or signal quality metrics (RSSI, SNR), that directly quantify the trade-off between communication performance and energy consumption in operational AMI networks.

The main objective of this research is therefore to evaluate the feasibility of LoRaWAN as a communication framework for AMI systems, with a particular focus on energy efficiency, reliability, and sustainable network operation. The study combines simulation and field validation, employing a custom-built LoRaWAN network simulator that integrates *Adaptive Data Rate* (ADR) optimization and *K-means* clustering for gateway placement. The results aim to demonstrate that by appropriately tuning communication parameters and network topology, it is possible to achieve high delivery reliability with reduced power usage, supporting the principles of Green ICT in smart metering communication.

## Advanced Metering Infrastructure system requirements

The general requirements defined for the *Advanced Metering Infrastructure* (AMI) system specify a series of functional and communication objectives that the proposed solution must fulfill. The proposed system primarily enables the transmission of measurement profiles from electricity meters in the LoRaWAN network and the delivery of this data to the AMI system (Fig. 1).

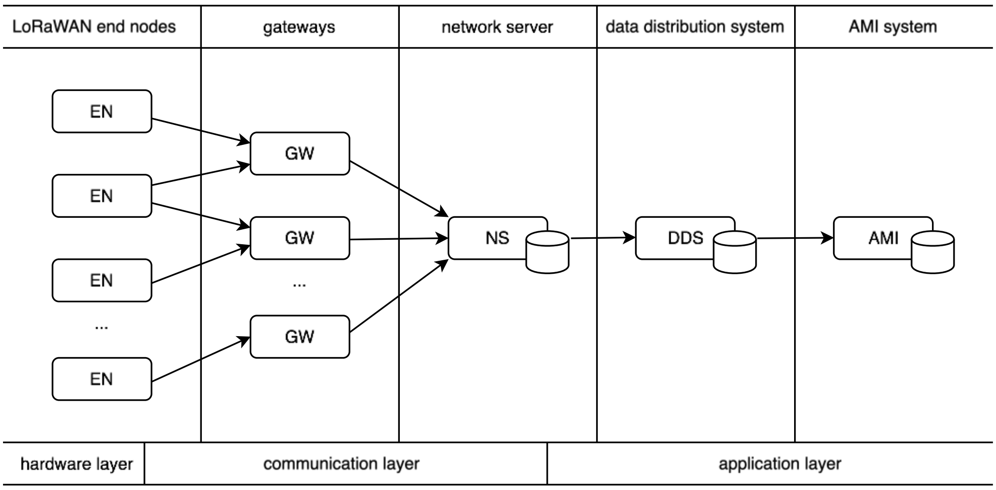

**Fig. 1. Simplified block diagram of the system, showing bidirectional data flow between end devices (ED), gateways (GW), network server and AMI platform (developed by the author).**

### *Technology overview*

LoRaWAN, a network standard developed under the *LoRa Alliance* (2018), is based on the proprietary LoRa modulation technology, which utilizes the *Chirp Spread Spectrum* (CSS) technique originally designed and patented by *Semtech Corporation* (2015). This modulation approach allows for long-range, low-power communication while maintaining robust signal integrity in noisy environments. LoRaWAN operates within unlicensed ISM radio bands, the specific frequency allocations of which vary by geographic region and local regulations.

In the European region, the *LoRa Alliance* has designated two primary frequency bands for LoRaWAN operation: EU433, covering the 433.05–434.79 MHz range, and EU863–870 MHz, commonly referred to as EU868. The principal modulation parameter in LoRa technology is the spreading factor (SF), which directly affects both the data rate and the communication range. Spreading factors typically range from SF7 to SF12, enabling a trade-off between transmission distance and data throughput. Signals encoded with different spreading factors are quasi-orthogonal, allowing for simultaneous transmission and decoding within the same frequency channel without significant mutual interference.

LoRaWAN technology is compatible with public, private, and hybrid network architectures, offering broader coverage than conventional cellular systems as presented by Bor et al. (2016). Its flexible and open design allows for seamless integration with existing communication infrastructure, facilitating the implementation of cost-effective, battery-powered IoT applications in a wide range of industrial and utility sectors.

Semtech's LoRa transceiver chips are integrated into a broad spectrum of devices produced by numerous IoT hardware and solution manufacturers. These end devices connect to LoRaWAN wide-area networks (WANs), which provide large-scale connectivity for distributed IoT ecosystems. The associated network and data management services are typically supported by dedicated cloud-based platforms, enabling secure device authentication, scalable data handling, and efficient network operation.

Collectively, these characteristics make LoRaWAN an ideal choice for *Advanced Metering Infrastructure* (AMI) applications, where long-range, low-power, and reliable communication are critical to achieving both operational efficiency and environmental sustainability.

## *System requirements*

First and foremost, the system must enable two-way communication between the operator's billing platform and electricity meters, ensuring full interoperability and data exchange. This communication will rely on standard application-level protocols such as MQTT, SOAP or REST API, which guarantee flexibility and compatibility with existing IT systems and operator's billing platform, and was analyzed by Venkatesan (2022). The implemented solution should allow defining specific data sets to be transmitted from electricity meters, providing adaptability to various operational and analytical needs. Furthermore, the system must support the periodic transfer of data recorded by the meters, often referred to as load profiles and ensure that these records are transmitted automatically upon registration in the meter's memory.

A critical requirement is that all data recorded and made available by the meter must be successfully delivered to the central system, preserving data completeness and integrity. Additionally, the system must enable the on-demand transmission of data, either from a single meter or a group of meters, initiated by a request generated within the platform. Such a request may concern both real-time readings and historical data collected within a specified time range, provided that the meter supports this functionality.

Finally, the architecture should allow remote modification of meter firmware and configuration directly from the management system, whenever this capability is available in the device. This functionality ensures scalability, facilitates remote maintenance and enables the rapid implementation of software updates across large groups of meters within the AMI network.

## *End devices requirements*

In the proposed AMI architecture (Fig. 1), LoRaWAN end devices act as communication interfaces between electricity meters and the data acquisition network. Their main purpose is to collect, process, and transmit metering data in compliance with the LoRaWAN protocol while ensuring reliability, security and low energy consumption. The following design principles and technical requirements define the operation and integration of these end devices within the system.

The end device must fully comply with the *LoRaWAN 1.0.3 specification* defined by LoRa Alliance (2018), ensuring interoperability with the network server and gateways. To support continuous data transmission and responsiveness to network commands, the device is required to operate in *Class C* mode, which allows it to remain in a constant receive state except during transmission periods.

Device registration in the network is performed using the *Over-The-Air Activation* (OTAA) procedure, providing enhanced security through dynamic session key generation. Furthermore, each device must support the *Adaptive Data Rate* (ADR) mechanism, allowing automatic optimization of transmission parameters based on link quality and network conditions, thereby reducing airtime and energy usage.

For physical connectivity, the device includes an RS-485 communication port, enabling direct interfacing with the electricity meter. Power is supplied directly from the meter terminals (230 V AC), eliminating the need for external power sources or batteries and ensuring long-term maintenance-free operation.

Functionally, the end device performs cyclic data acquisition from the electricity meter, mirroring the meter's internal registration interval. When physical connection to a meter is unavailable, the device must simulate data acquisition for testing and validation purposes. The collected information, such as load profiles and billing registers, is transmitted to the AMI system at synchronized intervals. This acquisition cycle can be temporarily interrupted to execute control commands issued from the AMI platform.

In addition, the end device must be capable of handling or simulating selected AMI-level commands, such as reading instantaneous or historical data, retrieving meter date and time, verifying communication integrity, obtaining tariff names, reading firmware versions, and synchronizing meter time settings.

It should also support the simulation of commands requiring data write operations to the meter, such as firmware updates, configuration changes, or the activation and deactivation of the consumer's contactor. These functions are essential for testing interoperability and ensuring readiness for future Firmware Update Over The Air (FUOTA) operations and are recommended by *LoRa Alliance* (2022).

Finally, each end device must allow remote configuration management, enabling modification of its operational parameters directly from the AMI platform. This functionality ensures flexibility, simplifies large-scale maintenance, and supports dynamic optimization of the metering infrastructure within the communication network.

## *Implementation of LoRaWAN gateways*

In the system architecture, defined by *The Things Network* (2025), LoRaWAN gateways serve as the intermediate communication nodes linking end devices with the network server. Their primary role is to receive uplink transmissions from meters, forward them to the central server, and relay downlink commands back to the field layer. The gateways must ensure continuous operation, high reliability, and compliance with the LoRaWAN protocol to maintain seamless data exchange within the AMI environment.

Each gateway is required to operate in accordance with the *LoRaWAN 1.0.3 specification* (2018), supporting both uplink and downlink channels defined for the EU868 MHz ISM band. To achieve stable operation and broad coverage, gateways must support multi-channel, multi-SF reception, enabling simultaneous demodulation of multiple packets transmitted at different spreading factors. The gateway transceiver subsystem should be capable of handling at least eight parallel uplink channels and one downlink channel in compliance with the LoRaWAN Regional Parameters for Europe.

The gateway's connectivity to the network server is established through a secure IP connection over Ethernet, LTE, or Wi-Fi backhaul. Communication utilizes MQTT or HTTPS protocols, ensuring message integrity and encryption between the gateway and the network server. The system should also support redundant connectivity options to prevent data loss in case of network disruption.

To guarantee interoperability, gateways must integrate seamlessly with the *ChirpStack* LoRaWAN Network Server (NS) used in this system, which is available on *chirpstack.io*. This integration enables efficient management of device sessions, ADR control, and message scheduling. Each gateway periodically reports operational statistics, including RSSI, SNR, channel occupancy, and packet error rates to the network server for continuous monitoring and adaptive network optimization.

In terms of hardware, the gateway is implemented as an industrial-grade device, designed for 24/7 outdoor operation with IP-rated protection against environmental factors such as humidity, dust and temperature variations. Power can be supplied either through AC mains or *Power over Ethernet* (PoE), depending on the deployment site. For enhanced sustainability, selected units may also incorporate solar-powered backup systems, aligning with the project's low-emission design goals.

Gateways must also support remote configuration and firmware updates to facilitate maintenance and scalability. Configuration parameters, including frequency plans, transmission power, and duty-cycle policies, are centrally managed via the network server interface. The system allows for dynamic modification of gateway parameters to adapt to changing network conditions and regulatory constraints.

To optimize the radio coverage and minimize overlap between cells, the placement of gateways is determined through a *K-means* clustering algorithm integrated into the system network simulator. This data-driven planning approach ensures optimal distribution of gateways across the target area while reducing infrastructure and energy costs. Simulation results indicate that, in a medium-sized urban environment, full coverage can be achieved using only a few strategically located gateways as it was.

Overall, the implemented gateway layer provides a robust, scalable, and energy-efficient backbone for AMI communication, ensuring that the point-to-point communication in network remains reliable, sustainable, and compliant with the principles of green energy management.

## *Communication and Data Management Layer*

The upper communication layer of the proposed architecture integrates the LoRaWAN *Network Server* (NS) with the *Data Distribution System* (DDS) and the operator's AMI platform, forming the core of the system's data management and control infrastructure. This layer ensures reliable message routing, centralized data processing, and secure interaction between thousands of field devices and the operator's billing platform.

At the foundation of this layer lies the LoRaWAN *Network Server*, which manages all radio communication processes, including device registration, session management, and message authentication. The network server ensures compliance with the *LoRaWAN 1.0.3 specification* (2018), maintaining end-to-end encryption through dynamic key management. The *Over-The-Air Activation* (OTAA) procedure is used for device onboarding, enabling secure generation of session keys and preventing unauthorized network access.

The network server is responsible for *Adaptive Data Rate* (ADR) control, which dynamically adjusts transmission parameters for each device based on radio conditions. By continuously analyzing metrics such as RSSI and SNR, the server optimizes spreading factors and transmission power levels, achieving reduced airtime and improved energy efficiency across the entire network. Additionally, it enforces regional duty-cycle limitations and schedules downlink messages to ensure legal spectrum compliance within the EU868 MHz band.

The *Data Distribution System* (DDS) acts as an intermediary layer between the LoRaWAN infrastructure and the upper-level system (Fig. 2). Developed as a middleware platform, the DDS provides protocol translation, message queuing and event-driven data management. Communication between the DDS and the platform is carried out using standardized REST and SOAP APIs, ensuring full interoperability with enterprise systems. The DDS supports message caching, buffering, and prioritization, which allows it to manage asynchronous communication and maintain data consistency even during temporary connectivity interruptions.

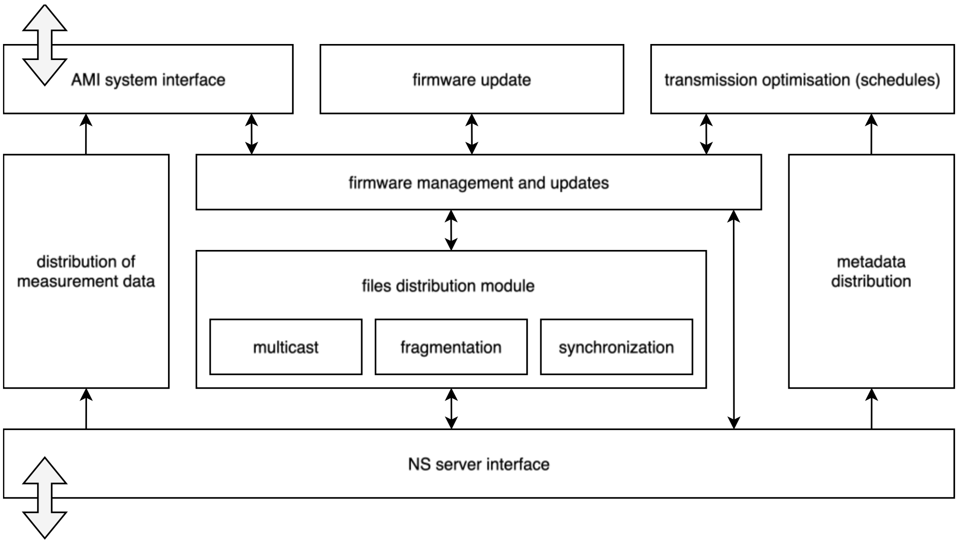

**Fig. 2. The DDS software architecture proposal (developed by the author).**

Within the DDS, all metering data received from field devices are parsed, validated and stored before being transferred to the platform. The system supports JSON and XML-based data structures, providing flexibility for integration with other applications. This architecture allows real-time monitoring of system performance and facilitates the implementation of new functionalities, such as *Firmware Update Over The Air* (FUOTA) distribution, multicast control and remote configuration management.

The operator's platform represents the enterprise-level component of the communication architecture. It performs advanced data analytics, billing, visualization and customer management. Data collected through the DDS are processed and transmitted to the operator's billing platform, where they are used for consumption analysis, dynamic tariff calculation and demand forecasting. It also provides interfaces for external systems, enabling energy market communication and regulatory reporting.

In terms of performance and reliability, the communication layer is designed with a scalable, distributed architecture. Multiple instances of the network server and the DDS can operate in parallel, providing horizontal scalability and redundancy. Load balancing mechanisms ensure efficient resource utilization, while database replication and backup procedures protect against data loss.

The combination of the NS, DDS and billing platforms creates a cohesive ecosystem that links energy meters with data analytics and billing systems in near real time. This integration not only enhances operational efficiency but also supports the principles of green ICT by reducing manual interventions, optimizing bandwidth usage, and ensuring low-latency communication with minimal energy footprint, meeting the requirements set out, among others, in Hilty et al. (2015).

## System Testing and Validation

To evaluate the performance, reliability, and scalability of the proposed system, a comprehensive series of simulation and field validation tests was conducted. The testing process focused on verifying communication stability under realistic conditions, measuring energy efficiency, and assessing the coverage and quality of LoRaWAN transmissions in an urban environment.

### *LoRaWAN Network Simulator*

Prior to field deployment, a dedicated LoRaWAN network simulator was developed to support system design and optimization. The simulator, built in Python using a Flask and web-based graphical interface, models the behavior of LoRaWAN networks at both the physical and MAC layers. It incorporates several widely recognized propagation models, including *COST-231 Hata*, published by *European Commission* (1999) and *Log-Distance*, and allows users to configure simulation parameters such as spreading factors, transmission power, duty cycles, node density and reporting intervals.

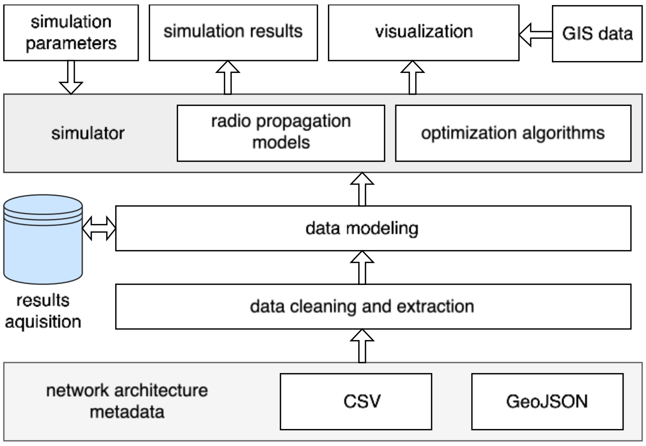

**Fig. 3. LoRaWAN simulator architecture (developed by the author).**

The tool enables the visualization of radio coverage using *OpenStreetMap* (2025) GIS data and allows the comparison of different gateway placement strategies. In addition, the simulator integrates a *K-means* clustering algorithm to determine optimal gateway locations that maximize coverage while minimizing overlapping regions and energy usage. Simulation outputs include key performance indicators such as *Packet Delivery Ratio* (PDR), *Data Extraction Rate* (DER), collision probability, time-on-air, and energy consumption per transmitted byte. These parameters provide insight into how network configuration and traffic scheduling influence scalability and power efficiency. A detailed description of the simulator is presented in the article by Piechowiak et al. (2023).

The simulator was used iteratively during system development to refine communication parameters and to predict the impact of ADR, LBT and slot-based scheduling mechanisms before deploying them in the physical network. In other words, the simulator was used during system parameter tuning through independent tests in predefined network scenarios and using its modules in the system's online operation (e.g. to determine multicast groups and synchronise transmission time slots). Fig. 3 shows the LoRaWAN simulator architecture, data flows and main functional blocks.

## *Field Deployment and Experimental Setup*

The physical validation phase was carried out, where the prototype infrastructure was installed and tested in a real urban environment. The network consisted of four *Kerlink Wirnet iStation* gateways, strategically located to ensure optimal coverage of the test area, and seven STM32WL-based LoRaWAN end devices, each connected to an MT174 electricity meter (Iskraemeco 2022).

All gateways were connected to the central *ChirpStack Network Server* and integrated with the DDS middleware and operator's billing platform, ensuring end-to-end communication between meters and the operator's data management system. The devices were configured to operate in *Class C* mode, with data transmitted in 15-minute intervals and additional transmissions triggered on demand from the system interface.

Measurements were collected over several weeks to capture variations in environmental and interference conditions. Each transmission was logged with parameters such as RSSI, SNR, spreading factor, transmission power, and gateway reception time, providing a comprehensive dataset for performance analysis.

## *Results and Analysis*

The field experiments demonstrated a high level of reliability and network stability. The average *Data Extraction Rate* (DER) exceeded 0.90 across all test nodes, confirming that LoRaWAN can efficiently support periodic AMI communication even in urban areas with moderate signal obstruction.

Measured RSSI values for devices operating at spreading factors SF7 and SF12 were consistent with simulation results obtained from the COST-231 Hata model. Reliable communication was observed up to approximately 1.4 km, even in dense city conditions with multiple obstacles. This close correlation between simulation and measurement validated the accuracy of the planning methodology and the simulator's propagation models. See Fig. 4 in the report for a graphical comparison of measured and modeled RSSI results.

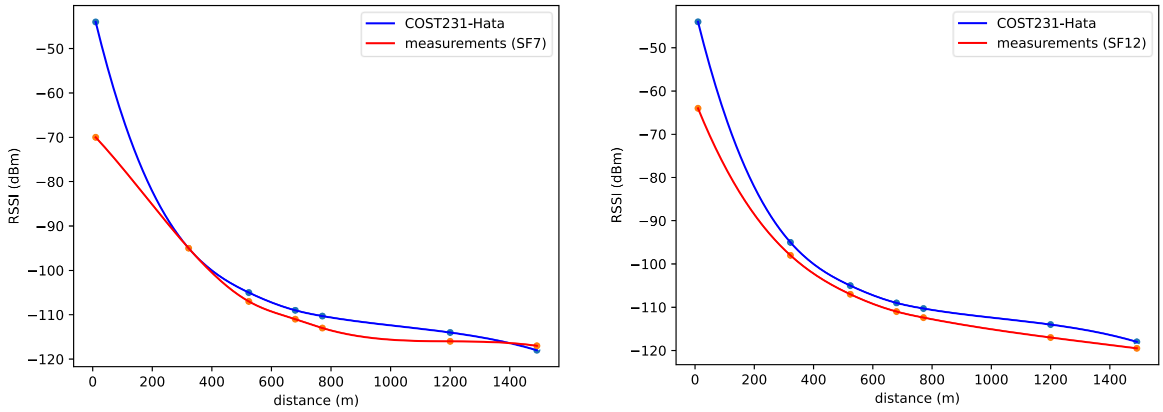

**Fig. 4. Received signal strength (RSSI) as a function of distance from the LoRaWAN gateway for SF7 (a) and SF12 (b) in the city center**

The implementation of time-slot scheduling reduced packet collisions by over 60%, significantly improving the effective throughput of the network. Moreover, the use of *Adaptive Data Rate* (ADR) and optimized gateway placement reduced the average energy consumption per device by approximately 20%, compared to a static configuration scenario.

The network achieved an overall coverage factor of 0.996, confirming the efficiency of the gateway placement algorithm and the robustness of the LoRaWAN signal under diverse propagation conditions. These results indicate that the proposed system architecture can scale effectively to cover larger metropolitan areas with minimal additional infrastructure.

**Table 1. Aggregated results of LoRaWAN performance indicators collected during the field tests and simulation experiments.**

| metric | mean | min | max | std_dev | description |
|---|---|---|---|---|---|
| RSSI [dBm] | -87.5 | -101 | -73 | 8.4 | measured at GW3 (urban zone) |
| DER | 0.96 | 0.89 | 0.99 | 0.03 | average message delivery ratio |
| PDR | 0.91 | 0.84 | 0.95 | 0.04 | *Packet Delivery Ratio* from simulator |

Statistical analysis was performed on RSSI and DER metrics obtained from both field measurements and simulator output (Table 1). The average DER of 0.96 confirms network stability, with a standard deviation below 0.03, indicating consistent performance. The measured RSSI values varied between -101 dBm and -73 dBm, reflecting typical urban signal dispersion within the tested coverage area.

The presented experiments were conducted in a limited urban area using four gateways and seven end devices. The study duration was approximately four weeks, which provided sufficient temporal variability but did not capture long-term seasonal effects. Environmental factors such as temperature and building density influenced propagation results, but these parameters were not individually isolated in this analysis. Future studies will extend measurements across diverse climatic and topographic conditions to further validate proposed model.

### *Discussion of Energy Efficiency and Sustainability*

From an environmental and operational perspective, the proposal system validation confirmed that LoRaWAN provides an excellent balance between low energy consumption and high communication reliability. The reduced airtime minimized retransmissions and optimized gateway utilization collectively contribute to lower carbon and energy footprints compared to conventional AMI communication technologies.

By employing adaptive and data-driven control strategies, the system not only enhances communication efficiency but also supports the principles of Green ICT. The demonstrated approach provides a foundation for sustainable network expansion and for integrating renewable-powered nodes and gateways in future implementations.

## Results Discussion and Future Work

The results of the project confirm that LoRaWAN technology represents a practical, scalable and environmentally sustainable solution for AMI systems. The achieved technical outcomes demonstrate that the combination of adaptive communication mechanisms and optimized network planning allows for substantial energy savings, while maintaining the quality and reliability required for large-scale smart metering applications.

The communication performance of the tested infrastructure – characterized by a *Data Extraction Rate* (DER) above 0.90 and a coverage factor of 0.996 – indicates that LoRaWAN is well suited for urban AMI environments, where interference and signal attenuation typically present major challenges. The alignment between simulation results and field measurements validates the system design methodology and confirms the accuracy of the developed LoRaWAN simulator as a predictive planning tool. The results are presented in detail in a separate article devoted to the use of the LoRaWAN network simulator by Piechowiak et al. (2023).

From the perspective of energy efficiency, the system provides measurable improvements compared to conventional communication technologies. The application of *Adaptive Data Rate* (ADR) dynamically tailors transmission parameters to link conditions, effectively reducing airtime and radio power consumption. Meanwhile, time-slot scheduling and *Listen Before Talk* (LBT) mechanisms help to mitigate collisions and minimize retransmissions – both major contributors to unnecessary energy waste. These optimizations, when applied across thousands of smart meters, translate into significant cumulative reductions in energy usage and network congestion.

This project also highlights the importance of data-driven network optimization. By integrating *K-means* clustering into gateway placement planning, the network achieved wide coverage with minimal infrastructure density according to Piechowiak et al. (2023). This approach not only reduced installation costs but also lowered the energy footprint associated with equipment operation and maintenance.

Beyond technical performance, the implemented architecture embodies the principles of Green ICT and sustainable energy management. Its lightweight infrastructure, low power operation, and compatibility with renewable-powered nodes contribute to the broader environmental goals of reducing carbon emissions and improving the efficiency of national energy systems. The system's modular and open architecture enables integration with distributed renewable energy sources, electric vehicle charging stations, and smart grid management platforms.

Looking ahead, future development will focus on three main directions. First, the integration of artificial intelligence (AI) and machine learning will enhance the adaptability of communication parameters and improve predictive maintenance capabilities. AI-based algorithms can anticipate network congestion, dynamically reconfigure scheduling, and optimize power levels in real time.

Second, the project aims to expand its deployment to larger metropolitan and regional areas, enabling commercial-scale implementations that connect tens of thousands of meters. Such large-scale validation will allow for further assessment of system resilience, interoperability with multiple AMI vendors, and long-term operational cost analysis.

In summary, the project successfully demonstrates that LoRaWAN can serve as the foundation for a new generation of green, intelligent, and scalable smart metering systems. Its combination of technological innovation and environmental awareness provides a replicable model for sustainable digital infrastructure in the energy sector, paving the way toward smarter, cleaner, and more efficient cities of the future.

## References

- Dell'Isola, M., Ficco, G., Canale, L., Palella, B.I., Puglisi, G. (2019). An IoT integrated tool to enhance user awareness on energy consumption in residential buildings. *Atmosphere* 2019, 10, 743.
- de Castro Tomé M., Nardelli P. H. J., Alves H. (2019). Long-Range Low-Power Wireless Networks and Sampling Strategies in Electricity Metering. *in IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 1629-1637, Feb. 2019.
- Harinda E., Hosseinzadeh S., Larijani H., Gibson R. M. (2019). Comparative Performance Analysis of Empirical Propagation Models for LoRaWAN 868MHz in an Urban Scenario. *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*, Limerick, Ireland, pp. 154-159, 2019.
- Silva, B.N., Khan, M., Han, K. (2018). Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities. *Sustain. Cities Soc.* 2018, 38, 697–713.
- Abbas, S., Khan, M. A., Falcon-Morales, L. E., Rehman, A., Saeed, Y., Zareei, M., Zeb, A., Mohamed, E. M. (2020). Modeling, simulation and optimization of power plant energy sustainability for IoT enabled smart cities empowered with deep extreme learning machine. *IEEE Access* 2020, 8, 39982–39997.
- Peruzzi, G., Pozzebon, A. (2022). Combining LoRaWAN and NB-IoT for Edge-to-Cloud Low Power Connectivity Leveraging on Fog Computing. *Appl. Sci.* 2022, 12, 1497.
- Leonardi, L., Lo Bello, L., Patti, G., Pirri, A., Pirri, M. (2023). Combined Use of LoRaWAN Medium Access Control Protocols for IoT Applications. *Appl. Sci.* 2023, 13, 2341.
- Noreen, U., Bounceur, A., Clavier, L. (2017). A study of LoRa low power and wide area network technology. *In Proceedings of the 2017 International Conference on Advanced Technologies for Signal and Image Processing* (ATSIP), Fez, Morocco, 22–24 May 2017, pp. 1–6.
- The Things Network (2025). LoRaWAN Architecture. https://www.thethingsnetwork.org/docs/lorawan/architecture/, 2025 (available online).
- LoRa Alliance (2018). LoRaWAN 1.0.3 specification. *https://resources.lora-alliance.org/document/lorawan-specification-v1-0-3*, 2018 (available online).
- LoRa Alliance (2019). FUOTA Process Summary Technical Recommendation. *https://lora-alliance.org/wp-content/uploads/2020/11/tr002-fuota_process_summary-v1.0.0.pdf*, 2019 (available online).
- Semtech Corporation (2015). AN1200.22 LoRa Modulation Basics, Revision 2. May 2015. *https://semtech.my.salesforce-sites.com/sfc/servlet.shepherd/document/download/0692A00000SmPFrQAN* (available online).
- Bor M. C., Roedig U., Voigt T. and Alonso J. M. (2016). Do lora low-power wide-area networks scale? *In Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM '16*, page 59–67, New York, NY, USA, 2016. Association for Computing Machinery.

- Venkatesan, R. (2022). RESTful API Integrations in Telecom Billing System Management. *Proceedings of the International Conference on Cognitive and Intelligent Computing*, pp. 323–329, 2022.
- Piechowiak, M., Zwierzykowski, P., Musznicki, B. (2023). LoRaWAN Metering Infrastructure Planning in Smart Cities. *Applied Sciences*, 13(14), 8431.
- European Commission (1999). COST Action 231 Digital mobile radio towards future generation systems: Final Report. *https://op.europa.eu/en/publication-detail/-/publication/f2f42003-4028-4496-af95-beaa38fd475f*, 1999 (available online).
- Hilty, L. M., Aebischer, B. (2015). ICT Innovations for Sustainability. *Springer*, 2015.
- Chirpstack (2025). ChirpStack, open-source LoRaWAN Network Server. *chirpstack.io*, 2025 (available online).
- OpenStreetMap contributors (2025). OpenStreetMap – Free geographic data and mapping. *OpenStreetMap Foundation*, https://www.openstreetmap.org (available online), 2025.
- Iskraemeco (2022). MT174 Smart Electricity Meter – Technical Specification. Iskraemeco, Kranj, Slovenia, *https://www.iskraemeco.com* (available online), 2022.