WaterGrid-Sense: A LoRa-based Sensor Node for Industrial IoT applications

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WaterGrid-Sense: A LoRa-Based Sensor Node for Industrial IoT Applications

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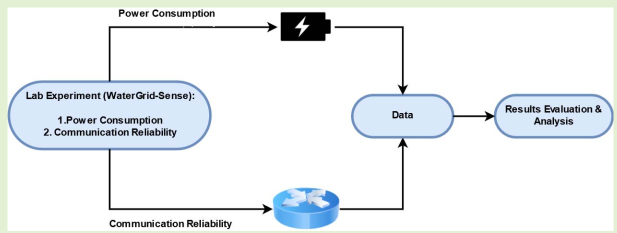
***Abstract*—A Wireless sensor-network is used in the industry to monitor critical parameters. However, its industrial usage in harsh environments presents some challenges to the wireless communication signals such as noise, interference, etc. which contribute to poor quality of service. This paper presents analysis of WaterGrid-Sense, as a full-stack node based on LoRa deployed on a smart water management system. It has a smart interface platform and the ability to monitor and control in real-time. To determine its effectiveness for industrial usage, we conducted experiments to evaluate its power consumption rate and the reliability of the communication link while deployed in a harsh environment. The results obtained show that the sensor node can operate effectively with a battery for a long period of time until a cut-off voltage of 3.2 V. Moreover, despite the harsh environment, the received signals were sufficiently reliable. Thus, a WaterGrid-Sense could be deployed for industrial usage with great reliability and less maintenance costs.**



***Index Terms*— LoRa, LoRaWAN, IWSN, Industrial applications.**

I. Introduction

WIRELESS sensor networks (WSN) is a network technology equipped with sensor nodes to sense, process and transmit data wirelessly to help comprehend the behavior of the monitored environment and to respond to resulting events [1]–[3]. WSN has important attributes such as self-organizing and local processing abilities, making it a driving force for industrial monitoring, controlling, and tracking activities. In particular, WSNs have been widely used in several applications such as medical health care, energy, emergency recovery, agriculture, smart buildings and cities, military rescue, industrial automation and so on [1], [2], [4].

Currently, WSNs have invaded the industrial communication systems and have been considered the future of Internet of Things (IoT). Industrial IoT (IIoT) consists of the autonomous large number of sensors which are deployed to monitor critical parameters such as physical conditions, motor efficiency, vibration, etc. [2], [5]. The data sensed, locally processed, and transmitted is critical to important decision making. Moreover, in order to be in line with the envisioned IIoT applications and take the advantages provided by WSN, the research community has positioned itself in advancing the nature of WSN from sensor nodes designs, to communication technologies and protocols. WSNs are gradually replacing legacy wired systems due to their low-cost, rapid deployment, flexibility, ease of maintenance, scalability etc. [1], [2].

Albeit, WSN has received much interest and adoption from research and development (R&D), several challenges in node designs, communications technologies, and protocols still lingers. Wireless sensors as the engines of WSN are characterized by their small size, have resource constraints, low processing power at the perception layer, and inefficient energy consumption [1], [2]. Due to these challenges, R&D activities have been channeled to: 1.) network communications technologies that are adaptive and do not consume extensive power from network nodes while transmitting data. 2.) Design of intelligent low-cost sensor nodes that are resource efficient and resource aware. 3.) network topologies that are efficient, intelligent and fault tolerant, and 4.) energy harvesting techniques to prolong sensor nodes' lifespan resulting in low maintenance costs. These are important and have to be taken

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into consideration when designing sensor node as they are critical to IIoT solutions [1], [2]. Moreover, a low-cost and low-power sensor is ideal as most IIoT consist of monitoring and tracking. In addition, an energy-harvesting source is a necessity to node development. In terms of node software, authors in [6] advised on the use of various operating systems to ensure flexibility.

The recent developments in wireless communication links have given birth to low-powered networks classified as low power wide area networks (LPWANs), enabling wide area communication for low powered devices. LPWANs are characterized by low-cost devices for low-cost network deployment like IoT, low power consumption, easy to deploy network infrastructure nationwide, secure and extended coverage [6], [7]. An example is the long-range low power wireless technology platform called LoRa [6]. LoRa uses LoRaWAN protocol with the aim to eliminate repeaters, reduce device cost, increase battery life on devices, improve network capacity, and support a large number of device connectivity. Currently, there are lots of developments in LPWAN networks [7] and one important application is in water distribution networks.

This paper presents a LoRa/LoRaWAN based device known as WaterGrid-Sense, which is a smart interface platform with the ability to monitor and control in real-time, the components in smart networks. We evaluated the power consumption of WaterGrid-Sense while in normal operation over time and observed the performance of LoRa when the end-device is deployed indoors while communicating with the gateway (GW) located outdoors. We carried out experiments with the device in terms of the power consumption and the communication link and the data collected were analyzed, and presented. The performance evaluation confirms the effectiveness and the impact of LoRa on energy efficiency and link reliability.

The remaining parts of this paper is organized as follows: Section II presents the related works on Sensor nodes designs, Section III presents WaterGrid-Sense Node, Section IV presents empirical evaluation and Section V presents data collection method. Lastly, we present results and analysis in Section VI and Section VII concludes the paper.

II. Related Works

IIoT presents some challenges such as interference, noise, multipath fading, shadowing and so on which make the establishment of quality of service (QoS) difficult [3], [8]. Industrial environments are hasher as a result of unpredictable variations of temperature, pressure, humidity, and others [9]. Its nature of deployments requires sensor nodes that can handle such environmental conditions. Moreover, the sensors have to be of low-cost with certain limitations such as low rate and low processing power while preserving QoS [3], [10]. Authors in [4] showed that at present, there are no full-stack LoRa network nodes available for IoT deployment. R&D have been using either single board computers and attaching a LoRa module, or plug-and-sense devices that are expensive and not flexible for deployment. Several works have been performed and some are ongoing in regards to the development of WSN nodes. Some of these works are discussed in the rest of this section:

Gungor and Hancke [1] explored the challenges of node design in IIoT and some countermeasures. Some design principles were defined and described technical approaches to assist R&D when designing sensor nodes for IIoT deployments. In the same vein, Stoopman *et al*. [11] presented a system and circuit design, of an external radio frequency (RF) powered 2.4 GHz-based complementary metal oxide semiconductor (CMOS) transmitter integrated into modern autonomous wireless sensor nodes. It uses the dedicated RF signal for energy harvesting and frequency synthesis to eliminate inductors in circuit design, enabling low-complexity, low power, and area efficient solution.

Liu *et al*. [12] designed a low-power sensor node to address the challenge of monitoring building temperature and light intensity for energy-efficient building design. The sensor integrates detecting light intensity, temperature, motion tracking, and compressive image acquisition in a single board. Moreover, *Lu et al.* [13] developed the world's smallest sensor node with ultralow power consumption and buried pump interconnection technology. They explored applicable practical approaches for green sensor node integration with existing systems and assembling them.

Paul *et al.* [14] designed an always-on always-off energy-harvesting wireless sensor node that features a near-threshold voltage IA-32 microcontroller. It is based on edge computing, having a tightly integrated sensor interface, an onboard processing unit, and onboard communication in a single board. Accordingly, Cheong *et al.* [15] also designed a WSN node based on ZigBee technology for ultraviolet detection of flames in WSN safety applications using a spectroscopic technique. In the same vein, Kan and Chen [16] designed and implemented a small-sized wearable inertial sensor node for body motion analysis. To achieve the smallest node size, they printed an Inverted-F antenna and integrated it on a four-layer Printed Circuit Board (PCB).

Somov *et al.* [17] designed a real-world wireless sensor node for gas sensing. To evaluate their sensor, they compared it with an identical platform that uses the Wheatstone bridge. To reduce power consumption, a voltage divider was used instead of a traditional Wheatstone bridge. Also, Chen *et al.* [9] proposed a novel sensor node called Multi-Module Separated Linear underwater sensor node to operate in underwater WSNs. They focused on robust coverage and good communication performance. Furthermore, Imran *et al.* [18] investigated the use of SRAM-based Field-programmable gate array (FPGA) design for duty-cycled wireless vision sensor networks. They present a low-complexity, energy efficient, and reconfigurable vision sensor node using a design matrix, which includes task partitioning between the server and the node addressing both processing and communication energy consumption.

The above discussions are some of the research works and innovations on node design mainly for WSN. Reference [1] emphasized on node power consumption, [14] used energy harvesting techniques from external sources to power their nodes using solar cell while [11] harvested energy from

Fig. 1. Top and bottom view WaterGrid-Sense V2.1.

surrounding magnetic fields. Harvesting is advantageous to sensor nodes and prolong node lifetime in terms of power. Moreover, in terms of node size [1], the smallest node was achieved in [13], for green gas sensing as well as algorithm for energy conservation. The sensor node utilized the CMOS technology since it is good for integrating diverse sensing capabilities, signal processing on a single board [12], and realized as a building block for energy efficient node design. However, what we gathered from the literature is that LoRa platforms are lacking, most manufacturers focus on producing only LoRa modules, hence there is a need to develop a generic monitoring, and control platform based on LoRa.

III. WaterGrid-Sense Node Overview

This section presents an overview of a LoRa-based sensor node called the WaterGrid-Sense.

A. WaterGrid-Sense

WaterGrid-Sense is a LoRa-based sensor node currently used in a smart water management system (SWMS). It is a smart interface platform with the ability to monitor and control in real-time the components involved in SWMS. WaterGrid-Sense comes as a full-stack node that includes a single PCB, processing unit, power management unit, two transceiver interfaces, and sensor interfaces, with a small size design (See Fig. 1). The node provides a wide range of usage for different applications and WaterGrid-Sense supports a long-range communication based on LoRa/LoRaWAN using 868 MHz.

The network stack used for SWMS is a three-layered network stack: application, abstraction and the perception. However, this paper will focus on the perception layer of the stack, which consists of end-devices (EDs) or sensor nodes and the communication medium use with abstraction layer (GW). LoRa is employed in the physical layer, which uses a LoRaWAN communication protocol between the GW and the ED.

B. WaterGrid-Sense Components

WaterGrid-Sense has an onboard LoRa module using LoRaWAN™Class A protocol stack, sensor interfacing, onboard processor, memory and finally onboard battery and solar interfacing. They form the main components of the LoRa device (ED) to function in a LoRa network. Fig. 2 shows the block diagram featuring the major components of the WaterGrid-Sense:

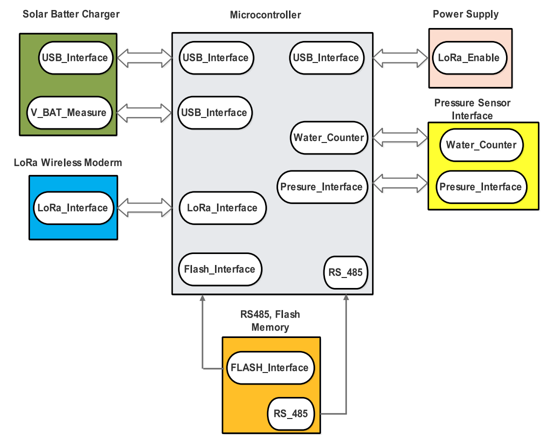

Fig. 2. Block diagram WaterGrid-Sense.

C. General Operations

WaterGrid-Sense is based on LoRa using 868 MHz. Data is transmitted by attaching an external LoRa compliant antenna through the onboard antenna interfacing, which establishes a link with the gateway. The device is powered by a Li-Ion battery and harvests external energy through a solar panel. The node is designed to save energy at all costs, increase the battery life by employing LoRa. LoRa ensures that the battery lasts longer due to the deployed network setup, which uses a star topology and allows inactive nodes to enter sleep mode to save battery energy. Solar energy charges the battery during the day when there is sunlight and node runs on the battery source at nighttime. The battery voltage is 3.7 V, with a capacity of 1000mAh and the maximum charge the battery can handle is 4.2 V at 500 mA.

Currently, WaterGrid-Sense has two sensor interfaces: a pressure sensor and a pulse sensor. The Pressure sensor uses I^2C intra-board communication for data transmission from the pressure sensor, attached to the water pipe, to the WaterGrid-Sense interface. The pulse sensor is attached to a water Reed switch on the actual water meter, the pulse magnetic field sends an analog signal to the pulse sensor interface on the WaterGrid-Sense. Both pressure value and water meter reading embedded into one packet and send to the back-end system through LoRa Gateway. Moreover, other supporting components, such as voltage regulator are in place to protect the device and regulate the functionality of all other components.

D. Handlings

To use the WaterGrid-Sense the following activities are performed:

1) Interfacing the Mote With the Water Meter: The WaterGrid-Sense interfaces with four components for the water meter application: the battery to power up the device; the solar panel, and the Reed switch which connects via cable to the meter. The device and the battery are packed inside a small package and placed inside a metal enclosure while the solar panel is attached to the enclosure to expose it to the sun. Moreover, the antenna is placed atop of the metal enclosure for better line of sight between the LoRa gateway and the device. This is to

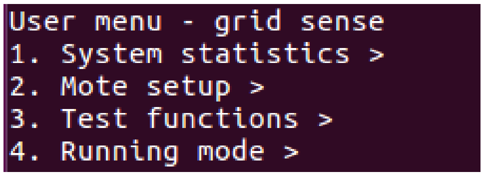

Fig. 3. WaterGrid-Sense configuration menu.

keep it safe and protect against damages from people or natural disasters.

2) Device Configuration: To connect the device to the network the first time, it must be configured via an USB interface. This involves flashing the settings for water metering application to the device. That is, set the present water meter reading, set the clock date and time, and set the water counter multiplier. Once this is done, the device is plugged to the laptop and then we start the configuration program by running the command, sudo minicom –s this command starts a minicom serial port communication program [19] that enables configuration of WaterGrid-Sense. Once the configuration program starts, then a menu with a list of options appears as shown in Fig. 3. available options are system statistics, the system log, view the mote settings, perform testing, run the device by joining the network and so on.

IV. Empirical Evaluation

This section presents investigation into the battery life and battery usage of the device without the external solar energy source as well as its behavior during the initial communication routine when first connected to the network and also, while in operation.

A. Setting

Experiments were performed in a laboratory and conducted for a short duration. While the SWMS deployed at the Council for Scientific and Industrial Research (CSIR) campus and nodes were attached to water meters and pressure sensors installed in the actual water grid around the campus. The deployment environment is considered harsh due to the presence of trees, tall buildings, hills and so on. This allows testing of different network aspects such as the link budget since the network communication is wireless. Moreover, it can be affected by many factors such as distance, obstacles, external network interference and so on [3], [5], [8]–[10], [20]. Since LoRa is a leading LPWAN amongst others, we anticipate good sensitivity, low path loss, and good obstacle penetration [20].

B. Tasks

In this paper, our goal is to evaluate the power consumption rate and the communication link reliability or behavior of the WaterGrid-Sense deployed at the CSIR campus. Tasks are set as follows:

- Study/observe initial communication with the gateway.
- Study/observe communication behavior overtime.
- Study/observe power consumption overtime, and present Current Voltage and Power results.
- Evaluate how long the node can operate on battery without external energy harvester source.

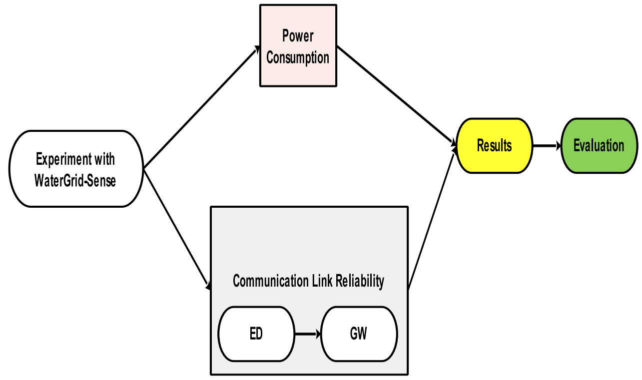

Fig. 4. Experimental design framework.

- Evaluate the reliability and effectiveness of the communication link using RSSI, SNR, SF, PDR and PER.

The experiment scenario implemented is the node located indoors and the gateway located outdoors, hence indoor to outdoor communication. Based on the scenario, we tried to constrain the communication as much as possible to emulate worst case scenarios found in industrial environments.

C. Power Consumption Rate

WSN has been constrained by energy consumption which is considered inefficient leading to several nodes' failure. Thus, extending the lifetime of sensor nodes, power conservation, and management techniques play a significant role in sensor nodes design [1]. To address this menace, several techniques have been proposed such as operating in synchronous mode [5] and so on. This study is conducted to measure how long the node could last if operated only on battery without solar source.

D. Reliability of Communication Links

Deploying WSN in the industry comes with some challenges that emanate from the environment. Industrial environments are harsh (such as noise, interference, etc.) and can adversely affect the deployed wireless communication links [1], [3], [5], [8], [10]. Thus, the deployed technologies in such environments should be able to handle such harsh conditions to ensure the reliability of the system at hand with respect to data transmission. Real-time data will require links that are more reliable and can provide wide bandwidth and high data rates. In this case, WaterGrid-Sense generates and logs data to the server and, therefore, its communication is not immune to the harsh environment. Thus, the data logged will be used to measure the reliability of the communication link when the device is located indoors and communicating with the gateway located outdoors. The experimental design framework is shown in Fig.4.

V. Data Collection

Two kinds of data are collected, the network data and the power consumption data. The network data is collected through the backend server, as the node communicated with the gateway. In addition, the experiment setup depicted in Fig. 5 was used to power up the node and measure its energy

Fig. 5. Experiment setup.

consumption over time while in operation. Upon the setup of the experiment, the link budget was computed using an online link calculator called LigoWave [21]. To calculate the link budget, (1) is used and parameters substituted as described below. The results of this computation are discussed in the next section.

$$P_{rx}(dBm) = P_{tx}(dBm) + G_{system}(dB) - L_{system}(dB) - L_{channel}(dB) - M(dB) \quad (1)$$

where:

- P_{rx} = expected power loss occurrence at the receiver
- P_{tx} = the transmitter power
- G_{system} = system gains such as those associated with directional antennas, etc.
- L_{system} = losses associated with the system such as feed-lines, antennas (height of an antenna) etc.
- $L_{channel}$ = losses due to the propagation channel, either calculated via a wide range of channel models or from empirical data
- M = fading margin, again either calculated or from empirical data

A. Set-up and Variables

The purpose of this experiment is to observe the power consumption of WaterGrid-Sense while in its normal operation over time and to assess its behavior during the initial communication routine when first joining the network, in relation to battery usage. The study presents an indoor to an outdoor communication scenario with the node placed indoors and gateway outdoors. As shown in Fig. 5, the sensor node was programmed, configured, and connected to the network. The battery voltage was 3.7 V, capacity of 1000 mAh, and with a maximum charge of 4.2V at 500 mA was used to power the node. A dummy resistor of 1.4 ohms was attached between the battery and the node to measure the current and voltage. The 868 MHz antenna was attached to the node to connect to the LoRa GW and the experimental setup was left running for two days while the node was in normal operation and the data was logged.

Fig. 5 shows the whole setup, where a Delphin Expert Key 100L [22] data logger was used for logging the data in mV for both the battery and the load created by the dummy resistor. The data logger was configured to record 10 samples per second and then display the corresponding node operation with respect to time. From the logged data, we have load voltage (V_L) in mV, which is the voltage across the dummy resistor, and battery voltage (V_L) in mV, which is the voltage across the battery. (2) computes the current flowing through from the battery, (3) computes the voltage through the node while (4) measures the power consumed by the node

$$I_L = \frac{V_L}{R} \quad (2)$$

$$V_N = V_B + V_L \quad (3)$$

$$P = I^2 R \quad (4)$$

$$V_B = V_L + V_N \quad (5)$$

where I_L is the current from the battery through the load to the circuit, V_L is the voltage across the dummy resistor, R is the 1.4 ohms' dummy resistor, V_N is voltage at the sensor node, V_B is battery voltage calculated using (5) while P represents the power obtained through (3). The node under test was configured together with other nodes connected to the network, to transmit data after every 10 minutes. The data was logged over two days and used to measure the reliability of the communication link using the received signal strength indicator (RSSI) and the signal to noise ratio (SNR).

B. Gateway

The gateway utilized is the MultiConnect Conduit from Multitech. It is a flexible gateway that offers configurability, ease of management, and communication scalability for industrial IoT. For our network, it is deployed outdoors, placed 10 meters above a hill on CSIR campus.

VI. Results and Analysis

This section presents the results and their analysis from the experiments performed.

A. Link Path

This section presents the results of the link budget computed by the online calculator as shown in Fig. 6. It shows path loss, receiver signal level, thermal fade margin, link available, and the distance between the node and gateway [21]. In Fig. 6, a limited link occurs when after all the link calculation the incident power at the receiver is lower than that required, to meet the SNR requirement of the receiver in order to be able to demodulate the received data. LoRa, on the other hand, can detect signals up to -134 dBm below the noise floor. Moreover, normalization is a process of adjusting the height of the antennas in reference to the line of sight (LOS) shown on the LOS path after the calculation; this process is required to improve the link. Therefore, the gateway is placed 10 meters above a hill.

B. Power Consumption Rate

For the power consumed by the WaterGrid-Sense device deployed for two days with external power source, Fig. 7 shows the initial operation when the node performs join operation with the LoRa network server. Multiple beacons were sent to the server and after the joining operation, the sensor node enters the active state for some time until it enters sleep and transmission mode.

Fig. 6. Link-budget estimation calculation results.

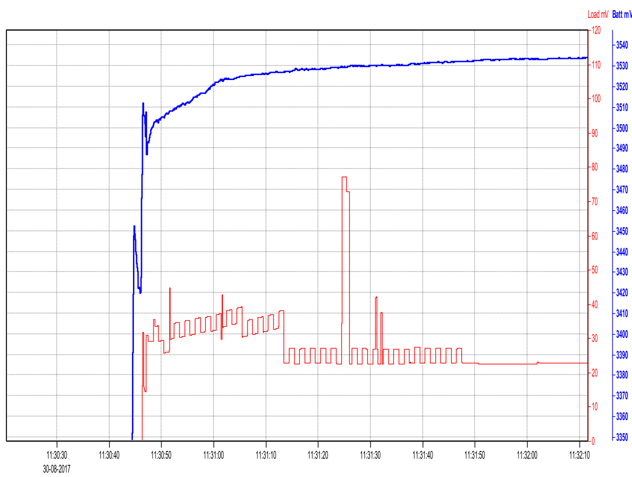

Fig. 7. LoRa join operation.

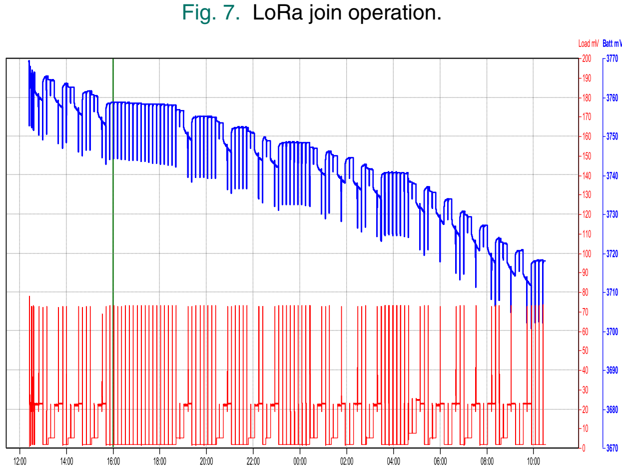

Fig. 8. Node operation over time.

[Fig. 8](#) shows the operation of the node against time. The blue line represents the battery voltage usage and the red line represents the different states of the sensor node over time. The voltage dropped from 3.770V to about 3.703V over a period of 1 day. The sensor node has 3 different operational states: sleep, sensor-reading, and radio-transmission. The sleep state uses 0.1 mV, where no operation is active on the device and the active state is divided into two states which are the Sensor-reading state which uses about 23mV and the Radio-transmission state, which uses 73mV. Accordingly, more voltage was drawn from the battery as the sensor node transmits the data to the gateway. The advantage is that the transmission only occurs after every 10 minutes, contributing more to energy conservation.

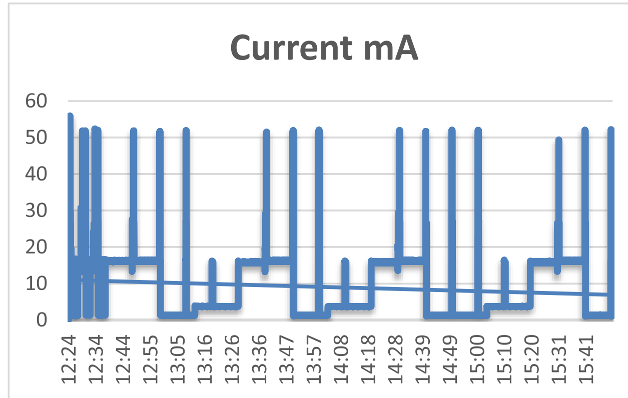

Fig. 9. Current with respect to time.

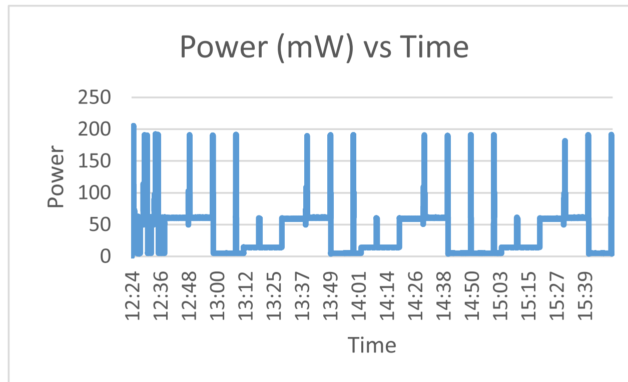

Fig. 10. Power consumption with respect to time.

Furthermore, the sensor node under observation was monitored from the server side during its operational states. We found that it sometimes initiates the linking procedure with the network due to weak received signal strength from the gateway side. However, the node has the capability to go from the sleep state to radio-transmission state and transmit data successfully as shown in Fig. 9. From around 15:40 pm to 18:40 pm the sensor node was operating from the sleep state and radio-transmission state, which resulted in a constant voltage and consequently, a lot of energy conservation as well. Power consumed in respect to the states of the sensor node during transmission was 190 mW, sensing states or idle state the node is 52 mW and 0.1 mW for sleep state as shown in Fig. 10. In general, the battery consumed was about 0.067 V per day, which resulted in the battery lasting about 2 months.

In the same vein, after the stipulated period, an energy harvesting technique was introduced via a solar panel to charge the battery, thus, extending the lifetime of each sensor node on the network. To obtain the cut-off point required to drive sensor node voltage, the sensor node was powered with a

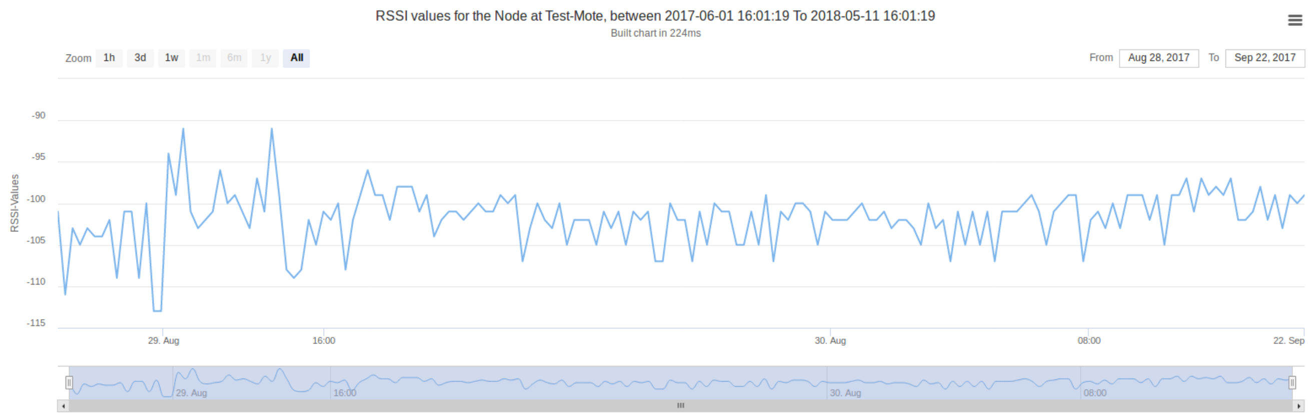

Fig. 11. Test node RSSI over time.

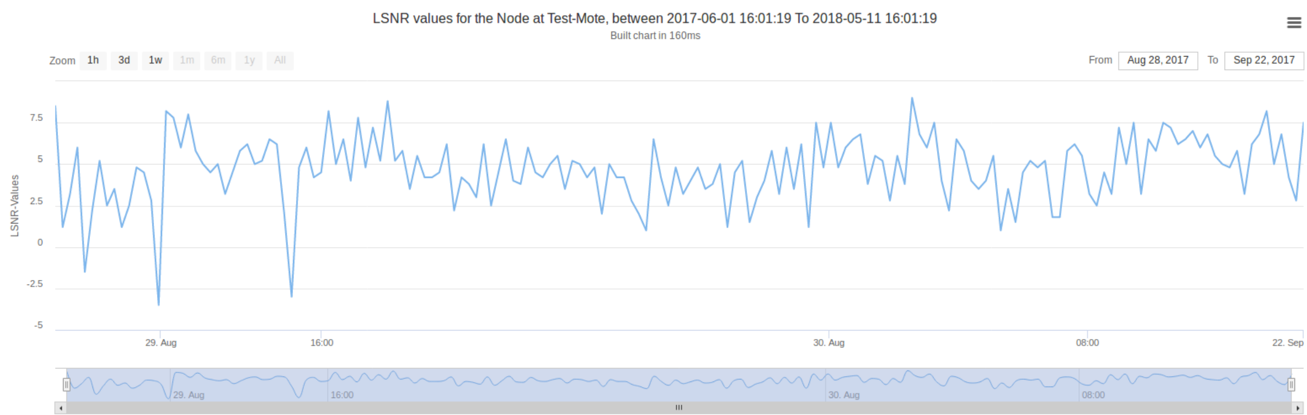

Fig. 12. Test node SNR values over time.

TABLE I
AVERAGE POWER CONSUMPTION

Variable	Transmission	Idle/Reading	Sleep
Voltage	73 mV	23 Mv	0.1 mV
Current	0.52 mA	0.16 mA	0.1 mA
Power	190 mW	52 mW	0.1 mW

*V = volt, A = Ampere, W = Watt

voltage supplier and the voltage was reduced accordingly, and the resultant voltage cut-off was 3.2V.

The node while in operation has three states as observed in Fig. 7, Fig. 8, and Fig. 9, the transmission state (Tx), the idle/reading state, and the sleep state respectively. The results in Fig. 9 show that during Tx the node draws an average current of 0.52 mA, during the idle state 0.16 mA and 0.1 mA for sleep state. These results, in the context of this paper, are acceptable and correspond to works found in the literature.

C. Communication Link Reliability

In the above experimental setup, we tracked the network data from the server side as it was transmitted from the test sensor node shown in Fig. 5. The goal was to measure the reliability of the communication link of LoRa when the ED deployed indoors is communicating with the gateway located outdoors. Fig. 11 shows the RSSI measured in dBm. The best value attained was -91 dBm and worst value was -119 dBm.

TABLE II
AVERAGE COMMUNICATION PERFORMANCE

Node	RSSI (dB)	SNR (dB)	SF	PDR (%)	PER (%)
Test Node	-101.69	4.7	12	99.42	0.58

The RSSI indicated the received signal power level after a combination of all possible loss along the propagation. The higher the RSSI value the stronger the received signal strength. Accordingly, LoRa can detect signals up to -134 dBm below the noise floor. This makes it one of the robust LPWAN wireless communication technology. Also, Fig. 12 presents SNR with ranges between 9 dB down to -3.1 dB throughout.

VII. CONCLUSION

IIoT literature on sensor nodes revealed that the design of low powered nodes is still an ongoing research. In this paper, we conducted node experiments using a novel LoRa based full-stack sensor node for IWSN called WaterGrid-Sense. It integrated all the main components on a single board and followed the SoC design for energy conservation. As the state-of-the-art node designs suggest that a node should have an external or on-chip energy harvesting source, WaterGrid-Sense employs a solar panel to harvest energy and recharges the battery source that powers the sensor node.

To assess the WaterGrid-Sense for deployment, we conducted two experiments, 1) power consumption of the sensor node and, 2) communication reliability provided by the sensor node. The results obtained show that without the external energy harvester the sensor node can operate for more than two months on a battery until cut-off voltage, which is 3.2 V. In terms of communication reliability, the node produced outstanding results as summarized.

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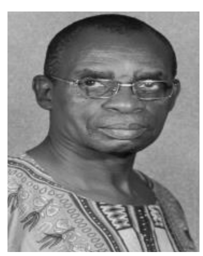

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