The Impact of Gateway Node Density on the Performance of LoRaWAN

Rachel Kufakunesu[1], Gerhard P. Hancke[1,2], Adnan M. Abu-Mahfouz [1,3]

[1]*Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa*

[2]*Nanjing University of Posts and Telecommunications, Nanjing 210023, China*

[3]*Council for Scientific and Industrial Research (CSIR), Pretoria, 0184, South Africa*

[1]rachel.kufakunesu@tuks.co.za

Abstract— **The concept of Internet of Things (IoT) has increased in prominence as the demand for device interconnectedness increases worldwide. Numerous technologies have been proposed to provide the required technology and network infrastructure. Low Power Wide Area Networks (LPWAN) have emerged as popular preference, providing low power, long range communication, and low-cost devices, particularly in Long Range Wide Area Networks (LoRaWAN). Components of the LoRaWAN architecture such as the number of end devices (EDs) and gateways (GWs) connected to the network impact the overall network performance. The Adaptive Data Rate (ADR) protocol, which is an essential component of LoRaWAN, allows ED transmission parameters to be dynamically adjusted to adapt to network conditions to improve the network's lifetime. Extensive work has been done in literature to analyse LoRaWAN performance but focuses on single gateway networks. In this work, we present the impact of the GW and ED node density on the performance of the LoRaWAN network through extensive simulations in NS-3. The evaluation measures packet success rate, packet delivery ratio and energy consumption. The results obtained showed that GW node density improves energy efficiency and battery life of the EDs. The analysis aids in understanding the behaviour of LoRaWAN ADR and provides means to optimise the network.**

***Keywords*— Adaptive Data Rate, Internet of Things, LoRaWAN, low-power wide area network (LPWAN), simulation**

I. INTRODUCTION

LoRaWAN is a fast-growing technology in the Low Power Wide Area Network (LPWAN) in Internet of Things deployments. It competes with Sigfox and NB-IoT in the LPWAN territory but has an edge because it is non-proprietary, and meets the requirements of IoT applications. The typical architecture of a LoRaWAN network consists of end devices (EDs) which have sensors that collect data to be transmitted via a gateway (GW), to a network server (NS) which them passes information to the application servers as shown in Fig 1.

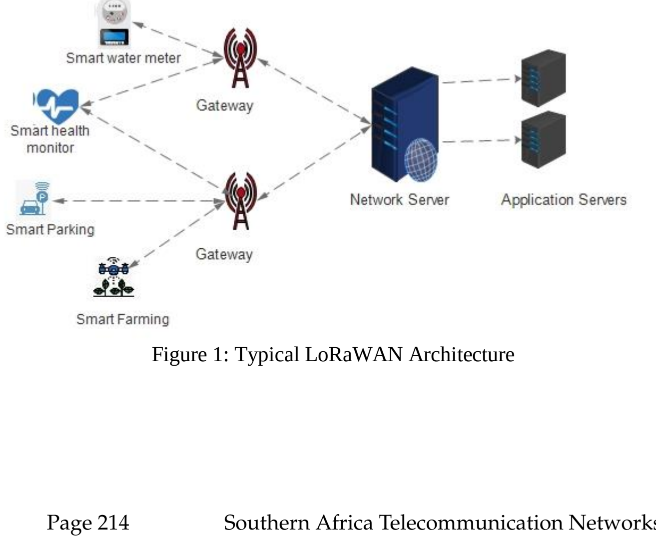

Figure 1: Typical LoRaWAN Architecture

LoRaWAN's topology is referred to as "star of star," wherein end devices do not connect directly to a single gateway but instead broadcast to all GWs within range. A single GW covers up to five kilometres in urban areas and fifteen kilometres in the rural environment[1]. The duplication of data packets transmitted to the multiple GWs is eliminated by the network server and have no implicit usage besides redundancy as provision for GW malfunction. The communication protocol consists of the physical layer (LoRa) which enables the long-distance communication and the Medium Access Control (MAC) layer (LoRaWAN) which accesses the communication channel utilising the pure ALOHA MAC protocol [2]. This means EDs are asynchronous and communicate only when they have data packets to send whether it is scheduled or event driven. The chirp spread spectrum modulation allows the packets generated by EDs to have direct transmission to the communication channel without the need to perform carrier or collision detection beforehand. The spread spectrum modulation means signals are almost orthogonal. Because of its simplicity, this protocol decreases power consumption, communication overhead of the EDs. LoRaWAN works in the license-free, region-dependent Industrial, Scientific, and Medical ISM) frequency bands as detailed in the LoRa Specifications [3].

Communication is bidirectional, so devices can send data to the network via uplink and receive messages via downlink. The LoRaWAN Standard does not allow direct communication between EDs, thus, data packets require to be transmitted through a GW both for uplink and downlink transmissions. The Adaptive Data Rate scheme is an essential component of the LoRaWAN which improves scalability and optimises battery lifetime by optimally selecting transmission parameters, namely, spreading factor, bandwidth, transmission power and coding rate. If proper tuning of these parameters can potentially improve LoRaWAN network performance, a thorough understanding of the network's behaviour, particularly with regard to congestion and transmission conditions is an important process.

Because end devices rely on gateways to transmit data to the internet, gateway placement is important in ensuring ED coverage. Proper gateway placement aids in determining the overall number of gateways required in the network and their optimal locations [4]. This helps to reduce network congestion and enhance throughput although this might come at an increased deployment cost.

The main contributions of this paper are outlined as follows:

- An overview of LoRaWAN ADR scheme and some related work.
- An analysis on the performance of LoRaWAN with respect to the different GW and ED densities.

The remainder of the paper is organized as follows: Section II provides some background on LoRaWAN simulation and related work, Section III introduces the simulation of the LoRaWAN network under ns-3, Section IV presents the results and the analysis of the results. Section V concludes this paper.

II. BACKGROUND AND RELATED WORK

Testbeds for LoRaWAN networks are costly and as such, numerous evaluations and analyses are implemented using simulation tools. Simulation tools provide a platform to experiment and analyse the network behaviour under different parameters, which aids in developing better algorithms.

A. LoRaWAN Simulation Model

A number of open-source LoRaWAN simulation tools have been implemented in NS-3 [5]. The authors in [6] conducted a comprehensive review of the four NS-3 LoRaWAN implementations available namely NS-3 LoRaWAN [7], lora-ns3 [8], AWGN LoRaWAN[9] and CSMA LoRaWAN [10] We resolved to simulate the LoRaWAN network using the NS-3 LoRaWAN module developed by D Magrin [7] available at [11]. This model has excellent documentation and has available developers support. It is a widely used NS-3 LoRaWAN simulator out of all the available simulation tools.

B. Adaptive Data Rate Algorithm

The ADR scheme is used in the LoRaWAN network to adjust the transmission power and data rate for each ED independently. Because end devices have limited battery capacity, power consumption in the EDs has a direct impact on LoRaWAN network performance. The ADR algorithm dynamically modifies the transmission parameters as a means to extend the battery life and maximise throughput. In order to activate the ADR scheme, the end device selects the ADR bit in an uplink message header requesting that the network server manage data rate adaptation. Data rate selection is based on the transmission parameters , spreading factor, bandwidth, transmission power and coding rate calculated considering the previous performance of each ED.

Based on the LoRaWAN Regional Parameters and Specifications [3, 12], EDs are required to accommodate specified data rates, further complicating the power limitation situation because signal-to-noise ratio (SNR) figures must range across specific thresholds and power levels. Given that the EDs must respond to the network's channel conditions, it is necessary that they have the ability to adjust the data rates and transmission power appropriately. The spreading factor, SF∈[7,8,9,10,11,12], has an effect on the data rate as shown in Equation 1:

$$R_b = SF * \frac{BW}{2^{SF}} \quad (1)$$

where R_b is the data rate

BW is the channel bandwidth,

SF is the spreading factor.

A higher spreading factor increases the SNR, which increases the communication range, lengthens the time-on-air, lowering data rate, and increasing energy consumption. The opposite is true for lower spreading factor values.

C. Related Work

The throughput of a LoRaWAN network is influenced by the distance of the EDs from the GW. EDs placed at the network edge can have a throughput as low as 100 bits per second and 2 kilobits per second for EDs close to the GW [13]. The effect of interference in a single GW LoRa network was studied in [14]. Their results show that coverage probability decreases exponentially as the number of EDs increases caused by co-SF interference, that is, interference of signals transmitting using the same spreading factor. According to [15] the GW has the ability to handle a high density of EDs for an average traffic load but would not guarantee the QoS for "bursty" traffic. This problem could be mitigated by increasing the number of gateways in the network. The work in [16] demonstrates how allocating spreading factors among EDs has a significant impact on the uplink capacity and how gateway placement needs careful planning to meet various application requirements. In [17] the authors proposed an ADR algorithm that determines the link quality by obtaining information from multiple GWs to allocate appropriate spreading factor and transmit power of EDs. The proposed approach illustrated an improvement in throughput, energy efficiency and battery life. ADR_{opt} is an adaptive data rate scheme that was developed in [18]. It improved the data extraction rate using multiple gateways reaching high levels of reliability in the LoRaWAN network, even in harsh network conditions.

The authors in [19] reviewed the methods that are used in gateway placement. Different QoS requirements determine which approach of gateway placement will be used, for example, collision probability reduction [20], throughput optimization [21], scalability [22]. In [23] the authors used different strategies to analyse the optimum placement of sixteen and twenty five gateways. Using Fuzzy C-means, they improved the performance of sixteen gateways to match that of twenty-five gateways with a similar packet delivery ratio.

In this paper we analysed the impact of multiple gateways in a LoRaWAN network on packet success rate, packet delivery ratio and energy consumption. We investigated how a fixed number of end devices can be served by an increased number of gateways, improving the stability of the connections between those EDs and the network server.

III. SIMULATION OF LORAWAN NETWORK UNDER NS-3

For our experiments and evaluations, we used ns-3 LoRaWAN module available at [11]. We study the effect of the LoRaWAN ADR optimising transmission power and spreading factor in a short duration, for example three hours, when the application data interval is kept constant at one packet every 20 minutes. We use the European regional parameters EU868.1MHz[12] and implement confirmed packet transmission. For the accurate analysis of the network performance we used a simple LoRaWAN network with a small number of nodes. We used up to 7 GW nodes, one NS node and 50 to 250 ED nodes. The network covers an area of 5000m x5 000m and the end devices are placed in a uniform random distribution. The gateways are located within the network using the hexagonal grid allocation method. The end device and gateway nodes are static. We use the log-distance path loss model, ignoring shadowing and fading in our simulations. We consider confirmed packet transmission, where every uplink packet sent must receive a corresponding downlink packet from the network server. Parameters listed in Table 1 were used in the evaluation.

TABLE I
PARAMETERS USED FOR EVALUATION

Parameter	**Value**
Number of EDs	50 – 250
Number of GWs	1-7
Number of NS	1
Simulation Time	3.3 hours
App. Data Interval	1 packet per 20 minutes
Initial Energy of EDs	1000 Joules
Supply Voltage	3.3V
Carrier Frequency	868Mhz
Channel Bandwidth	125kHz

IV. RESULTS AND DISCUSSION

For this analysis, we used three different performance indicators which are commonly used in several previous works to evaluate the performance of LoRaWAN, namely:

1. Packet Success Rate (PSR)
2. Packet Delivery Ratio (PDR)
3. Total Consumed Energy (E_T)

1) *Packet Success Rate (PSR)*: The probability that the transmitted uplink packets and their corresponding downlink packets are appropriately received by the network server and the ED respectively, in at least one of the transmissions attempts available.

$$PSR = \frac{DL_r}{UL_s} \quad (2)$$

where

DL_r is the downlink packets successfully received at ED for at least one corresponding UL_s packet sent over the uplink to the network server.

Fig. 2 shows the relationship between ED and GW density with packet success rate.

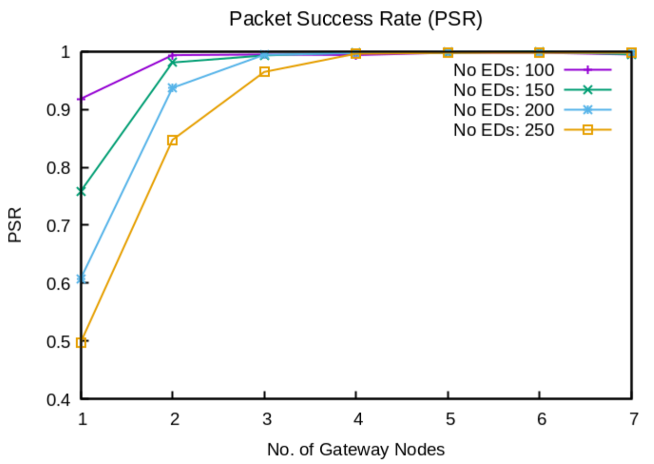

Figure 2: Comparison of Packet Success Ratio

The increase in number of gateway nodes significantly improves the performance in terms of PSR. For a fixed number of end devices, increasing the number of GWs reduces interference as more channels become available for transmission. According to our network setup, five gateways are the optimal number of gateways ensuring the maximum packet success rate.

2) *Packet Delivery Ratio (PDR).*: The probability that transmitted packets (UL_s) are properly received (UL_r) is defined as Packet Delivery Ratio (PDR).

$$PDR = \frac{UL_r}{UL_s} \quad (3)$$

Fig. 3 shows the relationship between ED and GW density with respect to packet delivery ratio. We measure the ratio of uplink packets successfully delivered to the GW over those generated at the EDs.

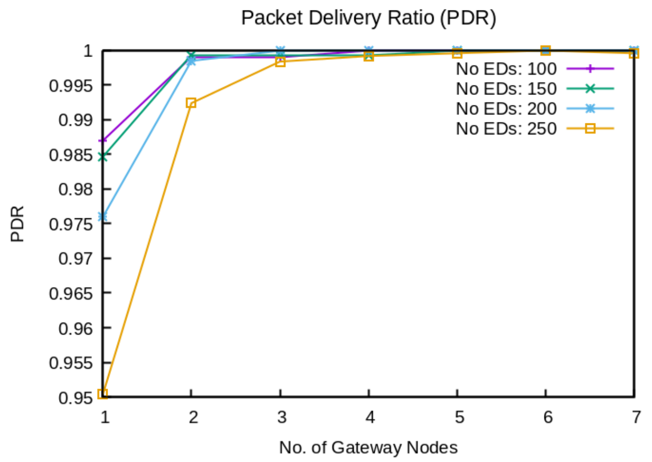

Figure 3: Comparison of Packet Delivery Ratio

The increase in number of gateway nodes significantly improves the performance in terms of PDR. This is because the spreading factor at the EDs decreases, as the number of GWs increases, thereby decreasing the time-on-air. This results in a decrease in a number of collisions, hence increasing the PDR of the network given a constant network radius. But if we carefully scrutinise the above graph, we can observe that after four gateway nodes, we are unable to distinguish the change in performance with respect to density of the EDs. We would require a different metric to analyse the behaviour of the network more closely. This also highlights the need to optimize the number of GWs required for a network to maximise efficiency.

3) *Total Energy Consumption (E_T):*

We used the energy model implemented in NS-3 to estimate energy consumption at the ED [10]. The energy consumption model is a realistic reflection of the duty cycle MAC layer operation [24, 25]. The ED is assumed to transition through three states, defined as transmit, receive, and sleep. The energy consumed by each ED, E_{D_i} comprises of the amount of energy expended in each state expressed as E_{tx_i}, E_{rx_i} and E_{s_i} respectively:

$$E_{D_i} = E_{tx_i} + E_{rx_i} + E_{s_i} \qquad i = \{1,2,\dots,n\} \quad (4)$$

$$E_{D_i} = T_{tx_i}P_{tx_i} + T_{rx_i}P_{rx_i} + T_{s_i}P_{s_i} \quad (5)$$

where n is the total number of EDs in the network.

E_{D_i} is the energy consumed by each end device i,

$T_{tx_i}, T_{rx_i}, T_{s_i}$ and $P_{tx_i}, P_{rx_i}, P_{s_i}$ are time spent and power consumed in the transition states respectively.

The total energy consumption (E_T) is the energy consumed by all the EDs given by:

$$E_T = \sum_{i=1}^{n} E_{D_i} \quad (6)$$

Fig. 4 below shows the relationship between ED and GW density with energy consumption.

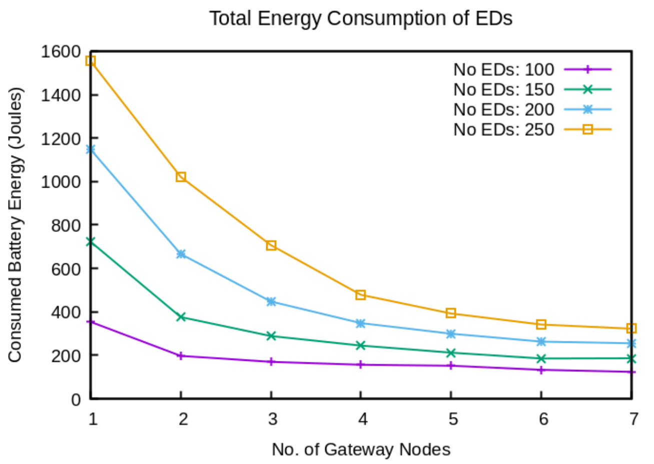

Figure 4: Comparison of Total Energy Consumption

Even though the total energy consumption is increasing with respect to the increase in ED node density, interestingly, energy utilisation is decreases with respect to the increase in GW nodes. The ADR algorithm is playing a major role in this decrease in total energy consumption because, it optimises the transmission power with respect to the distance of the EDs to their nearest GW node. This results from more end nodes being able to transmit with a lower SF thereby reducing interference and the number of retransmissions. Evidently, using more GW nodes will minimise the energy consumption of the LoRaWAN network. A lower SF implies a higher data rate and a shorter time-on-air resulting in less energy being expended.

From the results produced in Section III, the following findings and observations were established.

- The results show that the performance of LoRaWAN significantly improves with respect to the increase of GW nodes. It is important to select an optimal number of gateways without compromising network performance.
- The network performance decreases with respect to the increase in ED node density. There is an inverse relationship between the number of EDs and network performance. Determining the optimal capacity of the network is important.
- The ADR algorithm contributes significantly to the decrease in total energy consumption with the dynamic adjustment of the transmission parameters with respect to the changes in GW node density.

V. Conclusion

Evaluation of the network performance of LoRaWAN was conducted in this paper, with different parameters and suitable metrics. Packet delivery ratio, packet success rate, and energy consumption were used to show the performance with respect to number of EDs and a different number of gateway nodes. We were able to demonstrate that the LoRaWAN architecture scales well owing to the fact that increasing the number of gateways improves the coverage and reliability of the uplink. The ADR algorithm plays a significant role in the decrease of energy consumption with respect to the increase in GW density. This is because the ADR optimises the transmission power with respect to the distance of the EDs to their nearest GW node. This means that using more GW nodes minimises the energy consumption of the LoRaWAN network. The findings from our work may be employed for the optimisation of the LoRaWAN ADR performance by properly selecting the optimal number of gateways for a given network. Future work could look at developing a model which could predict multiple gateway capacity in different network conditions.

Acknowledgment

This work is based on the research supported in part by our industry partner Telkom. The grant holder acknowledges that opinions, findings and conclusions or recommendations expressed in any publication generated by this research are that of the authors, and that our industry partners accept no liability in this regard.

References

[1] L. Alliance, "LoRa and LoRaWAN-A Technical Overview," *White paper*, 2019.

[2] T. Polonelli, D. Brunelli, A. Marzocchi, and L. Benini, "Slotted aloha on lorawan-design, analysis, and deployment," *Sensors*, vol. 19, no. 4, p. 838, 2019.

[3] L. Alliance. "LoRaWAN 1.0. 3 specification." https://lora-alliance.org/resource-hub/lorawanr-specification-v103 (accessed August 2021, 1).

[4] A. M. Ahmed, A. H. Abdalla, and I. El-Azhary, "Gateway placement approaches in wireless mesh network: Study survey," in *2013 INTERNATIONAL CONFERENCE ON COMPUTING, ELECTRICAL AND ELECTRONIC ENGINEERING (ICCEEE)*, 2013: IEEE, pp. 545-547.

[5] N.-. Consortium. "A Discrete-Event Network Simulator for Internet Systems." https://www.nsnam.org/ (accessed May 2021, 2021).

[6] J. C. da Silva, D. d. L. Flor, V. A. de Sousa Junior, N. S. Bezerra, and A. A. de Medeiros, "A Survey of LoRaWAN Simulation Tools in ns-3," *Journal of Communication and Information Systems*, vol. 36, no. 1, pp. 17-30, 2021.

[7] D. Magrin, M. Centenaro, and L. Vangelista, "Performance evaluation of LoRa networks in a smart city scenario," in *2017 IEEE International Conference on communications (ICC)*, 2017: ieee, pp. 1-7.

[8] B. Reynders, Q. Wang, and S. Pollin, "A LoRaWAN module for ns-3: Implementation and evaluation," in *Proceedings of the 10th Workshop on ns-3*, 2018, pp. 61-68.

[9] F. Van den Abeele, J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Scalability analysis of large-scale LoRaWAN networks in ns-3," *IEEE Internet of Things Journal*, vol. 4, no. 6, pp. 2186-2198, 2017.

[10] T.-H. To and A. Duda, "Simulation of lora in ns-3: Improving lora performance with csma," in *2018 IEEE International Conference on Communications (ICC)*, 2018: IEEE, pp. 1-7.
[11] D. Magrin and M. Capuzzo. "LoRaWAN ns-3 Module " https://github.com/signetlabdei/lorawan (accessed May, 2021).
[12] L. Alliance, "LoRaWAN 1.1 regional parameters," *Technical Specification,* 2017.
[13] K. Mikhaylov, J. Petaejaejaervi, and T. Haenninen, "Analysis of capacity and scalability of the LoRa low power wide area network technology," in *European Wireless 2016; 22th European Wireless Conference*, 2016: VDE, pp. 1-6.
[14] O. Georgiou and U. Raza, "Low power wide area network analysis: Can LoRa scale?," *IEEE Wireless Communications Letters,* vol. 6, no. 2, pp. 162-165, 2017.
[15] M. Bor and U. Roedig, "LoRa transmission parameter selection," in *2017 13th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, 2017: IEEE, pp. 27-34.
[16] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the limits of LoRaWAN," *IEEE Communications magazine,* vol. 55, no. 9, pp. 34-40, 2017.
[17] L.-H. Chang, Y. Chang, C.-K. Guan, T.-Y. Juang, and W.-C. Fang, "An adaptive data rate algorithm for improving energy efficiency for multi-gateway LoRaWANs," *International Journal of Ad Hoc and Ubiquitous Computing,* vol. 33, no. 4, pp. 197-215, 2020.
[18] U. Coutaud, M. Heusse, and B. Tourancheau, "Adaptive data rate for multiple gateways LoRaWAN networks," in *2020 16th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2020: IEEE, pp. 1-6.
[19] S. Mnguni, A. M. Abu-Mahfouz, P. Mudali, and M. O. Adigun, "A review of gateway placement algorithms on Internet of Things," in *2019 International Conference on Advances in Big Data, Computing and Data Communication Systems (icABCD)*, 2019: IEEE, pp. 1-6.
[20] F. Loh, N. Mehling, S. Geißler, and T. Hoßfeld, "Graph-Based Gateway Placement for Better Performance in LoRaWAN Deployments," in *2022 20th Mediterranean Communication and Computer Networking Conference (MedComNet)*, 2022: IEEE, pp. 190-199.
[21] S. Patil and P. Gokhale, "Throughput Optimization-Based Gateways Placement Methods in Wireless Networks."
[22] F. Loh, D. Bau, J. Zink, A. Wolff, and T. Hoßfeld, "Robust Gateway Placement for Scalable LoRaWAN," in *2021 13th IFIP Wireless and Mobile Networking Conference (WMNC)*, 2021: IEEE, pp. 71-78.
[23] N. Matni, J. Moraes, D. Rosário, E. Cerqueira, and A. Neto, "Optimal gateway placement based on fuzzy C-means for low power wide area networks," in *2019 IEEE Latin-American Conference on Communications (LATINCOM)*, 2019: IEEE, pp. 1-6.
[24] H. Wu, S. Nabar, and R. Poovendran, "An energy framework for the network simulator 3 (ns-3)," in *Proceedings of the 4th international ICST conference on simulation tools and techniques*, 2011, pp. 222-230.
[25] B. Martinez, M. Monton, I. Vilajosana, and J. D. Prades, "The power of models: Modeling power consumption for IoT devices," *IEEE Sensors Journal,* vol. 15, no. 10, pp. 5777-5789, 2015.

Rachel Kufakunesu (Student Member, IEEE) received her B. Tech and M. Tech degrees in Electrical Engineering from the University of South Africa. She is currently pursuing a PhD in Electronic Engineering at the University of Pretoria. Her research interests include Internet of Things, wireless sensor networks, low power wide area networks.

Gerhard P. Hancke (M’88, SM’00, F’16, LF’19) received the B.Sc., B.Eng. and M.Eng. from the University of Stellenbosch, and the D.Eng. from the University of Pretoria (UP). He is a Professor with the Department of Electrical, Electronic and Computer Engineering at the University of Pretoria, South Africa, and the Colleges for Automation and Artificial Intelligence at the Nanjing University of Posts and Telecommunications, China. He is recognized internationally as a pioneer and leading scholar in Industrial Wireless Sensor Network (IWSN) research, and was elevated to IEEE Fellow “for contributions to wireless sensor networks”. He co-edited a textbook, Industrial Wireless Sensor Networks: Applications, Protocols and Standards (2013), the first on the topic. He initiated and co-edited the first Special Section on Industrial Wireless Sensor Networks in the IEEE Transactions on Industrial Electronics in 2009 and the IEEE Transactions on Industrial Informatics (TII) in 2013. He received the TII Best Paper Award for 2012. Two of his papers in the TII on IWSN are listed by ESI as Highly Cited, ranked 3rd and 7th out of a total of 4,859 published in the TII (as of 2022-05-09). He has acted as AE and GE for TII, TIE and IEEE Access, Co-EiC for TII (since 2019), and Senior Editor for IEEE Access (since 2019). Currently, he is a Co-Editor-in-Chief of the IEEE Transactions on Industrial Electronics and a Senior Editor of IEEE Access.

Adnan M. Abu-Mafouz (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in computer engineering from the University of Pretoria, Pretoria, South Africa, in 2005 and 2011, respectively. He is currently a Chief Researcher and the Centre Manager of the Emerging Digital Technologies for 4IR (EDT4IR) Research Centre, Council for Scientific and Industrial Research, Pretoria; an Extraordinary Professor with University of Pretoria; a Professor Extraordinaire with the Tshwane University of Technology, Pretoria; and a Visiting Professor with the University of Johannesburg, Johannesburg, South Africa. His research interests are wireless sensor and actuator network, low power wide area networks, software-defined wireless sensor network, cognitive radio, network security, network management, and sensor/actuator node development. Prof Abu-Mahfouz is a Section Editor-in-Chief with the Journal of Sensor and Actuator Networks, an Associate Editor at IEEE INTERNET OF THINGS, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE TRANSACTIONS ON CYBERNETICS and IEEE ACCESS, and a member of many IEEE technical communities.