Characterizing Packet Loss in City-Scale LoRaWAN Deployment: Analysis and Implications

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***Abstract*—With the popularity of LoRaWAN network deployments, it is critical to understand the packet transmission performance in various application settings. Previous efforts on LoRaWAN network measurement are either simulation-based or small-scale, which is not sufficient to reflect the true state of large operational LoRaWAN networks. In this paper, we provide an in-depth investigation of the packet loss rate (PLR) using the trace collected from a large-scale LoRaWAN network in Shanghai over eight months. We extract the performance parameters that have a direct impact on PLR from the trace information of packets and analyze the influence of these parameters on PLR. We also provide a comprehensive case study to find out in what circumstances the data packets are more likely to be lost. Our study shows the relationship between several indicators that are commonly considered to affect PLR. The lessons learned provide important guidelines for future LoRaWAN network optimization and deployments.**

***Index Terms*—LoRa, LoRaWAN, packets loss rate, measurements, smart city**

I. INTRODUCTION

In the past decade, the Internet of Things (IoT) have been applied in a range of fields, such as health monitoring and smart city etc [1]–[3]. A typical IoT network works as a distributed measurement system, with widely distributed end-devices transmitting the raw sensing data to the data processing center [4]. Many IoT applications require wireless communication technologies with the characteristics of wide coverage and low power consumption, which are hard to fulfill using traditional cellular and short-range wireless technologies [5]. To fulfill these requirements, numerous LPWAN (Low Power Wide Area Network) technologies are designed to complement the traditional IoT ecosystem. LoRa is one of the most successful LPWAN technologies due to its benefits in low power consumption and low deployment cost. In general, networks based on LoRa technology are flexible and autonomous because LoRa works on unlicensed ISM spectrum.

LoRaWAN is the MAC layer protocol that builds on the top of the LoRa modulation scheme. For a LoRaWAN network, the transmission quality of data packets has a significant impact on the performance of the entire network. The channel quality of links impairs the reliability of communications in networks, and consequently affects various upper-layer applications. Data loss may occur due to channel preemption or channel noise. LoRaWAN supports both confirmed-data message and unconfirmed-data message. A confirmed-data message has to be acknowledged by the receiver. End-devices will retransmit the data packets when they did not receive the acknowledgment. However, retransmission will result in additional energy consumption that impacts the battery life of end-devices. An unconfirmed-data message does not require an acknowledgment. Data loss may occur due to channel preemption or channel noise. Data loss may reduce the reliability level of applications and even cause serious consequences. For example, the loss of smoke detector signal may delay the response to potential fire accident. In addition, a large amount of data loss will reduce the data integrity and thus hamper the accuracy in IoT data analytics.

Since the release of its specification in 2015, LoRaWAN attracted increasing attention from both academia and industry. Despite the maturity in specification, there is still a big gap between the actual networking performance and the specifications, and there is a lack of analysis on how large-scale networks performed. Understanding the packet delivery performance of real LoRaWAN networks is important and necessary for network deployment and operation. Although there have been previous efforts that carry out exploratory measurement and analysis on various performance indicators in LoRaWAN networks, these studies are generally based on either simulations or small-scale testbeds, which is not sufficient to provide insights for the actual development of the industry. Measurements in large-scale real networks are still rare. Meanwhile, only a few existing studies have included packet loss into their investigation. And existing efforts mainly focus on packet transmission performance directly, rather than its influencing factors. Therefore, the results of previous work are neither sufficient to represent the realistic performance of packet transmission in large-scale LoRaWAN networks, nor thorough in revealing the potential causes of packet loss.

In this paper, we take a first look at the characteristics of packet loss in a commercial city-scale LoRaWAN network (say, with over 66,000 end-devices) by analyzing the dataset collected inside the LoRaWAN network over an eight-month period. In particular, the key contributions of this work are presented as follows.

- We conduct a series of measurements on this real city-scale LoRaWAN network which focus on the packet delivery performance, and analyze the relationship between the PLR and some relevant performance indicators in detail.
- We investigate the factors that have a strong impact on the

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TABLE I
LoRaWAN NETWORK DEPLOYMENTS

Type	Project	# Gateways	# Devices	Coverage	Duration	Location
simulation	[6]	47	11,681	–	–	Greater London, UK
testbed	[7]	1	19	$600m \times 800m$	–	Taiwan
testbed	[8]	3	>50	$3 \times 3km$	–	Campus in Singapore
testbed	[9]	6	24	$7.5km^2$	7 months	Southampton, UK
testbed	[10]	1	331	$2163.8m^2$	28 days	Campus in Finland
real	[11]	4	33	$33.000m^2$	8 months	Stadium in Denmark
real	[12]	691	1,618	–	8 months	The Things Network in Netherlands
real	Our work	544	66,556	$139.6km^2$	8 months	Shanghai,China

PLR and the potential causes of packet loss. This can help LoRaWAN network operators to understand and mitigate the adverse effects of these factors.

To the best of our knowledge, we are the first to analyze the packet delivery performance in a real LoRaWAN network at this magnitude of scale and reveal the root causes of packet loss events.

The rest of this paper is organized as follows. In Section II, we review some of the previous work on LoRaWAN deployment and measurement. Section III provides background knowledge on LoRa and LoRaWAN. Section IV describes the actual deployment of our LoRaWAN network and key factors that impact PLR. Section V describes the measurement and analysis of PLR, with emphasis on the root causes of PLR. We give a discussion and summary of our network deployment and measurement in Section VI. Finally, we conclude this paper in Section VII.

II. RELATED WORK

There have been previous efforts in discussing and analyzing the network performance of LoRa LPWAN. Here we summarize some typical work in Table I.

A. Simulation-based measurements

Several recent papers have simulated the structure of LoRaWAN network and performed a series of measurements and analysis, the majority of which use ns-3 for network simulation. Ochoa *et al.* [13] use the improved WSNet simulator for homogeneous networks and heterogeneous networks, to strengthen the performance of large-scale deployments (up to 10,000 nodes per gateway). Finnegan *et al.* [14], Van Den Abeele *et al.* [15] and Lavric *et al.* [16] attach importance to the energy consumption, network scalability and channel capacity, respectively. While Yu *et al.* [6], Barro *et al.* [17] and Magrin *et al.* [18] investigated the performance of LoRa-based IoT networks in typical smart city scenarios and demonstrated their feasibility and scalability using simulators.

Although these measurements revealed or demonstrated some of the characteristics of the LoRaWAN network to some extent, these studies are all simulation-based. Results from the pure software environment and simplified model are insufficient to reflect the performance in the actual physical environment.

B. Testbed-based measurements

Testbeds for LoRaWAN networks have emerged in the past few years, most of which are deployed in campuses by researchers. Lee *et al.* [7] evaluated a new topology which can improve the packet delivery ratio in a network on campus. Yousuf *et al.* [19] analyzed the performance differences of LoRaWAN networks between indoor and outdoor while Liando *et al.* [8] and Ohta *et al.* [20] focus on the line-of-sight and non-line-of-sight conditions. Johnston *et al.* [9] and Yasmin *et al.* [10] carried out pilot LoRaWAN network deployments for smart city scenarios like air quality monitoring and building monitoring, which shed light on the possibility of large-scale deployment.

Compared with simulations, these testbeds provide a platform that is close to a more realistic physical environment.

C. Real Network Deployment

There are also several deployments of small-scale LoRaWAN networks over the years. Petrić *et al.* [21] performed and analysed some measurements about the performance of a LoRaWAN network with one gateway and three stations. Meanwhile, Rodriguez *et al.* [11] deployed an integrated multi-site indoor environment monitoring wireless system, consisting of 33 multi-sensor nodes and 4 gateways. At present, there is only one large-scale LoRaWAN network instance known to us, which is a large-scale network with publicly available data called ”The Things Network [22] ”. Blenn *et al.* [12] measured and analyzed the performance of this network and described the use of LoRaWAN in practice with the data of more than 600 gateways.

Real network deployments can reflect the actual network state more effectively than the simulation-based and testbed-based studies, but at present real deployments are rare and most of them are small in scale. With the increase in the network scale, the impact of different factors on network performance will become more complicated. Therefore, these efforts cannot provide an effective reference for the large-scale deployment of LoRaWAN network applications. Meanwhile, only a few studies have simply measured the PLR, and there is still a lack of in-depth analysis of possible causes. Therefore, research on PLR in large-scale real networks is urgently needed. To our knowledge, our work represents the first attempt in a real city-scale LoRaWAN network. Our LoRaWAN network is deployed to support large-scale smart city applications. The related factors of packet loss in the network are extensively measured, and the possible causes of packet loss are thoroughly explained.

III. PRELIMINARIES

Before starting the detailed analysis, we first give a brief introduction on the background of LoRa.

A. LoRa

LoRa is an ultra-long-range wireless transmission scheme based on a spread spectrum technology called Chirp Spread Spectrum (CSS) modulation. Data transmission using CSS technology can effectively combat the effect of Doppler shift. In addition, power consumption can be reduced because CSS does not require time synchronization. Moreover, LoRa applies Forward Error Correction(FEC) coding technology to improve link robustness.

B. LoRaWAN

LoRaWAN is the default MAC layer protocol on the top of LoRa modulation scheme. The standard LoRaWAN specification was proposed by the LoRa Alliance, which is led by Semtech and other top enterprises in the industry.

LoRaWAN Network Architecture: LoRaWAN networks are organized in a star-of-stars topology which includes three types of devices includes gateways, end-devices and a central Network Server [23]. They perform networking and data transmission in the following ways as shown in Fig. 1.

- End-devices communicate to one or more gateways over single-hop LoRa or Frequency-shift keying (FSK) [24] modulation. There is no direct communication between end-devices.
- Gateways forward raw LoRaWAN data frames from end-devices to a network server via IP connections. The network server routes the packets from gateways to the associated application servers via IP connections, too.
- All communications in LoRaWAN are bi-directional, although the uplink communications are expected to be the main traffic.

Protocol Stack: The physical layer enables the long-range communication link by LoRa modulation, which operates in the lower Industrial, Scientific, and Medical (ISM) bandwidths [25]. The MAC layer is standardized by LoRaWAN protocol and it includes three classes of devices. Class A end-devices can only open the downlink receive window after an uplink transmission data and sleeps most of the time. Therefore, it is the lowest-power-cost class but the downlink communication is limited. Class B end-devices can periodically listen to incoming data messages with a beacon from the gateway at the scheduled time. Class C end-devices monitor the downlink reception as much as possible, and stop downlink reception only at the moment of uplink transmission. The protocol requires that each end-device must support Class A functionality, while Class B and Class C are optional functions [23].

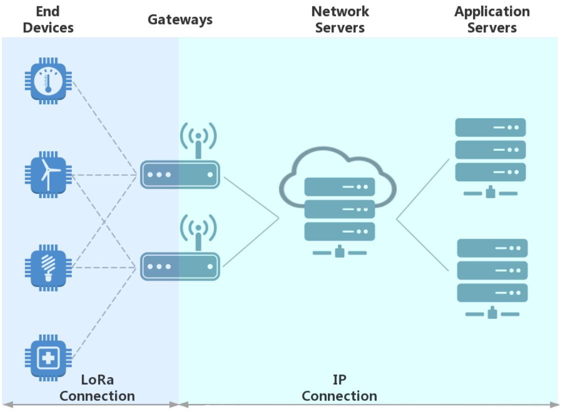


Fig. 1. Architecture of LoRaWAN networks

C. ALOHA

To further reduce energy consumption, end-devices of our network are all Class A devices which use ALOHA-type of protocol for data transmission. The main working principles of ALOHA are as follows:

- Any end-device can send the data frame immediately after it is generated. They require an acknowledgment or an answer by the downlink signal to determine whether the transmission is successful.
- If the transmission fails, the end-device will retransmit the data after waiting for a random time.

Since each end-device can send uplink data at any time and pay no attention to whether the channel is already occupied, to achieve the purpose of reducing power consumption. However, for this reason, when two or more end-devices use the same spreading factor to transfer data in one channel simultaneously, packet collision will occur and it may lead to packet loss.

IV. NETWORK SETTING AND KEY FACTORS OF PLR

In this section, we give a brief overview of the LoRa network and the PLR of end-devices. Several factors that impact the PLR are also discussed.

A. Network setting

The data used in this study is collected from a standard LoRa network in Shanghai that provides smart city services. Architecturally, the network is deployed in a star-of-stars topology, in which each end-device reaches the gateway through a single hop and then the gateway passes data to the network server. This network is designed as an infrastructure to support a variety of applications ranging from water quality monitoring, to fire prevention and control. Since the end-devices in the network are mainly used for raw data collection and do not require downlink communication, the end-devices adopt the most energy-efficient Class A mode. When various types of sensor data were collected for data analysis, we found that the packet loss events are not rare. The missing data have a serious impact on the integrity and correctness of time series analysis. This motivated us to investigate the different factors that impact the packet transmission performance in the network.

The network has been running and collecting data since March 2019. We used a total of 8 months of data from March 2019 to October 2019 for analysis. The network's end-devices include 26 types of sensors that collect data for 45 different scenarios in smart city. There are three kinds of gateways list below.

1) **Large gateways:** Gateways with a theoretical maximum transmission distance of 5km and deployed outdoor. To achieve the maximum signal coverage, most of the gateways in our network are of this type.
2) **Small outdoor gateways:** Gateways with a theoretical maximum transmission distance of 100m. They were deployed at the top of the buildings, to improve signal coverage as supplements of the large gateways.
3) **Small indoor gateways:** Gateways with a theoretical maximum transmission distance of 100m and used in indoors with poor transmission environment, such as the basements and garages. It is difficult for the signal of outdoor gateways to reach these places.

At present, the network is distributed in three adjacent municipal districts of Shanghai: Putuo District, Yangpu District, and Hongkou District. It is constantly expanding in size based on new data analysis requirements and operation requirements. We choose Putuo District and Yangpu District for comparative analysis in this work. As of October 2019, this portion of network consists of 544 gateways and 66,556 end-devices, covering an area of 139.6 km^2 across 23.2 km from east to west and 14.2 km from north to south. The geographical distribution of the gateways in these two districts is shown in Fig. 2. Note that the left partwith indoor gateways, is Putuo District and the right part is Yangpu District.

Each end-device sends data packets to one or more gateways within it's transmission distance, and each sending packet carries some log messages. When a packet arrives at a gateway, its log information will be enriched with some measurement such as the receiving gateway ID, RSSI (Received Signal Strength Indication) and SNR (Signal-to-Noise Ratio) of current channel. Also, each uplink packet has an uplink packet counter called $FCntUp$, indicating the sequence of the generated packets at each device. For each device, the FCntUp of sent packets should be a continuous sequence, any out-of-order packet whose $FCntUp$ is uncontinuous indicates a packet loss event. We calculate the ratio of the amount of loss packets to the amount of total packets for each device as its PLR. According to our measurements, the PLR of most devices ranges from 0% to 10%, while a few devices have a very high PLR, even reaching over 90%. As an example, the PLR distribution for the door magnets in Yangpu District is shown in Fig. 3.

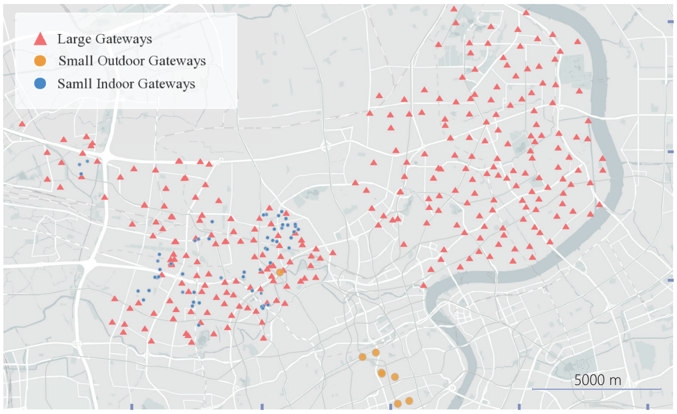


Fig. 2. Geographical distribution of the gateways

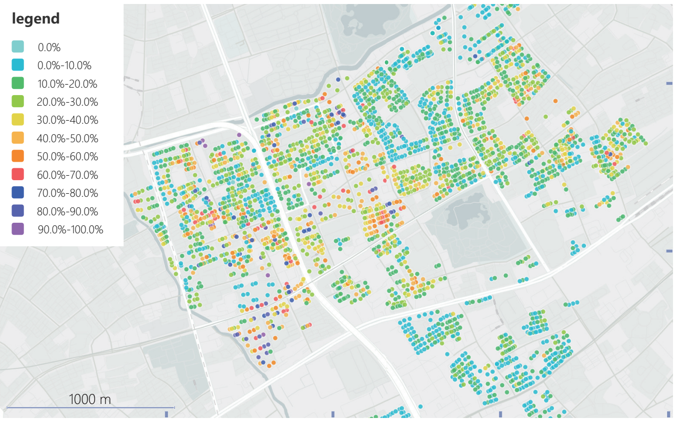


Fig. 3. The PLR of door magnetic sensors in Yangpu District

Firstly, we analyzed the abnormal situations with extremely high PLR. It is found that most end-devices with extremely high PLR have been disconnected for a long time, or there are cases where no packets transmit for more than 3 days. Both situations above are deemed to be device failures and we first remove the faulty devices in further analysis. There are about 2,700 faulty end-devices, accounting for 4% of the total end-devices.

B. Key Causes of PLR

End-device malfunction: Packets transmission may fail due to energy exhaustion or software/hardware faults at end-devices. Such cases usually exhibit extremely high PLR and long time of inactivation in sending packets. We mark the end-devices which do not send any packet for more than 3 days as faulty devices, which is around 4% of the total number of end-devices. We exclude such end-devices in our further analysis.

Channel factors: Packet transmission performance is closely related to channel state, which is directly determined by RSSI and SNR. 1) RSSI is a relative value of signal power measured by the gateway at the receiving end, which decays with the increase of distance. It is usually negative because of the low transmitting power and the large air attenuation. The closer the value is to zero, the stronger the signal is. 2) SNR is the ratio of signal power to the noise power measured under specified conditions. In general, the higher the SNR is, the smaller the noise mixed in the signal, and the easier it is to separate the effective signal.

Packet collision: Channel contention occurs when multiple devices attempt to send data over one channel simultaneously [26]. The device does not check if the channel is preempted by other devices before transmitting packets, so it may cause packet collision. Since the MAC message type we use is unconfirmed data up (MType code: 010), the device will not receive any acknowledgement no matter whether the packet is sent successfully or not. Therefore, once the data packet is lost, it will not be retransmitted.

V. ROOT CAUSES OF PACKET LOSS EVENTS

To investigate the root causes of the packet loss events, we would like to analyze the PLR and the various correlative factors mentioned above.

We first show the PLR of Yangpu District and Putuo District in Fig. 4. The average PLR in Putuo District and Yangpu District are 42.90% and 24.35% respectively, which is not satisfactory. Nevertheless, the PLR of the LoRaWAN networks generally behaves like this in previous research, such as 40% of work [21] and 41.3% of work [7]. The PLR of end-devices in Yangpu District is usually below 30% and there are a few high PLR end-devices. Such PLR distribution indicates that the packets transmission performance in Yangpu District is well and stable. In Putuo District, the PLR is distributed uniformly in various ranges, which is a very poor situation, and the overall packet transmission performance is unsatisfactory.

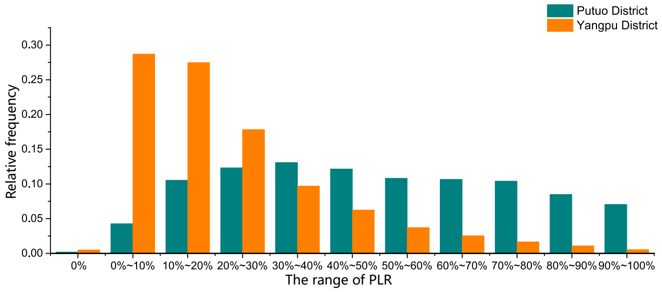
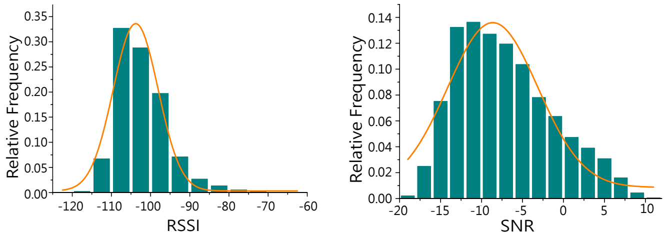


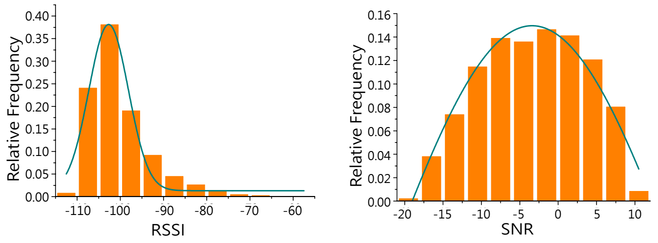
Fig. 4. The packet loss rate in Putuo District and Yangpu District

A. Electromagnetic environmental factors

For each device, we collect the RSSI and SNR of all upload links to calculate their mean value, indicating the uplink performance of each end-device. Fig. 5 shows the distribution for RSSI and SNR of end-devices in Yangpu District and Putuo District, and the detail statistics are shown in Table II. For the average RSSI and average SNR of the end-devices, the mean of Yangpu District is higher than that of Putuo District, indicating that the channel state of Yangpu District is better than that of Putuo District. Meanwhile, the standard deviation of average RSSI and average SNR in Yangpu District are both lower than those of Putuo District, which means the channel state of Yangpu District is more stable than that of Putuo District. This is an important reason that the PLR in Yangpu District is far lower than that in Putuo District.

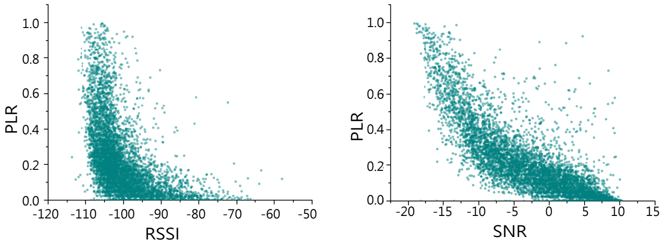


(a) RSSI in Putuo District (b) SNR in Putuo District



(c) RSSI in Yangpu District (d) SNR in Yangpu District

Fig. 5. Frequency Counts of RSSI and SNR



(a) Changes with RSSI (b) Changes with SNR

Fig. 6. PLR for various RSSI and SNR in Yangpu District

TABLE II
STATISTICS OF RSSI AND PLR IN TWO DISTRICTS

District	**RSSI Mean**	**RSSI SD**	**SNR Mean**	**SNR SD**	**PLR mean**
Putuo	-103.80	0.50	-8.63	0.48	42.90%
Yangpu	-102.70	0.39	-3.40	0.35	24.35%

Taking the data of Yangpu District as an example, we explore how PLR changes along with RSSI and SNR, which shows in Fig. 6. The result shows that high-PLR devices reduce significantly with the increase of RSSI, which is similar when the SNR increases. In Fig. 6 (a), when RSSI changes from -120 to -110, the PLR of most end-devices decreases but its distribution is generally scattered. While in Fig. 6 (b), the

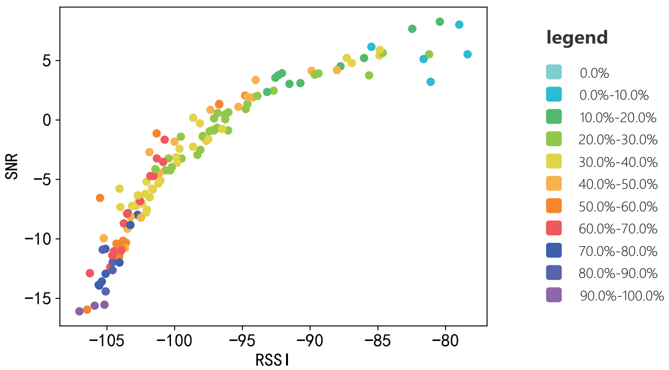


Fig. 7. PLR and the number of received packets per hour for a device

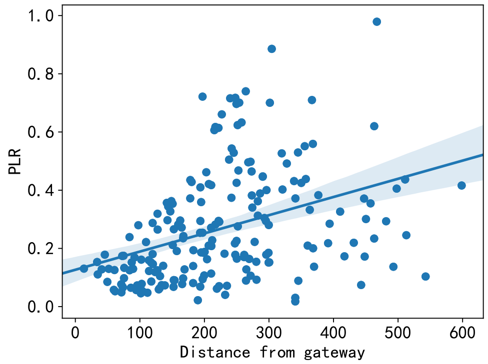


Fig. 8. PLR with various transmission distance

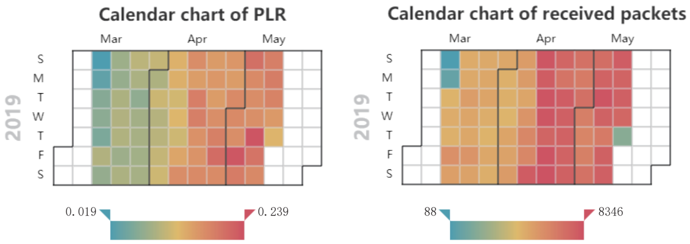


Fig. 9. Number of Packets Received by a Gateway and the PLR of the Day

tendency of PLR decreasing with the SNR approaching zero is more pronounced. Therefore, we assume that SNR has a greater impact on PLR than RSSI.

TABLE III
CORRELATION COEFFICIENT BETWEEN PLR AND RSSI, PLR AND SNR

Putuo District		**Yangpu District**	
RSSI	SNR	RSSI	SNR
-4.788	-0.805	-0.512	-0.784

To find out which of these two factors has a greater impact on the PLR, we calculate the correlation coefficients of them in Putuo District and Yangpu District respectively. The result values in Table III are all negative, which shows that PLR has a negative correlation with RSSI and SNR. Additionally, the absolute value of the correlation coefficient between PLR and SNR is closer to 1, which proves that SNR has a greater impact on PLR.

It can be seen from Fig. 7 that the combined effect of RSSI and SNR on PLR is more clear. The dots in this scatter plot indicate the end-devices that transmit data with the same gateway. When the PLR of the points in the figure is small, the color of dots in the figure tends to be cold tone. First, let's observe the horizontal axis and vertical axis separately, the law of PLR changing with RSSI and the law of PLR changing with SNR are consistent with above. Then observe the results of the combined effect of RSSI and SNR, the PLR of the devices decreases accordingly when RSSI and SNR increase.

We also want to discuss how RSSI and SNR affect PLR. The path loss of transmission channel is directly affected by RSSI and SNR [27]

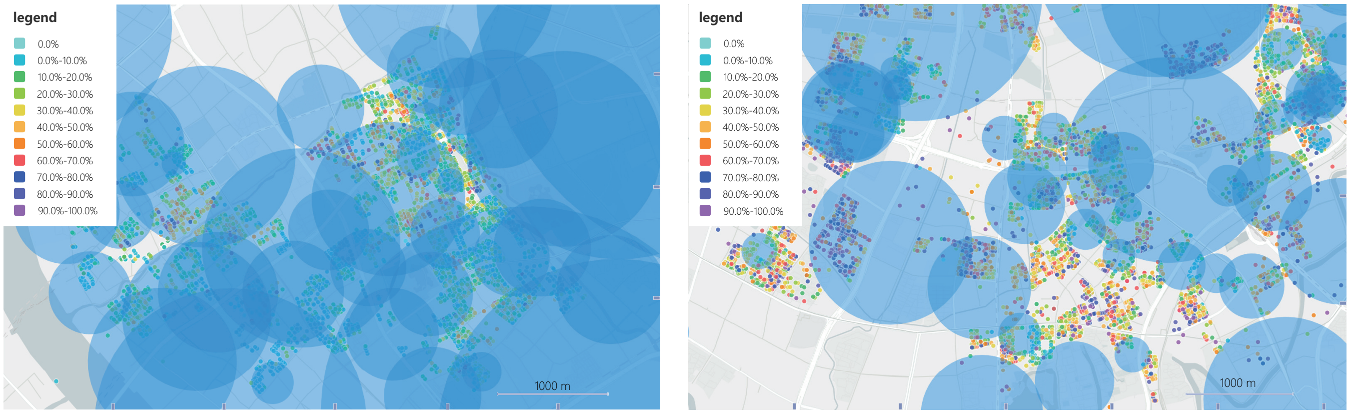
B. Transmission distance

For each gateway, we calculate the PLR of the end-devices with which it has data transmission, then we use the GPS information of these end-devices and gateways to calculate the transmission distance between them. The relationship between PLR and transmission distance of a typical gateway is shown in Fig. 8. Among these end-devices, the PLR with a transmission distance of fewer than 100 m is about 20%, and with the increase of transmission distance, the number of end-devices with high PLR appears. To sum up, Fig. 8 demonstrates that for each gateway, the farther the transmission distance is, the higher the PLR is. What are the reasons for this phenomenon? There are three possible reasons listed below.

- In free space, long transmission distance results in large expected path loss and increases the signal attenuation on the channel [27].
- In the long-distance transmission, the radio signal degrades as the number of obstacles the signal passes through increases, such as high-rise buildings. Shadow fading caused by obstructions can cause severe signal loss.
- The environmental factors of long-distance transmission are more complicated and may generate more noise and interference.

This means every gateway has its own effective distance and devices may have low PLR within it. Based on this fact, we can calculate the effective coverage for each gateway and use it to evaluate the performance of gateways.

The following local maps in Fig. 10 show the effective coverage of gateways in Putuo District and Yangpu District. The blue circles in these figures indicate the corresponding gateway's effective coverage which is calculated as the average transmission distance between the gateway and all the end-devices in range with low PLR. As we can see in these two figures, the effective coverage area in Putuo District is generally smaller than that in Yangpu District. Besides, many devices in Putuo District are outside the effective coverage



(a) Yangpu District

(b) Putuo District

Fig. 10. Effective coverage of gateways in Yangpu District and Putuo District

area, while there are overlaps in many gateways' coverage in Yangpu District and few devices outside the effective distance. It also shows that the PLR of devices at the edge of the coverage area is higher than those who are closer to the center of the coverage area. This discovery has great inspiration for our follow-up operation and maintenance work, that is, it can supplement the signal coverage at the edge of gateways.

C. Packet collision

We choose a typical gateway, and calculate the number of packets received each day and its corresponding PLR, which is shown as the heat map in Fig. 9. The closer the colors of these cells are to the cold tone, the smaller the value is, and larger on the contrary. It can be concluded in this set of charts that with the increase of the number of data packets, the PLR increases accordingly. This is because when the number of data packets in transmission increases, the probability of multiple data packets select the same channel increases. Meanwhile, the probability of packet loss will increase according to the ALOHA protocol used by LoRaWAN. When a packet is transmitted in a channel, other end-devices that select this channel for transmission at the same time will encounter packet collision. According to the unconfirmed MAC message type (Unconfirmed Data Up) we use, the damaged packets will not be retransmitted. Regardless of other affecting factors, the result of multiple packets competing for the same channel is that only the first packet that selects this channel can be successfully transmitted to the gateway.

In addition to the detailed rules, we also observed the number of packets and the PLR of a door magnetic device for 24 hours, shown as the line-chart in Fig. 11. Since fewer people travel at night, the door magnetic device has a lower frequency of packet delivery, and the PLR is lower accordingly. Furthermore, the packet transmission becomes frequent when people travel frequently during the day, the packet loss rate also increases. The trends of the two lines are very similar in this hourly chart, showing a strong dependence between these variables. This indicates that there is a positive correlation between packet collision and the packets loss events.

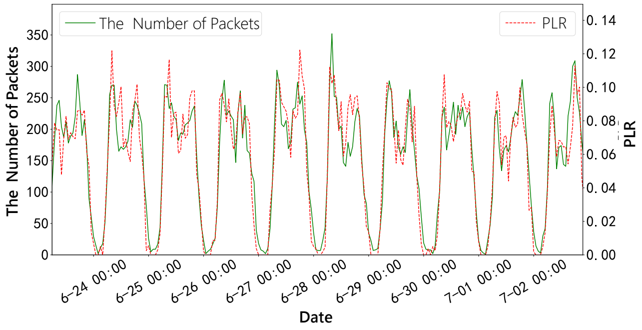


Fig. 11. PLR and the number of received packets per hour for a device

D. Type of end-devices

We choose two different types of end-devices in the LoRaWAN network, smoke alarm sensors and door magnets, to compare the performance of PLR. Fig. 12 shows the comparison of PLR of these two kinds of end-devices in Yangpu District.

We can tell that the PLR of smoke sensors is much lower than that of door magnets. The highest PLR of smoke sensors is below 40%, and most of the devices have not lost data packets. Most of the devices with packet loss are concentrated in less than 10%. However, the performance of PLR of gate magnets is barely satisfactory. There are many devices with high PLR, even extremely high PLR. A large amount of data on gate magnets equipment was lost.

The reason is that the smoke sensors have larger packet-sending intervals than gate magnets. Each smoke sensor is set up to transmit only one packet per day unless there's a smoke alarm event. Nevertheless, the door magnets send packets much more frequently than smoke sensors. In addition to the packet triggered by gate switching events, a heartbeat packet representing the current state is generally sent every 5

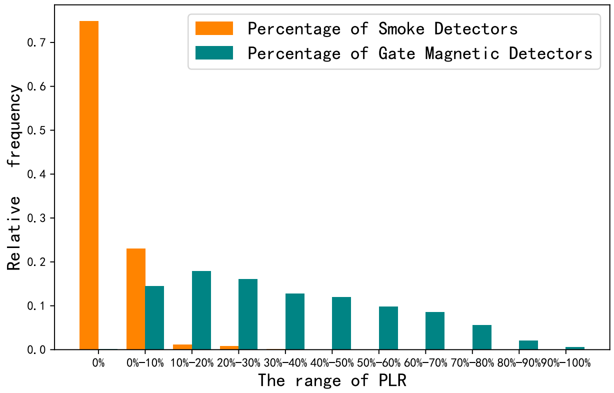


Fig. 12. PLR Comparison between smoke sensors and door magnets

minutes. Therefore, the number of data packet transmissions of gate magnetic devices is much larger than that of smoke sensors, which will not only cause more packet collisions, but also accelerates the energy consumption of end-devices, and the PLR will increase accordingly.

VI. DISCUSSIONS AND LESSONS LEARNED

We give a summary of the observation and the lessons we learned from the study in this section.

1. The difference of PLR between Yangpu District and Putuo District: There are two reasons for the discrepancy between these two districts listed as follows.

1) **Quantity of end-device:** Putuo District covers an area of 55.53 km^2 and Yangpu District covers an area of 60.61 km^2, but Putuo District has arranged about three times as many end-devices as Yangpu District. In this way, the volume of packet traffic in Putuo District is much higher than that of Yangpu District, and the probability of packet collision also increases remarkably.
2) **Gateway deployment:** The effective coverage area of gateways in Yangpu District is generally larger than that in Putuo District, and there are overlaps in many gateways, only a few devices are outside the effective distance of the gateways. In contrast, the placement of the gateways in Putuo District needs further optimization. Despite that many small gateways are added to the network, there are still a large number of end-devices that are not covered by the gateway's effective signal. As shown in Fig. 13, the effective distance of most gateways in Putuo District is within 280m, and more than 90% of the effective distance of these gateways is below 550m. While there are only about 60% of the effective distance of the gateways in Yangpu District below 550m, and most of them are between 280m to 550m. To improve the transmission performance, the distance between the device and the gateway should be less than effective distance during deployment.

2. The difference of PLR among different types of end-devices: The data transmission frequency of devices is the main factor that causes the difference in PLR among different types of end-devices. Firstly, the more frequently the end-devices send packets, the higher the loss of the end-devices themselves are, which affects the sending and receiving operation. Secondly, frequent packet delivery leads to increased packet traffic and in turn make the channel competition more intense and a higher probability of packet collision.

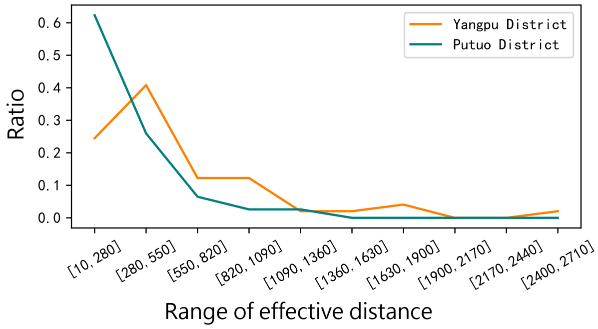


Fig. 13. Effective distance distribution of gateways

3. The impact of packet collision and PLR on applications: Class A mode that we use in this network adopts asynchronous ALOHA protocol. Its simple working principle may cause packet collision, which may lead to packet loss. As some urban IoT applications have low requirements in real-time packet delivery, the negative impact of device-to-gateway transmission efficiency on the entire network is not significant. Meanwhile, as coarse-grained aggregation can also reflect the state of city operation to some extent, some urban IoT applications are tolerant of packet loss. However, for other applications, such as fire alarm detectors, which have stringent requirements in real-time and reliable delivery, the impacts of packet collision and PLR are very significant. Therefore, the underlying network needs to be tuned to eliminate packet loss.

We investigate the influencing factors of PLR and found that none of them can dominate the performance of the end-devices completely, which indicates that the evaluation of PLR needs to consider a variety of factors. Here are some suggestions for future network deployments.

- First of all, gateway placement planning is critical for packet delivery performance. There are many possible optimization objectives, e.g. the number of gateways, and the coverage range under a given budget. One possible objective of gateway placement is to cover as many end-devices as possible within the effective transmission range of the gateways. The signal coverage information of the gateways and the packet loss rate can be used to adding extra gateways as a remedy to achieving full coverage of the end-devices.
- We also need to notice the frequency of packets delivery, not just the number of end-devices. We can classify different types end-devices base on the frequency of packets sending, and calculate the expected average number of packet transmission per unit time per unit area. For areas with dense end-devices and frequent packets delivery, it is necessary to add gateways to achieve overlapping

coverage to reduce the load on the gateways and avoid packet collision.

- Finally, it is also necessary to track the status of end-devices and to schedule timely replacement of malfunctioning end-devices.

VII. CONCLUSIONS

In this paper, we measured and analyzed the packet delivery performance of a city-scale LoRaWAN network in Shanghai. We perform spatial-temporal analysis on the packet loss rate (PLR) to find how the correlating factors affecting the PLR, and then reveal the root causes of packet loss events. The result shows that the channel state and packet collision both can affect PLR in different ways and to different degrees. Notably, the distance of data transmission and the traffic pattern of different end-devices are the dominant reasons. These analysis and implications are summarized to give important guidance to further large-scale LoRaWAN network deployments and operations.

In future work, we intend to explore the following two issues. First, we would like to investigate the placement of gateways according to the location information and the traffic pattern of end-devices. Second, we would like to minimize packet collision by balancing the load of adjacent gateways.

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REFERENCES

[1] W. Ayoub, A. E. Samhat, F. Nouvel, M. Mroue, and J. christophe Prevotet, "Internet of Mobile Things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and Supported Mobility," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1561–1581, 2018.

[2] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," *IEEE Internet Things J*, vol. 1, no. 1, pp. 22–32, 2014.

[3] "SynchroniCity," https://synchronicity-iot.eu/.

[4] M. Rizzi, P. Ferrari, A. Flammini, and E. Sisinni, "Evaluation of the IoT LoRaWAN Solution for Distributed Measurement Applications," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 12, pp. 3340–3349, Dec 2017.

[5] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low Power Wide Area Networks: An Overview," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 855–873, 2017.

[6] F. Yu, Z. Zhu, and Z. Fan, "Study on the feasibility of LoRaWAN for smart city applications," in *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob).* IEEE, 2017, pp. 334–340.

[7] H.-C. Lee and K.-H. Ke, "Monitoring of Large-Area IoT Sensors Using a LoRa Wireless Mesh Network System: Design and Evaluation," *IEEE Transactions on Instrumentation and Measurement*, vol. PP, pp. 1–11, 03 2018.

[8] J. C. Liando, A. Gamage, A. W. Tengourtius, and M. Li, "Known and Unknown Facts of LoRa," *ACM Transactions on Sensor Networks*, vol. 15, no. 2, pp. 1–35, 2019.

[9] S. J. Johnston, P. J. Basford, F. M. Bulot, M. Apetroaie-Cristea, N. H. Easton, C. Davenport, G. L. Foster, M. Loxham, A. K. Morris, and S. J. Cox, "City Scale Particulate Matter Monitoring Using LoRaWAN Based Air Quality IoT Devices," *Sensors (Switzerland)*, vol. 19, no. 1, pp. 1–20, 2019.

[10] R. Yasmin, J. Petäjäjärvi, K. Mikhaylov, and A. Pouttu, "Large and Dense LoRaWAN Deployment to Monitor Real Estate Conditions and Utilization Rate," in *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC).* IEEE, Sep 2018, pp. 1–6.

[11] I. Rodriguez, M. Lauridsen, G. Vasluianu, A. N. Poulsen, and P. Mogensen, "The Gigantium Smart City Living Lab: A Multi-Arena LoRa-based Testbed," in *2018 15th International Symposium on Wireless Communication Systems (ISWCS).* IEEE, Aug 2018, pp. 1–6.

[12] N. Blenn and F. Kuipers, "LoRaWAN in the Wild:Measurements from The Things Network," *arXiv preprint arXiv:1706.03086*, 2017.

[13] M. N. Ochoa, L. Suraty, M. Maman, and A. Duda, "Large Scale LoRa Networks: From Homogeneous to Heterogeneous Deployments," in *2018 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob).* IEEE, Oct 2018, pp. 192–199.

[14] J. Finnegan, S. Brown, and R. Farrell, "Modeling the Energy Consumption of LoRaWAN in ns-3 Based on Real World Measurements," *2018 Global Information Infrastructure and Networking Symposium (GIIS)*, pp. 1–4, 2018.

[15] F. Van Den Abeele, J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Scalability Analysis of Large-Scale LoRaWAN Networks in ns-3," *IEEE Internet Things J*, vol. 4, no. 6, pp. 2186–2198, 2017.

[16] A. Lavric and V. Popa, "Performance Evaluation of LoRaWAN Communication Scalability in Large-Scale Wireless Sensor Networks," *Wireless Communications and Mobile Computing*, vol. 2018, 2018.

[17] P. Barro, M. Zennaro, J. Degila, and E. Pietrosemoli, "A Smart Cities LoRaWAN Network Based on Autonomous Base Stations (BS) for Some Countries with Limited Internet Access," *Future Internet*, vol. 11, no. 4, p. 93, 2019.

[18] D. Magrin, M. Centenaro, and L. Vangelista, "Performance Evaluation of LoRa Networks in a Smart City Scenario," *IEEE International Conference on Communications (ICC)*, pp. 1–7, 2017.

[19] A. M. Yousuf, E. M. Rochester, and M. Ghaderi, "A Low-Cost LoRaWAN Testbed for IoT : Implementation and Measurements," *2018 IEEE 4th World Forum on Internet of Things (WF-IoT)*, pp. 361–366, 2018.

[20] M. Ohta, K. Adachi, N. Aihara, O. Takyu, T. Fujii, and M. Taromaru, "Measurement Experiments on 920 MHz Band for Spectrum Sharing with LoRaWAN," *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*, pp. 1–5, 2018.

[21] T. Petrić, M. Goessens, L. Nuaymi, L. Toutain, and A. Pelov, "Measurements, Performance and Analysis of LoRa FABIAN, a real-world implementation of LPWAN," in *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Sep. 2016, pp. 1–7.

[22] "The Things Network," https://www.thethingsnetwork.org/.

[23] "LoRaWAN™ 1.1 Specification," https://lora-alliance.org/resource-hub/lorawanr-specification-v11.

[24] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A Study of LoRa: Long Range & Low Power Networks for the Internet of Things ," *Sensors (Switzerland)*, vol. 16, no. 9, pp. 1–18, 2016.

[25] M. Saari, A. Muzaffar Bin Baharudin, P. Sillberg, S. Hyrynsalmi, and W. Yan, "LoRa - A Survey of Recent Research Trends," *2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics, MIPRO 2018 - Proceedings*, pp. 872–877, 2018.

[26] N. Varsier and J. Schwoerer, "Capacity Limits of LoRaWAN Technology for Smart Metering Applications," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

[27] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, and M. Pettissalo, "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology," in *2015 14th International Conference on ITS Telecommunications (ITST)*, Dec 2015, pp. 55–59.