A Low-Cost LoRaWAN Testbed for IoT: Implementation and Measurements

Asif M. Yousuf, Edward M. Rochester, and Majid Ghaderi
Department of Computer Science
University of Calgary

***Abstract*—One of the challenges in deploying IoT applications is the cost of building and operating the communication infrastructure. This paper studies the feasibility of building a low-cost IoT network based on LoRa, a leading Low-Power Wide-Area Network (LPWAN) technology, using off-the-shelf components and open source software. To this end, we describe our LoRa testbed, which includes gateways, end devices and a variety of sensors. We then present extensive measurement results to characterize the performance of our LoRa network over the 915 MHz unlicensed ISM band in both indoor and outdoor scenarios for various network setups. Our results show that even in a harsh propagation environment, *e.g.*, when the gateway is located inside a concrete building, the low-cost network is able to achieve great coverage. Specifically, we observed that: i) the indoor coverage is sufficient to cover an entire seven-story office building with minimal packet drop, ii) the outdoor coverage is very dependent on the environment, where in our experiments, a communication range of 4.4 km was achieved with only 15% packet drop, iii) network parameters such as spreading factor and packet size greatly affect the coverage; for example, we observed that a payload size of 242 bytes leads to 90% packet drop versus less than 5% drop with a payload size of 1 byte.**

I. Introduction

A. Background and Motivation

The Internet of Things (IoT) is an emerging paradigm in which everyday objects are equipped with Internet connectivity, enabling them to collect and exchange information. It is estimated that around 30 billion IoT devices will be deployed by 2025, a quarter of which will be connected to the Internet using Low-Power Wide-Area Network (LPWAN) technologies [1]. LPWAN represents a new communication paradigm, which complements traditional cellular and short range wireless technologies to address diverse requirements of IoT applications. LPWAN technologies offer long-range connectivity for low power and low rate devices, not provided by legacy technologies. It is worth mentioning that LPWAN technologies are not meant to address each and every IoT use case, rather they cater to a niche area in IoT landscape. Specifically, LPWAN technologies are considered for those applications that are delay tolerant, do not need high data rates, and typically require low power consumption and *low cost*.

Currently, there are several competing LPWAN technologies on the market, such as LoRa [2], Sigfox [3], RPMA [4], Telensa [5], and Weightless [6], each employing a different technique to achieve long-range low-power operation. These technologies are required to provide connectivity for a massive number of heterogeneous IoT devices scattered over a wide geographic area, where devices may communicate over distances exceeding 10 Km [7]. Such a requirement is defined by major applications foreseen for LPWAN, among which are the automotive and intelligent transportation systems (incident report and alerts, fleet management, *etc.*), metering applications (*e.g.*, electrical, water and gas consumption monitoring, medical metering and alerts) and smart homes (*e.g.*, thermostat control and security systems) [7], [8].

One of the major obstacles in deploying IoT applications is the cost of building and operating the communication infrastructure required, even when only a small-scale system is considered. This has led to an emerging market for offering IoT connectivity as a service [9], [10]. While IoT service providers help to lower the barrier to entry for average users, they still require users to pay subscription fees that could be beyond reach for many people. With the rise of Do-It-Yourself (DIY) electronics (*e.g.*, Arduino and Raspberri PI) and open software projects (*e.g.*, Linux and LMiC), we believe there is an opportunity to provide IoT solutions that are low-cost and accessible to a larger portion of the society. This has been recognized by the community, an as a result, there are several open projects on how to build and operate LPWAN networks [11]. What is missing, however, is comprehensive data on the performance of such networks to understand how they compare against commercial deployments. This is the problem considered in this paper.

B. Related Work

There are few works in the literature on the performance of LPWAN technologies, specifically LoRa, as they are relatively new and still under active development and standardization. In the following, we will briefly review a few recent works that are relevant to our work.

An overview of various LPWAN technologies, including LoRa and SigFox, is provided in [12]. The authors qualitatively (i.e., based on technology specifications) compare various LPWAN technologies using metrics such as network topology, hardware cost, and theoretical throughput. The main conclusion is that there is no one size fits all solution with each of the technologies having their pros and cons. One of the application areas considered for LPWAN is smart grid. The work in [13] compares LoRa and RF Mesh technologies in the context of smart grid applications. Bankov et al. [14] studied the limits of the LoRaWAN [1] channel access mechanism and provided suggestions on how to improve its scalability. According to [14], the duty-cycle based channel access mechanism of LoRaWAN may increase packet delay and collision probability. Toussaint et al. [15] analyzed the performance of over-the-air activation (OTAA) mechanism of LoRaWAN using a Markov chain model. They studied the impact of several parameters such as duty cycling and channel availability on the performance of OTAA.

A measurement study of the performance of LoRa for indoor deployments was presented in [16]. The measurements were conducted using a single device and a single gateway located in an office building. The network was deployed in Strasbourg, France and considered three channels at EU ISM 868 MHz band only. Petajajarvi et al. [17] focused on the Doppler effect on the performance of LoRa in different mobility scenarios. They showed that mobility of the receiver or transmitter could significantly degrade the communication quality, and hence the coverage of the network. In another work Petajajarvi et al. [18] focused on the range evaluation and channel attenuation model for LoRa technology. The measurement study was conducted in Oulu, Finland over the EU ISM 868 MHz band. The work in [19] provides an overview of various LPWAN technologies and presents the results of a measurement study consisting of a single-cell LoRa deployment in Padova, Italy. The measurement experiments show a coverage range of about 2 Km in an urban environment.

C. Our Work

In this work, we describe the design and implementation of a low-cost LoRa testbed and report measurement results characterizing its coverage performance in indoor and outdoor urban environments. There are two distinguishing features that differentiate our work from the works described above.

First, all of the above works considered European deployment and scenarios, where the radio frequency regulations are different from those in North America. It is unclear if the same conclusions remain valid in North America. For example, while in Europe, only 8 channels at the 868 MHz ISM band are available to LoRa devices, in North America, LoRa Alliance specifies 72 dedicated uplink channels at the 915 MHz ISM band. More detailed overview of LoRa technology and differences between European and North America jurisdictions are provided in Section II, but we expect that the differences in transmit power and frequency hopping restrictions have significant impact on the throughput and coverage of LoRa networks. Second, all of the aforementioned works use commercial-grade LoRa gateways that use high performance components such as advanced concentrator chips. Such commercial solutions cost from several hundred to several thousand dollars depending on their features, *e.g.*, 8-channel or 64-channel. In scenarios of small to medium size network deployments, it is critical to keep the cost of building the network low. Although C. Pham in [20] presented a low-cost LoRa network for small to medium size LoRa IoT deployments, the deployed network i) is for small ad hoc deployments that are not LoRaWAN compliant, ii) was designed for European standards, and iii) provided no deployment measurements or performance data.

The testbed described in this paper is a LoRaWAN compliant network assembled using off the shelf, DIY, low-cost hardware components that are programmed using open source libraries for gateways and end devices. The network operates at 915 ISM band following LoRaWAN specification for North America. We report on our experiments with this network and provide various deployment measurement data and statistics to characterize its performance in both indoor and outdoor scenarios.

D. Paper Organization

An overview of LoRa technology is presented in Section II. Our DIY testbed is described in Section III. Measurement results and their analysis are presented in Section IV. Section V concludes the paper.

II. Overview of LoRa Technology

LoRa (Long Range) is an LPWAN technology developed by Semtech Corporation [21]. To keep the complexity of the network low, LoRa relies on a star topology in which end devices directly communicate with a few *gateways* in a single-hop manner. Gateways in turn forward data received from end devices to a central network server. Gateways and end-devices communicate with each other using different frequency channels and data rates, where the selection of a particular data rate provides a trade off between communication range and message duration. In recent years, LoRa has attracted a significant amount of attention due to its inherent ability to efficiently trade communication range for high data-rates, which in return enables it as a compelling communication technology for IoT applications at an urban scale. Semtech specifications define three major components of LoRa networks, namely the physical (PHY) layer, link layer, and the network architecture [22].

A. PHY Layer

LoRa implements Chirp Spread Spectrum (CSS) with integrated Forward Error Correction (FEC) [2]. Due to this design, end devices using different data rates do not interfere with each other. It also operates over multiple channels which increases the capacity of the network. LoRa networks operate in unlicensed ISM frequency band, which for North America is the frequency band $902 - 928$ MHz with center frequency of 915 MHz. For this band, the LoRa specifications define 64 channels of 125 KHz bandwidth from 902.3 to 914.9 MHz in 200 KHz increments. There are an additional eight 500 KHz uplink channels in 1.6 MHz increments from 903 MHz to 914.9 MHz. This brings the total number of uplink channels to 72 channels, although the eight 500 KHz channels are overlapping with the remaining 64 channels. There are eight downlink channels, each 500 KHz wide starting from 923.3 MHz

[1]LoRaWAN refers to the complete network stack for LoRa-based networks, while LoRa refers to the physical layer technology used in such networks [2].

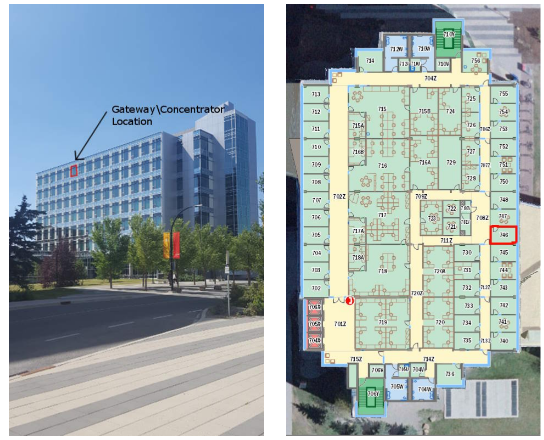
to 927.5 MHz. Compared to the European regulations, the Federal Communications Commission (FCC) allows a higher peak power of 1 Watt (30 dBm) if the bandwidth of the channel is at least 500 KHz. For lower bandwidths, the LoRa device has to implement Frequency Hopping (FH) with a maximum dwell time of 400 msec per channel. This makes the lowest LoRa date rates not usable, as transmitting the packet preamble alone takes more than 400 msec.

In addition to the above, one must decide on the spreading factor (SF) and coding rate (CR) used by the end devices. Such variables are consequential for robustness to interference and time on air of the transmissions. LoRa technology uses orthogonal spreading factors, which enable multiple packets with different SF's to be transmitted over the same channel concurrently, in return improving LoRa network efficiency and throughput. For European deployments, there is an option of SF between 7 and 12, while North America specifications define SF between 7 and 10, affecting the time it takes to transmit a packet. LoRa also implements a form of FEC, which permits the recovery of the information in case of the corruption of messages due to interference. Applying FEC requires additional coding data to be included in each transmitted packet, where the amount of coding data is determined by the coding rate. Depending on which CR is selected, one may attain an additional robustness in the presence of interference, with the available options being $\{4/5, 4/6, 4/7, 4/8\}$.

B. Link Layer

LoRaWAN defines the MAC layer that operates on top of LoRa PHY layer. It distinguishes between three end-device classes, namely class A, B, and C, where B and C class devices are required to be compatible with class A devices. Class A devices are optimized for power consumption, where a device receives downlink messages only immediately after an uplink transmission, by opening two short receive windows. In addition to the two receive windows defined for class A devices, class B devices open extra downlink receive windows at scheduled times, where time is synchronized with beacons transmitted by the gateway. Class C devices, on the other hand, continuously keep the receive window open, only closing the window when transmitting.

LoRaWAN protocol specifications define bidirectional communication between the gateway and all classes of end-devices, thus allowing not only to transmit data to the server, but also to receive acknowledgments from it. Despite that, communication in LoRa network is asymmetric, with uplink (from end-device to the gateway) dominating the communication. The communication asymmetry is utilized to prolong the end-device battery life, since any synchronization mechanism (for downlink communication) consumes significant energy and is the main driver of battery lifetime reduction [2]. The channel access mechanism in LoRaWAN is pure ALOHA, in which an end device accesses the channel without sensing the channel for ongoing communications. This is to further prolong device battery life by avoiding spending energy for listening to the communication channel as done, for example, in CSMA-based WiFi networks.



(a) ICT building. (b) The room hosting gateways.

Fig. 1: Location of LoRa gateways on campus.

C. Network Architecture

LoRaWAN networks are organized in a star-topology with each gateway directly receiving messages from multiple end-devices. Gateways are connected to a network server and use TCP/IP protocols to communicate with the server. Each end-device may adjust its data rate manually or using adaptive data rate (ADR) [22]. The network server implements ADR and determines the optimal data rate to be used by each end device. Since end devices broadcast their messages, the same message may be received by multiple gateways who will forward the message to the network server, where the redundant messages are filtered. Within this network architecture, the network server is also responsible for security, diagnostics and, if so desired, acknowledgments [22].

III. Low-Cost LoRa Testbed

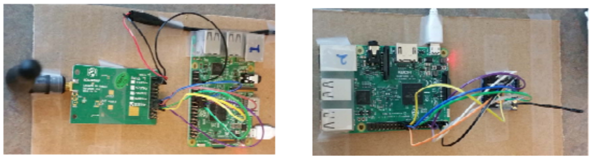
In this section, we give an overview of our LoRa testbed including its location and various gateways and end devices.

A. Testbed Location

The testbed is deployed on the campus of the University of Calgary in Canada. Specifically, the gateways are located in an *enclosed office* on the top floor of the Information and Communications Technology (ICT) building. The ICT building shown in Fig. 1 is a 7-story building comprised of a large number of offices and is built from concrete and drywall panels with substantial number of metal components for windows, plumbing, and ventilation. The indoor measurements took place in different floors of the ICT building, while the outdoor measurements took place in its surrounding vicinity.

B. Gateways

The testbed consists of two custom-built low-cost gateways operating at the 915 MHz ISM band. Both gateways are powered by Raspberry PI 3 Model B running the latest version of the Raspbian operating system. One of the gateways is connected to a certified 8 channel concentrator board (see Fig. 2(a)), while the other one is connected to an SX1276



(a) Multi-channel gateway. (b) Single-channel gateway.

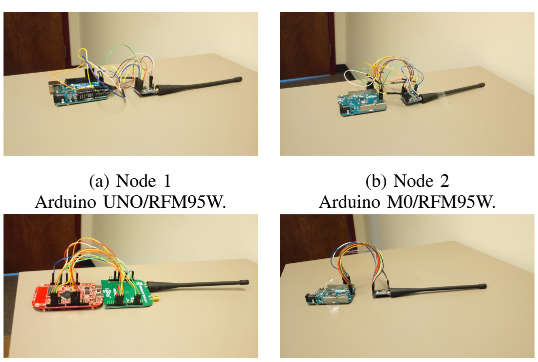
Fig. 2: Raspberry PI based gateways.

LoRa transceiver module (see Fig. 2(b)), which operates over a single channel. Both gateways are equipped with external antennas with 3 dBi gain, and are located on the 7th (top) floor of the ICT building, as show in Fig. 1(b). The RPI's run open-source single channel [23] and multi-channel [24] gateway codes. We use the free crowd sourced network server hosted by The Things Network (TTN) [11]. TTN provides users with an option to choose a server to host their application on, which, for the purposes of our paper is US-West server. The end devices encrypt their payloads, which are then decrypted by the TTN network server.

C. End Devices

We built four end devices, as described below:

- **Node 1:** Arduino UNO board connected to RFM95W LoRa transceiver (Fig. 3(a)), transmitting on frequency 904.1 MHz;
- **Node 2:** Arduino M0 board connected to RFM95W LoRa transceiver (Fig. 3(b)), transmitting on frequency 904.3 MHz;
- **Node 3:** Mbed FRDM-KL46Z Freedom board connected to SX1276MB1LAS LoRa shield (Fig. 3(c)), transmitting on frequency 905.1 MHz;
- **Node 4:** Arduino M0 Pro board connected to RFM95W LoRa transceiver (Fig. 3(d)), transmitting on frequency 904.5 MHz;



(a) Node 1 Arduino UNO/RFM95W. (b) Node 2 Arduino M0/RFM95W.

(c) Node 3 Mbed FRMD/SX1276MB1LAS. (d) Node 4 Arduino M0 Pro/RFM95W.

Fig. 3: Custom-built LoRa end devices.

All end devices are equipped with external antennas with 3 dBi gain. The output power for the transceivers was set to 23 dBm. Since, some test locations are in the areas with poor signal propagation conditions, unless mentioned otherwise, the SF is set to the largest possible, *i.e.*, 10, with 125 KHz channel bandwidth and each device broadcasts its messages as soon as possible, without any sort of acknowledgment or synchronization mechanism. Each message consists of pre-defined LoRa and TTN headers with hard-coded payload of various sizes, where the size depends on the measurements done at the moment and specified for each of the test cases. The Arduino-based nodes run the LMiC library [25], which is a slightly modified version of the LoRaWAN implementation by IBM. The Mbed-based node runs the reference implementation of LoRaWAN provided by Semtech.

D. Sensors

The current network setup includes a variety of sensors to collect temperature, humidity, pressure, air quality and loudness data within the ICT building. Information collected is being transmitted to the gateways described above, forwarded to the TTN server, from where we fetch the sensor data and graphically represent it in real-time on our website [2].

IV. Measurement Results

A. Performance Criteria

We focus on measuring the coverage of LoRa in an urban environment. To characterize coverage at a location, we calculate the *packet delivery ratio* (PDR) at that location. PDR is the ratio of the number of packets successfully received at the network server over the total number of packets transmitted by an end device. To calculate the packet delivery ratio at each location, we use multiple end devices and transmit a series of packets simultaneously over different channels, so their transmissions will not interfere with each other. We then compute the average PDR at each location using the calculated packet delivery ratio of each end device.

B. Indoor Coverage Results

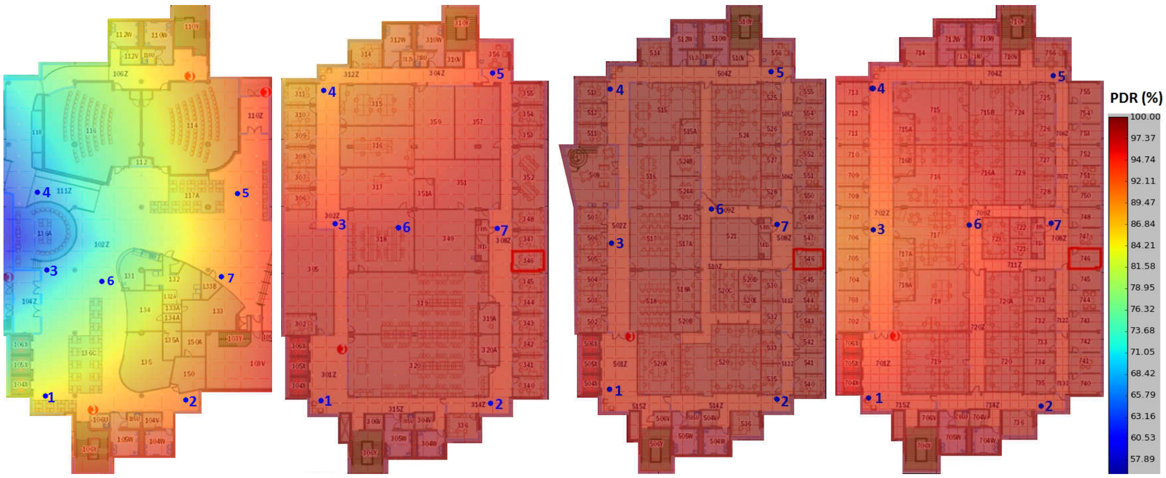
The indoor measurements were conducted in 7 different locations on floors 1, 3, 5, and 7 of the ICT building. Only first three end devices were used for this set of measurements, where each device transmitted 200 packets back-to-back. The results of indoor measurements are summarized in Table I, where the table shows the average PDR in percentage and corresponding standard deviation of the values per floor. Locations marked for each measured floor as well as visualization of the measurement results are shown in Fig. 4.

TABLE I: Indoor measurement results.

Floor	Average PDR (%)	Standard Deviation
1	94.42	3.003
3	97.22	1.042
5	98.8	0.599
7	98.3	0.552

From the results one can see that in the indoor scenario, the PDR exceeds 89% even for the first floor locations, which are farthest away from gateways. The results imply that even when the communication takes place in a harsh propagation environment, it is still possible to use low-cost LoRa for effective communication.

[2]The Things Lab, http://things.cs.ucalgary.ca



(a) Floor 1. (b) Floor 3. (c) Floor 5. (d) Floor 7.

Fig. 4: Visualization of indoor measurement results.

C. *Outdoor Coverage Results*

The outdoor measurements were conducted in the vicinity of the ICT building as shown in Fig. 5. For the measurement locations, we considered what could be a typical case in a practical application, with some notable examples being:

- The O-4 location is a shopping plaza representing a typical urban area, with the path between the end devices and gateways is slightly obstructed by a few buildings.
- The O-5 location is a park area, located roughly 2.6 Km away from the gateways, with trees and buildings obstructing the line of sight.
- The O-1 location is in a different park area, but on top of a hill, which allowed for an almost unobstructed line of sight, at a distance of about 4.4 Km.

TABLE II: Outdoor measurement results.

Location	Distance	Average PDR (%)
O-1	4.37 km	84.5%
O-2	990 m	85.5 %
O-3	730 m	92.5 %
O-4	700 m	93.5 %
O-5	2.18 km	54.33 %
O-6	2.63 km	80.5 %
O-7	3.77 km	76.8 %
O-8	1.43 km	75.5 %
O-9	2.49 km	76 %
O-10	410 m	85 %

For outdoor measurements, end devices were positioned in four different directions from the ICT building at distances of up to 5 Km. The 5 Km range was chosen after measurements at a distance of 10 Km showed that no packets could be received by gateways. For each direction, each of the devices transmitted 200 packets. Measurement results are summarized in Table II. The heat map in Fig. 5 shows the coverage of the gateway based on the results of the measurements.

We observed that when there is an obstructed line of sight between the end devices and gateways, there is a substantial drop in PDR, even at distances below 3 Km. In our experiments, the average PDR was below 60% in such scenarios.

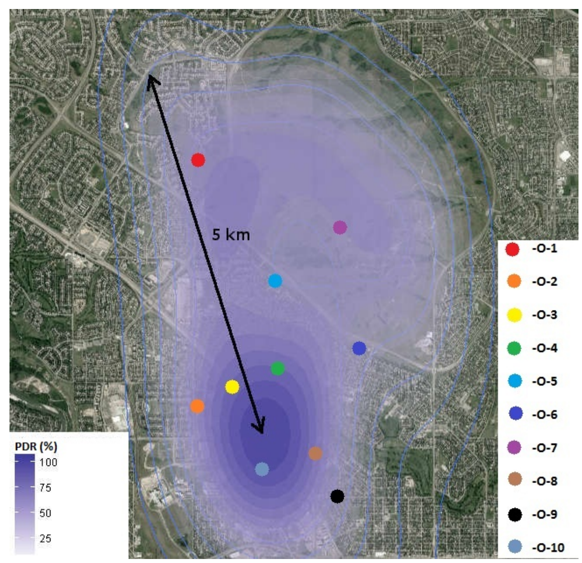


Fig. 5: Visualization of outdoor measurement results.

The drawback of an indoor gateway location was especially apparent when the measurements were done on the opposite side of the building where the gateway was located. In such scenarios, no packets could be received even at 1 Km distance. We observed that indoor location of the gateway created a sector where PDR was substantially higher, compared to other surrounding locations, due to the fact that other directions were obstructed by the building walls and/or surrounding urban area, trees and other obstacles. As a result, when the line of sight was not obstructed, a PDR of over 85% at a distance of 4.4 Km was observed. Our results suggest that, if the gateways are installed at a non-obstructed location such as on top of a building or a tower, it is possible to reach coverage ranges similar to those reported in [18] using commercial grade equipment.

TABLE III: Effect of SF on PDR and message airtime.

SF	AirTime (ms)	PDR
7	41.216	73%
8	82.432	68%
9	144.384	88%
10	288.768	85%

D. Effect of Network Parameters

In order to characterize how different network parameters affect PDR, three different sets of experiments were conducted. The location of all the experiments was the outdoor location O-4 in Fig. 5.

1) Effect of Spreading Factor: In the first two sets of experiments, we changed the spreading factor (SF) and measured the corresponding airtime and PDR. The results are summarized in Table III, where PDR is the average between all four end devices over a total of 800 packet transmissions. We observed that increasing SF results in higher PDR (*i.e.*, 12% compared to SF7) at the expense of increased message airtime (*i.e.*, 700% compared to SF7).

2) Effect of Packet Size: Last experiment was conducted to characterize how payload size affects PDR. To this end, 800 packets, with payloads between 1 and 242 bytes, were transmitted in total, per measurement. The Maximum packet size allowed in LoRaWAN is 255 bytes, but 13 bytes are used as the header for a packet with no extra options specified. Thus the maximum achievable payload is 242 bytes [26]. One should note that within the LoRaWAN protocol specifications, the 242 bytes of payload is used only with SF7 and SF8, which makes this experiment non-LoRaWAN compliant [22]. The results of the experiment are depicted in Fig. 6. We observe that increasing the payload leads to significant drop in PDR. Specifically, increasing the payload from 1 byte to 242 bytes results in a PDR as low as 10%.

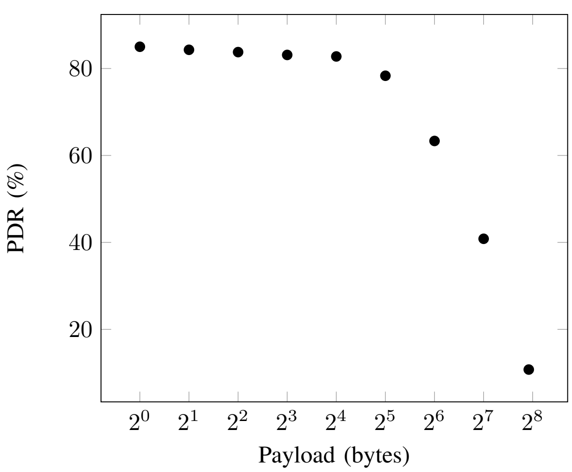


Fig. 6: Effect of payload size on PDR.

V. Conclusion

In this work, we reported on our experiments with a low-cost DIY LoRa network. The hardware and software components of the network are readily available to public for free or at a very low cost. We conducted extensive measurements to characterize the coverage performance of our low-cost network in both indoor and outdoor scenarios in an urban environment. The results show that, even with sub-optimal gateway placement, our low-cost gateways and devices are able to communicate reliably in a variety of situations characterized by a harsh propagation environment and long distances. In the future, we plan to study the scalability and capacity of low-cost LoRa networks, when many IoT devices are required to be connected to the network.

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