LoRaWAN for Smart Cities: Experimental Study in a Campus Deployment

Rakshit Ramesh*, Mukunth Arunachalam*, Hari Krishna Atluri**, Chetan Kumar S†, S.V.R. Anand*, Paventhan Arumugam*a, and Bharadwaj Amrutur*

*Robert Bosch Centre for Cyber Physical Systems, IISc **ERNET India †Aikaan Labs Pvt. Ltd
*Corresponding: paventhan@eis.ernet.in

16.1 INTRODUCTION

According to the UN report [1], 55% of the world population live in urban areas and it is projected to grow to 68% by 2050. Many countries are adopting smart cities approach to address the urbanization challenge by integrating cyber-physical system technologies with city infrastructure towards improving the overall quality of life in a sustainable manner [2]. Government agencies and municipalities worldwide deploy wide area network infrastructure to collect data and analyse it to provide advanced applications such as smart energy, smart transportation, smart healthcare, smart water management, smart waste management and smart governance. LoRa technology is considered to be one of the enablers that contributes to smart city solutions.

With the advent of LoRa (the radio technology) and LoRaWAN (the underlying networking protocol) in 2012 by Semtech, two important problems have been addressed, i.e Long range and Low Power Communication. Owing to LoRa’s sub-GHz band of operation (433-1000 MHz) and underlying proprietary Chirp Spread Spectrum (CSS) modulation technique with a maximum link budget of 157 dB and a high sensitivity of -137dBm, the signals are capable of traveling through buildings and are capable of being demodulated despite heavy fading and degradation. This paves way for fewer base stations/gateways to receive signals and employ smaller antennas.

One of the major advantages of LoRa is its ease of deploying an operational network through easy on-boarding of end nodes, LoRa gateways and establishing connectivity to a network server. This aspect has allowed public aggregators such as The Things Network [3] to cover large swathes of urban environments in cities.
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with a publicly accessible network for radios so developers can focus more on their applications. Contrasting LoRa with other multi-hop mesh networks such as IEEE 802.15.4 (2.4GHz), issues related to campus scale deployment has been studied in [4]. In this paper, the authors point out unlike LoRa, higher battery consumption and short range of the mesh networks as the limiting factors in the campus deployment.

While LoRa offers long range communication, deploying large scale IoT network that covers the entire city poses challenges for radio propagation due to the lack of LoS (Line of Sight) communication especially in environments dominated by dense foliage and interspersed buildings. In this chapter, we focus on such radio environment and present our results obtained from the experimentation carried out to study LoRa performance in our campus at Indian Institute of Science (IISc), Bangalore that mimics this setting. We present the results of our campus experimentation and offer insights and analysis in section 16.3.

In city scale IoT deployments where multiple networks of different kinds coexist, there is a need for an interoperable middleware which interfaces to servers servicing devices running on different radio technologies. For a city that would like to make some of its publicly deployed sensors to become discoverable, there arises a need for a city-scale central platform that allows for these resources to be searched and acts as a single point of contact for data ingestion. We discuss, in section 16.4, the integration of our LoRaWAN deployment closely with IUDX [5] (India Urban Data Exchange) which allows for sensor/resource discovery and a seamless way of accessing data.

An often overlooked aspect of network deployment is network maintenance and seamless access to debug and audit certain network parameters. In this regard we go into detail in section 16.4.2 on our Network Management System (NMS) and highlight the importance of having one.

16.2 LORA, RADIO AND NETWORK

In this section, we give an overview of the technology covering both LoRa’s physical layer and LoRaWAN’s open standard.

16.2.1 LORA MODULATION BASICS

LoRa corresponds to the physical layer for radio communication which supports the use of media access control (MAC) protocols such as LoRaWAN, Symphony Link, MoT: MAC on Time, etc on top of it [6]. We use LoRaWAN (Long Range Wide Area Network) as the network protocol with LoRa which is optimized for battery powered devices and offers long range communication link in the sub-GHz (400-1100MHz) band. The network is typically laid out in a star of star topology with the device’s radio (node) communicates to a gateway which relays messages to the orchestrator (Network server).
Communication between the node and the gateway is spread out on different frequency channels and modulating data rates. LoRa uses a proprietary spread spectrum modulation scheme that is derivative of Chirp Spread Spectrum modulation (CSS) [7]. CSS modulated waves have a chip signals represented by chirps which spreads the information signal across its bandwidth. These chips are usually up-chirps of a fixed bandwidth usually between 4 kHz to 500 kHz. This scheme allows for a total 6 modulation schemes or data rates commonly called as Spread Factors (SF), ranging from SF7 to SF12. The datarates of SF12 modulation typically are around 0.2Kbps whereas data rates of SF7 modulation are around 5Kbps. There is further Forward Error Correction which provides additional coding gain, reducing the overall bit rate. In this section, we discuss some key formulations that play an important role in determining the desired network, especially the packet air time and bitrate.

### 16.2.1.1 Bit rates

The bit rate for a given spread factor is given by -

\[
R_b = SF \times \frac{BW}{2^{SF}} \times CR
\]

(16.1)

where:
- \( R_b \) = Bit rate offered by the LoRa signal
- \( SF \) = Spread factor \( \subset \{7, 8, 9, 10, 11, 12\} \)
- \( BW \) = Chip signal bandwidth
- \( CR \) = Coding rates \( \subset \{4/5, 4/6, 4/7, 4/8\} \)

A message is composed of a combination of \( 2^{SF} \) symbols that are spread across that many frequency levels. There is an inverse correlation between spread factor and distance at which the signal can be decoded. Clearly, a larger spread factor, for example SF12, spreads the signal into \( 2^{12} \) different chips when compared to SF7 which spreads the data signal into \( 2^7 \) signal chips making SF12 more robust to interference and fading based deterioration of the signal. The caveat with long range is the slow bitrate. The effects of this spreading is discussed in [8].

### 16.2.1.2 Packet air time

Each spread factor also determines the air time occupied by the signal to completely transmit a message.

\[
T_{sym} = \frac{2^{SF}}{BW}
\]

(16.2)

where - \( T_{sym} \) is the symbol time. With every CSS modulation scheme, there is a need to synchronize the receiver and transmitter radios. This synchronization is achieved by a lock on the packet’s prefixed \( n \) preamble symbols transmitted. Every packet is transmitted first with a preamble to synchronize the radios, the packet time a symbol
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takes to transmit is given by -

\[ T_{\text{preamble}} = (n_{\text{preamble}} + 4.25)T_{\text{sym}} \]  \hspace{1cm} (16.3)

where -

\[ n_{\text{preamble}} = \text{Number of symbols constituting the preamble} \]
\[ T_{\text{sym}} = \text{Symbol time as given in equation (16.2)} \]

The extra 4.25 symbols are reserved to indicate the end of a preamble sequence. The maximum number of symbols that constitute the packet payload is given by:

\[ n_{\text{payload}} = 8 + \max \left( \left\lceil \frac{8P_{L} - 4S + 28 + 16 - 20H}{CR(S - 2DE)} \right\rceil, 0 \right) \]

\hspace{1cm} (16.4)

where -

\[ P_{L} = \text{Number of payload bytes} \]
\[ H = 0 \text{ if addition LoRa header is present, } 1 \text{ if not} \]
\[ DE = 1 \text{ when low data rate optimization is enabled} \]
\[ CR = \text{Coding rates } \subset \{4/5, 4/6, 4/7, 4/8\} \]

Header H is the low level header which indicates the type of coding rate used, the payload length and CRC. DE is a mode intended to correct for clock drifts in SF11 and SF12. Therefore,

\[ T_{\text{payload}} = n_{\text{payload}} \times T_{\text{sym}} \]  \hspace{1cm} (16.5)

With these, we can now define total packet time as -

\[ T_{\text{packet}} = T_{\text{preamble}} + T_{\text{payload}} \]  \hspace{1cm} (16.6)

We will see in further sections how these equations affect a network deployment.
16.2 LoRa, Radio and Network

16.2.2 LORAWAN PROTOCOL

LoRaWAN network topology showing two gateways covering different regions A and B. Also shown, a few end nodes at different distances with the choice of SF and its effect on the duty cycle.

LoRa-Wide Area Network (LoRaWAN) is the network management scheme commonly used by all LoRa nodes to ensure scalable and sustainable deployments of nodes on LoRa networks ensuring secure communication and reliable management of available bandwidth and channels [9].

16.2.2.1 LoRaWAN Nodes

LoRaWAN nodes are broadly classified into 3 categories based on the power optimization scheme of transceivers employed. Class A devices are bi-directional end devices which wake up from deep sleep to transmit an uplink packet and then turn off after a fixed reception window where it may receive a downlink packet from the server (ALOHA), making it the most power consumption optimized class. Class B devices are bi-directional end devices with scheduled receive slots. This is also a power optimized category but transmissions/receptions are on fixed time slots instead of random ALOHA slots. This enables periodic/slotted reception on the end node possible in cases where the device has less to transmit but more to receive and actuate upon. Class C devices are the least optimized for power consumption and have their receive windows open always. This category most suits applications where a request-response styled behaviour on the downlink is desired.

Since LoRaWAN in most countries operates on the free and unlicensed spectrum, there is great impetus on the fair use of channels by the end nodes and applications. Therefore all channels are duty cycled and allowed to transmit only a limited number
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of times in a day. This applies moderately to uplinks from the nodes to gateways but a lot more to downlinks from gateways to the nodes, since there are fewer (only one fixed downlink channel) for all nodes. It is to be noted that in most deployments, Class A and Class C devices are preferably used because Class B devices require strict synchronization between all the gateways and radio nodes of the system.

16.2.2.2 LoRaWAN channel management

LoRaWAN with its available 2MHz bandwidth (865MHz-867MHz in India), the most commonly used channel plan is to split this into 3 pseudo randomly selected uplink + downlink channels and 1 fixed downlink channel. Each of these channels are of 125 KHz bandwidth each. Sufficient guard band intervals are allowed to prevent inter channel interference. There are limits on scalability owing to just 2 MHz of unlicensed spectrum allocated.

The high demand of unlicensed spectrum used by LoRa leads to heavy contention by the devices. To support many devices in LoRaWAN there is a duty cycle imposition capping the packet transmission frequency. There are three duty cycle regimes that are employed, 1%, 0.1%, 0.01% depending on the packet air time taken and the transmit power used. The amount of time between subsequent transmissions is given by

$$T_{\text{next}} = \frac{T_{\text{packet}}}{\text{DutyCycle}} - T_{\text{packet}}$$ (16.7)

where $T_{\text{packet}}$ can be obtained from equation (16.6) implying that for the best range using SF12, and a maximum packet size for this SF being 51 bytes, it would take around 2 seconds for the packet to be transmitted. Therefore the next transmission on the typical 1% duty cycle band would be 3 minutes later. For downlink messages from the server to the node, the duty cycles are even more stricter at 0.01% duty cycle (due to a single fixed downlink band) implying around 10 downlink messages per day (SF10 only).

Channel capacity for LoRa networks is discussed in detail in [10], where it is shown that for a 500 device system with 3 channels running on a 1% duty cycle scheme, the maximum throughput is 84 packets per node per hour (each message of 51 bytes). [8] gives a detailed discussion on Outage and Coverage probabilities, which indicate the probabilities that a message be received or missed respectively. It therefore becomes crucial to optimize channel utilization and selection. To address this, LoRaWAN allows for an Adaptive Data Rate (ADR) scheme to be used which would enable the network to determine the optimum spread factor for the nodes to use. Nodes can further fragment messages to transmit longer infrequent messages.

16.2.2.3 LoRaWAN gateway

LoRaWAN gateways are practically “dumb” packet forwarders in the architecture whose role is to simply forward packets to its affiliate LoRa Network Server through
a secure TLS based MQTT connection. Configurations on the gateway need to be made to set the proper channels and TX power lookup tables to ensure compliance with the spectrum policy of the country and to comply with the device’s channels. Apart from these, the gateways have no knowledge of the devices in the network, etc.

16.2.2.4 Packet encoding with Protobuf
An important aspect in LoRaWAN communication is the payload size. In a related work [11], the authors proposed a schema for communication with the smart streetlight, which is based on JSON owing to its properties of self description and sheer readability. However due to LoRaWAN packet size limitations, we see that sending a JSON data representation for the sensor values on the uplink and actuation commands on the downlink is bandwidth inefficient, due to unnecessary usage of characters like “{”, “}”, and so on. To minimize the payload size which in turn reduces the bandwidth requirements, a process of data serialization is performed on the payload. The choice of data serialization format for an application depends on factors such as data complexity, need for human readability, speed and storage space constraints. BSON, YAML, CBOR, Avro, MsgPack, and Protobuf are some commonly used data serialization formats. A comparison of these can be found in [12]. We use Google’s Protobuf and it’s embedded library nanopb [13] for encoding and decoding messages. This involves defining a proto-file that represents field names with byte “flags” and involves varint encoding for most datatype. An example proto-file we used in our smart streetlight application is provided in [14]. At the receiving end, the same proto-file is used to reference the memory location of a field in the message body and decode the message to JSON.

16.2.2.5 LoRa Network Server
The bulk of routing and device management is undertaken by the Network Server. This includes AES based key management to ensure secure communication, device address management to ensure correct activation with session management of context and keys, adaptive data rate to ensure proper channel selection, duty cycling and gateway packet de-duplication to ensure multiple packets from the same device coming in from different gateways aren’t logged separately. An Application Server is co-located with this Network Server which deals with Device/User management and providing interfaces to make the devices data available to users having appropriate credentials. The figure 16.1 summarizes LoRa Network topology showing sensors at different distances in regions A and B with two well separated non-interfering gateways, their probable SFs and respective next packet transmit times for an uplink and downlink message.
16.3 PERFORMANCE IN REAL-WORLD LORAWAN DEPLOYMENT SCENARIOS

In this section we focus on the network deployment specifically at IISc, its performance, means and metrics to ascertain the network coverage. We briefly mention some of the other LoRaWAN global deployments.

16.3.1 CAMPUS WIDE LORAWAN DEPLOYMENT

We conducted an experiment inside the IISc campus having a continuous layer of foliage, housing a few buildings beneath the canopy. Figure 16.2 shows a satellite terrain view of the campus with region A depicting the area of experimentation of network coverage.

![IISc Campus satellite view](image)

A satellite view of the campus showing the dense forest cover and interspersed buildings. In contrast, a dense urban area is shown, which is typically the subject matter of most studies.

The position of the gateway is indicated and it is clear that only few spots lie in the LoS of the gateway with heavy interference from the thick foliage of the campus. Region B depicted in the figure is surrounding area in the vicinity of the IISc campus, which is an urban area with mainly residential dwellings and very little tree cover. This offers a stark contrast between the conditions described in previous experiments describing an urban environment (like region B).
16.3 Performance in real-world LoRaWAN deployment scenarios

16.3.1.1 Experimental setup

For our experiments one among the two gateways in IISc campus was turned on and this was located at the terrace of a five-storied building at a height of approximately 20 m.

The gateway used here is Kerlink Wirnet 868 MHz station [19] with an antenna of gain 3dBi and an Ethernet backhaul to the network server. The end node used was IMST’s im880b [20] which are equipped with a Semtech SX1272 transceiver and a 3dBi antenna. The end device was mounted on to a tripod and was taken to different locations in the campus. The transmission power of the end-device was set to 14 dBm. Coding rate was set to the standard 4/5 which is most prevalent. Bandwidth was the standard 125kHz that is generally prescribed in European and Indian bands. Packet acknowledgment and retransmission was turned off. The test was performed on spread factors SF7 to SF12 by transmitting 30 packets of size 51 bytes (MAC) to the network server from each spread factor. Packets thus transmitted were received by the LoRa Network Server [22] (viz. the gateway) and packet specific information such as the Received Signal Strength Indicator (RSSI) and the Signal to Noise ratio (SNR) were logged. A special case with LoRa is that packets can still be decoded when it’s SNR is below 0 [8]. In this case \( \text{RSSI} = \text{RSSI} + \text{SNR} \).

By the end of transmission of the 30 packets, a PER (Packet Error Rate) could also be derived. The network coverage heatmap for the region of interest (within campus limits) was obtained by statistical cubic interpolation across the RSSI values logged at different regions, the path loss curve was obtained by curve fitting. We have also made the code for this available [21].
16.3.1.2 Measurements on SF7

FIGURE 16.3 SF 7 Network Coverage map

Network coverage for SF 7. Range is limited to a 200m radius around the gateway.

With reference to equation (16.1) we find that on substituting $SF = 7$ makes $R_b = 5468$ bits/sec. With reference to equation (16.2) we find $T_{ran} = 1.024 ms$. Since 51 MAC bytes were used, we obtain from (16.4) $n_{payload} = 88$ symbols in total, for which maximum air time would be $T_{air} = 102 ms$. From (16.7) we obtain time between subsequent transmissions to be $T_{next} = 10 s$. This means that the end node can transmit data at the highest bitrate and occupy the lowest time for that band with the caveat of reduced range owing to fewer encoded chips. As seen in figure 16.2 with the gateway shown as a triangle, regions around it (100m) have excellent PER rates (nearly 0%) and good RSSI (nearly -80dBm). Regions (A) and (B) show the gradient along which signal predominantly propagates, owing to low lying buildings and parting in the foliage to allow for roads, etc. Region (C) faces large PER (96%) and low RSSI (-130dB). Surprisingly, region (D) faces better PER and higher RSSI. This is because of a tall building in its vicinity which is causing a fringing effect and offering a reflected line of sight to the gateway. Region (E) is in the shadow of the network owing to large concentrations of high rise (4+ storied) buildings in its vicinity. Overall, SF7 offers a maximum range of around 350 m.
16.3 Performance in real-world LoRaWAN deployment scenarios

16.3.1.3 Measurements on SF12

**FIGURE 16.4** SF 12 Network Coverage map

Network coverage for SF 12. Range is limited to 800m and good PER rates for areas closer than 500m.

With reference to equation (16.1) we find that on substituting $SF = 12$ makes $R_b = 292$ bits/sec. With reference to equation (16.2) we find $T_{sym} = 32.768ms$. Since 51 MAC bytes were used, we obtain from (16.4) $n_{payload} = 53$ symbols in total, for which maximum air time would be $T_{air} = 2138ms$. From (16.7) we obtain time between subsequent transmissions to be $T_{next} = 213s$. This means that the end node can transmit data for the largest distance (due to data being spread over $2^{12}$ number of chips) with the caveat of occupying the channel for a longer period of time.

Clearly regions around it (300m) have excellent PER rates (nearly 0%) and good RSSI (nearly -100dBm). Packets transmitted at SF12 are decoded at very low RSSI values. As expected, a significantly larger area can be covered using SF12. As with SF7, even for SF12 regions (A) and (B) show the gradient along which signal predominantly propagate. We can also see that region (C) now has good coverage (RSSI = -115dB PER = 10%). Region (D) exhibits interesting behaviour; note that there are regions where the PER is 0% but the quality slowly degrades over a very small region. We believe this is because of a tower (20m) that is in direct line of sight with the gateway. The tower now exhibits fringe effect which causes EM waves transmitted from region (D) to reflect off of it and render itself to the gateway, though there...
is no clear line of sight. Region (F) also exhibits good network coverage with PER less than 10% in some regions. This is because of an occluded line of sight from the gateway and the existence of a straight road along the gateway which guides the wave towards the gateway. Overall, maximum range was observed to be 860 m.

16.3.1.4 Range and PER for SF8 to SF11

For the sake of brevity, we have only shown results of SF12 and SF7. Our experiments show that the range of network gradually increases with increase in spread factor and the PER for peripheral regions in each spread factor becomes smaller. In SF11 (comparing with 16.4), it is observed that region G is not covered by the network and regions E experience PER > than 80%. In SF8 (comparing with 16.3), it is observed that region D comes under the network coverage and region C PER decreases to < 80%. Likewise the trends for SF9 and SF10 become increasingly better.

16.3.1.5 Path Loss estimation

An important parameter that indicates the nature of the propagation environment is the Path Loss Exponent \( \gamma \). Considering the Friis equation for free space propagation of an EM Wave from [23],

\[
P_r = \frac{P_t G_r G_t}{L} \left( \frac{\lambda}{4\pi d} \right)^\gamma \tag{16.8}
\]

where -

- \( P_r \) and \( P_t \) = Received and transmitted power respectively
- \( G_r \) and \( G_t \) = Gain of receiver and transmitter antenna respectively
- \( L \) = System Loss (attenuation) like insertion loss, matching loss, etc
- \( d \) = Distance between the receiver and transmitter antenna
- \( \lambda \) = \( c/f \) where \( f = 865 \) MHz
- \( \gamma \) = The path loss exponent

Converting to decibels and substituting for our test setup \( G_r = G_t = 3dBi \). Insertion loss of 0.5dB for antenna and 0.5dB matching loss at worst, \( P_r = 14dBm \), \( f = 865MHz \), we get

\[
P_r(dBm) = 19 - 10\log_{10}(d) \tag{16.9}
\]
16.3 Performance in real-world LoRaWAN deployment scenarios

We now empirically find the path loss exponent $\gamma$ by fitting the above equation (using the Levenberg-Marquadt method) to the data we collected. For this experiment, we chose only SF 12 measurements, since path loss is not affected by the modulation scheme.

With $\gamma = 5.616$, we can clearly see how much of a harsh environment the campus is for LoRa signals. This is mainly owing to heavy scattering of signals due to trees, and very little reflections. A similar experiment over a smaller region was conducted in [4] where path loss exponents for less dense regions in the IISc campus are provided.

16.3.1.6 Campus deployment: key observations

As a result of our experiments, we arrive at the following conclusions.

- The best range LoRa radios (14dBm TX Power, 3dBi antenna gain) can offer is 0.8 km in campus with thick foliage.
- Path Loss Exponent $\gamma$ for the campus is 5.616. This indicates that the campus is a very harsh environment for signals to propagate. Keeping this in mind, we increase the deployment density of gateways around “QoS-Shadow” regions to offer better coverage.

We provide below a few guidelines that a Network Service Provider would need to keep in mind while deploying their network.

- To determine how many gateways a region requires, a thorough field survey with an end node needs to be made for all SFs. Usually, one would go with the manufacturers claims that LoRa affords 10km range but we have found this to not be
true in urban settings.

- It is possible that a region may face lesser PERs despite no clear line of sight to the gateway, and despite being further away radially than a region with higher PERs. This is owing to the topology of that region, reflected line of sight components, etc, at that region.
- Placement of the node/gateway plays an important effect in network coverage. Gateway height should be as high as possible making sure that a clear line of sight is available to all nodes. There should be no obstacle in the near field of node or gateway (along the LoS). Node and gateway antennas should be oriented in such a way that their field of maximum radiation align with each other.

### 16.3.2 NOTE ON SCALABILITY AND DRAWBACKS OF LORAWAN UNDER DENSE FOLIAGE SCENARIO

Our experimentation in the campus has given us key insights on scalability and performance aspects of LoRaWAN in dense foliage radio environments within a city. Our experimentation as was mentioned in 16.3.1.3, has shown that a radio range of around 500m is the expected radio range with 10% PER with the LoRa device operating at SF12. This crucial result throws light on the scalability of LoRaWAN in terms of cost, performance and operational management. For a city scale deployment, the range of around 500m between device and gateway demands more gateways to be deployed, and the spread factor of SF12 results in less number of devices per gateway for a given duty cycle [10]. All this leads to higher installation costs and operational expenditure.

For a scalable deployment with regions of urban foliage, careful network planning involving optimal gateway placement that minimizes the cost while improving the radio coverage, and the selection of appropriate applications that can tolerate low duty cycle operation are essential.

### 16.3.3 OTHER GLOBAL LORAWAN DEPLOYMENTS

As mentioned earlier in section 16.3, below are some of the other LoRaWAN global deployments.

#### 16.3.3.1 Bologna, Italy

The network deployed in Bologna [15] to server applications like environment monitoring was focused on two districts, Saragozza and Navile, with one gateway at each location. Radios used had 3dBi gateway receiver antenna gain and 2dBi transmitter antenna gain with signals transmitted at 14dBm TX power. At Saragozza a region with fairly low height buildings and near line of sight from the position of the gateway positioned at 71m above ground level, it is observed that the maximum range obtained was in the order of 1-2km for SF12.
16.3.3.2 Paris, France
The network was deployed in a suburb of Paris [16] with fairly low lying buildings with clear line of sight between gateway and end nodes. The radios again had similar antenna gain parameters as the ones used in Bologna. It was observed that a maximum range of around 2.5km was obtained in a LoS path.

16.3.3.3 Bangkok, Thailand
The experiment [17] was composed of one end-device, one gateway and one server with MQTT protocol. The gateway and end device were from Libelium with the gateway antenna having a 5dBi gain and end-device with a 4.5dBi antenna. The results of the experiment show that the range are only up to 2 km in outdoor rural area and 55-100m in an indoor urban environment.

16.3.3.4 Lille, France
The network was deployed at the Scientific Campus of the University of Lille in the North of France [18]. The end device was a Libelium Wasmote with antenna gain of 4.5dBi and the gateway used was a Kerlink Wirnet 868 MHz station with gain 3dBi and was situated at the first floor of Building in the campus. The results of the experiment showed that LoRaWAN provides good performances over the major part of the Campus over a distance of 1.2km. Poor signals are due to the presence of high rise buildings, which disturb the local quality of data transmission.

16.4 IoT MIDDLEWARE FOR SMART CITIES
In the case of a smart city IoT network deployment, LoRaWAN has to coexist with networks of various kinds like SigFox, Zigbee. In addition, network servers of this kind don’t take into consideration discovery of other LoRa networks and the geographical and network management contexts of constituent LoRa nodes which could facilitate in network planning and management. Network servers also cannot report quality of the sensors interfaced by the radio which would aid in sensor prognostics.
FIGURE 16.6 Interoperable network architecture

An interoperable network architecture showing how devices running on different network modalities can be accessed from a common middleware.

In this regard, our implementation details a second server, the smart city middleware which interfaces with network servers of different protocols like LoRa/Zigbee/NB-IoT etc and plugs the void between radio management and sensor/device management. It is required that these servers make their data access interfaces known and available to ensure seamless and interoperable data brokering as shown in 16.6.

16.4.1 INTEROPERABILITY ASPECTS IN IOT NETWORK DEPLOYMENTS

Typical low bandwidth network implementations present a siloed approach of an IoT system, wherein all devices follow one kind of radio technology for example, LoRa. For instance, a device on WiFi cannot communicate with another device on LoRa. This prohibits applications running on one platform to consume sensor information from devices on another platform. To address this limitation, we have developed a middleware framework, IUDX [5], that enables applications to work with devices on heterogeneous networks. IUDX offers features such as data queuing over a PubSub broker (Publish-Subscribe), data storage, security and APIs to make application development simple. It specifies modalities of interactions, i.e the query language, semantics and keyword definitions that are well defined and regulated. In the context of LoRaWAN the process typically involves a thorough description of the LoRaWAN based resources including static attributes like the resource’s ID, application server, resource location, provider of the resource etc and data attributes like the sensor values, sensor units, the sensor data range, etc. Additional GIS information of the topography of the region where the nodes are deployed can be obtained through discovery features made available through a catalogue.

IUDX expects payloads to purely be in JSON format, therefore it is important
to have a component that does this translation from Protobuf. Onboarding to IUDX then involves writing a software module *adapter* that maps APIs from one particular type of network server to the IUDX’s APIs.

An adapter is essentially a software entity residing in the middleware that is a client to both the middleware and the foreign platform (private LoRa Network Server for example). Its role is to consume sensor data from the foreign platform and publish it into IUDX and similarly extract data from IUDX and publish it to the devices on the foreign platform. Further, it has the ability to process this data and make it usable by either platforms. As a real-world example, the adapter does the Protobuf to JSON conversion for messages originating from the streetlight on the foreign platform side and JSON to Protobuf conversion for streetlight actuation commands from applications on IUDX. It can even download the encode/decode descriptions via entries made in a catalog on IUDX at the time of device registration and generate the required classes to perform data conversion.

**FIGURE 16.7 Adapter architecture overview**

Solving the interoperability problem through adapters, which acts as a client to both the middleware and the network server, converting packet format where necessary.

### 16.4.2 LORAWAN OPERATION AND MANAGEMENT

As mentioned earlier, IUDX makes it possible to dispatch device maintenance teams by integrating sensor stream analytics (which could detect a faulty sensor) to the LoRa network management suite. In addition, sensor refresh (upload) rates can be controlled on an on-demand basis with inputs from the sensor stream analytics. The operational and management aspect of LoRaWAN includes the ability to configure the LoRa network to meet end application demands, monitor the network status and performance, quick fault diagnosis and minimize service disruption with predictive maintenance. To achieve these essential objectives, ISO recommends FCAPS model [24], Fault management (F), Configuration management (C), Accounting management/Administration, Performance management (P) and Security management (S).
16.4.3 CONFIGURABLE PARAMETERS

For configuring and optimizing the performance, LoRaWAN offers various configurable parameters such as Spread Factor, Coding Rate, Bandwidth, Operating Channel, Transmit power and an Adaptive Data Rate mode for devices and gateways.

In our implementation, the configuration is done at the LoRa network server over RESTful APIs. The server then pushes the configuration to the LoRa gateways and subsequently to node over a secure MQTT channel.

16.4.4 NETWORK MANAGEMENT

Performance management enables building a reliable system by monitoring performance parameters in real-time and predict failures, thereby aiding in minimizing the downtime and maintain the QoS of the end applications. This section outlines the mechanisms and methods for collecting system level operational telemetry from various LoRa entities, processing, analyzing and visualizing of operational telemetry data and publishing it to authorized consumers.

The main parameters that determine the performance of LoRa are RSSI, SNR, SF, PDR. Monitoring these parameters help the network operators to provide reliable and timely data to the end applications and thereby ensure QoS. The operational telemetry can further be processed at Network Management System (NMS).

The NMS performs system telemetry operation by i) monitoring various parameters of interest pertaining to devices, communication network infrastructure and systems, ii) alerting, iii) report generation, iv) dash-boarding, v) data visualization through time-series plots and so forth. For LoRaWAN it is also important to take spacial and temporal information into consideration. The operational telemetry while assisting in the routine troubleshooting and making performance measurements, also assists in predictive maintenance, and resource planning with the help of analytics.

Due to current lack of standardized and comprehensive management framework,
16.5 Summary

LoRa operations and management system is expected to work with a vendor specific framework. In our implementation, we used commercial edge controller [26] software with customization to process the operational telemetry data received at the LoRa gateway. The Gateway further pushes the telemetry data (as header section of the data payload) to LoRa server. The LoRa server offers RESTful API to retrieve the telemetry using which we developed a dashboard and visualization systems using LoRa telemetry data. As shown in 16.8, the presence of an Interoperability layer such as IUDX streamlines such integration.

The fault management in a network deployment includes, fault detection, fault isolation and fault resolution of network devices and their connectivity. For accomplishing this, it is important for an IoT Network Service Provider to have continuous access to their remotely located gateways which might be LoRa gateways, Zigbee border routers and so on. In a practical scenario where a LoRa gateway is connected to a 4G/LTE network backhaul which often is assigned a dynamic IP address, it is hard to access the gateway via SSH. To circumvent this problem, we have developed a network management service whereby the administrator will still be able to SSH to the LoRa gateway seamlessly by establishing a managed reverse SSH tunnel to the administrator’s server. Architectural details and code for this is available in [25].

16.5 SUMMARY

In this chapter we covered the performance and operational management aspects of a LoRaWAN deployment for supporting smart city applications in an environment comprising of regions of moderate to dense foliage and buildings as can be typically found in large campuses, parks and so forth.

Through extensive physical testbed experimentation done in a large academic campus that represents such an environment we evaluate the performance of LoRaWAN by considering key metrics such as PER, and radio range for various LoRa Spread Factors. We believe this study would be useful to the network service providers in the design and deployment of LoRaWAN in the scenario considered and can be directly scaled up for city wide deployments.

In this context, we briefly presented studies done in some of the large scale LoRaWAN deployments found in the literature. As LoRaWAN offers network services to the data layer in the overall architecture of a smart city application, we introduce an interoperable data exchange platform, IUDX, an ongoing effort undertaken by one of the smart city initiatives in India. We discussed the operational management activities that need to be carried out to ensure smooth functioning of the LoRaWAN that meets the QoS requirements of smart city applications.


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