Mathematical Statistician and Engineering Applications
ISSN: 2094-0343
2326-9865

Design and Evaluation of Condition Monitoring of Distribution Transformers for Developing Countries

1] Dejenie Birile Gemeda, [2] Markus Lehner, [3] Wilhelm Stork
[1], [2],[3] Karlsruhe Institute of Technology
[1]dejenie.gemeda@kit.edu, [2]markus.lehner@student.kit.edu, [3] wilhelm.stork@kit.edu

Article Info
Page Number: 1939 – 1950
Publication Issue:
Vol. 71 No. 3s2 (2022)

Article History
Article Received: 22 April 2022
Revised: 10 May 2022
Accepted: 15 June 2022
Publication: 19 July 2022

Abstract—Machine learning is becoming popular recently for real-time dynamic monitoring of existing systems. 1939 his process requires previous historical recorded dataset for model training and current measurements for testing. However, these are not readily available in large infrastructure projects like power distribution networks, especially in developing countries. There is no existing infrastructure for condition monitoring and data transmission in power distribution networks and a big budget is required to deploy legacy communication systems. To fill this gap, this paper presents a Low Power Wide Area Network (LPWAN) capable of condition monitoring of power distribution transformer to enable connectivity to the Internet of Things (IoT). In the proposed LPWAN, sensors are employed in a wireless mesh network (WMN) to monitor and diagnose distribution transformer conditions for reliable operation of the distribution grid. Very critical operation indicators like load current, winding temperatures, oil temperature, and oil level status of each distribution transformer are transmitted to a LoRa gateway via distributed sensor networks in urban areas. This data is then sent to the control center through conventional internet connectivity.

Keywords – Condition monitoring, distribution transformers, distributed sensor network, Internet of Things, LoRa.

I. INTRODUCTION

Big Data and machine learning are becoming very popular to find efficiency gains in established processes. These tools require vast amounts of training data that must be collected first. This can be easily achieved in high-tech processes, where everything is connected to a controller. But in "low-tech" areas this can be a very challenging task, especially in big infrastructure projects like pipelines or transmission lines. Usually there are no existing networks for data transmission and a big budget is required to implement a new one. For developing countries, it is difficult to establish this infrastructure and a new way of acquiring data is urgently needed.

Today many (legacy) wireless transmission systems exist, but their range is mostly very limited. In the last decade some technologies have been developed to close this gap. Out of these, the LoRa protocol is very promising, allowing distances of up to 10 kilometers under line-of-sight conditions. But even this is not sufficient to cover long stretches of infrastructure like power distribution transformers, which are mostly in urban areas. To overcome this problem a mesh-network based on the LoRa protocol is proposed in this paper.

The aim of this paper is to develop such a wireless sensor network, that is inexpensive and covers far stretching infrastructures such as electrical power network systems.

In electrical power systems, energy is generated, transmitted, and distributed to the end users in real-time. As a result, real-time condition monitoring is very critical for continuous operation of power systems. In the power distribution subsystem, distribution transformers are very critical [1], heavily used in the power distribution network to distribute power to end users. Usually, power transformers are designed to operate for 25-40 years by their manufacturers, but sometimes they fail earlier [2]. Any failure of a distribution transformers can affect many consumers and incur huge financial losses to the utility company. It is therefore extremely important to continuously monitor and control the distribution transformers, to avoid transformer failures [3], [4]. To stretch the operational lifetime of distribution transformers for years, it is very important to operate them under the rated nameplate conditions [5], [6]. Distribution transformers are conventionally protected by differential protection schemes to detect abnormalities [5], [24]. But this scheme does not have a mechanism for early detection of distribution transformer failures.

Recently, electricity demand is growing in developing countries like Ethiopia due to high demand associated with population growth and urbanization as well as economic growth. To cope with continues growth, new power plants with new transmission and distribution networks are being built in different areas based on a variety of renewable energy sources. However, with all these developments at hand, the customers are currently not provided with reliable and continuous electric power. Some of the causes are related to distribution power transformer overloading [7] or overheating of the transformer oil [8]. The failures of transformers can have a big impact on the whole grid, as the power grid requires a fine balance. With these frequent power outages, the transformer failures are not only a nuisance to the residents, but also limit the development of the country's economy.

In this paper, a LoRa WMN is presented as a novel solution for developing countries, to solve the challenges observed in power distribution networks. IoT enabled distributed wireless sensor networks can be utilized to efficiently monitor the conditions of distribution transformers and overload management. As a result, it is enabling improved grid management for utility companies.

II. LPWANs and LoRa Technology Overview

A. LPWAN networks

A Low Power Wide Area Network (LPWAN) is a network designed for long range communication while using little power. LPWAN technology is supporting the growth of the Internet of Things, because it enables communication with distant nodes while still offering low power and low-cost communication characteristics [9], [10]. NB-IoT (Narrowband IoT), LTE-M [11], SigFox [12] and LoRaWAN [13] are among the main LPWAN technologies. The main difference among them is related to the cost of licensing the technology. The NB-IoT network is a reduced version of commercial LTE (Long Term Evolution) networks and therefore easily deployable by cellular service carriers. SigFox needs a network operator and requires a subscription with the Sigfox network operator. Unlike Sigfox and NB-IoT, LoRaWAN does not need any subscription for the use of the network. LoRaWAN is an open standard wireless technology that allows users to set up the infrastructure needed for its operation.

B. LoRa Physical layer

LoRa is acronym for low power and long range, and it enables to communication over long distances with a low energy consumption. It is a physical layer modulation which was developed and patented by Semtech. LoRa uses wide band sub-GHz frequency bands using

chirp spread spectrum (CSS) [15] to modulate signals, which allows it to cover long distances with low levels of interference [14]. LoRa networks operate in the unlicensed ISM (Industrial, Scientific and Medical) bands, i.e., 868 MHz in Europe, 915 MHz in Australia and North America, and 433 MHz in Asia [15]. This allows private networks to be established and requires a lower cost (compared to other LPWANs) for setting up.
The LoRa physical layer can be configured by selecting carrier frequency (CF), code rate (CR), spreading factor (SF), and bandwidth, to manage power consumption, transmission range and noise resilience [16]. LoRa technology gives the user the opportunity to sacrifice data rate for a better maximum range by varying the spreading factor of the transceiver.

C. LoRaWAN Technology

LoRaWAN is a network standard that allows the creation of an LPWAN that uses the LoRa modulation on the physical layer. To support the development of LPWANs based on LoRa, the LoRa Alliance was founded in 2015 and released the first version of the LoRaWAN protocol stack.
A LoRaWAN network is defined by a unique network identifier called NetID, that is 24 bit long and is assigned by the LoRa Alliance. This network consists of end nodes, LoRaWAN gateways, a network server, a join server, and an application server. Only the end nodes and the LoRa Gateway communicate using the LoRa physical layer. All the other communication is done with conventional internet protocols. The end nodes periodically send their data, this data is received by one or more LoRaWAN gateways who forward this data to the network server. Depending on the type of message, the network server forwards the message to either the join server or the application server, it is therefore the end point of communication on layer 2. It also controls the data-rate and frequency of each end node to optimize the transmissions [17]. An overview of this structure is shown in Fig. 1.

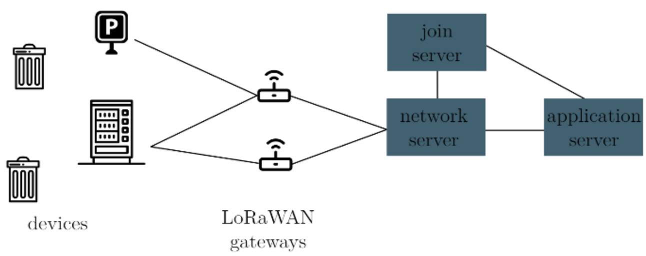

Fig. 1. Schematic structure of a LoRaWAN network

Conventionally, LoRaWAN is organized in a star architecture with gateways at the center, these relay messages between the end nodes and the application server. It is a protocol for medium access control (MAC), which was specifically designed with internet of things (IoT) applications in mind. LoRaWAN nodes are not bound to a specific gateway, their transmissions are being received by all gateways in range. LoRaWAN also introduces features, such as imply adaptive data rate (ADR) by varying the code rate (CR) and spreading factor estimations. It is designed to run on unlicensed radio frequency bands; therefore, some limitations are imposed on the transmission duty cycle. These are defined by the local administrations in each region, ETSI (European Telecommunications Standards Institute-Sophia-Antipolis, France) and FCC (Federal Communications Commission - Washington, DC, USA). In Europe a duty cycle of less or equal than 1% is required for all sub-channels.

III. SYSTEM ARCHITECTURE

This paper proposes a wireless mesh network (WMN) monitoring architecture for power distribution transformers that are distributed in a large geographical. A WMN is a communication network made up of radio nodes organized in a mesh topology instead of the star topology used in most of the LPWANs. The main difference to the star topology is, that every node can have multiple links and these links are not only to the gateway, but also to other nodes. This allows nodes that do not have a direct connection to the gateway to establish a connection via other nodes that it has links with. This is different to LoRaWAN, where the nodes rely on a direct communication with the LoRaWAN gateway. The difference between these topologies is displayed in Fig. 2.

Due to the mesh topology of the proposed network, a routing protocol is needed. A good routing algorithm is very important for the network, as it also reduces the number of transmissions. This is beneficial in two ways; it decreases the energy consumption of the nodes allowing longer battery life for the sensor nodes. The other benefit is a decreased duty cycle of the overall network, which allows a higher number of nodes or more frequent measurements. In this paper a location-based routing algorithm is used as routing protocol. The problem with this approach is the need to know the exact position of the current node, as well as the position of all neighbouring nodes. With moving nodes this quickly becomes a very challenging task, but for static networks like in this paper, this approach can be an effective routing algorithm.

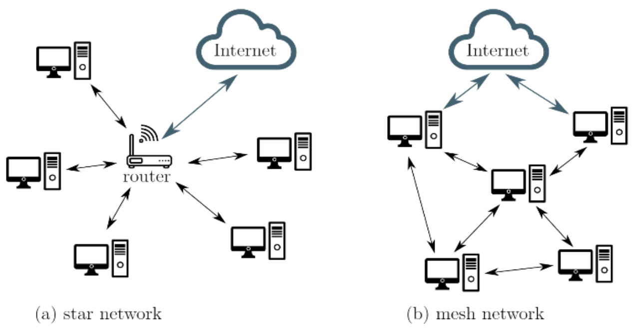

Fig. 2. Sample networks with a star topology (a) and a mesh topology (b).

IV. EXAMPLE SCENARIO

Power distribution transformer is one example of typical large infrastructure that is randomly distributed over vast areas that are far apart, mostly in urban areas with big buildings. Because of this not all points of interest will have a direct link to the control central. Furthermore, because of their distribution location and analog nature they usually have no existing network connectivity with the control centre.

With these requirements, a LPWAN mesh network is developed in this paper. The main goal is to enable the monitoring of distribution transformers, that are hard to cover using networks with star topology due to their distribution from control centre. The data to be transmitted is assumed to be less than 100 bytes and the monitoring interval not smaller than 5 minutes. The network will carry these packets over multiple hops towards a central gateway, that provides connectivity to a server, where the data can be evaluated. Fig. 3 shows a possible distribution transformer placement scenario in in an urban setting.

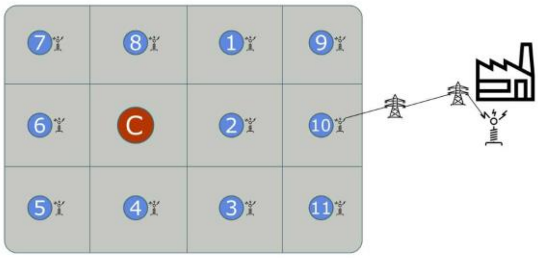

Fig. 3. Example scenario of distribution transformers in an urban setting, with the control centre marked with red.

V. Structure of proposed network

LoRa was chosen as the target technology, as it is the LPWAN technology with the most open architecture, both hardware and software. Only the LoRa modulation is used, all LoRaWAN functionality is omitted and replaced by a custom protocol. But the channel used will be in the same ISM bands around 868MHz as LoRaWAN, to allow the use of existing hardware as well as avoiding licensing costs. LoRa transceiver modules have been widely adopted for many industry applications. This offers a great choice to find suitable hardware for testing later.

The network will be made up of two types of nodes, a central node acting as a gateway with continuous power and internet access as well as battery powered sensor nodes without access to the internet. The sensor nodes are located at the points of interest and equipped with the sensors to measure the properties of interest. The central nodes have more computation power and have a connection to the server. Because of this most of the protocol implementation shall be done on them. This reduces the load on the sensor nodes and makes controlling the network easier.

A. Physical layer (PHY)

On the physical layer the LoRa modulation technique from Semtech is used. As the network will be designed in Europe and operating in the ISM bands, it needs to obey the fair use policy. The main point of this policy is the one percent duty cycle limitation of each application defined in the European norms EN 300 220-1 [25] and EN 300 220-2 [26]. Each application can only be actively using the shared ISM spectrum for one percent of a given observation interval T_{obs}. With the active time defined as the cumulative time of transmission $T_{\text{on\_com}}$ the duty cycle DC can be calculated as

$$DC = \frac{T_{\text{on\_com}}}{T_{\text{obs}}} \qquad (1)$$

The timing of the transmissions inside T_{obs} does not matter, so the device can be sending consecutively at the beginning of T_{obs} and then stay silent until the next observation interval starts [25], [26]. When assuming an observation interval T_{obs} = 1 day = 86400 seconds, the maximum transmission time is

$$T_{on\_\text{com}} = DC \cdot T_{\text{obs}} = 0.01 \cdot 86400\text{s} = 864\text{s}. \qquad (2)$$

This is the maximum time the application is allowed to send in each area. The area with the highest number of traffic will be the central node, because all the uplink packets are routed there. The airtime t_{air} of each packet is mainly dependent on the spreading factor SF and the payload size as expressed in equation 3.

$$t_{air} = \left(N_{pre} + 12.25 + \left[\frac{8N_{pay}+4SF+28}{4SF}\right](4 + CR)\right)T_s \qquad (3)$$

where N_{pay} is the number of payload bytes the packet is carrying, N_{pre} is the length of the preamble, SF is spreading factors, and CR is code rate [27].

With a fixed monitoring interval I_{mon} and assuming every packet reaches the central node only once, the maximum number of nodes $N_{\mathrm{c,max}}$for each cell can be calculated using as:

$$N_{\mathrm{c,max}} = \frac{0.01\, I_{mon}}{t_{air}} \qquad (4)$$

With a fixed number of nodes this equation can also be used to calculate the minimum monitoring interval possible. When designing the monitoring application, the number of monitoring locations and the monitoring interval are both of interest and need to be evaluated together. Fig. 4 shows all possible designs for different spreading factors with a bandwidth B_c = 125 kHz, the preamble set to N_{pre} = 12 bytes and a payload size of N_{pay} = 26 bytes.

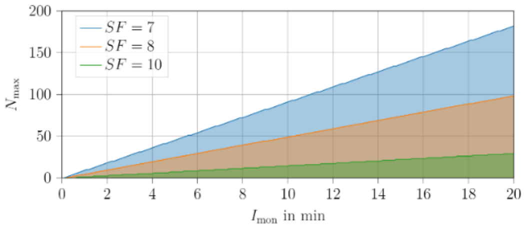

Fig. 4. Area of valid application designs with SF = 7, 8 and 10, B_c = 125 kHz, N_{pre} =12 bytes and a payload of N_{pay}= 26 bytes.

The influence of the spreading factor on the network performance can be seen. For the maximum interval evaluated the maximum number of nodes differs quite drastically. For SF = 7, 182 nodes can be connected, but for SF = 10 this is reduced to only 29 nodes. It must be noted, that these number are only the theoretical optimum, when no packet is sent multiple times. In praxis this maximum number will be significantly lower due to imperfections of the routing algorithm.

B. Medium Access Control (MAC)

The protocol uses no specific MAC algorithm on the physical layer. All nodes are utilizing the ALOHA principle of sending at any time. When the nodes are not receiving a packet and they themselves have a packet to transmit, they start sending immediately. The application layer will introduce mechanisms to reduce the likelihood of collisions by organizing the transmission times of the nodes.

C. Routing

The routing protocol is responsible for directing the packets towards their destination. A centralized location-based routing algorithm was chosen for the designed network. The implementation of this routing algorithm is quite simple due to the static positions of the nodes, yet still effective. The routing algorithm will be implemented in every cell, as each cell can be treated as an encapsuled subnetwork.

Every node has a parameter called distance d_n that is representing its location in the cell relative to the central node. This distance is determined dynamically at the start-up of the

network by a join procedure for all deployed nodes. The logic for this is implemented in the central node.
When all nodes have been assigned a distance, the setup needed for the routing protocol is complete. Now the nodes will relay packets that are from the same network. To improve the efficiency of the routing protocol, every packet is assigned a unique packet-ID called PID. When relaying a packet this packet-ID is stored locally for a fixed amount of time. A packet whose PID is already stored locally will not be relayed, because this would lead to multiple transmissions of the same data. Furthermore, a fail-safe is implemented, by limiting the maximum number of times a packet can be relayed. This maximum number of hops, $N_{\mathrm{h,max}}$, as well as the current number of hops, $N_{\mathrm{h,cur}}$,is transmitted with each packet. When a packet is relayed, the current number of hops is increased by one. When $N_{\mathrm{h,max}} = N_{\mathrm{h,cur}}$ the packet is not relayed anymore. This prevents a packet circulating around the network indefinitely and blocking other transmissions.
Another problem with relaying packets in a mesh network is the multiple re-transmission of the same packet leading to collisions. To reduce the likelihood of this occurring, a relay window I_{rel} was proposed. Within I_{rel} the packet can be re-transmitted at any time t_{trans}, with each start time being equally likely. It is then occupying the channel for the time t_{air} defined in equation 3. This means the transmission will occur within $I_{rel} + t_{air}$. Neglecting the propagation time from the sender to the receiving nodes, all receiving nodes randomly select a start time t_{trans} for relaying the packet. Such a scenario is depicted in Fig. 5.

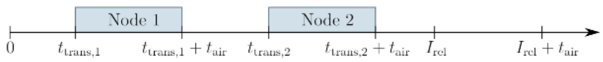

Fig. 5. Exemplary relay interval for two nodes without a collision

D. Transport and Application layer

The main purpose of the proposed network protocol is monitoring certain parameters of an infrastructure project. This is done periodically with the monitoring interval I_{mon}. Every interval lasts for I_{mon} and has the same structure. Synchronization of the nodes is needed to reduce the active time of the nodes while still allowing multi-hop connections The nodes are only active for a time T_{act} at the beginning of the interval. The rest of the interval the nodes are in sleep mode to conserve battery. This means that all communication must take place in the active part of the interval. This part is again split into two different paths. The first part is reserved for all scheduled data packets from the nodes. Every node is assigned a slot in which it is allowed to send. All slots have the same length T_{slot} and thus the time required for all scheduled transmissions is $T_{sched} = N_{con} \cdot T_{slot}$, where N_{con} is the number of nodes connected to the central node of the cell. After the scheduled transmission window is finished, the second part of the active part of the interval is reserved for unplanned transmissions like commands. These can only be initiated by the central node and can be used for administration task. The length T_{ext} of this interval is fixed at the start of the network. After the windows for sending commands has ended, the nodes start sleeping. To ensure the nodes are awake at the beginning of the next interval they wake up a bit earlier than needed. This buffer T_{buf} is defined at network start-up and is the same for all nodes. The structure of an exemplary interval with three connected nodes is shown in Fig. 7.

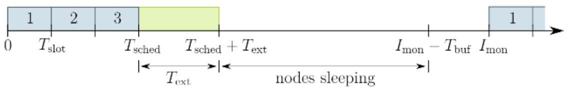

Fig. 7. Structure of a monitoring interval with N_{con} = 3 and the time relative to the interval $t_{int,start}$.

Setting up the network is done in three phases. First the nodes are registering with the central node and joining the cell. After this is completed the monitoring interval is synchronized with all nodes, and they are assigned their respective sending slot inside this interval. When all nodes have successfully adjusted to the interval a command is broadcast to all nodes to start sending. The central node waits until it has received at least one data packet from each node. After it has done so, the network was successfully started, and monitoring can begin.

Once the network has been set up, the monitored data is sent to the central node. Because the nodes have a sending schedule, the successful reception can be checked. After $t_{int,start}$ + T_{sched} a receive-check is executed, and it is checked if a packet was received from all nodes that are currently sending. If a packet is missing, the central node is sending a command to the node and requesting the data to be sent again. These commands are sent inside the second part T_{ext} of the active part of the interval.

The transmissions in the network will be organized in packets. These packets consist of a fixed header and the actual payload. The header is also called overhead, because it is not carrying any information that the user is interested in, but it is needed for routing and other application specific tasks. The protocol implements different packet types for different actions the application needs to perform, for example the join requests.

VI. SIMULATION

To test the proposed network protocol a simulator was written in Python. With the help of this simulator the protocol could be easily debugged and improved. The simulator is time-based and works by continuously updating the entities in the simulation world. The sensor nodes were implemented as a world entity which were using a simulated transceiver module for communicating. This module keeps track of the current transmissions and can also detect collisions. The nodes have a logic module which is a simulation of the code that will be running on the hardware in the future. This allows the code to be easily changed and makes comparing different design easy.

Fig. 8 shows the example scenario of section V in the simulation world. The arrows between the different nodes symbolize the existence of a communication link between two nodes. This scenario was simulated for 24 hours with a monitoring interval T_{mon} = 10 min. Furthermore, the influence of the static transmission error $P_{c,static}$ was evaluated. For every value of $P_{c,static}$ 10 simulations were done for the proposed network and a simple flooding algorithm.

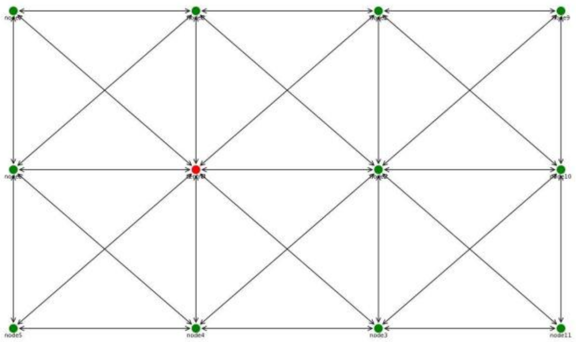

Fig. 8. Automatically generated schematic for used scenario configuration. The arrows indicate possible data transmission direction between nodes.

VII. RESULT AND DISCUSSION

The simulations of the example scenario showed a promising reliability of the proposed network protocol. The overall packet deliver ratio (PDR) of the network was close to 100%. Even the node furthest away from the central node achieved a similar PDR. This is better when compared to a simple flooding algorithm, which is sending nearly ten times the number of packets. To stay under the 1% duty cycle in Europe with the chosen configuration, a maximum of around 15.000 packets can be sent per day. The proposed network is just shy of that limit, while with flooding it is exceeded by a large margin. The results of these simulations are analyzed using a boxplot and shown in Fig. 9.

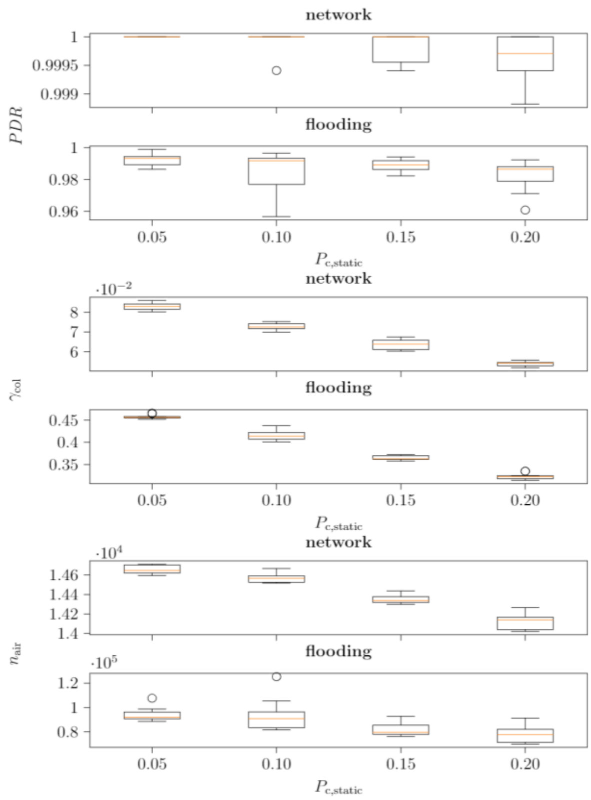

Fig. 9. Simulation results of the considered scenario with T_{mon} = 10 min. Boxplot over 10 simulations for each value of $P_{c,static}$. Analyzing the packet deliver ration PDR, averaged collisions rate Υ_{col} over all transceivers and number of packets on the channel at the central n_{air}.

VIII. CONCLUSION

IoT-based real-time condition monitoring and controlling of distribution transformers is cost effective and superior to tedious manual inspection monitoring techniques. The paper focuses on condition monitoring of distribution transformers using a distributed sensor network for transmitting sensor data from each transformer to the control center using a LoRa WMN. This can enable distribution system operators (DSO) to continuously monitor distribution transformers and provide them with timely alerts. With these warnings they can take the necessary actions, thereby stretching the operational lifetime of distribution transformers, automating the trouble shooting in distribution networks and continuously supplying the customer with power.

The simulations of the network protocol showed that a mesh network formed by a chain of distributed sensors can achieve a good packet delivery ratio for monitoring purposes. Based on these promising simulation results, the next step is a physical test of the network protocol on the university campus. This will hopefully provide more evidence that the proposed network can be used for distribution transformer monitoring and in the future help improve the power grind stability of developing nations like Ethiopia.

ACKNOWLEDGMENTS

The work was financed by the German Federal Ministry of Education and Research (BMBF) under the project 1DG20026 Smart-e-Meter African project within the framework of internationalization of education, science, and research under funding announcement Development and establishment of contract research in African innovation systems.

REFERENCES

[1] T. Mariprasath and V. Kirubakaran, "A real time study on condition monitoring of distribution transformer using thermal imager", Infr. Phys. Technol., vol. 90, pp. 78-86, May 2018.

[2] C. AJ, M. A. Salam, Q. M. Rahman, F. Wen, S. P. Ang and W. Voon, "Causes of transformer failures and diagnostic methods—A review", Renew. Sustain. Energy Rev., vol. 82, pp. 1442-1456, Feb. 2018.

[3] Hitendrasinh C. Chawda, "Causes of Failure of Distribution Transformer and its Remedial Measures", Indian Journal of Applied Research, vol. 5, no. 7, pp. 606-607, July 2015.

[4] I. G. N. S. Hernanda, A. C. Mulyana, D. A. Asfani, I. M. Y. Negara and D. Fahmi, "Application of health index method for transformer condition assessment," TENCON 2014 - 2014 IEEE Region 10 Conference, 2014, pp. 1-6, doi: 10.1109/TENCON.2014.7022433.

[5] J. Perez, "Fundamental principles of transformer thermal loading and protection," 2010 63rd Annual Conference for Protective Relay Engineers, 2010, pp. 1-14, doi: 10.1109/CPRE.2010.5469518.

[6] Agarwal, A. . (2022). Co-Integrable Sets and Probability. International Journal on Recent Trends in Life Science and Mathematics, 9(2), 41–46. https://doi.org/10.17762/ijlsm.v9i2.134

[7] A. Kumar and A. Ajitha, "Development of IOT based solution for monitoring and controlling of distribution transformers," 2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT), 2017, pp. 1457-1461, doi: 10.1109/ICICICT1.2017.8342784.

[8] V.K. Mehta and R. Mehta, Principles of Power System, pp. 354-373, 1999.

[9] R. Godina, E.M.G. Rodrigues, M. Shafie-khah, J.C.O. Matias and J.P.S. Catalão, "Overloading Analysis of an Industrial Client Distribution Transformer in a Portuguese Island", IEEE International Energy Conference (ENERGYCON), pp. 1-6, 2016.

[10] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," ICT Exp., vol. 5, no. 1, pp. 1–7, 2019.

[11] BS. Chaudhari, M. Zennaro and S. Borkar, "LPWAN Technologies: Emerging Application Characteristics Requirements and Design Considerations", Future Internet, vol. 12, pp. 46, 2020.

[12] A. B. YILMAZ, Y. S. TASPINAR, and M. Koklu, "Classification of Malicious Android Applications Using Naive Bayes and Support Vector Machine Algorithms", Int J Intell Syst Appl Eng, vol. 10, no. 2, pp. 269–274, May 2022.

[13] K. Flynn, Standardization of NB-IOT Completed, Sep. 2017, [online]Available:http://www.3gpp.org/news-events/3gpp-news/1785-nb_iot_complete.

[14] Sigfox—The Global Communications Service Provider for the Internet of Things (IoT), Sep. 2017, [online] Available: https://www.sigfox.com/en.

[15] LoRa-Alliance, Sep. 2017, [online] Available: https://www.lora-alliance.org/.

[16] AN1200.22 LoRa™ Modulation Basics, May 2015, [online] Available: http://www.semtech.com.

[17] O. Georgiou and U. Raza, "Low Power Wide Area Network Analysis: Can LoRa Scale?" in IEEE Wireless Communications Letters, vol. 6, no. 2, pp. 162-165, April 2017, doi: 10.1109/LWC.2016.2647247.

[18] M. Bor and U. Roedig, "LoRa Transmission Parameter Selection," 2017 13th International Conference on Distributed Computing in Sensor Systems (DCOSS), 2017, pp. 27-34, doi: 10.1109/DCOSS.2017.10.

[19] Prof. Dr. Martina Zitterbart. Internet of Everything: 5. Low Power Wide Area Networks. Karlsruhe, 2021.

[20] Heltec Automation. WiFi LoRa 32 (V2). Ed. by Heltec Automation. url: https://heltec.org/project/wifi-lora-32/.

[21] RAK Wireless. RAK811 WisDuo LPWAN Module Datasheet. Ed.by RAK Wireless. url: https://dl-docs.rakwireless.com/api/render/?emulateScreenMedia=false & pdf. format = legal & url = https % 3A % 2F % 2Fdocs. rakwireless. com % 2FProduct-Categories%2FWisDuo%2FRAK811-Module%2FDatasheet%2F.

[22] Gill, D. R. . (2022). A Study of Framework of Behavioural Driven Development: Methodologies, Advantages, and Challenges. International Journal on Future Revolution in Computer Science &Amp; Communication Engineering, 8(2), 09–12. https://doi.org/10.17762/ijfrcsce.v8i2.2068

[23] Heltec Automation. WiFi LoRa 32 V2 (868-915). Ed. by Heltec Automation. url: https://resource.heltec.cn/download/WiFi_LoRa_32/V2/WIFI_LoRa_32_V2(868-915).PDF.

[24] NanJing Top Power ASIC Corp. TP4056: 1A Standalone 1A Standalone Linear Li-lon Battery Charger with Thermal Regulation in SOP-8. Ed. by NanJing Top Power ASIC Corp. url: http://www.tp4056.com/d/tp4056.pdf.

[25] Semtech Corporation. SX1276/77/78/79: SX1276/77/78/79 - 137 MHz to 1020 MHz Low Power Long Range Transceiver. May 1, 2020.

[26] u-blox.NEO-6: u-blox 6 GPS Modules. Ed. by u-blox. 2022-03.05.url:https://www.ublox.com/sites/default/files/products/documents/NEO-6_DataSheet_%28GPS.G6-HW-0900 5%29.pdf.

[27] L. A. Kojovic, M. T. Bishop and D. Sharma, "Innovative Differential Protection of Power Transformers Using Low-Energy Current Sensors," in IEEE Transactions on Industry Applications, vol. 49, no. 5, pp. 1971-1978, Sept.-Oct. 2013, doi: 10.1109/TIA.2013.2264792.

[28] European Telecommunications Standards Institute. Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz: Part 1: Technical characteristics and. 2017-02. url: https://www.etsi.org/deliver/etsi_en/300200_300299/30022001/03.01.01_60/en_30022001v030101p.pdf.

[29] Varun, B. N. ., S. . Vasavi, and S. . Basu. "Python Implementation of Intelligent System for Quality Control of Argo Floats Using Alpha Convex Hull". International Journal on Recent and Innovation Trends in Computing and Communication, vol. 10, no. 5, May 2022, pp. 60-64, doi:10.17762/ijritcc.v10i5.5554.

[30] European Telecommunications Standards Institute. Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz: Part 2: Harmonised Standard for access to radio spectrum. 2018-06. url: https://www.etsi.org/deliver/etsi_en/300200_300299/30022002/03.02.01_60/en_30022002v030201p.pdf.

[31] Semtech Corporation. SX1276/77/78/79: SX1276/77/78/79 - 137 MHz to 1020 MHz Low Power Long Range Transceiver. May 1, 2020.

[32] Pawan Kumar Tiwari, Mukesh Kumar Yadav, R. K. G. A. . (2022). Design Simulation and Review of Solar PV Power Forecasting Using Computing Techniques. International Journal on Recent Technologies in Mechanical and Electrical Engineering, 9(5), 18–27. https://doi.org/10.17762/ijrmee.v9i5.370