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Scalability and Reliability Determination of Low-Power Wide Area Network (LPWAN) Architecture

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ABSTRACT: The objective of this paper is to evaluate the reliability and scalability of Low-Power Wide Area Network (LPWAN) architecture using ns-3 simulation and modelling. The study provides a more comprehensive investigation of the scalability, reliability, and capacity of LoRa networks (LoRaWAN) as the number of end devices grows to hundreds or thousands per gateway. This was achieved by modeling LoRaWAN networks as pure and slotted ALOHA networks, with consideration for important characteristics such as the capture effect. The relationship between transmission rates and spread factor was also investigated. Using the LoRaWAN ns-3 module, a scalability analysis of LoRaWAN shows the detrimental impact on packet delivery ratio (PDR) of increasing the number of nodes per gateway and presents the results of transmission rate at varying spread factors.

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Low-Power Wide Area Networks (LPWANs) a wireless technology that provides the ability to communicate between two or more entities over long-range distances without the use of wires or cables (Neumann, et al, 2016). LPWAN is one of the most useful, optimized communication technologies to implement and model network architecture for IoT and Wireless sensor networks (WSNs) applications (Gupta, and Singh, 2022). Classically, these technologies communicate even under low Signal Noise Ratio (SNR) and low Receive Signal Strength Indication (RSSI) values due to the usage of robust modulation schemes. The commonly used LPWAN technologies in the long-range communication ecosystem are LoRa, Sigfox, Ingenu, Weightless, LTE-M, or NB-IoT and some of them are proprietary and patented solutions (Milarokostas, et al, 2022). Currently, LoRa Wide-Area Network (LoRaWAN) technology is considered the most adopted LPWAN technology (Ibrahim, 2019), e.g., LoRaWAN Alliance counts with 500+ associated members, as well as 140+ LoRaWAN deployments and 130+ Network Operators in different countries (Matni, et al, 2020). More specifically, LoRaWAN promises ubiquitous connectivity for many IoT applications, while keeping network structures and management simple (Adelantado *et al.*, 2017).

Despite the LoRaWAN's large coverage area, low energy consumption, and other benefits come also a number of drawbacks, including the limited data rate available, scalability issues, and the reliance on low power channel access methods which can negatively impact performance in a highly dense network.

Previous works have raised questions in terms of the reliability, scalability, and capacity of LoRa networks (LoRaWAN) as the number of end devices grows to hundreds or thousands per gateway. Some works have modeled LoRaWAN networks as pure ALOHA networks but failed to capture important characteristics such as the capture effect and the effects of interference (Fraccaroli, and Quaglia, 2020). Several works have shown that dense networks, with many devices, may degrade the overall network performance with longer delays and low reliability. LoRaWAN uses ALOHA as the MAC protocol, which does not perform well when traffic load or node density increases due to interference and

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packet collisions (Van den, et al, 2017). These reliability, scalability and network capacity issues can be studied by leveraging the different built-in ways in which LoRaWAN allows the network designer to alter its performance. In particular, the quasi-orthogonality of the LoRa modulation Spreading Factors (SFs) and the Adaptive Data Rate (ADR) algorithms are both ways that a network can trade off some of its benefits, such as low power consumption and high range for improved scalability. However, because of the practical unfeasibility of setting up thousands of devices to carry out empirical assessments over these properties, most of the reliability and scalability analysis on the protocol is dealt with via theoretical means and discrete-time packet-level simulations. Generally, due to the mathematical complexity of modeling a thoroughly accurate network, most theoretical research limits the scope of the analysis to simpler, less realistic configurations, usually by reducing the number of variables involved in a realistic network design. This simplification also occurs to a certain extent for discrete-time software simulations (Shiang, and Van Der Schaar, 2007). Therefore, the objective of this paper is to evaluate the scalability and reliability of Low-Power Wide Area Network (LPWAN) architecture using ns-3 simulation and modelling.

MATERIALS AND METHODS

In this simulation, several LoRa nodes were connected in clusters to a Proxy node that works as a routing layer or relay which was in turn connected to other relays in a mesh network topology. The advantage of this topology is the expansion of the typical LoRaWAN communication coverage range as it is limited to about 2km at 100 percent PER for the selected study location. The simulation was carried out using the LoRaWAN and LoRa Modules available in NS3 (da Silva *et al.,* 2021).

The modules include loramaster, lorawan, allinone, simple-network-example, complete-network-example, and network-server-example modules coupled with inbuilt NS3 classes: ns-3 class Spectrum-Phy to build the PHY layer, thus allowing for inter-protocol interference; ns-3 class Spectrum-Mac to build the Mac layer (Reynders, et al, 2018). Then, a network topology was formed by creating "nodes" and assigning A PHY and MAC behavior to these nodes, as well as an application that allows generating data.

The class spectrum-signal parameters are used to set up parameters such as the SF and bandwidth (Luzzatto, and Haridim, 2016). The LoRa-example class (simple-lorawan-network-example. cc), illustrates what steps are made to send one packet from an end device (ED) to a gateway. This example follows the usual ns-3 steps for a simulation of a wireless network.

The results obtained using the NS3 simulator, which gave insights into the performance of LoRa and the impacts of different setups were plotted in MATLAB Software.

RESULTS AND DISCUSSION

To determine the scalability criteria for the number of deployed nodes. LoraWAN operates in two modes in the MAC layer; Pure ALOHA (P-ALOHA) and Slotted ALOHA (S-ALOHA). It was necessary to determine which of these modes would be best for the deployment situation considered using the metric of PDR as this is an indicator of the expected transmission rate of our adopted network topology. Figure 1 is shown the result of the simulation of a hypothetical LoraWAN network starting from as many as 50 nodes transmitting to one receiving station operating on pure ALOHA.

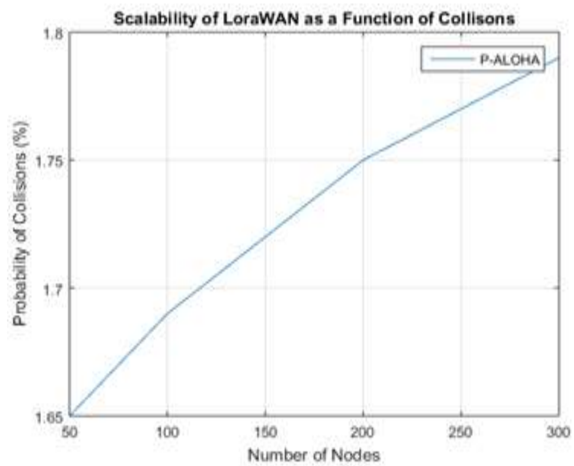

Fig 1: Probability of Collisions versus Number of nodes P_ALOHA

It can be seen that the probability of collisions increases per increase in a number of nodes and this indicates a rather severe impairment to packets received and negatively affects PDR for the network.

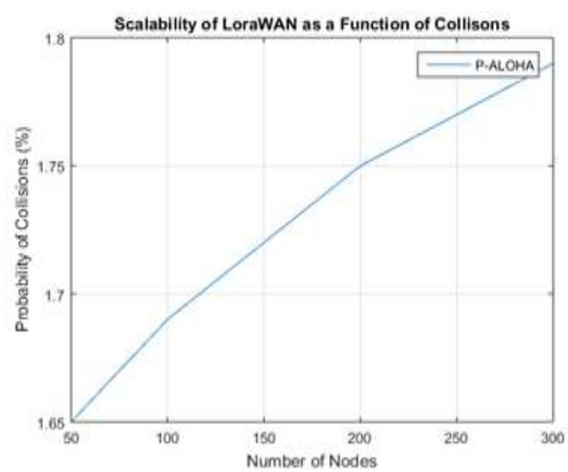

Fig 2: PDR versus Number of nodes (P-ALOHA)

The corresponding estimated drop in PDR using P-ALOHA is presented in Figure 2. This shows an overwhelming decrease in PDR as the number of nodes increases. This is rightly attributed to the increase in collisions on the channel. Figure 3 shows the probability of collisions against the number of nodes as the nodes increase from 50 upward to 300 of a LoraWAN communication link operating on S-ALOHA

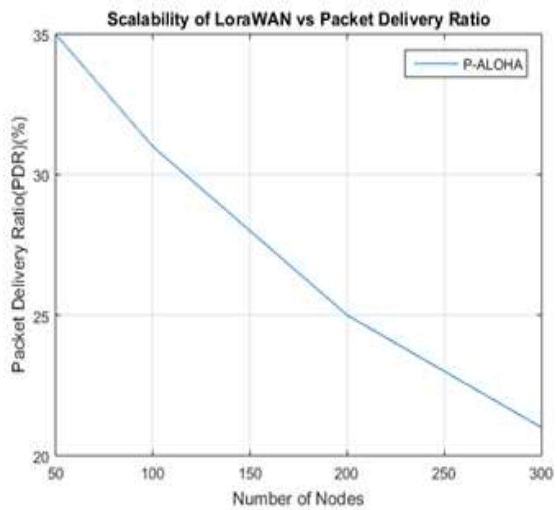

Fig 3: Collison Probability vs Number of nodes S-ALOHA

As is shown in Figure 3 the probability of collisions increases per increase in the number of nodes and this indicates a rather severe impairment to packets received and negatively affects PDR for the network, however, S-ALOHA provides a far less likelihood for collisions compared to its P-ALOHA counterpart for the same scenario. Figure 4: shows the corresponding PDR for the same scenario, this time however implemented with S-ALOHA.

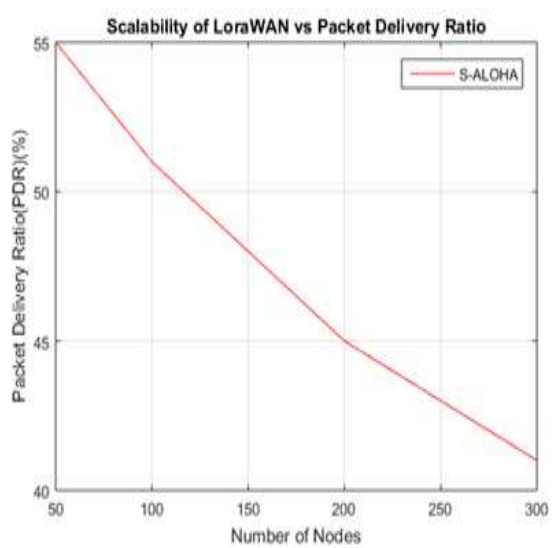

Fig 4: PDR versus Number of nodes (S-ALOHA)

The corresponding estimated drop in PDR using P-ALOHA is presented in Figure 4. This shows a linear decrease in PDR as the number of nodes increase. This is rightly attributed to the increase in collisions on the channel. Figure 5 shows the combined graphical representations of the probability of collisions for P-ALOHA and S-ALOHA. This shows the suitability of S-ALOHA for large-scale deployments of nodes over 50 compared to P-ALOHA for LoraWAN.

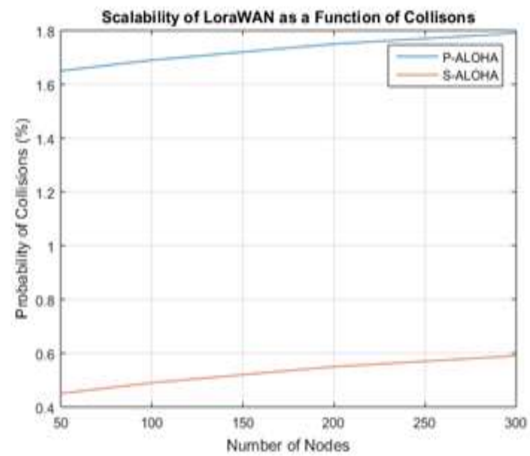

Fig 5: Probability of Collisions versus Number of nodes (S-ALOHA) and (P-ALOHA)

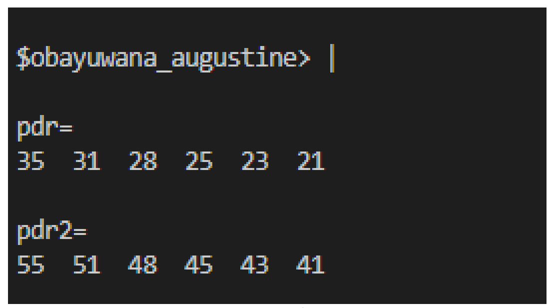

Fig 6: ns3 screenshot showing PDR for P-ALOHA and S-ALOHA

Figure 6 shows the PDR for P-ALOHA represented by Pdr and S-ALOHA by Pdr2 respectively, in the ns3.30 simulation. It shows a higher PDR for S-ALOHA per each number of nodes (50 – 300) for the simulated scenario. This further points to S-ALOHA as more preferable a choice with an increasing number of nodes.

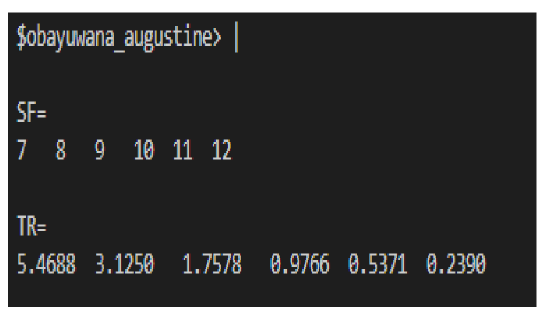

Fig 7: SF at 125kHz showing transmission rate

Transmission rate Simulation using spread factor. The relationship between transmission rate and Spread factor (SF) was simulated using ns3 and MATLAB© to ascertain the network transmission rate and the optimal spread factor at various bandwidths for the chosen architecture. It is recommended in LoraWAN specifications that at larger distances a larger spread factor should be used. Figures 7, 8, 9 and 10 reference ns3 simulation of LoraWAN module transmitting at various spread factors and the corresponding transmission rate for a 125kHZ bandwidth. From Figure 7 it can be seen that there is a drop-in transmission rate (TR) from about 5.4688kbps to about 0.2390 kbps as the SF increases from 7 to 12 for a bandwidth of 125kHz.

```
$obayuwana_augustine> |

SF=
7   8   9   10  11  12

TR=
10.9375  6.25  3.5156   1.9531  1.0742  0.5859
```

Fig 8: SF at 250kHz showing transmission rate

From Figure 8 it can be seen that there is a corresponding drop-in transmission rate (TR) from about 10.9375kbps to about 0.5859 kbps as the SF increases from 7 to 12 for a bandwidth of 250kHz.

```
$obayuwana_augustine> |

SF=
7   8   9   10  11  12

TR=
21.8750  12.5   7.0313  3.9063  2.1484 1.1719
```

Fig 9: SF at 500kHz showing transmission rate

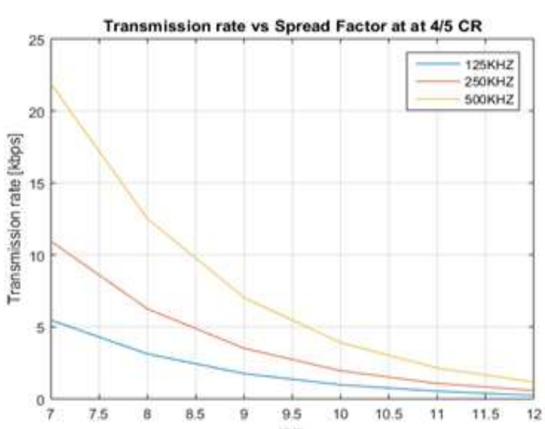

Fig 10 TR vs SF at 125, 250 and 500kHz

From Figure 9 it can be seen that there is a corresponding drop-in transmission rate (TR) from about 21.9750kbps to about 1.179 kbps as the SF increases from 7 to 12 for a bandwidth of 500kHz.

Figure 10 presents a MATLAB simulation of transmission rate at different SF available in LoraWAN at the three bandwidths of 125,250 and 500kHz respectively. The highest TR is obtained at a bandwidth of 500kHz, 250kHz, and 125kHz in that order and at lower SF. The simulation was carried out at a 4/5 Code Rate (CR).

Conclusion: In this study, it was observed that the scalability of the network was highly dependent on the node density and the MAC protocol employed. As the number of nodes increased, the network experienced an increased probability of collision, packet loss and decreased reliability as in the case of P-ALOHA. In scenarios with low node density, the network exhibited high reliability. However, by implementing an efficient MAC protocol (Slotted-ALOHA), it was able to maintain a reasonable level of scalability and reliability.

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