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SMART CITY LIGHTING IN THE CITY OF STOCKHOLM

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Abstract

The vision of the Smart City and Internet of Things is gradually becoming a reality. Many cities around the world have initiated a modernization process towards more intelligent and efficient management systems and Stockholm is not an exception. This work is chiefly devoted to public lighting; owing to its ubiquitous nature, it may certainly play a major role driving this transformation. It addresses the main concerns of the Traffic Office, in charge of this installation, in relation with the architecture, underlying protocols, opportunities, and available systems in the market, among others.

The lack of a unified standard as well as legal, human and security issues have initially hampered the maturing process of this new paradigm. The existence of multiple alternatives leads to the overchoice phenomenon and often discourages industries and governments to adopt IoT solutions. Therefore, an extensive survey has been conducted to analyze the suitability of different protocols with the requirements of the installation. Solutions have been classified in three main categories, and one instance of each, namely IEEE 802.15.4, NB-IoT and LoRa, have been evaluated to illustrate an example architecture and calculate capacity and cost metrics.

The demands of such deployment have been identified by agreeing on a basic set of services. As a result, two scenarios (worst-case and optimistic) have been proposed to model system's traffic. A mathematical methodology has been used to establish a soft limit on the maximum amount of devices served by a single gateway that should be considered by implementers. In case of NB-IoT, the capacity depends entirely upon the network operator, consequently the comparative is based on a third model (minimum traffic) focused on reducing the operation cost. In this way, this thesis provides the Traffic Office with an initial approach to the matter and an unbiased reference framework to decide the future development of street lighting in Stockholm.

Keywords: Smart City, lighting, capacity, IEEE 802.15.4, NB-IoT, LoRa.

Resumen

La visión de la Ciudad Inteligente y el Internet de las Cosas está cada vez más cerca de convertirse en una realidad. Una gran cantidad de municipios por todo el mundo han comenzado un proceso de modernización hacia sistemas de gestión más eficientes y eficaces y Estocolmo no es una excepción. Este trabajo está principalmente dedicado al área de la iluminación pública, puesto que su presencia ubicua la convierten en uno de los entes principales que impulsan esta transformación. Más concretamente, responde a las dudas del departamento de Tráfico de la ciudad sobre la posible infraestructura, protocolos de comunicación, oportunidades y disponibilidad de sistemas en el mercado, entre otros asuntos.

La falta de un estándar unificado junto con la aparición de diferentes cuestiones legales y problemas de seguridad ha dificultado la maduración de este nuevo paradigma de comunicaciones. De la misma manera, la existencia de múltiples alternativas en el mercado ha generado cierta reticencia del sector gubernamental e industrial debido a la indecisión provocada por el exceso de oferta. Por este motivo, se ha realizado un estudio cualitativo sobre la idoneidad de las diferentes soluciones para los requerimientos que imponen este tipo de instalaciones. Se han identificado tres principales categorías y se ha analizado el protocolo más representativo de cada una de ellas para ejemplificar la arquitectura del sistema y obtener medidas orientativas sobre su coste y capacidad.

Una vez identificados los servicios básicos que deberían proporcionarse, se han planteado dos escenarios que modelan el tráfico en la red para una situación desfavorable y otra optimista. A través de un desarrollo matemático se ha obtenido la cantidad máxima de dispositivos que pueden conectarse a un mismo Gateway para cada tecnología, con el fin de proporcionar un dato orientativo para la entidad encargada del diseño del sistema. En el caso de tecnologías celulares, la infraestructura depende por completo del operador, por lo que se ha determinado más provechoso estudiar el coste de operación con un tercer modelo orientado a la reducción del mismo. De esta forma, este trabajo provee al departamento de Tráfico de un primer acercamiento al problema y un marco de referencia para tomar con coherencia futuras decisiones sobre la modernización del servicio de alumbrado público en Estocolmo.

Palabras clave: ciudad inteligente, iluminación, IEEE 802.15.4, NB-IoT, LoRa.

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Ignacio J. Pascual Pelayo

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Abbreviations

BLE Bluetooth Low Energy

CCM Counter with CBC-MAC

CoAP Constrained Application Protocol

CSMA Carrier Sense Multiple Access

DBPSK Differential Binary Phase Shift Keying

DIY Do It Yourself

EDGE Enhanced Data For GSM Evolution

FIRE Future Internet Research and Experimentation

FTTX Fiber To The X (Home, building, curb, etc.)

GMSK Gaussian Minimum Shift Keying

GPRS General Radio Packet Service

ICMP Internet Control Message Protocol

ICT Information and Communication technologies

IEC International Electrotechnical Commission

IEEE Institute of Electrical and Electronics Engineers

IoT Internet of Things

ISA International Society of Automation

ISM Industrial, Scientific and Medical

ISO International Organization for Standardization

IT Information Technologies

LAN Local Area Network

LTE Long Term Evolution

M2M Machine To machine

MIC Message Integrity Code

MLE Mesh Link Establishment

MNO Mobile Network Operator

MQTT Message Queuing Telemetry Transport

MTC Machine Type Communication

MTU Maximum Transfer Unit

NATO North Atlantic Treat Organization

NFC Near Field Communication

OSI Open Systems Interconnection

PAN Personal Area Network

PER Packet Error Ratio

QAM Quadrature Amplitude Modulation

QoS Quality of Service

RAT Radio Access Technology

REST Representational State Transfer

RF Radio Frequency

RFID Radio Frequency Identification

RIP Routing Information Protocol

RPL Routing Protocol for Low-Power and Lossy networks

RRC Radio Resource Control

TCP Transport Control Protocol

TDMA Time Division Multiple Access

UDP User Datagram Protocol

UPC Polytechnic University of Catalonia

URI Uniform Resource Identifier

WCDMA Wideband Code Division Multiple Access

Nomenclature

DR Number of LoRa's spreading factors used

F Number of LoRa channels

$RSSI$ Received Signal Strength Indicator

SF Spreading factor

ToA Time on Air

$\mathbb{W}_i^{one}$ Probability of both frames being unsuccessful at the data rate i

$\mathbb{W}_{i,k}^{GW}$ Probability of total interfering signal from k motes being less power than the mote's signal plus the co-channel rejection at the data rate i and measured at the gateway

$\mathbb{W}_{i,k}^{Mote}$ Probability of total interfering signal from k motes being less power than the GW's signal plus the co-channel rejection at the data rate i and measured at the node

$\mathbb{W}_i^{one}$ Probability of one frame being more powerful than another at the data rate i. One will be successful, while the other needs a retransmission.

Chapter 1

Introduction

Nowadays, the expectancy of people living longer, the increased international mobility, the rural to urban migration and other factors not only have created unprecedented commercial, social and educational opportunities, but also have arisen new needs within the city and its population. In order to accommodate these current growing trends, the historical understanding of city as an entity is bound to evolve. In this context, the concept of Smart City has attained a considerable momentum in the last few years. It involves the integration of information and communication technologies in a secure and simple way to manage a city's assets and improve the life of its residents, businesses and visitors [1]. This is made possible through enhanced connectivity, publicly accessible data, cutting-edge IT platforms, sensors and other technologies.

1.1 Background

The City of Stockholm has established the ambitious objective to become the world's smartest and most connected city by 2040 [2]. This involves the conception of a society where accessibility, growth, innovation, low environmental impact and equality come naturally as the new normal. In this process, sustainability is certain to constitute a major role. Any implementation will be built upon what is currently done and must be designed in a long-term and cost-effective way in which further incremental developments and reuse pose minimal difficulties.

Smart lighting is one of the main active investigations that remain to advance towards an implementation of a Smart City. According to the European Commission, public lighting accounts for up to 60% of the total costs of a typical municipality [3]. Commonly, light schedules are governed by predefined and static on and off times and fixtures are based on either mercury vapor, high pressure sodium (HPS), or metal halide lamps, which happen to be the most common type in Stockholm. In contrast, this city has a slightly different system but still rather simple. In a centralized manner, sunlight intensity is measured and the street lights are controlled via broadcast messages propagating in a reserved frequency.

As cities become progressively smarter, these methods come to be outdated for various reasons. The irruption of LED technology and its elevated energy savings has been one of the principal driving factors. Not less important are light pollution, security, and other elements closely associated with an enhanced quality of life. All over the world, new projects have emerged and are already under development [4], [5] or [6]. Public infrastructures are continuously adapting to promote safety, increased intelligence and cost reduction, and Stockholm cannot lag behind.

1.2 Problem definition

The identification of solutions in such an heterogeneous and broad field results in a complex task comprised of many unanswered questions, uncertainties and variables. One of the principal issues is the jungle of presently available technologies and communication protocols. The majority of today's systems are proprietary solutions from individual lighting suppliers that only work within their own ecosystem and cannot communication between each other. This might result in a future lock-in situation, which is not sustainable and desirable for a large city like Stockholm.

In addition to operation, maintenance is another share of the system that is in urgent need for profound transformation. Current practices are suboptimal in regard with the use of both economic and human assets. The future street lighting system should be conceived to facilitate maintenance labors and lessen its current high costs.

Last but not least stands the energy efficiency goal. Smart Lighting should not only minimize light pollution and the waste of resources but, at the same time, dealt with subjective matters such as the perceived security level and citizen's comfortability.

1.3 Objectives

The main objective of this thesis is twofold. On the one hand, providing clear guidelines for the criteria of the future street lighting system development in regard with the choice of the underlying communication technology, the networking protocol and its conceptual architecture. On the other hand, serving as a scientific and equitable reference framework for the decision making responsible entities in the City of Stockholm oriented to maximize the benefits for the society. Recommendations will be based on an unbiased analysis of various alternatives with respect to quantitative metrics such as capacity and economic cost.

1.4 Requirements

In [2], the city of Stockholm establishes general guidelines for the common IT solution and several of its possible applications, including smart lighting. The most relevant are the following.

- New installations must be built on existing infrastructures and its design should encompass seamless interoperability, long-term perspective and ecological responsibility.
- Citizens are the center of this evolution and must be provided with the means to participate and express their opinion.
- Resources have to be equally distributed making possible for everyone to leverage new services, regardless their origin or status.
- Private business must be considered as another strong driving force of the transformation.

These areas are illustrated in Figure 1.1 and it becomes clear that sustainability stands above them as the major condition for this digitalization process.

Making this happen demands interaction with different entities and stakeholders, including telecommunication companies, various offices from the city council and some others organizations. In this way, this thesis is committed to offer a feasible and pragmatic alternative taking into account present and likely future circumstances in Stockholm.

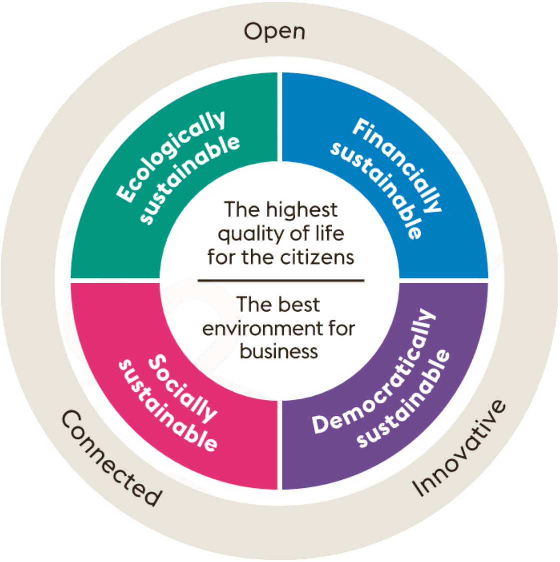

Figure 1.1: Target areas for the City's digital development.

The remainder of this work is organized as follows. The state of the art in the Smart Lighting field and the Smart City environment is investigated in chapter 2. Chapter 3 is devoted to a thorough analysis of the IoT market presenting the most relevant protocols given the above mentioned requirements. Three of them are selected to illustrate an example architecture of the system and obtain estimates on its dimension and cost. Chapter 5 concludes this thesis by summarizing key concepts and results and introducing future lines of research.

Chapter 2

State of the art

This second chapter introduces a small overview of the Smart City development and the Smart Lighting sector by describing general concepts, key points, ongoing projects and specifications.

2.1 Next Generation Internet

The Internet was originally devised in a military setting, but it did not take long until it was generally adopted by governments, the academia and, later, businesses and citizens. In the last quarter of the century, mankind has experimented a constant changing process leading to the so called digital society, which has the Internet as one of its intrinsic components. Connectivity is nowadays a quite profitable commercial activity and has opened possibilities to previously unforeseen business models. Not less important is the ceaseless evolution of human interaction with this technology and the current trends moving towards a continuous connection paradigm: interconnectedness, ease of communication and collaboration.

Numerous questions have arisen on how the Internet should be in the future and whether international organisms ought to take active part in its transformation [7]. In this sense, the European Commission has promoted the Future Internet Public Private Partnership (FI PPP) to address those questions, foster the cooperation among main European stakeholders and develop cross-domain next generation platforms suitable for different usage areas and businesses in order to improve market dynamics [1]. This organization has defined the future Internet as a socio-technical system comprising Internet-accessible information and services, coupled to the physical environment and human behavior, and supporting smart applications of societal importance [8].

Technological heterogeneity will be the supporter of infrastructures demanding a high degree of autonomy and interaction that span administrative, public and private boundaries. Institutions must count with enough preparation to successfully meet significant challenges at distinct domains in a pursuit of benefiting the whole society [9].

- **Decentralization**: determine the socioeconomic implications of holding monopolies and foster edge computing, IoT and blockchains based on open standards.
- **Privacy**: increased awareness of personal citizen's data requires new regulations to respond with transparency and easy to understand terms.
- **Multidisciplinarity**: offer easy access to open research and public data and support interoperability to enable multi-technology interconnected networks.
- **Legislation**: reform the ineffective and outdated legislative process to keep up with the technological development.

In this context, street lighting has been identified as a key sector in this modernization process and it should intelligently respond to the ever changing needs and interests of the stakeholders.

2.2 The LED revolution

Long lifespan, lack of hazardous chemicals, reduced maintenance costs and energy efficiency are among many of the Light Emitting Diodes (LEDs) benefits over traditional high pressure sodium lamps or mercury vapor lamps. These considerable advantages have led to a progressing retrofit of public and private lighting systems, known as *LEDification* [10] and illustrated in Figure 2.1. On current trends, it is expected that 9 out of 10 bulbs will be LED by 2025 [11]. Yet light pollution, defined as the inefficient and unnecessary use of light, is starting to be considered as another form of environmental pollution. Recent studies have raised concern about the uncertain adverse effects of this type of illumination on human and wildlife health [12], more precisely on the circadian rhythm and the quality of sleep. Hence the increasing importance of smart control beyond the energy dimension.

Very low onset time, quick switching times, full dimming capacity and high adaptability make LEDs perfectly suitable for Smart Lighting applications. However, in order to fully benefit from their capabilities, a telemetry layer coordinating its operation becomes essential [13]. According to a recent practical investigation in a real-life setting [14], energy savings have an average above 37 % and the potential to reach 75 % when LED, adaptive control and solar power are combined together. Still, modernization of lighting installations has become an onerous task because many operators lack smart control in their deployments or are bound to proprietary solutions. Sadly, the scarcity of studies and the absence of standards contribute to poor deployment planning and counter the above-mentioned gains.

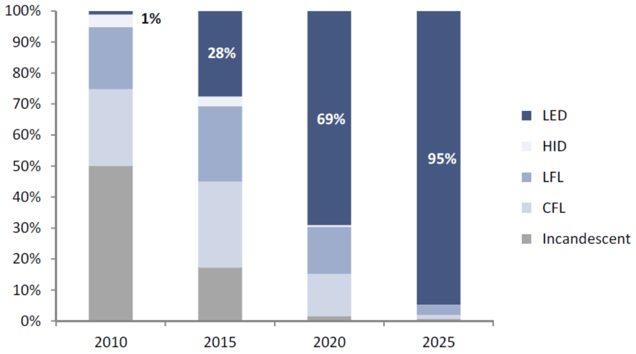

Figure 2.1: Market share by technology in the global lighting market [11], where HID stands for High Intensity Discharge, LFL for Linear Fluorescent Light and CFL for Compact Fluorescent Light.

2.3 Smart City projects

In the dawn of the next technological revolution, Smart Lighting stands out with plenty of projects materializing at an incredible fast pace. Cities such as Glasgow [15], Los Angeles [16], London [17], Amsterdam [18], Chicago [19] or Dubai [5] have already concluded pilot stages and are ready to carry out considerable sized deployments. In most cases, the responsible public entity has established a partnership with a certain group of private companies whose standalone proprietary solutions will be installed. Unfortunately, it has not been possible to find precise technical details on any of these installations.

Luckily, this author had the golden opportunity to attend the Smart City Expo World Congress that took place in Barcelona in 2017 and gain valuable insights into this sector. Among other topics such as mobility, sustainability or circular economy, intelligent lighting was ubiquitously present all around the congress. It was a perfect setting for the research as I could discover the kind of technologies private companies are using in real deployments, ask engineers for further technical details and find out about state-of-the-art implementations. Not so surprisingly, most vendors are providing radio solutions based on either 6LoWPAN, Zigbee or Wi-Fi.

For that reason, this section expands on several Smart City projects and initiatives, mostly funded by the European Commission, well documented and accessible. Even though they are not strictly devoted to Smart Lighting, they represent an excellent example and their conclusions and lessons-learned can be easily extrapolated to our field of focus.

2.3.1 SmartSantander

It is a city-scale experimental facility within FIRE initiative for the research and experimentation of IoT services and applications in the Smart City ecosystem. It was initially created to overcome the serious limitations of already deployed testbeds, have a realistic assessment of users' acceptance and enable the development of new applications [20]. More than 10 000 devices, comprised of fixed and mobile nodes, NFC, gateways and smartphones, are spread throughout the city [21] to support new innovative services for the municipality and its citizens. Some examples are environmental monitoring, outdoor parking management, parks and gardens irrigation or traffic intensity monitoring. Integration of different protocols and technologies is key to enable large-scale operation, hence SmartSantander is built as a three tier architecture to deal with this heterogeneity, see Figure 2.2.

- **IoT nodes** are the majority of devices in the testbed. They are resource constrained (memory, energy and power) and placed in harsh environmental conditions.
- **IoT Gateways** are more powerful nodes, but still based on embedded devices. Their primary functions are connecting IoT devices with the core network, sensor reading and maintenance.
- **Servers** are powerful devices directly connected to the core network and belonging to a virtual cloud infrastructure. Their main use is to host IoT data and applications.

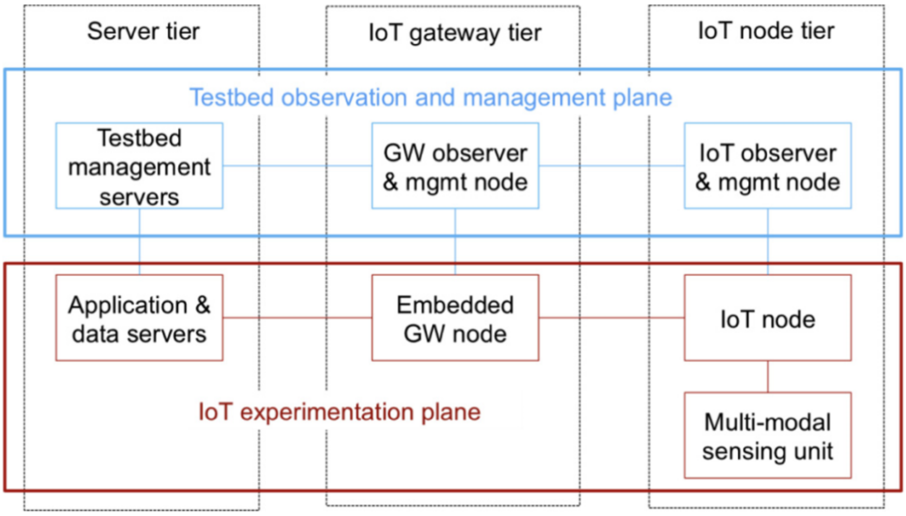

Figure 2.2: SmartSantander architecture overview [6].

Meanwhile, the necessity of minimizing human intervention as well as ensuring scalability and tractability is addressed by a horizontal logical division into two planes.

- **Observation and management** in charge of general management, plug-and-play configuration and fault detection.

- **IoT experimentation** is devoted to configure and execute experiments.

Participatory Sensing is probably one of the most disruptive features of this project, as it involves citizens' participation. In this scenario, different kinds of information are fed to the platform by means of personal portable electronic devices, e.g. GPS coordinates, compass, noise, temperature, etc. Additionally, subscription to incident reports and alarms are included in a service named *the pace of the city*, which opens up the possibility to massive collaboration between users and institutions.

Even though smart lighting control has not been implemented as a use case, multiple references will appear through the document to SmartSantander. It constitutes an excellent source of information full of valuable lessons that must be taken into account when designing any massive IoT infrastructure. Finally, it is worthy to mention that the platform envisions federation and interoperability with other experimental facilities such as the ones in Belgrade, Guildford or Lübeck.

2.3.2 Oulu Ubiquitous Smart City

It is a Smart City testbed created in the city of Oulu, northern Finland, so that researchers could establish technical and cultural readiness, identify the critical mass of users and predict the future success of different applications in a real world context [22]. Among the many challenges this large scale installation presented, covering operational and renewal expenses after the initial capital investment, measuring success by assessing its socioeconomic impact and dealing with the impatient local media and general public are the most relevant. Ultimately, the goal was to create a completely user-centric Smart City, providing personalized but non intrusive services, which would increase the interactivity with citizens.

The infrastructure is composed of interactive public displays, the panOULU network and a middle-ware layer providing resources to support different experiments. panOULU is a municipal wireless network equipped with several technologies to accomplish manifold purposes.

- **WiFi**: provides free Internet access without limitations, stores comprehensive network traces for posterior analysis and allows user location estimation through a MAC address register.
- **Bluetooth**: access points are scattered across the city center, mainly installed in traffic lights, to model pedestrian and vehicular flows and publish multimedia content to personal portable electronic devices.
- **6LoWPAN**: wireless sensor network for household energy metering and environmental monitoring.

Although a lighting control system has been neither considered in this project, Oulu is an excellent example for the integration of various radio technologies, each with an specific mission, in harmonious coexistence, which is a fundamental aspect for a complete Smart City solution.

2.3.3 Sense Smart Region

In the Västerbotten region (northern Sweden), the Sense Smart Region project was initiated with the objective of combining real and virtual information to enhance citizens experiences, municipality services and other products. A partnership between Luleå University of Technology, the municipalities of Luleå and Skellefteå and a consortium of private entities has been established to make this happen. Fortunately, it was possible to have an interview with Leig Häggmark, project manager, and Chister Åhlund, chairman and project owner, to delve into the technicalities and future lines of development.

The project has already been running for 3.5 years and is based on FIWARE, a European IoT platform that aims to establish a reference set of Future Internet enablers for the development of smart applications in multiple sectors [23]. LoRaWAN is the underlying network technology due to its long range, independence from operators and positioning capabilities. The already deployed optical fiber network was re-used for the backbone connection between distant LoRa gateways and the platform servers. So far, tests have been carried out in a controlled environment, mainly focused on scalability analysis [24], but there are plans to turn the infrastructure into an open space free for anyone to access. Regarding lighting, there is a running project to manage smartly maintenance labors in the system.

The final purpose is to create a secure and reliable platform able to adapt to the coming new technological advances and provision regional authorities with the necessary information to have a better understanding and properly address citizen's issues. Although the whole project is still in early stages, I considered relevant to highlight this paradigm shift, from the Smart City to the Smart region. This propels the collaboration between towns to seek for a common technological solution, leaving behind IoT silos.

This idea of Smart City as a federation of deployments is not new. A few examples of different initiatives are the OneLab Consortium [25], mainly oriented to research facilities, The Things Network, community using LoRaWAN solutions and FIESTA-IoT [26], which emphasizes in semantic interoperability, among others.

2.4 Technology classification

IoT is an umbrella keyword under which a collection of different technologies with unique characteristics are grouped together. Coverage is without doubt the most common metric for classification and is selected for this investigation as well. As a result, two categories with very similar acronyms emerge.

- **Low Power Wireless Personal Area Networks** (LoWPAN): is a short distance network specifically designed for peer-to-peer communications on low rate, low power and harsh environment conditions. Initially, Personal Area Networks were focused on connecting devices centered around a person's workspace, but the concept extended to include any constrained network with limited range. Examples are IEEE 802.15.4 based protocols (Zigbee, Thread, 6LoWPAN, etc.), NFC, Bluetooth or RFID.
- **Low Power Wide Area Networks** (LPWAN): is a long distance wireless network tailored to enable low rate communication with principally sensors and actuators over large geographical areas. Solutions such as LoRaWAN and Sigfox were born owing to the unsuitability of traditional cellular technologies to meet IoT stringent energy efficiency requirements and the lack of mobility support in LoWPANs [27]. Later, cellular technologies evolved and adapted to this new paradigm of communication, appearing solutions like EC-GSM, LTE-M or NB-IoT.

An in-depth comparative between the two technologies considering the different OSI layers can be found in [28]. Note than in the remainder of this thesis, there will be a distinction between ISM and LPWAN cellular technologies. The reason is to clearly differentiate solutions in which the infrastructure is owned by the final user (the former) or is owned by an operator that commercializes its use as a service (the latter).

Chapter 3

Market research

This chapter presents a comprehensive overview of the current jungle of technologies available in the Smart City context. Along with few details of several standard organizations, the most dominant features of their protocols are explained. Note that more extensive explanations are given of those solutions with either a rosy future or an important share of the market today.

3.1 Wired solutions

Wired technologies have experienced a boom in the past few years, mainly due to the exponential increase of fixed broadband service subscribers, the development of the backhaul network and the massive and rapid deployment of FTTX solutions. The economics of scale made financially viable the otherwise inexorable high fixed costs of the triple play provisioning through wired solutions, but this does not completely apply to other market segments where, in general, wireless technologies are definitely better in terms of cost-effectiveness and efficiency. Nonetheless, Stockholm stands out as a singular exception to this statement and sufficient proof will be offered in the following sections. Anyhow, the most common wired transmission media are:

- Twisted pair is the oldest, simplest and, until recent years, most common conducting medium of communication. The reason for twisting the cables is to offer a better signal quality by canceling external electromagnetic interferences.

- Optical fiber transfers information in the shape of light signals through a plastic material. The transmission is based on the total internal reflection principle.

- Power line transmission transmits data together with electrical power using the existing power lines by superposing a low energy and high frequency signal.

Attending primarily to economic matters, power line communication suitability for street lighting is superior to the other alternatives. The main reasons are its compatibility with the current infrastructure and the avoidance of costly and disturbing public constructions. Among the various protocols supporting this technology, DALI (Digital Addressable Lighting Interface) is the one prevailing in most investigations [29] [30] [10], and installations nowadays, either standalone or combined with other technologies [31]. This is an international standard described in IEC 60929 specifically tailored for lighting control. It defines a maximum system size of 64 single units and 16 groups with flexible topology; bus, star or a combination. Simplicity is one its principal features, both at the architecture and protocol level. Despite being a well accepted and spread solution, it is not a viable choice in our case, as it would go against one of the project's prime requirements: the complete independence of the communication infrastructure from the power system.

Being power line communications not further considered, twisted pair can be discarded as well. The current trend moves towards a complete replacement with optical fiber all over Europe. Although fiber for low power and low throughput networks would be far from optimal in most cases due to the prohibitive installation cost, in the peculiar circumstance of Stockholm it might pose a viable choice for street lighting. In order to fully understand this, a short summary of the recent IT history of the city is presented.

Stokab AB

Right after the deregularization of the telecommunications sector, a political consensus on the necessity of a public dark fiber infrastructure was reached in the City of Stockholm. This decision brought about the birth of the public company Stokab AB in 1994, which would be responsible for the expansion, maintenance and leasing of passive optic communications. A gradual deployment was driven at first by large public entities, but soon involved the private market, being this university, KTH, the very first customer of Stokab AB. Their singular business model is not dependent on any public subsidies, but entirely funded by customer revenues. Hence, their strategy initially focused on revenue generating businesses to finance a following residential roll out in collaboration with real state companies.

The estimation at the end of 2012 was that the service reached 90% of all Stockholm's households and nearly the totality of companies. Over 100 service providers make use today of about 1.250.000 km of fiber. Additionally, the fiber network largely facilitated the deployment of high-speed mobile networks like 3G and 4G/LTE, being Stockholm the only city in Europe with four competing LTE networks [32]. This not only promoted Stockholm to the top digital economy in 2011 [33] and top sustainable in 2016 [34], but also created a perfect environment for innovative and relevant Internet companies such as Skype or Spotify. For more details on its model and history, refer to [32].

Conclusion

Installing an optic fiber ubiquitous network is not viable for most cities due to its prohibitive costs and construction chaos. Still, it might be a plausible solution in the specific case of Stockholm thanks to its already extensive network. In a personal interview with Åke Sundin, from ST Erik Kommunikation AB, a subsidiary of Stokab AB, he advocates its viability as long as politicians reach a new consensus and the network deployment encompasses not only lighting but also other Smart City services.

3.2 Wireless solutions

3.2.1 LoRa Alliance

The LoRa Alliance [35] is a non profit industry association whose main product is the LoRaWAN specification, intended for enabling the Internet of Things at a regional, national or global level. Mainly impulsed by Microchip, Semtech and IBM, this protocol has already achieved a relative international recognition and is progressively been deployed by telecommunication operators like Orange in France, Swisscom in Switzerland or KPN in the Netherlands [36]. Not least among these initiatives are community created collaborative networks such as The Things Network [37].

Physical layer

The physical layer is proprietary and its most innovative feature. The modulation uses the chirp spread spectrum technique providing great resistance against multipath and Doppler effect even at low power conditions, and eliminating the necessity of a highly accurate clock source for synchronization. The selection of different spreading factors enables a trade off between data rate and coverage, link robustness or energy consumption. The total capacity largely depends on the frequency band and the spreading factor, but also on the payload size. More detailed information can be found in [38].

Topology

The basic architecture of a LoRaWAN network is commonly laid out in a star topology and includes three different types of devices.

- **End node**: sensing devices.
- **Gateway**: relays connected to the Internet and retransmitting messages to and fro the servers. Timing capabilities are required to schedule the downlink transmission to end nodes at the predefined transmission windows, given that the delay of the core network is unknown. Unlike cellular technologies, end devices are not tied or registered into a certain gateway, i.e. all gateways seeing a message will retransmit it and it is up to the server how to deal with this.
- **Server**: gathers most of the system's intelligence. Among its main tasks are packet decoding, response generation and gateway selection. Although there is not much open source information available regarding its actual operation, [39] shows that the protocol is extremely sensitive to channel load. Thus, an improper sever configuration can easily degrade the performance and it should be carefully taken into consideration to ensure scalability.

Device classification

In LoRaWAN, multiple communication paradigms are addressed with these three classes of devices. The table 3.1, adapted from [40] presents an overview.

- **Class A** devices offer the lowest battery consumption. Each uplink transmission, scheduled in a random basis as ALOHA, is followed by two downlink windows. Any other transmission from the server has to wait until these slots are available again.
- **Class B** devices have the capability of scheduling extra reception slots by means of a synchronization beacon coming from the gateway.

- **Class C** devices employ an almost continuous reception window and are convenient for applications in which downlink transmissions are predominant. This results in a lower latency at the cost of a greater battery consumption.

Security in LoRaWAN is also taken into consideration with several encryption layers. Nonetheless, this protocol does not ensure QoS and, thus, should not be employed for any time critical applications.

Class A	**Class B**	**Class C**
Predefined slots	Scheduled slots	Continuous window
	Low latency	Minimum latency
Unicast	Unicast and multicast	Unicast and multicast
End device initiates the communication	Extra reception slots on demand basis	End devices can receive whenever needed

Table 3.1: Classes of LoRaWAN devices.

3.2.2 Weightless

The Weightless Special Interest Group [41] is a non-profit global standard organization focusing on the development of an open standard for LPWAN, specifically designed for IoT connectivity using either license or unlicensed spectrum. Three different standards have been published so far to support a range of modalities and use cases [42].

- **Weightless-W** operates in TV white spaces, a clean part of the spectrum with extraordinary propagation conditions. Unfortunately, this band is usually subject to local regulations. Supports several modulations schemes including QAM and DBPSK.

- **Weightless-N** is an ultra narrow band system for simplex communications from end devices to the base station. This translates into significant energy efficiency at the cost of a limited flexibility. Operates in the sub-GHz ISM bands.

- **Weightless-P** offers bidirectional high performance communications with the ability to provide QoS. The use of GMSK and QPSK modulations reduce the range of operation up to around 2 km, which is still useful for private networks.

3.2.3 DASH7 Alliance

It is non profit industry corporation formed to develop the standard with the same name for wireless sensor/actuator networks over unlicensed sub-GHz bands (usually 433 MHz) [43]. The standard has its roots in the well established ISO/IEC 1800-7 and is widely used in the military sector, e.g. the US Department of Defense or NATO [44], for monitoring diverse logistic processes. Its most prominent features are the following, please check [45] for a more in depth description.

- Defines a complete network stack (OSI model) supporting multiple communication paradigms and adaptable to be used with other physical layer implementations.

- The majority of interactions between network elements are carried out using file access actions. These files or structured data elements and their properties are managed in a file system and can be modified at any time enabling a highly customizable behavior.

- Presents a query-response communication model in which the addressing is context based, allowing to group devices in different subsets according to their purpose. Moreover, the queries can be configured as event based, thus avoiding unwanted responses and reducing traffic.

- Uses a low power wake-up system to optimize energy consumption in end nodes.

3.2.4 The 3rd Generation Partnership Project

The 3GPP is a worldwide known and reputed partnership project focused on cellular telecommunication technologies [46]. Their most known and widespread specifications are WCDMA and LTE, but the organization keeps evolving and pushing towards Next Generation Networks. In this context, the new paradigm initiated by the Internet of Things has already been recognized and Release 13 specification includes a collection of features tailored to fulfill its main requirements, i.e. coverage extension, long battery lifetime and complexity reduction, while maintaining a certain degree of backwards compatibility. As a result, three new technologies called EC-GSM, LTE-M and NB-IoT have emerged.

3.2.4.1 EC-GSM

Little introduction is needed for the Global System for Mobile communications and its evolutions GPRS and EDGE. It is this last one which has been extensively commercialized and used in M2M communications due to its excellent coverage and affordable prices, although it was not originally intended for these purposes. For this reason, a new version, specifically devoted to the IoT paradigm, and denominated Extended coverage GSM IoT (EC-GSM-IoT) has been released. It is based on eGPRS and offers high capacity, long range, low energy and low complexity compared to its predecessors [47]. However, at least in Europe and north America, it is not generating as much expectation as LTE Cat M or NB IoT. Unfortunately, it was difficult to find any technology overview, real implementation or document in this regard.

3.2.4.2 LTE M

LTE (Long-Term Evolution) is a standard for wireless communication of high-speed data for mobile phones and data terminals. An increased capacity and speed is possible means of a different radio interface advances together with core network improvements. Unfortunately, its high complexity makes it unsuitable for M2M communications, hence the need of a new technology (LTE-M) which could fulfill the following objectives.

- **Long battery life** Power saving mode (PSM) was introduced to cope with constrained battery resources. A timer determines when a device is reachable (checking for paging) and when is in deep sleep mode.
- **Low cost** The evolution of mobile technologies has been focused on optimize the performance, hence increasing end nodes complexity. New device categories (Cat 0, Cat 1.4 MHz and Cat 200 kHz) have been defined to drive the necessary cost reductions.

The decrease in modem complexity can be better appreciated in Table 3.2, which summarizes the principal characteristics of the different categories and highlights the technological progress. The main and necessary simplifications were made in these areas:

- **Antennas** Radio interface was reduced to a single antenna.
- **Transport Block Size** was restricted to 1000 bits of unicast data per sub-frame, decreasing the maximum data rate to 1 Mbps in both uplink and downlink.

- **Communication system** Half duplex permits simplifications in RF switches and duplexers as well as the removal of the second phase locked loop for frequency conversion, at the cost of higher switching times between transmission and reception.

	Release 8	Release 12	Release 13	Release 13
	Cat 1	**Cat 0**	**Cat 1.4 MHz**	**Cat 200 kHz**
Downlink peak rate	10 Mbps	1 Mbps	1 Mbps	200 kbps
Uplink peak rate	5 Mbps	1 Mbps	1 Mbps	144 kbps
Number of antennas	2	1	1	1
Duplex mode	Full duplex	Half duplex	Half duplex	Half duplex
UE reception bandwidth	20 MHz	20 MHz	1.4 MHz	200 kHz
Modem complexity	80%	40%	20%	<15%

Table 3.2: Characteristics of various LTE categories [48].

3.2.4.3 NB IoT

Narrow Band Internet of Things is also a new system built from existing LTE functionalities with the same goal to extend new generation cellular networks to support a massive number of low complexity devices. Essential simplifications and optimizations were similarly carried out, but the reuse of LTE design has not only maximized backwards compatibility, but also minimized the development effort and the time to market. Evidently, complicated features such as inter-RAT mobility, handover, measurements or real-time services among others are not supported, but it still holds an advantage over other legacy or less optimized technologies.

- Improved indoor coverage of 20 dB compared to legacy GPRS [49].

- Enhanced power efficiency by means of several techniques.
  - RRC connection suspend/resume eliminates the need of establishing a new RRC connection every report instance.
  - User data transmission via control plane.

  - Extended discontinuous reception (eDRX) wakes the device during certain periods of time looking for messages without the need to set up again all the signaling.
  - Power saving mode for deep sleep operation.
- Reporting latency of 10 seconds or less.

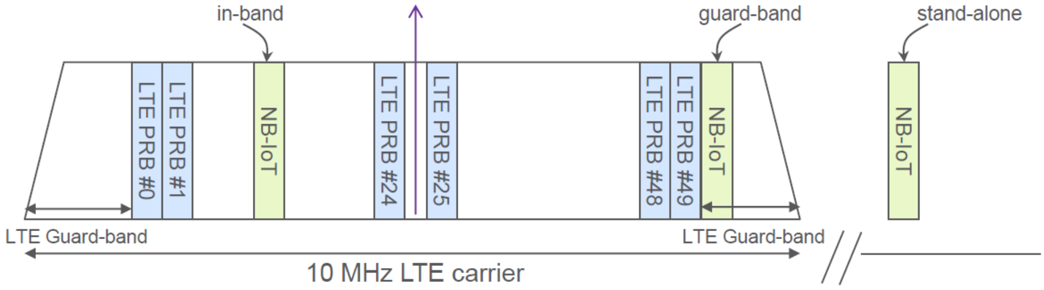

Figure 3.1: Deployment options of NB-IoT with a 10 MHz LTE carrier [50].

Deployment flexibility is possible thanks to a minimum system bandwidth of 180 kHz for both uplink and downlink, compatibility with the LTE core network, support for networks services, i.e. authentication, security, tracking and charging policy, and three different operation modes depending on the operator's existing available spectrum. It can be configured as standalone, in a dedicated carrier replacing a GSM channel (200 kHz), or inband, within the LTE spectrum allocation and either inside an existing carrier or within its guard band. This three scenarios are depicted in Figure 3.1. Especially in inband configuration, the preservation of numerology and orthogonality are essential so that performance of conventional LTE users would not be compromised. In essence, NB-IoT uses in this mode one LTE PRB in the frequency domain, i.e. twelve subcarriers of 15 kHz bandwidth over a total of 180 kHz.

This system continues evolving and Release 14 was already published by the 3GPP. It came with important enhancements in areas such as positioning, mobility or paging and included multicast support and new power classes [51].

Finally, NB-IoT and LTE M have clearly a common ground and share many characteristics, but are not competing technologies. Figure 3.2 better illustrates the distinct market target and different use cases addressed by each. Whilst NB-IoT (yellow stripes) centers on low speed and high latency, LTE-M (blue stripes) is oriented to more time critical applications, although there are of course common areas.

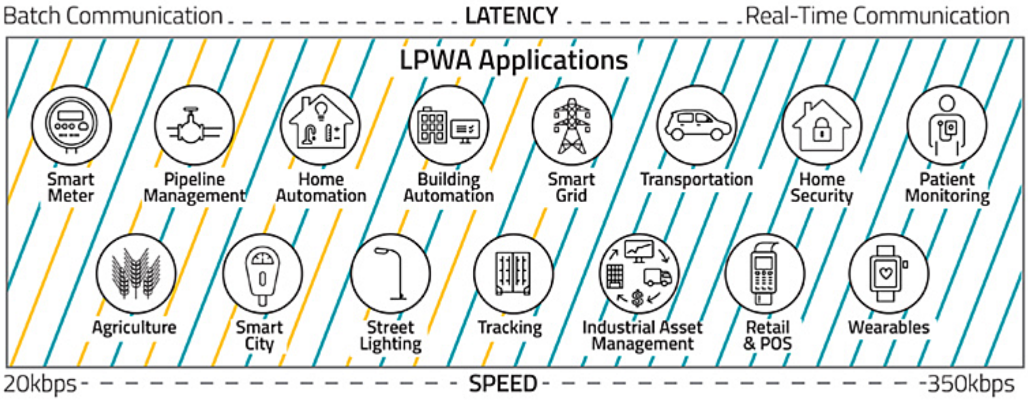

Figure 3.2: NB-IoT and LTE-M use cases [52].

3.2.5 Bluetooth

Bluetooth is a truly global, multi-vendor and interoperable standard, present in million of portable electronic devices such as tablets, smartphones, wearables, computers, etc. In mid 2017, Bluetooth SIG (Special Interest Group) released and added Bluetooth Mesh, which was incorporated to the new Bluetooth 5 specification in order to extend the support and cover different segments in the IoT market.

Bluetooth Mesh Networking is built on the foundations of Bluetooth Low Energy [53], therefore most chipsets could enjoy mesh support by means of a software update [54] [55]. Its two most attractive features is the use of a publish/subscribe model for data exchange and the restricted flooding mechanism, preventing messages from being relayed in loops. The specification provides several ways to configure the network depending on the characteristics and requirements of the specific installation. This has a considerable impact on its performance and scalability providing that there is not any centralized operation, i.e. after devices have been provisioned, no coordinator is required. For this reason, the standard defines several characteristics a node may possess according to its role within the network.

- **Relay** retransmits messages extending the maximum range.
- **Friend** stores and forwards messages addressed to an associated Low Power Node on its behalf.
- **Low Power Node** is a power-constrained node with an extremely reduced duty cycle which can operate within the mesh network efficiently thanks to the support of a Friend Node.

- **Proxy** plays a key role to enable seamless compatibility with non-mesh BLE devices by adapting and retransmitting the messages using legacy Bluetooth connectivity.

3.2.6 IEEE 802.15.4

It is a technical standard first published by the IEEE in 2003 that targets low manufacturing costs with technological simplicity. Its mission is to empower simple devices with a reliable and robust wireless technology to be run for years in standard batteries and bring the creation of RF links closer to average users.

The standard operates in the 2.4 GHz ISM band with rates up to 250 kbps and specifies low duty-cycle communication schemes that allow the device to spend most of its time in an ultra-low power conservative state. Only the two first layers of the OSI protocol stack framework are defined, i.e. physical and MAC layers. Hence, different specifications and commercial solutions completing the upper layers have emerged in the last few years. This section summarizes key aspects of the most relevant alternatives.

3.2.6.1 Zigbee

Zigbee PRO is a trademark of the Zigbee alliance, an organization composed by companies, government agencies and universities. The standard is open-source and specifies important functionalities such as ad-hoc networking or service discovery and defines the application and network layers. Precisely, Zigbee Light Link is one of these application profiles and is specifically oriented to control indoor and outdoor lighting elements such as LED fixtures, light bulbs, remotes and switches [56]. Its most relevant features are the following:

- Defines a commissioning method named Touchlink that removes the need of a coordinator. Yet it requires the target devices to be physically close to a control device called initiator.
- Network addresses have 16 bit length and are assigned by the initiator from an allocated range of possibilities. Group identifiers to encompass different number of devices are also available.
- Network level security using a 128 bit AES encryption network key. Its distribution during the initial stages is secured using the ZLL master key pre-installed in all ZLL certified devices.
- As other lighting specific protocols, includes several predefined profiles that can be applied to create ”scenes” for different situations.

3.2.6.2 ISA100 Wireless

It provides a reliable and secure wireless technology for non-critical monitoring, supervisory control, and open/close loop applications with delays in the order of 100 ms [57]. Being developed by the ISA, along with WirelessHART [58], is becoming particularly relevant in the Industrial Internet of Things (IIoT) field thanks to its robustness and the use of IPv6. In fact, its adoption rate has surpassed 67% in the past two years [59].

In contrast to all the other protocols presented in this section, MAC layer is not fully compliant with 802.15.4 standard as is implemented in a slightly different manner. Channel hopping, slot timing communications, and time synchronized TDMA/CSMA are included to reduce interference and noise. Fortunately, some of these key features have already been added to 802.15.4e amendment [60]. Among its most relevant characteristics appear: support for multiple protocols and applications (e.g. compatibility at the application layer with ModBus, HART, and many other industrial wired standards), flexibility, star and mesh topologies or larger address space [61]. Generally, ISA100.11a is more complex and expensive compared to other technologies such as Zigbee, because the loss of data can be costly for operators in the industrial ecosystem. A clear evidence yields in the network architecture, composed of various elements: Security Manager, System Manager, gateway, backbone routers and field devices.

Transport	UDP
Network	IPv6
Adaptation	6LoWPAN
MAC	MAC enhancements IEEE 802.15.4
Physical	IEEE 802.15.4

Table 3.3: ISA100.11a protocol stack.

3.2.6.3 6LoWPAN

It is a term referring to a set of standards created by the IETF to enable the efficient use of IPv6 over limited power and relaxed throughput wireless networks running in simple embedded devices. This is achieved by means of a new adaptation layer, a series of compression mechanisms and the optimization of related protocols. Internet Protocol's importance is unnecessary to highlight as it is omnipresent in our modern world, as a consequence, seamless interoperability with other IP-based systems can be a decisive factor for successful IoT installations. In this way, 6LoWPAN ensures an ideal integration through an stateless, efficient and transparent adaptation performed by edge routers. More details on the relevance of IPv6 for Iot can be consulted in the annex, please refer to section .1.

The protocol stack is shown in Table 3.4. The optimization is performed in the small adaptation layer between Network and MAC layer, which is IEEE 802.15.4 in this specific case, although others are supported as well. High compression rates are achieved relying on the premise that shared information is implicitly known by all nodes. Therefore, the hierarchical address space in IPv6 addresses can be elided most of the time by host and routers within the LoWPAN. In other words, neither hosts nor internal routers need to work with full IPv6 stack or full application protocols.

Application	CoAP
Transport	UDP
Network	IPv6/RPL
Adaptation	6LoWPAN
MAC	IEEE 802.15.4
Physical	IEEE 802.15.4

Table 3.4: 6LoWPAN Protocol Stack.

In a summarized manner, some of the key characteristics of this protocol are the following:

- UDP is principally used as a transport protocol due to its low overhead and simplicity versus the complexity of TCP.

- ICMPv6 is used for control messaging and Neighbor Discovery, which has been redesigned and optimized for unreliable networks.

- No need for address resolution, there is a direct mapping of the link layer address on to the 64-bit interface identifier of IPv6 address.

- Two categories of routing performed at different layers are defined: link-layer (*mesh-under*) and IP based (*route-over*).

- Support of different link layer technologies, mainly IEEE 802.15.4, power line communications and sub-GHz ISM bands.

- Fragmentation and reassembly capabilities to adapt IPv6 (maximum of 1280 bytes) to IEEE 802.15.4 maximum size (127 bytes).

- Uses RPL, a distance vector routing algorithm designed to run on nodes with limited energy.

The IoT paradigm often relates to autonomous devices operating in self-sufficient networks. This protocol possesses several mechanisms for the auto-configuration of some physical, link and network layer parameters (e.g. channel setting, security keys, addresses etc) and to minimize human intervention; this is also denominated *bootstrapping*. An optimized version of *Neighbor Discovery*, an IPv6 key feature in charge of basic bootstrapping and maintenance, has been defined in the standard so as to carry out certain tasks such as discovering other nodes on the same link, determine their link-layer addresses, find routers or maintain reachability information about the paths to active neighbors [62]. Finally, *Neighbor Discovery* establishes three different roles according to the device's capabilities:

- **Host** is the final node, typically sensors or actuators with limited resources.

- **Router** it can be either a better equipped final node or an additional agent specifically devoted to the role of forwarding IP packets within the scope of the 6LoWPAN.

- **Edge router** are fundamental to the network. In addition to routing the traffic, it performs the required adaptation and compression techniques to communicate with external IP networks.

A LoWPAN can be understood as a collection of nodes sharing a common IPv6 prefix (the first 64 bits of the IPv6 address). Thanks to the mesh topology and multi-hop forwarding, the network can overcome physical coverage limitations due to the harsh environment and expand without the necessity of a expensive infrastructure. Nonetheless, these networks do not act commonly as a transit to other networks but as a final destination. In this regard, three kind of low power networks have been defined in the standard:

- **Ad-hoc network** is completely isolated; not connected to Internet or other networks. Nevertheless, a simplified edge router is required in order to perform local address generation and handle Neighbor discovery.
- **Simple network** connected to another network through only one Edge Router. This is the one later studied in this work.
- **Extended network** comprises multiple Edge Routers interconnected by means of a backbone link within the same LoWPAN.

Finally, in reference to security, link-layer connections are secured by 128-bit AES encryption. However, end-to-end encryption is completely necessary at the application layer because the previously stated network limitations prevent from using the full IPsec suite or sophisticated firewalls in the nodes. This might result in vulnerabilities when the information travels beyond the edge router. Most of the material described here has been obtained from [62]. Yet slightly outdated, it is an excellent source and highly recommended for more in-depth explanations about 6LoWPAN. A detailed but summarized version can be also found in my bachelor thesis [63].

3.2.6.4 Thread

Thread is an open wireless mesh networking protocol built upon existing IEEE 802.15.4 and 6LoWPAN (IETF) standards. Its principal goal is to improve the interoperability of different vendor devices while ensuring simple and secure network installation and operation. It is designed for cost-effective and low-power communications mainly in the Smart Home environment, but similarly envisions larger scenarios [64]. It was developed by the Thread Group, a consortium of private companies including Silicon Labs, Schneider Electric, Google, ARM or Qualcomm that promotes the use of Thread and offers product certification [65], a missing point in 6LoWPAN.

The first relevant difference with 6LoWPAN relates to network architecture. In addition to those categories introduced in the previous section, Thread defines three others [66]:

- **Leader** manages a registry of routers ID and decides which REED might become router. In case of failure, another leader is elected without human intervention.
- **REEDs** (Router Eligible End Devices) can become routers subject to network conditions. Meanwhile they are final host, i.e. they cannot relay messages nor provide joining or security services to other nodes.
- **Sleepy devices** are final hosts that communicate only with their parent router and cannot relay messages.

Transport	UDP+DTLS
Network	IPv6/RIP
Adaptation	6LoWPAN
MAC	IEEE 802.15.4
Physical	IEEE 802.15.4

Table 3.5: Thread protocol Stack.

The second clear disparity is the implementation of RIP routing algorithm, a well-known distance vector protocol. However, Mesh Link Establishment specific message formats, developed by IETF, are used alternatively. Some of its core functions are to establish and configure links, detect neighboring devices, and maintain routing costs [67]. Furthermore, MLE is responsible of distributing the common configuration values shared across the network and securing that asymmetric costs are taken into consideration for the routing cost calculations.

There are other substantial discrepancies with 6LoWPAN, which for the sake of simplicity, are going to be presented along with other key features of this protocol in a shortened manner.

- DHCPv6 is used in lieu of 6LoWPAN's version of *Neighbor Discovery* for the assignment of IP addresses.
- The application layer is not defined (see Table 3.5). Instead, devices are offered a generic way to communicate and applications can be specifically designed depending on the requirements.

- Only IEEE 802.15.4 IP-based routing is supported (*route-over*).
- Network is limited to 32 active routers due to the restricted amount of routing and link-cost information fitting into IEEE 802.15.4 packets.
- Fully compatible with most of existing IEEE 802.15.4 modules with only a software update.

3.3 Qualitative analysis

This section is devoted to a thorough analysis and judgment of the protocols explained above. In accordance with the Smart City context laid out in Section 1.2, a comparison framework is established so as to tackle the topic from an unbiased and accurate position. Afterwards, a side by side comparison relating the different protocols and their characteristics is presented.

3.3.1 Framework

A rigorous comparison requires establishing an agreed set of common rules and metrics. Nevertheless, the absence of an internationally recognized convention further hinders the protocol selection process, being this figure particularly complex to collate and mostly subject to the specific details of the project. As a result, this type of analysis is often influenced by other factors such as personal inclinations and business interests. In an effort to shun these flaws, the chosen metrics described below derive from a combination of the writer's own criteria and published models, more precisely [68], [69] and [70]. Note that the order of appearance is trivial and does not correspond to its relevance.

- **Availability** of equipment in the market is of utmost importance. Large deployments demand multi-vendor support so as to avoid possible lock-in situations.
- **Scalability** Enlargement of massive infrastructures must be predictable, automatic and lack any disruption. The protocol should secure, by means of a flexible topology, that the network coverage and number of devices are easily extensible whilst latency is maintained within tolerable margins.
- **Reliability** The network implements self-healing capacity, i.e. it is capable of monitoring its components and, more importantly, recovering from failures and operate during catastrophic events.

- **Security** in IoT is currently one of the most dominant topics. Given the absence of industry standards and the potential damaging effect of cyberattacks, integrity and authentication must be built in every component of the ecosystem from the very first phase of the project; all the way down from the physical level up to the application level.
- **Cost** Business models differ depending on the provider and sort of infrastructure installed. This does not consider the cost of the deployment.
  - **Free** open standards and platforms working in ISM bands and royalty free.
  - **Pay per node** in a subscription basis. Typical of LPWAN, for instance, GSM, NB-IoT or LoRaWAN.

3.3.2 Protocol comparison

In the IoT protocol jungle, some protocols enjoy remarkable success, are generally accepted and hardware is readily available for developers. Meanwhile, others do not manage to get beyond the standardization phase and lack relevant deployments to qualify as serious alternatives. This is the case of Weightless. Notwithstanding a promising potential with three different standards and a few implementations [71], there is only one hardware provider currently in the market. This does not comply with the first point of our comparative framework and one of the fundamental requirements of this project. Therefore, Weightless can not been considered as a suitable option.

Another example of a protocol which has not maintained considerable momentum is DASH7. Unfortunately, it has not been possible to find transcendent successful commercial implementations. Nonetheless, its not-too-distant future might not be too gloomy thanks to IDLab, a joint research initiative between the University of Antwert and Ghent University. An open source stack, named OSS-7 [72], has been released so as to provide a reference implementation and foster its expansion. Currently, a few platforms are supported and practical assistance is offered to extend the supply. DASH7 could become a serious competitor, but the uncertainty makes it unsuitable for a project of this magnitude right now.

On the other hand, it is not always desirable for massive public installations that the technology has a global spread, since it might pose major security risks. For instance, Bluetooth, present in million of personal devices, might not be the best choice inasmuch as street lights should not be neither visible nor configurable from a citizen's portable electronic device. Bluetooth Mesh is a great step forward in IoT but mainly conceived for home automation and with serious limitations to extend beyond this area. Moreover, interoperability might not be as smooth as advertised due to the need of an adaptation hub to connect with legacy devices. This makes the network not purely coordinatorless and might result in additional scalability issues. Lastly, earlier this year, several security flaws were found in the core protocol [73], chiefly affecting the data privacy and integrity.

Zigbee is already firmly established as an IoT protocol adequate for the Smart City ecosystem. Easily, abundant academic resources can be found on its applicability [74], [75], [76] and [77]. Meanwhile, Zigbee Light Link has been endorsed by several manufacturers in the lighting industry [56] and ensures an effortless interoperability with other Zigbee products. Unfortunately, it is mainly targeted to final consumers and small scale installations [78] in the home automation area. In fact, it has been impossible to find any reference to a massive deployment using ZLL. Conversely, Zigbee PRO can be a feasible solution, but it will require a proper network planning and it does not support IP. To overcome this, Zigbee IP, based on 6LoWPAN, was introduced [79], but at the cost of losing interoperability with other Zigbee technologies, let alone other protocols. Another minor drawback of Zigbee is the intellectual property and certification cost, inherent to the integrated circuit production.

Having all sensors and actuators running the latest version of IP protocol and being able to integrate seamlessly with existing networks supposes a tremendous advantage to get past the era of IoT islands. The IP domain is rapidly expanding out of the LAN boundaries and into new market sectors. There are different solutions enabling this; those based in IEEE 802.15.4 (6LoWPAN and Thread) and ISA100.

ISA100.11a is characterized by its high resilience against interference (e.g. machinery noise), elevated implementation costs, enormous flexibility, structural complexity and perfect fitting for process automation. Another decisive element is the use of a series of pre-programmed hopping patterns that allow coexistence with IEEE 802.11. In spite of its industrial orientation, this protocol might be a strong contender to be carefully considered for the whole Smart City ecosystem, specially, if Smart Lighting is deployed along with other services that demand support of more reliable and deterministic transmissions. Otherwise, the possibilities offered by ISA100.11a outstrips the real needs for a lighting system, being preferred simpler and more economic alternatives.

Thread has lately gained considerable momentum thanks to the support of industry leaders as Google or Samsung. It was born to overcome the divergence of 6LoWPAN installations, offer certified IoT products and simplify network configuration in the home automation area. Despite being an open standard now, it has raised some concerns and is currently treated with little skepticism [80]. Until the public release of the OpenThread project [81], the standard specifications were only accessible to members of the alliance requiring a costly subscription. Besides, the fact that the network supports a limited amount of active routers might complicate its scalability in extensive deployments. Finally, its novelty involves risks as well; it is still not well proven, its applications are not concretely defined and critical bugs are present in the OpenThread project [82].

6LoWPAN is the standard on which other protocols are based to enable IP over low power and lossy networks. Different solutions, such as the ones presented above, have emerged to optimize its operation to a concrete field of application and address some concerning issues, for instance, security threats (e.g. [83]). Nonetheless, a correct implementation of 6LoWPAN itself permits a considerable degree of customization, a key factor for future improvements and the inclusion of other services not yet envisioned. Another argument in favor of 6LoWPAN is being successfully tested in real massive implementations such as SmartSantander (Section 2.3.1) and in Smart Lighting applications (see [84] and [85]). In fact, during my visit to the Smart City Expo World Congress 2017, 6LoWPAN was constantly recurred in round-table discussions and the majority of vendor stands, some of which showcased their medium scale installations throughout Europe, mainly in villages and small towns, employing this standard. All of this makes 6LoWPAN a highly recommended option for a future deployment.

The mobile industry has supported the standardization of different LPWAN technologies, understanding that there is no single solution ideally suited to all the different potential massive IoT applications [68]. In this way, GSM (or EC-GSM) and NB-IoT can complement each other subject to the specific requirements of the project. In case of Smart Lighting, GSM has been used in different configurations [86], mainly in the back-haul connection [87], but it largely depends on the system architecture. Despite of the higher power consumption, the more complex modems and the longer synchronization delays, it is a well established and proven standard with an extensive international coverage. Meanwhile, NB-IoT is specifically tailored for ultra-low end IoT devices, i.e. dealing with extreme coverage conditions (e.g. underground sensors) or minimum bit rates. Scalability is guaranteed as each 200 kHz carrier can support up to 200.000 subscribers and offers different methods to increment this amount. Even though there is limited coverage at the moment, telecommunication operators are investing heavily in the network deployment and it will probably be the preferred solution for urban areas in the near future (along with LTE-M). A limiting factor might be the fact that the network belongs to the operator and, most commonly, it provides its own management platform. Lastly, the cost is determined on a subscription basis by the system size, and it is probably its major downside, given the magnitude of the public lighting installation.

In contrast with NB-IoT, LoRaWAN is a mature ecosystem with plenty of available components in the market. Its applicability to Smart Lighting has already been validated [88] and is possible thanks to the simple network configuration and excellent coverage, which could provide service to the whole Belgium with only seven gateways [89]. However, the advertised performance has been achieved in isolated networks and is being questioned especially after some investigations [90] and unsuccessful experiences. For small scale installations, the performance is limited by the duty cycle constraint typical of ISM bands, while in large deployments, the lack of coordination between gateways hampers scalability owing to the increased amount of collisions. Many operators are offering LoRa solutions on a yearly subscription basis. Yet LoRa is in a clear disadvantage against cellular networks in this area, which can offer QoS, as a result of the completely unplanned deployment of different interfering technologies in ISM bands.

One might wonder why a so renowned and widely accepted protocol such as Sigfox has not yet been introduced in this thesis. There are diverse reasons, but principally it has to do with the project requirements (Section 1.4).

- Sigfox is a proprietary technology offering complete IoT network solutions which can only be operated with its own cloud and management tools.
- The support of bidirectional communications is not entirely clear due to the lack of an open standard. Different sources are giving opposite facts in this regard (see [71], [91] and [92]).
- Even though radio interfaces are produced by multiple manufacturers at a relatively inexpensive price, Sigfox has already established partnerships with different operators granting exclusive rights over an area. This makes impossible to deploy private networks and creates dependency on a single entity for providing service.

- Its business model is based on a pay-per-node and subscription basis. Yet, it is the cloud infrastructure what increments the cost significantly.

The qualitative examination carried out in this section demonstrates the absence of a perfect match for, generally, any IoT project. There will be always a trade-off between cost, flexibility and complexity, and it is up to the implementer to choose among the most suitable. To conclude this section, a side by side technical comparison between the most relevant characteristics of the protocols is shown in a summarized way in Table 3.6. Additionally, another table relates technologies based on IEEE 802.15.4, i.e. Zigbee, Thread and 6LoWPAN, to highlight its differences in other qualitative dimensions.

	Frequency	**Latency**	**Topology**	**Max Output Power**	**Range**	**Security**	**Cost**
Bluetooth Mesh	2.4 GHz	6 ms	mesh	3 mW	100 m	AES 128 CCM	Low
DASH7	433/868 MHz	>15 ms	tree, star, mesh	1 mW	0-5 km	AES 128 EAX	Low
ISA 100.11a	2.4 GHz	1 s	star, mesh	1 mW	100 m	AES 128	High
GSM	900/1800 MHz	1 s	star	2 W	<35 km		Medium
NB-IoT	800 Mhz	>10 s	star	0.2 W	10-15 km		Medium
Sigfox	868 MHz	>45 s	star	25 mW	3-10 km	AES 128 HMAC	Medium
LoRaWAN	433/868 MHz	2 s	star	25 mW	2-5 km	128 AES ECB	Low
IEEE 802.15.4	2.4 GHz		star, mesh	100 mW		AES 128	Low

Table 3.6: Comparison between the different IoT technologies available.

	ZLL	Zigbee Pro	6LoWPAN	Thread
Smart City	✗	✓	✓	✗
Smart Home	✓	✓	✓	✓
Lighting Specific	✓	✗	✗	✗
Certification	✓	✓	✗	✓

Table 3.7: Qualitative comparison of IEEE 802.15.4 based protocols.

Chapter 4

Architecture

The previous chapter introduced a plethora of wireless protocols organized in three main groups: Low Power Wide Area Network, Wireless Personal Area Network and cellular systems. This chapter focuses on describing different alternatives at the architectural level and sets out initial estimates for a future deployment. Firstly, a set of services related to Smart Lighting are proposed to construct a hypothesis of the network necessities. Then, a representative protocol from each group has been selected, network dimensioning calculations have been carried out and an illustrative architecture example is laid out.

4.1 Requirements

The Smart Lighting infrastructure provides authorities with useful information aggregated from different types of sensors situated in fixtures spread around the city. An in-depth analysis of the actual necessities counting with the council's supervision has been conducted to identify a basic set of services essential for this project. Additionally, technical aspects in regard with periodicity, estimated payload and the need of acknowledgments for each service are described in Table 4.1.

Dense networks are highly intricate to model, specially in popular ISM bands and urban scenarios where there are many sources of interference (see Appendix .2). For this reason, the following assumptions have been made to reduce the complexity, bearing in mind that these might result in an overestimate of the network load and a tight upper bound of its maximum dimension.

- Timers are initialized randomly so as to avoid constant collisions and retransmission problems.

- The transmitted data is a result of directly mapping the sensor's output into the MAC layer payload. Overhead from application layer protocols has not been examined. The values shown in Table 4.1 have been obtained from the data sheets of commercially available sensors, refer to Annex .3 for more information.

- Data aggregation from different sources is not contemplated.

- Traffic intensity sensors are present in approximately 10% of the installed luminaries. This figure proceeds from analyzing the amount of fixtures per cabinet, their position within a regular street, and reasoning with a similar criteria as in [93].

- Aperiodic events such as on demand dimming or alarm triggered (crash detection and cabinet opening) will not be investigated in this section as they are not relevant for this capacity analysis. Nonetheless, it is known that these kind of messages should use acknowledgments owing to its sporadic nature.

Name	Messages	Period (hours)	Payload (bytes)	ACK
On/Off	2	24	1	Yes
Status	1	1	2	Yes
Light intensity	1	1	3	Yes
Traffic intensity	4	0,02	8	No
Temperature	1	1	5	No
Power metering	1	1	2	No
Dimming	-	-	1	Yes
Crash detector	-	-	1	Yes
Cabinet opened	-	-	1	Yes

Table 4.1: Hypothesis on the data demands of the installation.

The following sections expand on the network dimensioning for three different technologies, more precisely IEEE 802.15.4, LoRa and NB-IoT (although this latter one will slightly differ). For this analysis, two distinct traffic models have been built to observe the performance under different situations and obtain realistic capacity boundaries.

- **Worst-case**: devices send a single type of measurement per packet resulting in an average of 28 packets per hour with a maximum MAC payload of 8 bytes. Fixtures accommodate all sensors mentioned in Table 4.1, with the exception of traffic intensity meters, which are distributed as mentioned above.

- **Optimistic**: devices might aggregate information from different sensors into the same packet. Not all fixtures necessarily contain the complete set of sensors; temperature, light and traffic intensity are distributed according to the deployment plan specifics. Consequently, a common fixture sends only one message per hour, while fixtures with traffic intensity meters transmit 15 messages per hour in IEEE 802.15.4 and twice as many in LoRa due to packet size dependency on the spreading factor. In average, this results approximately in 3 and 4 messages respectively per hour and device with maximum payload, where all transmissions are acknowledged. Anyways, figures for the unacknowledged case are included as well for the sake of completeness.

Note that these are mean values obtained from combining the packet generation rate from devices with and without traffic sensors given its density. The intention is to provide a general idea rather than closed definite boundaries.

4.2 IEEE 802.15.4

Present in many IoT deployments in the shape of its multiple variants, IEEE 802.15.4 is a well established technology whose maximum performance has already been extensively characterized. The network under investigation is configured in tree topology (Figure 4.1), uses the beaconless operation mode with CSMA/CA access technique and comprises a single PAN coordinator serving an unknown number of devices with the characteristics mentioned in Section 4.1. In addition to sensing, devices may perform routing tasks.

Research in this field includes mathematical methodologies such as [94], which examines the worst case scenario for a cluster tree topology by means of the Network Calculus theory applied in deterministic queuing systems, and more experimental procedures, for instance [95], which employs several metrics to characterize the simulator. The analysis presented in this thesis could be reckoned as a halfway approach combining their most relevant aspects and being principally based on [96].

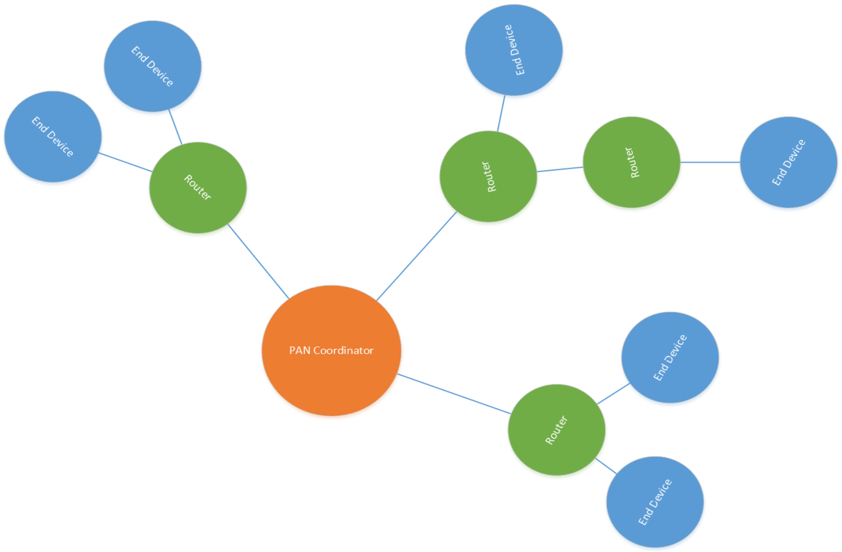

Figure 4.1: Cluster tree topology.

Initially, performance has been evaluated as a function of the payload and ACK presence for single-hop transmission. In multihop networks, this maximum is shared among nodes situated within an interfering distance from the transmitter (regarded as R_{INT}) as illustrated in Figure 4.2. This quantity is defined by the parameter ω, so as to maintain consistency with [97], and modifies the total throughput in the following manner.

$$Throughput = \frac{n * 8}{\omega * T_{tx}} \tag{4.1}$$

where n denotes the payload size in bytes and T_{tx} the time duration of a single hop packet transmission. For the sake of simplicity, it is assumed that there is a minimum back-off exponent for the CSMA/CA algorithm, i.e. $T_{rand} = 0.32ms$, and propagation time (τ) is negligible. These and other parameters are summarized in Table 4.2, along with their definitions.

The transmission time calculation for both cases has been carried out following the reasoning presented in [96] by sorting and adding the different time intervals that compose a frame transmission. For normal operation conditions, the inter-frame time T_{IFS} overlaps with the CSMA/CA and is absorbed by the back-off time [98].

$$T_{tx-NACK} = T_{Data} + max(T_{IFS}, T_{rand} + T_{CCA} + T_{swTX}) \tag{4.2}$$

$$T_{tx-ACK} = 2\tau + T_{tx-NACK} + T_{ACK} \tag{4.3}$$

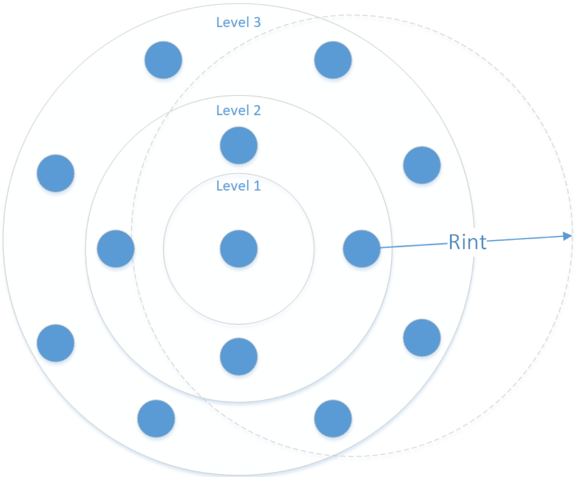

Figure 4.2: Cluster tree with interference rings.

where T_{Data} and T_{ACK} stand for the time duration of an information packet and ACK, respectively, and according to the assumptions presented in Section 4.2.1 are calculated as follows:

$$T_{ACK} = T_{swTX} + \frac{11 * 8}{250} = 0.544ms \tag{4.4}$$

$$T_{Data}(n) = T_{TXhdr} + T_{TXdata} + T_{TXftr} = \frac{(31 + n) * 8}{250}ms \tag{4.5}$$

Symbol	**Estimation**	**Description**
τ	0 ms	Radio signal propagation delay
T_{rand}	0.32 ms	Backoff period
T_{CCA}	0.128 ms	Clear Channel Assessment
T_{swTX}	0.192 ms	Turnaround time
T_{TXhdr}	0.1 ms	PHY and MAC headers transmission
T_{TXhdr}	24 µs	MAC footer transmission
$T_{ACKdelay}$	0.192 ms	ACK preparation before transmission
T_{IFS}	0.64 ms	Inter-frame space

Table 4.2: Time intervals for data frame transmission in IEEE 802.15.4 [99].

4.2.1 Data packet format

The calculation of a packet's time duration involves an perfect understanding of its structure. The previous formulas present a set of fields that are graphically explained in Figure 4.3. Please refer to the standard for more details on the specifics of each field [99].

As any other public infrastructure, Smart Lighting must be equipped with a certain degree of security, particularly given the current rise in cybercrime. The envisioned services should compromise between protection and protocol overhead, but always ensure data confidentiality and authenticity. This has been the criteria applied to choose the values of the parameters described below independently of the service. Nonetheless, the configuration can be easily adapted even up to a frame-by-frame basis if required.

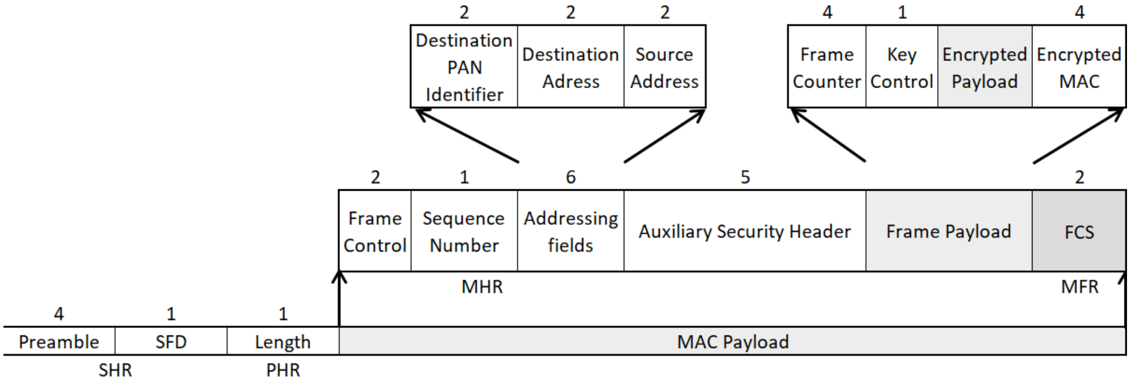

Figure 4.3: IEEE 802.15.4 frame format with AES security enabled.

- **Auxiliary Security Header**. Both data confidentiality and authenticity are ensured by the Security mechanism. The key is determined implicitly from the originator and recipient, resulting in a field length of 5 bytes.

- **Encrypted MAC**. Security is in level 5 according to the classification described in [96]. Thus, the MIC introduces 4 bytes of overhead.

- **Addressing fields**. It is assumed that in a controlled environment the totality of addresses does not exceed 2^{16}. The total length is 6 bytes, where each address occupies 2 bytes and the source PAN identifier is suppressed due to the activation of PAN ID Compression in the Frame Control Field.

The maximum packet size specified in the standard is 133 bytes. Therefore, the maximum possible payload taking into account the overhead introduced by security, MAC and PHY layers is 102 bytes.

4.2.2 Luminaries distribution

Stockholm has a total area of 188 km^2 and is built on 14 islands. This complicated arrangement entails a high complexity owing to a rather irregular distribution of constructions, particularly when compared with completely orderly areas such as the Example district in Barcelona or Manhattan in New York.

A central area of the city has been selected, see Figure 4.4, to define the quantity and allocation of fixtures around a random block, which are marked in red. It can be inferred than the distance between consecutive fixtures in the same sidewalk is around 20 meters and 30 meters between hanging luminaries present in the middle of main streets, i.e. Sveavägen in the image.

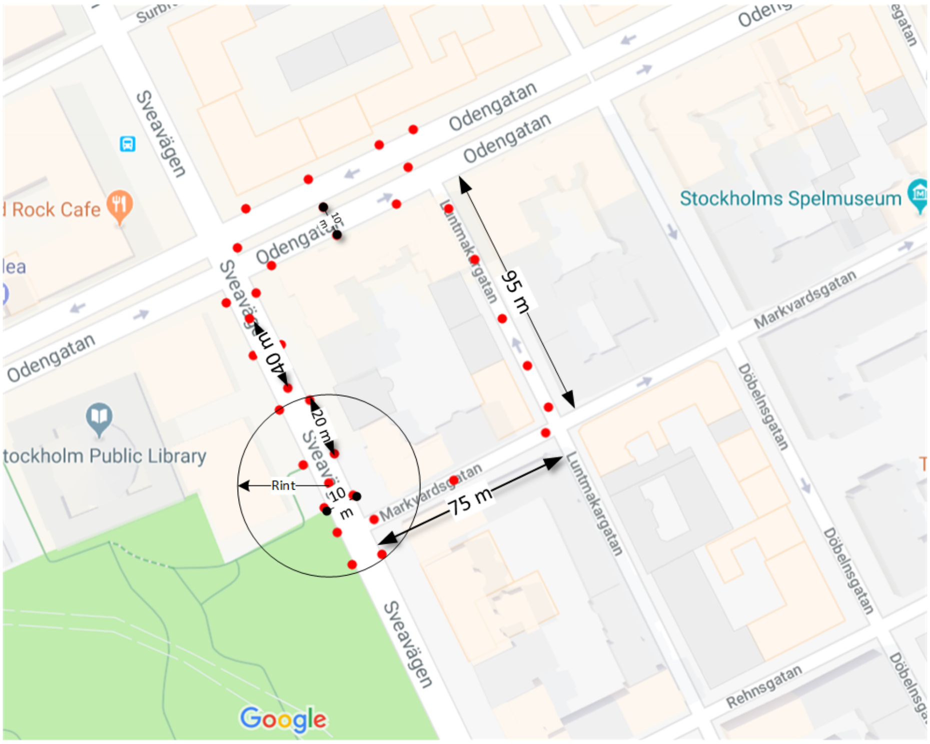

Figure 4.4: Luminaries distribution in a central area of Stockholm [100].

The Log Distance propagation model is used to characterize the radio propagation and evaluate the co-channel interference. It is a prediction model based on the following empirical mathematical formulation.

$$PL = PL(d_0) + 10nlog(\frac{d}{d_0}) \tag{4.6}$$

where $PL(d_0)$ is the free space power loss at a reference distance (d_0), one meter in this study, n is the path loss coefficient and d is the distance between transmitter and receiver. In this model, the coefficient represents the effect of obstructions present in the scenario and has a significant influence in the outcome. Its value has been chosen ($n = 3$) according to the simulations presented in [101] for outdoor propagation between buildings.

The coverage area of a transmitter has to be sufficient to reach nodes in sparsely dense streets, for example, Markvardsgatan in Figure 4.4, while minimizing the co-channel interference caused to and by other nodes. Assuming a mean distance of 25 meters, path loss equals approximately 72 dB. The well-known standard XBee Pro transceiver [102], with a sensitivity of -100 dBm, should be configured with a transmission power of -28 dBm at least. Nearly 10 nodes at most will fall within this interference area (depicted with a circle in Figure 4.4) having a considerable negative impact in the network performance. In other areas, for instance parks, touristic streets or universities, this number may drastically vary. Fortunately, in Smart Lighting scenarios, the existing relative consistency of the above used metrics facilitates radio parameters configuration so as to maintain this undesirable effect under control.

4.2.3 Analysis and results

Firstly, the maximum throughput for a single-hop configuration is obtained and depicted in Figure 4.5 to illustrate the effect of payload and the use of acknowledge transmissions. Throughput increases with the payload size, which ranges between 1 and 102 bytes. The highest value for unacknowledged transmissions is 166.7 kbps and corresponds with a channel utilization of about 67% on the physical rate. In case of acknowledged communication, the maximum is 155.5 kbps with a a channel utilization of about 62%. Secondly, the maximum throughput has been analyzed as a function of both the payload and the parameter ω, related to the number of devices within the interference radio for multiple-hop transmission. Results are presented in Figure 4.6 showing an exponential decay of performance with increasing interfering nodes and proves the necessity of a thorough network deployment plan to lessen this effect.

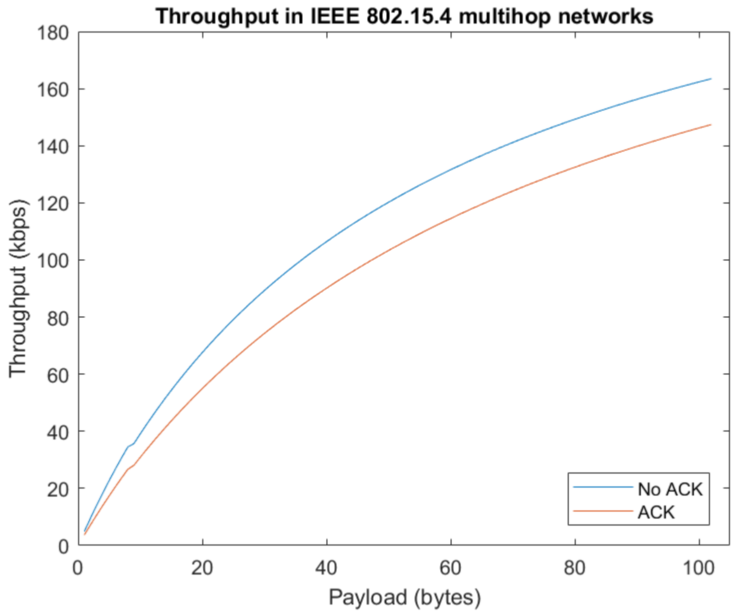

Figure 4.5: Effect of payload on the maximum data throughput for non-beacon enabled IEEE 802.15.4.

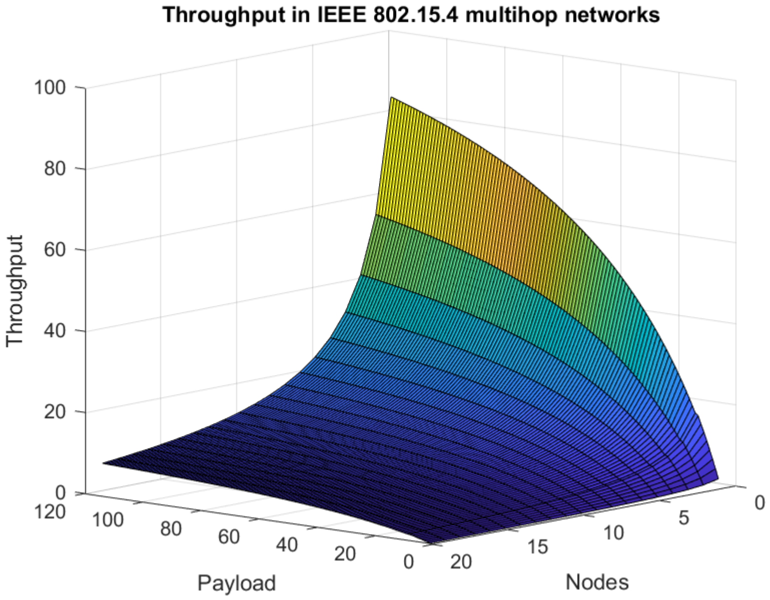

Figure 4.6: Effect of payload and number of devices within the interference range on the maximum data throughput for non-beacon enabled IEEE 802.15.4.

Model	**ACK**	**No ACK**
Worst case	5202	6172
Optimistic	20787	22281

Table 4.3: Maximum IEEE 802.14.5 devices served by a single coordinator.

Finally, an estimation of the amount of devices deployed in a cluster tree topology and served by a single PAN coordinator can be computed by dividing the maximum network throughput by the required rate per device established in Section 4.1. Results are presented in Table 4.3 and surprisingly show a reduction in the penalty caused by the use of ACKs with more favorable conditions (15% in worst-case while 7% in the optimistic model). A plausible explanation for this outcome is that with such network size ACK's effect on saturation might not be negligible anymore.

$$N_{Devices} = \frac{Maximum \quad throughput}{Throughput_{Device}} \tag{4.7}$$

4.2.4 Practical maximum capacity

In terms of capacity, IEEE 802.15.4 has proven more than capable of handling the whole public lighting installation of the city with a few PAN coordinators. Nonetheless, this might not be feasible with regard to a desired level of delay and reliability in a real life scenario, although it would significantly reduce the deployment complexity. For instance, should a coordinator fail, a substantial portion of the fixtures would be left without communication service, but still would be operative. Physical redundancy is a valid solution, but it is commonly preferred to limit the size of the tree according to certain QoS specifications in order to lessen this risk.

A precise calculation of the delay and PER is an onerous and complicated task, specially in multiple hop networks. In the scientific literature, there exist several proposals for beaconless IEEE 802.15.4, although most of the work has focused on the beacon enabled mode owing to its predictability. In [103], a mathematical method is exposed to characterize the un-slotted CSMA/CA with the busy cycle of a M/G/1 queue system. It describes the device's behavior with a non-linear system of stochastic equations to be solved analytically for non-saturated conditions. Saturated scenarios have been investigated by the same authors in [104], and might be of interest if new services are demanded. While these papers analyze sensor networks deployed in star topology, this project considers a cluster tree topology, which is thoroughly studied in [105]. An iterative edge pruning algorithm is proposed to find the maximum amount of hops in the tree given certain QoS constrains. Although a complete and detailed mathematical characterization is presented, the expressions must be solved analytically as well. A MATLAB routine has been designed for this assignment, still without success since the output yields incoherent results. For this reason, an estimation of delay bounds under 50 ms and PER around 20% has been obtained from the simulations in [103]. More research is necessary to fully characterize either by computer simulation or real life testing the true capabilities of this technology.

System's reliability can be defined as the network's robustness to correctly deliver legitimate packets from source to destination even in adverse conditions [106]. The packet delivery probability is a suitable indicator since the deeper the tree, the more likely a packet is unable to reach the root node. A reasonable assumption is that IEEE 802.15.4 would be able to tolerate a PER between 1 and 10%, particularly if application level retries are employed, without significant impact on battery life [107]. Nevertheless, the high levels of interference present in urban scenarios (see Appendix .2) make 20% a more proper estimate. Furthermore, the error probability in ACKs is an order of magnitude less than data packets, thus initially it can be neglected.

A conservative strategy would be to require a packet delivery ratio of 90% (p_{del}). Consequently, the maximum number of hops in a path is restricted to:

$$h \leq \frac{ln(p_{del})}{ln(1-q)} \tag{4.8}$$

where q is the packet discard probability given by $q = p^{r+1}$ with the following dependencies:

- r is the maximum number of retries after a transmission failure, set by default to 3 in the standard [99].
- p is the packet error ratio in every link.

The maximum depth of the three would be 65 hops with this method. It is known that the worst case scenario might suffer from a tighter restriction because of its more frequent packet transmission. In principle, this does not affect the previous values of network size, but testing and validation of this analytical development would be convenient in future research.

4.3 LoRa

The main advantage of LoRa over the previous technology is its long range, network simplicity and relatively easy scalability. Unlike traditional cellular technologies, LoRaWAN is dominated by uplink traffic and is deployed on-demand basis, consequently not always in the most efficient and ordered manner. As a result, LoRa's potential to cope with inter-cell interference in dense deployments is a significant matter being currently researched.

In this case, the network under investigation is configured in star topology and comprises a single gateway serving an unknown number of Class A devices with the characteristics mentioned in Section 4.1. Nodes are uniformly distributed around the gateway. Okumura-Hata model has been used to account for propagation losses in the urban environment. For simplicity, only the three mandatory channels in 868 MHz are used (125 kHz bandwidth), naturally characterized by a duty cycle restriction of 1 percent for this band.

Two approximations are presented in this section. The first approach develops an analytical model using common metrics. In contrast, the second method is purely mathematical and it has already been conceived recognizing the interference resilience, hence not needing any further revision.

4.3.1 Packet format

LoRa frame is composed of a preamble with synchronization word, physical header with additional CRC, payload and CRC checksum. The structure is specified in [108] and illustrated in Figure 4.7. Its header is optional and can be disabled when the payload length, the coding rate and CRC presence are known in advance (implicit mode). The total time-on air largely varies depending on the symbol time and the payload length, which are determined by the selected data rate as shown in Table 4.4, and it is given by Equation 4.9.

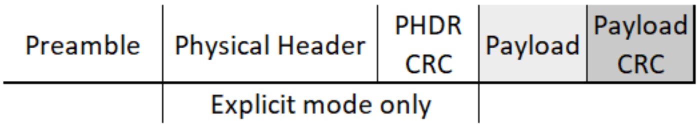

Figure 4.7: LoRa frame format.

$$ToA = T_{preamble} + T_{payload} \tag{4.9}$$

DR	SF	Max MAC payload	Max ToA
0	12	59 bytes	2.793 s
1	11	59 bytes	1.561 s
2	10	59 bytes	0.698 s
3	9	123 bytes	0.677 s
4	8	250 bytes	0.707 s
5	7	250 bytes	0.400 s

Table 4.4: LoRaWAN data rates (DR) and characteristics [109].

Preamble configuration is common to all modems and its duration is given by:

$$T_{preamble} = (n_{preamble} + 4,25) * T_{symbol} \tag{4.10}$$

Where $n_{preamble}$ is the number of programmed preamble symbols and is set by default to 8. The duration of the payload and header is calculated with:

$$T_{payload} = T_{symbol} * \left[8 + max\left(\left\lceil\frac{8PL - 4S + 28 + 16 - 20H}{4(SF - 2DE)}\right\rceil(CR + 4), 0\right)\right] \tag{4.11}$$

With the following dependencies:

- PL refers to the number of payload bytes. In this case, it will be 8 bytes as specified in the requirements, plus an additional 13 bytes for MAC layer overhead.
- SF is the spreading factor. Only the ones shown in Table 4.4 are considered, creating the coverage area depicted in Figure 4.8. Numeric values for the radius of each area can be found in Table 4.5. The sensitivity values of the transceiver HOPERF RFM95w [110] have been used, since this LoRa module will be used in the experimentation.
- H stands for the presence of the optional header. Explicit mode is considered, hence this is disabled.
- DE relates to LoRa's low data rate optimization. It is mandatory for the two first data rates ($SF = 12, 11$), while it is disabled for the remaining.
- CR is the applied coding rate, ranging from 1 to 4. The minimum has been assumed.

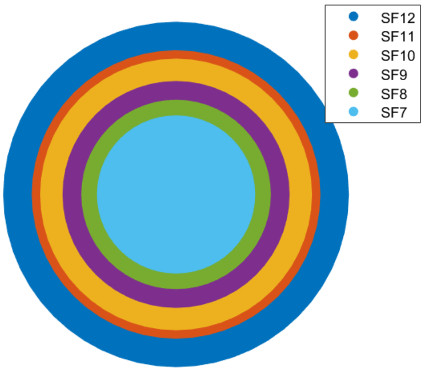

Figure 4.8: LoRa HOPERF RFM95W module coverage areas as a function of the Spreading Factor.

4.3.2 Approximation based on metrics

This first approach is based on [109] which estimates the maximum number of devices served by a single base station for different MTC use cases. The calculation is extrapolated from a single device study under the assumptions of a pure ALOHA channel access, the absence of ACKs and the presence of frequency regulation constraints.

For the sake of clarity, the covered area has been divided in several sectors as shown in Figure 4.8 according to the employed spreading factor with the Okumura Hata propagation model in metropolitan areas [111] and the aforementioned transceiver. The amount of devices in each one has been computed using the following formula and results are shown in Table 4.5.

$$N_{Devices} = \left\lfloor \sum_{i=1}^{6} \frac{n_{i,k} * T * \eta}{ToA_i} \right\rfloor \tag{4.12}$$

where $n_{i,k}$ refers to the number of channels per data rate (there are 3 mandatory channels for 868 MHz), T is the node's reporting period (equals the inverse of the device's data rate $T = \frac{1}{\lambda_D}$), and η stands for the total efficiency of LoRa, which because of the access scheme resemblance with pure ALOHA could be considered 18.4% [112]. Recall that a device may transmit on any channel and data rate at any time.

		Worst case			Optimistic		
SF	**Radius (km)**	**ToA (ms)**	**Throughput (kbps)**	**Devices**	**ToA (ms)**	**Throughput (kbps)**	**Devices**
12	1.76	1646.59	0.102	42	2957.31	0.173	223
11	2.11	823.30	0.204	85	1642.50	0.312	403
10	2.52	411.65	0.408	171	738.33	0.693	895
9	3.02	205.82	0.816	343	410.62	1.247	1613
8	3.21	113.15	1.480	625	225.79	2.268	2933
7	3.84	61.70	2.723	1146	128.26	3.992	5164
			Total	**2412**		**Total**	**11231**

Table 4.5: LoRa calculation results of the analysis based on metrics

The protocol makes impossible for devices to transmit bursts of data by imposing stricter requirements in duty cycle than those established by the spectrum's regulator. The waiting time after a transmission is proportional to the packet's time on air before the next attempt in the same sub-channel.

$$Toff_{subband} = ToA * \left(\frac{1}{DutyCycle} - 1 \right) \tag{4.13}$$

Fortunately, the average message period complies with this constraint and it does not restrict the maximum number of devices. Nevertheless, note that traffic intensity sensors have higher transmission rate requirements and, therefore, at the implementation stage, are not suitable to be allocated in the three outmost rings owing to this restriction.

LoRa's maximum MAC payload varies as a function of the Spreading Factor, see Table 4.4. Yet for the simplicity of calculations, it has been considered that the maximum payload is uniform for all modes and equals 51 bytes (the most restrictive) [113], with 8 bytes of overhead from the network and MAC layers. This is the reason behind such low throughput values presented in Table 4.5 specially for the last spreading factor.

In conclusion, the maximum number of devices given the conditions established in Section 4.1, the assumptions above-mentioned and taking into consideration duty cycle limitations is 2412 for the worst-case and 11231 for the optimistic model without any interference.

4.3.3 Mathematical model

The mathematical methodology exposed in [114] has been followed to estimate the maximum amount of nodes that could be supported by a single LoRa gateway. It already accounts for the capture effect, i.e. the possibility of a packet to be correctly received despite having intersected with other packets. In other words, LoRa's proprietary PHY layer might be capable of decoding successfully a received packet even in case of interference but depending on the interferer's RSSI and the portion of the packet affected. The following assumptions have been made in order to simplify the calculations of the model:

- No fading is considered when employing Okumura Hata path-loss model.
- The signal power of the gateway's ACK is larger than the total power of the other motes transmitting at the same time ($\mathbb{W}_{i,k}^{Mote} = 1$).
- A device cannot retrieve a frame if it is interfered by two or more frames at once ($\mathbb{W}_{i,k}^{GW}, \mathbb{W}_{i,k}^{One}, \mathbb{W}_{i,k}^{Mote} = 0 \quad \forall k > 1$)
- The probability of a retransmission resulting in a new collision equals the probability of choosing the same spreading factor and the same channel $\left(P_c = \frac{1}{F}\frac{1}{DR} = 0.0556\right)$.
- HOPERF RFM95w sensitivity and co-channel rejection values have been used to determine the coverage regions and level of interference.

The model evaluates as a function of the network load the Packet Error rate, which is the inverse of the probability of a successful transmission.

$$P_S = \sum_i p_i \left(P_{1,i} P_i^{S,1} + (1 - P_{1,i}) P_i^{S,Re} \right) \tag{4.14}$$

where $P_{1,i}$ is the probability of being the first transmission attempt and is reverse to the average number of attempts per frame, and $P_i^{S,1}$ and $P_i^{S,Re}$ are the probabilities of successful transmissions for both the first try and the retransmission, respectively. They are defined by:

$$P_i^{S,1} = P_i^{Data} P_i^{Ack} \qquad P_i^{S,Re} = P_{i,Re}^{Data} P_i^{Ack} \tag{4.15}$$

The first transmission attempt can be described by a Poisson process, however this is not applicable to retransmissions. Therefore, they are defined as a combination of different event's probabilities ($\mathbb{W}^{GW}, \mathbb{W}^{One}, \mathbb{W}^{Both}$) [114].

The probability of successful uplink transmission for both cases is defined by:

$$P_i^{Data} = e^{-(2T_i^{Data}+P_iT_i^{Ack})r_i} + \sum_{k=1}^{N-1} \frac{(2r_iT_i^{Data})^k}{k!} e^{-2r_iT_i^{Data}} \mathbb{W}_{i,k}^{GW} \tag{4.16}$$

$$P_{i,Re}^{Data} = \frac{\mathbb{W}_i^{One} + \mathbb{W}_i^{Both}(1 - P_i^c)}{1 - \mathbb{W}_{i,1}^{GW}} P_i^{Data} \tag{4.17}$$

Finally, the packet error ratio can be calculated as the inverse of P_S.

$$PER = 1 - P_S \tag{4.18}$$

An analysis of the model's performance has been conducted for different values of application layer payload and network load in the two scenarios introduced in Section 4.1. Worst-case results are presented in Figure 4.9 and display a constant variation rate until the network saturates, when load approximates a message per second. Figure 4.10 shows the relation between the amount of nodes and the network's throughput and its shape clearly resembles ALOHA's performance. In the optimistic case, saturation happens when load approaches 10 messages per second, therefore a bigger amount of nodes is supported. Graphs show similar trends to the other scenario and, for that reason, have been omitted. Throughput values have been obtained using the following expression:

$$Throughput = \lambda_N * P_S \tag{4.19}$$

where λ_N is the total network load, which takes on values between 10^{-2} and 100 messages per second. The number of devices is derived from both this value and the generated traffic in each device specified in Section 4.1.

$$N_{Devices} = \lambda_N / \lambda_D \tag{4.20}$$

The maximum quantity of devices that can be served by a single gateway given the data rate and payload conditions established in Section 4.1 is approximately 3424 for the worst-case and 17910 for the optimistic model. This estimate has been obtained considering that the system operates at the highest possible throughput given a payload, see Figure 4.10. This point determines the maximum load supported by the system before saturation, which is characterized by performance degradation.

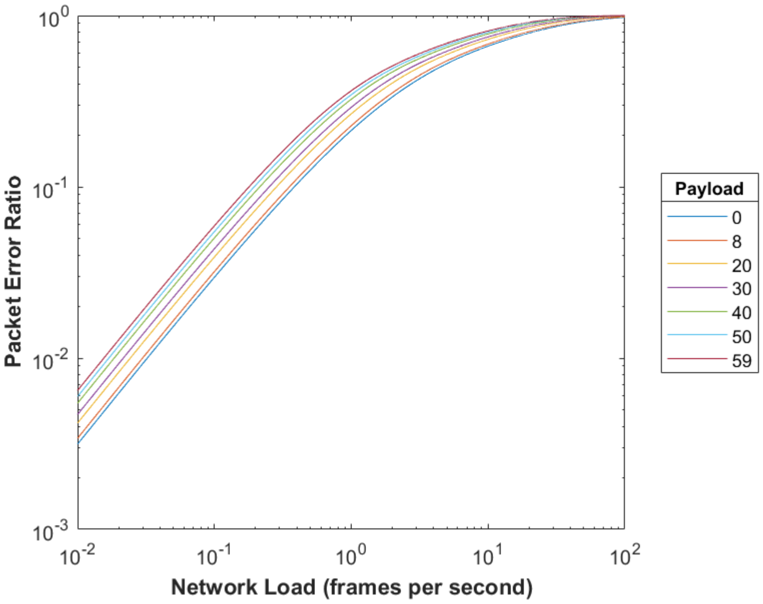

Figure 4.9: Relation between LoRa's PER, packet payload and network load.

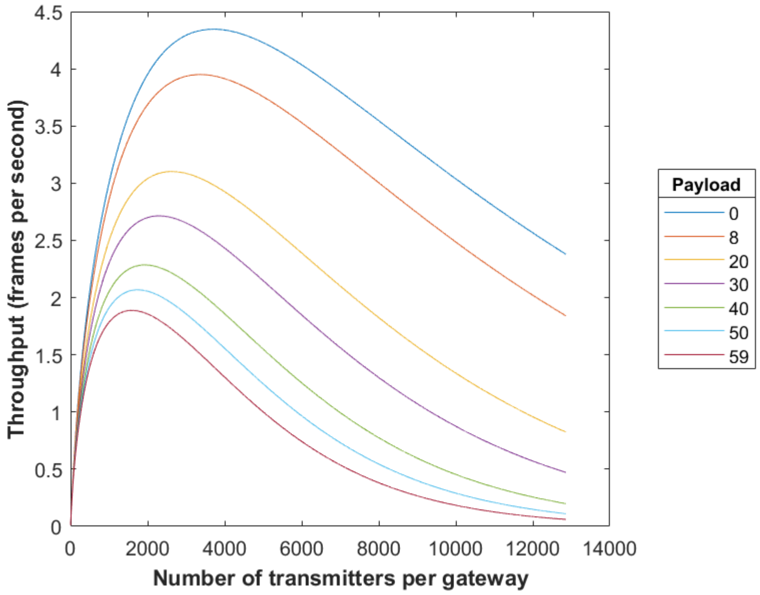

Figure 4.10: Relation between LoRa's throughput, packet payload and number of end devices.

4.3.4 Conclusions

In this thesis, two different methodologies have been employed: a mathematical model and an assessment based on metrics and estimations. Table 4.6 evidences the considerable difference in their results. Regard LoRa as a pure ALOHA channel access scheme clearly underestimates its actual capacity, more precisely 42% in the worst-case and around 60% in the optimistic model. LoRa's robust physical layer and the packet capture phenomenon have a significant effect on the calculation outcome.

Approach	**Worst-case**	**Optimistic**
Metrics	2412	11231
Mathematical	3424	17910

Table 4.6: Number of devices in the two methodologies used for LoRa analysis.

4.4 NB-IoT

As the massive IoT becomes a reality, mobile network operators (MNOs) begin from a quite advantageous position. The infrastructure is mostly already deployed, shortening the time to market and enabling without delay the creation of new revenue streams, the provision of proper device management (activation/de-activation, consumption monitoring, statistics, etc.) and drive the necessary technological maturity. These kind of deployments are arousing high expectations in the media, however little is known about the actual MNO's specific plans for Sweden.

All over the world, MNOs are currently offering small scale NB-IoT and LTE-M support in certain locations on demand basis. These have been mainly conceived as demonstrations of IoT's potential to attract investments. Nonetheless, the intention of operators such as Telia is to extend its coverage within their whole footprint, in this case, Baltic and Nordic countries [115] as soon as possible [116]. In Spain and the rest of Europe, the situation is similar, being MNOs in a fierce competition to deploy cellular IoT solutions first. As of today, operators have focused and are commercializing only one technology, either LTE-M or NB-IoT. The differences are substantial so as the target markets, but both fit under the umbrella of the Smart City and have common ground, see Figure 3.2. A technical comparison is presented in Table 4.7.

	LTE-M	**NB-IoT**
Peak data rate	384 kbps	<100 kbps
Bandwidth	20 MHz	200 kHz
Latency	50-100 ms	1.5-10 seconds
Mobility	Yes	No
Power consumption	Best at medium DR	Best at low DR
Voice	Yes	No

Table 4.7: Technological comparison between LTE-M and NB-IoT.

The characteristics of the Smart Lighting service proposed in this work fit better into the features offered by NB-IoT. Nonetheless, the analysis developed next does not relate to crucial technicalities and could be applied for both technologies.

4.4.1 Data dimensioning

It would be rather complicated and of little interest to obtain an estimate of the maximum number of devices per NB-IoT cell, as it completely depends on each operator 4G deployment. This data is confidential, however, given the excellent cellular coverage in Stockholm and the capacities offered by this technology, it surely would not result in tight restrictions. Moreover, the City of Stockholm, as a customer, would not be interested in the infrastructure operation and maintenance, but in the total amount of data generated by the installation, which is the charging metric. In this work, the data volume is evaluated for the two models presented above and an extra scenario aimed to reduce the packet transmission rate.

For the calculations, it is assumed that information is encapsulated in IPv6 packets using the Constrained Application Protocol (CoAP). This is a specialized web application transfer protocol designed and optimized for operating in devices and networks with constrained resources. It relies on the Representational State Transfer (REST) architecture, which makes information available by means of identifiers named URIs, and defines the familiar four request methods: GET, PUT, POST, and DELETE. Additionally, CoAP runs over UDP transport protocol which introduces minimum overhead.

Model	**Payload**	**Rate**	**Data**
Optimistic	102 bytes	3 msg/hour	334.8 KB/month
Worst-case	8 bytes	28 msg/hour	1.23 MB/month
Minimum	72 bytes	4 msg/day	15 KB/month
	966 bytes	2 msg/hour	1.46 MB/month

Table 4.8: Data volumes per month generated in the different models.

The worst case and optimistic models have been conceived without any other requirements than those essential for service providing (see Section 4.1). The use of IPv6 and CoAP brings in an extra 53 bytes of data overhead because of protocol headers and checksums, making these scenarios totally unsuitable for this implementation. Payloads as little as 8 or 102 bytes would suppose a high overhead ratio being greatly inefficient. Still, they have been included in the analysis so as to maintain coherence with previous sections and present a fair comparison. It is worthy to mention that these two are modeled by average traffic values, hence fluctuations could reduce the accuracy of the numeric figures presented.

The new proposed model acknowledges the data transmission cost and it is optimized by minimizing the number of packets, while maximizing its information content, i.e. using the maximum possible payload. The standard Ethernet MTU (1500 bytes) is used to avoid useless fragmentation in the core network. It is assumed that a fixture with traffic intensity sensor generates 1932 bytes per hour, whilst a common luminary produces 12 bytes in the same amount of time. Furthermore, two messages per hour with half of the payload (966 bytes) and one message every six hours with the aggregated information (72 bytes) are sent for each type, respectively.

This mode has been denominated *minimum case* and it is compared to the other two in Table 4.8. For the sake of clarity, calculations have been carried out separately for fixtures with and without traffic sensors. Lastly, under the given conditions, it is certain that any node regardless the scenario will have a data consumption under 1.5 MB per month.

4.5 Cost comparison

Neither NB-IoT nor LTE-M has been officially commercialized in Sweden yet and prices from LoRa and IEEE 802.15.4 components largely vary on the specifics of the deployment, giving this section a rather speculative flavor. The reasoning and figures presented here are based on the following hypotheses:

- There number of fixtures in the city is approximately 140000 and are connected to 1160 cabinets uniformly.
- MNOs might in general continue with the current charging method for NB-IoT, i.e. invoicing customers on the amount of data. This is a quite reasonable assumption since MNOs core network has been built and designed to be monetized in this way and this arrangement is already used in extensively deployed GSM based MTC services.
- All devices are external to the fixtures. Although it is possible that it could be already incorporated in newly acquired fixtures, old equipment should also be considered so as to guarantee a smooth transition.

On the one hand, in cellular solutions, the infrastructure is owned by the operator, therefore they will probably charge an activation and a monthly connection fee. Besides, they could offer extra services such as customer care, data analysis, platform management, etc. not included in the normal subscription price as well as a discount policy for years of commitment to the service. It has been very laborious to find available resources on the current price of GSM M2M services. Table 4.9 summarizes the tariffs procured by two relevant European operators, Movistar (Spain) and Telenor (Sweden), located in a couple of slightly outdated documents [117] and [118]. It becomes clear that the data volume offer far surpasses the necessities of the installation shown in Table 4.8, so cost estimations should be taken with a pinch of salt. Furthermore, the cost of NB-IoT modems is expected to exceed GSM's current price and be in a similar order of magnitude to the other solutions.

On the other hand, in LoRa and IEEE 802.15.4, the infrastructure is owned by the municipality, being the deployment the costly phase and reducing the operation costs to management and maintenance. Taking LoRa and given the supposed number of luminaries, the whole city could be covered with at least 42 and 8 gateways for the worst-case and optimistic model, respectively, while in case of IEEE 802.15.4, it would be necessary only 26 and 7 gateways for each scenario.

	Movistar	**Telenor**
Connection price	21 €	100 SEK
Monthly price	3 €	25 SEK
Data packet price	Included	29 SEK
Max. data	15 MB	50 MB

Table 4.9: GSM M2M prices in Spain and Sweden operators.

	NB-IoT	**IEEE 802.15.4**	**LoRa**
Deployment	Low	Medium	High
Operation	High	Low	Low

Table 4.10: Infrastructure cost estimation.

Finally, a superficial research of the present market possibilities has been carried out to obtain an idea of the total infrastructure cost in each case. To begin with, the cost of a LoRaWAN gateway ranges from 100€ (single channel only) to 1200€. Different options can be found for every budget in the market from different vendors [119] or [120], but probably the cheaper options do not fulfill the strong demands of such a large implementation. For a rather representative list, refer to [121]. Additionally, a fair estimate could be 100€ per end-device, already including placement. The same could be assumed for IEEE 802.15.4 both end-nodes and gateways, having the latter enhanced computing capabilities. To conclude the analysis, a qualitative summary of the differences between each approach is presented in Table 4.10. Note that NB-IoT does only consider the cost of the devices, while LoRa's expensive gateways greatly increment the price compared to IEEE 802.15.4.

Chapter 5

Conclusions

This master thesis was conceived as an initial attempt to tackle the deployment of an smart lighting infrastructure in Stockholm within the Smart City context. In the beginning, an extensive research of the future Internet paradigm, the Smart City ecosystem and the illumination industry was carried out to settle the scope of this work. The primary objectives were set to investigate the current state of the field, shed light on the heterogeneity of solutions available in the market and provide practical recommendations to successfully accomplish an installation of such kind.

The lack of a solid standard for the Internet of Things and the exponential growth of connected devices has led to a fragmented market with an overwhelming diversity of networking protocols, each claiming to be the ideal alternative. For this reason, a comprehensive survey was conducted to filter out the least suitable candidates. Three distinct categories were identified as a function of their operating nature, namely cellular, LPWAN and LWPAN, and various possibilities were revised among them. An special emphasis was set on the most relevant according to the acquired author's criteria during the research, i.e. NB-IoT, LoRa and IEEE 802.15.4.

The inherent differences between those selected required the elaboration of two traffic models (optimistic and worst-case) in order to fairly evaluate, compare and become aware of their potential. These scenarios were derived from establishing a basic set of functionalities that should be offer by the system and estimating frequency and payload size demands. A complete mathematical methodology was conducted for these purposes and was partly validated with more advanced simulations and conclusions from the scientific literature.

Efforts were centered on determining the maximum theoretical capacity of a single LoRa and IEEE 802.15.4 gateway. In LoRa, the purely mathematical procedure achieved higher capacities than the approximation based on metrics due to the consideration of the channel capture effect. Additionally, it was studied the impact in the IEEE 802.15.4 network capacity under certain Quality of Service variables. In contrast, in NB-IoT the focus was on the necessary data volumes for operating the system since, for a customer, the annual operation cost is rather more decisive than the architecture itself, which entirely depends on the provider. A new model was introduced to account for this new priority so as to offer a complete picture of the scenario.

Finally, deployment and operation cost of solutions such as LoRa or IEEE 802.15.4, where the infrastructure is owned by the municipality, is compared in a qualitative manner to cellular networks (e.g. NB-IoT), in which a private company is remunerated for procuring connection services. On the one hand, operation and management expenditures are significantly cheaper in the first case. However, installation is far more expensive, although this will largely depend on commercialization prices of NB-IoT devices when this technology becomes eventually available.

5.1 Future lines of research

Owing to a limited time span, this thesis has chiefly focused on the network level of the future Stockholm Smart Lighting service. It would be fascinating to extend the scope of the analysis to the application layer and management platform. There exist multiple options readily available in the market, both open-source and proprietary, but an extensive investigation should be carried out to find its scalability limits, semantics efficiency, interoperability, and adaptability to the forthcoming technological advances.

The methodology laid out in Chapter 4 is based on mathematical models of complex and highly variable metrics such as propagation losses, interference, processing time, delay and error probability. Therefore, it would be very convenient to carry out first a simulation and then a real-life implementation so as to validate the proposed assumptions and verify the theoretical conclusions against experimental results. Particularly, the interference between LoRa cells and the actual performance of dense IEEE 802.15.4 networks deployed in cluster tree topology are topics of growing interest since little information has been found in the scientific literature and their characterization is essential to predict the performance and behavior of future installations.

To conclude with, the described system just contemplates a confined set of essential basic services. Smart lighting goes beyond only scheduling the operating hours of luminaries and report a few measurements. In this way, this thesis has established the fundamentals for future development. Now there is actually limitless applications and business opportunities emerging to enhance the city ecosystem and improve life quality that can be investigated.

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Appendix

.1 The relevance of IPv6 in IoT

The standardization of IPv6 and the slow replacement of IPv4 has been a huge and critical innovation for the future of Internet communications. New technologies are already making use of its advantages and it gives space for the appearance of many more. Among other arguments, three essential aspects of this transformation are highlighted here to proof the significance of IPv6 in the conception and generalization of the Internet of Things.

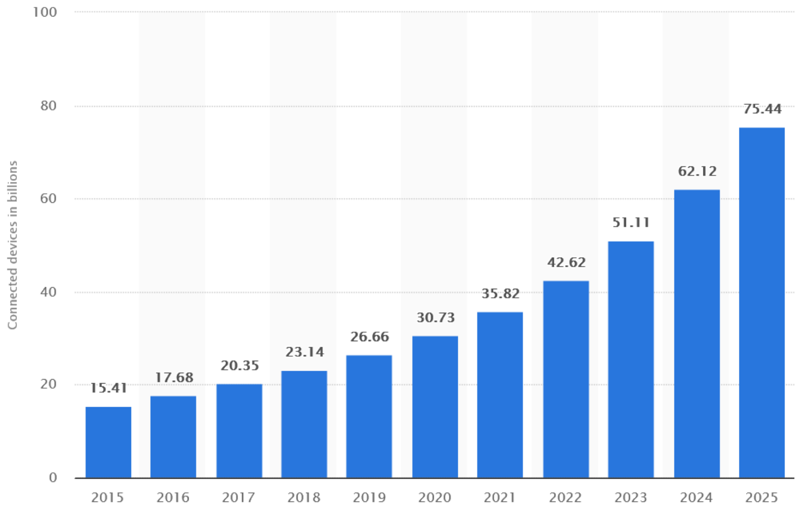


Figure .1: IoT connected devices installed worldwide [122].

- **Scalability.** Although numbers and expectations may vary depending on the source, latest estimates point to a substantial increase on the number of connected devices in the next few years. According to the American research and advisor firm Gartner Inc [123], by the end of this year 8.1 billion devices will be in use, representing an increment of

31% from last year. Still, the current scheme of Internet Governance (IPv4) only provides a theoretical maximum of 2^{32}, little over 4 billion, unique addresses. In this regard, IPv6 addresses consist of 128 bits divided into eight 16-bits blocks. Each block is then converted into 4-digit hexadecimal numbers separated by colon symbols, so addresses can include both numbers and letters. This is sufficient to cover the needs of any present and future communication scheme.

- **NAT barrier.** The restrictions of IPv4 as well as the unexpected and rapid expansion of the Internet led to the adoption of a temporary solution to overcome the lack of addresses, this was the Network Address Translation (NAT). It allows several users and devices to share the same public IP address. However, it makes rather cumbersome to reach private devices from their public addresses, which in the IoT context, might pose serious limitations. End-points are expected to be used by different independent stakeholders managing the vast amount of generated information, therefore universal identification is a must and, depending on the paradigm, objects should as well be individually reachable from remote networks, which is unmanageable within a NAT system.

- **Security.** IPv6 has a number of security features that may guarantee a better protection compared to its predecessor. First, IPsec is already implemented in the protocol, this also existed in IPv4 but in an optional manner. Its universal application ensures safer Internet connections thanks to end-to-end encryption and integrity checking, which will increase the resilience against Man-in-the-middle attacks, i.e. the interception and manipulation of web communications. Second, a better header design permits a cleaner division between encryption metadata and the encrypted payload and enables the support of a more-secure name resolution, the Secure Neighbor Discovery (SEND) protocol. This allows cryptographic confirmation of the host integrity at the time of the connection, reducing the possibilities of Address Resolution Protocol (ARP) poisoning and other naming-based attacks.

.2 Benefits of licensed spectrum

Radio spectrum is a scarce and limited resource. In Sweden, the regulatory entity in charge of planning, assigning, monitoring and supervising the use of radio frequency transmitters is the Swedish Post and Telecom Authority. This organism grants the license holder with exclusive rights over a certain bandwidth in a designed territory to operate without interference or spectrum crowding and provides legal protection preventing other operators to transmit at the same frequency [124].

Although bandwidth availability can be an issue, licensed spectrum solutions offer several benefits.

- Fewer regulatory limitations in the effective radiated power (EIRP) or the duty cycle, resulting in a better coverage with a reduced number of devices.
- Interference in ISM bands is experimenting an exponential growth due to the large number of systems making use of these frequencies and their universal use. Figure .2 shows the received power intensity in different environments of a medium sized European city.
- Possibility to offer quality of service.
- Better optimization of battery powered devices.
- Lack of easily accessible equipment in licensed spectrum may result in facing less security risks.

The economic cost is presumably the main drawback of license spectrum solutions. Firstly, equipment should be specifically designed for each application and its cost is normally several orders of magnitude more expensive than in unlicensed spectrum. Secondly, purchasing licenses is costly not only in economic, but also in administrative terms. Last but not least, interoperability with other technologies becomes more difficult and it should be relegated to upper layers, e.g. the Smart City operation and management platform.

.3 Types of sensors

The model developed in Chapter 4 is based on suppositions of distinct nature. A rapid market and technical analysis was carried out to determine the most relevant sensors used in Smart Lighting and establish the amount of bytes generated in each measurement. Information from each sensor specification was used in most of the cases, however, for application specific services, it was not possible to find reliable sources, thus reasonable assumptions are laid out.

The services envisioned in this project were the following:

- **On/Off**: A single byte should be enough to provide this functionality.
- **Status**: This does not have high demand as well. Based on the headers of control messages in the MQTT application protocol [126], it can be estimated that 2 bytes would be necessary to report this metric.
- **Light intensity**: MAX44009 is a common Ambient Light sensor, which barely operates with a consumption of 1 µAand features a wide dynamic range of 22 bits. Measurement are transmitted with a total of 12 bits through an I^2C interface [127].
- **Traffic intensity**: There are multiple techniques available in the market for traffic characterization, namely, video cameras, inductive loops, magnetometers, ultrasound and laser. This latter is rather common and does not require installation on the road, but on the sideways. It is the solution implemented in [93] and the model UTM-30LX-EW has also been considered in this work. 8 bytes measurements are sent via an Ethernet cable [128].
- **Temperature**: the ubiquitous temperature and humidity sensor in DIY projects DHT22 has been chosen for its small size, low consumption and adequate performance price trade-off. It produces 40 bits of information per measurement [129].
- **Power metering**: The split core current transformer SCT-013 has been selected to provide this service due to its reduced size and optimal characteristics. It gives measurements of 2 bytes in an aggregated manner, i.e. the absolute consumption is transmitted in every message and the platform is in charge of processing the differences [130].

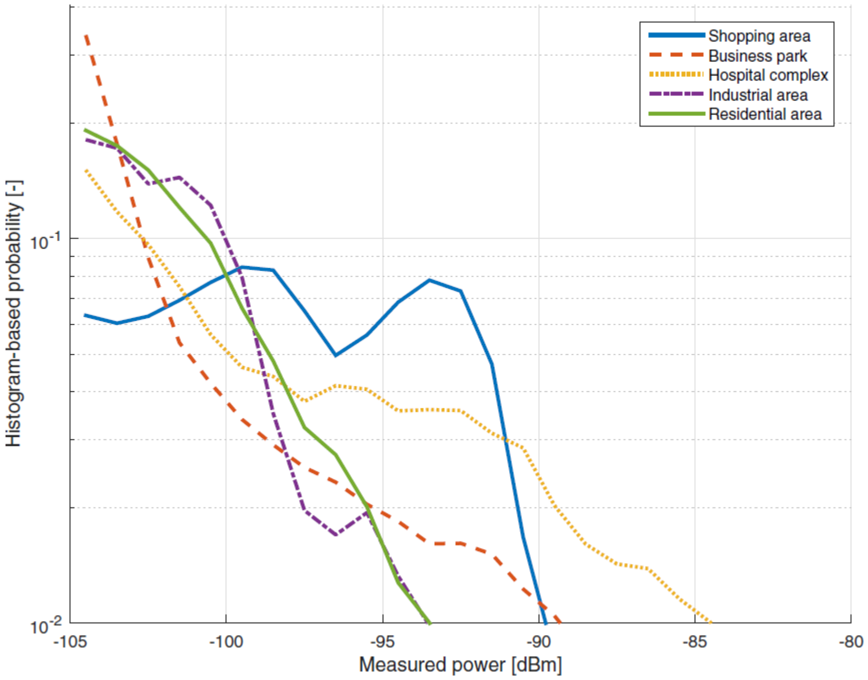
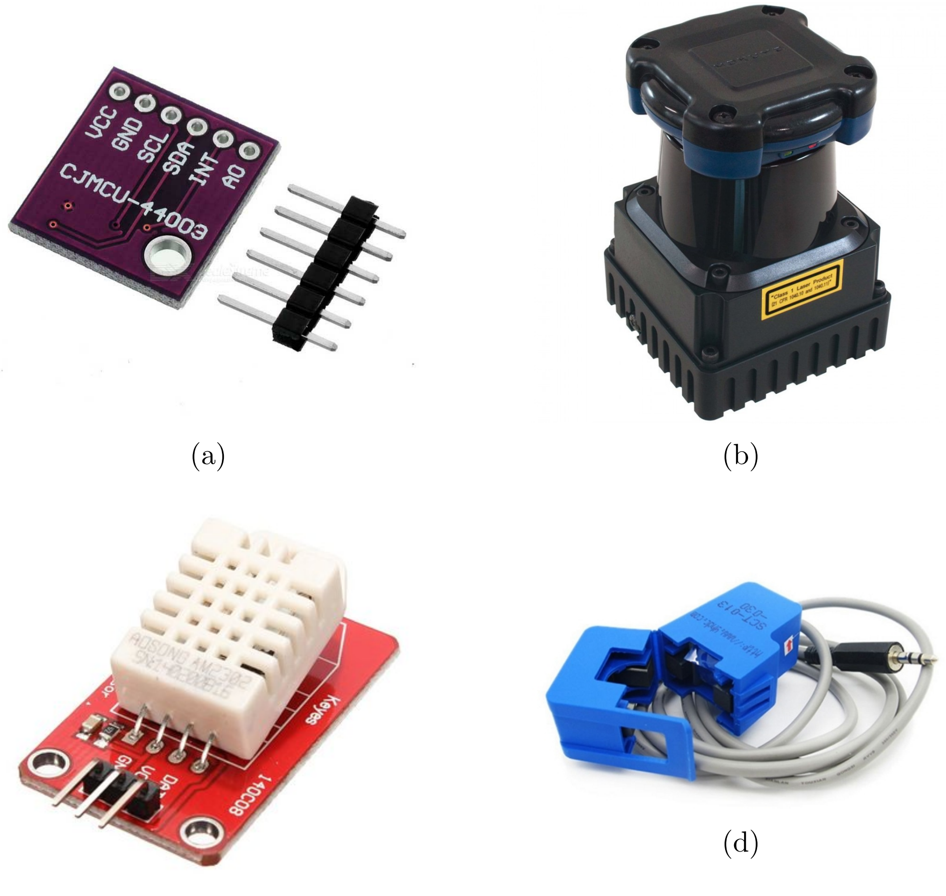


Figure .2: Interference level probability density function based on a normalized histogram in the 868 MHz band in Aalborg (Denmark). [125].



(a) (b)

(d)

(c)

Figure .3: Example sensors (a) MAX44009 ambient light sensor [131], (b) UTM-30LX-EW scanning laser rangefinder [131], (c) DHT22 temperature and humidity sensor [132], and (d) SCT-013-030 current sensor [133].