Impact of the Packet Delivery Ratio (PDR) and Network Throughput in Gateway Placement LoRaWAN Networks.

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***Abstract*—Internet of Things (IoT) is a fast and rapidly growing environment with LoRa technology as a leading Low-Power Wide-Area Network (LPWAN). It is paramount important to understand the LoRaWAN limitations/drawbacks and capabilities in terms of its scalability, coverage, probability and network throughput while LoRa networks are being rapidly deployed across the globe. Therefore, this paper intends to evaluate the LoRa network performance through the use of improved LoRa gateway algorithm for a Long-Range transmission technology and FLoRa (Framework for LoRa) which is a simulation framework for carrying out end-to-end simulations for LoRa networks. More specific, this study analyse and present the results of data collected from the FLoRa simulator after implementing the gateway placement algorithm optimized. To characterize the coverage of every LoRa nodes in the network, packet delivery ratio (PDR) for each node has been calculated. The extensive results obtained shows that as few as two gateways deployed in the network is sufficient to cover an approximately 10 km radius of a dense urban area.**

***Index Terms*—IoT, LoRa Networks, PDR, LPWAN, FLoRa.**

I. Introduction

Internet of Things (IoT) is expected to grow exponentially such that devices connected to the internet reach 125 billion during the year 2030. For data transmission to the IoT end node devices rely on Gateways and to ensure coverage for IoT devices Gateways need to be optimally placed [1]. However, physical infrastructure and topography as features of the target area are essential for IoT gateway's optimal placement. Recently, Wireless Mesh Networks (WMN) has gained an important role in current communication technologies. It has been used in several applications such as surveillance and rescue systems. Network congestion can be minimized and throughput can be improved by placing many gateways but it can be very costly, deployment and interference will increase. Therefore, this work focuses on the gateway placement algorithms on the newly developed wireless technology called Long Range Wide Area Networks (LoRaWAN) protocol and its performance using matrices such as PDR, network throughput, and success probability of nodes.

Gateway placement is essential in long-range transmission of data for commercialization of the IoT technology due to its capability to facilitate data transmission in a long range,since demand for large amount of data transmission, low-power and long range (LoRa) arises. For a long-range and low power communication the LoRa technology is available but not suitable for transmission of large amount of data due to low transmission rate. The LoRa communication technology is a low power, long range wireless protocol developed by Semtech. High extendibility, low power consumption and high efficiency as compared to 3G/4G technologies are the main advantages of LoRa technology. However, low transmission rate is the notable disadvantage of LoRa technology [2].

Low Power Wide Area Network (LPWAN) provides Wireless connectivity, long-range transmission and increased power efficiency [3]. LoRa is the most promising technology with a lot of capabilities which is provided by LPWAN. LoRaWAN communication protocols/ standard are used by a lot of LoRa devices since they have a potential to improve power efficiency and it can sustain device batteries estimated up to 10 years. It is important to note that LPWAN consist of LoRa technology which uses LoRaWAN as the communication protocol. Furthermore, as a emerging wireless technology LPWANs compliments short range wireless technologies and traditional cellular to address requirements of IoT applications that are diverse. Not only short-range connectivity is offered by LPWAN technologies but also long-range connectivity with low rate and low power devices, not provided by ancient technologies. Applications that need low data rate, delay tolerant, and typically require the low consumption of power are specifically considered by LPWAN technologies [4].

The rest of this paper is organized as follows: Section II evaluates the importance of LoRaWAN protocol and gives a brief background on LoRa and LoRaWAN. Section III gives some details on a related work for this study. Section IV discusses the simulation procedure followed. Section V present the simulation results obtained. And Section VI concludes the paper.

II. THE LORAWAN PROTOCOL

Companies using the IoT devices are already benefiting from the use of LoRaWAN. There are two main components of LoRa network which is LoRa and LoRaWAN, each of these component in a protocol stack corresponds with different layer. In the other hand, LoRaWAN is describe by the LoRa Alliance as an open standard where LoRa physical layer is developed by Semtech which remains the only integrated LoRa circuit. Figure 1. represents protocol stack of network servers, IoT devices and gateways, while gateways acting as a middle man forwarding messages between sensors (i.e.. IoT devices) and the network server. The sensors are implemented on the application layer.

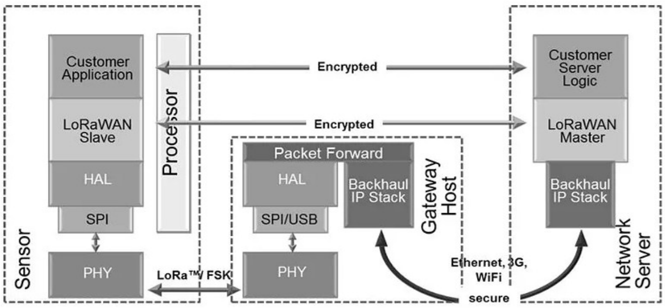

Fig. 1. Protocol stack in LoRaWAN with various devices.

A. LoRa

LoRa is a new promising and fast growing network designed for unlicensed,low power and long range operation. In order to meet the data and range requirements LoRa wireless uses a chip-spread-spectrum (CSS) modulation with options for different bandwidth (BW) and spreading factor (SF) for modulation optimization. 433 MHZ, 868 MHz and 915 MHz are all ISM band where LoRa operates depending on jurisdiction with the band divided up into channels [5]. In LoRa networks the combination of bandwidth and SF compromise speed for range. Other parameters affecting the communication range and data range includes center frequency, code rate and transmission power, not only SF and bandwidth.

The ratio between the chip rate and and data symbol rate is labelled as SF, therefore, tuning the reachable distance and the data rate is allowed through the configuration of SF. In fact, the higher the SF allows longer range at the expense of low data rate, and vice versa. The configuration of transmission power is mostly depends on the bandwidth and region used for transmission, whereas the code rate is regarded as forward error correction and it affects the data transmission airtime. The center frequency rely on the ISM band of chosen region. finally, the bandwidth plays a significance role in the data rate of transmission. 14dBm is the limited transmission power in Europe with the duty cycle of 1% for air time. However, the usage of these bands differs across the world [6].

B. LoRaWAN

LoRaWAN is a ALOHA based communication protocol and system architecture for LoRa physical layer used by the network. Using gateways to communicate over the air is the strongest ability of LoRaWAN due to gateways ability to facilitate communication amongst IoT devices and it involves LoRa wireless channels in a protocol stack, where gateways communicate with network servers and the communication between gateway and LoRa nodes are created by LoRa physical layer. To reduce the complexity of LoRa nodes in the network, LoRaWAN depends on ALOHA based MAC protocol [7].

LoRaWAN technology has the capability of adapting its principal parameters in order to optimize the energy consumption. Figure 2. shows the architecture of the LoRaWAN network, LoRa/LoRaWAN RF interface is used to facilitate communication between end nodes and the gateway. Ethernet,3G/4G, Wi-Fi and etc are all non-LoRaWAN network which are used by gateway to transmit frames to the network server and TCP/IP SSL is responsible for the protection of critical application from threat of attack.

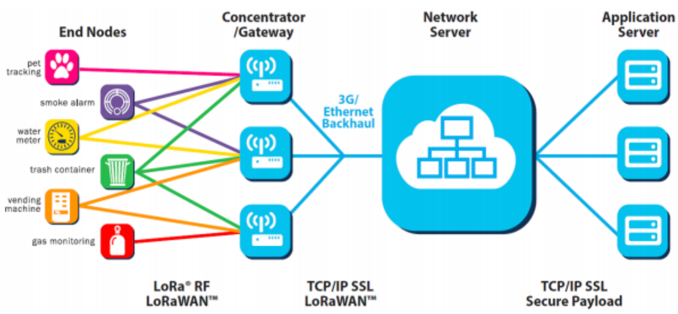

Fig. 2. The LoRaWANArchitecture [8]

III. RELATED WORK

Since LoRaWAN is an active study, network throughput, Packet Delivery Ratio (PDR) and success probability are being the main stand out matrices to evaluate the network performance especially in gateway placement. In [9] authors evaluated the scalability, coverage and throughput of LoRa LPWAN for Internet of Things, this was a simulation based study where custom-built simulator was used for characterization of LoRa network scalability under variety of network settings and traffic. The two measurements indoor and outdoor were conducted and to visualize the network coverage, PDR was imposed for the gateways on Google maps network coverage for a heatmap. A 95.3% of PDR was achieved at distance of $7.5km$ even though the gateways are placed close to the downtown area network coverage extends beyond the city edges.

Another authors in [10] evaluated LoRa LPWAN technology for remote health and wellbeing monitoring . A different of transmitting power, bandwidth and spreading factors were used. The results obtained in this study gave insight on what can be covered by the single base station, since they obtain 96.7% of success packet delivery ratio. However, they never really looked at the LoRa gateway placement and its algorithms for different technologies but only the parameters that can be used.

In [11] scholars analysed the LoRa networks using certain case perspective, some of the cases that were considered includes areas like vehicle fleet tracking, smart street lights, smart parking and smart metering. This study was carried out using a simulator called LoRaSim, which is a packet-level discrete event simulator for LoRa networks. According to their findings, up to 380% packet delivery ratio was achieved through the fastest data rate correspond settings and uses 0.004 times the energy compared to other evaluated settings, while support IoT cases mentioned here.

LoRa/LoRaWAN study is categorized as follows throughput analysis, Interference analysis, Gateway coverage and latency analysis:

A. LoRa/LoRaWAN analysis of Throughput

The network throughput for LoRa that is analysed in [12], [6] and [13], which specifically focused on Class A devices revealed that, at the edge of the network throughput can be as low as 100 bps. Furthermore, although Aloha is used by LoRaWAN a 32% packet loss is convertible despite the increase of up to 1000 nodes per gateway which is caused by the LoRa's robustness modulation technique. In other words, a packets collision massively impact the network throughput in a low transmission rate. However, network throughput can also be impacted by the duty life cycle at a high rate transmission and Acknowledgement at a great extent especially in Class A device can reduce the achievable network throughput. The drawbacks of the existing study in the network throughput is that they only focus on few spreading factors which is SF7 and SF12 with 125KHz of bandwidth.

B. Interference analysis

In [14] and [15] a co-spreading factor interference and LoRa network interference analysis is presented. The use of multiple gateways and directional antennas were examined to combat interference from neighbouring LoRa networks. The results stated that, using multiple gateways to combat the LoRa networks interference is the better option as compared to the use of directional antennas since it increases the Packet Delivery Ration (PDR). Furthermore, it is observed that using one spreading factor drops the probability of successful packet due to high interfering signals.

C. Gateway coverage

In [16] and [17] the scalability and LoRa gateway coverage are being analysed some of the results shown that at least $2km$ of radius can be covered by a LoRa cell in a harsh propagation conditions, it was also observed that at the network edge the LoRa nodes are only guaranteed the lowest bit rate. The studies also revealed that with a 30 gateways deployed a metropolitan city of approximately $100km^2$ can be covered.

D. Latency analysis

In [18] and [19], an analytical model for uplink latency considering duty cycling regulation of Class A devices is presented. The results shown that for a given data load the impact on latency is caused by combining and sub-band selection. Furthermore, a large number of channels can help minimize the delays in the presence of networks that are heavily dominated by large number of nodes.

IV. Simulation procedure

To evaluate the performance of LoRa networks FLoRa was used. Furthermore, two network scenarios were created, the first one consisted a network of 100 LoRa nodes which were varied from 100 to 700 with a step of 100. The LoRa physical layer European environmental parameters were used as explained in Table I, and for both scenarios gateway varied from one to two. In the second network scenario 20 LoRa nodes with different gateways were deployed, where spreading factor and transmission power were arbitrarily picked by the nodes distributed within the permissible range.

TABLE I
Simulation Parameters

Parameters	Value(s)
Code Rate	4/8
Carrier Frequency	868 MHz
Spreading Factor	7 to 12
Transmission Power	2 dBm to 14 dBm
Bandwidth	125 kHz

In order to achieve zero packet loss with a transmission delay of 10ms, INET framework played a vital role to model the backhaul network. Sensing application was among the parameters considered in the simulation. With a mean of $1,000s$, each LoRa nodes were able to send a 20-byte packet after distribution time. In the first scenario, $500m$ x $500m$ was set as a size of deployment area and in the second scenario $10000m$ x $10000m$ was set. The square region was used to locate all LoRa devices deployed in the network in order to make sure nodes communicate with the gateway(s), since nodes were randomly place. The simulation process lasted exactly one day for both experiments and for the accuracy results purposes 10 iterations were done. LoRa networks performance was evaluated with and without Adaptive Data Rate (ADR). The mechanisms is disabled in the networks with no ADR for both at the LoRa nodes and network servers.

A. Simulation script

Algorithm 1. explain in details the main steps followed by the simulation script. A different scenarios are presented in different scripts for different purposes. LoRaNetworkTest.in and betTest.in files define the scenarios. Scenario consist of certain features including LoRaNodes, gateway(s), and a network server, for every network scenario created LoRaNodes were randomly distributed in deployment area keeping in mind a radius. Transmission power and spreading factors are allocated for every nodes from available settings, in the nodes and network server ADR was disabled and enabled where necessary. 1 day was configured as the simulation time limit with a warm-up period of 5 hours, cloudDelay.xml file consist of backhaul network configuration and its link on package.ned file.

Algorithm 1 Simulation Script.

Input: Number of Gateways.
Input: Number of LoRaNodes.
Input: Radius for deployment area.

```
Assign UDPApps in LoRaGW, LoRaNodes, and Server.
Create parkert forwarder for all ports
Sim-time-limit = 1d
 Warm-up period =5h
Create LoRaNodes features.
 ADR inNode = True/False
InitialLoRaSF= (7,12)
InitialLoRaBW= (125KHz)
InitialLoRaCR= (4)
InitialLoRaTP= (2dBm + 3dBm * uniform (0,4))
 Setup GW features
Start the simulation
Save the simulation results
return
```

V. Simulation Results

The various matrices used in this study are analysed in this section with the help of LoRa modules added to Framework for LoRa (FLoRa). The throughput for some performance network matrices such as Packet Delivery Ratio (PDR) and packet success probability were explored.

A. Packet Delivery Ratio (PDR)

To characterize the coverage of every LoRa nodes in the network, PDR for each node has been calculated. A ratio of a successfully received data packetsover a totally sent data packets is called PDR. Equation 3.1 is used to calculate PDR for each nodes:

$$PDR = \frac{Packetsreceived}{Packettransmitted} * 100 \qquad (1)$$

In some cases the node disconnect from the network and try to reconnect at a later stage, most of these packet might not be successfully delivered to the gateway after failed to re-join the network. Therefore, equation 1. defines PDR solely focused on data packets and thus does not reflect in anyway the success ratio of join-request. Therefore, when the calculation is performed in the simulation using the equation a minor error will be observed compare of that simulation. PDR equation does not include join request because they have to be tracked manually in the LoRa nodes as gateway will be aware of any unsuccessful join request and only starts logging a LoRa nodes once it has successful joined.

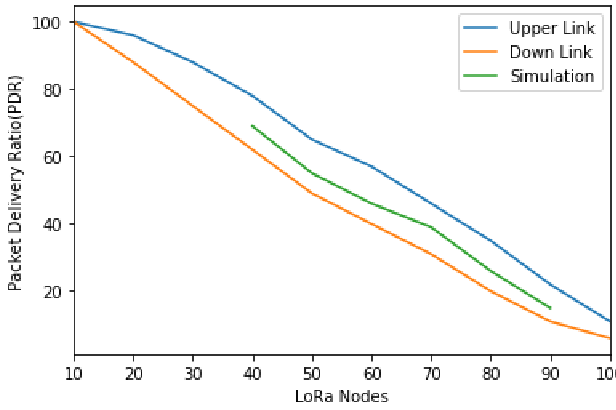

Fig. 3. Successful delivery ratio probability experimental dependence.

Figure 3. illustrate the experimental dependence of the probability of successful delivery on the number of devices. The simulation consist of two links upper and down links, the blue line represents upper link of theoretical value packet delivery ratio. The orange line represents the down link of theoretical value of packet delivery ratio. And the middle one, green in colour shows the experimental results of the actual results. From this simulation it is observed that the experimental value is slightly closed to upper link theoretical value due to congestion in the down link which leads to massive packet loss as the network expands.

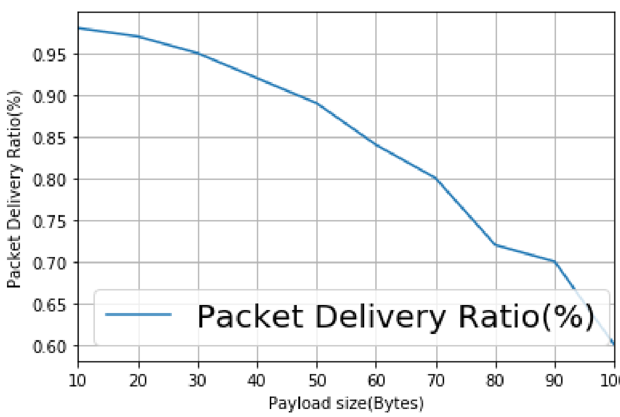

Fig. 4. Packet Delivery Ratio versus payload size for a 100 LoRa nodes.

The variation of the payload size ranged from 10 Bytes to 100 Bytes, with a transmission rate of 1 packet per second for each LoRa nodes deployed in the network. According to the results obtained as explained in Figure 4, it is observed that to obtain at least 90.0% of packet delivery ratio payload size should be kept under 45 Bytes with a 125 kHz bandwidth and coding rate of 4/5. This was a much better and improved performance in terms of PDR as compared to this study [20] which was done in a different environment with a change in parameters. This is an enormous improvement of the transmission rate by the algorithm implemented in this study as compared to the one existing, where most of them enables the network to reach percentage of 90.0% once the reporting time nearly clocks 700 seconds with less LoRa nodes deployed in the networks compare of that 100 LoRa nodes used in this study.

B. Network performance evaluation

In this section we analyse and evaluate the network performance through the packet success probability and network throughput. These matrices used here are influenced by the LoRa modules added in FLoRa for LoRaWAN simulation networks. The first step, was to evaluate and visualize the results obtained for network throughput for performance purposes. The second step, was to actually evaluate the success probability of the packet sent for every network scenario created in a LoRaWAN communication protocol.

Throughput performance

The network throughput in this simulation campaign is characterized by S as a function offered by network traffic G where the function aims to evaluate network throughput. In this equation N denotes LoRa nodes placed around GW at a chosen radius r from the simulator. The value of radius is chosen based on SF=12, since r is the maximum range where LoRa nodes and GWs can be able to transmit packet using SF=12 and considering a propagation loss. Multiply LoRa channel was considered for this simulation section performed, for all simulations measuring throughput the gateway was configured to only have one receive path enabled.

It is supposed that LoRaNodes i=1..., for the computation of throughput. Where N generates every τ_i seconds a packet which occupies the channel for t_p,i in order to be transmitted. The duty cycle limitation for this simulation section is always 1% and when not specified it is not applied at all, the main aim is to test the LoRaWAN access scheme. The network offered traffic is computed as described in the equation below [21]:

$$\sum_{i=1}^{N} \frac{t_{p,i}}{\tau_i} \qquad (2)$$

The fraction of LoRa nodes packet transmission over time taken by the LoRa channel is called offered traffic as expressed in equation . The LoRa channel is underutilized if G<1 where no packet transmission or communication between the devices takes place in the network. However if G>1, it simple state that even during a free flowing transmission in the network some packets will attempt to use same channel simultaneous, which may lead to packet collision. Therefore now, throughput S is obtained through a given value of G as follows:

$$S{=}G{\cdot}P_{succ} \qquad (3)$$

Again the total number of packet sent and total number of packet successfully received ratio in the simulation is said to be the approximation packet success probability denoted as P_{succ}. Perfect synchronization between LoRa devices inspired by a network offering of 1 can prevent the high packet loss during transmission by mitigating the probability of packet collision, and that will results into throughput of 1. of course, it is very difficult or impossible to achieve a 100 percent free flowing synchronization between the LoRa devices, so S<1 is expected.

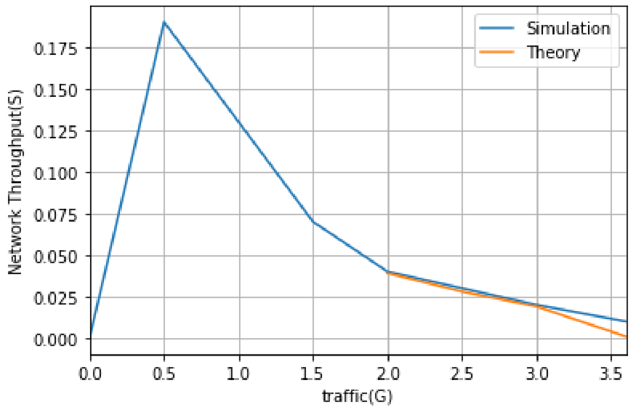

Fig. 5. Ideal packet collision and throughput of SF=7.

It is expected that a shape of the throughput becomes curved under ideal channel condition, and follow typically ALOHA network in a varying offered traffic G as shown in Figure 5. All LoRa nodes are configured to transmit using SF7 and all transmitted packet have the same time on air (ToA) provided payload length is fixed and gateway receives the packets at the same rate of power, these conditions takes place when the link measurement model is off. The number of LoRa nodes N plays a significant role in expressing the traffic offered by the network as shown below:

$$G{=}\frac{N{\cdot}t_7}{\tau_i} \qquad (4)$$

This transmission happen at a fixed payload length for all packet using SF7 as a range of transmission, where t_7 is ToA.

Success probability performance

The aim of this simulation experiments is the estimation probability of successfully receiving a transmitted packet from LoRa nodes to LoRa gateway(s). Even though some network simulation scenarios featured more than one GW only LoRa devices are within the range covered were considered. Therefore, it is only LoRa nodes within the radius have their generated traffic considered for success probability [22].Figure 6. shows the decline of the probability success ratio as the network expands, all packets that arrives at the GW under the sensitivity are being ignored due to shadowing or massive building loss. Therefore, this eventually lead to a declining success probability because of path loss reception and interference of any different kind. In this scenario, 22% of LoRa nodes were unable to reach the gateway due to insufficient power.

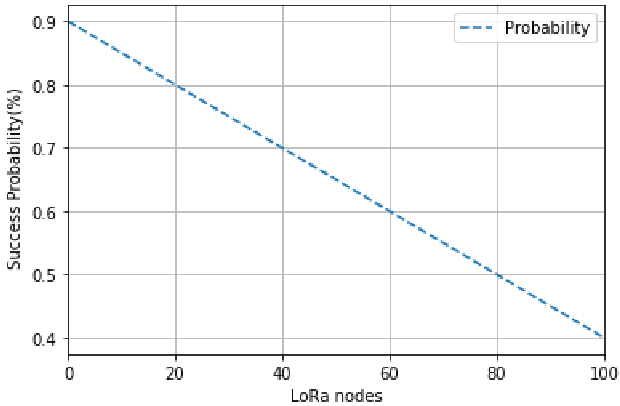

Fig. 6. Packet success probability as a function of LoRa devices.

The simulation actually lasted one day with 5 hours of warm up and the simulation was repeated 10 times for accuracy purposes. As the network increases the trend of the graph appears to be decreasing linear. The gateway(s) that were tasked to accommodate all the LoRa devices formed network scenarios were able to achieve a success probability of almost 91%.

VI. Conclusion

This study as a whole was set out to construct a LoRaWAN simulation with the purpose to execute a performance evaluation of the improve gateway placement algorithm in this new arising and fast developing technology. The results obtained through the simulation showed that for both upper link and down link the PDR percentage drops as the network expands at a different level including for that of simulation. Although this should be the trend for the calculated PDR of a network with different LoRa node our improved algorithm appears to give the better performance compare to other algorithms used before. However, in future the algorithm performance still need to be tested in a different environment such as testbed.

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