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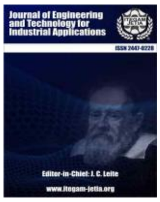

RESEARCH ARTICLE OPEN ACCESS

HETEROGENEOUS LORAWAN DEPLOYMENT FOR APPLICATION DEPENDENT IOT NETWORKS

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ABSTRACT

In this study, we present an application-dependent heterogeneous LoRa network. Previous studies on LoRaWAN and particularly studies that rely on the use of adaptive data rate to optimize the performance of the network are based purely on the path loss of the nodes in the network with the assumption that all nodes in the network have similar requirements in terms of data rate and latency. In a real-life full-scale deployment, this is unlikely to be the case as the current LoRaWAN deployment trend shows that practical implementations are service-based. This approach means that critical applications will suffer reliability issues since they will have to compete with non-critical services for the same resources. To address this problem, we propose a heterogeneous LoRaWAN that is capable of providing support for applications ranging from delay-tolerant to delay intolerant with improved reliability through preferential transmission parameter allocation. Our study shows that this approach can increase the probability of successful uplink transmission of the critical applications by up to 44 percent and for transmitting nodes within a 3 km radius of the gateway, heterogeneous LoRaWAN possesses a 20 percent higher uplink packet delivery rate in comparison with the homogeneous network at the cost of slightly higher energy consumption.

I. INTRODUCTION

The long-range wide area network (LoRaWAN) is a type of Low Power Wide Area Network (LPWAN) that is specifically designed for long-range, low power, low cost, and low data rate applications [1]. These important characteristics ensure that the LoRaWAN occupies a very important role in the future of the Internet of Things (IoT), where billions of battery-powered IoT devices will be required to communicate over several kilometers with minimal energy consumption [2].

However, the ALOHA-like access scheme employed in LoRaWAN pre-disposes the network to a high rate of collision which in turn leads to other problems like low packet delivery rate (PDR), high latency, and other scalability-related issues [3]. Several research efforts have been aimed at solving several of these undermining problems of LoRaWAN with the overarching goal of ensuring the reliability and integrity of LoRaWAN devices. A general assumption in most of these researches is the homogeneity of the network. In this sense, all nodes and applications in the network are assumed to have similar requirements in terms of data rate, failure tolerance, energy usage pattern, and latency.

One may be tempted to excuse this assumption for two reasons. One, LoRaWAN was initially proposed for applications like soil monitoring, weather monitoring, and several other similar applications that are insensitive to delays and packet losses. Secondly, path loss between end-devices (ED) and gateways was considered as the single most important factor in LoRaWAN design.

While this assumption simplifies both theoretical and experimental analysis of the network, it drags it further away from what would be obtainable in a full-scale real-life deployment scenario. A fundamental requirement for a truly functional Long Range (LoRa) network will be the ability to provide support for multiple applications with different requirements. The need for this kind of requirement is even further exacerbated by the current deployment pattern of LoRaWAN in which connectivity through gateways is been provided like a service similar to what is obtainable in cellular networks [4]. This approach implies that gateways must function almost like base stations and coordinate a vast number of visible EDs with different constraints all while operating within an ALOHA-like access scheme network.

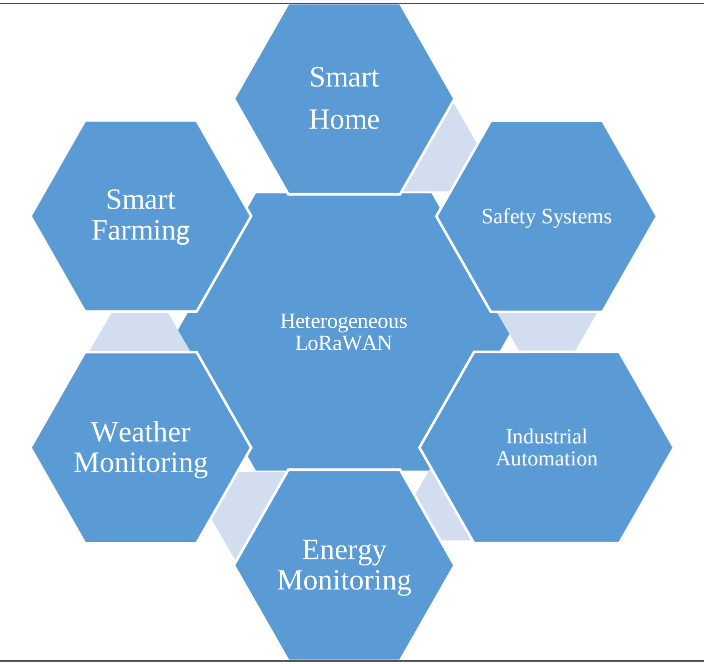

Figure 1: Heterogeneous network.
Source: Authors, (2022).

In this work, we propose a truly functional heterogeneous LoRaWAN application scenario and highlight the critical challenges such a network presents over homogeneous networks that have been the subject of most research on LoRaWAN. As shown in Figure 1, the proposed heterogeneous network runs applications that are categorized as either delay-tolerant low-reliability requiring applications (e.g., smart farming and weather monitoring), average delay tolerance, and average reliability requiring applications (such as smart home, energy monitoring, or smart grid) or delay intolerant high reliability requiring applications (such as safety systems and industrial automation applications). For the study, we assume all EDs operate within a line-of-sight environment. In other words, all transmitting nodes within the network are within the reach of the network gateway and thus have a moderate probability of successful uplink irrespective of their transmitting power or data rate.

Our experiment shows that at distances of about 3 km or less, heterogeneous LoRaWAN has about 20 percent higher uplink packet delivery rate in comparison to homogeneous network but at the cost of slightly higher energy consumption. However, the approach ensures that critical applications running on the network are guaranteed at least a 44 percent higher probability of successful transmission when compared with non-critical applications which are largely due to shorter time of air.

The rest of this paper is organized as follows: Section II provides a basic background to LoRaWAN together with published studies on wireless communication technology. In section III, we present the methodology for the study as well as the simulation parameters. In section IV, we present and discuss the results obtained from the study, and finally, in section V, we conclude the study.

II. THEORETICAL REFERENCE

II.1 BACKGROUND TO STUDY AND RELATED WORKS

IoT is one of the most rapidly expanding fields in today's world. The term is used to specifically describe the interconnection of sensors and actuators that share data over the internet [5]. As more IoT applications and services evolve, the limitations of existing technologies are becoming more and more prominent. For instance, existing wireless technologies like IEEE 802.11 wireless local area networks, IEEE 802.15.1 (Bluetooth), IEEE 803.15.3 (ZigBee), Near Field Communication (NFC), and Radio Frequency Identification (RFID) are principally for short-range communication [6]. While a few of these wireless technologies are capable of high data rate communication, their transmission range is limited to only a few meters (typically less than 100 meters) thus making them more suitable for short-ranged heavyweight applications. They are also mostly power demanding and thus can only be battery operated for only a relatively short period, usually a few weeks at most. Poor energy efficiency is the same reason, cellular networks like 2G, 3G, 4G, and LTE are considered unsuitable for most IoT applications despite their excellent transmission range [6], [7].

LPWANs on the other hand are very suitable for low data rate, energy-limited IoT applications. They are cheap, long-ranged, and can be battery-powered for several years [8]. They are currently available in several proprietary solutions like Long Range (LoRa) [9], SigFox [10], Narrowband-IoT [11], Ingenu [12], and Weightless [13].

LoRaWAN is arguably the de facto standard for the LPWAN technologies due to the open-access nature of its media access control (MAC) layer together with very extensive documentation [14]. LoRa, which is the proprietary physical (PHY) layer of the technology utilizes the direct sequence spread spectrum (DSSS) scheme to ensure a single hop, long-range communication through a gateway to a network server [15]. The gateway in LoRaWAN acts like a bridge between the LoRa node and the network server. The network server on the other hand aggregates all the uplink packets from the end devices or nodes, removes duplicates in case of multiple gateways, and routes the packets to the correct application server. The network server is also responsible for sending acknowledgment (ACK) to the end devices as a confirmation of successful receipt of uplink transmission.

ACK downlink is important in LoRaWAN because of the media access control technique adopted in the network. Specifically, the LoRaWAN MAC uses an ALOHA-like access control for the sake of simplicity [16]. This access protocol does not implement any form of collision detection or avoidance technique, hence uplinks from EDs are random and only limited by regional duty cycle restrictions [17]. This random nature LoRaWAN end devices uplink transmission presents a myriad of challenges with collision and poor packet delivery rate being the most important. Finding a suitable solution to these challenges has been the focus of several researchers in the LoRaWAN space. At the center of these different approaches in solving these problems is the use of the Adaptive Data Rate (ADR) [18]. The ADR is part of the specification of the LoRaWAN standard for optimizing the data rate and energy consumption in the LoRa network. The ADR algorithm uses the path loss and ACK signals from the network server to dynamically adjust the data rate (using the spreading factor) and transmission power of the EDs in the network. Authors in [19] and [20] carried out a comprehensive study on the agility of the ADR implementation in LoRaWAN. The challenges identified by the researchers include high convergence time of the ADR algorithm, sub-optimal convergence of the algorithm to low data rate as well as constant oscillations of nodes between different parameter combinations.

Several other authors have proposed different variations to the LoRaWAN ADR to enhance the functionality of the network, particularly in real-life deployment scenarios. For example, studies conducted by [21] proposed a slight modification to the ADR algorithm. The authors noted that the average of the SNR of end devices should be used in evaluating the link margin against the maximum SNR value proposed by the standard. In [22], the authors proposed a novel spreading factor allocation algorithm to extend the performance of LoRa. To achieve this, EXPLoRa-SF and EXPLoRa-AT algorithms were proposed. The proposed algorithms worked by dividing all end devices within the range of a particular gateway into six groups for six spreading factor assignments. However, for these two algorithms, since the six spreading factors were distributed based on the EDs distance from the gateway, there was no way of accommodating the peculiarity of the different applications the EDs may be serving. The study in [20] proposed an extension of the study carried out in [22] by proposing the inclusion of a back-off time of between two to six seconds for collision-related problems in LoRaWAN.

The ADR algorithms proposed by authors in [19]–[23] all have the limitation of only being practicable in a homogeneous LoRa network since the goal of the network is to ensure that all EDs in the network has an equal probability of successful uplink transmission. Fairness to all transmitting EDs was the central motivation behind the study conducted by [24], [25].

However, for LoRaWAN to truly reach maximum potential, there is the need to exploit its usage in a heterogeneous setting. In this sense, the network will be capable of successfully accommodating all the different evolving IoT applications leveraging the technology. Unfortunately, studies on heterogeneous LoRaWAN are limited. There is a somewhat confusing description of what constitutes a Heterogeneous LoRaWAN in literature. Authors in [26] describe a heterogeneous network as one in which individual nodes in the network selects their own LoRa configuration based on its link budget as against a homogenous network in which all nodes use the same LoRaWAN configuration. The study in [27] proposed a heterogeneous LoRa-based wireless multimedia sensor network. The network in this study was termed heterogeneous because it uses a platform that consists of a multimedia processor (Raspberry Pi 3) in addition to a low-power microprocessor used by the LoRaWAN end devices. The heterogeneity of the LoRa network proposed in [28] was based on spreading factor allocation while the one proposed in [29] was premised on the fact the network includes both ZigBee and LoRa which are two different LPWAN technology with different protocols and interfaces.

In this study, however, we define the heterogeneity of a network in terms of individual applications serviced by the network. In this sense, we assume a network with n number of independent applications where each node within the application network can take on a LoRaWAN configuration as defined within a boundary set by the requirements of the application.

III. MATERIALS AND METHODS

In highlighting the performance of a heterogeneous LoRaWAN vis-a-vis a homogeneous network, we propose the architecture shown in **Erro! Fonte de referência não encontrada.** The focus is to show the inherent challenges these networks will have to overcome in terms of packet delivery rate, energy utilization, and latency.

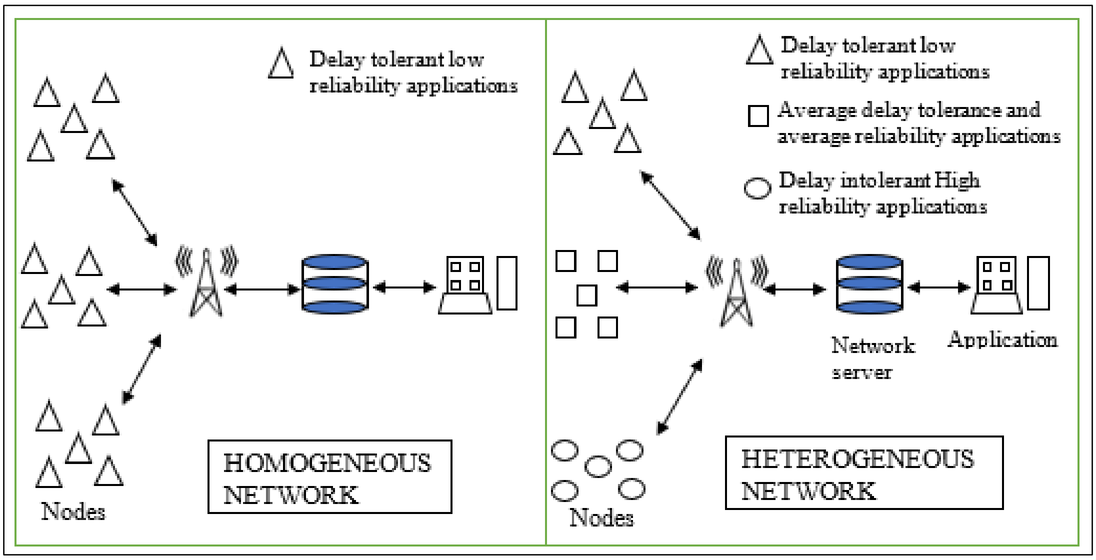

Figure 2: Homogeneous and Heterogeneous LoRaWAN setup.
Source: Authors, (2022).

For the study, we experimented with three different applications. These applications were classified as either delay-tolerant low reliability requiring applications, moderate delay tolerance moderate reliability requiring applications, and delay intolerant high-reliability applications. The delay tolerant low-reliability application is non-critical and a few seconds delay or few packet losses in the network will not have a severe impact on the application because the application environment is not sufficiently dynamic and generated data do not change too often. A good example of these is smart farming or agriculture application. At the other end are delay intolerant high-reliability applications like security and safety applications, fall detection in electronically monitored patients, industrial automation, etc. The cost of packet losses and delays in these applications can be enormous. In between the delay-tolerant and delay intolerant applications are applications like smart home and energy monitoring applications that are moderately impacted by delays and packet losses.

III.1 CHANNEL MODEL

If we denote N as the set of all end devices visible to the gateway, then the assumption is held that:

$$\text{For all node } n \in \text{N} = \{P_R > S\} \quad (1)$$

This implies a network configuration where all end devices have a link budget that allows them to be within reach of the gateway irrespective of their network parameter and are only limited by the boundary set for their respective application.

S in equation (1) is the sensitivity of the gateway and P_R the received power from the end devices at the gateway which is as described by equation 2.

$$P_R\,[dBm] = P_T\,[dBm] + G_A^T[dB] + G_A^R\,[dB] - L[dB] \quad (2)$$

Where P_T is the transmit power of the end device, G_A^T the gain of the transmitting antenna, G_A^R, the gain of the receiving antenna and L the path loss as given in Equation (3)

$$L = 69.55 + 26.16\log_{10}(f)\ \log - 13.82\log_{10}(h_b) - C_H + (44.9 - 6.55\log_{10}(h_b)).\log_{10}(d) + s \quad (3)$$

From Equation (3), f is the frequency in MHz, h_b is the height of the gateway, d the distance between the gateway and the end device and C_H the height correction factor as described in equation (4).

$$C_H = 3.2(\ \log_{10}(11.75h_m))^2 - 4.97 \quad (4)$$

h_m in equation (4) is the height of the end device antenna.

MATLAB-based LoRaWAN simulator [30] was employed with the Okumura-Hata model [31] implemented in the model development.

III.2 LORA PARAMETER ASSIGNMENT

To achieve the set task for the study, different data rates were assigned as shown in Table 1. Applications that are most sensitive to delays were assigned the highest data rate, while those with the least sensitivity are allocated to the lowest data rate. For the experiment, the application allotment was done in the ratio of 30:30:40. 30 percent of the end devices were delay intolerant application, another 30 percent for the average delay tolerant application while the remaining 40 percent was reserved to delay intolerant application.

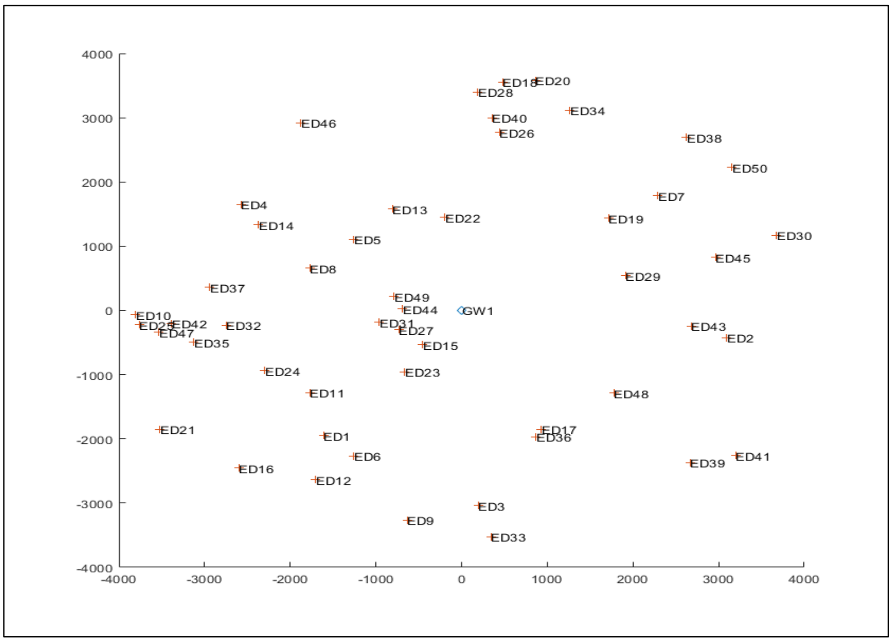

Figure 3: ED distribution around the gateway.
Source: Authors, (2022).

The end devices were randomly distributed around the gateway as could be seen in Figure 3.

Table 1: Heterogeneous Network Data Rate Allocation.

Data Rate	Spreading Factor	ApplicationApplication
DR0 – DR1	SF12 – SF11	Delay tolerant low-reliability applications
DR2 – DR3	SF10 – SF9	Average tolerance to delay and packet loss
DR4 – DR5	SF8 – SF7	Delay intolerant high-reliability application

Source: Authors, (2022).

The network was simulated with the simulation parameters shown in Table 2.

Table 2: Simulation Parameters.

S/N	Parameter	Value
1	Packet Size	20 bytes
2	Average Sending Interval	10 Seconds
3	Bandwidth	125 kHz
4	Coding Rate	4/5
5	LoRaWAN Header Size	7 bytes
6	Number of Gateway	1
7	Duty Cycle	1%
8	No of preamble	8

Source: Authors, (2022).

III.3 NETWORK EVALUATION

Finally, the network parameter for both homogeneous and heterogeneous scenarios was evaluated using the packet delivery rate, energy consumption, and latency. The packet delivery rate (PDR) and energy consumption (E) were estimated using equations (5) and (6) respectively. The latency was characterized by the time of arrival (ToA). The ToA is the time it takes the packet generated by the end device to arrive at the gateway and it is dependent on the data rate used for the transmission.

$$PDR = \frac{\sum_{n=1}^{N} d_n}{\sum_{n}^{N} T_n} \quad (5)$$

$$E = \frac{1}{N}\sum_{n=1}^{N} E_n \quad (6)$$

Where d_n is the packet successfully delivered by the end devices, T_n the number of transmitted packets and E_n the energy consumption of the end devices. The ToA was estimated using equation (7) – (11) [32]. The parameter definition for the ToA estimation is as shown in Table 3.

$$T_{sym} = \frac{2^{SF}}{BW} \quad (7)$$

$$T_{preamble} = \left(n_{preamble} + 4.25\right)T_{sym} \quad (8)$$

$$n_{payloadSym} = 8 + max\left\{ceil\left(\frac{8PL - 4SF + 28 + 16 - 20H}{4(SF - 2DE)}\right)(CR + 4), 0\right\} \quad (9)$$

$$T_{payload} = n_{payloadSym} \times T_{sym} \quad (10)$$

$$T_{packet} = T_{preamble} + T_{payload} \quad (11)$$

Table 3: Parameter definition for ToA Estimation.

ToA Parameter	Definition
T_{sym}	Symbol duration
SF	Spreading factor
BW	Bandwidth
$T_{preamble}$	Preamble duration
$n_{preamble}$	Number of preamble symbols
$n_{payloadSym}$	Number of payload symbol
$T_{payload}$	Payload duration
PL	Number of payload bytes
DE	Data rate optimization factor
H	Header enabled (H=0) or disabled (H=1)

Source: Authors, (2022).

IV. RESULTS AND DISCUSSIONS

First, we sought to understand how individual ED distances from the gateway impact the uplink packet delivery rate in both homogeneous and heterogeneous networks. The result is presented in Figure 4. The result highlights one of the major challenges heterogeneous networks may face in comparison to homogeneous networks. The result shows that homogeneous networks generally have a better uplink packet delivery rate in comparison to the heterogeneous network at distances exceeding 3 km while the heterogeneous network superior delivery rate for distances of about 3 Km or less. This result outlook is because, at short distances, the ADR algorithm converges all the EDs on the homogeneous to use the same transmission parameter thus leading to a high collision rate and less PDR. For the heterogeneous network, there is a better distribution of transmission parameters as shown in Figure 5. The energy consumption of the two networks is depicted in Figure 6. Energy consumption was found to be higher in the heterogeneous network at distances of about 4 Km or less but much less in comparison with homogeneous networks thereafter. A heterogeneous network has a better distribution of the SF thereby having better energy usage, particularly at larger distances.

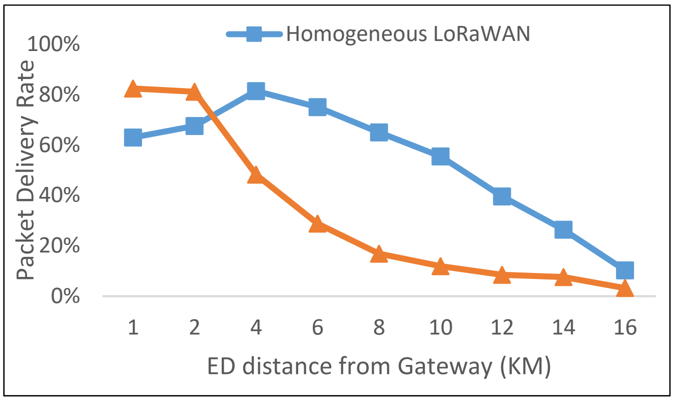

Figure 4: Uplink delivery rate variation with distance from the gateway.
Source: Authors, (2022).

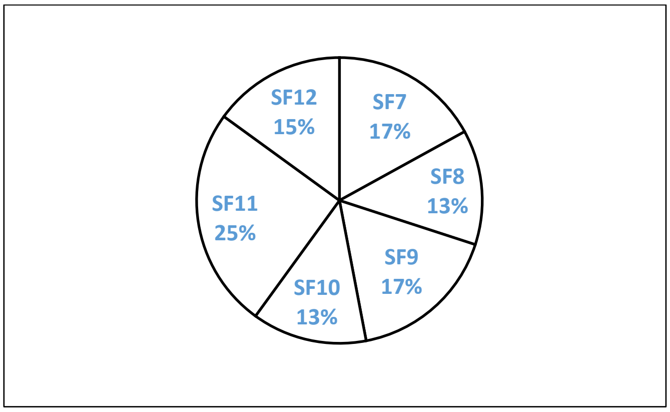

Figure 5: SF allocation for Het. Network at 2 KM.
Source: Authors, (2022).

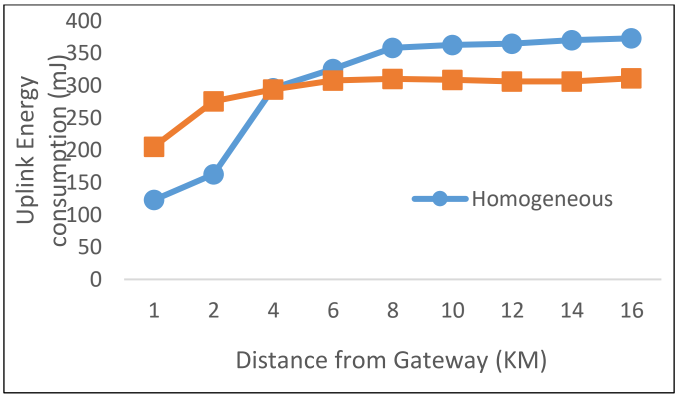

Figure 6: Uplink energy consumption with distance.
Source: Authors, (2022).

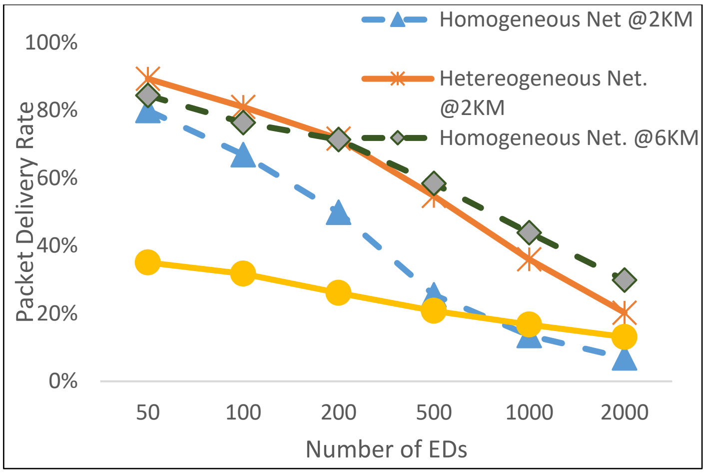

Figure 7: LoRaWAN PDR with varying number of EDs.
Source: Authors, (2022).

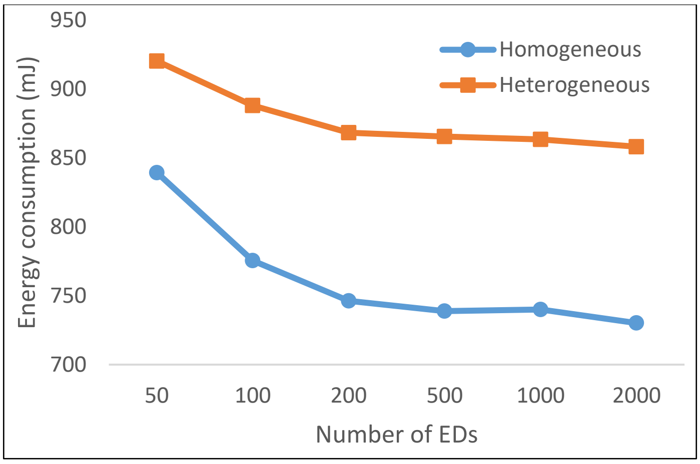

Figure 8: Energy consumption with varying number of Eds.
Source: Authors, (2022).

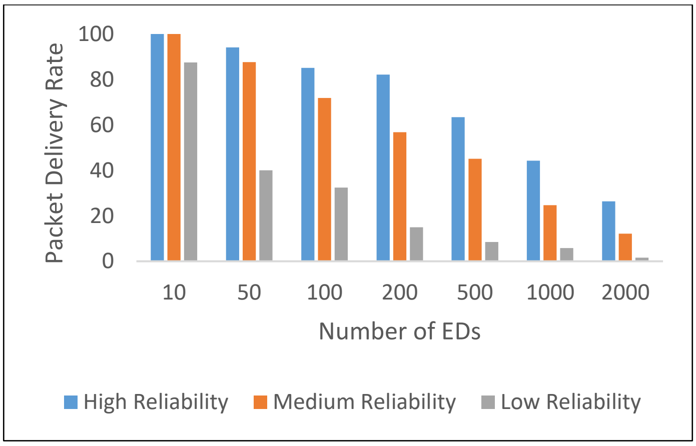

Figure 9: PDR for applications on the Heterogeneous LoRaWAN.
Source: Authors, (2022).

Figure 7 shows how the number of EDs affects the LoRaWAN uplink PDR. Generally, for both networks, the PDR expectedly reduces as the network size increases. At a distance of 2 KM, the heterogeneous network outperforms the homogeneous network due to high collision on the homogeneous network largely. However, for a distance of 6 km, the challenge of heterogeneous networks becomes glaring as it is outperformed by the homogeneous network. Energy usage at these large distances is also much higher in heterogenous LoRaWAN as shown in Figure 8.

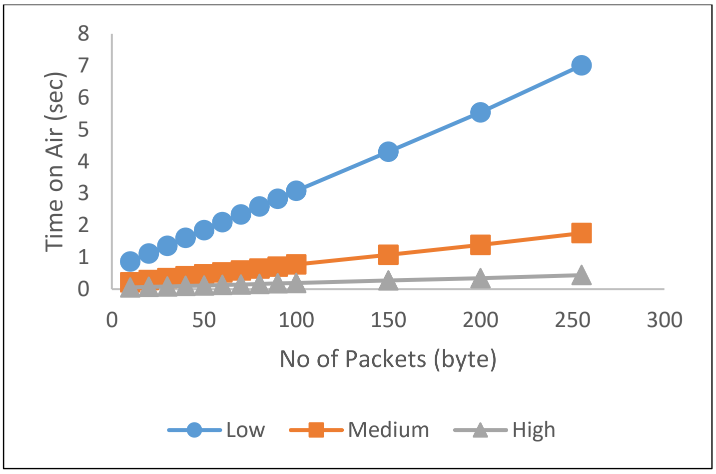

Figure 10: Time on Air for low, medium, and high reliability demanding applications.
Source: Authors, (2022).

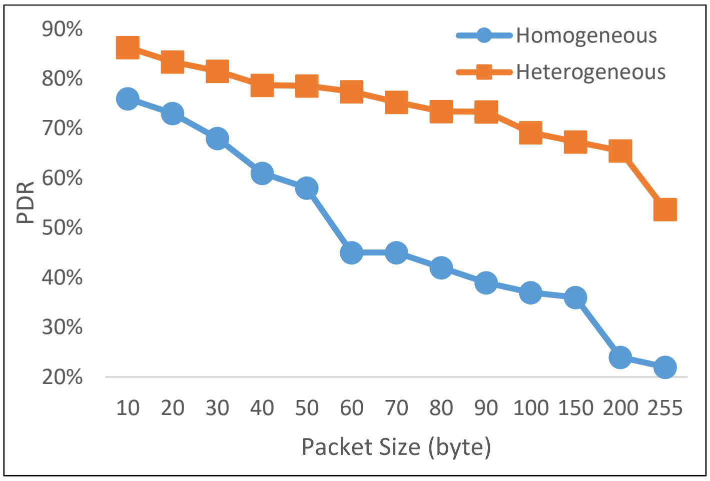

Figure 11: PDR with packet size.
Source: Authors, (2022).

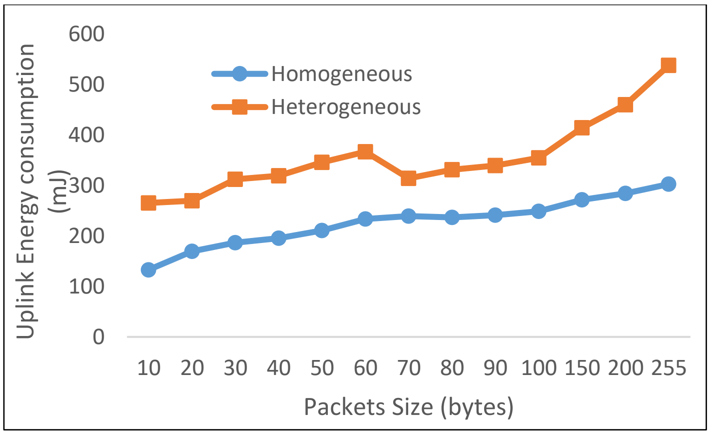

Figure 12: Energy consumption with packet size.
Source: Authors, (2022).

Figure 9 shows the PDR for each of the different applications on the Heterogeneous Network. The result shows that the critical application gets the priority by having 44 percent higher PDR in comparison to applications that require either medium reliability or low reliability which is good since there is no guarantee of better packet delivery for critical applications running on the homogeneous network. The higher PDR is directly linked to the shorter time on air as shown in Figure 10. Since the packet transmission takes much less time in critical applications, the probability of collision is greatly reduced.

The variation of uplink packet delivery rate with packet size is shown in Figure 11. Clearly, the larger the packet size, the lower the packet delivery rate. However, the performance of the heterogeneous network well outperforms that of the homogeneous network largely because of the allocation of transmission parameters for the transmission of the packets as against homogeneous network which uses the same parameter for the packets.

The energy consumption variation with packet sizes is as shown in Figure 12. The energy consumption varies proportionally with the increase in packet sizes. However, energy consumption is much higher in heterogeneous LoRaWAN than in homogeneous LoRaWAN.

V. CONCLUSIONS

In this study, we proposed a heterogeneous network and compared its performance with the homogeneous network which has been the focus of most studies on LoRaWAN. The heterogeneous network was designed to the application dependent and can consequently provide simultaneous support for applications with different requirements in terms of data rate and latency. We established that while such a system is limited in range and slightly more energy-consuming, they possess a higher probability of successful uplink since critical applications can enjoy preferential parameter allocation.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Olaide Ayodeji Agbolade, Folasade Mojisola Dahunsi and Samson Adenle Oyetunji.
Methodology: Olaide Ayodeji Agbolade and Folasade Mojisola Dahunsi.
Investigation: Olaide Ayodeji Agbolade.
Discussion of results: Olaide Ayodeji Agbolade.
Writing – Original Draft: Olaide Ayodeji Agbolade.
Writing – Review and Editing: Olaide Ayodeji Agbolade and Folasade Mojisola Dahunsi.
Resources: Olaide Ayodeji Agbolade and Samson Adenle Oyetunji.
Supervision: Folasade Mojisola Dahunsi and Samson Adenle Oyetunji.
Approval of the final text: Olaide Ayodeji Agbolade, Folasade Mojisola Dahunsi and Samson Adenle Oyetunji.

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