Survey of Communication Technologies for IoT Deployments in Developing Regions

Namugenyi Ephrance Eunice, Julianne Sansa Otim, Marco Zennaro, Stephen D. Wolthusen

***Abstract*—**The Internet of Things (IoT) is a network of connected data processing devices, mechanical and digital machinery, items, animals, or people that may send data across a network without requiring human-to-human or human-to-computer interaction. Each component has sensors that can pick up on specific phenomena, as well as processing software and other technologies that can link to and communicate with other systems and/or devices over the Internet or other communication networks and exchange data with them. IoT is increasingly being used in fields other than consumer electronics, such as public safety, emergency response, industrial automation, autonomous vehicles, the Internet of Medical Things (IoMT), and general environmental monitoring. Consumer-based IoT applications, like smart home gadgets and wearables, are also becoming more prevalent. This paper presents the main IoT deployment areas for environmental monitoring in developing regions and the backhaul options suitable for them based on a couple of related works. The study includes an overview of existing IoT deployments, the underlying communication architectures, protocols, and technologies that support them. This overview shows that Low Power Wireless Area Networks (LPWANs) are very well suited for monitoring environment architectures designed for remote locations. LoRa technology, particularly the LoRaWAN protocol, has an advantage over other technologies due to its low power consumption, adaptability, and suitable communication range. The current challenges of various architectures are discussed in detail, with the major issue identified as obstruction of communication paths by buildings, trees, hills, etc.

***Keywords*—**Communication technologies, environmental monitoring, Internet of Things, IoT, IoT deployment challenges.

I. Introduction

THE advent of the IoT has revolutionized the field of environmental monitoring, enabling us to seamlessly collect and analyze real-time data to better understand and safeguard our natural surroundings. The IoT [1], [2] is a key emerging technology for future industries and environmental monitoring. It can be defined as intelligently interconnecting devices and enabling new types of communication between things and people, as well as between things themselves. Computers such as smartphones, Internet televisions, sensors, and actuators are connected to the Internet. In recent years, IoT has advanced significantly, giving a fresh perspective to the field of information and communication technology. The research conducted in this paper demonstrates the need to make comparisons between different communication technologies and the underlying protocols of different environmental monitoring architectures in developing regions. Applying best practices and considerations and upgrading IoT devices is one way to mitigate the challenges associated with IoT infrastructures and is critical to maintaining operational functionality, minimizing cybersecurity risks, and maintaining quality of service requirements.

The remainder of the paper is organized as follows: Section II is the related work, Section III: overview of communication technologies in existing IoT implementations, Section IV: research gaps/challenges, Section V: recommendations for future work, and Section VI: conclusions.

II. Related Work

This section presents the general structure of IoT deployment, basic components, communication models, network topologies, operation of network standards and frequency regulations, channel modeling and characterization, network simulations, and theoretical calculations.

A. General IoT Deployment Structure

In a wireless personal area network (WPAN), devices are typically connected to a gateway via routing protocols for short-range connections. And the gateway device is connected to the cloud or the Internet via a cellular network or a low-power wide area network (LPWAN).

B. Description of IoT Basic Components [4]

An IoT installation includes the following components:

- Sensors serve as the connectivity layer of connected devices in asset control systems. These sophisticated sensors send the data they continuously gather from the surrounding environment to the layer below.
- Hardware for central control: A control panel controls traffic going both ways between various networks and protocols. Additionally, it interprets several network protocols and guarantees the compatibility of sensors and connected devices.
- IoT cloud tools are available to gather, manage, process, and store massive amounts of data in real-time.
- An effective user interface guarantees little user effort and promotes more interactions.
- Network interconnection: The IoT's most significant recent trend is the exponential growth of linked and Internet-controlled devices.
- System security: Common IoT vulnerabilities are exploited with malice, yet many of them are readily and affordably avoidable.
- Analog data from linked smart devices and sensors are

Ephrance Eunice Namugenyi is with Makerere University, Uganda (e-mail: ephrancenamugenyi@gmail.com).

transformed into actionable insights using data analytics. These insights can then be processed, evaluated, and used for in-depth study.

Fig. 1 General IoT structure [3]

C. Communication Models and Enabling Technologies in IoT

IoT gadgets [4] are pervasive and will facilitate the dissemination of intelligence in the future. Knowing how various IoT devices interact with one another is crucial and helpful for operational awareness. The IoT communication models [4], [5] are extremely useful. The different types of communication models include the request-response model, the publisher-participant model, the push-pull model, and the exclusive pair. IoT-enabled technologies include wireless sensor networks, cloud computing, Big Data analytics, communication protocols, and embedded systems.

Wi-Fi (IEEE 802.11 a/g/n/ah), Bluetooth (IEEE 802.15.1), both classic and low energy (BLE) variants, ZigBee (IEEE 802.15.4), LoRaWAN protocol, and LTE-M technologies are the main alternatives among the various technologies [4]-[6] available in the market to connect multiple devices for smart city, smart farming, or industrial IoT applications in short- to long-range wireless (5G).

According to their average coverage area, the protocols can be divided into three categories: short-range, medium-range, and long-range communication protocols [6]. Fig. 2 offers a brief comparison of the key characteristics of the aforementioned standards.

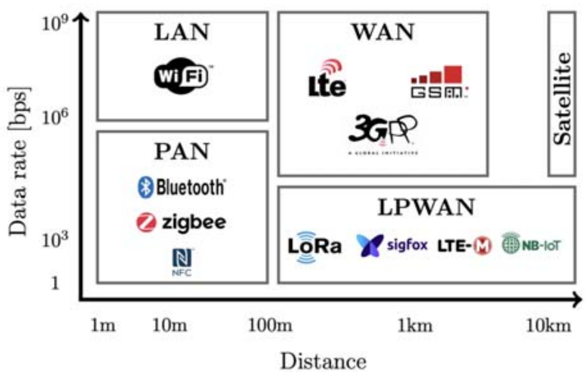

Fig. 2 Comparison of the characteristics of IoT Standards [6]

D. Types of IoT Wireless Technology and Use Cases [5], [7]

All IoT sensor types can be connected via LPWANs, opening up a wide range of possibilities for applications including asset tracking, environmental monitoring, building management, occupancy detection, and consumable monitoring. However, LPWANS are better suited for use cases that do not demand large bandwidth and are not time-sensitive because they can only transfer short blocks of data at low speeds.

A variety of voice conversations and video streaming services are supported by cellular networks (3G/4G/5G), which offer dependable broadband communications. They have relatively high operating expenses and power consumption, which is a drawback. They are ideally suited for some use cases, like as fleet management in logistics and transportation, but are not viable for the majority of IoT applications driven by battery-operated sensor networks.

Zigbee is a short-range (< 100 m), low-power wireless standard (IEEE 802.15.4) that is commonly deployed in a mesh topology to extend coverage by forwarding sensor data across multiple sensor nodes. Due to its mesh architecture, Zigbee has substantially lower energy efficiency than LPWAN but offers faster data speeds. Zigbee and related mesh protocols, such as Z-Wave, Thread, etc., work well for medium-range IoT applications where there is a uniform distribution of nodes close to each other.

Bluetooth is a short-range communication technology that is well positioned in the consumer market. Bluetooth Classic was originally intended for point-to-point or point-to-multipoint data exchange (up to seven slave nodes) between consumer devices. Bluetooth Low-Energy, which is optimized for power consumption, was later introduced to enable small consumer IoT applications.

Wi-Fi is essential for enabling high-throughput data transfers in both office and domestic settings. This technology is much less widespread in IoT space, though, as a result of significant coverage, scalability, and power consumption constraints.

With Radio Frequency Identification (RFID), tiny data packets can be sent over very short distances from an RFID tag to a reader using radio waves. Retail and logistics have

World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:17, No:6, 2023

undergone a significant shift thanks to technology so far.

The most suitable radio technologies for different applications have been identified and summarized in Fig. 3. However, for our case and interest, it is necessary to point out that LPWAN technology is the most widely used technology for environmental monitoring and smart agriculture and therefore will be used as the main reference in this document.

Critical IoT Verticals	LPWAN (Star)	Cellular (Star)	Zigbee (Mostly Mesh)	BLE (Star & Mesh)	Wi-Fi (Star & Mesh)	RFID (Point-to-point)
Industry 4.0	●	○	○			
Digital meters	●					
Smart city	●					
Smart building	●		○	○		
Intelligent home			●	●	●	
Shrewd Home Wearables	○			●		
Connected Car					○	
Connected Health		●		●		
Smart Retail		○		●	○	●
Logistics and asset tracking	○	●				●
Environmental Monitoring	●					
Smart Agriculture	●					

● Very Applicable. ○ Moderately Applicable

Fig. 3 Comparison of wireless technologies and their best use cases

Aspect	Standard IEEE	Frequency
WiFi Wireless Fidelity	802.11	Channel Number 1 - 14 2401- 2473 MHz – Lower Frequency 2412- 2484 MHz –Middle Frequency 2423- 2495 MHz – Upper Frequency
White-Fi	802.11af	470 - 710MHz
Microwave Wi-Fi	802.11ad	57.0 - 64.0 GHz ISM band (Regional variations apply) Channels: 58,32, 60.48, 62.64, and 64.80 GHz
ZigBee	802.11	-

Fig. 4 Protocol standards and frequency ranges [1]

E. Network Topologies

The development and deployment of IoT WSNs have taken traditional network topologies in new directions. Different wireless sensor network topologies [4], [5] are bus, tree, star, ring, mesh, circle, and grid.

Depending on the type of terrain and the desired application, different researchers can choose an appropriate network topology. The mesh and star topologies are still the most used ones.

Comparison of performance under different topologies has been done in [8]. However, there is a need to reduce the energy consumption to improve the network performance in terms of lifetime. The overload of the sensor nodes should be limited, and the network load should be balanced.

F. Network Standards Layer Functionality and Frequency Regulations for IoT Deployments

Communication technology is used in both sensor and backhaul networks. Sensor network standards such as ZigBee, RFID, Bluetooth, and 802.15.4 operate over relatively short distances with low data rates and low power consumption. On the other hand, standards such as GPRS, LTE, WiMAX, etc., operate over long distances and provide high data throughput; however, they consume more energy and require an expensive and fixed infrastructure of base stations with proper line of sight [9]. Fig. 4 shows the functions of the commonly used communication standards within the layered architecture and frequency ranges.

The recently identified LPWAN standard is the LoRa WAN (Low-Power Long Range Wireless Area Network) [10] network protocol used to wirelessly connect battery-powered "things" to the Internet in local, regional, and international networks. It offers end-to-end security, is set up for bidirectional communication at data speeds ranging from 0.3 kbit/s to 50 kbit/s and can operate at frequencies of up to 900 MHz in various locations.

G. Channel Modeling and Characterization in IoT Deployments

The rapid proliferation of ICT and the rapid development of new technologies in recent years has increased the importance of precise planning and deployment of new LPWAN wireless technologies for IoT. However, the success of such technologies depends on the robustness of signal propagation, especially in complex terrain and irregular elevation profiles [11], [12]. LoRa technology stands out from all other LPWAN technologies presented in that it offers a wide range of coverage options; it can span hundreds of meters or tens of kilometers, depending on the environment and the factors that directly affect its performance [13]-[15]. In contrast, widely used LoRa channel models do not recognize this high variability, and typical on-site measurement capabilities are inaccurate given the vast geographic areas covered [13], [14]. As a result, several studies have been conducted in this area, such as [9], [12], [16], and [17].

H. Network Simulations and Theoretical Calculations for IoT Deployments

Analysis and review of simulation and deployment tools: The analysis of available tools revealed that WSN test systems such as OMNET++ and NS -3 should be modified to obtain accurate results. In terms of adaptability, NS-3 is less powerful than all other investigated test systems discussed in [17] and [18].

MATLAB was found to be an advanced simulation tool that combines the working frameworks with good code execution. Reviews found that writing versatile models and active geography changes is useful in a large part of the transformation stages separated from TOSSIM, but limited [18], [19]. Likewise, J-Sim can emulate a huge sensor hub of about 500 [18].

The Things Network, commonly abbreviated as TTN (www.thethingsnetwork.com), is a new crowdsourced deployment platform for testing LoRa-enabled devices, applications, and integrations. TTN enables the integration of IoT devices according to certain documented rules.

Theoretical Analysis: IoT services must be reviewed in order to assure their performance, which may be done based on the following two factors. Measuring performance right away after the services are created and implemented is the most logical course of action. Such performance measurement yields absolute measurements that capture the features of IoT services. But, especially for big IoT systems, measurement is extremely expensive and sometimes unfeasible. A different strategy is to create a mathematical model that predicts outcomes based on the characteristics of the services or systems being designed and to analyze performance measures quantitatively. For instance, in [10], a theoretical method for assessing the performance of IoT services is put out in order to quantitatively forecast the performance metrics prior to the implementation of the system. Performance indicators are obtained after a thorough quantitative model analysis given under various requirement distributions.

III. A Review of Communication Technologies within Existing IoT Deployments

This chapter provides a description of the communication technologies and underlying infrastructures in existing IoT implementations from various research papers.

A. A LoRa-Enabled IoT-Based Air Quality Monitoring System for Smart City

The researchers from the Faculty of Science and Technology at the University of Rwanda (UR) [10] introduce a home air pollution monitoring system that utilizes LoRa-enabled IoT. Two CO_2 and PM 2.5 sensors were strategically positioned in the cafeteria kitchen and laboratory for data collection. These sensors are crucial for monitoring air quality. The LoRaWAN protocol-enabled gateway, which serves as an interface between the network's sensors and the cloud component, was used to send the measured parameters to the cloud. The system may be queried by end users, who can also obtain data and analysis information via the dashboard-like web user interface that has been designed. To make it easier to configure triggers for each sensor node and deliver notifications when a measured parameter exceeds a predetermined threshold, simple algorithms were suggested and put into practice. The entire system was designed to monitor an indoor environment at UR. Analysis of the data over more than ten months and discussion of the results confirmed the reliability of data communication over LoRa-based environmental monitoring applications.

B. The WIMEA-ICT Automatic Weather Station Network

The WIMEA-ICT lab [20] has developed and deployed 30 weather stations with the goal of extending the lifetime of sensor nodes, as these stations are deployed in remote, off-grid locations and rely on energy harvesting technologies for their power supply. In addition, grid connectivity options are limited at these locations. The most widespread connectivity is the cellular network, which was the most used. A few stations were connected via the Lora WAN network. The communication path of a typical Automated Weather Station (AWS) is shown in Fig. 5.

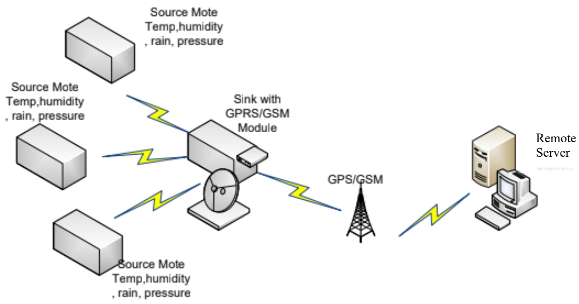

Fig. 5 Weather station communication path [20]

A typical AWS consists of wireless sensor nodes, each powered by solar energy, that transmit environmental data to a gateway device that uploads the data to a central server via one of the various communication paths used. This gateway resides on a Raspberry Pi, or a custom-built low-power gateway connected to an uplink device. The applications running on the sensor nodes and the gateway are developed using free and open-source technologies such as the GNU compiler toolchain and the Linux operating system. A typical use case of AWS is at Makerere College. The system collects recorded values of temperature, humidity, solar radiation, wind speed, and wind direction, which are transmitted to a repository on the remote server maintained by the Uganda National Meteorological Authority (UNMA). The repository may contain older data imported from various weather stations. There, the data are modeled for forecasting purposes using tools such as The Consortium for Small-scale Modeling (COSMO) and Weather Research and Forecasting Model (WRF) [21]. The weather forecasts or predictions are then accessed through websites, cell phones, televisions, and other traditional methods. The forecasts can be customized in the form of agricultural advice, such as when to plant or harvest, or what crops to grow at what time of year.

The WIMEA-ICT laboratory [20] has observed some successful deployments in [22]-[25], using the WRF model. Most diagnostic information is obtained from data sent by gateways over cellular or campus networks to a central repository. Deployment of these architectures presents challenges in power reduction, solar module sizing, battery selection, and basic operational requirements. The motivation for the work done in [23] stems from the need to redesign how these AWS data packets can be effectively sent to the remote destination.

The work in [22] uses an architecture implementation based on the low-power ATMEGA256RFR2 sink node called RS2 Mote from Radio Sensors AB in Sweden [26] to observe the reduction in power consumption. The architecture in [25] also explores various conventional and cutting-edge battery technologies that can be used in Africa to deploy automated environmental monitoring devices using Wireless Sensor Networks (WSNs), as well as the factors that designers must take into account when putting these systems into practice.

It is crucial to remember that WSN environmental monitoring applications typically place a greater emphasis on lowering power consumption and improving data transmission than on the restrictions placed on energy storage by their applications and deployment locations. The authors in the above articles highlight the requirements needed for environmental monitoring applications, especially in remote areas in Africa. Therefore, one of the most desirable options would be to rely on LPWAN technology such as LoRa, which has very low power consumption with massive sensor data collection, accuracy, and overall robustness.

C. Research and Education Network for Uganda (RENU)

RENU [27] is Uganda's National Research and Education Network (NREN) and was established to operate a national private network to meet the connectivity needs of all eligible research and education institutions. Fig. 6 shows the structure of RENU, which connects over 400 sites.

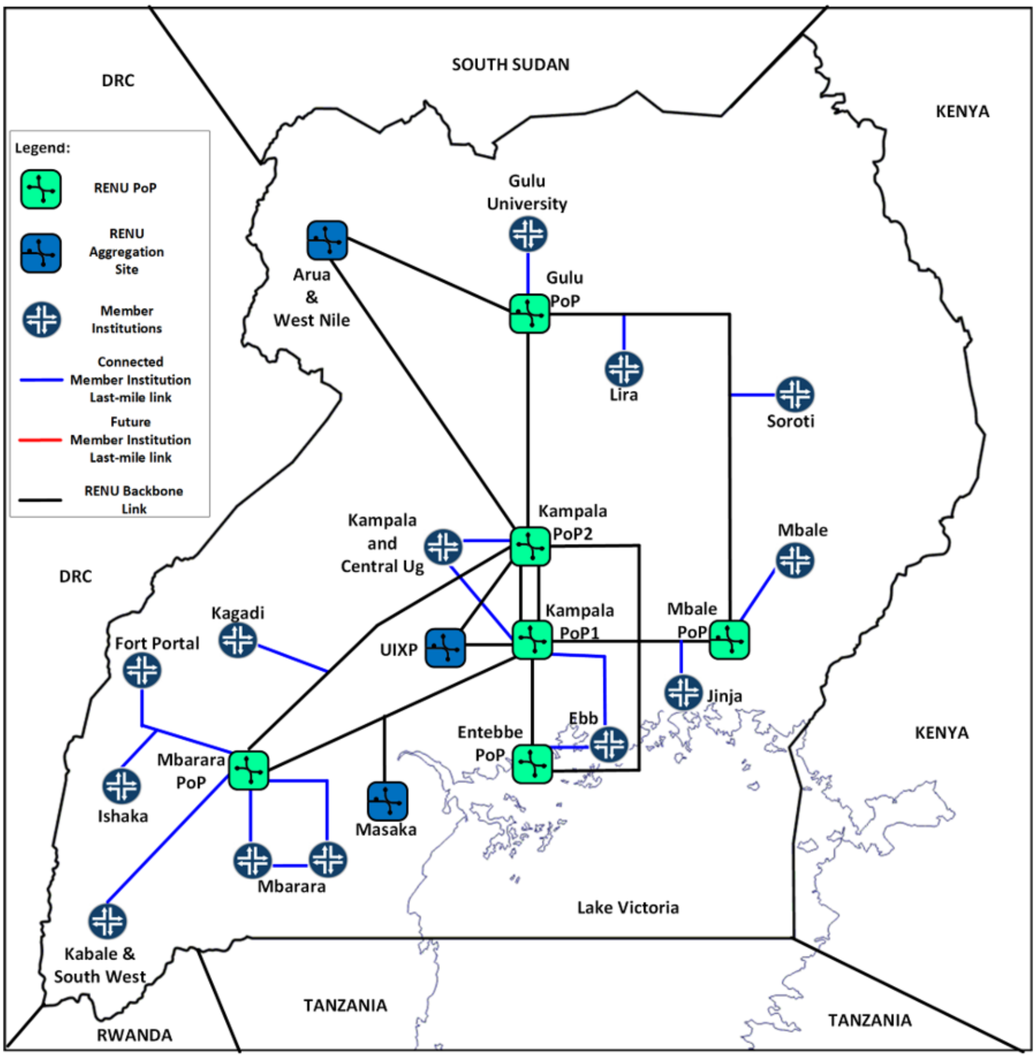

Fig. 6 RENU network design [27]

In 2021, RENU deployed its first LoRaWAN gateway in Kampala [27], which raised expectations that IoT deployments in Uganda can now use the LoRaWAN connectivity option that offers more sustainable data transmission. This is because the LoRaWAN radio frequency is license-free, so there are no operational costs. RENU has deployed several other LoRaWAN gateways and plans to continue to do so.

In various experiments conducted by RENU, we found that LoRaWAN connectivity had better performance, reliability, and energy efficiency compared to the original fiber optic link deployed in several areas.

D. Energy-Efficient WSNs for Precision Agriculture: A Review

In [28], the potential of using wireless communication protocols or technologies in agriculture is investigated and the technology with the best power consumption and communication range is identified. It also examines the taxonomy of energy efficient and energy saving techniques to address the power consumption problems in agriculture and identifies the methods that are best suited to address these problems. The existing solutions, applicability, and limitations of WSN application in agriculture were reviewed and compared. In a comprehensive analysis [28], recent research on the utilization of WSNs in Physical Activity (PA) applications within the framework of IoT was examined and compared. The study focused on various aspects, including the types of sensors and actuators employed, the IoT end devices utilized, the IoT platforms implemented, and the IoT application layer considerations. The wireless protocols studied in [28] include ZigBee, Bluetooth, Wi-Fi, GPRS/3G/4G, Sigfox, and LoRa. A basic comparison of the functionality of each of these protocols based on power consumption and communication distance has been presented in Fig. 7.

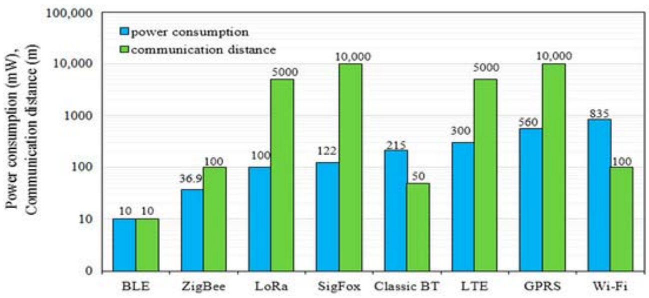

Fig. 7 Different wireless technologies in terms of power consumption and communication distance [28]

In terms of communication distance, GPRS, SigFox, LoRa, and LTE perform the best. In terms of power consumption, BLE, ZigBee, LoRa, and SigFox perform the best. This makes LoRa and SigFox more attractive for further exploration to support other IoT deployments.

E. LoRa Communications as an Enabler for Internet of Drones towards Large-Scale Livestock Monitoring in Rural Farms [29]

The objective of this paper is to develop a farm monitoring system that uses UAV, LPWAN, and IoT technologies to transform current farm management and help farmers obtain actionable data from their farms. An IoT-based water quality monitoring system was developed, as water is an essential aspect for livestock development. Based on LoRa WAN-LPWAN technology, a multi-channel LoRa WAN gateway was developed and integrated with a vertical take-off and landing drone to transmit data collected by sensors to the cloud for further analysis. To develop the LoRa WAN-based airborne communication, a series of measurements and simulations were also conducted under different configurations and scenarios.

To improve the efficiency of the network, airborne data collection was observed, and UAV path planning was optimized. The complexity of the architecture was caused by the drone operation. The good thing is that LoRa-enabled topologies can be adapted to such complex architectures.

F. Successful Deployment of a WSN for Precision Agriculture in Malawi [30]

This article demonstrates how a WSN can be used to actually create an Irrigation Management System (IMS). It describes an IMS that was founded in Manja Township in Blantyre City in particular. The system contained a remote monitoring component that reported soil temperature, soil moisture, WSN linkage power, and solar power using a General Packet Radio Service modem. To irrigate the field, irrigation valves were turned on. The study's preliminary findings showed several technical issues with the system's implementation, such as energy restrictions. Nevertheless, chances for development of a strong, completely autonomous, inexpensive, solar-powered IMS that would satisfy the socioeconomic needs of smallholder farmers in underdeveloped nations were found. Incorporating LPWAN technology could be another fundamental solution.

G. A Review of GSM-Based Automated Water Deployment System for Irrigation Using WSN and Android Mobile [31]

This paper shows how an automated water deployment system (AWDS) can be practically proposed by a WSN composed of a Wireless Sensor Unit (WSU) and a Wireless Information Unit (WIU). It is to be developed to minimize water consumption for crops. The proposed system ensures that water is properly distributed in the field. The system includes remote monitoring mechanism through Global System for Mobile Communication (GSM) module to report soil temperature, soil moisture and humidity. In the irrigation field, automatic systems, powerful embedded microcontrollers, and power-saving technology are used to develop the WSN. The wireless network is placed in the root zone of plants to sense and control the irrigation system in real time. In addition, the WIU unit processes sensor information and transmits data to an Android smartphone. To help farmers access and manage their irrigation systems and regulate crop water demand, an adaptable monitoring architecture using LPWAN technology would be a good solution.

H. A Framework for Deployment of Easy-to-Use WSNs for Farm Soil Monitoring and Control: A Case Study of Horticulture Farms in Pwani Region Tanzania [32]

In the proposed framework, the communication within the network (intra-communication) is done through the ZigBee module in the coordinator, while the analysis, interpretation, and transmission of information to the farmers and the remote server is done in the base station connected to the coordinator. The system was implemented and tested in the Ruvu area in the Pwani region of Tanzania. The system measured environmental parameters of ambient temperature (Ta), soil temperature (Ts), relative humidity (RH), soil moisture (SM), and macronutrients nitrogen (N), phosphorus (P), and potassium (K), as well as light intensity (Li) and carbon dioxide (CO_2). Each node processed the raw data and continuously displayed the results on a screen LCD. Horticulturists can thus obtain information about the condition of their farms and the need for action and take the necessary measures in good time.

Monitoring and control of soil parameters such as temperature, moisture, and micronutrients play an important role in the production of high-quality horticultural crops. Accurate monitoring and control of soil parameters without worrying about the communication aspects, energy efficiency and network challenges can be effectively carried out by incorporating LPWAN technology into the architecture.

I. Experimental Evaluation of Temporal and Energy Characteristics of an Outdoor Sensor Network [33]

This paper revisits the issue of link quality in WSNs by examining the temporal and energy characteristics of a 2.4 GHz sensor network in an outdoor environment. Using different values for output power and sampling period, researchers analyze the battery behavior of motes located at different distances and show that motes located farther away have shorter battery life.

The wireless network communication for the proposed system uses an integrated radio transceiver, the TI CC2420 (formerly ChipCon). The CC2420 is IEEE 802.15.4 compliant and operates in the unlicensed frequency bands from 2.4 GHz to 2.4835 GHz ISM. The IC includes a 2.4 GHz transmitter/ receiver RF with a digital Direct Sequence Spread Spectrum (DSSS) baseband modem with MAC support.

Experiments were conducted to measure the variability of the wireless links and analyze the behavior of the SUNSPOT mote batteries under different conditions. The results showed that: (1) The quality of WSN connections varies over time, (2) the connection quality is related to the position of the mots, and (3) the battery lifetime is also related to the position of the mots as well as the sampling period and output power.

These results suggest that when deployed outdoors, the sampling period of the WSN needs to be adjusted according to the distance to normalize the battery lifetime, and a more accurate energy-aware routing protocol such as the LoRaWAN can be used.

J. The Energy Conservation and Consumption in WSNs Based on Energy Efficiency Clustering Routing Protocol [34]

In this paper, the energy conservation and consumption in WSNs based on clustering routing protocol is proposed. The protocol uses clustering technology to solve the hot spots problem and proposes a cluster head prioritization mechanism to reduce the energy consumption of the head nodes in the cluster partition. First, a new network structure model using cluster members and cluster head is combined with the existing energy consumption model to develop a new method to determine the optimum for overall energy saving. Finally, this protocol was simulated with a network capacity of 100 nodes. The simulation results show that the proposed protocol can effectively improve the performance of LEACH in terms of first dead node, network lifetime, and throughput. Further analysis can be done to show whether the performance is much better when LPWAN-LoRa nodes are deployed.

K. Study on an Agricultural Environment Monitoring Server System Using WSNs [35]

In this paper, an agricultural environment monitoring server system is proposed to monitor outdoor agricultural production environment information using WSNs. The proposed agricultural environment monitoring server system collects outdoor environmental and soil information through WSN-based environmental and soil sensors, collects image information through CCTVs, and collects location information through GPS modules. This collected information is converted into a database through the agricultural environment monitoring server, which consists of a sensor manager that manages the information collected by WSN sensors, an image information manager that manages the image information collected by CCTVs, and a GPS manager that processes the location information from the agricultural environment monitoring server system and makes it available to producers. In addition, a solar panel-based power supply for the server system was implemented so that it can be used in agricultural environments with insufficient power infrastructure.

To increase crop yields and improve quality in the fields, decision-making by farmers can be supported by viable analysis of the collected information, using LPWAN technology such as LoRa.

L. Sensor Network for Precision Agriculture [36]

The report suggests the creation of a brand-new monitoring system for agricultural fields based on atmospheric sensors to gauge various aspects of the air and soil. The authors of this chapter suggest a hybrid periodic routing algorithm that adapts to thresholds for environmental data collection. The suggested algorithm deploys sensor nodes that effectively cover the entire agricultural area using region-based clustering techniques. To establish an ideal cluster head and increase energy efficiency in WSN, a clustering technique based on the combination of residual energy and distance between nearby nodes is also proposed. The suggested routing method surpasses other well-known algorithms in terms of packet delivery, energy usage, and network lifetime, according to simulation results. It has been demonstrated that monitoring numerous crop parameters of interest is a beneficial technique for enhancing agricultural output. Several technologies can be used to monitor crops in precision agriculture, but the use of WSN s enables low-power deployment and emerges as the preferred choice.

M.Summary

In the previous papers, numerous wireless communication protocols [37] have been proposed for the environmental monitoring domain. Based on these protocols, devices in a distributed architecture system can interact, exchange information, and make decisions to monitor and control various parameter conditions and improve production efficiency. Typical low-power communication protocols used in environmental monitoring for long-distance communication include LoRa [29], Sigfox [38], and NB-IoT (Narrowband-IoT) [12]. The various factors mentioned in developing efficient protocols in WSNs for efficient communication include the type of transmission media, data aggregation in the network, fault tolerance, type of node provisioning, and quality of service.

IV. Research Gap/Challenges

This section identifies the gaps and summaries the challenges faced in existing LPWAN deployments.

Gap Analysis

In situations involving smart spaces like agriculture, forests, coastal protection, and disaster connectivity survival, the growth of IoT devices in remote places and the necessity for network resilience in such deployments are becoming more and more crucial. Communication paths still face obstacles because of orography or structures, despite the recommended communication technologies and protocols that provide high connectivity ranges being detailed in Section III. Due to a lack of network or power infrastructure, particularly in East Africa, it is still impossible to reach large areas with cable gateways.

The fact is that wireless networks will enable a wide range of existing and emerging applications. As the use of wireless local area networks expands beyond simple data transmission to include bandwidth-intensive, delay-sensitive, and loss-tolerant multimedia applications, addressing quality of service issues becomes extremely important.

Huge amounts of data are collected and processed, making monitoring, and obtaining consent for data processing a challenge. Data protection laws require that data be encrypted at rest and in transit to protect it from unauthorized access and misuse, which is still a problem in deployments in developing regions.

Table I summarizes the challenges faced by various IoT platforms for environmental monitoring.

TABLE I
IoT Challenges in Existing Deployments

Category	Descriptions of challenges
Security	-Lack of encryption -Insufficient testing and updates -Brute forcing and the risk of default passwords -IoT malware and ransomware -IoT botnet targeting cryptocurrencies
Design	-Short battery life -Increased cost
Deployment	-Limited connectivity -Inability to be used across platforms -Difficult data collection and processing -Lack of expertise

Based on the objective of this paper to review IoT deployments in developing regions and the backhaul options that support them, LPWAN technology, especially LoRa, can be adopted, integrated, and modified to support various environmental monitoring and smart agriculture applications that include weather, crops, pests, livestock, and so on. Various parameters can be adjusted to achieve the desired optimization of UAV path planning and airborne data collection.

The next section describes recommendations for future work.

V. Recommendations for Future Work

This section identifies further gaps for future works and gives recommendations for what can be done.

Future Work: Future work on IoT deployments with power management should include further investigations into node platforms, balancing unequal power distributions, and long-term behavioral studies of systems in real deployments. For node platforms, it might be of particular interest to explore hybrid architectures since high-performance data processing is offloaded to the sensor while system and communication control is centralized. In addition, the problem of unevenly distributed energy availability should be addressed. This includes both the spatial and the temporal distribution of the energy availability. Adaptive sampling algorithms have already been presented in the literature, but further investigation of the possibilities for system improvement and integration into the network structures seems to be necessary. Long-term studies of systems under construction could provide data linking environmental conditions and system behavior. Energy-efficient self-monitoring mechanisms are necessary to enable these studies without unnecessarily impacting system lifetime.

In addition, all radios involved in wireless networks use specific frequency bands for communication. Typically, cellular networks need to be allocated licensed spectrum to ensure more efficient network traffic, higher reliability, better Quality of Service (QoS), better security, comprehensive coverage, and reduced initialization infrastructure costs for users. However, the use of licensed frequency bands comes up against some limitations, e.g., high data transmission costs and the low energy efficiency of IoT devices [37]. Studies can be conducted to demonstrate the efficiency of unlicensed frequency bands in the mm-wave range. The reason for this is that extremely little energy is usually consumed here, and large transmission distances and high data rates are possible [39].

Finally, the literature points out that the terrain profile, the environment, and the transmission distance are important when selecting the specific propagation model of a planning tool. For a detailed analysis of monitoring urban, suburban and rural environments, researchers need to examine different physical layer settings to determine the most appropriate model based on propagation conditions. In addition, experimental studies must be conducted to discuss influencing factors such as the Doppler effect, the Fresnel zone, environmental factors, and interference, to name a few. These factors are critical if we want to extend coverage and maximize channel bandwidth utilization and efficiency. It also makes sense to explore the development of an adaptive communications architecture that takes advantage of LoRaWAN technologies combined with support for drones in locations where connectivity is utterly lacking.

Recommendations: The overview of communication technologies for IoT deployments in this research has shown that for the integration of IoT into the environmental monitoring sector, communication technologies need to gradually improve the development of IoT devices, as they play an important role in the development of IoT systems, especially in developing regions.

Second, based on the discussed communication requirements, LPWAN technology can be integrated for general environmental monitoring to monitor crops, pests, and livestock, adjusting the parameters to the desired optimization of UAV path planning and airborne data collection. The comparison results showed that ZigBee and LoRa wireless protocols are the more suitable LPWAN technologies for environmental monitoring applications due to low power consumption and suitable communication range for ZigBee and long range for LoRa. The LoRaWAN protocol is being considered specifically for monitoring agricultural environments with 90% power efficiency and may be useful. These approaches are also expected to increase the number of ways to process IoT data. However, there are several challenges/gaps identified in the deployment of LPWAN-enabled environmental monitoring architectures that need to be mitigated.

Third, determining the communication spectrum and operating protocol of IoT devices depends on the structure in which IoT devices are deployed for environmental monitoring applications in developing regions. As discussed in the literature, network structures for environmental monitoring typically have two main types of nodes: Sensor and Backhaul nodes [37]. Common characteristics of IoT sensor nodes include short communication distance, low data rate, and high energy efficiency. It is important to note that IoT backhaul nodes often require long transmission distances, high throughput, and high data rates. Therefore, depending on the role of each IoT network node, sensor or backhaul nodes need to select and install appropriate communication technologies.

In addition, the complexity of data storage and processing presented in previous research is due to the unique characteristics of the smart environment monitoring field, which include unstructured data and various formats such as text, images, audio and video, economic figures, and market information. Recent solutions and technologies have introduced the use of cloud platforms for data storage and analysis. In addition, cloud-based Big Data analytics solutions such as edge computing [40] or Fog computing [2] can be used to reduce latency and cost and meet QoS requirements

In conclusion, choosing the best IoT depends on several factors such as range, bandwidth, QoS, security, power consumption, and network management. In addition, the general IoT applications can be improved by creating sensor logging applications, location tracking applications, and a social network of things with status updates so that one can control the location parameters based on the current location itself. This is very useful when it comes to data collection in environmental monitoring systems.

VI. Conclusion

Long link ranges are made possible by LPWAN technologies like LoRa, but large areas are still difficult to cover with wired gateways due to the lack of grid or power infrastructure, particularly in East Africa. Communication paths can also be impeded by orography or buildings. Several obstacles still need to be solved before most farmers, notably small and medium-sized farms, can afford IoT systems. In addition, security technologies need to be continuously improved. However, in our opinion, the application of IoT solutions for smart agriculture is inevitable and will increase productivity, provide clean and environmentally friendly food, support food traceability, reduce human labor, and improve production efficiency. To address the infrastructure challenges for IoT in rural developing areas, we will explore the design of an adaptive communication architecture that takes advantage of LoRa technology combined with drone support in places where connectivity does not exist.

Author Contributions

All authors contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding

This research was supported by funding from NORAD through the NORHED2 program under grant agreement QZA-21/0159 as part of the AdEMNEA project.

Acknowledgments

The authors gratefully acknowledge the support of the project WIMEA-ICT (www.wimea-ict.net) and RENU (www.renu.ac.ug) for the information provided and the design of the figures in this document.

Conflict of Interest

The authors declare no conflicts of interest.

References

[1] Porkodi, R., & Bhuvaneswari, V. (2014). The Internet of things (IoT) applications and communication enabling technology standards: An overview. *2014 International Conference on Intelligent Computing Applications*. https://doi.org/10.1109/icica.2014.73
[2] Quy, V. K., Hau, N. V., Anh, D. V., & Ngoc, L. A. (2021). Smart healthcare IoT applications based on fog computing: Architecture, applications, and challenges. *Complex & Intelligent Systems*, *8*(5), 3805-3815. https://doi.org/10.1007/s40747-021-00582-9
[3] *IoT deployment models*. (2018, October 8). LinkedIn. https://www.linkedin.com/pulse/iot-deployment-models-bhargava-c-s/ Accessed 14/09/2022.
[4] https://comarkcorp.com/internet-of-things/ Accessed 14/09/2022.
[5] Tim Keary, Research Article: Network Topologies: The advantages and disadvantages of each. https://www.comparitech.com/netadmin/network-topologies-advantages-disadvantages/. Updated: June 27, 2022
[6] *Which are the most common Internet of things wireless protocols?* (2020, October 14). Emanuele Pagliari. https://emanuelepagliari.it/2020/10/13/internet-of-things-wireless-communication-protocols/
[7] Ho. (2021, September 7). *6 leading types of IoT wireless technologies and their best use cases*. BehrTech. https://behrtech.com/blog/6-leading-types-of-iot-wireless-tech-and-their-best-use-cases/
[8] Network Topologies in Wireless Sensor Networks: A Review Divya Sharma, Sandeep Verma, Kanika Sharma 1,2,3Dept. of ECE, NITTTR, Chandigarh, UT, India. IJECT Vol. 4, Issue Spl - 3, April - June 2013
[9] Lee, I., & Kim, M. (2016). Interference-aware self-optimizing Wi-Fi for high efficiency Internet of things in dense networks. *Computer Communications*, *89-90*, 60-74. https://doi.org/10.1016/j.comcom.2016.03.008
[10] Twahirwa, E., Mtonga, K., Ngabo, D., & Kumaran, S. (2021). A Lora enabled IoT-based air quality monitoring system for smart city. *2021 IEEE World AI IoT Congress (AIIoT)*. https://doi.org/10.1109/aiiot52608.2021.9454232

[11] Sanchez-Iborra, R., Sanchez-Gomez, J., Ballesta-Viñas, J., Cano, M., & Skarmeta, A. (2018). Performance evaluation of Lora considering scenario conditions. *Sensors*, *18*(3), 772. https://doi.org/10.3390/s18030772

[12] Nordin, R., Mohamad, H., Behjati, M., Kelechi, A. H., Ramli, N., Ishizu, K., Kojima, F., Ismail, M., & Idris, M. (2017). The world-first deployment of narrowband IoT for rural hydrological monitoring in UNESCO biosphere environment. *2017 IEEE 4th International Conference on Smart Instrumentation, Measurement and Application (ICSIMA)*. https://doi.org/10.1109/icsima.2017.8311981

[13] El Chall, R., Lahoud, S., & El Helou, M. (2019). LoRaWAN network: Radio propagation models and performance evaluation in various environments in Lebanon. *IEEE Internet of Things Journal*, *6*(2), 2366-2378. https://doi.org/10.1109/jiot.2019.2906838

[14] Demetri, S., Zúñiga, M., Picco, G. P., Kuipers, F., Bruzzone, L., & Telkamp, T. (2019). Automated estimation of link quality for Lora. *Proceedings of the 18th International Conference on Information Processing in Sensor Networks*. https://doi.org/10.1145/3302506.3310396

[15] Elijah, O., Rahman, T. A., Saharuddin, H., & Khairodin, F. (2019). Factors that impact Lora IoT communication technology. *2019 IEEE 14th Malaysia International Conference on Communication (MICC)*. https://doi.org/10.1109/micc48337.2019.9037503

[16] Triantafyllou, A., Sarigiannidis, P., & Lagkas, T. D. (2018). Network protocols, schemes, and mechanisms for Internet of things (IoT): Features, open challenges, and trends. *Wireless Communications and Mobile Computing*, *2018*, 1-24. https://doi.org/10.1155/2018/5349894

[17] Ferrag, M. A., Maglaras, L. A., Janicke, H., Jiang, J., & Shu, L. (2017). Authentication protocols for Internet of things: A comprehensive survey. *Security and Communication Networks*, *2017*, 1-41. https://doi.org/10.1155/2017/6562953

[18] White, G., Nallur, V., & Clarke, S. (2017). Quality of service approaches in IoT: A systematic mapping. *Journal of Systems and Software*, *132*, 186-203. https://doi.org/10.1016/j.jss.2017.05.125

[19] *Azlan, Syed Nor, and Syarifah Ezdiani. "Versatile Quality of Service for IoT-based Wireless Sensor Networks." PhD diss., Auckland University of Technology, 2018* (Unpublished doctoral dissertation). (n.d.).

[20] Sciences, C. o. (2016). WIMEA-ICT. (n.d.). WIMEA-ICT. https://wimea.mak.ac.ug/ (accessed 2 Aug 2022) WIMEA ICT Project. (2013). (Makerere University) www.wimea.mak.ac.ug

[21] Isaac Mugume, Charles Basalirwa, Daniel Waiswa, Mary Nsabagwa, Triphonia Jacob Ngailo, Joachim Reuder, Schattler Ulrich, Musa Semujju. A Comparative Analysis of the Performance of COSMO and WRF Models in Quantitative Rainfall Prediction. World Academy of Science, Engineering and Technology International Journal of Marine and Environmental Sciences Vol:12, No:2, 2018.

[22] Maximus Byamukama, Janet Nakato Nannono, Kabonire Ruhinda, Björn Pehrson, Mary Nsabagwa, Roselyn Akol, Robert Olsson, Geoffrey Bakkabulindi, Emmanuel Kondela. Design Guidelines for Ultra-low Power Gateways in Environment Monitoring Wireless Sensor Networks. IEEE Africon 2017 Proceedings.

[23] Maximus Byamukama, Mary Nsabagwa, and Julianne Sansa-Otim. Leveraging Inter-Institutional Connectivity to Facilitate Weather Data Transmission from Automatic Weather Stations in Uganda. ISSN 2223-7062 Proceedings and Report of the 9th UbuntuNet Alliance Annual Conference, 2016 pp 9-16.

[24] Byamukama, M., Bakkabulindi, G., Pehrson, B., Nsabagwa, M., & Akol, R. (2018). Powering environment monitoring wireless sensor networks: A review of design and operational challenges in eastern Africa. *EAI Endorsed Transactions on Internet of Things*, *4*(14), 155570. https://doi.org/10.4108/eai.13-7-2018.155570

[25] Byamukama, M., Akol, R., Bakkabulindi, G., Pehrson, B., Olsson, R., & Sansa-Otim, J. (2018). Energy storage options for environment monitoring wireless sensor networks in rural Africa. *2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018)*. https://doi.org/10.1109/cpe.2018.8372600

[26] Radio Sensors AB, (Online). Available: (n.d.). notitle. https://www.radiosensors.com. (Accessed 1 October 2017).

[27] (n.d.). RENU Website. https://www.renu.ac.ug/ (accessed 15 Aug 2022).

[28] Jawad, H., Nordin, R., Gharghan, S., Jawad, A., & Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: A review. *Sensors*, *17*(8), 1781. https://doi.org/10.3390/s17081781

[29] Behjati, M., Mohd Noh, A. B., Alobaidy, H. A., Zulkifley, M. A., Nordin, R., & Abdullah, N. F. (2021). Lora communications as an enabler for internet of drones towards large-scale livestock monitoring in rural farms. *Sensors*, *21*(15), 5044. https://doi.org/10.3390/s21155044

[30] Mafuta, M., Zennaro, M., Bagula, A., Ault, G., Gombachika, H., & Chadza, T. (2013). Successful deployment of a wireless sensor network for precision agriculture in Malawi. *International Journal of Distributed Sensor Networks*, *9*(5), 150703. https://doi.org/10.1155/2013/150703

[31] Kuchekar, N. D. (2015). GSM based advanced water deployment system for irrigation using a wireless sensor network & Android mobile. *International Journal of Electrical Electronics and Data Communication*, *3*(8). https://doi.org/10.18479/ijeedc/2015/v3i8/48355

[32] Kapis, K. (2015). A framework for deployment of easy-to-use wireless sensor networks for farm soil monitoring and control: A case study of horticulture farms in pwani region Tanzania. *International Journal of New Computer Architectures and their Applications*, *5*(3), 107-118. https://doi.org/10.17781/p001927

[33] Zennaro, M., Ntareme, H., & Bagula, A. (2008). Experimental evaluation of temporal and energy characteristics of an outdoor sensor network. *Proceedings of the International Conference on Mobile Technology, Applications, and Systems - Mobility '08*. https://doi.org/10.1145/1506270.1506391

[34] Tesha, G. S., & Amanul, M. (2020). The energy conservation and consumption in wireless sensor networks based on energy efficiency clustering routing protocol. *Advances in Intelligent Systems and Computing*, 55-72. https://doi.org/10.1007/978-3-030-55190-2_5

[35] Hwang, J., Shin, C., & Yoe, H. (2010). Study on an agricultural environment monitoring server system using wireless sensor networks. *Sensors*, *10*(12), 11189-11211. https://doi.org/10.3390/s101211189

[36] Khelifi, F. (2020). Monitoring system based in wireless sensor network for precision agriculture. *Internet of Things (IoT)*, 461-472. https://doi.org/10.1007/978-3-030-37468-6_24

[37] Quy, V. K., Hau, N. V., Anh, D. V., Quy, N. M., Ban, N. T., Lanza, S., Randazzo, G., & Muzirafuti, A. (2022). IoT-enabled smart agriculture: Architecture, applications, and challenges. *Applied Sciences*, *12*(7), 3396. https://doi.org/10.3390/app12073396

[38] Joris, L., Dupont, F., Laurent, P., Bellier, P., Stoukatch, S., & Redoute, J. (2019). An autonomous Sigfox wireless sensor node for environmental monitoring. *IEEE Sensors Letters*, *3*(7), 01-04. https://doi.org/10.1109/lsens.2019.2924058

[39] Patriciello, N., Lagen, S., Bojovic, B., & Giupponi, L. (2020). NR-U and IEEE 802.11 technologies coexistence in unlicensed mmWave spectrum: Models and evaluation. *IEEE Access*, *8*, 71254-71271. https://doi.org/10.1109/access.2020.2987467

[40] Zhang, X., Cao, Z., & Dong, W. (2020). Overview of edge computing in the agricultural Internet of things: Key technologies, applications, challenges. *IEEE Access*, *8*, 141748-141761. https://doi.org/10.1109/access.2020.3013005