Final Year Paper

A proposed network topology for low cost scenarios in a large scale network within a smart city

Abigail Musa
amg@ic.ufal.br

Supervisors:

Prof. Lucas Amorim
Prof. Rodrigo Peixoto

Maceió, Março de 2020

Abigail Musa

A proposed network topology for low cost scenarios in a large scale network within a smart city

A Final year project submitted in partial fulfilment for the Bachelor Degree in Computer engineering (Honour's Degree) to the Institute of Computing under the guidance and supervision of the lecturers José Sarmento Peixoto and Lucas Amorim at the Federal university of Alagoas.

Supervisors:

Prof. Lucas Amorim

Prof. Rodrigo Peixoto

Maceió, Março de 2020

Catalogação na fonte
Universidade Federal de Alagoas
Biblioteca Central
Divisão de Tratamento Técnico
Bibliotecária: Taciana Sousa dos Santos – CRB-4 – 2062

M985p Musa, Abigail.
A proposet network topology for low cost scenarios in a large scale network within a smart city / Abigail Musa. – 2020.
43 f. : il., figs. e tabs. color.

Orientador: Rodrigo Peixoto.
Coorientador: Lucas Amorim.
Monografia (Trabalho de Conclusão de Curso em Engenharia da Computação) – Universidade Federal de Alagoas. Instituto de Computação. Maceió, 2020.

Bibliografia: f. 42-43.

1. Redes de computadores. 2. Topologias de rede. 3. Internet das coisas. 4. Sistemas embarcados (Computadores). I. Título.

CDU: 004.722

A Final year project submitted in partial fulfilment for the Bachelor Degree in Computer engineering (Honour's Degree) to the Institute of Computing under the guidance and supervision of the lecturers José Sarmento Peixoto and Lucas Amorim at the Federal university of Alagoas.

Prof. Lucas Amorim - Supervisor
Institute of Computing
Federal University of Alagoas

Prof. Rodrigo Peixoto - Supervisor
Institute of Computing
Federal University of Alagoas

Prof. Dr. Thiago D. Cordeiro - Examiner
Institute of Computing
Federal University of Alagoas

Prof. Dr. Davi Bibiano - Examiner
Institute of Computing
Federal University of Alagoas

Maceió, Março de 2020

Acknowledgements

First and foremost, I would like to thank God Almighty for giving me the ability and opportunity to undertake my studies and to persevere to the end. Without his blessings, this achievement would not have been possible.

Secondly, I would like to thank my parents for their continual support, timely encouragement, and endless patience. Most essentially, you two have shown me the importance of putting things into perspective so that I can learn from my failures and reflect on my successes. This final project in particular would not have been possible without these life lessons.

I would also like to thank my siblings for their unfailing emotional support, love and kindness. These guys have been my rock.

I cannot forget friends who went through hard times together, cheered me on, and celebrated each accomplishment: Clóvis Gabriel and Jonathás Lima.

I deeply thank my teachers, who helped me grow academically, professionally and personally, particularly our Head Of Department, Dr Thiago D. Cordeiro, for his timely encouragement and support.

I would also like to thank my supervisors Professor Rodrigo Peixoto and Professor Lucas Amorim for providing me with invaluable advice on how to state and rework many of my points.

Abigail Musa

"Let us hold unswervingly to the hope we profess, for he who promised is faithful."

– Hebrews 10:23

"Self-discipline is a key to many doors. Not least of which is one that leads to a better, stronger, and healthier version of yourself."

– Zero Dean

Resumo

Este estudo tem como objetivo explorar algumas das diferentes tecnologias e topologias de rede que podem ser usadas para gerenciar muitos nós em uma cidade inteligente. Além disso, o estudo se concentrou mais naqueles que ofereciam baixos custos. O estudo procura responder à pergunta de pesquisa “Qual é a topologia proposta mais adequada para cenários de baixo custo em uma cidade inteligente? O objetivo aqui é indicar as várias topologias disponíveis, compará-las e contrastá-las, determinando o melhor para alguns cenários muito específicos. Desde o advento da IoT, as pessoas sempre tiveram que escolher a melhor topologia adequada para um determinado conjunto de nós, de modo a alavancar a comunicação entre eles e reduzir custos. Com a evolução da IoT, mais topologias foram criadas, algumas foram feitas para casos muito específicos, enquanto outras foram mais generalizadas. Nos últimos anos, houve ondas constantes dessas topologias usadas em vários casos em uma configuração de cidade inteligente. Por esse motivo, pesquisadores e engenheiros de sistemas embarcados realizaram vários estudos analisando diferentes aspectos das topologias de rede, como a faixa de comunicação, o número máximo de nós, as taxas de transmissão e recepção de dados e assim por diante, mas uma coisa que não foi estudada é se existe ou não um superior a todos os outros em termos de eficácia. Este estudo incluirá uma pesquisa aprofundada sobre as topologias de rede, seus recursos e os contrastes entre elas. Serão apresentados cenários de casos de uso específicos, nos quais será necessário empregar a técnica de topologia mais abrangente para ajustar-se ao aplicativo.

Palavras-chave: Internet das coisas, Sistemas Embarcados, Redes de Computadores, Padrões de Comunicação, Topologias, Estudo de caso.

Abstract

This study aims to explore some of the different network technologies and topologies that can be used to manage many nodes in a smart city. In addition, the study focused more on those that offered low costs. The study seeks to answer the research question " What is the most adequate proposed topology for low costs scenarios in a smart city? " The goal here is to state the various topologies available, compare and contrast them, thereby ascertaining the best for some very specific scenarios. Since the advent of IoT, people have always had to choose the most suitable topology for a given set of nodes, so as to leverage the communication between them and cut down costs. With the evolution of IoT, more topologies have been created, some were made for very specific cases while others were more generalised. There have been constant waves of these topologies over the last few years used in several cases in a smart city setup. Because of this, researchers and embedded systems engineers have performed numerous studies analysing different aspects of network topologies such as the communication range, the maximum number of nodes, the transmission and reception data rates and so on, but one thing that hasn't been studied is whether or not there's one that is superior to all the others in terms of efficacy. This study is going to include an in depth research into the network topologies, their features, and the contrasts between them. Specific use case scenarios will be given, whereby it will necessary to employ the most encompassing topology technique to fit the application.

Key words: Internet of Things, Embedded Systems, Computer Networks, Communication standard, Topologies, Case Study.

Contents

List of Figures

List of Tables

1

Introduction

This day, the increased need to make the world more liveable for people, especially in urban areas has become a major concern. This can be seen by the constant surge of technological trends. In order to be attuned to this current trends, drastic changes need to be made to some of the infrastructures within a city. The concept of smart city has been firmly established and makes it possible to manage a city's applications in a simple and automated way, which in turn improves the quality of life of its residents. All this was fuelled by the internet, IoT and other technologies.

1.1 Background

The term "The Internet of Things" was coined by Kevin Ashton in a presentation about supply-chain management to Proctor Gamble in 1999 Ashton (2009). The Internet of Things — IoT, for short is the concept of connecting any device to the internet and to other connected devices. IoT devices include not only computers and smartphones, but also objects that have been equipped with sensors to collect, send and receive data over a network. Such connected objects will range from smart microwaves, which automatically warm your food for the right length of time, wearable fitness devices that measure your heart rate and the amount of calories burnt during a certain workout, then use that information to suggest exercise plans tailored to you, commercial security systems and smart city technologies — such as those used to monitor traffic and weather conditions. This concept has incredible impact on the relationship between people and things(devices).

A report from the McKinsey Global Institute estimates that the IoT could have an annual economic impact of $3.9 trillion to $11.1 trillion by 2025 across many different settings, including factories, cities, retail environments, and the human body McKinsey&Company (2015). Over the years, IoT has become increasingly relevant in our ever changing world and more applicable to real life situations. With the evolution of internet access, many tasks that are time and energy gluttons have been automated, which leads to substantial time and energy savings Guardian (2016).

The advancement of IoT has revolutionised our world in diverse ways, by changing the way we live and by making tasks easier, smarter and more efficient. Apart from the ample opportunities it brought, it also has its fair share of challenges, like security issues in sharing data, limited interaction between application of different brands i.e there is no unified system that bridges the gap between the different IoT brands, and so on.

1.2 Related Work

In this section, a brief review of the community's efforts in the context of of this work, particularly those related to smart street lighting systems were outlined.

Jha Ashish K. (2017) uses a hardware setup that comprises of components such as light dependent resistor(LDR), passive infrastructure(PIR) to detect motion, LM35 to sense temperature, MQ-7 to check air pollution caused by carbon monoxide and hydrogen, together with Arduino as its microcontroller and LoRa as its communication technology. The aim of this research was to minimise energy consumption and automate the functionality of the street lighting system as a whole. Unlike our approach which has a slightly different hardware setup and functionalities.

JGustavo W. Denardin and do Prado (2009) used a Zigbee compatible transceiver to help control the binary functions of the HPS lamps. All this was done in a bid to increase the communication capabilities and overall manageability of the street lighting system already in use, which is seemingly outdated. The system is a wireless data network-based intelligent system. As opposed to our approach, the communication technology adopted is totally different, and even the circuitry in general.

In recent years, the usage of smart street lighting systems has escalated and thus far shown great results related to their traditional counterparts. Studies have been made in order to find the most adequate communication standard, together with its topology to achieve better results. This has helped not only in terms of costs, scalability, reliabity and security, but also in terms of reducing air and noise pollution, thereby making the environment more conducive for human habitation.

1.3 Objectives

The main objective of this monograph is to propose the most adequate network topology in a large scale network within a smart city that is cost effective. The work presents guidelines on choosing the appropriate network topology, communication technology and protocol for a smart street lighting system in Maceió. This could also serve as a reference structure to leverage the strengths of smart city applications. An impartial analysis of the various alternatives was carried out using both qualitative and quantitative metrics such as costs, energy consumption, coverage, scalability and latency.

1.4 Proposed Solution

In an attempt to put the proposed solution into effect, some changes needed to be made to the existing traditional street lighting systems such as replacing the luminaries with LED-powered ones, a makeover of the entire design and architecture of the systems, all in a bit to curb energy consumption and enhance other qualities like coverage and latency. In this way, this paper is committed to proffer a more realistic approach, considering the present condition of Maceió, the likely prospects of making the street lighting system entirely smart and thus linking it with other city management applications.

The rest of this work is organised as follows. The communication standards in chapter 2. Chapter 3 is dedicated to the basic network topologies with their respective strengths and weaknesses. A thorough analysis of the street lighting system in Maceió and the most suited network topology to attend to the thousands of nodes in the network in chapter 4. Chapter 5 concludes the paper by giving a brief statement of the main points, results and introducing future lines of research.

2

Communication technologies

2.1 A general overview

This study aims to explore some of the different low-power network technologies, their respective topologies and how to effectively use them to manage many nodes in a smart city. The study seeks to answer the research question “What is the most adequate proposed topology for low costs scenarios in a smart city?”. This section gives an overview of the characteristics of these networks, how they operate, their similarities and differences.

2.2 Long distance communication technologies

With the advances in IoT (*Internet Of Things*), devices and objects of all shapes and sizes communicate with each other via the internet. These devices include not only computers, laptops and Smartphones, but also objects that have been equipped with sensors to collect, send and receive data over a network. The interaction between the objects bring about the exchange of information used to give directions and detect possible problems before they occur. Such information gives rise to the automation of certain tasks, especially when these are tedious, time-consuming, or dangerous.

There is no one-size-fits-all technology that can serve all of the projected applications and volumes for IoT. However, some technologies have proven to be more efficient in certain applications than others. For example, cellular technology is a great fit for applications that need high data throughput and have a power source, WiFi and Bluetooth (BLE) are best suited for the applications related to communicating personal devices quite well, in LPWAN (*Low Power Wide Area Network*), the battery life lasts for more than a year, and it is majorly designed for sensors and applications that need to send small amounts of data over long distances from varying environments.

There are various technologies which can be used to leverage the key resources of the applications of a smart city effectively. Such technologies include LPWAN like: LoRa (*long range*), Mesh (like Zigbee, Z-wave, Thread), or LAN (*Local Area Network*) like: Bluetooth and Wi-Fi, etc. Whose topologies include star, tree, mesh or point-to-point.

2.2.1 LPWAN technologies

Low-Power Wide-Area Network (LPWAN) is a type of wireless communication network that is designed to send small data over relatively long distances, ensuring a longer life for the batteries during the communication and application processes. It represents a revolutionary movement in the advancement of IoT technologies. Unlike cellular networks which consume a lot of power, LPWAN technology is best suited for enabling devices with low data rates. Additionally, the key performance metrics defined for LPWAN are energy efficiency, scalability, and coverage. This section briefly reviews the main features of some of these technologies like LoRa, Sigfox, NB-IoT, LTE-M2 and the like.

LoRa

LoRa, short for long range, is a low-power, low-bit rate, wireless communication network, promoted by the LoRa Alliance. It targets deployments where devices, mainly battery-powered are required to last long and have low data rates. All these attributes makes it ideal for smart sensing, for example, in smart sensing or street light monitoring. One of the major advantages it has over Sigfox is that, after getting the licence, it can be designed to work according to the application in question, without depending on third parties to setup and monitor its usage.

LoRa primarily comprises of two layers :

i The physical layer that uses a radio modulation technique known as CSS (*Chirp Spectrum Spread*), which significantly increases the communication range.

ii The MAC (*Media Access Control*) layer protocol, otherwise known as LoRaWAN, which is the chief communication protocol for LoRa. It's designed to wirelessly connect battery operated devices to the internet in regional, national or global networks, and targets key IoT requirements such as bi-directional communication, end-to-end security, mobility and localization services.

LoRa Network Architecture

A typical LoRa network is usually a star-of-stars topology, which contains all the devices in the networks. The end devices as shown in the figure below use the LoRaWAN protocol of LoRa to talk with the gateways. The gateways forward the frames containing the messages from the end devices to a cloud-based server with a high throughput. As a result, with the gateways being bi-directional relays, the server decrypts the packets sent by the devices and generates those that should be sent back to the devices, in response to the request in the messages.

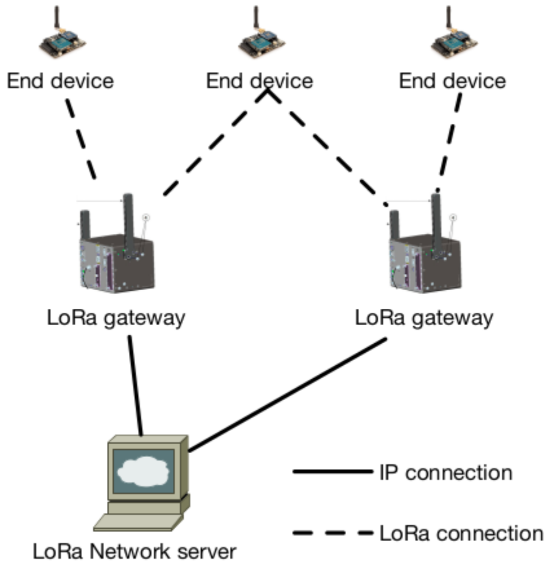

Figure 2.1: Lora network architecture. *(Santanu et al., 2013)*

The characteristics of LoRaWAN

LoRaWAN enables long range access in terms of coverage. Its low bandwidth makes it ideal for practical IoT deployments with small amount of data (for example in smart parking where you want to 'know' if a parking spot is free or not) Santanu et al. (2013). Upon getting the licence bands, its setup is easier because it involves less dependability on third parties, unlike its counterparts like Sigfox. It provides a layer of security for the network and uses the AES (*Advanced Encryption Standard*) to help curb security risks regarding IoT.

The components of a LoRa network

LoRaWAN is the communication protocol of LoRa, mainly tailored to IoT applications that require wide coverage and low power consumption when relaying messages to the internet. It serves to coordinate the nodes or devices (sensors and actuators), gateways (base stations), the network server and the application, usually developed on IoT platforms in a LoRa network. Deploying such a network could be complex or not as it largely depends on the given application.

Figure 2.2, as seen in the infographic above, a LoRa network comprises of 4 basic components and they shall be discussed hereafter.

Node (sensor) : They are the message (usually 12 bytes long) broadcasters and can either be predefined or event centric. At most, a node can send 140 messages per day, one every 10 minutes on average.Anciaux

In this network, not all nodes are of the same category, i.e there are 3 different classes of nodes.

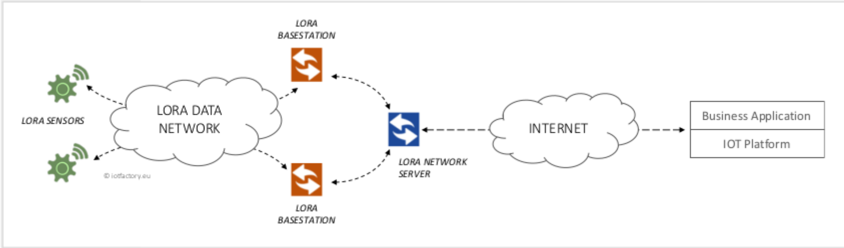

Figure 2.2: LoRa network. *(Anciaux)*

Class A:

• These nodes allow for bi-directional communication between a node and a gateway.

• Each node's uplink transmission is accompanied by 2 short downlink receive windows. The transmission or time slot scheduled for each window depends on the communication needs of the nodes.

• This category has the lowest power consumption for applications whose uplink transmission only requires a single downlink communication from the server.

Class B:

• Just like Class A, Class B nodes are bi-directional and have scheduled receive slots too.

• This class opens extra receive windows at allotted times when compared to class A. This usually happens when a time-synchronised beacon is received from the gateway alerting the server of the node's availability.

Class C:

• These nodes are bi-directional with maximal receive slots.

•The receive windows of these nodes are continuously open.

• This category's energy consumption is highest when compared to the other classes. It also supports low latency.

For LoRa nodes to be activated through the network server, it's imperative to consider the capacities of both the node and the server to better ascertain their strengths. There are two major types of acivation, which are OTAA (*Over The Air Activation*) and ABP (*Activation By Personalisation*). When using OTAA, a node is required to send its key to the network server and vice versa before a message is relayed for the first connection. While in ABP, the keys of both the node and network are predefined. Security is a primary concern in LPWAN and IoT applications. LoRaWAN uses two layers of security, which are network and application based. The network security ensures credibility of the node in the network, whereas the application layer of security ensures that access to the end-user's application data is not permissible.

Gateways (Base stations with antennas) : The messages broadcast by the nodes are received by the antennas of the gateways and relayed to the network server for analysis and interpretation. The gateways administer radio communication with nodes and are themselves governed by the network server. The gateways are connected to the server via some backhaul like 3G. One of the most crucial requirements of a LoRa-based gateway is the number of its communication channels.

Network server : this is the core of a network and coordinates all the activities of the network like the management of the gateways, the activation of nodes, data packets transmission and so on.

IoT Software Platform (The front-end or client view): the data collated from the network server is decoded, stored and accessed by the network manager. Infographic reports and histories of events are generated both for observational, precautionary and remedial purposes.

Sigfox

Sigfox is a network protocol whose communication is software-based, i.e It operates on a cloud based computing approach, where the data is managed in the cloud and not on the end devices themselves, but with a restriction on the maximum number of messages a device could send. Data transmission is done through the Ultra Narrow Band technique. This allows for devices to communicate over long distances reliably, even with interference or noise. To ensure efficiency and high quality when sending a message, the device also sends two replicas at different frequencies and time. This increases the resistance to interference by allowing the data to traverse through different paths.

Its architecture has two main layers, the Network Equipment - which receives the messages from the devices - and the Sigfox Support System - which processes the data and sends it to the user. To put it simply, imagine Sigfox as a new cellular communication network, created exclusively to transmit data between devices that need to be continuously connected.

Network Architecture Overview

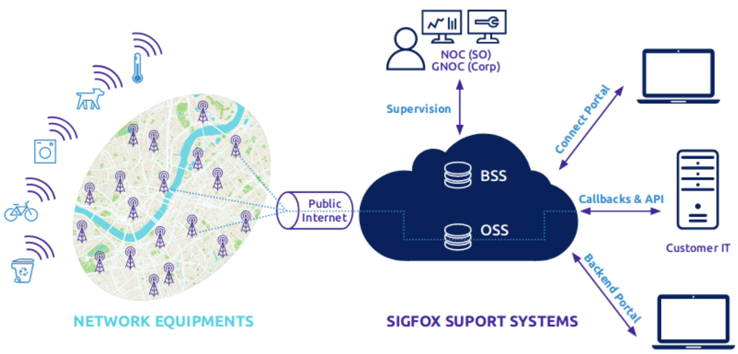

Figure 2.3: Sigfox network architecture. *[(Brasil, 2017)]*

The Sigfox network has a horizontal and narrow architecture, composed of 2 main layers: The Network Equipment layer consists of base stations responsible for receiving the messages sent by the devices and sending them to the Sigfox Support Systems layer. The Sigfox Support System layer constitutes the main network being in charge of processing the messages and sending them through callbacks to the client's system. This layer also provides the entry point for different ecosystem actors (Sigfox operators, Sigfox channels and end clients) to interact with the system through web service interfaces or APIs. It also includes modules and features that are essential to ensure deployment, operation and monitoring of the network, such as the business support system for requests and charges, and radio support to ensure the proper functioning of the network.

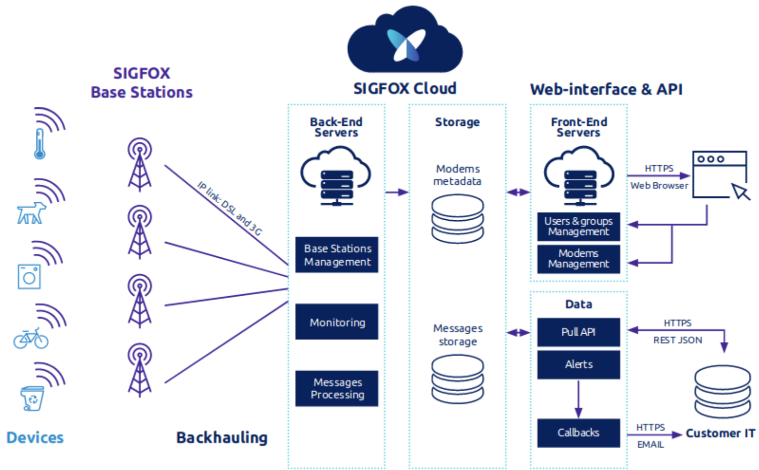

Figure 2.4: Sigfox network architecture. *(Brasil, 2017)]*

The characteristics of Sigfox

Here are some of the characteristics of Sigfox network:

i The Sigfox network has a high network capacity allowing the scale of billions of connected devices. This network owes its capacity from factors like Ultra-narrow band modulation, diversity of time, frequency and spatial diversity due to overlapping network cells.

ii The high energy efficiency allowed by Sigfox technology allows partners to produce chips that consume from less than 50mA during transmission.

iii One of the main advantages of Sigfox technology is in the large coverage possible and with a relatively small number of base stations. This advantage stems from the very good link budget of Sigfox technology. The budget link is the sum of the sensitivity of the base station, the output power of the device, and antenna gain. It indicates how much the signal can be attenuated and still have a perfect reception. In Sigfox technology the budget link is 158dB, of the same order as LTE and NB-IOT.

iv Sigfox technology owes its high resilience to interferers due to the unique capabilities it possesses and the intrinsic robustness along with spatial diversity of base stations.

v Based on its expertise and partnerships, Sigfox applied security by design principles in all stages of defining its protocol and in the development of its infrastructure.

Narrowband IoT

NarrowBand is a new cellular-based licensed technology, that was built from existing LTE (*Long-Term Evolution*) functionalities. The technology standard was introduced by 3GPP (*3rd Generation Partnership Project*), which promises to operate at a low data rate, have a wider coverage for a large number of devices, reduce costs, and cut down power consumption of user devices in applications.

In addition, NB-IoT network supports three deployment operation modes to provide flexibility based on existing cellular infrastructure :

i Acting as a standalone and dedicated carrier. In standalone operation, NB-IoT network can be used as a replacement for one or more GSM (*Global System for Mobile*) carriers. This allows the efficient re-farming of GSM infrastructure for IoT.

ii Acting in-band within the reserved PRB (*Physical Resource Block*) of a wideband LTE carrier. Here, all communication channels are shared between LTE and NB-IoT network, with the possibility of using power spectral density boosting on the NB-IoT PRB.

iii Acting as the guard-band of an existing LTE carrier. In the guard-band mode of operation, NB-IoT network utilises new resource blocks within the guard-band of an LTE carrier.

NB-IoT focuses on applications for smart transportation, logistic management, and so on. Some Telecom giants have shown interests in using NB-IoT networks to implement coverage in major cities.

LTE-M1

LTE-M (*Long-Term Evolution*) has higher data rates than NB-IoT. This allows for LTE-M to have a richer solution set, as it will offer the broadest range of cellular capabilities. And while LTE-M allows you to go up to really high data rates, that can also help you benefit from the same power budget as NB-IoT or Sigfox.

2.2.2 Mesh

These wireless technologies are highly efficient and offer low costs. Zigbee and Z-Wave will be discussed below.

Zigbee

Zigbee is a standards-based wireless technology developed to enable low-cost, low-power wireless machine-to-machine (M2M) and internet of things (IoT) networks. It is an open standard, packet based protocol used for more reliable, low power wireless networks. Their frequencies require a low data transfer rate of 250 Kb/sec across 16 different channels.

Its wireless networking is simpler to design, less expensive, highly stable and offers more secure networking. The discovery of Zigbee protocol has successfully eliminated the risk of single point signal failures. Zigbee technology provides a stable, high efficient networking using low data transfer rates when the information and communication of the devices are less.

Zigbee architecture (also known as Zigbee Stack) consists of the two main sections:

•Foundation Layers

•Application and Interface Section

Foundation Layers

This Layer is defined by IEEE 802.15.4 standard. Both Physical layer and MAC layer act as foundation layers for this technology. The physical and electrical characteristics are defined by the physical layer. Whereas, MAC layer provides interface between the physical and network layers.

Application and Interface Section

This section is defined by Zigbee Specifications and contains Network Layer and Application Layer:

The network Layer provides interface between MAC layer and the application layer. It is responsible for routing and establishing different network topologies namely star, mesh and tree topologies. Initiation of a network, assigning node addresses, configuring of new devices, providing secured transmission is the responsibility of the network layer.

The Application Layer consists of sub layers namely Application Support Sub Layer and Application Framework. Application Support Sub Layer (APS) is responsible for filtering of packets for end devices, checks for duplicity of packets which is common in a network that supports automatic retries. The Application Framework represents how end points are implemented, how data requests and data confirmation is executed for that particular vendor.

Zigbee Network Nodes

Zigbee's system structure consists of three different devices or nodes within a single network. They are:

• Coordinator

• Routers

• End Devices.

i The coordinator forms the root of a centralised network tree. It is responsible for initiating and establishing the network. The coordinator selects and manages network parameters like radio frequency, stores information about the network, etc.

ii In routing, the routers act as middlemen between the nodes, relaying data from other devices. A router can connect to an existing network, accept connections from other nodes which could also be routers and be a re-transmitter.

iii End devices are battery-powered devices or leaf nodes which communicate only through their parent nodes(either the coordinator or the routers). They collect information from sensors, but can not relay data from other nodes. End devices are categorised into two types based on their network stack. They are:

• Sleepy End Devices

• Non-Sleepy Devices

Sleepy End Devices

These devices do not have to stay awake all the time. When the device is in idle state, it turns off the radio so as to conserve resources.

Non-Sleepy Devices

These devices have to stay awake all the time , i.e they are in “ON” state even when idle. The standard Zigbee devices are of this type.

The applications of Zigbee technology include :
• Home Automation System,
• Wireless Sensor Networks,
• Smart energy, etc.

Zigbee can potentially handle more than 65,000 units in a network while maintaining signal strength and the ability to send and receive data.

Z-Wave

Z-Wave emerged from a Danish company called Zensys, and is a less expensive alternative to Zigbee. Z-Wave is a wireless protocol that essentially focus on connectivity within the smart home. As the smart home's popularity grows, more connected devices are being added to people's houses. A lot of these devices – sensors, light bulbs, heating controls, and the like – pack in Z-Wave to communicate with each other. It's poor consumption is much lower compared to Wi-Fi, but has a bigger range than Bluetooth. Z-Wave operates using low-energy radio waves to communicate from device to device.

Z-Wave's big win is that its devices are completely inter-operable. All Z-Wave devices, without exception, work with other Z-Wave devices – and that's down to the Z-Wave Alliance being owned and maintained by a private organisation.

Thread

Thread is a wireless networking protocol that uses 6LOWPAN (*IPv6 over Low-Power Wireless Personal Area Networks*), IP data transfer and runs on existing 802.15.4 silicon to support the internet of things. It was designed to improve existing standards to curb battery life, security and overall costs. It aids reliability in both device-to-device and device-to-cloud communications using real internet protocols in a wireless mesh network.

Thread networks can self-heal and reconfigure when a device is added or removed, and they are simple to setup and use. It is based on the broadly supported IEEE 802.15.4 radio standard, which is designed from the ground up for extremely low power consumption and low latency. A key enabler for the IoT is interoperability. Thread addresses this challenge by providing a certification program that validates a device's conformance to the specification as well as its interoperability against a blended network comprised of multiple certified stacks.

2.2.3 Local Area Networks (LAN)

As the name suggests, these are wireless technologies, whose coverage is shorter in comparison to LPWAN. In this section, Bluetooth and Wi-Fi will be discussed.

Bluetooth

Bluetooth is a short-range wireless technology, designed for wireless communication between devices. This communication protocol is primarily designed for low power consumption with short-range based on low-cost transmitter microchips in each device. It provides a way to connect and exchange information between devices such as cell phones, computers and digital video game consoles through a licensed and secure radio frequency. Bluetooth specifications have been developed and licensed by the Bluetooth Special Interest Group.

Over the years, Bluetooth has evolved from Bluetooth 1.0 to Bluetooth 5.1. Each of which has its distinct features and application where it is most fitted.

This study is geared towards Bluetooth 5.1, which was launched in January this year by SIG(Special Interest Group). This technology was developed for applications that only need to send little information, sporadically leaving the sleep mode only to make connections that last only milliseconds. It proffers a solution that enables the transfer of data between two devices and a location services solution in a reliable mesh network.

Network topologies

In BLE, three types of network topologies are common:

- Peer-to-Peer (P2P),
- Broadcast and
- Mesh network.

• Peer-to-Peer is a network topology used for establishing one-to-one (1:1) device communications. It optimises data transfer like audio streaming and is well suited for a wide range of wireless connected devices, such as headsets, smart watches and other accessories. For example, the interaction between your smart phone and a headset.

• Broadcast is a network topology used for establishing one-to-many (1:m) device communications. This topology is optimised for localised information sharing and is suited for location services such as indoor navigation, way-finding and asset tracking.

• Mesh is a network topology used for establishing many-to-many (m:m) device communications. It enables the creation of large-scale device networks and is ideally suited for control, monitoring, and automation systems where tens, hundreds, or thousands of devices need to reliably and securely communicate with one another.

Bluetooth 5.1

Bluetooth 5.1 takes a different approach than Bluetooth Classic, so it is not intended to replace its predecessor, but rather to offer new solutions like direction finding and expand its use. BLE is simple and has an inexpensive architecture coupled with its low power consumption and small size, which make this technology perfect for use in sensors and applications that require energy efficiency. In this way, the battery life can be extended for years, at a much lower cost.

Bluetooth 5.1 focuses on location services and direction finding, especially indoor positioning systems (IPS). The ability to detect a beacon(usually a transmitter) and how close it is to the location engine. Bluetooth location services proffers solutions to problems related to wayfinding and assets tracking in places like airports, warehouses and grocery stores. Such facilities employ the use of Bluetooth real time locating systems(RTLS) to better manage resources. These solutions fall into two categories:

• Proximity solutions

• And positioning systems.

Figure 2.5: Proximity Solution of Bluetooth 5.1. *(Bluetooth, 2019)*

i This is the simplest of the two categories and aid in detecting a Bluetooth device and determine how close it is to another Bluetooth device in a given area. This Bluetooth proximity solutions is further sub-divided into two more, which are item finding and point of interest information(POI).

   i In item finding solutions, tags (battery-powered devices) are attached to movable objects like car keys. They also include an application that enables the Bluetooth radio in smartphones to listen and estimate the distance of a specific tag. This solution help consumers in finding misplaced items like car keys, if the tags are connected to the app.

   ii In POI solution, beacons are employed to improve a visitor's experience. For instance, in museums, a visitor is given more information by the beacons. Usually, the visitor installs an application on their smartphone that enables the Bluetooth radio in their phone to listen for nearby beacons and then presents more information to the user based on the beacons it detects.

ii These positioning systems use Bluetooth to find the exact position of a device and they involve more sophisticated deployments. The two most widely known positioning systems are Real-time locating systems (RTLS) and indoor positioning systems (IPS).

   i Real time locating systems are used to track and locate the position of items, assets or people in an indoor location such as a warehouse. RTLS solutions are based on the deployments of receiver tags, also known as locators in fixed location within a facility. The receivers connect back to a centralised server(location engine). The transmitters (battery-powered tags) are attached to the objects or assets to be tracked.

   The transmitters are programmed to signals on how the real time locating estimates need to be. Each locator continuously gives feedback to the location engine about the all tags it has sensed and their receiving signal strength (RSSI). The locator engine uses this information to calculate the estimates of the position of tags using trilateration. The accuracy of these estimates is influenced by a couple of factors like the number of locators deployed.

   ii Indoor positioning systems focus on wayfinding mainly indoor, i.e helping people, such as workers in a grocery store, navigate through a building or facility.

   In this method, Bluetooth transmitter (locator beacons) are deployed in fixed locations within a facility. Then with a corresponding app installed on a smartphone that enable the radio in the phone hear locator beacons, along with their positions and RSSI. Trilateration is also used here to calculate the exact location of the beacons.

Wi-Fi

Wi-Fi is a network technology that was built with the intent of replacing Ethernet using wireless communication over unlicensed bands. WiFi is one of the most preferred network technologies to support pluggable IoT deployments, whose range is small. For example, a home security system. It transmits data at frequencies of 2.4Ghz or 5Ghz, which implies that it has the edge over cellular networks in this respect. However, because of it's large payload, it consumes a lot of power and has a low range. A trade-off between power consumption and range.

2.2.4 A Comparative analysis of communication technologies

Criterion	Lora	Sigfox	Z-Wave	Zigbee	NB-IoT	LTE	Thread	Wi-Fi	BLE
Power	Low	Low	Low	Low	Low	Low	Low	High	High
Cost	Low	Low	Low	Low	Low	High	High	High	Low
Data(bps)	Low	Low	Low	High	High	Low	High	Low	High
Range	Long	Long	Short	Short	Long	Long	Short	Short	Short
Coverage	Large	Large	Small	Small	Large	Large	Long	Small	Small
Latency	High	High	Low	Low	Low	Low	Low	Low	High

Table 2.1: A comparative analysis of the aforementioned communication technologies (Mahmoud Shuker Mahmoud, 2016)

Discussion

Table 2.1 presents interesting results obtained during the comparative analysis between the technologies in terms of power consumption, range, coverage, data sent in bits per second and latency.

Wi-Fi consumes more energy than the others and the energy consumption is more when transmitting than when receiving. However, all the aforementioned technologies consume more energy when active than in sleep mode. For this reason, keeping the modules of the technologies in sleep mode when not transmitting or receiving is recommended.

The range and coverage are longest in LoRa, Sigfox, NB-IoT and Thread. This implies that those with the longest range are more suited for Wide Area Networks (WAN) like a smart city and those with the shortest range like Bluetooth are more suited for personal area networks(PAN) like wearables.

2.3 Summary

It's imperative to be well informed about network technologies before making network designs. Being familiar with the standard network technologies gives you a better understanding of the concepts and the various components in a network. Network topologies and technologies are closely linked, and knowing about them before embarking on a networking project saves a great deal of time, effort and paves the way for better designs. LPWAN technology is best known for enabling devices with low data rates, at low costs with high energy efficiency. LAN technology is also wireless but have a shorter range compared to LPWAN.

3

Topologies

The previous chapter stated a lot of wireless communication technologies organized in three main groups: Low Power Wide Area Network, Wireless Personal Area Network and Local Area Network. This chapter focuses on describing the different network topologies available, their strengths and weaknesses.

3.1 Network Topologies

A network topology outlines the way all the devices in a network are arranged and how they communicate with each other. These devices could be network servers, switches, hubs, clients, repeaters and routers. The layout of the interconnections is:

- Physical
- Logical.

i Physical layout is the physical arrangement of all the components in a network.

ii Logical layout illustrates how data flows within a network, regardless of its physical design, i.e how the devices are logically connected.

3.1.1 Types of Network Topologies:

There are 7 basic topologies in computer networks:

- Point to Point topology
- Bus topology
- Star topology
- Ring topology
- Mesh topology
- Hybrid topology

• Tree topology

i Point to Point

This topology is the simplest and easiest both in terms of setup and maintenance. There are only two devices, which are directly connected to each other.

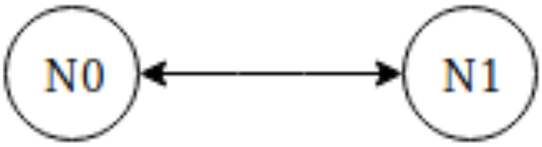

Figure 3.1: Point to Point Topology. *[(Santanu et al., 2013)]*

Advantages:

• It is fast compared to other network topologies, because it can access only two nodes and the bandwidth is shared between the two.

• Its setup and connectivity is simple, because it involves only two nodes.

Disadvantages:

• Because of the small amount of nodes, a failure in one will cause the breakdown of the entire network.

• It is not scalable, because it only has two nodes. Adding more nodes will modify the topology.

• This topology is best suited for small areas where the nodes are close to each other.

ii Bus

In this type of topology, all the nodes in the network are connected to a single bus known as the backbone or server. It is the one of the simplest ways to connect nodes in a network. All the nodes are linearly connected and thus any data sent across the bus will be visible to all the other nodes. Most times, other nodes can access the data, but only the target node, for which the data was intended can process it. For example, it is used to connect computers to a Workgroup.

Advantages:

• Easy to install, nodes are directly connected to the backbone without passing through a hub.

• Low cost because only a single backbone is required to connect all the nodes.

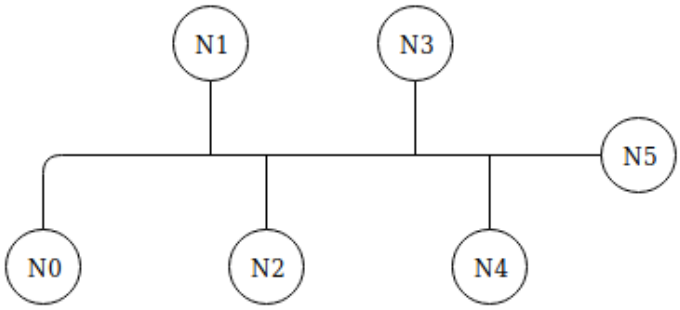

Figure 3.2: Bus Topology. *[(Santanu et al., 2013)]*

• Less cabling is required in comparison to star and mesh topologies.

• It's most suited for small networks or where the number of nodes is limited.

Disadvantages:

• Failure in the bus will affect the entire network, because all the nodes are directly connected to the cable.

• Collisions may occur between the nodes during data transmission which slows down the bus.

iii Star

In this topology, all the nodes connect to a central hub, which can be a network switch, router or server. The nodes aren't directly linked to each other. To enable communication between the nodes, the data from the sender node has to first pass through the hub, before it is relayed to its target node. For example, LoRa uses star topology, which is then used to make connections in homes and offices.

Advantages:

• Performance is fast, because each node is directly connected to the gateway and unto the network server.

• The number of cables required for connection is directly proportional to the number of nodes, thereby making its setup and troubleshooting easy.

• Failure in one node doesn't affect the entire network, i.e it only shuts down that particular port in the gateway and doesn't affect the others.

Disadvantages:

• It relies solely on the network server and failure in that renders the entire network inoperable.

• Cost is relatively high in a large network, because of the number of cables required for setup.

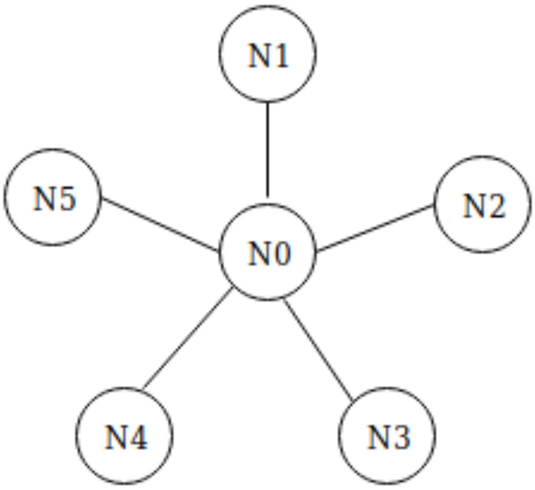

Figure 3.3: Star topology. *[(Santanu et al., 2013)]*

iv Ring

In this topology, each node is connected with the two nodes on either side of it and thus when all the nodes are connected in a similar fashion, they form a closed loop. Data flow is unidirectional i.e data flows from one node to another in one direction. In ring topology, each node has a repeater which helps in forwarding the data to its intended target within the network. For example, MAN (*Metropolitan Area Network*) use ring topology.

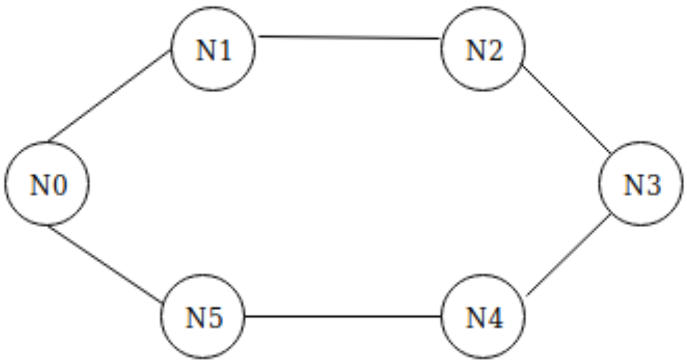

Figure 3.4: Ring Topology. *[(Santanu et al., 2013)]*

Advantages:

• It's more reliable because the entire network doesn't depend on a single network server.

• Collision is highly minimal, because data flow is in one direction.

• It is scalable, as only two links need to be modified for the addition or removal of a node.

Disadvantages:

• The failure of a link can affect the entire network as data flow is unidirectional.

• Congestion occurs due to the constant circulation of data in the network.

• The number of nodes in the network can cause delays in the communication flow, depending on the target's node path. This could lead to data flow taking too long to reach their intended node destination.

v Tree topology

In this topology, the nodes are grouped in hierarchical orders with the topmost node being the root node. Simply put, it is the combination of bus and star topologies. Typically, this hierarchy should have at least three levels. This topology is often used in wide area networks.

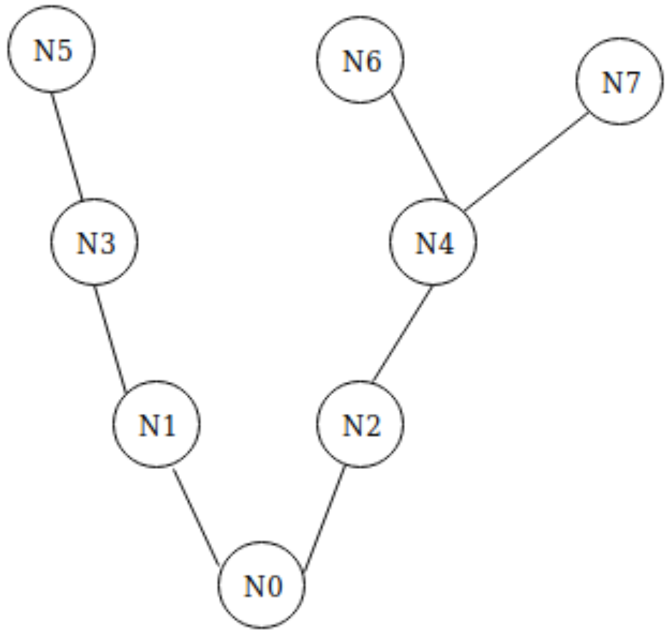

Figure 3.5: Tree Topology. *[* (Santanu et al., 2013)]

Advantages:

• The failure of a single node doesn't affect the entire network, except the root node.

• Error detection is relatively easy, because the path to which the error occurred could be traced easily, following the flux of data.

• The management and expansion of the nodes is easily achieved, because the network is divided into segments, which can be easily altered.

Disadvantages:

• It relies solely on the root node and if it fails, the entire network is rendered inoperable.

• It is expensive due to the costs of the devices needed for broadband transmissions.

vi Mesh topology

In this topology, each node is connected to every other node in the network via a dedicated link. Data is sent along the fastest route from the source to the target node, amongst the multiple routes available. Technologies such as Bluetooth use this topology. This topology is further subdivided into two others:

• Full mesh topology : in this topology, all the nodes are interconnected to one another, which implies that there's a point to point interconnection between them.

• Partial mesh topology : in this topology, not all the nodes are interconnected.

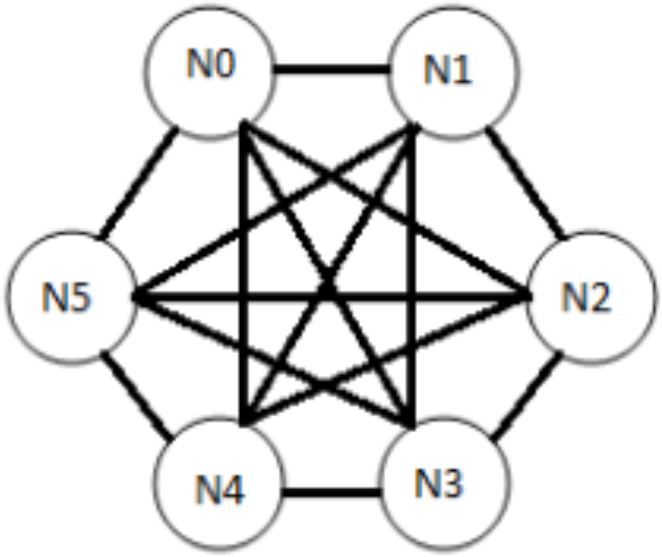

Figure 3.6: Mesh Topology. *[(Santanu et al., 2013)]*

Advantages:

• It's reliable and robust, because the failure of a link doesn't affect the network as there are multiple pathways to reach the intended node or better still data flow isn't interrupted. This also makes the network more secure.

• There are no data traffic issues, because of the dedicated links between the nodes.

• Faults are readily diagnosed.

• Reconfiguration is easily achieved with the addition or removal of a node.

Disadvantages:

• A huge amount of ports is required to connect all the nodes to one another, which makes maintenance difficult.

• It's overall cost is high due to the amount of cabling required to connect all the nodes.

• Mesh networks are usually large and can make design complex.

vii Hybrid topology

This topology occurs when two or more other network topologies are combined together in order to leverage the strengths of the constituent networks and minimise their weaknesses. This topology is specifically chosen in accordance with the requirement of the application. For example, if there is a ring topology in one office department while a bus topology in another department, connecting these two will result in a Hybrid topology MIT.

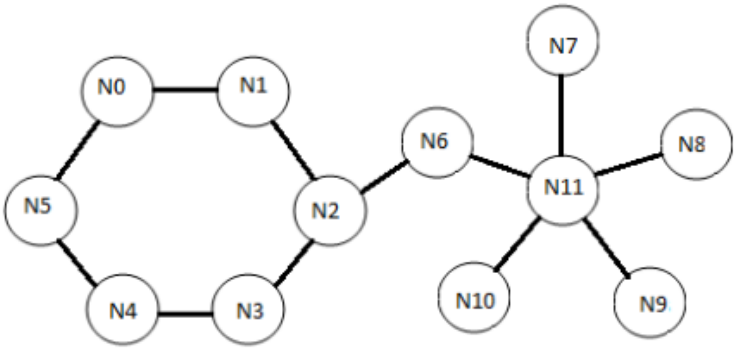

Figure 3.7: hybrid Topology. *(Santanu et al., 2013)*

Advantages:

• Expansion can be easily achieved by the addition of new nodes without affecting the existing network.

• It's reliable, because when one nodes ceases to work as intended, the whole network isn't affected

• Faults are readily diagnosed.

• Reconfiguration is easily done with the addition or removal of a node.

Disadvantages:

• Installation is difficult due to the cabling required and other highly developed network devices.

• Maintenance costs are high due to its complex design.

• Fault detection is difficult because of how large the network is.

3.1.2 A comparative analysis of topologies

Table 3.1 on page 24 outlines the comparative analysis between the different topologies reported earlier on.

Criterion	P2P	Bus	Star	Ring	Tree	Mesh	Hybrid
Installation	Easy	Easy	Easy	Difficult	Easy	Difficult	Difficult
Cost	Low	Low	High	Moderate	Low	High	High
Error detection	Easy	Hard	Hard	Hard	Easy	Easy	Easy
Reliability	Low	Moderate	High	High	Moderate	High	High
Extension	Easy	Easy	Easy	Easy	Easy	Complex	Complex
Robustness	No	No	Yes	No	No	Yes	Yes

Table 3.1: A comparative analysis of the aforementioned topologies (Mahmoud Shuker Mahmoud, 2016)

3.1.3 Which computer network topology is considered as the most secure and stable for a smart city?

There is no single network topology that ticks all the boxes for all applications. However, there are some topologies which are better suited for some applications than others. For example, LoRa uses the star topology which makes it suitable for smart city applications like smart parking, due to its good propagation, long range and low power consumption. And it's worth noting that one of the key features of the star topology is reliability due to the direct connection to the server through a dedicated gateway. When a given node or gateway fails, only the data flow of that link is disrupted, as that doesn't affect the entire network.

4

A case study of a smart street lighting system

The previous chapter introduced a plethora of network topologies and where they are best suited. This chapter focuses on describing the different alternatives to a street lighting system at the architectural layer, and the proposed topology, stating the reasons why it is a good fit in terms of quality and quantity metrics. Subsequently, the befitting communication standard or technology is also selected.

4.1 Intelligent environments

An intelligent environment is any space in our surrounding that responds intuitively to the needs of those using it. Its systems are proactive, purpose-driven and accessible, which are harnessed tandem to bring about the sustainability of the environment. A city within an intelligent environment is called an intelligent city. Furthermore, a smart city is one that uses the communication technologies available in an intelligent environment to make connections between the objects, so as to leverage the quality of urban utilities. According to McKinsey, more than 60 percent of the global population will live in cities by 2050 and 600 mega-cities are expected to generate 60% of the world's GDP by 2025 McKinsey&Company (2015).

Cities like New York and London were highlighted as the most developed smart cities in the world. The growth of these smart cities has brought an enormous improvement in the overall quality of life in those areas, for example, energy costs have been reduced through systems like smart street lighting systems, the quality of air in the environment is becoming better by the day, remote monitoring of water facilities to avoid wastage and so on. All these make the cities more liveable IESE. A lot of urban areas are seeking to embrace the movement of seamless connection of the cities around the globe.

Unfortunately, converting these cities into the envisioned utopias they've been touted as will not be easy. The steady growth of smart cities is fraught with challenges such as; the ballooning costs of smart home ownership, technology-empowered criminal behaviours (like hacking, stealing of confidential data and techno-terrorism), and the need for constant training, so as to keep up with the latest technological trends especially in IoT (*Internet Of Things*).

4.2 Lighting systems in cities

Lighting systems are used to illumine environments especially cities. There are two types of these systems: indoor and outdoor lighting systems. Indoor lighting is essentially the lighting of closed or covered areas like the home, office, and other facilities. While outdoor lighting simply means the lights used to illumine open areas outside a building, like streets, parking lot and others.

This study focuses on the outdoor lighting, particularly streetlights. The traditional street pole lamp fixtures are made of Aluminium, while the light bulbs are LED in nature. But with the surge of smart lighting in cities, these luminaires are gradually being replaced by their smart counterparts in a bid to make the street lighting systems more energy and cost efficient.

4.2.1 The traditional Street lighting system

For decades now, the traditional streetlights have been in use. But with the advent of smart cities, which brought about globalisation, smart street lighting was birthed. The traditional street lighting system comprises of luminaries, light poles, troffers, lamps, bolts and junction box. And so does its smart counterpart, with one of the major differences being the type of lamps used and how the lighting control takes place.

These traditional lighting systems work mainly on two manual operations, i.e on and off operations. This task can be simple, yet energy-consuming. According to research, these systems consume up to 60% of a city's energy consumption and it doesn't synergise with other city management systems. This system has been held onto for ages.

The advantages of traditional street lighting system

i The systems are relatively simple both in design and functionality compared to their smart counterparts;

ii The latest trends in technology don't have a direct impact on the already existing systems;

iii It helps in illuminating the city so as to prevent vehicular accidents, and pedestrians falling into sewers when it's dark;

iv It deters crimes (by vandals and thieves) particularly in the night-time;

v It makes the city more beautiful and liveable.

The limitations of traditional street lighting system

i Real time lamp failure detection is difficult;

ii It can not be integrated with other city management applications due to its limited interoperability;

iii There is a minimal number of operations, i.e off or on;

iv The street lamp control is done manually or through timed scheduler switches, thereby making time and energy consumption high.

4.2.2 The smart street lighting system and how it works

A smart street lighting system is one which is monitored and controlled remotely, and whose energy is conserved through the usage of optimised algorithms that have more than two binary functions (on, off, dimming and others). Such systems can seamlessly support connectivity with other management applications to help keep the city integrating synergistically with other city systems, and automate manpower.

The smart lighting infrastructure provides the city managers with helpful information collected from all the sensors located in fixtures spread around the city. A thorough analysis of the current necessities has been conducted to establish a basic set of functionalities essential for this project.

The benefits of a smart street lighting system

i The ability of an administrator to remotely monitor outages. This saves time and resources by eliminating the time spent on patrols by those in charge, to figure out faulty lights and in turn make repairs timely;

ii With the additional functionality of adaptive lighting as dimming, light sensors can adjust the brightness of the lamps depending on the weather and thus curb power consumption;

iii Some of street lighting systems light poles are loaded with sensors that give the city administrator a variety of features to help in dealing with public safety, for example, in case of a fire outbreak, these sensors can perceive the change and alert the administrator or even make the lights to be flashing so as to be easily recognised by the firefighters;

iv The ability to be adjoined to other city management applications like traffic control, smart parking, etc.

The limitations of a smart street lighting system

i The installation and configuration costs are higher than their traditional counterpart;

ii Maintenance is difficult because of its complexity;

iii Huge dependency on the latest technological trends due to technological obsolescence and the constant need for optimisation.

4.3 The wireless network technologies that serve outdoor applications like streetlights

The wireless network technologies that best serve streetlights are LPWAN technologies like LoRa, Sigfox or NB-IoT (cellular technologies), with LoRa and NB-IoT being the most widely used. These technologies have low power consumption, especially in sleep mode, thereby having a long battery life.

LoRa has the edge over NB-IoT, because LoRaWAN (an asynchronous protocol) has a lower power consumption compared to the synchronous protocol of NB-IoT (*NarrowBand-Internet Of Things*). The verdict is that LoRaWAN is best suited for wide area enterprises, both outdoor and indoor. The deployment costs of NB-IoT is higher, because it requires an area already covered by cellular networks (private network), compared to LoRaWAN, which is relatively cheaper because the network can either be private or public. According to LoRa Alliance, there are more LoRaWAN networks at various levels of commercial deployments than NB-IoT research for visionaries (2019).

4.3.1 Smart lighting networking options and characteristics

There are many networking solutions to be used in a street lighting system. Each of these solutions has its distinct strengths, weaknesses and where it is best applied. Amongst the technologies evaluated, two LPWAN technologies (LoRa and NB-IoT) stood out most. These two technologies compete strongly with each other. Both technologies have their ideal applications, benefits and challenges.

The coverage area of a transmitter has to be large enough to reach nodes in both sparse and dense streets, while minimising the interference caused by other nodes. The comparative analysis of the results are showed in figure 4.2, and surprisingly the table shows that LoRaWAN is better than NB-IoT for the given application. For example, in terms of capacity and bandwidth, LoRa has proven to be very capable of handling the whole luminary system. LoRa emerged as the winner because its solutions have good propagation for reaching

Technology Parameters	**LoRaWAN**	**NB-IoT**
Bandwidth	125kHz	180kHz
Coverage	165dB	164dB
Battery Life	15+ years	10+ years
Peak Current	32mA	120mA
Sleep Current	1 microA years	5microA
Throughput	50kbps	60kbps
Latency	Device class dependent	<10s
Security	AES 128 bits	3Gpp (128-256 bits)
Geolocation	Yes(TDOA)	Yes(in 3Gpp Rel 14)
Cost Efficiency(Network and Device)	Medium	High

Table 4.1: Technical aspects (research for visionaries, 2019)

indoor and outdoor locations, at a lower cost, and the ability to synergise with other applications. It also uses an unlicensed spectrum, which makes it possible for enterprises to exert complete authority over their infrastructure and devices.

4.4 Case study

Before delving into the proposed topology fully, the requirement of such a system are stated below.

4.4.1 Requirements

Before deploying the system, some requirements were laid to ensure that the system works as planned. Stated below are the details of how the system should run. Note that the system will be managed remotely by a city manager or administrator.

i There are about seventy four thousand nodes spread across the city;

ii The nodes or streetlights should be LED (*Light Emitting Diode*) in nature;

iii Each node or streetlight luminary has a sensor embedded in it. These sensors have the capacity to measure and collect variables like temperature an voltage;

iv The nodes should be able to receive commands from the network server and act accordingly;

v Messages from the nodes are forwarded to the network server or cloud through the gateways. The gateways are bi-directional in nature, i.e, they relay messages to and fro the network server;

vi The network needs to be reliable and secure;

vii Achieve a low latency of about a minute long;

viii The city manager monitors the lighting system via the application, i.e front-end. The application usually reports a graphic view of the lamps and their histories;

ix The network server manages lighting functions like adjusting the intensity of the lamps, their active hours and coordinates the entire lighting system;

x One of the ways to ensure energy efficiency is through colour rendition and visibility;

xi Light colour should be warm or neutral white, i.e the colour rendering index should be 90 and above, so as to enable further reduction of costs in order to boost economic recovery in this respect;

xii Timers are used to lessen the occurrence of collision and to evade retransmission problems;

xiii The system's design consists of 2 main components: Hardware and Software. The hardware layer consists of the physical and electrical components of the system like luminaire controller, sensors, street luminaries, drivers and so on. The software has the program which controls the entire system and how it works. An integral part of the software is the administrator's application, which is Web-based and should be accessible from any computer through standard Web browsers like Chrome, Safari, Firefox, and so on.

The existing system in Maceió didn't tick all the boxes in terms of the stated requirements. However, it works well and does a good job. Below is the rundown of how it works.

4.4.2 The existing street lighting system in Maceió, Brazil

Maceió is a small city, with a population of about 932,078, located on the eastern coast of Brazil and is approximately 1,901.6 km from Brasilia, the capital of Brazil. It's a touristic destination, widely known for its beautiful beaches and lagoons. Maceió is one of the first cities to embrace the use of a smart street lighting system in North eastern Brazil. In total, there are seventy four thousand points of light in the entire city, which are currently managed by Sima (*Superintendência Municipal de Energia e Iluminação Pública*).

Type of lamp	Quantity	Power Consumption Percentage
LED	7.743,00	10.44%
Mercury vapour	1.222,00	1.65%
Sodium vapour	55.617,00	75.00%
Metal halide	9.290,00	12.53%

Table 4.2: The types of lamps used and their respective quantities

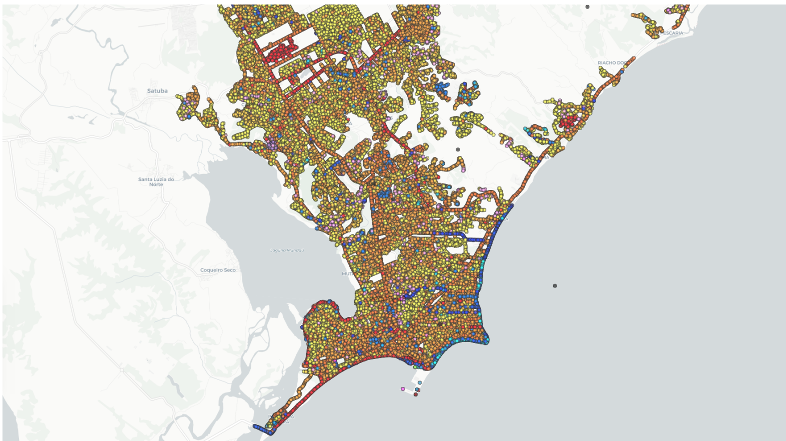

Figure 4.1: The seventy four thousand luminaries distribution in Maceió

Table 4.2 demonstrates the various types of luminaries used within the city, their quantity and energy consumption levels or percentage in the street lighting system currently in use in Maceió. Amongst all the lamps used, the LED luminary has one of the lowest power consumption level, thus making it more durable, i.e it is estimated to be have about 50,000 hours of operation. Sodium vapour luminaries are the second most commonly used in street lighting systems, with approximately 32,000 hours of operation. Metal halide has an estimate of 10,000 hours of operation and lastly mercury vapour has 12,000 hours of operation.

Existing system overview in Maceió

Over the years, one of the major concerns of embedded systems engineers and network administrators has been the need to know the most adequate communication standard and topology for a large scale network within a smart city, in order to achieve greater resilience, lower latency, cut down costs and energy consumption. In this quest, a list of options was found to be viable, but radio frequency(RF 915) was chosen as the communication standard, together with mesh topology. The deployment of the existing system was hinged on RF 915.

The street lighting project began a few years ago and till now, amongst the seventy four thousand nodes in the city, only two thousand five hundred (2500) points of light found around the Ponta Verde area. Each LED fixture installed contains a node that connects it to network gateways via a mesh topology. Communication is reliable, as messages are directly routed from one node to another, due to the interconnection between the nodes. Costs and energy consumption levels are higher in this topology, than in its counterparts like star topology. A similar system is also used in Recife, a nearby city where 3 gateways serve 600 devices.

In this system, the poles are 40 metres apart from one another, and messages are directly routed from one node to another, to the gateway and ultimately to the network server. Data transmission is distributed and as such the failure of a node doesn't affect the data flow in that region. One of the major problems encountered in this configuration is collision, because of the varied number of pathways to the gateway. This causes traffic congestion and in some cases slows down the system. Power consumption is relatively high because most of the nodes need to be awake in order to transmit messages.

The deployment of this system covered the entire city. However, amongst the LED-based luminaries in the Ponta Verde area, only 2500 are controlled remotely. The Ponta Verde beach area is a busy two-way street marking office buildings, residences and hotels on one side and retail stores on the other. The system measures some variables like temperature of the poles through the sensors embedded in the luminaries, voltage and current. This enables the adjustment of lights through adaptive control, and leverages costs in general. It's important to note that the current street lighting system of Maceió isn't entirely smart in nature, as it does the basic lighting control (On or off and dimming functions), sends failure alerts, measures the current, voltage and ambient brightness. Till date, the system has not been linked with other city management applications yet, but there are prospects for that.

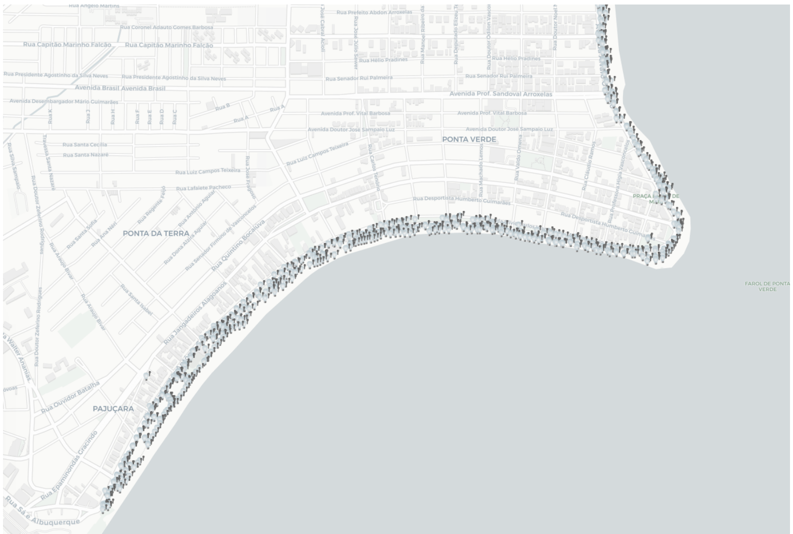

Figure 4.2: The LED-based luminaries distribution, remotely controlled in Maceió

Figure 4.2 shows the deployment area of the system in Maceió.

Using this system, the city achieved a considerable reduction in energy costs. Amongst the various types of luminaries used, the LED luminaries proffered better colour replication and also disseminate less heat. These luminaries are highly efficient and more durable.

The aforementioned street lighting system didn't satisfy all of the apparent requirements and thus did not resolve all the issues pertaining street lighting system. For this reason, a similar street lighting system is proposed, with LoRaWAN as the communication standard.

4.4.3 The proposed topology of the smart street lighting system

In order to ensure quality and optimal management, both in terms of costs and energy savings of the lighting system in Maceió, LoRaWAN was proposed. The proposal fits the bill, especially when important elements such as costs, coverage and power need to be checked. One of the fascinating features of LoRaWAN is how it attains long range of distances of transmissions (more than 10km in rural areas and more than 5 km in urban areas) with low power consumption. The proposal proffers an efficient solution that gives light when necessary with the aim of reducing the overall costs in cities.

As discussed in previous chapters, the star topology comprises of 3 different types of devices, which are end nodes (sensing devices), gateway (relays to the internet and retransmit messages to and fro the servers) and network server (which gather most of the system's intelligence) PELAYO (2018). This topology was selected according to the needs of the street lighting system. Using LoRa as a communication technology (LoRaWAN being the communication protocol), the gateways are connected to the network server through standard IP (Internet Protocol) connection and act as a transparent viaduct, converting RF (*Radio frequency*) packets to IP packets and vice versa. Jessin Mathew (2019)

In this setup, each gateway will serve all the nodes within a radius of 4km within that area, with at least two neighbouring gateways so as to act as cover-up if one of them fails. This would help to avoid a break in transmission of the gateways and will also help curb interference caused by buildings and other facilities. Overall, this aids in improving the penetration capacity of the network. Due to the varying distances between the nodes, LoRaWAN protocol to be precise, manages the data packets sent and received via the gateways daily. There will be about 450 gateways to serve the seventy four thousand nodes in the city.

Even with these interesting features, the star topology does have its drawbacks, but there are effective ways of overcoming them. Such drawbacks include the huge dependency on the network server, i.e the network largely depends on the server's capability. In the same vein, if all the nodes breakdown or the gateways, the network is equally rendered inoperable. In order to lessen the workload of the server, the use of sub-star networks could be employed, i.e the network is chunked into smaller networks, which ultimately communicates with the network server. In such a configuration, each sub-star network, transfers messages from the initiating node to the gateway unto the cloud server, and then back to the appropriate gateway and the intended destination node.

The system is based on demand and has appeared to cater for the prime needs of the street lighting system. It's noteworthy to reiterate that the star topology isn't the only suitable fit for such a system. Other topologies like mesh and hybrid will equally do a good job when deployed, but their configuration will be more complex.

Design

In some areas, the nodes aren't evenly distributed. Such tightly packed and dispersed nodes are intricate to design and configure, particularly in urban areas where there are many sources of interference. This design differs from that of the already existing system in both

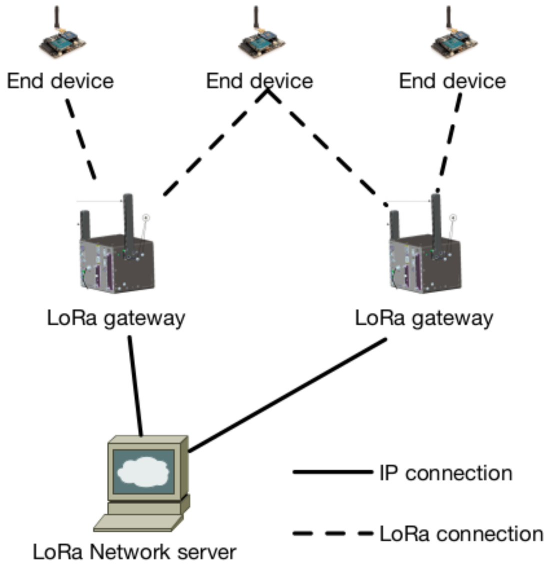

Figure 4.3: The components of a LoRa-based network. *(Santanu et al., 2013)*

the software and hardware layers, in the sense that there are additional components on both layers. The differences are stated as follows.

The hardware layer consists of physical components like more gateways, LoRaWAN modules, luminaire controller, LED luminaries, drivers and so on. The luminaire controller encompasses components like the integrated circuit, drivers,..etc. It serves to control and manage the switches and other components used to turn on and off the lights and dimming functions.

The software layer consists of the cloud (coordinates the network and shelters all the application functions, i.e from the back-end point of view) and the administrator's application, which is Web-based and is accessible from any computer through standard Web browsers like Chrome, Safari, Firefox, and so on. The application controls the entire lighting system remotely, i.e the means to alter and adjust the light intensity, dimming control schedules, turning on and off of the luminaries. The management of the streetlights is done via a graphical selection of street luminaries on a map, which outlines the histories of the luminaries and gateways in terms of the amount of energy consumed in kWh and their overall performance.

Security is a primary concern in street lighting systems and applications, especially the smart ones. LoRaWAN security uses the AES cryptographic primitive combined with several modes of operation: CMAC (*Cipher-based Message Authentication Code*) for integrity protection and CTR (*Click-through rate*) for encryption. GEMALTO and SEMTECH.

To ensure maximum security, LoRaWAN uses two layers of security, both at the network and application layers. At the network layer, security is ensured by safeguarding the authenticity of the nodes in the network, whereas at the application layer, security is ensured by not permitting access to the end-user's application data. Each LoRaWAN node is customised with an Appkey (unique 128 bit AES key) and a globally unique identifier (EUI-64-based De-

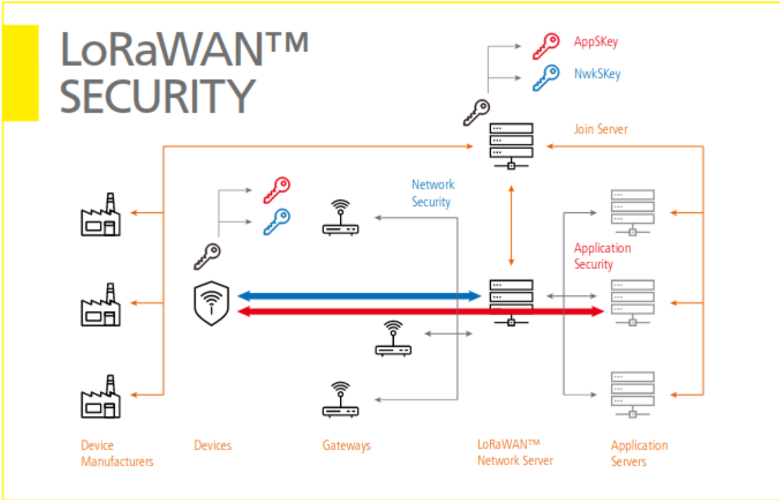

Figure 4.4: LoRaWAN security. *(GEMALTO and SEMTECH)*

vEUI), both of which are used during the node authentication process. Similarly, the network layer, the networks are identified by a 24-bit globally unique identifier assigned by the LoRa Alliance™

The cost of installing the proposed system

Costs and energy consumption have been some of the major constraints for the design and implementation of street lighting systems. Hence, the need for a more effective system, in which LoRaWAN protocol has proven to be adequate. Hitherto, LoRaWAN is fairly optimised and works well in large scale networks. However, there's always a trade-off between the communication range and power consumption. As energy consumption skyrockets globally, which in turn increase costs, specifically of lighting systems which accounts for about 35% of a city's energy bill, the need for energy savings and low costs became more apparent.

There are two options that could be employed; retrofitting or the installation of a new infrastructure. In the proposed system, the former seemed to be a better choice, because some parts of the old street lighting system could be reused, thereby cutting dowm costs. Furthermore all the luminaries need to be LED-based (which have the sensors embedded in them) as expounded in the proposed system design.

In order to test the efficacy of the proposed system, the costs involved must be lower than those of its counterparts. Infrastructural changes like the number of streetlight posts used, lamp heights and the need to contract reliable vendors. To implement this solution, chips made by Semtech or their licensees would need to be acquired. While there is a varied ecosystem of vendors, care needs to be taken when making the purchase so that all the LoRa modules will be interoperable. An example of such a vendor is American Towers.

Technologies that are suited for a street lighting system

Table 4.3 illustrates some of the network technologies that could be deployed when developing a street lighting system, their topologies and cost effectiveness.

Network technology	**Topology**	**Cost benefits**
Zigbee	Star, tree and mesh	High
Sigfox	Star	Relatively low
LoRa	Star	Low
NarrowBand Iot	Star	High

Table 4.3: The different network technologies that could be employed in a street lighting system.

Energy tariff for the proposed system

The energy tariff depends on the energy supplier and it can be offered at a fixed or variable rate. The prices are substantially based on factors like the suppliers (each supplier has its unique setting and price range), location of the user and how much energy is consumed in Kilowatts(kw). Generally, the prices for residential, commercial and industrial settings aren't the same, i.e both indoor and outdoor lighting.

With a total of 74,000 luminaries in Maceio, spread across the city. Each LED-based luminary has a brightness of 800 lumens and uses 10-30 watts. According to SIMA calculation model, each watt used by each lamp costs 0.25339 Reais. This implies that an approximate sum of 2,250103.2 reais is spent annually on streetlights. This has showed a significant reduction compared to the traditional system used which has a whooping sum of 3,000000 reais.

Furthermore, the system's design directly affects its energy consumption. In a quest to cut down costs, some measures need to be taken into consideration. Factors such as the lamp heights and lighting arrangements of the poles largely influence the monetary costs involved.

How LoRaWAN coordinates a street lighting system

The proposed LoRa-based street lighting system in Maceió has the following structure:

i The sensors in the LED lamps detect and collect variables like temperature, current, voltage and ambient brightness;

ii The lighting communication technology, which happens to be LoRa, connects the street lights to a LoRa-based gateway SEMTECH (2017). The gateway collects messages and data from all nearby sensors in the lamps;

iii Other smart city application sensors can also connect to the same gateway;

iv Messages from the gateway are forwarded to a network server where the data can be examined and processed;

v The network server or cloud is in charge of managing lighting functions like adjusting the intensity of the lamps, their active hours, detecting failures and coordinating the entire system remotely;

vi The LoRaWAN specification varies slightly from region to region based on the different regional spectrum allocations and regulatory requirements Workgroup (2015). Developing the LoRa-based gateways in Maceió is laborious, and thus caused some difficulties in the system's setup. The use of third party private networks could help limit that in a lot of ways. For instance, the LoRaWAN network made by the company American Towers would be a good option;

vii LoRa usually targets low data rates over relatively long distances so as to ensure a better communication. Its communication protocol, otherwise known as LoRaWAN is a great option due to its reliability, cost-effectiveness, vast coverage, low power and management;

viii Security is a primary concern of IoT applications. And as such, LoRaWAN ensures that both at the network and application layers, with AES encyption;

ix Affected links (nodes) can be readily identified or traced;

x Power is conserved, because the nodes aren't required to be constantly awake to receive and relay messages from other nodes, which implies that outside of transmission time, they can be in sleep mode consuming almost no power.

xi Suppose the network is a star-of-stars topology, which contains all the nodes in the network (consisting of the sub-stars). In the star topology configuration, all the nodes are connected to the network server, which is the control unit. There is no interconnection between the nodes. When a node or lamp wants to send data to another node in the network, the data has to pass through the network server first, before it's relayed to the target node. So, data packets have specific routes to go the server through the gateways. By so doing, the rate at which collisions occur are reduced;

xii Live monitoring SYSTEMS.

Figure 4.5 illustrates a typical connection of nodes within a city, i.e how the various components are interconnected and the routes messages take to get to the network server, which happens to be the cloud in the figure.

How the proposed street lighting system is managed

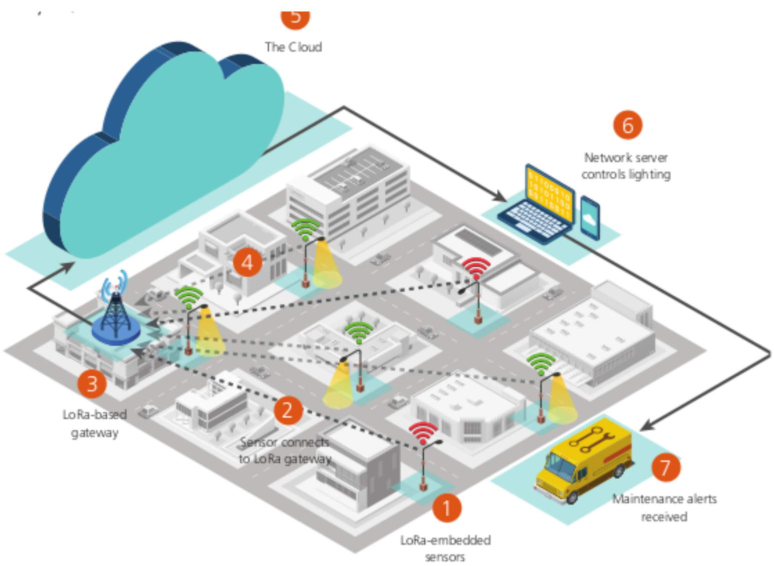

Figure 4.5: How LoRaWAN coordinates a street lighting system. *(SEMTECH, 2017)*

The system operator or city manager monitors the streetlights through the Web-based application, which consists of the server and database, linked to the work stations. There's the front-end (client's side or the Web-based user interface that the operator sees and interacts with) and the back-end (The server's side, which contains all the application processes of the system, made by the developers). From the front-end's perspective, the operator makes operations like turning on and off the lights, adjusting their luminosity levels and so on. While the back-end perspective deals with how those operations were made to function, the methods, classes, database and every other thing that goes on the server's side, and thus making the system work efficiently.

The application reports system information like lamp status, LED luminosity levels, diagnostics (in terms of failure detection of either the lamps, or gateways), and so on. It recounts the control functions that manages the data collected, the intensity or luminosity level of the street lights, the topology used, and the techniques used in collecting and processing the data. This application oversees the operational state by exhibiting a graphic view of the city maps together with their respective lighting points and their performance, making it possible to switch on and off the lamps remotely. In-depth knowledge on computer networks or embedded systems is not a requirement to be able to use the system, just having the basic training is sufficient. However, having more than the basic knowledge would be an added advantage.

Concerning control, the system operator send requests or instructions to either switch on or switch off the lighting poles as preprogrammed or in exceptional cases.

Figure 4.6 illustrates a typical case of how the system works. The points seen represent the lighting points. As clearly depicted, there are some distinct colours in the map, with each colour having a different connotation. The different colours signify the different types of

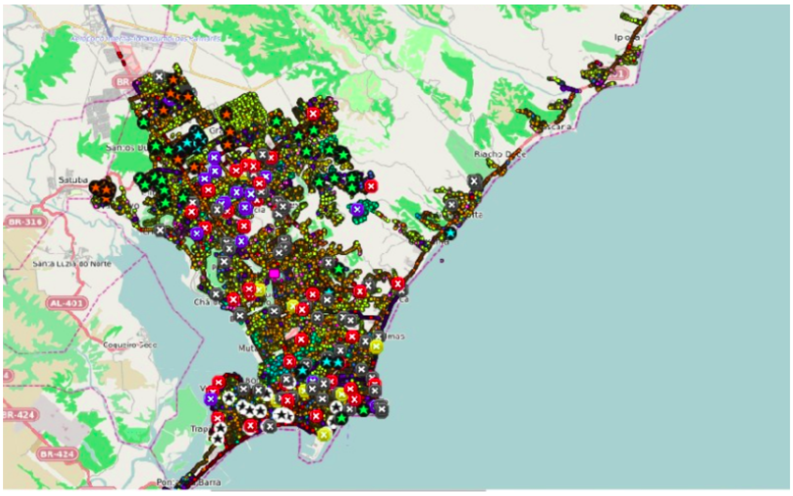

Figure 4.6: Screen obtained from Google Maps.

lamps used in the system, as mentioned in 4.2.

The difference between the existing street lighting system in Maceió and the proposed system

Table illustrates the differences between the existing system which uses radio frequency and the proposed LoRaWAN system.

Characteristics	Radio frequency	LoRaWAN
Topology	Mesh	Star
Collision rate	High	Low
Costs	High	Low
Latency	Low	Low
Energy consumption	High	Low
Reliability	High	High
Complexity of configuration	High	Low
Types of luminaries used	LED and others	LED
Application management	Locally and remotely	Remotely
Number of gateways	370	450
Penetration capacity	Low	High
Occurrence of interference	High	Low
Dependency on network server's capability	Largely	Largely
Security	High	High

Table 4.4: The difference in functionality of the existing street lighting system and the proposed system

5

Final considerations

5.1 Conclusions

This monograph originated from the need to better manage the street lighting infrastructure in Maceió, with the hope of making it entirely smart in the future. This is the first attempt towards such deployments. At the earliest stage of this implementation, a thorough research on IoT devices, the smart city ecosystem, communication technologies, topologies, and the lighting industry was carried out to ascertain its relevance. A systematic research was then carried out to discover and examine the key objectives of the current state of the field, the modifications that have been made so far, and eventual improvements.

A couple of alternatives were found in a quest to filter out the most suitable solution to the research question. A distinct category had the edge over the others, namely LPWAN with LoRa and NB-IoT been the most outstanding. Some scenarios were elaborated, with the basic set of functionalities that a typical street lighting system offers, to better evaluate the benefits, limitations and differences between the selected communication standards (LoRa and NB-IoT). A comparative analysis (both qualitative and quantitative) was made to determine the standard with the longest range, lowest costs, less power consumption, and widest coverage. LoRa emerged as the winner because it achieved the highest capacities compared to NB-IoT.

As depicted in 4.4, significant improvements were perceived in terms of costs and energy efficiencies. Factors like collision rate and interference occurrence were curbed in the proposed system. These problems still linger in the existing system in Maceio. The configuration complexity of the proposed system is lower than that of the existing system. All the luminaries are LED-based and as such more energy efficient. The application is strictly managed remotely. The increased number of gateways has improved the penetration capacity of the network and even reduced the effects of the occurrence of interference. The aforementioned factors help in boosting the city's economy. However, as always there's still room for improvement.

References

Lonel Anciaux.

K. Ashton. That internet of things thing. *RFID Journal*, 2009.

Bluetooth. Enhancing bluetooth location services with direction finding., Jan 2019. URL https://www.bluetooth.com/wp-content/uploads/2019/03/1901_Enhancing-Bluetooth-Location-Service_FINAL.pdf.

WND Brasil. Uma visão técnica da rede sigfox., Sept 2017. URL https://www.embarcados.com.br/uma-visao-tecnica-da-rede-sigfox/.

ACTILITY GEMALTO and SEMTECH.

The Guardian. What is the internet of things?, july 2016. URL https://www.theguardian.com/technology/2015/may/06/what-is-the-internet-of-things-google.

IESE.

RangitVarghese Jessin Mathew, Riya Rajan. Iot basedstreet lightmonitoring control with lora/lorawan network. *International Research Journal of Engineering and Technology(IRJET)*, 6:1175–1177, 2019.

Rafael A. Pinto Marcelo F. Silva Alexandre Campos JGustavo W. Denardin, Carlos H. Barriquello and Ricardo N. do Prado. An intelligent system for street lighting control and measurement. *Electronic Ballast Researching Group - GEDRE,IEEE*, 2009.

Ishan Ranjan Jha Ashish K., Bababe Adam B. Smart street light management system using lora technology. *International Journal of Science and Research (IJSR)*, 3:2349–2352, 2017.

Auday A. H. Mohamad Mahmoud Shuker Mahmoud. A study of efficient power consumption wireless communication techniques/modules for internet of things (iot) applicationst. *Scientific research publishing - Sci-Res*, 2016.

McKinsey&Company. The internet of things: Mapping the value beyond the hype., jun 2015.

MIT. Notes on hybrid technology. URL https://blossoms.mit.edu/sites/default/files/video/download/Notes-on-Hybrid-topology.pdf.

IGNACIO J. PASCUAL PELAYO. Smart city lighting in the city of stockholm? Technical report, Universitat Politècnica de Catalunya, May 2018. URL https://upcommons.upc.edu/bitstream/handle/2117/127194/SmartCity_PASCUAL.pdf?sequence=1&isAllowed=y.

ABI research for visionaries. Lorawan and nb-iot: Competitors or complementary? Technical report, LoRa Alliance, June 2019. URL https://lora-alliance.org/resource-hub/lorawan-and-nb-iot-competitors-or-complementary.

Pinaki Pratim Santanu, Dü Santral, and Acharjya. A study and analysis on computer network topology for data communication. *International Journal of Emerging Technology and Advanced Engineering (IJETAE)*, 3, 2013.

SEMTECH. Smart lighting., 2017. URL www.semtech.com.

AHOY SYSTEMS. Lora/lorawan - smart city streetlight. URL http://www.ahoysys.com/lora-street-light.php.

LoRa® Alliance Technical Marketing Workgroup. A technical overview of lora ® and lorawan tm. Technical report, LoRa Alliance, November 2015.