# Analyzing LoRa: a Use Case Perspective

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***Abstract*—Low-power wide-area networking (LPWAN) technologies are capable of supporting a large number of Internet of Things (IoT) use cases. While several LPWAN technologies exist, Long Range (LoRa) and its network architecture LoRaWAN, is currently the most adopted technology. LoRa provides a range of physical layer communication settings, such as bandwidth, spreading factor, coding rate, and transmission frequency. These settings impact throughput, reliability, and communication range. As IoT use cases result in varying communication patterns, it is essential to analyze how LoRa's different communication settings impact on real IoT use cases. In this paper, we analyze the impact of LoRa's communication settings on four IoT use cases, e.g. smart metering, smart parking, smart street lighting, and vehicle fleet tracking. Our results demonstrate that the setting corresponding to the fastest data rate achieves up to $380\%$ higher packet delivery ratio and uses 0.004 times the energy compared to other evaluated settings, while being suitable to support the IoT use cases presented here. However, the setting covers a smaller communication area compared to the slow data rate settings. Moreover, we modified the Aloha-based channel access mechanism used by LoRaWAN and our results demonstrate that the modified channel access positively impacts the performance of the different communication settings.**

***Index Terms*—Low-Power Wide Area Network (LPWAN), LoRa, Internet of Things (IoT).**

## I. Introduction

The Internet of Things (IoT) promises to create an ecosystem of billions of connected devices [1] supporting a wide range of smart city IoT use cases, such as smart metering, smart parking, vehicle fleet tracking, and smart street lighting to name but a few. Recently, low-power wide-area radio technologies, such as Long Range (LoRa) and LoRaWAN [2], SigFox [3], and Weightless [4] have emerged to support such smart cities use cases. The low-power wide-area networking (LPWAN) technologies use robust modulation techniques to cover long distances while supporting relatively low data rate applications. The long range characteristic of these technologies results in a star network topology making network deployment and maintenance relatively simple [5]. While there are many benefits of these technologies, their performance with regard to real IoT use cases is currently not well understood.

LoRa/LoRaWAN is one of the most successful LPWAN technologies due to its openness and open source software support. LoRa, which defines the physical layer, provides a large number of settings in order to support a broad operating range. In this paper, we analyze how LoRa physical layer settings impact different IoT use cases, such as smart metering, smart street lighting, smart street parking, and vehicle fleet tracking in order to provide insights into the technology's applicability to different IoT use cases. The use cases we consider have different data generation patterns ranging from one packet per day to a number of packets per hour. We also analyze how LoRa's physical layer settings influence each use case's scalability. As LoRaWAN uses an Aloha based medium access control (MAC) mechanism, which is well-known to scale poorly, we also analyze Aloha's impact on the performance of the IoT use cases. The following are our main contributions:

- Analysis of LoRa physical layer settings on the performance of a number of real IoT use cases.
- Analyzing Aloha MAC impact on IoT use cases and comparison with a modified MAC.
- Experimental results demonstrate: $(i)$ LoRa physical layer setting corresponding to the fastest data rate demonstrates up to $380\%$ higher PDR and uses as little as 0.004 times the energy compared to the other evaluated settings, $(ii)$ LoRa's physical layer settings, resulting in the slowest data rate, which are recommended for LoRa/LoRaWAN perform poorly for the evaluated use cases, and $(iii)$ our modified channel access mechanism positively impacts the evaluated settings' performance.

The rest of this paper is organized as follows. Section II provides an overview of LoRa and LoRaWAN. Related work is presented in Section III. Our experimental evaluation of the LoRa performance for different IoT use cases is presented in Section IV. Performance with the proposed modified channel access mechanism is presented in Section V, and conclusions and future work are presented in Section VI.

## II. LoRa/LoRaWAN Overview

This section provides a brief overview of the Long Range (LoRa) physical layer and the LoRaWAN medium access control (MAC) layer protocol and network architecture. LoRa/LoRaWAN is defined by the LoRa Alliance [2] with the objective to support a multitude of IoT use cases through a communication technology that can cover long distances in an energy-efficient manner.

### *A. The LoRa Physical Layer*

LoRa is a physical layer radio modulation technique based on chirp spread spectrum (CSS). The goal is to enable low throughput communication across long distances with low power consumption. LoRa enables a long communication distance as a LoRa receiver can decode transmissions at 19.5

dB below the noise floor due to the use of CSS. LoRa features include long range, multi-path resistance, robustness, low power consumption, forward error correction (FEC), and Doppler resistance. LoRa provides several physical layer parameters that can be customized. These parameters include spreading factor (SF), Bandwidth (BW), transmission power (TP), and code rate (CR). The parameters affect the available bit rate, resilience against interference, and ease of decoding.

Fig. 1 shows the LoRa physical frame format. It starts with a preamble, whose duration can be configured to be between 10.25 and 65,539.25 symbols. An optional header follows which is always transmitted with a CR of 4/8. The header contains the following information: payload length in bytes, CR used for payload, and whether or not a CRC is present. The length of the payload size is stored in 1 byte, hence the maximum payload is 255 bytes. The header field is optional and it is more energy-efficient to disable the header in situations where payload length, CR, and CRC presence are known in advance. The frame ends with an optional 16 bit CRC field. Payload and CRC are transmitted with a CR of $\frac{4}{(4+N)}$ with $(N \in \{1,..,4\})$. A more detailed discussion of LoRa can be found in [6].

## B. LoRaWAN

LoRaWAN [2] includes a MAC layer protocol designed for use with the LoRa physical layer. A LoRaWAN network mainly consists of the following three components, end devices, gateway(s), and a network server. An end device communicates with a gateway using LoRa and the LoRaWAN MAC and a gateway forwards the end device data to the server. A gateway is connected to the server using local-area or wide-area networking technologies, such as Ethernet, 3G/4G, or other WAN technologies. The server is responsible for the processing of data packets received from devices, detect duplicate packets, storing and analysis of received data. It may also generate packets addressed to devices. LoRaWAN considers the following three end device categories:

- Class A: Supports bi-directional communication with uplink transmissions scheduled based on an application's requirements. Two short downlink receive windows follow immediately after an uplink transmission, allowing downlink transmission only after an uplink transmission. This class has the lowest power consumption.
- Class B: In addition to class A functionality, devices in this class open extra receive windows at scheduled times. This requires a synchronization beacon for proper operation, which is advertised by the gateway.
- Class C: It also supports bi-directional communication. However, devices belonging to this class have an almost continuous receive window. Hence, devices belonging to this class have maximum power consumption.

Simple Aloha is used as the MAC protocol, which means that devices which have data to transmit do so without employing clear channel assessment. However, devices must obey strict duty cycle rules of a 1% duty cycle. For proper operation, LoRaWAN defines a range of MAC commands. A more detailed discussion of LoRa/LoRaWAN can be found in [2].

| Preamble | Header | Payload | CRC (Optional) |
|---|---|---|---|
| | CR= 4/8 | CR= 4/(4+N) | |

Fig. 1. LoRa Frame Structure

# III. Related Work

Existing research on different aspects of LoRa/LoRaWAN can be categorized into *throughput analysis*, *gateway coverage and scalability*, *interference and co-spreading factor interference analysis*, and *latency analysis*.

## A. LoRa/LoRaWAN Throughput Analysis

LoRa throughput is analyzed in [7], [8], [9], and [10], which have primarily focused on Class A devices. It has been shown that the throughput of nodes at the edge of the network can be as low as 100 bps [10]. Moreover, it has also been shown that although LoRaWAN uses Aloha, due to LoRa's robust modulation technique an increase of up to 1000 nodes per gateway results in only 32% more packet losses, whereas for the same scenario the losses are up to 90% in other simple Aloha-based networks [9]. In general, for a very low transmission rate (a few packets/day), throughput is impacted by packets collisions. However, at higher transmission rates duty cycling impacts the throughput. Acknowledgments also reduce achievable throughput to a great extent especially in Class A devices. The limitation of existing work is their focus on 125KHz bandwidth and that performance has been explored for only a few SFs, such as SF7 and SF12. Moreover, none of the existing works explore LoRa network throughput for different IoT use cases.

## B. Gateway Coverage

In [11], [12], and [13] LoRa gateway coverage and scalability are analyzed. It has been shown that in harsh propagation conditions, a LoRa cell can cover an approximately 2 km radius, but nodes at the network edge are only guaranteed the lowest bit rate. Therefore, a nominal coverage of 1.2 km was assumed. It has also been shown that a $100\,km^2$ area of a metropolitan city can be covered with 30 gateways, and this number is equal to half of the sites deployed by a popular cellular network service provider in the city of Padova, Italy. However, there is no research that addresses coverage with regard to different IoT use case requirements.

## C. Interference Analysis

In [14] and [15] an analysis of LoRa is presented from the perspective of neighboring LoRa networks interference and co-spreading factor interference. To combat interference from neighboring LoRa networks, the use of directional antennas and multiple gateways were examined. It is shown that to combat interference, using multiple gateways is a better option compared to directional antennas as it yields a substantially higher increase in packet delivery ratio (PDR). Moreover, it has also been shown that due to interfering signals using the same spreading factor, the coverage probability drops exponentially.

### D. Latency Analysis

In [16] and [17] latency analysis for Class A and confirmed downlink frames in Class B devices of LoRaWAN are presented respectively. In [16], an analytical model for uplink latency considering duty cycling regulation of Class A devices is presented. It has been shown that sub-band selection and combining has an impact on the latency for a given data load. Similarly, it has been shown in [17] that data rate and the number of sub-bands impact downlink latency. Moreover, in the presence of a large number of nodes, a large number of channels can help to decrease delay substantially. As is the case with other research, these studies also consider only a few physical layer settings and no consideration is given to the requirements of different IoT use cases. A detailed discussion on LoRa physical layer parameter selection can be found in [18].

### E. Discussion

Existing research on analyzing LoRa/LoRaWAN is somewhat limited as a number of factors have not been fully considered. These factors include traffic generation models for different IoT use cases and their quality of service (QoS) requirements. LoRa is capable of supporting a number of SFs, BW, CR, and TP, however existing work is mostly based on a few SFs along with BW of 125 KHz. LoRa uses Aloha, which is known not to scale well, however there is no research that tries to overcome some of the shortcomings of Aloha in a LoRa network. Therefore, in this paper we analyze the impact of a range of LoRa physical layer parameters on different IoT use cases, such as smart metering, street parking, vehicle fleet tracking, and street lighting. Moreover, we propose a simple wait before transmit extension to LoRaWAN's channel access mechanism, and analyze its impact on the use cases.

## IV. IoT Use Case Performance Analysis with LoRa

In this section, different IoT use cases and their performance for a number of LoRa physical layer settings are analyzed.

### A. Evaluated IoT Use Cases

In the absence of published data traffic models for IoT use cases, we made a number of assumptions for the data generation models of each use case as a representative for a broader range of possible IoT use cases.

*1) Smart Metering:* We choose the smart metering use case as a representative of those IoT use cases that transmit one packet per day. For this use case, we assume that a smart electricity, gas, or water meter transmits daily meter readings to the utility provider's server. If all smart meters transmit their reading at the same time, there is a very high data packet collision probability. Therefore, in our experiments, we assume that an application waits for a random duration before transmitting its data packet. In our experiments, the data packet transmission is delayed using a uniformly distributed random time interval in the range [0, 500] seconds.

*2) Smart Street Lighting:* We choose a smart street lighting use case as a representative of those use cases that transmit a few packets per day. We assume that during typical sunlight hours the lights remain switched off, and they are turned on just before sunset. After midnight, the lights remain off, and they are only switched on once movement on the street is detected. Just after sunrise the lights are switched off again. In our experiments, we assume that sunset is at 7 $pm$ and sunrise at 7 $am$. We model movement on a street after midnight as a Poisson arrival process with mean $(\lambda) = 30$ minutes. Whenever a light's status changes, a packet is transmitted to the server.

*3) Street Parking System:* We choose the smart street parking use case in a city as a representative of those IoT use cases that transmit a number of packets per day. In our experimental analysis, arrival and departure of cars are modeled using Poisson processes. We assume that whenever a parking space becomes available, it is occupied within 5 minutes, hence $\lambda$ for occupying a parking space is 5 minutes. Moreover, a vehicle can use a parking space for 1 hour, therefore $\lambda$ for a parking space to become free is 1 hour. Whenever, the status of a parking space changes a packet is transmitted to the server to maintain parking information. This model is very similar to the one reported in [19], which is based on extensive parking sensor readings from a deployment in a town in Northern Italy.

*4) Vehicle Fleet Tracking:* We choose the vehicle fleet tracking use case as a representative of those use cases that transmit many packets in a day. A number of events can be tracked, such as speeding, long idle time, and position information in response to a position update query. In our analysis, we model traffic generated by such a system through the Poisson process with mean arrival rate $(\lambda) = 5$ minutes. For this use case, we assume that a network is deployed in a way that there is always a gateway present on a vehicle's route.

### B. Performance Analysis

To analyze the performance of different IoT use cases we use the LoRaSim simulator, which is a packet-level discrete event simulator for LoRa networks [8]. For our experiments, we use a payload size of 20 bytes. This payload size is large enough to facilitate the different IoT use cases we consider, such as meter reading, geographical location reporting, event notification, etc. The duration of each simulation run is 1 month of real time. In our experiments we vary the number of nodes in a LoRa network cell from 200 to 1000 nodes in steps of 200 nodes. We use reliability and energy consumption as our performance benchmarks. For reliability we measure the Packet Delivery Ratio (PDR) and for energy consumption we measure and report total energy consumed by all the nodes in the network for the complete duration of a simulation. We analyze the impact of the following LoRa setting on the IoT use cases:

- $SN^1$ This setting uses the following parameters: SF12, BW = 125 kHz, and CR = 4/8. We analyze this setting because it is the slowest data rate setting and provides the highest level of resilience against interference.
- $SN^2$ Similar to $SN^1$ but randomly chooses between three different transmit frequencies (860, 864, and 868) MHz. We are interested in analyzing this setting to help us understand the impact of frequency diversity.
- $SN^3$ SF6, BW = 500 kHz, and CR = 4/5. We analyze this setting because it corresponds to the fastest possible data rate.
- $SN^4$ Uses optimized settings per node based on a node's distance from the gateway. We analyze this setting as it tries to optimize physical layer parameter selection based on distance from the gateway.
- $SN^5$ SF12, BW = 125 kHz, and CR = 4/8 is the recommended LoRaWAN setting.
- $SN^6$ This setting is similar to $SN^4$, however it also optimizes the transmit power. We analyze this setting because it also tries to minimize energy consumption.

Fig. 2 shows the impact of different LoRa physical layer settings on the considered IoT use cases. Fig. 2(a) and Fig. 2(b) show the settings impact on PDR and energy consumption in the smart metering and street parking use cases respectively. Corresponding to different number of nodes, $SN^3$ , $SN^4$, and $SN^6$ demonstrate almost perfect PDR. Use of $SN^1$ resulted in 48.67% PDR with 1000 nodes in the network and this is the lowest PDR we observed for this use case by any setting among those evaluated. $SN^1$ corresponds to LoRa's lowest data rate, which results in the highest air time. This causes a large number of collisions despite the uniformly distributed packet transmission delay and hence the setting demonstrates the lowest PDR. Similarly, the PDR caused by the use of $SN^2$ and $SN^5$ is also low, with 76% and 56.85% for 1000 nodes. $SN^3$ demonstrates the lowest energy consumption compared to other settings. In general, the use of $SN^3$ , $SN^4$, and $SN^6$ leads to up to 0.00413 times the energy consumption compared to other evaluated settings. Among the evaluated settings, $SN^3$ achieves the highest PDR with up to 104% higher PDR as compared to the use of $SN^1$. However, $SN^3$ covers a relatively small area compared to slow data rate settings such as $SN^1$.

Fig. 2(c) and Fig. 2(d) show the settings impact on PDR and energy consumption in the smart street parking use case. $SN^3$ , $SN^4$, and $SN^6$ demonstrate almost perfect PDR. $SN^1$ demonstrates 27.65% PDR when there were 1000 nodes in the network, and this is the lowest PDR we observed by any setting for this use case. $SN^1$ shows poor performance due to the same reasons as identified in the smart meter use case. $SN^2$ always achieves a PDR higher than 62.94% and $SN^5$ always demonstrates PDR higher than 36%. $SN^3$ demonstrates lower energy consumption compared to other settings. In general, $SN^3$ , $SN^4$, and $SN^6$ achieve up to 260% higher PDR with up to 0.00413 times the energy consumption compared to other evaluated settings. Among the evaluated settings $SN^3$ demonstrates the highest PDR with the lowest energy consumption.

Fig. 2(e) and Fig. 2(f) show the settings impact on PDR and energy consumption in the smart street lighting use case. $SN^3$ , $SN^4$, and $SN^6$ show almost perfect PDR. $SN^1$ demonstrates 56.28% PDR with 1000 nodes in the network, and this is the lowest PDR we observed in this use case for any setting. $SN^2$ always shows a PDR higher than 81%, and $SN^5$ achieves PDR higher than 65%. In general, $SN^3$ , $SN^4$, and $SN^6$ achieve up to 178% higher PDR with up to 0.00408 times the energy consumption compared to other evaluated settings. Among the evaluated settings, $SN^3$ achieves the highest PDR with the lowest energy consumption.

Fig. 2(g) and Fig. 2(h) show the settings impact on PDR and energy consumption in the vehicle fleet tracking use case. With the highest number of nodes, $SN^3$ , $SN^4$, and $SN^6$ achieve 96.23% , 94.93% , and 94.5% PDR respectively. Similarly, $SN^1$ , $SN^2$ , and $SN^5$ achieve only 2.5% , 9.4% , and 3% PDR respectively for the highest number of nodes. In general, $SN^3$ , $SN^4$, and $SN^6$ demonstrate up to 380% higher PDR with up to 0.00417 times the energy consumption compared to other evaluated settings. Among the evaluated settings, $SN^3$ demonstrates the highest PDR with the lowest energy consumption.

### C. Discussion

Among all evaluated LoRa physical layer settings, $SN^3$ , $SN^4$, and $SN^6$ not only scale well with regards to the number of nodes but also scale well with regards to the data generation rate. However, our results show that the recommended setting for LoRaWAN, ($SN^5$) and LoRa's slowest data rate setting, ($SN^1$) are not useful for any of the evaluated IoT use cases. These settings provide for long distance communication compared to the fastest possible data rate setting ($SN^3$), however their energy consumption is also very high compared to $SN^3$. The relative gains in terms of PDR and total energy consumption are higher using $SN^3$, and our results indicate that using a multi-hop LoRa network using $SN^3$ to cover a long distance may still achieve better PDR and energy consumption compared to $SN^1$ , $SN^2$ , and $SN^5$. However, in a multi-hop scenario nodes near the gateway may become bottlenecks (as they act as forwarders for data frames from possibly a large number of nodes), which may lead to network disconnections. However, as shown in other types of multi-hop networks, these issues can be solved by using routing protocols that try to avoid hot spots near the gateway.

## V. IoT Use Case Performance Analysis with Modified Channel Access

LoRaWAN uses pure Aloha as the MAC protocol. Our results in Section IV demonstrate that for some settings with a large number of nodes LoRa/LoRaWAN performance is poor. This may be due to the Aloha protocol, which is well known to have scalability issue. The purpose of this section is to modify the LoRaWAN MAC protocol and analyze its impact on the IoT use case performance. To modify the LoRa MAC

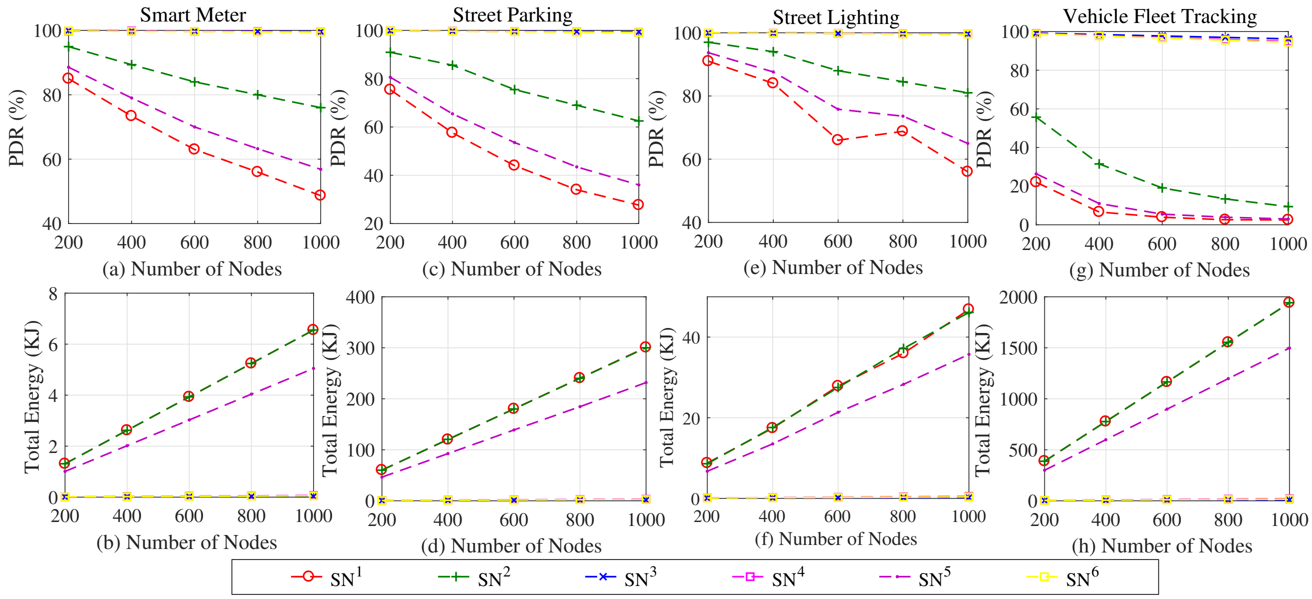


Fig. 2. IoT Use Cases' Performance Using LoRa

protocol we have a number of choices, such as sense before transmit and delay a data frame transmission for a random duration. However, sense before transmit is not suitable for LoRa type networks as it is energy hungry and a node can also use different frequencies to transmit different frames. Delaying the transmission of a data frame for a random duration is a simple option but can result in message buffer problems if a node generates multiple frames during the random delay. Also, in a network with a large number of nodes the probability of nodes picking the same random delay is increased, resulting in an increased probability of data frame collisions.

In our modified MAC protocol, we use a simple systematic approach for delaying a transmission. In a LoRa network, invariably nodes are assigned sequential IDs. We use a node's ID to calculate the amount of time the node has to wait before transmitting a data frame. We call this delay the delay before transmit ($D_{Bt}$), which is calculated using equation 1.

$$D_{BT} = (Node_{ID} \times U_d) \bmod Pkt_{iat} \tag{1}$$

Here, $Node_{ID}$ is a node's ID, $U_d$ is the delay in milliseconds (ms), and $Pkt_{iat}$ is a node's mean packet inter-arrival time in $ms$. It is possible that a LoRa node does not buffer frames, therefore to lower the packet drop probability, we use $\bmod$ to limit $D_{BT}$ to be within the mean packet inter-arrival time. $Pkt_{iat}$ and $U_d$ are configurable parameters. The values for these parameters depend on an application's requirements. In our experiments we use $U_d = 1000\,ms$. $Pkt_{iat}$ is also adjusted depending upon a use case's traffic generation pattern. Using the modified MAC protocol, we run the same set of experiments with the same simulation settings as in Section IV.

Fig. 3 shows the impact of different LoRa physical layer settings on the IoT use cases with our modified MAC. The trends shown in Fig. 3 are similar to the trends shown in Fig. 2, i.e., $SN^3$, $SN^4$, and $SN^6$ demonstrate higher PDR and lower energy consumption compared to the other evaluated settings and $SN^3$ is the best among all. Comparison of Fig. 3 with Fig. 2 reveals that our modified MAC does show a slight positive impact on the evaluated LoRa settings' PDR. Moreover, for those use cases that generate a large number of packets the total energy consumption has reduced. This is due to the fact that some packets were dropped while different nodes were waiting for their $D_{BT}$ periods to expire. Therefore, to minimize the number of dropped packets in such use cases, packet buffers should be used.

## VI. Conclusions and Future Work

We analyzed the impact of a number of LoRa physical layer settings on real IoT use cases, such as smart metering, smart street lighting, smart parking, and vehicle fleet tracking. The evaluated settings include LoRa physical layer settings for the slowest data rate, maximum protection against interference, fastest data rate, and recommended settings for LoRaWAN. Our analysis demonstrates that the settings recommended for LoRaWAN, e.g. ($SN^5$) along with LoRa's slowest data rate setting ($SN^1$) do not scale well with regard to the number of nodes nor with the data generation rate. They also consume more energy. Furthermore, our results show that the LoRa physical layer setting corresponding to the fastest data rate ($SN^3$) demonstrates the best performance amongst the evaluated settings. ($SN^3$) shows up to 380% higher PDR and up to 0.004 times the energy consumption compared to the other evaluated settings. We also modified the LoRaWAN channel access mechanism and analyzed the modified mechanism's impact on the IoT use cases. Our results show that the modified mechanism slightly improves PDR for the evaluated settings. In future, we plan to investigate the effects of LoRa/LoRaWAN settings on deployments using multiple gateways and directional antennas, and plan to investigate the impact of a multi-

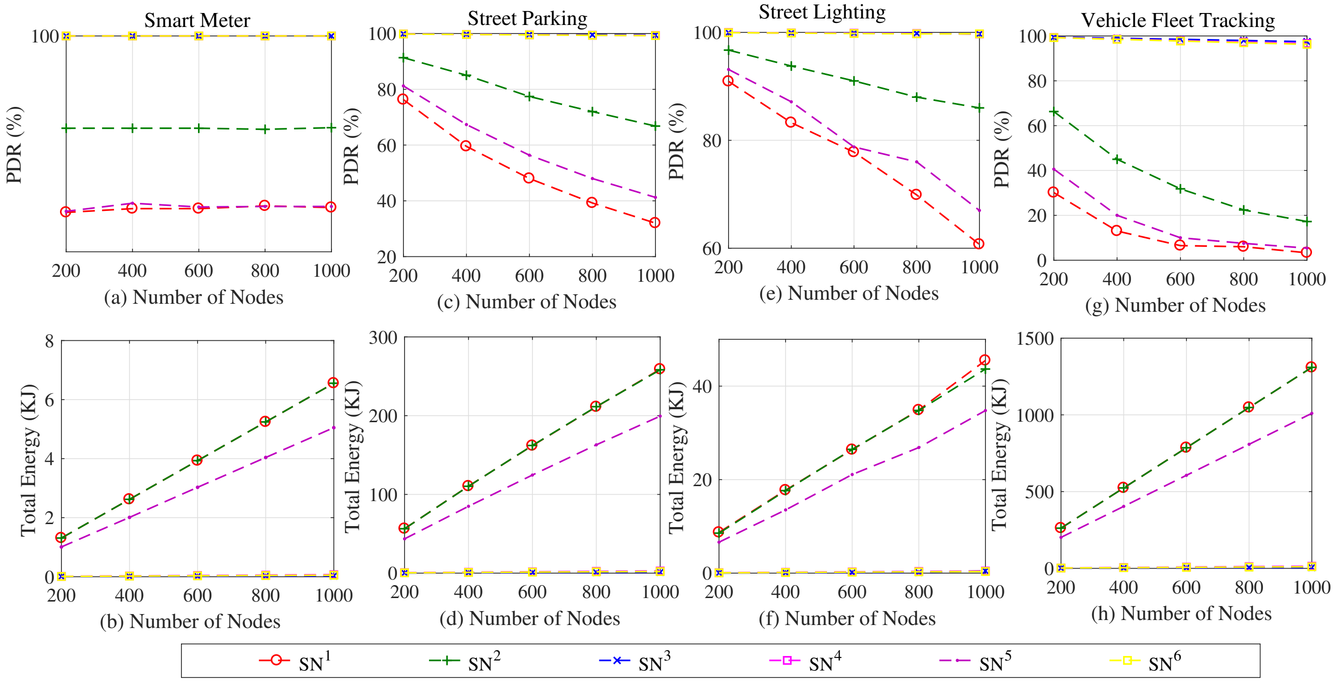


Fig. 3. IoT Use Cases' Performance Using LoRa With Modified MAC

hop LoRa network, especially on the $SN^3$ setting to cover longer distances.


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