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Open Source LoRaWAN Telemetry Test Bench for Smart Grid – a DLMS/COSEM Implementation Case Study

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Abstract. Internet of Energy (IoE) emphasizes the need for an intelligent and adaptable Energy Grid system that is based on smart energy meters (SM) and IoT communication technologies. However, many countries are still unable to meet their SM rollout plans due to obstacles such as the lack of human and financial resources, and the absence of interoperable and globally standardized communication protocols in the energy sector. Therefore, developing an open-source platform that can be implemented on top of the existing legacy infrastructure, while having the capability of transmitting metering data over a proven, easily adaptable, and already established long-range wireless communications technology, could accelerate the anticipated migration to Smart Grids. The aim of this work is the realization of an open-source, low-cost telemetry platform that is capable to integrate DLMS / COSEM compliant energy meters over LoRaWAN; DLMS / COSEM is the global standard application protocol for smart energy metering, control, and management which is getting widely accepted in Europe and US. In the proposed architecture, the electricity (consumption or generation) telemetry data are further forwarded to a blockchain network, through a LoRaWAN application server, to be certified and consumed by Distributed Applications (DApp). This way, producers and consumers will be able to exchange (sell or buy) energy (especially from distributed renewable energy sources) over the existing infrastructure, using blockchain technology to enhance integrity, transparency, and security, leading thus to a peer-to-peer electricity trading platform and the democratization of the energy market.

Keywords: Materials, Tools, LPWAN, LoRaWAN, Energy Smart Metering, DLMS/COSEM, Smart Grid.

INTRODUCTION

With the growing energy demand, the energy generation distribution, the integration of renewables sources and grid management challenges (e.g., outage management) on one side, and the explosion of IoT networks in Building Management systems (BMS) on the other, the energy sector has been forced to move towards the transformation of the traditional grid to a smarter and more efficient one. The smart grid is the integration of smart metering, actuation and networking technologies in the conventional electrical grid [1]. Building a Smart Grid (SG) consists of integrating a variety of smart technologies including smart meters, smart sensors (e.g., phase measurement sensors) and actuators, and different communication technologies based on standardized protocols for data exchange. As a consequence, the global smart grid technology consists of groups of individual technologies that cover the whole spectrum of grid management processes, including generation, transmission, and distribution[2]. In developed countries, smart grids have an essential role in the secure operation of the electricity distribution system by enabling low-cost solution

deployment and more powerful performance [3, 4]. With a smart grid, small and distributed Renewable Energy generation sources initially deployed as a disconnected cost-effective solution for the electrification of rural areas can be later seamlessly integrated into the national central electricity system.

Smart grid opens access to the markets through new transmission paths and demand response initiatives. On the other hand, one of the main SG features is the combination of secure and reliable data communication networks to successfully manage the sophisticated power system. Thus, this complex cyber-physical power system is susceptible to problems that are related to connectivity, communication, and topology modifications.

SG standardizations are important and crucial and they should be carefully taken into consideration. For this, W. Wang, et al. [4] and Z. Fan, et al. [5] describe the architecture of the existing SG communication networks and they present SG's protocols and standards. The three most important standards that have been proposed to enhance and develop the SG are the Distributed network protocol (DNP), Open smart grid protocol (OSGP), and the combination of Device Language Message Specification (DLMS) with Companion Specification for Energy Metering (COSEM), a.k.a. DLMS/COSEM. The DNP emerged in 1998, the DNP3 version was implemented at the distribution substations and it was used for equipment controlling and monitoring. The main functionality of this protocol is to transmit the equipment states to the control station and transfer configuration commands to the equipment. But DNP3 cannot guarantee communication quality. The OSGP [6] suggested by the European Telecommunications Standards Institute (ETSI), is used in combination with the ISO/IEC 14908 standard for SG network controlling. OSGP protocol affords a reliable transmission of commands and control information to the smart meter (SM), the Gateways, the Renewable Energy Sources, and the intelligent power measurement and control devices within the SG. DLMS User Association (UA) provides the DLMS/COSEM which is a group of international standards for energy metering. The energy meter is considered to contain all the information like energy consumption, registration, and maintenance[7]–[9]. COSEM combines a suite of protocol layers (Transport Layer and Application Layer) to be integrated with DLMS. Their combination, DLMS/COSEM, is adopted for energy metering data exchange as an interface model protocol for the meter functionality. This protocol was deployed worldwide and gained high interest from different big companies, utilities, and researchers.

In this paper a review of the DLMS/COSEM protocol is initially provided, followed by an introduction of LPWAN communication technologies and specifically LoRaWAN. The latter is proposed for the connection between an Advanced Metering Infrastructure (AMI) energy meter and a Data Concentrator Unit (DCU) [10], as it is increasingly adopted by utilities to support its own needs for IoT solutions. This work aims to propose and realize an open-source, low-cost test bench for testing and developing a solution that enables the use of modern technologies to evolve energy trading between prosumers and consumers, by using the standardized telemetry protocol. The provided solution can read DLMS/COSEM compliant energy meters and transmit the readings to an equivalent gateway through LoRaWAN using an appropriate adaptation protocol for packet compression.

Moreover, the proposed test bench optimizes data integrity and increases security by uploading the gathered energy data onto a blockchain to achieve energy market linearization where prosumers and consumers can exchange energy via a platform connected to the blockchain network. Such a platform would help developing countries that stand unable to meet the SM rollout projects and convert their conventional grid to a smart one due to the complexity induced by a missing interoperable and globally standardized communication protocol.

The hardware used has been chosen to be inexpensive and versatile, enabling thus a large scale of energy trading scenarios to be implemented and studied with the existing infrastructure, including in the current case, the constraints of implementing DLMS/COSEM over LoRaWAN. The rest of this paper is organized as follows: Section II gives an overview of the SG system, Section III provides technical details about the DLMS/COSEM protocol, Section IV discusses the metering protocols and the LoRaWAN wireless technology, in section V the subsystems of the suggested prototype are presented, in section VI the prototype setup deployment procedure and experimental results are analyzed, while in section VII an overall summary of the presented work is given.

SMART GRID AND ADVANCED METERING INFRASTRUCTURE

A Smart Grid is the new generation of the conventional electricity infrastructure that is going to be a solution to improve the electrical energy system not only by integrating Renewable Energy Resources (RES), but also the Distributed Generation (DG) and Distributed Storage (DS). Smart Grid targets to solve different existing problems in power delivery, answer the climate changes, improve energy efficiency and localization of energy exchanges, and open a new direction in electricity markets (like Peer-to-Peer P2P energy trading). A direct implication of the Smart Grid is to have an electric model that is capable of managing different generation and storage devices in an efficient

and decentralized way by deploying an Advanced Metering Infrastructure (AMI) where Smart Meters (SM) are the main components. An SM provides an accurate and remote measurement reading and communicates with smart home appliances to manage their power consumption efficiently. These functionalities are realized through two-way communication and advanced sensors. To achieve the two-way communication, AMI architecture uses different communication networks, each one having its requirements and considerations [11]: Home Area Network (HAN) for energy management at the consumer end, Neighborhood Area Network (NAN) as the last mile for providing the AMI and Wide Area Network (WAN) realizing the communication between all pieces of the SG including control center, renewable energy sources, and transmission, and distribution of Electricity. The HAN is connected to the WAN via NAN. The NAN provides the networking infrastructure for SMs and the data collected will be transmitted to the DCU (Data Concentrator Unit), which acts as a gateway between the SMs and the electricity substations. A high transmission data rate is required at the WAN level, and therefore, different wireless communications technologies than the ones used at the HAN/NAN level, e.g. WiMAX, 3G/LTE, and micro-wave are among the proposed ones [12]. Every network type has specific data rate needs, and TABLE 1 presents different communication technologies and the required data rates that can be used for each level in the networking hierarchy.

TABLE 1. Required data rate and potential communication technologies based on the Network Type

Network Type	Transmission Range	Required Data Rate	Possible Technologies
HAN/BAN	10 (m) - 100 (m)	Applications are using low data rate devices for communication	Zigbee, Wi-Fi, PLC
NAN	100 (m) - 10 (Km)	Depends on node density in the network	Zigbee, Wi-Fi, LoRaWAN, Sigfox, Cellular, NB-IoT
WAN	< 10 (Km)	High-end devices (routers/switches) with high speed (100Mbps)	Fiber optic, 3G/4G/ LTE WiMAX, NB-IoT

The DLMS/COSEM Standard

A basic review of DLMS/COSEM and data packet format will be presented in this section. The DLMS/COSEM is an interface model that is developed and used to exchange the data and information of the energy meter. This interface model gives a view of the meter functionalities as it is available at its interfaces. However, communication protocols specify how data can be accessed and transmitted. DLMS UA standard is described and presented by four documents Green Book, Yellow Book, Blue Book, and White Book [7]–[9]. The blue book presents COSEM meter object model and the object identification system (OBIS). The architecture and protocols are described in the green book. The yellow book for clarifications related to conformance testing.

The communication profiles of the DLMS and OSI model are represented in (FIGURE. 1). These communication profiles can be grouped into two parts with the Application Layer first and all other layers secondly. The application layer is composed of three layers: the COSEM Application Process layer, the COSEM Application Layer, and finally the COSEM connection manager layer. The lower layers are divided into three different ways based on the communication type.

These three different categories include CO-HDLC which represents directly the data link and the physical layer and has no transport layer. The data link layer contains two sub-layers the LLD and the HDLC. However, TCP-UDP/IP communication type contains a transport layer, where on top of it a wrapper sub-layer is added, and a data link layer. Finally, IEC61334-5 S-FSK PLC profile is proposed for PLC communication that includes the data link and physical link layers (FIGURE 1).

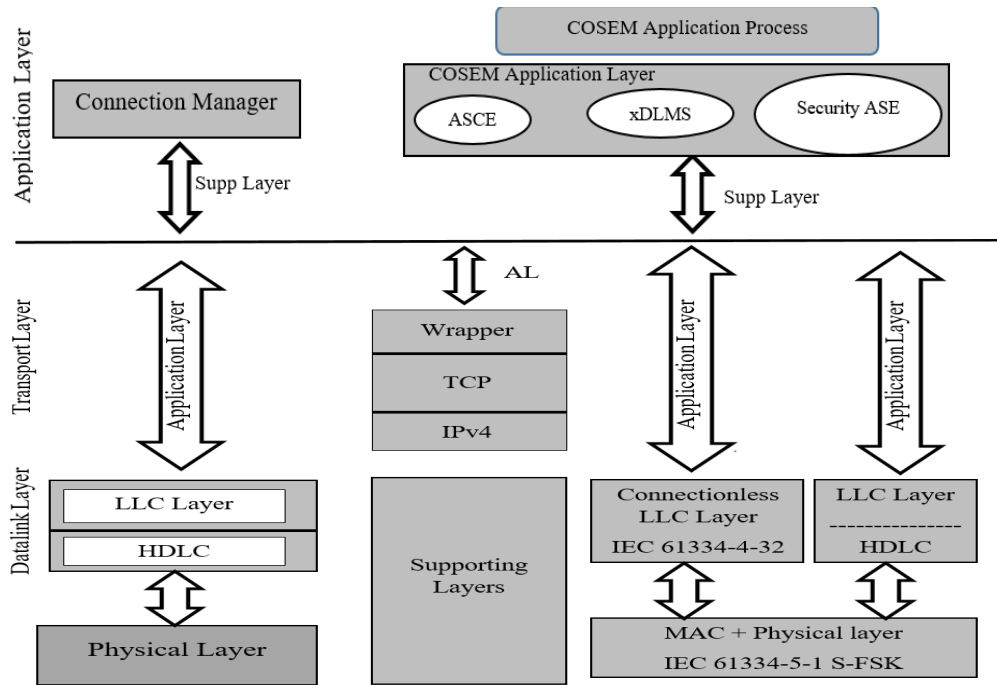


FIGURE 1. DLMS/COSEM Communication Profiles

DLMS/COSEM Sequence

The exchange of data between the energy smart meter and the DCU and is based on the client-server model, where the client will be the DCU and the energy smart meter has the role of server. For DLMS/COSEM the establishment of a connection between DCU and the SM is based on a sequence of packets exchange, which is divided into three phases: data link setup, data transfer, and finally the data link disconnection shown in (FIGURE 2).

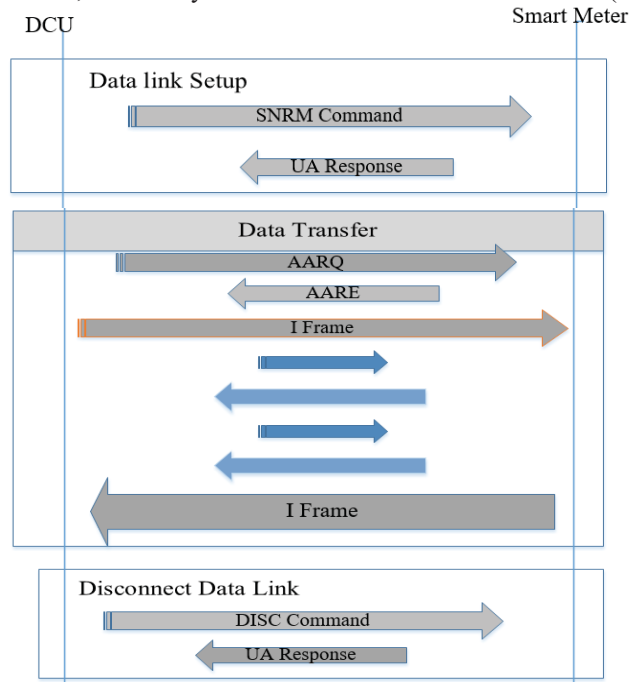


FIGURE 2. Connection Establishment and Packet Transfer of DLMS/COSEM

In the data link setup sequence, the DCU initiates a Set Normal Response Mode (SNRM) command to the SM. At the reception, if the SM is ready to establish a connection, it will send back an acknowledgment response named Unnumbered Acknowledge (UA).

In the data transfer sequence, once the DCU receives the UA and before establishing a connection, it initiates a command to check the SM properties called A-Associate Request (AARQ). In its turn, the SM will reply by sending the A-Associate Response (AARE). The AARQ packet contains all properties that a meter can have and the AARE is the meter properties. Once these packets exchange is completed now the DCU and the meter can exchange I-Frame (information packet).

In the data link disconnection sequence, once the exchange of data between the DCU and the SM is finished the DCU sends a disconnection command (Disconnect DISC) and the SM sends a UA response for confirmation.

DLMS/COSEM Packet Exchange Sample

The COSEM application process contains the Interface Class and Object Identification System code (OBIS). There is a class identity (class_id) for each interface and the number of interfaces depends on the type of process (e.g., for the data storage process there are nine interface classes as presented in (FIGURE 3)). OBIS code is a code for an identified parameter that DCU used to ask from SM. OBIS code is composed of six (6) groups from A to F where:

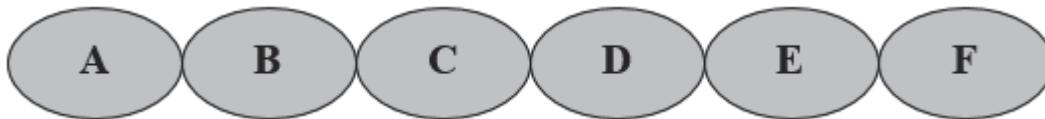


FIGURE 3. OBIS Structure

- Group A includes the data that we want to measure like gas electrical usage.
- Group B defines the type of channel in use like HDLC, RS232, and TCP-UDP/IP.
- Group C defines the parameter of the data source, including voltage, power, and temperature.
- Group D defines the measuring process of physical quantities that are related to the parameter of group A.
- Group E defines other measuring information like electricity fees.
- Group F defines historical information within the meter concerning group A to E parameters.

The COSEM application layer is divided into three sections: ACSE, xDLMS, and Security ASE (application service element). The xDLMS is a connection-oriented application protocol that is simple and easy to be read and understand by a human. The COSEM application layer will transform the xDLMS code to an Application Layer Protocol Data Unit (APDU). APDU size depends on the xDLMS length and TABLE 2 represents the APDU size of the exchange commands and responses between the DCU and the SM to establish a connection. The APDU will be transmitted to the lower layer by the COSEM application. In this article, only the transmission over CO-HDLC is considered. In our case, the data link is composed of two sub-layers the LLD and HDLC. The frame format of each sub-layer is presented in (FIGURE 4) and (FIGURE 5) respectively. After the data link, the frame will be transferred to LoRaWAN's physical layer (PHY).

TABLE 2. Commands APDU size in bytes

Packet type	Frame	Size in (Byte)
SNRM	7EA00000020023219318717E	12
UA	7EA023210002002373F6C581801405020080060 20080070400000001080400000001CE6A7E	33
AARQ	7EA02E0002002321107ECBE6E600601DA1090 60760857405080101BE10040E01000000065F1F 040000301DFFFFD4C57E	48
AARE	7EA03A2100020023309941E6E7006129A10906 0760857405080101A203020100A305A10302010 0BE10040E0800065F1F040000301D190000070 C527EE	60

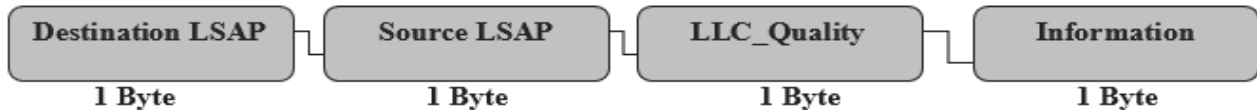


FIGURE 4. LLD Frame



FIGURE 5. HDLC Frame

Lpwan Communication Technologies and LoRaWAN

With the latest improvements in IoT networks, globally utilities are installing smart meters with different communication technologies. LPWAN technologies can be extensively used and deployed in today's scenarios as a long-range solution for smart metering. With a smart module that is integrated into the energy meter, the majority of smart meter functionalities can be achieved. The transmission of data utilizes low power, long-range, and narrowband transmission characteristics which lead to a stable and reliable network in addition to the low-cost benefits of the implementation. This smart module can be programmed in a way to provide the utility and the consumer with notifications at predefined intervals of time.

LPWAN technologies take place when other technologies (like Zigbee, Wi-Fi, and Bluetooth) are not good enough to fill all gaps in some case studies and even fail to achieve long-range coverage and performance [13]. Cellular M2M networks on the other side, are too expensive in terms of both hardware and services and their nodes have increased energy consumption demands to be autonomous. Hence LPWAN technologies are perfect to be deployed for nodes that need to transmit a small amount of data over a long-range while saving battery life [14]. The best two areas for deploying LPWAN technologies are:

- Smart cities and buildings, where LPWAN technologies are a perfect replacement for cellular M2M ones, for applications such as smart grid and smart lighting.
- Application domains where communication needs include low bandwidth but long battery life for the autonomous nodes (e.g., smart agriculture and water metering).

LoRa is a strong modulation technique for long-range, low data rate, and long battery life (up to 10 years) wireless communication technology. It is patented from Semtech and uses a chirped spread spectrum modulation for layer one (the physical layer) for LoRaWAN. The chirped spread spectrum modulation decreases the interference impact on data transmission providing increased reliability. LoRa MAC layer was developed by the LoRa Alliance and forms the data link and network layer. The adaptive rate is one of LoRa features, and it can be modified accordingly with the chosen bandwidth. The transmission energy is defined with the selection of the optimum spreading factor. The LoRa transceivers that must be integrated with the smart meter are not expensive compared to other technologies. LoRaWAN uses the ISM frequency bands with a data rate that varies from 0.3kbps to 50kbps and transmits data within a 5 km range in the urban region and 20 km in a rural area with a payload size of 243 bytes. In Europe, the adopted frequency band is between 863MHz and 870MHz, however, in the US the adopted frequency is 915Hz.

LoRa networks are typically following a star topology where the gateway is acting as a relay between the end node and the central server. The end node communicates with the gateway via LoRaWAN and the gateway communicates with the backend via the IP standard. LoRaWAN end devices operate in three different operation modes, namely A, B, and C, with each mode providing different uplink and downlink capabilities and energy needs accordingly [13].

- Class A nodes listen to incoming messages directly after the upload of some data and then they go back to sleep mode (batteries saving mode). The access mode in use is the ALOHA mode for uplink transmission, after the transmission the class A node listens for a reply within two downlink windows, therefore the node can be inactive for a time duration (low duty cycle) and therefore increase the battery life. Once the uplink transmission is deciphered successfully by the gateway then the downlink traffic can be transmitted. Hence, class A nodes are the lowest power consumption nodes with high latency in the transmission and the reception of packets.

- Class B nodes follow a different policy: the gateway sends beacon messages to the end device that is used to synchronize time windows for listening. This beacon is used for additional downlink traffic without previous successful uplink transmission. Class B devices are nodes with average power consumption and low latency in transmitting and receiving unicast and multicast packets. In our case, we have based the experimental setups on Class B end nodes since it provides a bi-directional communication that is mandatory for DLMS/COSEM, and also supports multicast communication for firmware upgrades over the air.
- Class C devices are always in listening mode; therefore, they are connected to a power supply. Class C nodes are nodes with high power consumption, with low latency in the transmission and the reception of unicast and multicast packets [15].

In the actual scenario, the existing Home Area Network (HAN) technologies that are well standardized and in use like Wi-Fi, Zigbee, Bluetooth, and Z-Wave, face some challenges in terms of power consumption and especially connectivity coverage. They belong to the short-range wireless communication technologies. To expand their coverage limitation due to their physical short-range (less than 100m), they commonly use a mesh networking topology. Hence, their major drawback is the high deployment cost to link a substantial number of nodes that are geographically scattered in a large area. Furthermore, since data is communicated via multi hops to the gateway, a considerable number of nodes are more loaded and congested than others which will impact their batteries' life (i.e., excessive use of energy), and therefore the network lifetime will be affected. Similar, the 2G, 3G, 4G, LTE cellular networks are developed to have a better traffic throughput, but they are not the best solution to be used for IoT applications due to battery consumption and they are proprietary to mobile operators.

Both short-range and cellular technologies are expensive solutions to be deployed in a vast area while LoRa is much simpler and presents a low-cost solution that is based on open standards. Furthermore, the next-generation cellular proposal NB-IoT for IoT application is not yet well-deployed worldwide, leaving a gap that is filled by LoRa technology, effectively servicing IoT nodes requiring a long battery life and low data transmission over a long distance.

LoRaWAN platforms are built by design according to these requirements and they are low-cost platforms. LoRaWAN fulfills the essential IoT requirements for transparent interoperability between smart things, without a sophisticated implementation. They provide the IoT ecosystem with secure bi-directional communication, tracking services, and mobility, which facilitating the rollout of new solutions or the smooth expansion of the existing ones.

BLOCKCHAIN ENABLING TECHNOLOGY for ENERGY TRADING and DATA INTEGRITY

Global electricity networks were initially built for unidirectional power flow, with fiat money flowing in reverse (Fiat money is a currency established as money, often by government regulation). Producers were expected to be larger than consumers but since the potential growth of prosumers has changed due to the technology advancements, a lot of challenges are currently under research. Reconstructing power networks is a difficult challenge to tackle, but re-engineering the electricity market is a different one.

Blockchains, in general, provides a distributed network, assuring information replication and operational resilience, and stability by leveraging a distributed infrastructure, while decreasing the costs of installation and maintenance of centralized resources. This is done by distributing computational and storage requirements among all blockchain nodes that constitute the network. This allows participants who may not know each other to safely and directly do business. The medium for this is Smart Contracts, which implement the necessary rules and actions that need to be carried out for any related business transaction, automatically and securely. Thus, such an approach eliminates the need for intermediaries, controlling or certifying authorities like legal representatives, banks, brokers, or even the government to intercede and supervise deals between two or more parties.

Blockchain will most probably disrupt the energy sector, in the following individual areas [17, 19]:

- Finance enhancement within distributed energy sources and battery storage.
- A solution to the split-incentive problem with multi-owner properties.
- Optimized utilization and increased value of network assets.
- Affordable and easier access to modern energy markets even for entry-level prosumers.
- Enablement of a decentralized platform for generating and distributing power.

According to [19] there are seven different research domains regarding blockchain and energy:

1. The decentralized energy markets
2. Micro grid and Smart grid
3. Energy internet
4. Smart contract
5. Peer-to-peer (P2P)
6. Renewable energy
7. Electric vehicle

In our case, we combine the DLMS/COSEM interface model and communication protocols to exchange data with smart meters and then upload them to a blockchain network. Generating, signing, and sending transactions from constrained resource devices is a task that needs sophisticated engineering. As in the case of our scenarios were not only the microcontroller-based communication module has to be plugged in the smart meters, but also to support a wide variety of meters and standards according to the SM manufacturer and the country under deployment. For this, the connection to the blockchain network has to be done on the server-side.

After certifying the data immunity by registering them on the blockchain network, then any device capable of running cryptography algorithms can directly utilize the benefits of smart contracts. Therefore, in an end-to-end adaptation of the COSEM protocol's services, we suggest their implementation in the corresponding smart contracts.

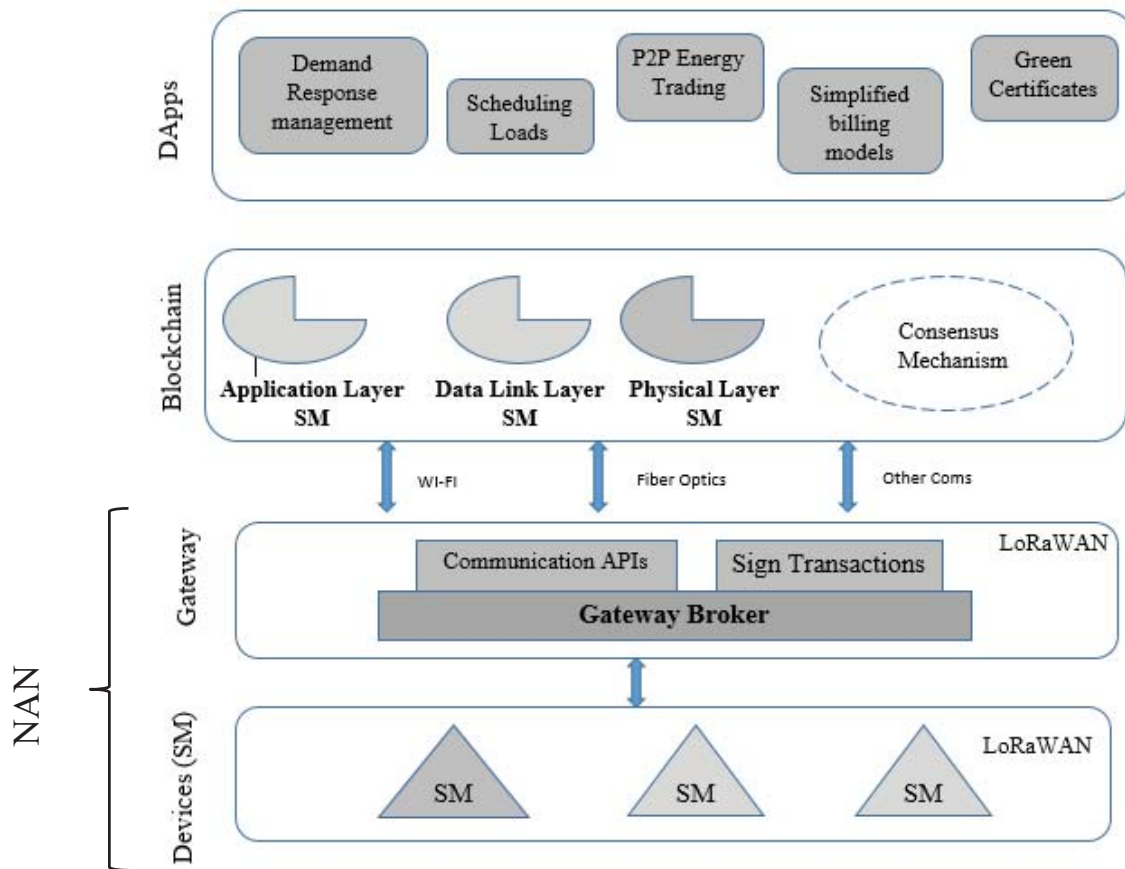


FIGURE 6. Proposed Architecture for Smart Meters Integration to a blockchain-based P2P electricity trading platform
In (FIGURE 6) the proposed System architecture is visualized following four hierarchical layers which in short are:

- Devices are the Smart Meters with the appropriate hardware and firmware that enables the data transmission of measurements over LoRa and control over other conventional communication technologies such as Zigbee, Wi-Fi, etc.

- Gateway is the device(s) that gets these measurements and signs them as transactions to forward them to the Blockchain layer. In this layer, the control commands for Smart Meters are also forwarded from the corresponding Smart Contract outputs.
- At the Blockchain layer, several Smart Contracts is deployed along with the Consensus Mechanism responsible for the validity of the information
- At the Dapps layer, the appropriate application for each use case is enabling the actual interaction with the Smart Meters. Whether it is for example the participation of a prosumer in a market that is open for bidding (P2P energy trading), or the Demand Response management of a medium-size producer.

Proposed Architecture and Implementation of tThe Neighborhood Area Network

Design Constraints

To convert the traditional energy meter to be smart, there are many constraints and challenges to be taken into consideration and should be predefined. The most important challenge is to design an interoperable module that can be easily integrated with the existing infrastructure and is capable to transport the DLMS/COSEM packet over LoRaWAN (FIGURE. 7). There is no standard defining the integration of LoRaWAN and DLMS/COSEM for smart grid networks. Considering the low power requirements, robustness, availability of LoRaWAN, and the specific device for smart meter applications, LoRaWAN has a lot of potential for deployment in the NAN network.

Design Modularity and Open-Source

In general, modular conception and open-source energy metering reading systems are for realizing traditional meters' migration with flexible functionality. This will assure the reliability, scalability, and modularity of the system to fit any additional new features.

Some challenges and needs should be defined before defining the hardware and software design of the system. The designed module in this paper is developed to add one of the smart features to the existing conventional meters. This system is user-friendly and can be used by researchers to test and study the best transmission scenario of DLMS/COSEM energy metering data packets over LoRaWAN taking into consideration both technologies' requirements.

Communication Protocol

For the communication network usually, a smart meter has two network interfaces: The one connected to the Home area network (HAN) where the commonly used technologies are Zigbee and Z-wave. The second network interface, the Neighbor Area Network (NAN) for communicating with the Network Operator where power line communication PLC and LPWAN technologies are used. In this article, we focus on the NAN area, where the designed module is developed to provide to the Network Operator, and the consumer/end-user the ability to read the energy consumption remotely in real-time and use them in a multitude of novel ways. Moreover, this module aims to transmit the energy consumption data via LoRa to a cloud server where it can be accessible and can be published to a blockchain for further certification and processing in the context of the P2P electricity trading platform.

Prototype Design and Implementation

The Lora module in this study is constituted of two main components: an Arduino platform and a LoRa shield that will allow the identification of the DLMS/COSEM energy consumption packet from the supported SM and transfer this data through a LoRaWAN gateway to the network server. The NAN Gateway is based on an iC880A-SPI extension board for a Raspberry Pi platform. This platform integrates Wi-Fi and Ethernet connectivity as well as adequate memory resources for the microprocessor that runs a Linux distribution with 16MB Flash and 4MB of RAM. LoRaWAN architecture is based on star-of-stars topology where the gateway plays only the role of a relay to transmit the data between the end device and the network server. The gateway is connected to the network server via the internet while the end-node is connected to the gateway via LoRa. Generally, end nodes communication is bi-directional, and all also support multicast communication for firmware upgrades over the air. The communication between LoRa node and the gateway can be performed using different frequencies and bandwidth.

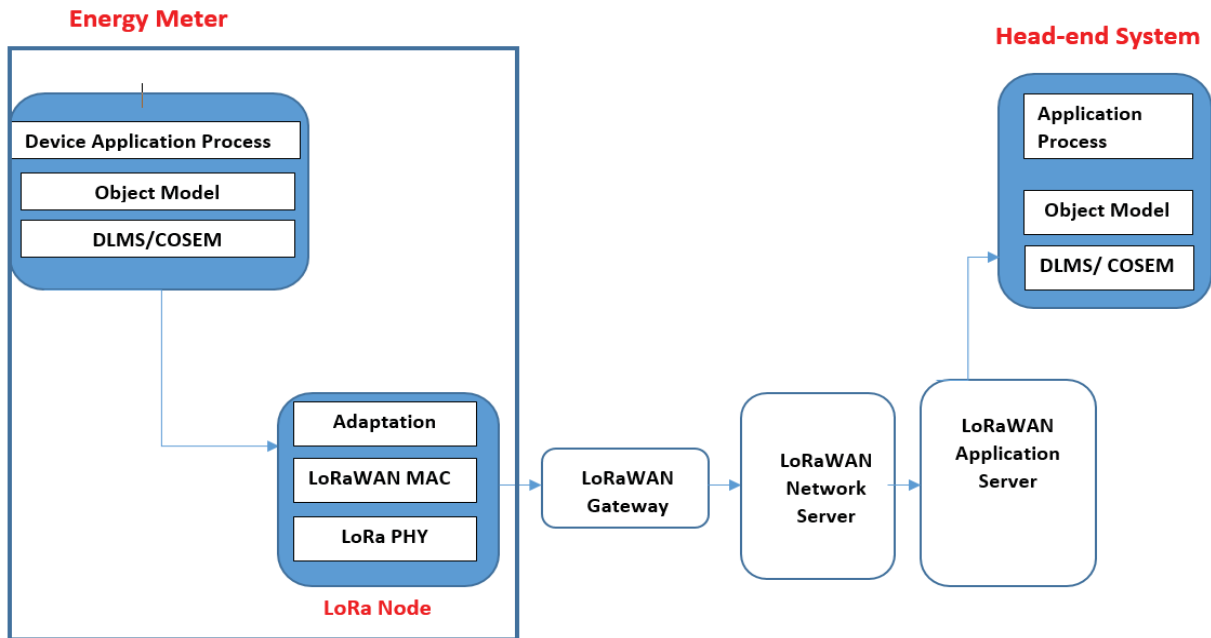


FIGURE 7. Proposed DLMS/COSEM over LoRaWAN Architecture

A typical LoRaWAN Gateway has been realized, based on the iM880B-L LoRa base station board from IMST GmbH integrated with a Raspberry Pi 4 used to retrieve the transmitted data and upload them onto an application server, rendering them accessible for further processing. For the SM wireless connectivity (FIGURE 8) an open-source platform based on the ATmega2560 microcontroller board has been utilized combined with an extension board (Dragino shield) for the LoRa Physical layers based on a Semtech SX1276 radio transceiver. The communication between the microcontroller and the LoRa transceiver is performed through a Serial Peripheral Interface (SPI) interface. The Gurux DLMS/COSEM open-source library [21] has been used to generate the metering packets, where for example the function `com_readAllObjects()` initializes the connection, reads the logical device name, the clock, and the profile containing the data. Once all the relevant data are parsed, they are serialized and transmitted using the LMIC LoRaWAN library to the gateway using the `LoRaSend()` function.

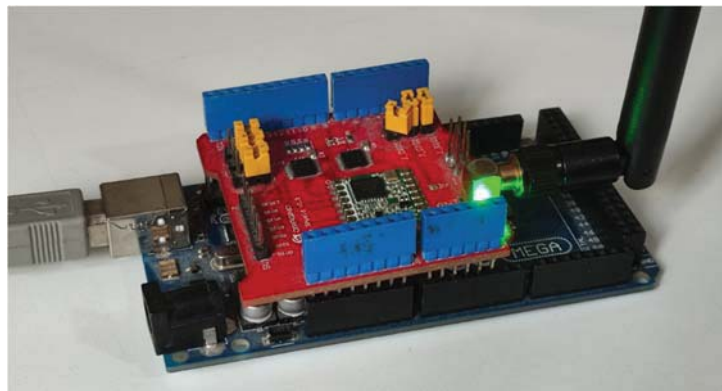


FIGURE 8. The DLMS/COSEM Compliant LoRaWAN Node for SM

In the proposed architecture, the LoRaWAN data rate (DR), which is defined by the Spreading Factor (SF), and the Bandwidth (BW) while the maximum packet size extremely depends on the distance to the NAN gateway and are also defined in the specification for each region. For example for the European 863-870MHz band, the maximum **application** packet size varies accordingly as is presented below and summarized in TABLE 3:

- 51 bytes for the slowest data rates, with SF10, SF11, and SF12 on 125kHz BW
- 115 bytes for SF9 on 125kHz BW
- 222 bytes for faster rates, SF7 and SF8 on 125kHz BW (and SF7 on 250kHz BW)

TABLE 3. LoRaWAN Constraints

SF	Bit Rate (bps)	Range (Km)	Time on the air (ms)	Max Payload (Byte)
SF10	980	8	371	11
SF9	1760	6	185	53
SF8	3125	4	103	125
SF7	5470	2	61	242

LoRaWAN protocol adds at least 13 Bytes to the application payload (FIGURE 9).

Preamble	Header + Header CRC (20bits)	PHY Payload In Bytes	Payload CRC
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FIGURE 9. LoRa Header

The constraints that we have taken into consideration during our testing are resumed in the below section:

For DLMS/COSEM, the Application Packet Data Unit (APDU) of information packet maximum size can be negotiated based on the Physical Layer, however, the default value is 128Bytes and the maximum 2030 Bytes. The APDU size of the commands packet that is exchanged to establish the connection is already mentioned in TABLE 1.

As we have seen in the previous section DLMS/ COSEM application packet can be transmitted with different transport and data link layer, where the added header size depends on the technologies in use. In the case of TCP-UDP/IP the minimum header, size is the below:

- Wrapper overhead is 8bytes
- UDP header is 6bytes
- TCP header is 20Bytes
- IP header is 20 Bytes
- MAC header 14 Bytes

Therefore, with the UDP option, the total header is equal to 48 Bytes, however with TCP total header 62 Bytes.

In the case of CO-HDLC the total header is equal to the LLD and HDLC header which is equal to 12Bytes. Therefore, to meet LoRa constraint concerning the maximum packet size we had to choose the CO- HDLC as a communication profile to do our test.

On the other hand, one of DLMS/ COSEM restrictions concerning the time transmission and reception is that the maximum delay time for a response should not exceed 500ms, and in generally:

$$Tr > Tr_{(theoretical)} + 2 * Tx_{(max)}$$

Where Tr = Time for Response and Tx = Frame retransmission

In addition to the above requirement and knowing that energy packet measurement should be sent every 15 min, we had to choose LoRa parameter in a way that the duty cycle, the time on the air meets the requirements. Based on some calculations we have taken as default parameter for LoRa, an SF =7, the Bandwidth 125 kHz, and coding rate of 4/5.

Base stations are required to be equipped with a GPS receiver. The 1-pps (pulse per second) output of the GPS receiver is used to synchronize all the base stations with an accuracy of up to 12 picoseconds per second assuring a global timing reference. This is very important since for firmware Over the Air (OTA) updates over LoRaWAN class B must be selected for all the SM LoRa nodes that provide specific time slots for downloading the required updates.

The aforementioned scenario was simulated using the FLORA model of the OMNeT++ simulator. Ten smart meters from each building were simulated and deployed on a 1km-by-1km square typical urban area (which is a typical maximum size for a NAN area) with evenly distributed buildings in blocks of 20m x 20m. Packets are being transmitted every 15 minutes, using the default predefined values of LoRa with SF of 7, a Bandwidth of 125 kHz, a

Coding Rate of 4, and a Transmission Power of 14dBm (FIGURE10). The payload size was set to the predefined parameters presented in TABLE 2 for all the related commands/messages (SNRM, UA, AARQ, and AARE).

```
#gateway features
**.LoRaGNic.radio.iAmGateway = true
**.loRaGW[*]**.initFromDisplayString = false
**.loRaGW[0]**.initialX = 500m
**.loRaGW[0]**.initialY = 500m

#nodes features
**.loRaNodes[*]**.initFromDisplayString = false
**.loRaNodes[*]**.evaluateADRinNode = false
**.loRaNodes[*]**.initialLoRaSF = 7
**.loRaNodes[*]**.initialLoRaBW = 125 kHz
**.loRaNodes[*]**.initialLoRaCR = 4
**.loRaNodes[*]**.initialLoRaTP = (14dBm)
```

FIGURE 10. LoRaWAN Energy Meters Simulation Parameters

The network consists of the SM nodes, the LoRa Gateway, the gateway router (gwRouter) for the interface with the Internet, the Network router (nsRouter), and the network server (networkServer) objects as depicted in the FIGURE below. The Smart Meter nodes transmit data to the LoRa Gateway (LoRaGW), which then transfers data to the network server via the gwRouter the internet and the nsRouter object (FIGURE 11).

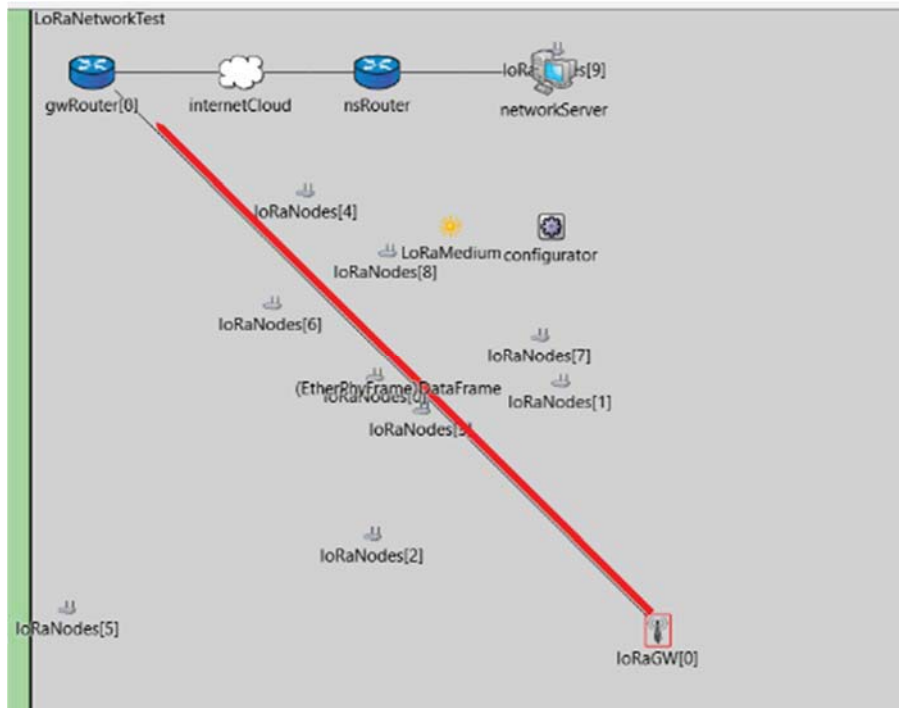


FIGURE 11. OMNeT++ Simulation Topology of the LoRa Nodes

RESULTS and DISCUSSION

The feasibility of a LoRaWAN enabled DLSSM/COSEM integration was investigated and argued on its benefits and demonstrated with experimental implementation. The proposed prototype is tested under the following experimental conditions:

- Class B LoRaWAN Node (for bi-directional communication)
- Simulation duration of 10-days
- 1000 smart meter devices
- Data aggregated on an 8 channel LoRaWAN gateway.
- Gateway deployed at the center of the setup area
- Smart Meter transmitting of the EU863-870 frequency band.
- Channels utilized: 868.10MHz, 868.30 MHz, 868.50 MHz, 868.70 MHz, 868.90 MHz, 869.10 MHz, 869.30 MHz, and 869.50 MHz
- A random (uniform distribution) start of transmission time for each node for the transmission period of 900 seconds
- The sensitivity of each LoRa modem was set at a typical -137dBm
- Isotropic antenna models on all nodes
- Urban environment path loss
- Data on the gateway is forwarded to an application server to be made available

During the scenario 1000 smart meter nodes were simulated in a LoRaWAN Class B configuration, divided into six groups of 125 meters, transmitting at eight different EU863-870 LoRaWAN channels. Those SMs were configured to transmit at an interval of 15 minutes, with a uniform distribution of messages during that timing window. The 15-minute sampling period is suggested by the European Union as the standard interval for energy smart metering.

The simulated system transmitted 96.000 messages per day, for a total of 960.000 messages during the 10-day simulation period. The RSSIs of the received messages were ranging from -105 dBm to -128dBm, a mean of -121dBm, and a standard deviation of 4,78 dBm.

A typical concern presented in LoRa or LoRaWAN configurations and systems is related to the possible collisions due to high channel utilization (FIGURE 12). In LoRa modulation, packet collisions happen when two or more packets are being transmitted at the same time, thus overlapping, and use the same LoRa parameters, such as the same Bandwidth (BW), central frequency, Spreading Factor (SF). The capture effect found in LoRa modulation offers the advantage of successfully receiving a packet with a higher power level of at least 6dB that is transmitted simultaneously with another and still being able to decode it. The chance of a collision depends on many factors, such as the number of nodes, the interval of transmissions, the Spreading Factor selected, the transmission power (TP), etc.

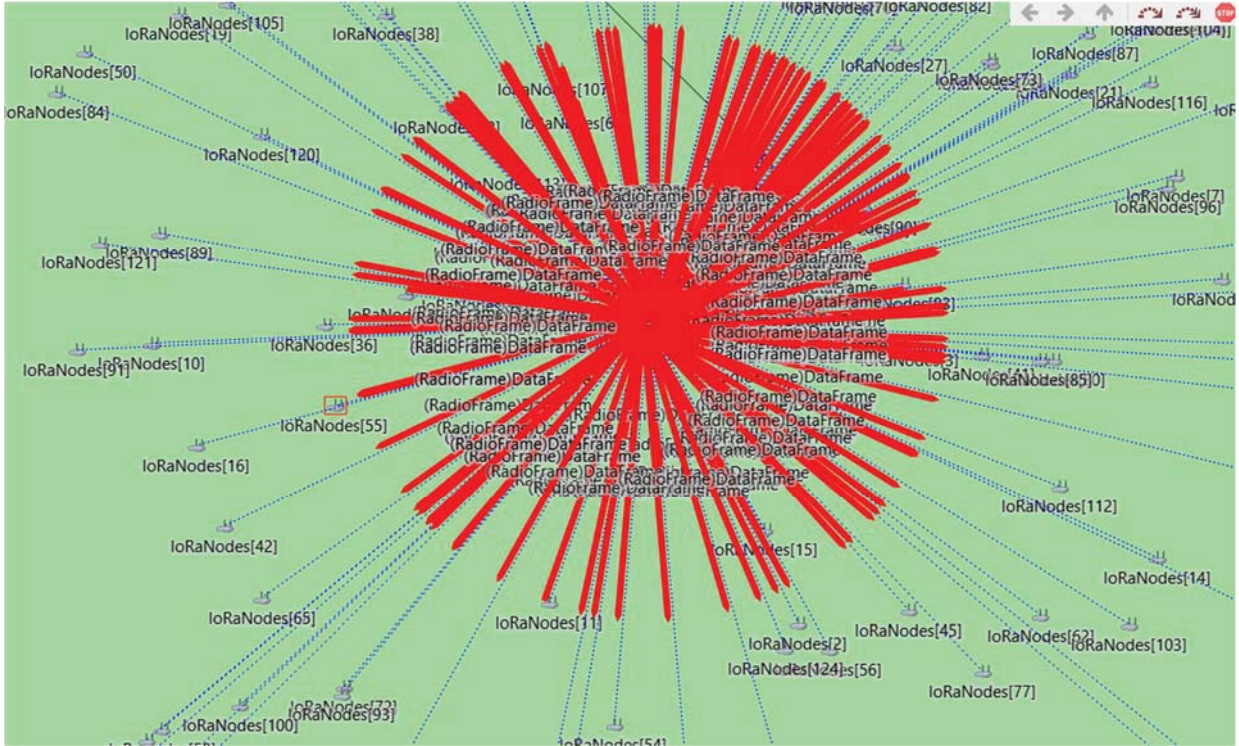


FIGURE 12. Multiple nodes transmitting simultaneously resulting in collisions

To minimize collisions, an experimental timing protocol to variate the interval between the DLMS/COSEM messages has been implemented, using the uniform function of OMNeT++, which returns a random variate with uniform distribution in the specified range. Additional mechanisms can also be implemented, such as Listen Before Talk (LBT) for each LoRa node, to check that the specific frequency band is not utilized by another node before transmitting. However, such a mechanism consumes additional power from the node and is not used by a standard LoRaWAN configuration and thus was not simulated [20].

The simulation results show that, by increasing the number of used channels to eight, as well as adopting the aforementioned timing protocol, only 0,8% of the message transmissions collided, resulting in a 99,2% success rate. This number of collisions is considered acceptable and within the typical design limits in LoRaWAN networks. With a 0.8% collision rate, the system will be fully functional in a high-density Smart Meter area, such as the simulated urban area, while fully complying with the duty cycle requirements and regulations. Any other area, with a lower population density, will have fewer SMs transmitting and receiving data resulting in even fewer collisions.

Taking into consideration the aforementioned results, we have successfully verified the feasibility and the functionality of the proposed DLMS/COSEM compliant implementation over the LoRaWAN architecture. Other experimental scenarios either did not meet the timing constraints of the maximum transmission time of 500ms, or the European regulations for the duty cycle. For example, by changing the LoRa Spreading Factor parameter, the time on-air will be directly affected. Time on air is the time to transmit a packet of data. A Spreading Factor (SF) is specified for each transmitted packet of data, the SF is equal to $SF = \log_2(Rc/Rs)$, where the chirp rate is Rc and the symbol rate is Rs . Therefore, there is a compromise that has to be made between the communication range and the Spreading Factor. When the SF is higher, the data rate is lower and the communication range will be longer. With different SFs the simulation failed to meet the DLMS/COSEM transmission time. As shown in (FIGURE 13) for example, when using an SF equal to 8 for a packet with a payload of 200 bytes, the airtime needed for a complete DLMS/COSEM sequence becomes equal to 594.4ms. As a result, the transmission violates the 500ms time limit and the four-transmissions per hour quote to meet the 15-minute sampling period. Only by selecting a Spreading Factor of 7 both the required transmission time (max 500ms) and the required duty cycle were met.

DR5 SF7 ^{BW} ₁₂₅	DR4 SF8 ^{BW} ₁₂₅	DR3 SF9 ^{BW} ₁₂₅ max size exceeded
338.2 _{ms}	594.4 _{ms}	1,066.0 _{ms}
33.8 _{sec} 106 ^{msg} / _{hour}	59.4 _{sec} 60 ^{msg} / _{hour}	106.6 _{sec} 33 ^{msg} / _{hour}
973.9 ^{sec} _(avg) 3.7 ^{avg} / _{hour} 88 ^{msg} / _{24h}	1,712.0 ^{sec} _(avg) 2.1 ^{avg} / _{hour} 50 ^{msg} / _{24h}	3,070.0 ^{sec} _(avg) 1.2 ^{avg} / _{hour} 28 ^{msg} / _{24h}

FIGURE 13. Time on Air variation with different Spreading Factors

The adoption of the above scenario allowed the transmission of DLMS/COSEM message sequences without violating the imposed payload constraints while at the same time meeting the transmission time requirements. However, an additional delay was detected in the implemented system that is related to the processing speed limitations of the Arduino platform as well as to the network latency during publishing the generated data packets via the TCP/IP stack to the network server. This delay is in the range of milliseconds and can be further minimized by using a more advanced microcontroller with a faster CPU and an embedded high-speed network modem. In any case, the implementation abides by the directives of the European Union for smart energy metering.

CONCLUSION

The ongoing effort of the energy sector transformation towards the Internet of Energy is affected by the wide diversity of communication technologies and data exchange protocols. In this article, we present the benefits of adopting low-cost IoT solutions and Smart Metering communication protocol standards targeting the renovation of existing electricity Grids to Smart Grids with peer-to-peer electricity exchange capabilities. Towards this scope, we propose a Smart Grid Architecture based on the DLMS/COSEM energy-metering communication standard and LPWAN communication technologies, while a Blockchain layer enables the smart-metering data integrity for electricity trading.

A case study has been designed, simulated, and implemented using open-source hardware and software components for the two lower layers of the proposed architecture focusing on the Neighborhood Area Network (NAN) electricity trading case study. Peer-to-peer electricity trading in a NAN was selected because electricity exchange between producers and consumers is vital for the enablement of the massive injection of renewable energy sources in the modern Smart Grids. For this specific case study, an experimental setup has been developed implementing the communication between the SMs and the NAN Gateways using open-source hardware and software components. Both implementation and simulations verified the successful transmission of DLMS/COSEM message sequences without violating the imposed payload constraints while at the same time meeting the transmission time requirements, as imposed by the EU standards and practices.

The proposed implementation of the DLMS/COSEM energy-metering standard over LoRaWAN NAN infrastructure can facilitate and encourage the deployment of further third-party added-value services, like the

aggregate manipulation of multiple distributed energy sources or loads to support scenarios such as virtual power plants, demand-side control for load-shifting, and energy curtailment for power savings through consumers awareness and engagement. And of course, the long-anticipated peer-to-peer energy trading for small distributed prosumers, including the encouraging of localized transactions.

The overall proposed architecture can be easily adopted and widely deployed by local communities due to its low-cost requirements, standards interoperability, and legacy infrastructure compatibility. As such, it can be valuable to the scientific community and the electricity companies for experimentation and evaluation of smart metering implementation strategies based on IoT technologies.

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