IoT Devices and Applications based on LoRa/LoRaWAN

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Abstract— Internet of Things (IoT) has revolutionized the traditional Internet where only human-centric services were offered. It has enabled objects to have the ability to connect and communicate through the Internet. IoT has several applications such as smart water management systems. However, they require high energy-efficient sensor nodes that are able to communicate across long distance. This motivates the development of many Low-Power Wide Area Networks (LPWAN) technologies, such as LoRa, to fulfill these requirements. Therefore, in this paper, we survey IoT devices and different applications based on LoRa and LoRaWAN in order understand the current stream of devices used. The objective is to contribute toward the realization of LoRa as a viable communication technology for applications that needs long-range links and deployed in a distributed manner. We highlighted the device parameter settings and the output of each experiment surveyed.

Keywords—IoT, LPWAN, LoRa, LoRaWAN, wireless sensor network.

I. INTRODUCTION

The Internet of Things (IoT) paradigm presents itself as the next future of Internet. It is aiming at giving any object (i.e. thing) the ability to connect to the Internet and communicate with other objects ranging from cars, animals, plants etc. Several types of research are been conducted on IoT, which led to its improvement and developing categories based on specific projects undertaken. For instance, formed categories that are commonly known are Smart Homes, Smart Cities, Smart Transportation, Smart Environment, Smart Grid and Smart Water Systems [1], [2]. There is no fixed model of deployment for IoT but all depends on use cases. One solution of IoT-based in one category can serve as a solution in another category. This has led to experts anticipating the connection of more than 50 billion objects by 2020 [3].

Communication is the key point that brings all Thing's in IoT together to form an Internet of Things network. Wireless communication (WC) provides the benefits of mobility, cable-less, easy to add more devices to the network, and easy to give any object the ability to connect to the internet [4]. Moreover, Wireless Sensor Networks (WSN) is one of the most successful technologies used for IoT deployments. WSN presents itself as a key part of IoT because it serves a purpose of enabling the interconnection and integration of the physical world objects with cyberspace. It also makes IoT developments and deployments inexpensive due to advances and innovation taking place in WC's. WSN consists of low-powered wireless sensors that are valid as infrastructure for a deployment that will serve for a longer time. However, WSN is associated with many inherited challenges due to the sensor nodes constraints such as energy capacity, computational capability, and communication bandwidth [5], [6]. Network management and security still require more attention [7]–[10].

Different scenarios require a different model of deployment with different parameters of a network. For instance, smart transportation will require a network deployment that is able to handle mobility, smart cities will require network deployment that will be able to handle long-range communications, and smart environment will require network deployment that will be able to handle natural disasters and so on. Today, several WC technologies have been developed in each perspective ranging from short range (ZigBee, 6LowPAN [11], [12]) to the long, medium range (LoRa, Sigfox, UNB, weightless, LTE-M, etc.) [13]. Low Power Wide-Area Networks (LPWANs) will improve Existing and many new IoT applications due to the low power and long-range communication associated with them. LPWANs operate in wireless bands that are licensed and unlicensed. The major characteristics of LPWANs that should guide the design for IoT networks are:

- Low-cost devices for low-cost network deployment
- Low power consumption
- Easy to deploy network infrastructure nationwide
- Secure
- Extended coverage

Currently, there is a lot of development in LPWAN networks. However, one technology cannot solve all challenges. Thus, LPWANs are deployed to address only a portion on challenges in IoT. LPWANs are specifically targeting situations where extended coverage is most needed, with low cost of deployment, involving devices that are delay tolerant, do not need a high data rates and require low power consumption network [14]. In particular, monitoring of a system or conditions is a perfect case where LPWANs fit. In this case, we assume LPWANs can be a perfect fit for Water Distribution Networks (WDN) where small data is collected in order to monitor different parts of the network. This paper performs a comprehensive survey of LoRa devices and their

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behaviour in different applications to see the potential viability to fit on water distributed network for monitoring purposes.

The rest of the paper is organized as follows: Section II present an overview of LoRa and LoRaWAN in terms of IoT devices and applications based on LoRa technology. Section III present comparison and Section IV is the paper discussion. Section V concludes the paper.

II. LoRa and LoRaWAN Overview

LoRa is a long range low power wireless technology platform that uses unlicensed radio spectrum in the industrial, scientific, and medical radio band (ISM band) [15]. LoRa aims to eliminate repeaters, reduce device cost, increase battery lifetime on devices, improve network capacity, and support a large number of devices. It is a physical layer used for long-range communication. To achieve low power, most wireless technologies use Frequency Shift Key (FSK) modulation. However, LoRa uses Chirp-spread-spectrum (CSS) modulation to maintain low power characteristics for the benefit of increasing communication range. It is the first implementation for low-cost infrastructure to be commercialized using CSS. CSS has been used in long-range communications by military and space agencies due to its ability to withstand interference.

LoRaWAN protocol is a wireless communication protocol developed by LoRa Allience to serve for challenges faced with long-range communication faced with IoT. It specifically deals with long range, low power consumption at a low bit rate due to its LoRaWAN-based system architecture. The protocol and its network architecture have a great influence in determining a node battery lifetime, network capacity, quality of service (QoS), security, and a variety of applications served by the network.

III. LoRa and LoRaWAN Devices with Applications

This section discusses several devices used for LoRa deployments together with their configurations and briefly highlights which applications they were used in. A comparison amongst the devices used and applications is provided in the next section.

A. *LoRaSIM [16]*

Bor *et al.* [16] investigated the scalability of a network composed of LoRa devices using LoRaWAN protocol. Their setup is based on a scalable network for a smart city application. To be able to study the link behaviour, they use NetBlocks XRange SX1272 LoRa module. They first studied the link behaviour of the device with practical experiments and they specified the limits to (i) communication range independence of communication settings Spreading Factor (SF) and Bandwidth (BW) (ii) Capture effect of LoRa transmissions depending on transmission timings and power. The purpose of their study was to assist them in the development of models that will help them build a LoRa simulator, which they called LoRaSIM. According to the authors, the simulator captures link behaviour and enables evaluation of scalable LoRa networks. They performed the smart city experiment on the LoRaSIM. The results showed that a typical city would deploy at most 120 nodes per 3.8 ha. This is possible due to the typical ALOHA protocol. However, with dynamic multiple BS (gateways) the network would scale well.

B. *Mobile LoRaWAN* [13]

Petäjäjärvi, *et al.* [13] conducted a real-life research experiment to investigate the coverage of a LoRa network as distance increase between the transmitter(ED) and receiver (BS). The goal of their research was to find the maximum communication range the network setup can reach, based on the location of deployment. Their findings can be used in locations similar to theirs as LoRaWAN parameters are known to be differed according to locations. They used the maximum SF which also improved the base station sensitivity. LoRaMote was the ED mounted in a mobile car and boat for the ability to measure the packets transferred and lost as the moving car increases the distance between the ED and Kerlink's BS that was placed at the top of the building in University of Oulu at a height of 24 m. Their experiment focused on percentages of packets lost and transmitted. The frequency channels used were restricted to the EU regulations. However, the nodes were able to choose between the available 6 channels for communication. Their results show 80% successful transmission for 5km, 60% between 5-10km and reasonable loss for distance more than 10km for the node attached to the car. On the boat, 70% successful packets transmission for up to 15km and communication range was reached for 30km. From the results, they were able to present to attenuation model that can be used to estimate base station density.

C. *LoRaWAN Single Node Throughput* [17]

Authors in [17], also conducted a LoRaWAN experiment to evaluate the maximal throughput a single node can obtain, their test used 6 channels of 125KHz, and varied SF from 7-12. Several tests were conducted and in each test, 100 packets transmitted with a maximum payload of 51 bytes. The results showed that for low packet sizes the channel duty cycle is not the one limiting the throughput but rather the period the ED receive windows opens, the ED cannot transmit packets once the receiver windows are still open. The authors concluded that the maximum size of the frame depends on data rate used. Furthermore, LoRaWAN does not have a mechanism to split large payloads over multiple frames and that a transmission should never send a payload larger than 36 bytes. This is the largest payload for LoRaWAN resulting to loss of capacity if a large amount of data was sent. They also suggest that a fragmentation mechanism should be added in the next LoRaWAN specification revision.

D. *LoRa Indoor Deployment* [18]

Neumann *et al.* [18] conducted an indoor environment LoRaWAN experiment to evaluate its performance and observe its limitations and define its use in 5G networks. They showed that limitations were driven by the ISM band regulation, which affects the amount of data sent per day. In addition, if not set correctly at the initial configuration of the ED data rate can also be a factor of loss. They deployed one gateway and one minimal server that decodes and log the sent LoRaWAN frames to the database. The BS is made up of a Raspberry Pi 2, Interfaced with IMST IC880A through an SPI bus. The packet forwarder code used is from Semtech and the ED made up of Raspberry Pi 2 interfaced with LoRa mote RN2483 through UART interface. Parameters settings they used are presented in TABLE I.

E. LoRa Indoor Propagation [19]

Gregora *et al.* [19] conducted a research experiment based on LoRa to test indoor signal propagation capabilities for LoRa technology long range coverage. Two scenarios were performed in which the receiver was placed in the basement of a building and on the roof top, with transmitter position being altered as measurements are taken. The devices they used were custom made for the experiment. IMST iU880A was used as an ED transmitter and it was connected to a PC by USB serial converter. The node setting is controlled from WiMOD LoRAWAN EndNode Studio. The experiment parameter settings are shown in TABLE I.

F. LoRa FABIAN [20]

Petrić *et al.* [20] described their experiment and designed their LoRa based setup called FABIAN deployed in the city of Renne. Star topology following ALOHA protocol was used as the network topology. Evaluations were performed to measure QoS. The study focused on the traffic between the nodes and base stations. They were able to generate traffic similar to that can be used in applications such as sensor monitoring. Observed performance metrics such as packet error rate (PER), and RSSI related to LoRa Physical layer and signal noise ratio (SNR). The nodes used were composed of an Arduino and FroggyFactory LoRa Shield running a modified version of contiki OS. The ED is configured to be able to communicate using the LoRaWAN protocol and Kerlink as the BS. They varied parameters that can affect QoS and results were presented

G. LoRa Wi-Fi [21]

Kim *et al.* [21] designed a multi-interface module that integrates both Wi-Fi and LoRa to achieve low power, long range, and high data transmission. This was aimed to provide LoRa technology with the ability to transmit the high amount of data and offer different services with various sensors. The Elix board provided Wi-Fi and LoRa device composed of Semtech and Waspmote SX-1272 chipset, Raspberry Pi and Arduino. The Wi-Fi handler and LoRa handler sends data through Wi-Fi and LoRa module respectively. They system is integrated with a power and data scheduler that chooses between Wi-Fi and LoRa according to the priority of sensed data to regulate power usage. The experiments were much based on measuring the RSSI and SNR, from 6 km to maximum of 20 Km communication range.

H. LoRaWAN Channel Access [22]

Bankov *et al.* [22] studied the performance of LoRaWAN based on channel access, as the most important component for machine type communication (MTC). The aim of their work was also to evaluate the weakness of LoRaWAN and propose a solution. Evaluating LoRaWAN based on simulations does not provide full potential of such system. Thus, their evaluation was based on a more realistic approach. The evaluations based on channel access showed that transmission collisions do occur when two transmissions at the same data rate overlap in time. Their network setup consists of N motes connected to a gateway. One channel is used for downlink and 3 main channels for uplink all channels are 125 KHz wide. Devices are set to use data rates from 0–5, which is a SF of 7–12. All motes are set to transmit 64-bytes payload (51-byte being Frame Payload). They also studied packet error rate (PER) and packet loss ratio (PLR) for load less 0.1 per second. The network experience small packet loss and when load increases more packet loss is experienced due to collisions that occur. With 100 motes, packets can be sent once per 20 minutes. The possible solution proposed is then to increase the density of LoRaWAN gateways.

I. PHY and Data link testbed [17]

Augustin *et al.* [17] designed a testbed to thoroughly evaluate the performance of the data link layer and the physical layer both via simulation and field tests. Their work is remarkable because they presented the in-depth analysis of the LoRa components. Similar to authors in [13], the study evaluated the LoRa network coverage among others by placing the gateway indoor and the end-device node in outdoor space. They varied the distance and the SF as they measured packet delivery ratio and their results show that better coverage and packets were achieved on the maximum SF, which is 12 than other lower SF. They concluded that a LoRaWAN network is able to achieve higher delivery ratio.

J. LoRaWAN Nordic Cities [23]

Ahlers *et al.* [23] On their on-going research projects for measuring urban greenhouse gas emissions in Nordic cities, deployed a LoRaWAN. It is a low cost automated system for greenhouse gas emissions monitoring network around their city. Their system addresses the issue of not having a system that gives statistics about gas emissions in Norway and making the data available to every citizen via municipality platform. They used two sensor technologies namely, Libelium's Plug & Sense Smart Environment Pro (PSSEP) and Sodaq's Autonomo (SA). LoRaWAN was the communication protocol used to cover their minimum gateways deployed across the city. In support of the battery life of nodes, they mounted solar panel beside their node for power support. Nodes were equipped with different sensors to measure different parameters of gasses. They measured CO2 levels for a period of 6 months and the battery power remained constant throughout this period. They concluded this type of network is viable or industrial sensing.

K. uPnP-WAN temperature monitor [24]

Ramachandran *et al.* [24] introduced uPnP-WAN device aimed at providing plug and play for none expects in embedded systems for IoT. The device said to be able to achieve a range of 3.5 kilometers in ad-hoc suburban deployment. The main purpose of their work was to design a system to monitor the temperature of blood fridges in DC Congo. Their plug-and-play device battery said to last 6 years in realistic real work operation. The geolocation of antenna elevation has an impact on the effectiveness of the range. uPnP-WAN uses Microchip's

RN2483 LoRa module for class A LoRaWAN operation. AtMega1284p micro-controller with 10 MHz MCU, 16 kB RAM, 128 kB Flash, is used to implement uPnP running Contiki OS with Erbium CoAP stack. The uPnP and RN2483 are interfaced by UART communication. Evaluations were made on battery life and range. The system proved to reach 3.5 km range because of LoRa single-hop deployment architecture. Moreover, compared to their previously uPnP-WAN project that used mesh, the battery now from calculations is able to last 10 years. The uPnP-WAN was configured to transmit sensor reading to the gateway every 15 minutes.

L. *Troughs Water Level monitoring system* [25]

Tanumihardja and E. Gunawan [25] designed a system to monitor troughs water level using WSN that deploys LoRa and LoRaWAN as their physical layer and communication protocol. They designed a system for cattlemen to monitor their trough ubiquity using their personal devices. The gateway used is a Raspberry Pi to push the sensed data to the server. The system is said to be self-configuring, as it is designed for cattlemen with a minimum background in engineering. ATMega is used for the deployed nodes around the farm to satisfy the low power system for remote while the float switch GE-1307 is used as the sensor to read water condition. In the study, bandwidth was measured as the distance between the gateway and node was adjusted due to how low the nodes were placed while the gateway was placed on top of the house that can be 8 meters high. They conclude that for this setup horizontal antenna polarization is suitable.

M. *EM Energy Harvester* [26]

Orfei *et al.* [26] conducted an interesting research in terms of battery-less LoRa wireless sensor network deployed in a real world application to monitor road condition of a bridge by measuring the temperature of the asphalt and the presence of rain. Electromagnetic vibration energy harvester based on Halbach configuration powers the system. The energy from the harvester stored in supercapacitor to power the node. The critical component of the system is the ARM Cortex M0+, designed by Microelectronics. The MAC for this experiment is disabled for the LoRa module to keep power consumption low. Two antennas are used on the transmitter 433 MHz and 868 MHz.. In addition, current and voltage are measured with respect to time and the energy harvested is 123 mJ.

N. *WaterGrid-Sense* [2]

Abu-Mahfouz *et al.* [2] conducted a study on Water Distribution Network (WDN) and started a Smart Water Management System (SWMS) for water loss reduction. SWMS consists of three parts, smart water network, dynamic hydraulic model, and active network management. Initially, they developed a meter interface node [27], based on modulo sensor node [28] to collect water meter readings and send it to the gateway. They also developed a WaterGrid-Sense, which is a smart interface platform with the ability to monitor and control in real-time the components of a WDN. WaterGrid-Sense supports short range communication based on IEEE 802.15.4 that use 2.4GHz and long range communication based on LoRa using 868 MHz. The mote it attached to seventeen water meters and five pressure sensors. The collected data is fed into the dynamic hydraulic model which consists of various techniques such as pressure management system [29]–[31] and leakage detection and localization algorithm.

IV. Comparison and Discussion

In TABLE I, we present the parameters of different reviewed device settings based on their different LoRa and LoRaWAN applications. We should note that the above experiments approached their deployments differently; some used traditional single board computers attached with LoRa modules designed by different vendors which might behave differently accordingly and some used complete stack plug and sense devices. Though LoRa devices operate differently according to different regional regulations mainly in USA, Asia, and EU. Moreover, some are built specifically for specific regions. A LoRa device comes with default settings and can be adjusted based on the use case. As shown in TABLE I, it is clear that almost all the reviewed devices used the default 125 kHz bandwidth, which supports all SF 7-12. One important aspect about bandwidth channel is that it does not change regardless of where the channel is located on the spectrum. In [16] they used three different BW 125 kHz as default, 250 kHz which is between DR3 and DR4, and lastly 500 kHz which is used for both upstream and downstream. upstream it has 8 channels from 64-71 at DR4 while downstream also has 8 channels from 0-7 at DR10 to DR13. Moreover, most devices used transmission power of 14 dBm, which ranges between SF of 11 and 12 for good results. The transmission power of 20 dBm as used by [19] is considered good as it enables the system to mitigated noise interference and increases signal propagation. This transmission power is mostly used in 2.4 GHz ISM-band for relatively wide channels. The results show common parameter settings across the applications. However, more of exploration with different settings would enable a researcher to discover optimizations techniques for LoRa.

Range is at the core of LoRa devices. The shortest range observed in one of these studies was 50cm in [18]. LoRa always gives near nodes first priority to reduce network congestion and near devices are able to transfer at a low TOA. Current research in LoRa technology is more focused on testing its ability and ensure long-range communication with low power consumption as the future innovations for IoT. In addition, satisfying results are observed in studies done by authors in [13], where they reached a link of 30km between the gateway and the ED.

From the articles considered in this paper, we found that different scenarios have employed to test the viability of LoRa technology such as the indoor deployment by [18] and [19] as well as outdoor deployment by [23] and [25]. LoRa devices provide flexibility as they fit in most network setups, and integrate well in existing networks and technologies. For instance, Khan et al. [21] designed a system that combines LoRa with Wi-Fi to achieve maximum throughput together with long range. The most notable application was performed by Raza and Kulkarni [26] where they designed a LoRa device that is battery-less and harvest energy from the vibrations of the bridge as the cars pass by the bridge. Their solutions show that there are innovation opportunities with LoRa technology depending on the type of application carried out and the location of deployment.

In a nutshell, TABLE I shows the compared parameter settings of different LoRa devices and modules to see their differences as applied in different applications. It is visible that using a LoRa device in a network does not require much configuration, rather a configuration according to the setup needs. The future of LPWANs relies on the devices used, if these devices are able to meet the requirements and get equipped with functionalities that are more intelligent, they can create a broad future for IoT.

TABLE I. COMPARISON OF LORA APPLICATIONS

Device:	Nodes	Range	SF	Band	BW KHz	Payload (bytes)	TX Power (dBm)	Application	LoRa Module	Output
LoRaSIM [16]	2	100m	7-12	868MHz	125 250 500	20	2-17	Smart City (Simulation)	NetBlocks XRange SX1272	LoRa simulator that enables evaluation of scalable LoRa networks
Mobile LoRaWAN [13]	2	30km	-	868MHz	125	50	14	Testbed	Semtech SX1272,	attenuation model that can be used to estimate base station density
Single Node Throughput [17]	1	2.8km	7-12	868MHz	125	51	14	Testbed	Semtech SX1276 MBED	evaluate the maximal throughput
LoRa Indoor Deployment [18]	9	60m	12	863-870 MHz	125	4	14	Indoor experiment	Microchip RN2483	LoRa limitations
LoRa Indoor Propagation [19]	1	-	12	433MHz 868MHz	125	-	20	Indoor testbed	IMST iU880A	Best placement of devices when deploying
LoRa FABIAN [20]	-	-	7-12	-	125	64	-	Testbed & Smart City	FroggyFactory LoRa Shield	Network Protocol Stack and experimental network setup (LoRa FABIAN)
LoRa Wi-Fi [21]	-	6 km 20km	12	-	125	-	-	Testbed	Waspmote SX-1272,	System that uses both WiFi and LoRa
LoRaWAN Channel Access [22]	-	-	7-12	-	125	64	-	Testbed	-	Increase gateway density to accommodate more motes in the network
PHY and Data link testbed [17]	-	2.8km	7-12	-	125	-	2	Testbed	Semtech SX1276 MBED	Higher Delivery Ratio
LoRaWAN Nordic Cities [23]	10	-	-	-	125	54	-	Testbed, Smart City	Libelium's plug & sense	municipal greenhouse gas monitoring
uPnP-WAN [24]	-	3.5km	12	868MHz	125	-	-	Monitoring System	Microchip RN2483	monitor temperature of blood fridges
Troughs Water Level monitoring system [25]	5	1 km 5km	12	915MHz	125	26	14	Troughs Water Level monitoring	Atmel HopeRF RFM95	System utilized by cattlemen
EM Energy Harvester [26]	3	-	12	433MHz 868MHz	125	8	14	monitor road condition of a bridge	Microchip RN2483 by	Battery less LoRa wireless sensor.
WaterGrid-Sense [2]	15	1.25km	7-12	2.4GHz 868MHz	125	18	-	Smart water management system	Microchip RN2483	Smart Water Management System (SWMS)

V. CONCLUSION

With advancement in IoT, devices that are able to communicate in a long-range space and consume less energy are a necessity. LPWAN has been formed or realized to serve this challenge. Currently, there are several innovative developments in LPWAN networks and technologies such as LoRa. In this paper, we surveyed IoT devices and applications based on LoRa/LoRaWAN, with the goal of discovering the current deployment of devices that are used in LoRa networks and the type of applications they are used for. From the analysis and evaluation performed, the results are shown in TABLE I. We found that current works done on LoRa are similar and the devices used are standard across all the applications. Single board computers with LoRa modules attached were used in most deployments for LoRa communication. In addition, some applications used plug and sense devices, which are full-stack for LoRa deployment, but their shortfall is that they can be expensive for large-scale deployment. Moreover, the current deployments can be classified into three groups: real implementation, testbeds and simulations. However, the applications that dominate are those for monitoring purposes. Moreover, to increase the adoption of LoRa in the future, it is necessary to develop a cross platform device for monitoring and control based on LoRa.

REFERENCES

[1] A. M. Abu-Mahfouz, T. Olwal, A. Kurien, J. L. Munda, and K. Djouani, "Toward developing a distributed autonomous energy management system (DAEMS)," in *Proc of the IEEE AFRICON 2015 Conference*, 3. 14–17 September, Addis Ababa, Ethiopia, 2015, pp. 1–6.

[2] A. M. Abu-Mahfouz, Y. Hamam, P. R. Page, and K. Djouani, “Real-time dynamic hydraulic model for potable water loss reduction,” *Procedia Eng.*, vol. 154, no. 7, pp. 99–106, 2016.

[3] Want, Roy, Bill N. Schilit, and Scott Jenson. "Enabling the internet of things," *Computer, vol.* 48, no. 1, pp 28-35, 2015.

[4] Z. Khan, J. J. Lehtomaki, S. I. Iellamo, R. Vuohtoniemi, E. Hossain, and Z. Han, “IoT Connectivity in Radar Bands: A Shared Access Model Based on Spectrum Measurements,” *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 88–96, Feb. 2017.

[5] H. I. Kobo, A. M. Abu-Mahfouz, and G. P. Hancke, “A Survey on Software-Defined Wireless Sensor Networks: Challenges and Design Requirements,” *IEEE Access*, vol. 5, no. 1, pp. 1872–1899, 2017.

[6] K. M. Modieginyane, B. B. Letswamotse, R. Malekian, and A. M. Abu-Mahfouz, “Software Defined Wireless Sensor Networks Application Opportunities for Efficient Network Management: A Survey,” *Comput. Electr. Eng.*, 2017.

[7] M. Ndiaye, G. Hancke, and A. Abu-Mahfouz, “Software Defined Networking for Improved Wireless Sensor Network Management: A Survey,” *Sensors*, vol. 17, no. 5: 1031, pp. 1–32, 2017.

[8] N. Ntuli and A. M. Abu-Mahfouz, “A Simple Security Architecture for Smart Water Management System,” *Procedia Comput. Sci.*, vol. 83, no. 4, pp. 1164–1169, 2016.

[9] J. Louw, G. Niezen, T. D. Ramotsoela, and A. M. Abu-Mahfouz, “A key distribution scheme using elliptic curve cryptography in wireless sensor networks,” in *Proceedings of the 14th IEEE International Conference on Industrial Informatics*, 2016, pp. 1166–1170.

[10] A. M. Abu-Mahfouz and G. P. Hancke, “Evaluating ALWadHA for providing secure localisation for wireless sensor networks,” in *IEEE AFRICON Conference*, 2013, pp. 501–505.

[11] A. G. Dludla, A. M. Abu-Mahfouz, C. P. Kruger, and J. S. Isaac, “Wireless sensor networks testbed: ASNTbed,” in *Proceeding of the IST-Africa 2013 Conference*, 2013, pp. 1–10.

[12] A. M. Abu-Mahfouz, L. P. Steyn, S. J. Isaac, and G. P. Hancke, “Multi-level Infrastructure of Interconnected Testbeds of Large-scale Wireless Sensor Networks (MI2T-WSN),” in *Proceedings of the International Conference on Wireless Networks*, 2012, pp. 445–450.

[13] Petajajarvi, Juha, et al. "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology." in the 14th IEEE International Conference on ITS Telecommunications *2015,* pp. 55-59

[14] U. Raza, P. Kulkarni, and M. Sooriyabandara, “Low Power Wide Area Networks: An Overview,” *IEEE Commun. Surv. Tutorials*, vol. 19, no. 2, pp. 855–873, 2017.

[15] A. J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia, and N. Strachan, “Evaluation of LoRa and LoRaWAN for wireless sensor networks,” *IEEE SENSORS*, 2016, pp. 1–3.

[16] M. Bor, U. Roedig, T. Voigt and J. Alonso, "Do LoRa low-power wide-area networks scale?." *The 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*. 2016.

[17] A. Augustin, J. Yi, T. Clausen, and W. Townsley, “A Study of LoRa: Long Range & Low Power Networks for the Internet of Things,” *Sensors*, vol. 16, no. 12, p. 1466, Sep. 2016.

[18] P. Neumann, J. Montavont, and T. Noel, “Indoor deployment of low-power wide area networks (LPWAN): A LoRaWAN case study,” in the *IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications*, 2016, pp. 1–8.

[19] Gregora, Lukas, Lukas Vojtech, and Marek Neruda. "Indoor signal propagation of LoRa technology." in the IEEE *17th International Conference on Mechatronics-Mechatronika, 2016, pp. 1-4*.

[20] T. Petric, M. Goessens, L. Nuaymi, L. Toutain, and A. Pelov, “Measurements, performance and analysis of LoRa FABIAN, a real-world implementation of LPWAN,” in the *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications*, 2016, pp. 1–7.

[21] D. H. Kim, J. Y. Lim, and J. D. Kim, “Low-Power, Long-Range, High-Data Transmission Using Wi-Fi and LoRa,” in the *6th International Conference on IT Convergence and Security*, 2016, pp. 1–3.

[22] D. Bankov, E. Khorov, and A. Lyakhov, “On the Limits of LoRaWAN Channel Access,” in the *International Conference on Engineering and Telecommunication*, 2016, pp. 10–14.

[23] Ahlers, Dirk, et al. "A measurement-driven approach to understand urban greenhouse gas emissions in Nordic cities." NIK, 2016.

[24] F. Yang, G. S. Ramachandran, P. Lawrence, S. Michiels, W. Joosen, and D. Hughes, “PnP-WAN: Wide Area Plug and Play Sensing and Actuation with LoRa,” in *the IEEE International SoC Design Conference,* pp. 225–226, 2016.

[25] Tanumihardja, Wisena Aditya, and Edy Gunawan. "On the application of IoT: Monitoring of troughs water level using WSN," in *IEEE Conference on Wireless Sensors*, 2015, pp. 58-62

[26] F. Orfei, C. Mezzetti, and F. Cottone, “Vibrations powered LoRa sensor: An electromechanical energy harvester working on a real bridge,” *IEEE SENSORS,* pp. 1-3*,* 2016.

[27] M. J. Mudumbe and A. M. Abu-Mahfouz, “Smart water meter system for user-centric consumption measurement,” in *Proceeding of the IEEE International Conference on Industrial Informatics,*2015, pp. 993–998.

[28] C. P. Kruger, A. M. Abu-Mahfouz, and S. J. Isaac, “Modulo: A modular sensor network node optimised for research and product development,” in *Proc of the IST-Africa Conference and Exhibition,* 2013, pp. 1–9.

[29] P. R. Page, A. M. Abu-Mahfouz, and M. Mothetha, “Pressure management of water distribution systems via the remote real-time control of variable speed pumps,” *J. Water Resour. Plan. Manag.*, 5. , vol. 143, no. 8, 2017.

[30] P. R. Page, A. M. Abu-Mahfouz, and S. Yoyo, “Parameter-less remote real-time control for the adjustment of pressure in water distribution systems,” *J. Water Resour. Plan. Manag.*, 7. vol. 143, no. 9, 2017.

[31] P. R. Page, A. M. Abu-Mahfouz, and S. Yoyo, “Real-time Adjustment of Pressure to Demand in Water Distribution Systems: Parameter-less P-controller Algorithm,” *Procedia Eng.*, vol. 154, no. 7, pp. 391–397, 2016.