

**Enhancing public safety with smart street lighting:
Koules walkway case**

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Statement of Originality

The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution or any other purpose. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except as specified in references, acknowledgments or in footnotes. I certify that the intellectual content of this thesis is the product of my own work and all the assistance received in preparing this thesis and sources have been acknowledged.

Ntritsos Roland

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Abstract

The Internet of Things (IoT) paradigm has given new tools and countless opportunities to promote new Smart City initiatives on a worldwide scale. IoT provides the means to remotely monitor, manage and control devices, and to create new insights and actionable information from real-time data. Energy management is one of the most demanding issues within urban centers, owing to the complexity of the energy systems and their vital role (Calvillo, Sanchez-Mirallas, & Villar, 2016). Street lighting is an important community service that can consume as much as 40 percent of a city's energy budget. Consequently, street lighting has emerged as a leading smart city application. The objective of this thesis is to build a proof-of-concept smart lighting network and control system prototype to be used on the windbreaker walkway of the city of Heraklion. Depending on the wind intensity on the walkway, the color-tunable lights will be used to convey the safety situation to would-be visitors. The proposed solution is designed to utilize Wireless Sensor Networks (WSN) to create a grid of low-cost microcontrollers that will regulate lighting based on environmental input. The whole system is designed using open-source initiatives and offers a web-based management application, making it easy to integrate with existing Municipality web-based infrastructure. The main novelty of our system is the use of open standards, the low-cost integration to the existing lighting infrastructure without the need for modifications and the value-added by the proximity capabilities of the used microcontrollers.

Περίληψη

Οι εφαρμογές του Ίντερνετ των Πραγμάτων (IoT) έχουν προσφέρει καινοτόμα εργαλεία και αμέτρητες ευκαιρίες για την προώθηση νέων πρωτοβουλιών στις έξυπνες πόλεις. Το IoT παρέχει τα μέσα για την απομακρυσμένη παρακολούθηση, διαχείριση και έλεγχο συσκευών, και τη δημιουργία νέων πληροφοριών και δράσεων που μπορούν να ενεργοποιηθούν από δεδομένα που λαμβάνονται σε πραγματικό χρόνο. Η διαχείριση της ενέργειας είναι ένα από τα πιο απαιτητικά ζητήματα στα αστικά κέντρα, λόγω της πολυπλοκότητας των ενεργειακών συστημάτων και του ζωτικού τους ρόλου. Ο δημόσιος φωτισμός είναι μια σημαντική κοινοτική υπηρεσία που μπορεί να καταναλώσει έως και το 40% του ενεργειακού προϋπολογισμού μιας πόλης. Κατά συνέπεια ο φωτισμός έχει αναδειχθεί ως κορυφαία έξυπνη εφαρμογή για τις πόλεις. Στόχος της διπλωματικής εργασίας είναι η εννοιολογική και πρωτότυπη κατασκευή μιας εφαρμογής έξυπνου φωτισμού για τη παραθαλάσσια προβλήτα της πόλης του Ηρακλείου. Ανάλογα με την ένταση του ανέμου στη διαδρομή, τα έγχρωμα φώτα θα χρησιμοποιηθούν για να μεταδώσουν πληροφορίες σχετικά με την κατάσταση ασφαλείας σε πιθανούς επισκέπτες του πεζόδρομου. Η προτεινόμενη λύση υποστηρίζει την χρήση ασύρματου δικτύων αισθητήρων για να δημιουργήσει ένα πλέγμα μικροελεγκτών χαμηλού κόστους που θα ρυθμίζουν την λειτουργία του φωτισμού με βάση τα περιβαλλοντικά δεδομένα. Το όλο σύστημα έχει σχεδιαστεί με πρωτοβουλίες ανοικτού κώδικα και προσφέρει μια διαδικτυακή εφαρμογή διαχείρισης, γεγονός που καθιστά εύκολη την ενσωμάτωση με την υπάρχουσα διαδικτυακή υποδομή του Δήμου. Η κύρια καινοτομία του συστήματός μας είναι η χρήση ανοικτών προτύπων, η χαμηλού κόστους ενσωμάτωση στην υπάρχουσα υποδομή φωτισμού χωρίς την ανάγκη τροποποιήσεων και η προστιθέμενη αξία από τις δυνατότητες εγγύτητας των χρησιμοποιούμενων μικροελεγκτών.

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List of Abbreviations

<i>IoT</i>	Internet of Things
<i>RFID</i>	Radio-frequency Identification
<i>IR</i>	Infrared Receiver
<i>GPS</i>	Global Positioning System
<i>WSN</i>	Wireless sensor networks
<i>BLE</i>	Bluetooth Low Energy
<i>ICT</i>	Information and Communication Technology
<i>LED</i>	Light-Emitting Diodes
<i>MCU</i>	Microcontroller Unit
<i>SSL</i>	Solid-State Lighting
<i>OLED</i>	Organic Light-Emitting Diode
<i>CPU</i>	Central Processing Unit
<i>RISC</i>	Reduced Instruction Set Computer
<i>HCI</i>	Host Controller Interface
<i>UUID</i>	Universal Unique Identifier
<i>RSSI</i>	Power Level Indication
<i>LTE</i>	Long Term Evolution
<i>MH</i>	Metal-halide
<i>SoC</i>	System on Chip
<i>PDM</i>	Digital Microphone Interface
<i>Pi</i>	Raspberry Pi Zero W
<i>RF</i>	Radio Frequency
<i>TTL</i>	Time to Live
<i>URL</i>	Uniform Resource Locator
<i>MQTT</i>	Message Queuing Telemetry Transport
<i>TCP/IP</i>	Transmission Control Protocol/Internet Protocol
<i>M2M</i>	Machine-to-Machine
<i>ARM</i>	Advanced RISC Machine
<i>ISM</i>	Industrial, Scientific and Medical Radio Bands
<i>NFC</i>	Near Field Communication

1 Introduction

With the expeditious rise of urban populations during the last decades, modern cities are called to manage a growing number of technical, social and organizational issues, while at the same time meeting the increased expectations of their residents regarding their quality of life. These challenges have created an urgent need for cities to find smarter ways to deal with them (Nam & Pardo, 2011). As noted by (Kitchin, 2015), smart cities are “increasingly driven by technically inspired innovation, creativity and entrepreneurship”. Cities are becoming smart not only in terms of the way they can automate routine functions serving individual persons, buildings, and traffic systems but in ways that enable them to monitor, understand, analyze and plan the city to improve the efficiency, equity and quality of life for its citizens in real time (Batty, et al., 2012)

One of the essential components of urban development for a smart city should include smart technology, smart industry, smart services, smart management and smart life. Smart lighting systems are of particular interest as they evolve from traditional lighting control by introducing autonomous control of light through feedback from integrated sensors, user data, cloud services and user input, bringing with it a host of benefits including increased energy savings, enhanced functionality, and user-centric lighting (Chew, Karunatikala, Tan, & Kalavally, 2017). Creative street lighting deployments can enhance cultural aesthetics, promote public safety and well-being, while color combinations can affect behavioral and attitudinal practices of the citizens. By applying particular colors the citizens can be visually alerted of environmental hazards, like fierce winds or big waves, in a particular area.

The Internet of Things (IoT) is one of the key components of the ICT infrastructure of smart sustainable cities as an emerging urban development approach due to its great potential to advance environmental sustainability (Bibri, 2018). IoT is about installing sensors (RFID, IR, GPS, laser scanners, etc.) for everything, and connecting them to the Web through specific protocols for information exchange and communications, in order to achieve intelligent recognition, location, tracking, monitoring and management. With the technical support from IoT, smart city need to have three features of being instrumented, interconnected and intelligent (Kim, Ramos, & Mohammed, 2017). The tremendous rise of Smart Cities and IoT applications has

created the need for the development of efficient, scalable and reliable solutions that can work effortlessly with the existing infrastructure in urban areas. New open standards, protocols, architectures and services are constantly designed to better suits the needs of Smart Cities and overcome existing challenges.

The backbone of the IoT is the underlying networking technology that make it possible for physical devices, sensors, home appliances and other items embedded with electronics, to connect and exchange data. Wireless sensor networks (WSNs) have gained popularity within the research community and the industry because they provide a promising infrastructure for numerous control and monitoring applications. These simple low-cost networks allow monitoring processes to be conducted remotely, in real-time and with minimal human intervention (Pule, Yahya, & Chuma, 2018). A typical WSN network usually consists of two main components, nodes and base-station, as shown in Figure 1. A node is a device that commonly includes sensing, processing and communication capacities, while the base station is responsible for collecting and processing the data from all the nodes, while also providing gateway services that make it possible for the data to be managed remotely (Bhende, Wagh, & Utpat, 2014).

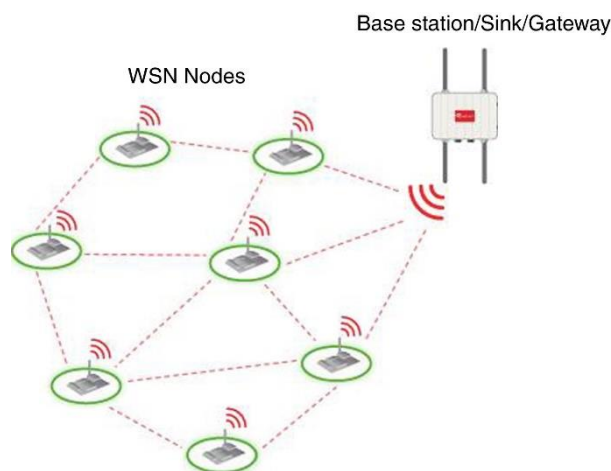


Figure 1: WSN topology (*Libelium, 2016*)

WSNs based around mesh network topologies have proved themselves to offer an effective approach to providing coverage of large areas, extending range and providing resilience. These systems run on a mesh topology network, with the information traveling a web of nodes, which can ‘talk’ directly to each other without the need to be connected to a central external network, until they reach the desired destination. Usage of WSNs in various Smart Cities initiatives has seen a huge increase, despite their

inherently resource constraints, such as limited amount of energy, short communication range, low bandwidth, and limited processing are there and there is stored in each node (Bhende, Wagh, & Utpat, 2014). Wireless mesh networks like Zigbee and Z-Wave are used extensively on home and building automation, smart lighting, traffic management systems, environmental monitoring, safety and security.

One of the more recent addition to mesh network solutions is the Bluetooth Mesh specifications released by the Bluetooth Special Interest Group (SIG)¹ on July 2017. Bluetooth mesh is a new topology available for Bluetooth Low Energy (BLE) devices and applications. Previously Bluetooth devices have been using point-to-point connectivity or broadcasting topologies to communicate with other devices. Bluetooth Mesh extends that and allows both many-to-many device communications via managed flooding and using Bluetooth devices in a mesh topology. This enables multi-hop communications between Bluetooth devices and mush larger-scale Bluetooth device networks that have been possible previously. Using Bluetooth mesh networking make it possible for the microcontroller unit to be used also as a beacon for providing localized information, asset-tracking and way-finding services. Standardization and widespread adoption of BLE, together with low-power consumption and beacon capabilities, makes Bluetooth mesh technology a suitable candidate for smart lighting solution in our specific case.

1.1 Scope and Objective

As cities becomes smarter, the public infrastructure benefits from features that improve safety and drastically reduce energy consumption costs. Smart streetlights, consisting of solid-state lighting (usually LEDs) equipped with sensors that can adjust light output to weather conditions and have networking capabilities, can play a vital role on reaching these goals. Despite all the benefits of LEDs streetlights, only about 10 percent of the about 300 million streetlights around the globe are LEDs, and it is estimated that only 1 percent of those are connected to a network (Marino, Leccese, & Pizzuti, 2017). Is becoming more and more apparent though that in the mid and longer-term, LED streetlights will be interlinked and dynamically interact with other city infrastructures, such as ICT and sensor networks, energy, facility, mobility and street lighting management systems, as well as renewable energy systems (Commision, 2013)

¹ <https://www.bluetooth.com/>

The reasons for the slow conversion is that outdoor lighting in public spaces presents a plethora of obstacles and challenges, ranging from technical to policy issues. The issues that Smart Cities face on public outdoor lighting can be grouped to three key challenges, namely financial, technical and regulatory, with each Municipality coming up with different solutions to overcome these challenges (Department of Energy, 2016). The cost of LED based street lighting systems are gradually lowered steadily during the last few years. Still, the initial capital investment for LED based street lighting is higher than that for conventional systems, but that is balanced by energy savings costs and the fact that the cost for maintaining LED street light systems is significantly lower than conventional lights. As LED technology evolves rapidly by offering consistently high-quality light output using smaller components and greater interoperability with other digital platforms, municipalities lack the expertise or capacity to assess reliability or performance concerns, and are often reluctant to change their existing conservative approach regarding street lighting until the LED technology has reached market maturity. The advancement on LED street light technology are proceeding on a fast pace, with areas like metering infrastructure, networked lighting control systems, networked adaptive lighting and sensor integration seeing constant development from many different companies and platforms. With issues like interoperability among components and architectures being all too real, municipalities have difficulties on choosing among the different technologies and communication protocols available, each of them with their specific advantages and disadvantages, for fear of lock-in effects on one or another proprietary system and components. One approach that many cities have taken to overcome those concerns is by conducting pilot programs on a low scale testing different products available on the market, including wireless monitoring and control systems, while taking into account local factors, like weather conditions and the surrounding landscape.

Every city has different needs so a unique approach is needed for its smart lighting system, taking into account the overall urban lighting strategy and a clear understanding of the lighting requirements and any shortcomings associated with the existing lighting infrastructure. Looking at the different existing smart lighting initiatives around Europe and from a societal needs point of view, we can identify the following characteristic that a smart lighting system needs to have, namely to be adaptable, interactive, modifiable, modular and open (Takhamo, 2014). The system needs to be adaptable to

different situations, like presence of citizens, pre-set schedules, season and weather conditions. Taking into accounts external data, it needs to adapt color, luminous flux and intensity distribution. The interaction with a smart lighting system can be informative and communicate visually messages to citizens, alerting of possible hazards and highlighting points of interest. The interface to interact with it needs to versatile and user-friendly, manageable from a remote location or on-site. Being on a network, updating system variables and upgrading it becomes easy and low-cost. Different components of the system can be modified securely and new services can be implemented as the needs arise and new technology advancements become available. Modularity makes it possible to reuse resources and integration with other Smart Cities initiatives. System management becomes easier and different parties involved on it can separate maintenance tasks. Open smart lighting system need to avoid dependence on proprietary solutions and niche technologies. Open standards and well-established technologies and architectures makes it possible to connect with other systems and offer compatibility with existing infrastructure.

In this Master Thesis, we use as a starting point the above guidelines to design a proof-of-concept smart lighting network and control system prototype to be used on the pier walkway of the city of Heraklion. The proposed solution is designed to support the recently released Bluetooth mesh specifications to create a network of low-cost microcontrollers (MCUs) that will regulate Bluetooth enabled lighting bulbs based on environmental input, pre-set schedules and user input. We examine proposed implementation in the literature based on different technologies and advocate that our implementation is more suitable for our case, due to its openness, the low-cost integration to the existing lighting infrastructure without the need for modifications and the value-added by the proximity (BLE beacons) capabilities of the used MCUs. Microcontrollers are ideally suited for BLE usage due to their ultra-low-power consumption and low cost, and work well with the light, temperature and humidity sensors that we implement on our board. To streamline programming and interaction with the MCU we use Espruino, an open-source run-time interpreter that allows resource constrained microcontrollers to be wirelessly programmed entirely in Javascript. A Raspberry Pi microcomputer is used to act as a gateway to connect the system to the Municipality wireless network, making it possible to collect and process data that are collected by the MCUs in-real-time, and we build a web-based interface

to interact with the system, which make it easy to integrate with existing Municipality infrastructure. Our hope is to pave the way for an on-site implementation of our proposed system on the pier walkway, and to motivate also other initiatives to use the site as a playground for smart lighting experimentation, using the results to provide Municipality with concrete data about the best practices and technologies that can be employed on a more city-wide scale.

1.2 Thesis Overview

The thesis is organized in seven chapters, as follows:

- **Chapter 1:** the current chapter, includes a brief introduction of the topic, highlights the scope and the main objectives of this dissertation.
- **Chapter 2:** provides the theoretical background for understanding basic related concept of the technologies and architectures used on smart lighting systems, like sensor networks, mesh topologies, hardware and software components.
- **Chapter 3:** presents an elaborate review of related work in an effort to identify, review and analyze the findings of all related studies and projects on indoor and outdoor smart lighting published during the last five years.
- **Chapter 4:** explains in detail the technical implementation. In this chapter, the smart lighting system that was developed during this master thesis is described in detail along with an introduction to Bluetooth Mesh specifications. Lastly, the web-based management applications is presented.
- **Chapter 5:** presents the validation results from the analysis of testing's performed on simulated situations and describe the value-added applications of proximity capabilities of our system.
- **Chapter 6:** includes the discussion over the results.
- **Chapter 7:** is the last chapter of this thesis and includes the conclusion and the possible directions to follow in future work.

2 Adopted Technologies

In this chapter we provide some background information to help the reader understand the concepts and technologies discussed in this proposal. At first, Section 2.1 provides general information about solid-state lighting (SSL) and their advantages over conventional lighting technologies. Section 2.2 offers a look on low-power microcontrollers and sensors, and their applications on lighting and other aspects of Smart Cities. Then, section 2.3 presents Bluetooth Low Energy. Section 2.4 describes IEEE 802.15.4, Zigbee, Z-wave, Bluetooth Mesh and 6LoWPAN, which are popular standards for low-power wireless communications and are usually used in existing smart outdoor lighting solutions. Finally, section 2.5 is dedicated to BLE beacons technologies and their applications in proximity-based services.

2.1 Solid-state lighting

Solid-state lighting (SSL) is energy-saving, energy-efficient green technology that has the potential to replace conventional lighting systems through the use of semiconductor light-emitting diodes (LEDs), organic light-emitting diodes (OLEDs), and polymer light-emitting diodes (PLEDs) instead of electrical filaments, plasma or gas. There is huge opportunity for environmentally friendly technology to flourish with SSL, which is designed to be compact, cost-effective, energy efficient, UV free and with wide variety of designable features, and eventually a high-quality replacement for incandescent and fluorescent lamps (Kalyani, Swart, & Dhoble, 2017).

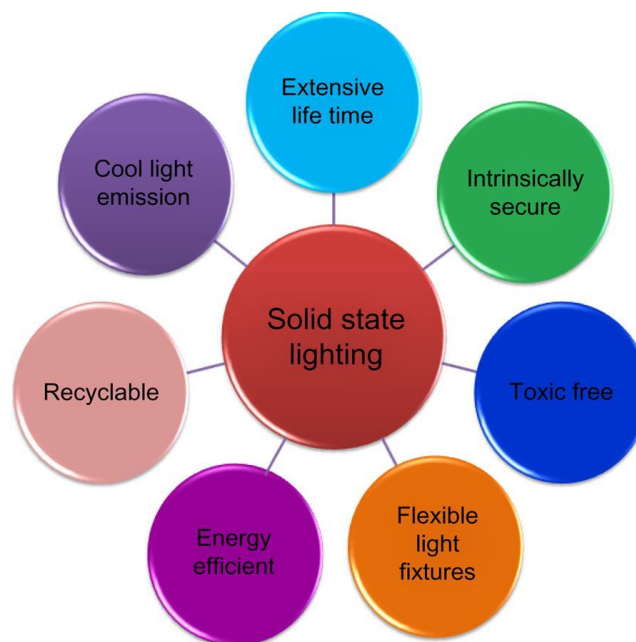


Figure 2: Solid-State Lighting (Kalyani, Swart, & Dhoble, 2017)

The phenomenon of electroluminescence was first observed by Henry Joseph Round in 1907, who later invented the first LED. With the arrival of semiconductors during the 1950s, a lot of research was conducted to replace existing lighting and display technologies by using them. In the mid-1990s Dr Shuji Nakamura invented high brightness GaN blue LED (Nakamura & Fasol, 1997), which opened the way for the development of white LED. LED is a two-lead semiconductor light source. It is a p-n junction diode that emits light when activated. When a suitable voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons.

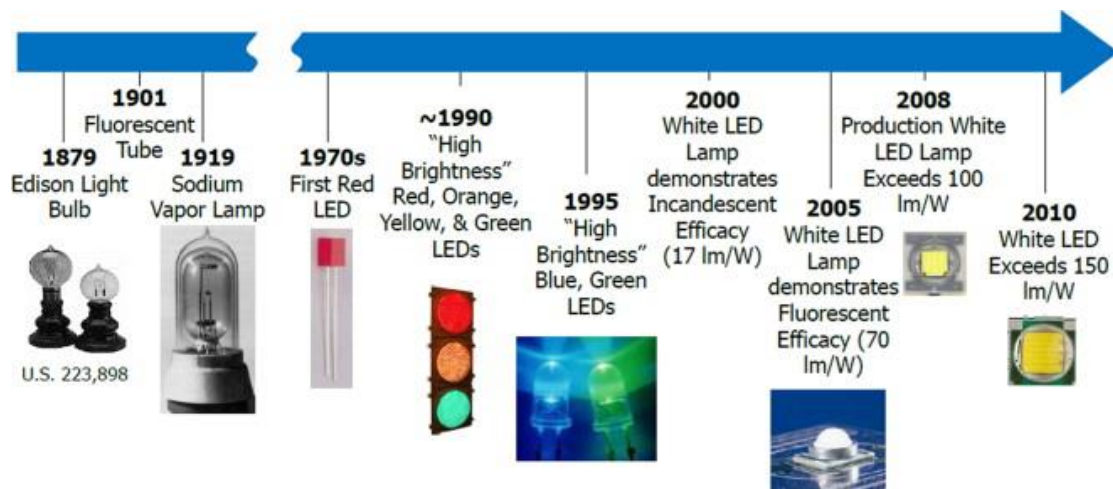


Figure 3: Brief history of lighting, highlighting milestones in LED development (Almeida, Santos, Paolo, & Quicheron, 2014)

LEDs have many advantages over incandescent light sources, including lower energy consumption, longer lifetime (around 35000-50000 hours of usage), improved physical robustness, smaller size, and faster switching. LED circuits are very small in size and are very easily integrated on printed circuit boards. They do not need to go on a heating or warming phase and reach their declared brightness on milliseconds (Krames, et al., 2007). Regarding monochromaticity, LEDs have much better efficiency than conventional lights, producing much more light for each watt (Wang, Wang, Chen, & Liu, 2011). They are considered green products, constructed with materials that do not contain elements that are not safe for the environment or living organisms, like for example lead or mercury. The research on lighting solutions has shown much promise for the future, with organic light-emitting diode (OLED) technology, made from organic, carbon-based components, having the potential to be used in next-generation lighting applications.

2.2 Microcontrollers

The term microcontroller defines a very small-scale computing unit that are integrated on a single circuit. Since usually MCUs are constructed to control a particular device in which they are embedded or accomplish a particular task, most of the times they have different characteristic that the microprocessors that are utilized for computing machines of a general purpose. The applications of MCUs are far and wide and they are found almost everywhere, on domestic appliances, factory automation, electronic devices, medical equipment, toys and even clothes.

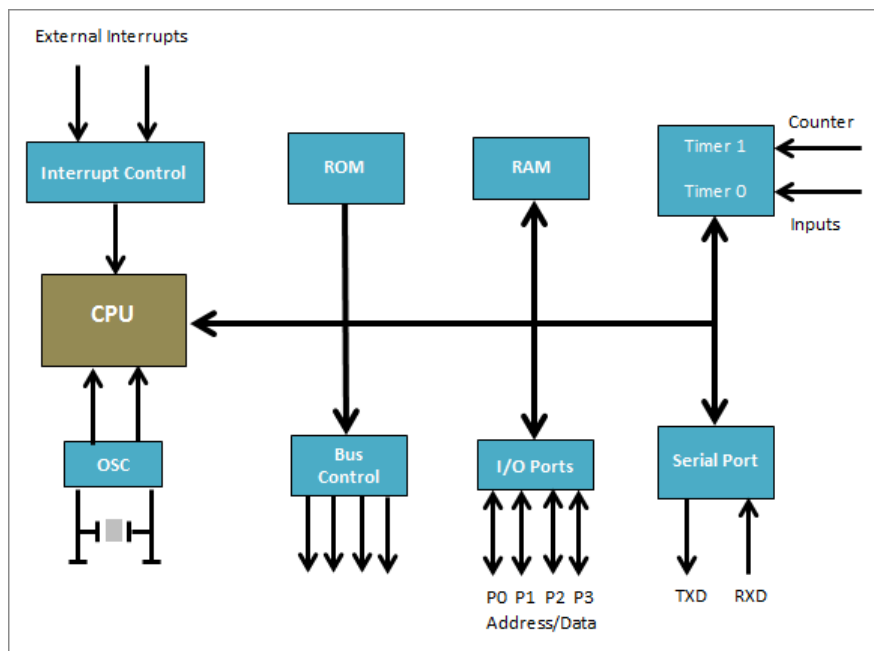


Figure 4: Intel 8051 microcontroller architecture (*CircuitDigest, 2016*)

A typical MCU consisted of three main parts, more particularly core, the circuit memory and any additional peripherals added. The core is consisted of one or more processing units (CPU) and the circuitry needed to control it. The memory consists of data memory used to store data and program memory that runs the instructions that the MCU is programmed with. The peripherals are the elements that truly make a MCU different from a microprocessor, allowing the MCU to interact with other systems and the outside world. Some common peripherals included on MCUs are digital or analog IO, counters, network components, timers and different types of sensors. One essential component of every computing unit is to have a clock signal, in case of MCUs this is usually made possible using a quartz oscillator. One feature of MCUs that have made them so popular is their low-power consumption, making it possible for them to run for many years on batteries.

The architecture that is the most widespread in the world of MCUs is the ARM architecture, with a huge adoption in embedded applications and products, and a solid support from the software perspective. ARM microprocessors are 32-bit and follow the RISC approach, in which each instruction is executed in a single data memory cycle at most. Because of the small set of instructions a RISC CPU is able to execute a set of instructions very fast and allows for optimized advanced design features, for example pipelining, where as an instruction executes, the next instruction can be loaded from memory and be ready for execution. Because of this simplicity in design RISC architecture can achieve very low-power consumption and that makes it ideal for embedded systems.

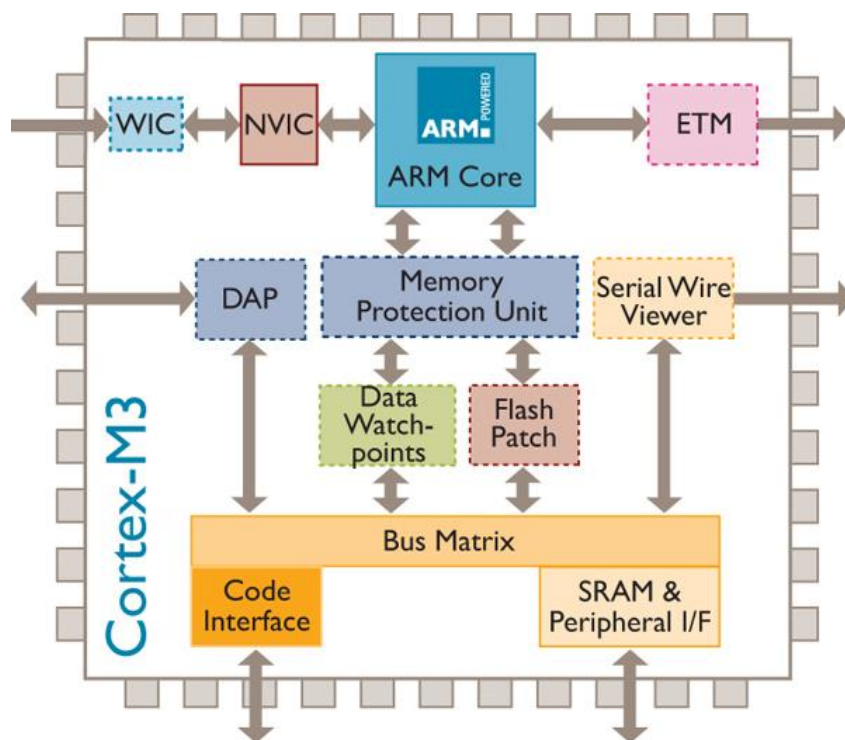


Figure 5: ARM Cortex-M3 processor (*Embedded Insights, 2018*)

2.3 Bluetooth Low Energy

BLE is used in very low power network and Internet of Things (IoT) solutions aimed for low-cost battery operated devices that can quickly connect and form simple wireless links. The key features of Bluetooth wireless technology are robustness, low-power consumption, and low cost. There are two forms of Bluetooth wireless technology systems: Basic Rate (BR) and Low Energy (LE). Both systems include device discovery, connection establishment and connection mechanisms. The LE system includes features designed to enable products that require lower current consumption,

lower complexity and lower cost than BR. The LE system is also designed for use cases and applications with lower data rates and has lower duty cycles.

As defined by Bluetooth Sig “the Bluetooth core system consists of a Host and one or more Controllers. A Host is a logical entity defined as all of the layers below the non-core profiles and above the Host Controller Interface (HCI). A Controller is a logical entity defined as all of the layers below HCI. An implementation of the Host and Controller may contain the respective parts of the HCI. An implementation of the Bluetooth Core has only one Primary Controller, which in case of an LE Controller includes the LE physical layer (PHY), Link Layer and optionally HCI. A Bluetooth core system may additionally have one or more Secondary Controllers.

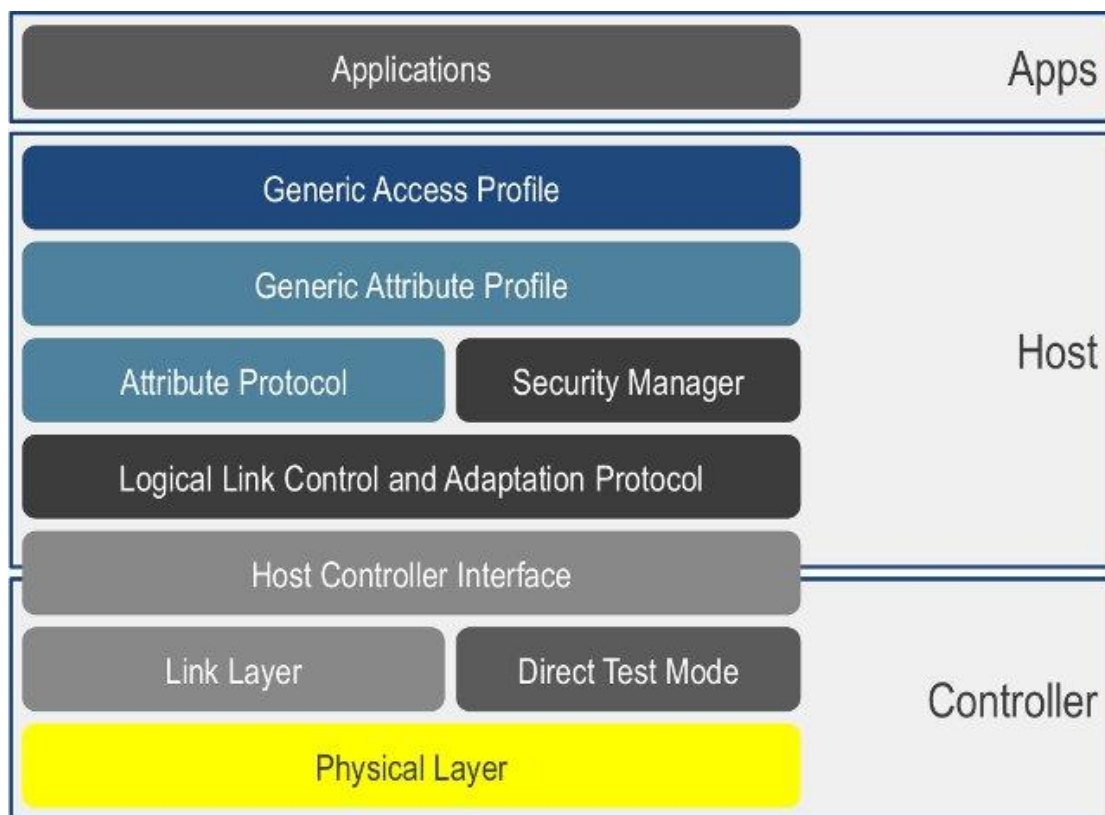


Figure 6: Bluetooth stack Architecture (CNXSoft, 2018)

LE radio operates in the unlicensed 2.4 GHz ISM band. The LE system employs a frequency hopping transceiver to combat interference and fading and provides many FHSS carriers. LE radio operation uses a shaped, binary frequency modulation to minimize transceiver complexity. The mandatory symbol rate is 1 megasymbol per second (Msym/s), where 1 symbol represents 1 bit therefore supporting a bit rate of 1 megabit per second (Mb/s). LE employs two multiple access schemes: Frequency division multiple access (FDMA) and time division multiple access (TDMA). Forty

physical channels, separated by 2 MHz, are used in the FDMA scheme. Three are used as primary advertising channels and 37 are used as secondary advertising channels and as data channels. A TDMA based polling scheme is used in which one device transmits a packet at a predetermined time and a corresponding device responds with a packet after a predetermined interval. The physical channel is sub-divided into time units known as events. Data is transmitted between LE devices in packets that are positioned in these events. There are four types of events: Advertising, Extended Advertising, Periodic Advertising, and Connection events.” Devices that transmit advertising packets on the advertising PHY channels are referred to as advertisers. Devices that receive advertising packets on the advertising channels without the intention to connect to the advertising device are referred to as scanners. Transmissions on the advertising PHY channels occur in advertising events. At the start of each advertising event, the advertiser sends an advertising packet corresponding to the advertising event type. Depending on the type of advertising packet, the scanner may make a request to the advertiser on the same advertising PHY channel which may be followed by a response from the advertiser on the same advertising PHY channel. The advertising PHY channel changes on the next advertising packet sent by the advertiser in the same advertising event. The advertiser may end the advertising event at any time during the event. The first advertising PHY channel is used at the start of the next advertising event. BLE also brings the possibility of doing broadcasting from one device to many devices, and that is the way how beacons work for example, where one device send a message and many devices are able to receive it.

With Bluetooth 5 release, Bluetooth become even better than Bluetooth 4.2, with the speed being twice faster, four times more range and as much as 200 meters outdoor, and even less power consumption. Bluetooth 5 also introduces advertising extensions, which in effects expand the payload size from 27 bytes to 251 bytes for more efficient data transfer. One of the application of this feature is for beacon applications, allowing beacons to send more information in the advertising packet to nearby smartphones.

2.4 Wireless sensor network technology

Wireless sensor networks are a group of specialized devices which are used to monitor different environmental conditions and to collect and organize that data at some certain central location. In a sensor node, the functionality of an embedded processor is to schedule tasks, process data and control the functionality of other hardware

components. The types of embedded processors that can be used in a sensor node include Microcontrollers, Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA) and Application-Specific Integrated Circuit. Among all these alternatives, the Microcontroller has been the most used embedded system for sensor nodes because of its flexibility to connect to other devices and its cheap price. The sensed data can be collected by a few sink nodes which have accesses to infrastructured networks, like Internet. There are four common sensor network topologies, namely point to point network, star network, tree network and mesh network.

On point to point network topology there is no central hub. A node can communicate directly to another node. This is the most common topology and it has a single data communication channel which offers a secure communication path. Each device can act as a client and a server in it.

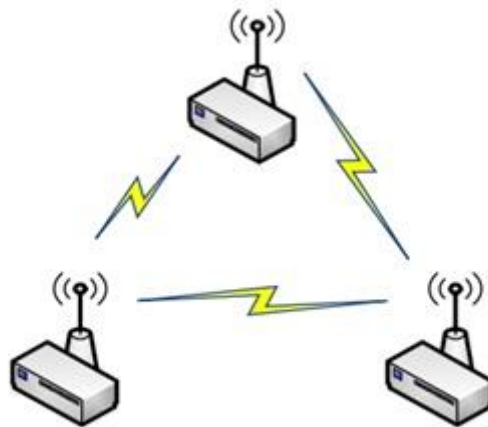


Figure 7: Point to point topology (*Microcontrollers Lab, 2018*)

Unlike point to point networks, a centralized communication hub is present in a star network. Each communication is done through this centralized hub and no direct communications between the nodes are possible. In this case, central hub is the server and the nodes are clients.

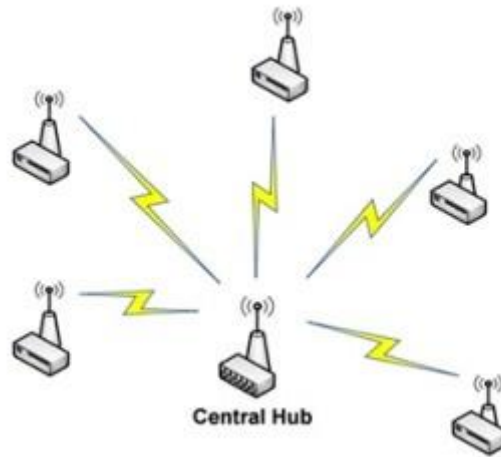


Figure 8: Star network topology (*Microcontrollers Lab, 2018*)

Tree network topology is said to be a hybrid of point to point and star topologies. The central hub in it is called a root node or the parent node. Data is passed on from leaf nodes to the parent node. The main advantage of this topology is less power consumption as compared to other networks.

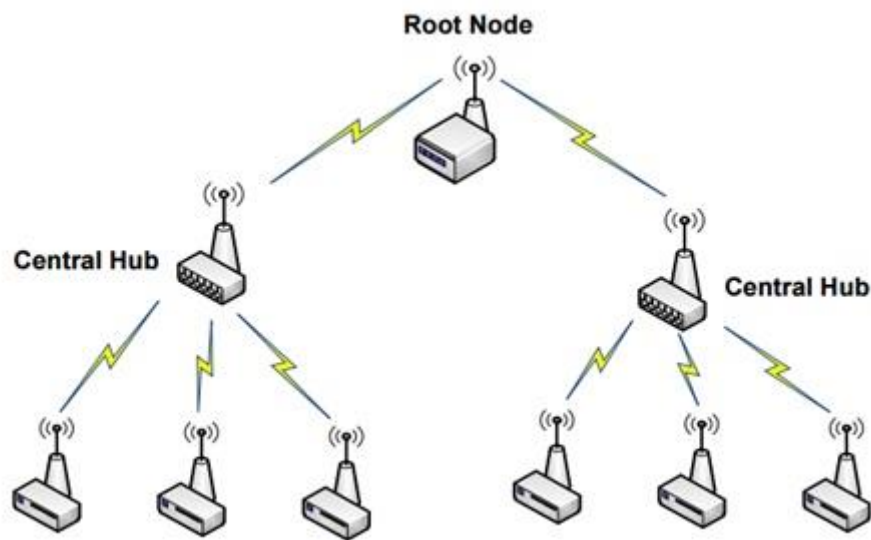


Figure 9: Tree network topology (*Microcontrollers Lab, 2018*)

In the mesh network, the data can ‘hop’ from one node to another. All the nodes can communicate with each other directly without having to depend on a central communication hub. This is the most reliable structure of network communication because there is no single point of failure in it.

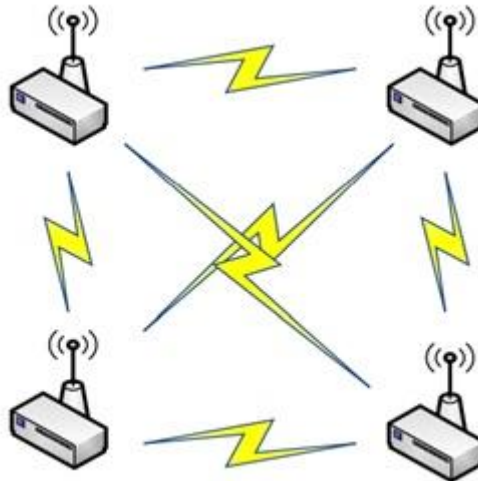


Figure 10: Mesh network topology (*Microcontrollers Lab, 2018*)

Wireless sensor networks differ from traditional ad hoc networks in a few very significant ways:

- Power awareness. Because nodes are placed in remote, hard to reach places, it is not feasible to replace dead batteries. All protocols must be designed to minimize energy consumption and preserve the life of the network.
- Sensor nodes lack global identifications (IDs), so that the networks lack the usual infrastructure. Attribute-based naming and clustering are used instead. Querying WSNs is done by asking for information regarding a specific attribute of the phenomenon, or asking for statistics about a specific area of the sensor field. This requires protocols that can handle requests for a specific type of information, as well as data-centric routing and data aggregation.
- Position of the nodes may not be engineered or pre-determined, and therefore, must provide data routes that are self-organizing.

A protocol stack for WSNs must support their typical features and singularities. According to (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002) “the sensor network protocol stack is much like the traditional protocol stack, with the following layers: application, transport, network, data link, and physical. The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation and data encryption. The data link layer is responsible for the multiplexing of data streams, data frame detection, medium access and error control. It ensures reliable point-to-point and point-to-multipoint connections in a communication

network. The network layer takes care of routing the data supplied by the transport layer.

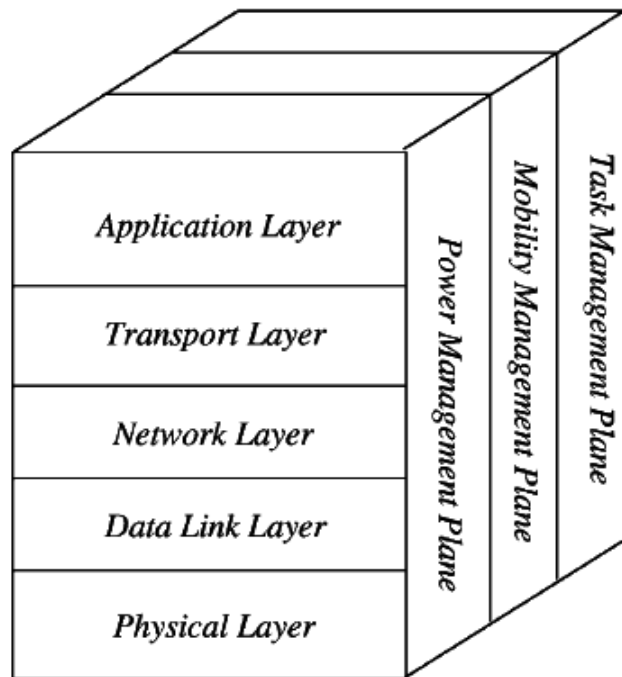


Figure 11: WSN protocol stack (*Intech, 2018*)

The network layer design in WSNs must consider the power efficiency, data-centric communication, data aggregation, etc. The transport layer helps to maintain the data flow and may be important if WSNs are planned to be accessed through the Internet or other external networks.”

The dominant issue that all WSNs have to deal with is congestion, which can be caused for different reasons. Some of these reasons can be buffer overflow, transmission made on the same time and packet collisions. One of the results of congestion is packet loss, and this can will affect negatively throughput and the energy required to resend the data packages. Communication in sensor networks can be broadly classified into two classes, data and control messages. Data messages, which will clearly be in majority in any application, are those messages which involve transfer of sensor data in one way or the other. Control messages broadly encompass all communication which do not involve transfer of user or sensor data. They include messages used for configuration, topology detection, neighbor discovery, route discovery, time synchronization, reprogramming, reliability and network management such as congestion and flow estimation and recovery. Since control messages are more essential than data messages, they have a higher priority in case of a congested input queue in a node, so they do not

get dropped. Below we review the most used wireless network technologies used in SWNs.

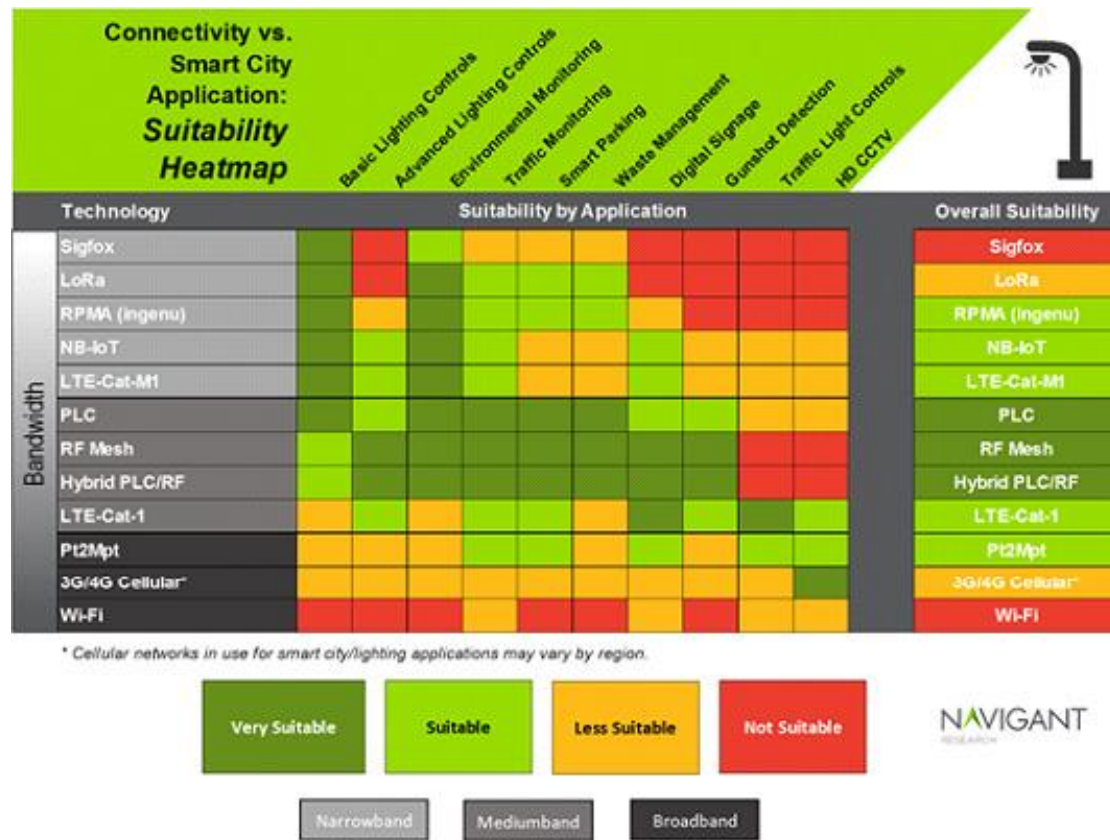


Figure 12: Networking technology heatmap (Navigant Research, 2017)

2.4.1 Zigbee

According to Zigbee Alliance “ZIGBEE is a wireless technology guided by the IEEE 802.15.4 Personal Area Networks standard. It is primarily designed for the wide ranging automation applications and to replace the existing non-standard technologies. It currently operates in the 868MHz band at a data rate of 20Kbps in Europe, 914MHz band at 40Kbps in the USA, and the 2.4GHz ISM bands Worldwide at a maximum data-rate of 250Kbps. The ZIGBEE specification is a combination of Home RF Lite and the 802.15.4 specification. The specification operates in the 2.4GHz (ISM) radio band, the same band as 802.11b standard, Bluetooth, microwaves and some other devices. It is capable of connecting 255 devices per network. The specification supports data transmission rates of up to 250 Kbps at a range of up to 30 meters (Gungor, Hancke, & Member, 2009). ZIGBEE's technology is slower than 802.11b (11 Mbps) and Bluetooth (1 Mbps) but it consumes significantly less power.”

2.4.2 Bluetooth Mesh

Bluetooth Mesh is the newest addition on the WSN arena, is a protocol based upon Bluetooth Low Energy that allows for many-to-many communication over Bluetooth radio. Communication is carried in the messages that may be up to 384 bytes long, when using Segmentation and Reassembly (SAR) mechanism, but most of the messages fit in one segment, which is 11 bytes. Although we do not implement a Bluetooth Mesh solution in this thesis, we strongly believe that Bluetooth Mesh is the most plausible WSN choice at the moment, due to its open specifications, availability from different system on a chip (SOC) manufacturers, and the ability to interact with smartphones via BLE. For these reasons we will go on more details about Bluetooth Mesh on Section [4.2.5](#).

2.4.3 Long range wide area network (LoRAWAN)

“LoRaWAN is a technology that has been designed for applications that need to send small amounts of data over long distances a few times per day. Its low power features offers the capability to achieve autonomy of up to 10 years (LoRa Alliance, 2015). LoRaWAN data rates range from 0.3 kbps to 50 kbps. LoRaWAN network architecture is typically laid out in a star-of-stars topology in which gateways is a transparent bridge relaying messages between end-devices and a central network server in the backend. Gateways are connected to the network server via standard IP connections while end-devices use single-hop wireless communication to one or many gateways. All end-point communication is generally bi-directional, but also supports operation such as multicast enabling software upgrade over the air or other mass distribution messages to reduce the on air communication time.”

2.4.4 SigFox

SigFox is the world's first cellular network dedicated to low bandwidth Machine-to-Machine and Internet of Things applications. Its patented Ultra Narrow Band (UNB) technology utilizes unlicensed frequency bands to transmit data over a very narrow spectrum. Sigfox has a range capability of up to 40 km in open space (SigFox, n.d.). “Using the Ultra Narrow Band modulation, Sigfox operate in the 200 kHz of the publicly available band to exchange radio messages over the air. Each message is 100 Hz wide and transferred at 100 or 600 bits per second a data rate, depending on the region.”

2.4.5 Z-Wave

“Z-wave is a protocol for communication among devices used for home automation. It uses radio frequency (RF) for signaling and control. Z-wave operates at 868.42 MHz in Europe using a mesh networking topology contain up to 232 nodes.” A central, network controller, device is required to setup and manage a Z-wave network. Each Z-Wave network is identified by a Network ID and each device is further identified by a Node ID. Network ID has a length of 4 bytes and is assigned to each device by the primary controller when the device is added into the network. Z-Wave uses a source-routed mesh network topology and has one primary controllers.

2.4.6 IEEE 802.15.4

IEEE 802.15.4 is a standard for low data rate, low power networks. IEEE 802.15.4 defines the physical (PHY) and Medium Access Control (MAC) layers and forms the basis for numerous upper layer networking specifications available today. Whilst IEEE 802.15.4 does not implement any networking layers it has been a popular choice for networking implementations. It defines two types of node devices in a network a Full-Function Device (FFD) and a Reduced Function Device (RFD). Networks can be built using peer-to-peer or star topologies.

Wireless standards	Frequency band (MHz)	Data rates (kbps)	Range capability	Network topology	Comparative power consumption
IEEE 802.15.4	2400, 915, 868	250, 40, 20	100 m+	Star	Low
ZigBee	2400, 915, 868	250, 40, 20	100 m+	Star, tree and mesh	Low
Bluetooth	2400	720	10–100 m	P2P, star, mesh	High
LoRaWAN	915, 868	50	10 km+	Star	Very low
SigFox	902, 868	1	40 km	Star	Very low

Table 1: A comparison of WSN standards (Digi International, 2007)

2.5 BLE Beacons

Using BLE, it is possible to create Beacons, which are very simple Bluetooth Smart devices, that do little else than to periodically broadcast their identifier to nearby

portable electronic devices with small 31 byte data packages. The technology enables smartphones, tablets and other devices to perform actions when in close proximity to a beacon. The data that is transmitted with each advertisement pulse can include a universally unique identifier (UUID), a power level indication (RSSI), a major as well as a minor value, or a URL which could link to a webpage and is displayed on the users smartphone notifications panel.

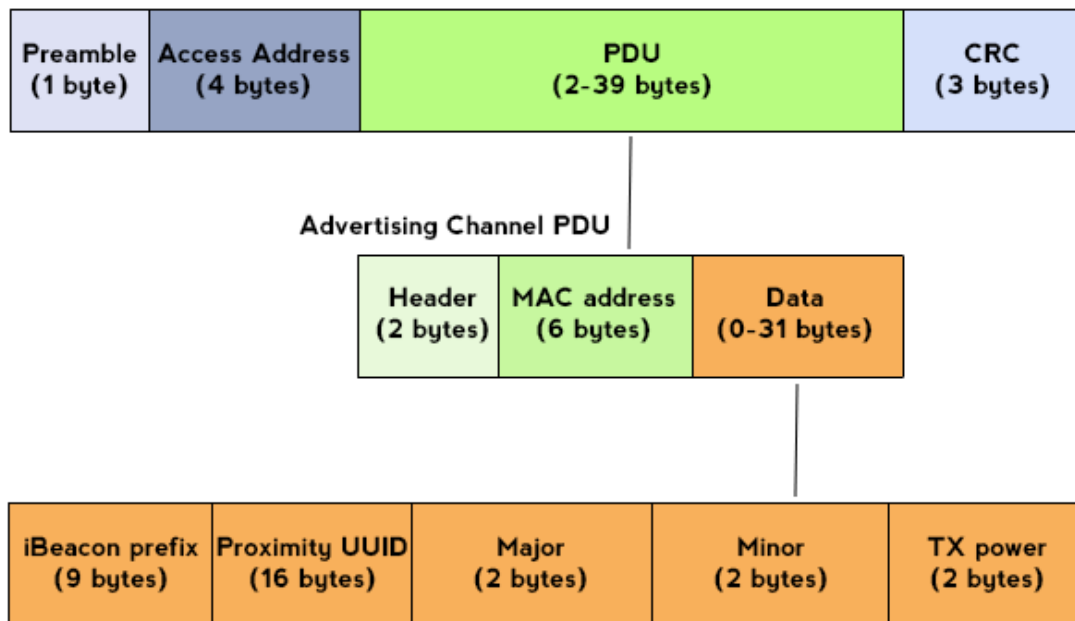


Figure 13: Beacon Advertisement PDU Breakdown

“The universally unique identifier (UUID) is represented in a special 128 bit (16-octets) string and is primarily used to identify beacons. This UUID is representative of a group, like a company, and is provided in the corresponding BLE application. Using the received signal strength indication (RSSI) sent with the advertisement package, it is possible to determine the approximate distance between a beacon and a user holding a BLE device. Although this measured distance is not completely accurate, and will deviate a little because of radio interference, it is still accurate enough to determine whether or not a user is within a certain distance from the beacon.”

3 Literature Review

From the invention of embedded technology many decades ago until today, numerous researchers and developers envisioned, designed and developed ubiquitous applications, to transform physical environments into smart spaces. Creating digital representations of the physical world is still an open research question, with a plethora of enabling drivers in the latest years, both in hardware and software. Hardware drivers include RFID technology, embedded sensors and actuators, QR codes, smart meters, smart power outlets, even nano-sensors. Software drivers involve middleware and frameworks for supporting interaction with pervasive areas, as well as operating systems and libraries that facilitate communication with smart devices. In this chapter, we have an in-depth look at the various proposal and implementations of smart lighting systems, various tools and methodologies to analyze and compare such systems. The chapter is organized as follows: Section 3.1 begins with comparative studies power consumption and lighting quality for LED and conventional lighting systems. Then, Section 3.2 presents various outdoor smart lighting solutions proposed and implemented in literature, together with their findings. Finally, in Section 3.3 we discuss different proposed control schemes and methodologies to analyze and compare smart lighting systems.

3.1 Smart lighting as a green technology

Smart lighting systems, with their ability to manipulate the light output via integrated sensors and user input, are considered to be the new paradigm in lighting technology and are taking their first steps to replace traditional lighting systems in modern cities (Chew, Karunatikala, Tan, & Kalavally, 2017). The ability to lower power consumption and the positive attitude and increased awareness of many cities toward using green technologies, have greatly helped in the adoption of smart lighting for outdoor and indoor environments (Haq, et al., 2014). The potential benefits of smart lighting systems are manifold, the most immediate being increased energy savings. As a consequence, most works in this fledgling field of study are currently focused on extracting maximum energy savings in conjunction with efficiently driven LEDs (Park & Lee, 2013) (Wang, Ruan, Yao, & Ye, 2011).

According to Haq et al, “the factors that affect the overall energy consumption of the lighting system can be understood from the basic equation of electrical energy consumption:

$$W = P \times T \text{ Watt hour (Wh)}$$

where P is the installed lighting power in Watt (W) and T is the operating time in hours (h). It is obvious that energy consumption W can be reduced by reducing either or both of the factors P and T. Installed lighting power (P) can be reduced using more efficient lamps, for example LEDs. An efficient lamp produces adequate amount of lighting output (lux) using as less power input as possible. The lux to watt ratio of lamps is called luminous efficacy. The higher the luminous efficacy of the lamp, the more efficient it is in using its input power. By using lamps with higher luminous efficacy, the overall lighting load can be significantly reduced. The lighting load can also be reduced by proper lighting design. Task lighting method in lighting design provides necessary levels of light where the tasks are performed, while maintaining a lower ambient lux level in other areas (Haq, et al., 2014).

Daylight-linked control systems also play a role in reducing lighting power (P) by utilizing the level of available daylight in the environment (Roisin, Bodart, Deneyr, & Herdt, 2008). Based on the daylight level on an area, the daylight-linked lighting control systems either switch or dim the light fixtures to maintain adequate light levels required for the task performed in the environment. In spaces where there is significant daylight penetration, lighting load can be considerably decreased by the control systems using switching or dimming method. When it comes to reducing the operating hour (T), institutional scheduling system like time switches can be useful. Occupancy sensors detect the presence of occupants in the room and can switch off the lights when the control area is unoccupied. Thus the operating hours can be reduced, causing a reduction in lighting energy consumption.”

Many street lighting facilities are obsolete and highly inefficient that leads to higher energy requirements and continuous maintenance. In these years the efforts are focused on the use of new lighting technologies as LED and automated and remote management systems combined with smart sensor networks (Marino, Leccese, & Pizzuti, 2017). Many cities have installed LED and automated and remote management lighting system with promising results. In 2015 Milan replaced almost all the 140000 point lights for the Expo event with an investment of €91 million, passing from annual 114 millions of

kWh to 55 millions of kWh (A2A Media Relations, 2014). In 2013 Los Angeles installed 140000 LED street lights and reported energy savings of 63 percent and costs savings of around \$8.7 million, In 2014, New York replaced 250000 old lamps with LEDs and since 2017, the city will save \$14 million in energy and maintenance costs (Marino, Leccese, & Pizzuti, 2017). Birmingham has the largest municipal LED deployment in Europe so far, comprising of 90.000 streetlights. An effective public lighting strategy has been implemented incorporating a smart networked controls, allowing dawn and dusk trimming of lighting levels and dynamic lighting output management for lumen depreciation; and a real-time monitoring system that allows the collection of performance data with subsequent optimization of lighting control. They expect 50% energy savings leading to a 2 million pounds reduction in annual running costs.

Several programs run by different Research Centers showed positive results for photovoltaics-powered LED outdoor lighting system for a more sustainable and efficient service (Patel, Patel, Vyas, & Patel, 2011), ensuring also photometric performance (Femia & Zamboni, 2012), energy savings (Lee, Li, & Hui, 2011), reduction of light pollution and CO₂ emission (Leccese & Cagnetti, 2014). But the use of renewable sources requires reliable power grids and additional investments for the public administration (Marino, Leccese, & Pizzuti, 2017).

Although the majority of the literature regarding outdoor and indoor lighting is focused on the benefits of new LEDs solutions on energy performance, there are also other benefits on health and quality of life, like circadian performance, vision performance and color quality to name a few. On (Oh, Yang, & Do, 2014), the authors discuss the new efforts to measure the impact of LED white lighting on circadian rhythms of animals and plants, and propose changes to existing lighting solutions so as to have optimal results. According to (Anderson, Glod, Cao, & Lockley, 2009) short-wavelength LED light sources may be effective in Seasonal Affective Disorder treatment at fewer lux than traditional fluorescent sources. According to (Massa, Kim, Wheeler, & Mitchell, 2008) it seems likely that custom-designed lighting systems based on LED technology could significantly reduce insect, disease, or pathogen loads on certain crops. On (Falchi, Cinzano, Elvidge, Keith, & Haim, 2011) the authors claim that migration from the now widely used sodium lamps to white lamps, LEDs included,

would produce an increase of pollution in the scotopic and melatonin suppression bands of more than five times the present levels, supposing the same photopic installed flux.

3.2 Smart lighting implementations

Worldwide, Light Emitting Diode (LED) is emerging as the most energy efficient technology for lighting applications. Most of the existing applications focus on replacing existing street lighting units with the more energy efficient LED, but without any type of control to take advantage of its usage pattern (Pipattanasomporn, Rahman, Flory, & Teklu, 2014). In most of the cases, the existing lighting grid suffers from the lack of pervasive and effective communications, poor visibility, monitoring, fault diagnostics, and automation (Gungor, Lu, & Hancke, 2010). Many implementations have been proposed to create wireless remote control systems, using different hardware and software approaches (Marino, Leccese, & Pizzuti, 2017).

- Leccese et. al. implement “an intelligent lamppost managed by a remote control system that uses LED-based lightweight supply and is powered by renewable energy (solar panel and battery) (Leccese & Leonowicz, 2012). The management is implemented through a network of sensors to gather the relevant info associated with the management and maintenance of the system, transferring the data in wireless mode using the ZigBee protocol. The system consists of a group of measuring stations in the street (one station located in each lamppost) and a base station located nearby. The system is designed as a modular system, easily extendable. The measuring stations are used to observe street conditions as the intensity of daylight and, depending on the conditions they activate or off the lamps. Other factors influencing the activation are: climatic conditions, seasons, geographical location, and many possible alternative factors. For these reasons every lamp was designed independent to decide about the activation of light. The base station conjointly checks if any lamp is correctly operating and sends the message using the wireless network to the operator who will act in case of malfunction. The measuring station located in every lamppost consists of many modules: the presence sensor, the sunshine sensor, the failure sensor and an emergency switch. These devices work along and transfer the information to a microcontroller that processes the information and chooses the action. Every of those sensors has an assigned priority of transmission, for instance, the emergency switch takes precedence

over the others. The management center is that the hub of the system, since it permits the visualization and control of the complete lighting system. The prototype was tested in variable real-life conditions to verify the general functionality and determine points for improvement and optimization. First test demonstrated that the system was in a position to transfer data from any chosen lamppost to the management center when passing the info through the remaining lampposts. During these cases they obtained a transmission rate 99.98% to 100% depending on the placement of sending unit”. One of the main disadvantage of this approach is the very high initial costs for its deployment.

- Elejoste et. al. propose “an intelligent streetlight system following a three-level hierarchical model (Elejoste, et al., 2013). The lower level is composed by motes or end nodes, using a commercial device (Waspote). These devices are integrated on all the lamps in a section providing the computing power needed for its control and regulation. The motes include wireless transceivers to communicate with the other lamps of the section creating a mesh-type network among them. At this level the system's sensing capacity is established, allowing the whole network to successfully measure and characterize environmental changes. The second level of the hierarchy is composed of remote concentrators located in the electric cabinets that power each light section. An embedded micro server system is installed to control all the spotlights integrated on the system that are powered by the cabinet, consisting of XBee 802.15.4 transponders with DigiMesh™ firmware for the 2.4 GHz band. These data are transferred through mobile broadband network or, if possible, using existing WiFi or wired connections, to the Internet and from there to the remote control system's resources in the third level. The control panel provides a Rich Internet Application (RIA) to control the operation of the sections of luminaries included in the system, generate activity reports and detect anomalies in the operation of any of the components in the system. On a testing scenario in real situation, the energy consumption of the entire line of nine lights for a week without the proposed system was 98 kW/h and using the described system it is 67 kW/h, implying that the achieved average savings are around 40%”. The main disadvantages of this approach are the very high initial costs for its deployment, the usage of proprietary technologies and the fact that the motes need to be

powered from the power grid, which means that modifications need to be done to the existing infrastructure.

- Leccese et. al. implemented a smart lighting system “designed and organized in different hierarchical layers, which perform local activities to physically control the lamp posts and transmit information with another for remote control (Leccese, Cagnetti, & Trinca, 2014). Locally, each lamp post used an electronic card for management and a ZigBee tlc network transmits data to a central control unit, which manages the whole group of lights. The central unit was realized with a Raspberry-Pi control card due to its good computing performance at very low price. A WiMAX connection was tested and used to remotely control the smart grid, thus overcoming the distance limitations of commercial Wi-Fi networks”. Testing of the system showed an average reliability of 100% regarding its communication structure. This approach is not viable in all the situations, as WiMAX infrastructure is not present in many cities and in general its usage is declining in favor of LTE.
- (Bellido-Outeirino, et al., 2016) propose a smart lighting system composed of wireless nodes, which communicate in a wireless way using IEEE 802.15.4. At the intermediate level, managing the wireless networks of a lighting sector, we can find an industrial computer with 802.15.4 communication that also acts as the network’s coordinator. This computer contains an application that enables the comfortable and user-friendly management of a given sector’s lighting network. This local computer can also act as a gateway towards central control of the lighting network. The communication with the central control is executed through another communication network that allows for greater distances, such as 3G/GPRS, WIFI or WIMAX. Lastly, the upper level contains the central control, which groups several sectors of the lighting network. In the tree topology, the coordinator is located on the first level of the network, with several end devices and a router. The router forms a new network level consisting of several end devices and a new router, and so on until the desired number of levels required in each case is achieved. The number of leaps allowed by the network layer must be high. The Digital Addressable Lighting Interface (DALI) is designed to digitally control electronic ballasts and luminaries that uses protocol IEEE 802.15.4, and it was used because it allows for bidirectional

communication. They designed custom wireless nodes because of the limited number of market components supporting DALI. The energy savings that were found during testing were about 30%–40% of the overall operation time of each lamp. The main disadvantages of this system are the usage of non-standard components and the extensive requirement for wireless network coverage of the area with the lamps.

- (Kaleem, Yoon, & Lee, 2016) designed a “ZigBee-based energy efficient outdoor lighting control system. For outdoor lighting environment, they selected the Hanyang University Lake as a test field and installed the LED lamps accompanied by ZigBee module, light sensors, occupancy sensors, and temperature sensors. The lamps continuously monitor the intensity of the sunlight by using the sensors connected to it, and based on that intensity ATmega128 microcontroller unit (MCU) takes the decision to dim and turn the lamps on or off. Information is transferred hop by hop from one lamp to another, where each lamp has a unique address in the system. Each lamp can only send the information to the nearest one until the information reaches the coordinator. The lamp monitoring system installed in each lamp consists of several modules: the light sensor, temperature sensor, and occupancy sensor, power metering IC, MCU, ballast actuator, and ZigBee radio communication module. Sensors are attached with ZigBee RCM nodes to continuously monitor the situation of the lamps. The sensors are used to observe the main parameters such as lamp-housing temperature, power consumption, and illumination condition of the place. These devices work together and transfer all of the information to MCU which processes the data and automatically sets the appropriate course of action. A gateway node is used to serve as a bridge between two networks, i.e., ZigBee and internet to perform the protocol conversion. Each lamp controller communicates with the data center via a gateway. The system was tested for two extreme months of summer and winter, i.e., during the months of June, July, December, and January, it consists of 22 units of 70 W LED lamps and 16 units of LED 140 W lamps”, with the spacing between the lamps being approximately 40 m. By using the proposed energy efficient system the energy consumption is reduced dramatically from 2628 KWH to 765 KWH, i.e., around 70.8% of the energy is saved per month in comparison with the old system of conventional

MH street lights. The main disadvantage of this system is that each lamp can send information to the nearest lamp only, which is prone to system failure, if one lamp stops functioning the whole system may become unresponsive.

Type	Architecture	Mesh	Savings	Disadvantages	Reference
Outdoor, real-situation testing	Two-level, one station at each lamppost, one central nearby	Zigbee	N/A	High initial costs for its deployment	(Leccese & Leonowicz, 2012)
Outdoor, real-situation testing	Three-level, end-nodes, micro-server, mobile-broadband-network	XBee	40%	Modifications needs to be done to the existing infrastructure	(Elejoste, et al., 2013)
Outdoor, controlled testing	Three-level, lamp-Zigbee, Raspberry Pi, WiMAX	Zigbee	N/A	WiMAX not available in many cases	(Leccese, Cagnetti, & Trinca, 2014)
Outdoor, controlled testing	Two-level, custom-wireless-nodes, computer	IEEE 802.15.4.	30-40%	Custom lampposts, wireless network needed	(Bellido-Outeirino, et al., 2016)
Outdoor, real-situation testing	Two-level, lamp-Zigbee, gateway-node	Zigbee	70.8%	Prone to system failure	(Kaleem, Yoon, & Lee, 2016)

Table 2: Smart lighting systems on literature

3.3 Control schemes on smart lighting systems

Research shows significant savings and increase in user satisfaction when lighting control schemes are used in indoor and outdoor lighting, especially from automatic schemes that can work without users input. Automatic schemes use different components and are based on different technologies, from simple on/off switches to

video processing to detect movement. In a basic level, the automatic controls can be used to switch on or off the lights, and on a more precise level they can control the level of illumination based on (Haq, et al., 2014) certain requirements (Williams, Atkinson, Garbesi, Page, & Rubinstein, 2012).

3.3.1 Occupancy-based schemes

According to (Haq, et al., 2014) “among the control schemes used for lighting automation, occupancy sensor technologies have been used for a long time and are used widely (Yun, Kim, & Kim, 2012). Occupancy sensors employ some sort of motion sensing technique to detect the presence of occupants in a given range of space, so the lights are switch on when it detects any occupant, and switched off when there is no occupant within a pre-fixed delay period. The technology of the sensor can be of different types and costs. Passive Infrared (PIR), Ultrasonic, Acoustic, Microwave type and other types are currently in use, and all of those have their pros and cons. Some are more susceptible to errors, i.e. they are triggered on by a false movement coming from an object other than an actual occupant. Others have the reverse effect and they tend to turn off even in the presence of an occupant. Researchers have found that instead of relying on a single occupancy sensor for a room or area, the percentage of these errors can be significantly reduced by using multiple sensors together. They can be of the same type or, for even better detection performance, of multiple sensor technologies (Guo, Tiller, Henze, & Waters, 2010). Despite the difference in the technology used to detect the motion, the underlying algorithm for the operation of the system remains pretty much the same. If motion from occupants is not detected, a timer, which is set during commissioning, starts counting. At the end of the counter, if the space is still unoccupied, i.e. no motion is detected by the sensor, the unoccupied state is set and the appropriate signals for turning the lights off is sent. If within this period any motion is detected, the counter is reset, as shown in Figure 14 (Delaney, O'Hare, & Ruzzelli, 2009).

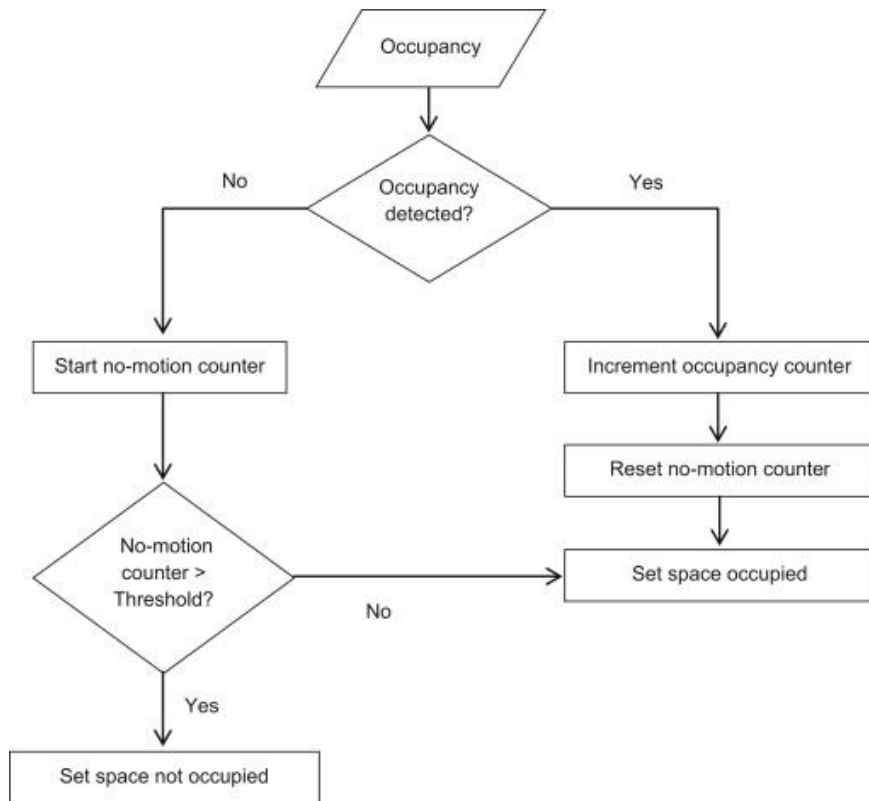


Figure 14: Occupancy sensor algorithm (Haq, et al., 2014)

Based on the type of actions performed by the controllers, occupancy schemes can be of two types: motion-based switching and motion-based dimming (Haq, et al., 2014). In the first case, depending on the movement detected by the occupancy sensor, this system switches the lights on or off. When the area covered by the sensor is unoccupied for a pre-determined time interval, the lights are switched off. They are switched on as occupancy is detected by the sensors. On outdoor street lighting systems, this type is not always desirable, as it essential that lighting is always on during nighttime and requires complex and prone to errors calculation of the pedestrian route. This implementation is more suitable for roadway lighting systems (Yoomak, Jettanasen, Ngaopitakkul, Bunjongjit, & Leelajindakrairerk, 2018). On motion-based dimming, the system can dim the lights when no occupancy is detected for a set time interval. The light level, to which the lights will be dimmed to in case of no occupancy, can be pre-set (Zou, et al., 2018). This approach is more suitable for outdoor lighting, where the light can be dimmed to a certain percentage when there is no occupancy and still offer adequate lighting. It requires though higher installation costs due to the need for dimmable lights and an automated control system that will restore lighting to adjacent lights based on the user movement. Based on the occupancy detection technique, there

can be several types of sensing system. Passive Infrared (PIR) and ultra-sonic sensors are widely used detections systems. New technologies like Radio Frequency Identification (RFID) and digital imaging are also being developed and gaining attention.

Savings reports can vary based on which type of occupancy control has been implemented. Roisin et al. made a comparison between occupancy based switching and dimming systems and found that 8.7% savings can be achieved with switching, while a slightly higher 11% is achieved using dimming systems (Roisin, Bodart, Deneyr, & Herdt, 2008). The sensors they had used were of the infrared type. Richman et al. (Richman, Dittmer, & Keller, 2013) used light loggers and ultrasonic occupancy sensors to calculate savings in lighting systems. Their study included 141 sample spaces. They used several different time delay settings to observe its effect on savings. Depending on the time delay which varied between 5 and 20 min, the research reported savings ranging from 50% to 3% respectively for private offices, and for restrooms, 86–73%.

3.3.2 Daylight-linked lighting controls

The lighting control schemes that are linked to daylight availability can provide the maximum amount of savings, given that the factors related to daylight availability like orientation, obstacles are in favor (Williams, Atkinson, Garbesi, Page, & Rubinstein, 2012). Indoor environments with adequate daylight penetration can benefit from using the available daylight, complementing the electrical lamps to provide adequate light levels (Li & Lam, 2001). Daylight-linked controls can either be used to switch lights on or off, which is more applicable for outdoor and common space light fixtures, or can be used in combination with dimmable electronic ballasts to provide the required artificial lighting level when daylight is present (Li, Cheung, Wong, & Lam, 2010). In case of outdoor spaces, simple setups of daylight controlled on-off switches can be used. This would not only ensure that the lights are turned off during day time, but would also make manual supervision of lights unnecessary and save labor time.

Daylight-linked lighting controls can be divided into two types based on how they control the lighting system, namely daylight-linked switching and daylight-linked dimming.

Daylight-linked switching can control the lights by switching between ‘On’ and ‘Off’ states based on available daylight. There may also be multi-level switching. For

instance, based on the level of available daylight in a particular control zone, 33%, 50% or 66% light of that zone may be switched off. These states are between the 100% on and 100% off states. Dimming systems control the lamp outputs continuously using dimmable electronic ballasts. Dimming requires dimmable ballasts to maintain the illuminance level of the lamps, so it is more expensive than switching system.

Daylight-linked systems can also be divided based on the algorithm of control, i.e. closed loop and open loop systems. A closed-loop system continuously detects lux levels of the control zone, which includes light from both daylight source and lamps. The change in the light levels of the lamps due to the availability of daylight is fed-back to the control system continuously, and it can make necessary adjustments based the feedback. Thus it makes a closed loop. Flowchart of a closed loop algorithm is shown below.

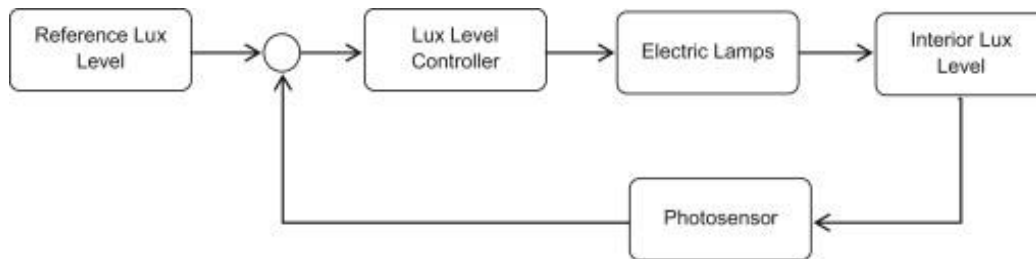


Figure 15: Daylight-linked closed loop algorithm (Haq, et al., 2014)

On the other hand, open-loop systems does not receive any feedback from the level of electrical lighting, it only detects available daylight levels. Based on the level of available daylight, it sends corresponding signal to the controller to provide corresponding lamp output. Flowchart of an open loop control system is shown below.

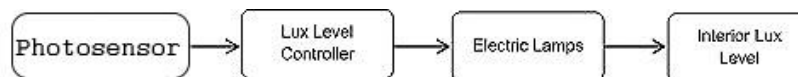


Figure 16: Daylight-linked open loop control system (Haq, et al., 2014)

Illumination engineers are constantly putting effort on developing advanced algorithms that would ensure best utilization of daylight for energy savings (Fischer, Wu, & Agathoklis, 2012) (Gorgulu & Ekren, 2013).

Many studies have tried to gain understanding of how to assess the energy savings achievable by installing a lighting control system for lighting that works according to the daylight contribution (Bonomolo, Beccali, Brano, & Zizzo, 2017).

Savings reported from a few such studies for indoor lighting are presented on Table 3 below (Haq, et al., 2014).

Room Type	Control method	Research method	Savings (%)	Reference
Office	Dimming	Pilot project	20	(Chung, Burnett, & Wu, 2001)
	Dimming	Field study	20	(Galasiu, Newsham, Suvagau, & Sander, 2007)
	Dimming	Experimental	30	(Gorgulu & Ekren, 2013)
	Dimming	Pilot project	25	(Guillemin & Morel, 2001)
	Dimming	Pilot project	20	(Hughes, Eng, & Dhannu, 2008)
	Dimming	Pilot project	27	(Jennings J. D., Rubinstein, DiBartolomeo, & Blanc, 2000)
	Dimming	Pilot project	9-27	(Rubinstein & Karayel, 1984)
	Dimming	Experimental	31	(Onaygil & Guler, 2003)
Classroom	Switching	Experimental	23.4-65.3	(Li, Cheung, Wong, & Lam, 2010)
	Dimming	Experimental	19.8-65	
	Switching +Dimming	Experimental	49.2	
Indoor Open space	Switching	Pilot project	11-17	(Atif & Galasiu, 2003)
	Dimming		46	

Table 3: Savings from daylight-linked controls

It should be noted that the savings reported above are measurements from actual implementations of daylight-linked control systems.

Selecting between daylight-based switching and dimming, and also between open and closed loop algorithms, are important steps for successful implementation of daylight schemes. Several factors determine if the switching or dimming method should be used on a system. Cost of installation of the systems is one of the key driving factors in adoption of the technologies. The effectiveness of the systems will also depend on the pattern of daylight availability in indoor environments throughout the day. Switching is suitable when the contribution of daylight is significant, and daylight is consistent throughout day hours. It is relatively easy to install and has a low initial cost compared to dimmable systems. Dimming is a better choice when the contribution of daylight is

variable throughout the day, and the savings in energy will be more substantial. Also dimming offers greater accuracy in control of the light. It has though higher initial cost and requires precise tuning for optimum performance.

Choosing open or close loop system and placing the sensors accordingly is essential for successful commissioning. When the sensor is used to control a single control zone or comparatively small areas, like private offices, closed loop systems can be very effective. When the goal is to control multiple control zones with a single sensor, open-loop system is more preferable (Haq, et al., 2014). Placement of sensor is also important, improper placement of photosensors can lead to failure of daylight harvesting project. The ideal location of the photosensor would be the task surface, but such a placement is not practical. Usually the photosensors are mounted on walls or ceilings. In some cases, they are built-in with the lamp fixtures. The critical issue for successful placement is to make sure the placement of the sensor is such that it detects a sample of daylight that best represents the daylight availability of the task surface in the control zone (DiLouie, 2008).

3.3.3 Lighting control by time scheduling

Lighting control systems based on scheduling operate on very simple principle based on fixing an operating time of the light fixtures. The lights that are controlled by the control system are switched on and off based on a pre-fixed schedule. Scheduling systems are based on time, so it is useful in areas where the occupancy pattern is accurately predictable. Rooms or spaces where events take place in very specific periods of time are perfectly suitable for application of scheduling systems. For application in indoor rooms or spaces, an override capability is usually provided for the users in case of out of pattern usage of lights. Due to these flexibilities and their relatively affordable cost, time switches are attractive options for energy management in places with strict occupancy patterns, particularly outdoor areas.

For user acceptance of time schedulers, override capability must be provided to make sure the users can use the lights beyond scheduled periods if the need arises. Multilevel switching should also be employed to make sure the users or not exposed to complete darkness suddenly. Advanced time clocks will flicker the lights to warn the users of imminent shut off, and they are given the window of opportunity to override the scheduling. In case of an override, the time switch should automatically return to scheduled mode after a certain time.

Properly commissioned time-based control systems can provide substantial savings. (Rubinstein & Karayel, 1984) reported savings in office building applications between 10% and 40%. Scheduling systems are commonly used in combination with other control systems like occupancy sensors and photocells as well.

3.3.4 Mixed control system

Each of the above described technologies has their unique characteristics. A particular control scheme may give better performance in a certain scenario over other schemes, but it may not give similar performance in other situations. These technologies often fail to provide satisfactory performances due the shortcomings associated with that particular technology. In order to overcome these disadvantages and ensure maximum amount of savings without compromising user satisfaction, researchers have experimented with combinations of multiple types of control schemes in one system. It has been seen that combining technologies together gives substantial improvements in performance in terms of accuracy and energy saving, as shown on Table 4 below:

Room Type	Combination	Savings (%)	Reference
Office	Occupancy+daylight	46	(Jennings J. D., Rubinstein, DiBartolomeo, & Blanc, 2000)
Office	Occupancy+daylight	68	(Hughes, Eng, & Dhannu, 2008)
Office	Occupancy+daylight	49-63	(Roisin, Bodart, Deneyr, & Herdt, 2008)
Office	Scheduling+daylight	38-61	(Rubinstein, Siminovitch, & Verderber, 1993)
Classroom	Scheduling+occupancy +daylight	35-42	(Martirano, 2011)

Table 4: Combining multiple types of control schemes

3.3.5 Current trends and future possibilities

Current research in the field of lighting controls is further pushing the possibilities of energy savings and user comfort. The current developments in this field can be seen from two perspectives; individual development of lighting control technologies and

development of combined control ecosystems. In terms of development of the technologies, there are new methods that are gaining focus in research. Instead of relying on already established methods of detecting occupation like PIR and ultrasound, researchers are focusing on improving detection using imaging systems and RFID. Apart from development of individual technologies, researchers are putting emphasis on developing networks of sensors to further automate and enhance the benefits from using lighting control schemes.” Furthermore, recent advancements in sensing technologies open the door to a host of feedback information previously unavailable. Accurate occupancy information such as user location and activity, light spectral data from microspectrometers, and richer light information such as chromaticity and illuminance distribution can be exploited to develop smarter algorithms that enhance energy efficiency, user satisfaction, comfort, light quality, and functionality of smart lighting systems.

4 Technical Implementation

Our proposal describes a versatile system that can work autonomously and can be remotely managed, with a “holistic and bottom-up approach to system design, which ensures standardization, interoperability and adaption to many needs and scenarios”. By using a mesh strategy we maximize fault tolerance, while using open source and open standards technologies to ensure easy integration to existing infrastructure and future maintenance. The chapter is organized as follows: Section 4.1 begins with requirements for public lighting systems as defined by national policies and best practices found in literature. Then, Section 4.2 presents the hardware and software components used to implement our solution. Section 4.3 presents the system architecture and the three layers consisting it. Section 4.4 describes the web-based user interface for remote control and management of the system. Finally, in Section 4.5 we present our smart lighting system proposal and its application on the windbreaker walkway.

4.1 Requirements for public lighting systems

Outdoor public lighting can gain much from utilizing LED solutions in modern cities. The energy savings and minimal luminous pollution are substantial, and they offer better quality of illumination when utilized properly. Used together with sensing and communication technologies, they are clearly the way to the future. However, when considering solutions regarding the implementation of public lighting systems, there are a wide aspects of choices that have to be made. Below we review some of the general design objectives that we will use as guidelines and will define our system architecture as well:

- Adaptability, having the ability to perform as an autonomous system and to react to different environmental input, dimming the lights depending on daylight availability and other weather conditions.
- Interactivity, to the users of public spaces and the managers of the system. The interaction with a smart lighting system should be informative and communicate visually messages to its users, alerting of possible hazards and highlighting points of interest. The management interface to interact with it needs to be versatile and user-friendly, manageable from a remote location or on-site.

- Modifiable, through the use of WSNs system variables and components should be easy to update and upgrade. Different parts of the system can be modified securely and new services can be implemented as the needs arise and new technology advancements become available.
- Modularity, making it possible to reuse resources and integration with other Smart Cities initiatives. System management becomes easier, changing a part of the system do not break it and different parties involved on it can separate maintenance tasks.
- Openness, smart lighting system need to avoid dependence on proprietary solutions and niche technologies. Open source, open standards and well-established technologies and architectures makes it possible to connect with other systems and offer compatibility with existing and future infrastructure.

There are many more suggestions and requirement found in literature that can optimize a public lighting system, but they are beyond the scope of the present dissertation, and could be easily added gradually to our proposed system.

4.2 Hardware and software components

Choosing between the different hardware and software options to implement our proposed system was done following certain criteria. The most important of those, for the software part, was that they had to be open source or open standards. Regarding hardware components, we strive to choose products that are widely used and available from different companies, while keeping the costs involved as low as possible.

4.2.1 Lamp bulbs

In this thesis we have strongly make the case for the benefits of using LEDs related technologies for public street lighting. Beside the energy savings, the very high life expectance, the uniformity of the light and the lower lumen depreciation, modern LEDs can be used to adjust the color temperature and offer full color tuning. This ability makes them suitable to change the color of the lights, which can be used for public safety purposes, in case of special festive event, or for the needs of retail and business districts in a Smart City context.

LEDs can be overly bright and thus one aspect when choosing LEDs street light in relation to non-LEDs is to replace them with ambient toned ones or with lower illumination levels. For our demonstration we chose a 15 watt Bluetooth enabled bulb,

with the ability to adjust the brightness and change the color. The lamp can be easily controlled via Bluetooth and can use encryption to make the connection secure.

4.2.2 Microcontroller

To select the most suitable microcontroller for our project, we need to take into account different considerations and review current and future needs. Special care is needed in accounting for all the external interfaces and peripherals that must be supported by the MCU, most importantly communication interfaces and digital/analog inputs and outputs. The software architecture (Espruino) that must support our specific requirements is another factor that affects the process of selecting a MCU, affecting the processing power that is needed and the frequency of the MCU. Memory is another important issue, the provided flash and RAM memory can play a crucial role for the eligibility of a MCU on a project. Power consumption is critical in most cases when the MCU is powered with batteries or solar energy. And of course the costs of the MCU is as always an important factor in the selection procedure.

With those considerations in mind and after reviewing possible candidates, we decide to use Puck.js² microcontroller, which is an open source hardware implementation. It is based on Nordic Semiconductor's nRF52832 SoC, which is ideally suited for BLE applications. The "nRF52832 is built around a 32-bit ARM® Cortex™-M4F CPU with 512kB flash memory and 64kB RAM, with the embedded 2.4GHz transceiver supporting Bluetooth 5. The nRF52832 SoC is an extremely power efficient device that can run from a supply between 1.7V and 3.6V. All individual peripherals and clocks offer complete flexibility of power down when not required for task operation", during the day on our smart lighting system, thus minimizing power consumption to a minimum. It also includes NFC™-A tag support and Digital Microphone Interface (PDM) on chip, for possible future applications. Puck.js can measure light, temperature, magnetic fields and capacitance. It comes pre-installed with Espruino, an open source JavaScript interpreter, making it possible to program it using JavaScript (JS). JS is one of the most popular high-level programming languages (Stack Overflow, 2017), and by using it the integration with web-based applications become effortless. Espruino has a built-in text mode debugger, which can be extremely useful to detect problems early on during development.

² <http://www.espruino.com/Puck.js>

4.2.3 Gateway to the Web

Remote control of our smart light proposition is an essential part of it. The essential requirements we are looking for is the support of BLE, thus making possible for it to communicate with the MCUs, and Wifi, so it can connect to Municipality wireless network. To enable the gathering of data from the MCUs and conveying instructions to them, we settled on a Raspberry Pi Zero W ('Pi'), which will act as a gateway to the Web, connecting our system with the rest of the world. The Pi is a cheap (10 euro), super-small single-board computer developed by the Raspberry Pi Foundation³. It features a 1GHz ARM processor and 512MB of Ram, and it has built-in Wifi and Bluetooth. To make the Pi functional, we need to provide it with a micro SD card with an Operating System (OS), in our case Raspbian Stretch Lite, a Debian-based OS especially tailored for Raspberry models.

4.2.4 MQTT and Node-Red

To mediate communication between the different components of our system, we need a standardized communication protocol “that is designed to allow devices with small processing power and storage to communicate over low-bandwidth and unreliable networks”. The communication protocol needs to be lightweight, simple, and to use minimum network bandwidth and hardware resources. One of the most used “machine-to-machine (M2M) communication protocols” on IoT applications is the MQTT (“Message Queuing Telemetry Transport”) protocol.

The MQTT⁴ is “a publish/subscribe based messaging protocol for constrained IoT devices and low-bandwidth, high-latency or unreliable networks”. It was originally designed by IBM and in 2013 was released as an open-standards for M2M communication. It operates “on top of the TCP/IP networking stack”. The requirements for MQTT are minimal as it is designed for resource-constrained embedded devices. In addition to a minimal footprint, MQTT was designed for communication efficiency, even over low-bandwidth networks, and minimal overhead (compared to protocols such as HTTP). Over 3G networks, MQTT throughput has been measured at 93 times faster than Representational State Transfer (REST) over HTTP, while it is 11 times less energy consuming to send messages and requires 170 times less energy to receive messages than HTTP (Intel Developers Zone, 2016).

³ <https://www.raspberrypi.org/>

⁴ <http://mqtt.org/>

“MQTT fundamentally is a publish/subscribe protocol. It allows clients to connect as a publisher, subscriber, or both. Clients connect to a server, termed as ‘Broker’, which handles all the message passing through it and is the point of contact for all the clients. A broker’s primary job is to queue and transmit messages from a publisher client to the subscriber client. When a client publishes a message on a subscribed topic, the Broker forwards the message to any client that has subscribed. However, it can also possess heavier capabilities (such as SSL certification, logs, database storage, etc.) based on requirements, set-up, and the broker service used.”

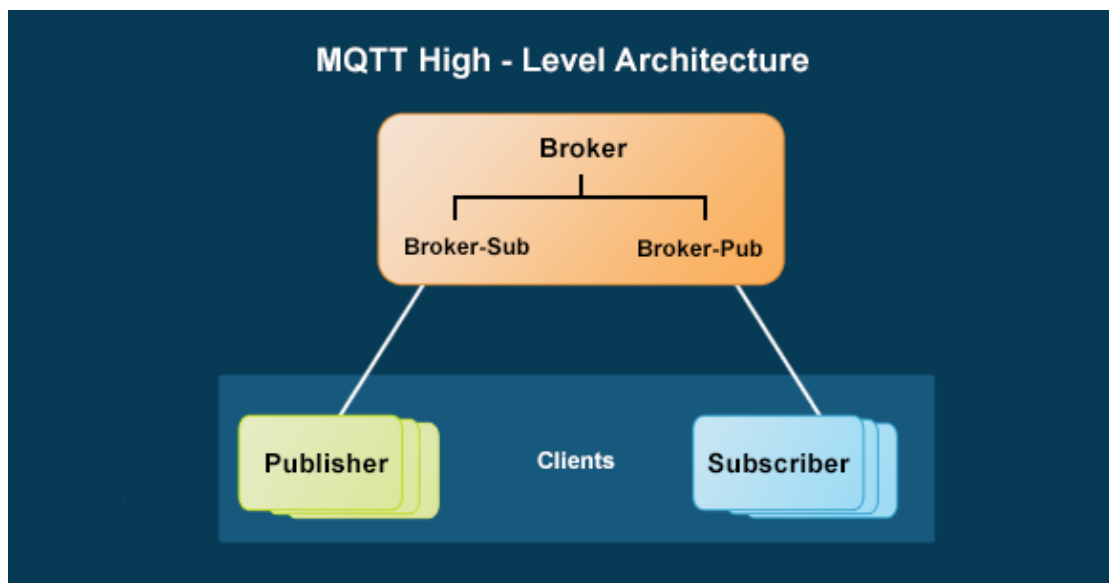


Figure 17: MQTT high-level architecture (DZone, 2018)

MQTT implements a publish/subscribe model with a minimal set of methods that indicate the action to be performed on an identified topic. Agents connect to a Broker, then publish topics or subscribe to topics. When finished, an agent disconnects from the broker (Dow, Bui, Chen, & Hwang, 2017). MQTT methods are defined as:

- Connect - Establish a connection to an MQTT broker.
- Disconnect - Tear down a connection from an MQTT broker.
- Publish - Publish a topic to an MQTT broker.
- Subscribe - Subscribe to a topic from an MQTT broker.
- Unsubscribe - Unsubscribe to a topic from an MQTT broker.

The central component in the MQTT communication protocol is the topic. A topic is in charge of many tasks, with its primary task being sending each message to the listener that has subscribed on that topic.

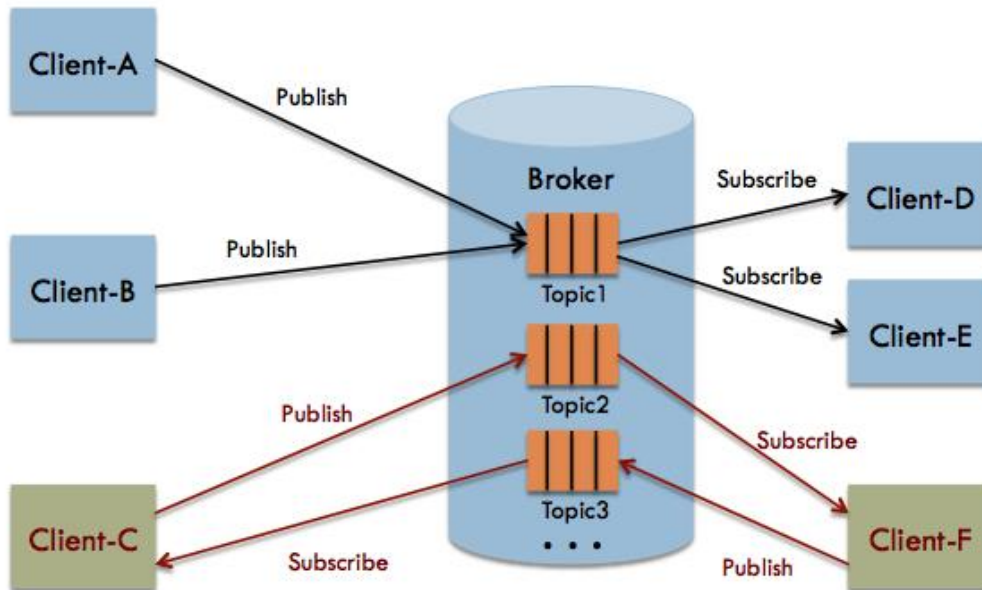


Figure 18: Topics on MQTT protocol (DZone, 2018)

Messages are usually formatted as plain-text, this way making it possible for the client to process the message payload to different formats as required. MQTT defines a topic as a file path, similar to a file system hierarchy, which acts as a simple communication filter: *topic = 'user/path/topic'*. MQTT filters any of the incoming messages depending on the point that a particular client subscribe in the tree path.

For reliability, MQTT offered three types of modes which are called Quality of Service (QoS). QoS 0 mode sends a packet only one time without requiring confirmation messages or ACK. QoS 1 mode ensure that the message is delivered at least once by requiring an ACK. QoS 2 mode guarantee that the message is delivered exactly once.

There are many message Brokers that implement the MQTT protocol, a popular choice and the one we are going to use for our system is Eclipse Mosquitto™ Broker⁵, which is in open-source initiative suitable for IoT lightweight messaging.

‘Wiring together’ the code blocks of our system, hardware devices, API’s, MQTT messages and online services, can be quite a challenge to manage from a software programming point of view. To simplify and expedite the process of building a project prototyping, we use Node-Red, a versatile open-source programming tool for making IoT applications with a focus on simplifying the ‘wiring together’ of code blocks to carry out tasks. Node-Red uses a visual, flow-based programming model that makes it

⁵ <https://mosquitto.org/>

easy to connect predefined code blocks, known as ‘nodes’, together to perform a task. The connected nodes, usually a combination of input nodes, processing nodes and output nodes, when wired together, make up ‘flows’.

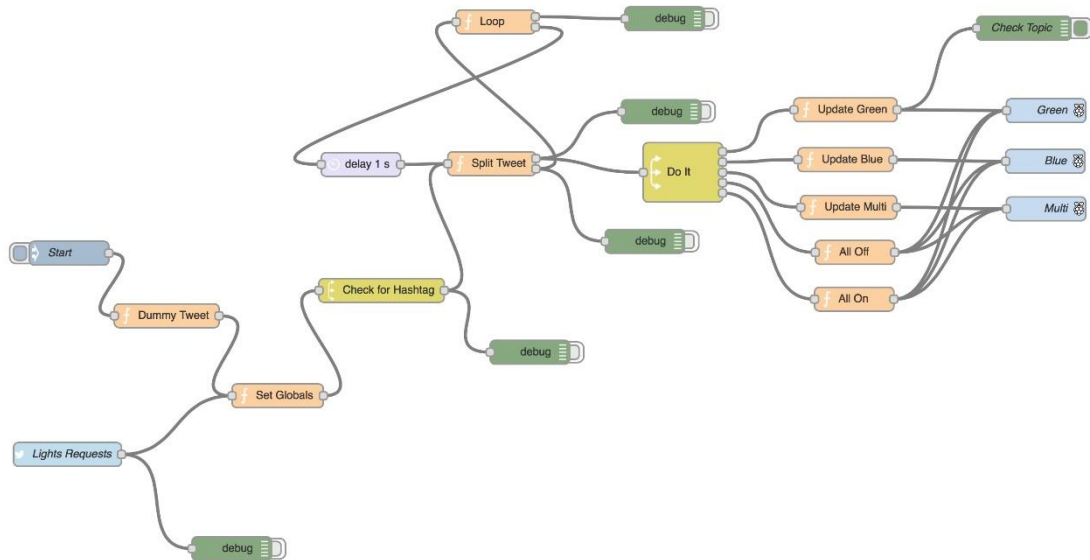


Figure 19: A typical Node-Red flow consisting of many nodes

Node-RED has integrated a browser-based flow editor, which make it possible to further manipulate and customize node behavior via JavaScript functions.

4.2.5 Bluetooth Mesh

Bluetooth Mesh (‘Mesh’) is a new specification that was released from the Bluetooth SIG in July 2017, and for the first time it extends Bluetooth connections to a true mesh, many-to-many, multi-hop topology. It doesn't have any new demands on Bluetooth hardware as it shares its lower layers with BLE, utilizing the BLE Advertiser and Scanner roles and communicating through BLE advertisement packets, allowing any Bluetooth hardware which is capable of running BLE to be able to operate on Mesh with a suitable software implementation.

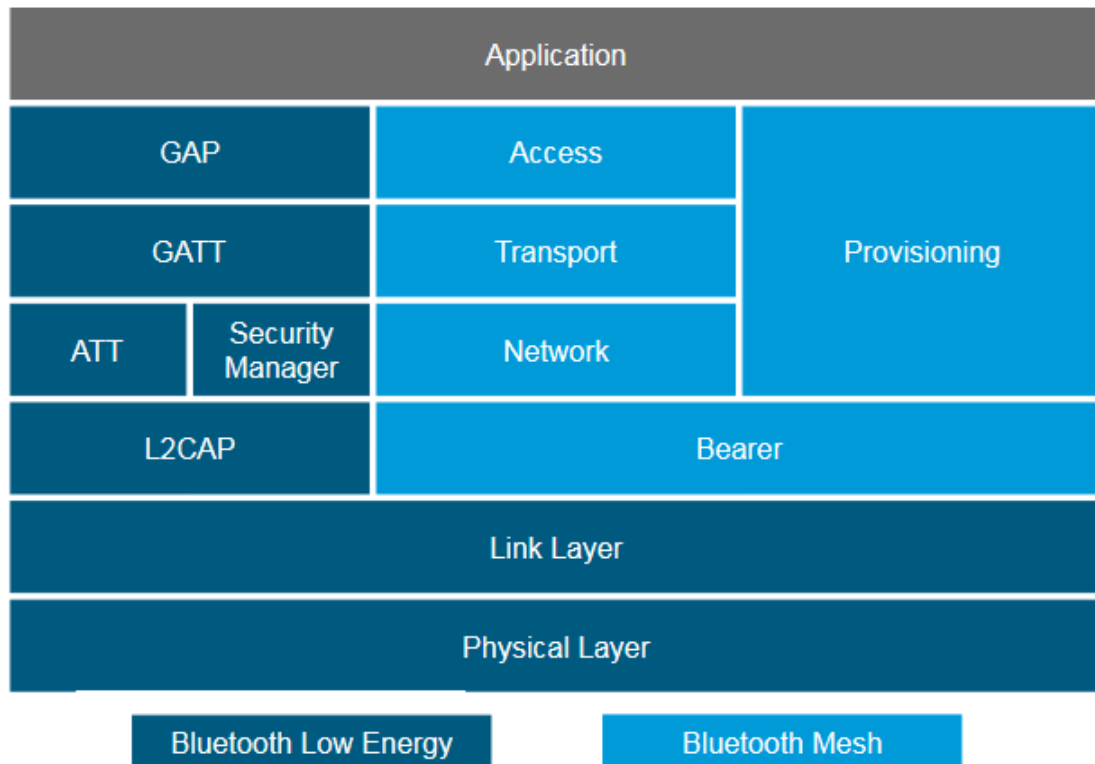


Figure 20: Relationship between BLE and Mesh (*Bluetooth Blog, 2018*)

A fundamental aspect of Bluetooth Mesh is that it broadcasts messages and relay them in a managed flooding approach, where every device sends and receives all messages to and from all devices within radio range. This method doesn't require complex routing, it is multipath, and so there is no single node that can cause failure to all the network. The data transfer speed of Bluetooth mesh is relatively low, so it's most suited for simple signaling of small packets. One of the biggest benefits of Mesh is that we get more range than we get with traditional Bluetooth, by having multiple nodes that can transmit single messages for many kilometers of range.

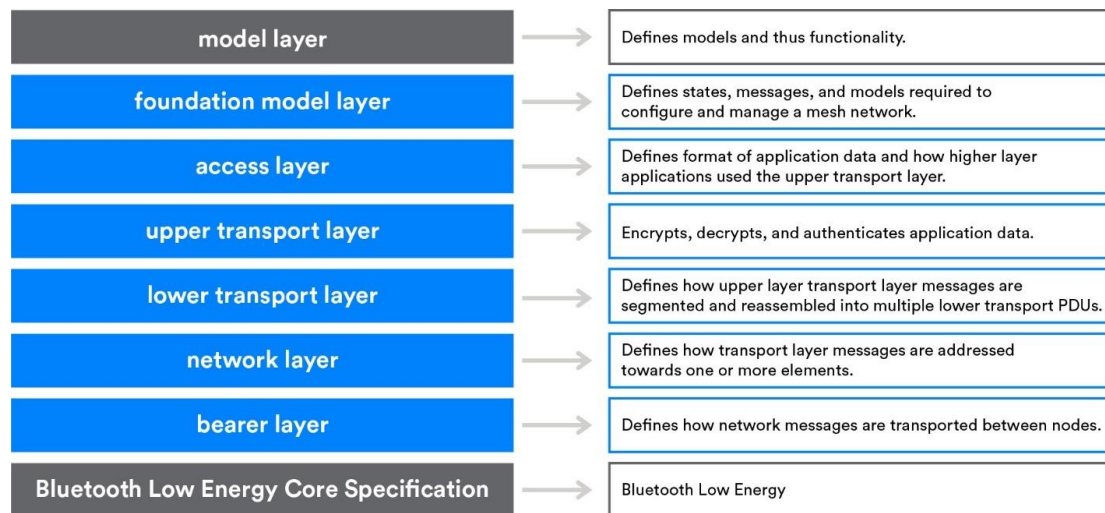


Figure 21: Bluetooth Mesh Architecture (*Bluetooth Blog, 2018*)

Devices which are part of a mesh network are called nodes and the ones that have not been added yet to the mesh are characterized as “unprovisioned devices”. At the root of a Mesh network there is a provisioner, which is responsible for managing the address space of the mesh network, and for taking any new unprovisioned devices and making them a functional node in the mesh network. The provisioner provides to each node a series of encryption keys which are known to it. One of these keys is called the network key (NetKey), all nodes in a mesh network possess at least one NetKey, and it is possession of this key that makes a device a member of the corresponding mesh network and as such, a node. According to the specifications “provisioning protocol uses P256 Elliptic Curve Diffie-Hellman Key Exchange to create a temporary key to encrypt network key and other information”.

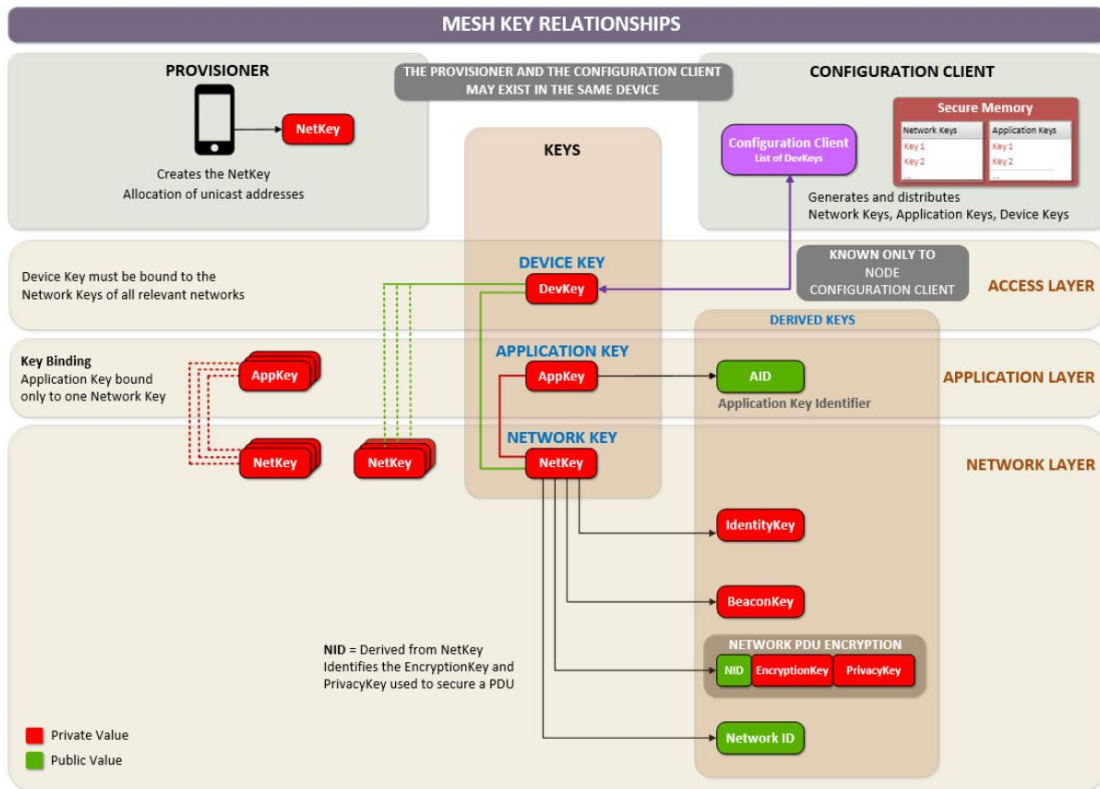


Figure 22: Bluetooth Mesh keys and derived keys (*Bluetooth Blog, 2018*)

The Mesh addressing scheme consist of three types of addresses:

- Unicast addresses: unique for every device
- Group addresses: allow forming a group of devices and address them all at once
- Virtual addresses: untracked UUID-based addresses with a large address space

The moment a device is inserted to a network, it is assigned a range of unicast addresses that represents it. A device's unicast addresses cannot be changed and are always sequential. The unicast address space can supports 32767 unicast addresses in a single mesh network. The group addresses are allocated and assigned as part of the network configuration procedure. A group address may represent any number of devices, and a device may be part of any number of groups. Nodes that are part of a Mesh network are capable of assuming different roles within the network, there is no need for all the nodes to belong to the same group. One group, i.e. the nodes that belong to it, can fulfill the role of controlling lights, another group can control smoke detectors, beacon services, home appliances and so on.

Each node has at least one element, known as the primary element, and may have additional elements. Every device on the Mesh has one or more elements, each acting as a virtual entity in the Mesh with its own unique unicast address, enabling each

elements' functionalities and condition to be addressable. Inside each element reside models, which define and implement a node's basic functionality, and each element must have one or more models. Models define and implement the functionality and behavior of a node while states define the condition of elements. Each incoming message is handled by a model instance in an element, and the model will only handle messages that are published to one of its subscription addresses or the containing element's unicast address.

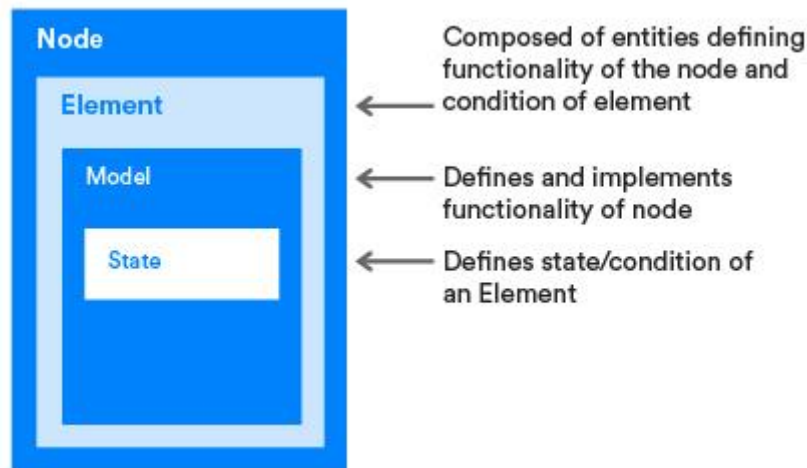


Figure 23: Node, Element, Model, State

“In a light bulb, for example, the model’s functionality can be On/Off and Brightness. The associated states are On/Off and 0-10 respectively:

- Model (functionality of node)
 - 1. On/Off
 - State => On or Off
 - 2. Brightness (0-10)
 - State => 0-10

Bluetooth mesh supports composite states, which are states composed of two or more values. A color changing lamp is an example, as the hue may change independently of color saturation or brightness.”

Message publication and subscription is a fundamental aspect of Mesh, being the way of organizing who is sending and who is receiving messages. Every node in the Mesh is both an observer and a broadcaster. Every message traversing the Mesh has a source and destination address, the destination address enable each node to decide if they need to process the message or just broadcast it along the Mesh. Each message that travel

into the Mesh is encrypted and authenticated. Messages can be categorized into three broad type, GET, SET and STATUS. “GET messages request the value of a given state from one or more nodes. A STATUS message is sent in response to a GET and contains the relevant state value. SET messages change the value of a given state”. An acknowledged SET message will result in a STATUS message being returned in response to the SET message whereas an unacknowledged SET message requires no response.

Messages are secured using an application key, which is specific for a particular application functionality, for example the application key for turning the lights on will be different that the one setting beacons URL at a particular node. To avoid endless loops, messages traversing the Mesh follow a time-to-live (TTL) mechanism. Every time that a message is received and retransmitted, the TTL is lower by one, and this will continue as long as TTL value ≥ 2 , then the message will not be transmitted anymore. To avoid the case where a node receives and forwards again a message that it has already transmitted, each node maintains a message cache, if a message is already in the cache, it is discarded and not transmitted again.

In the smart lighting system that we propose, the first steps will be the provision of all our MCUs devices, using the web-based management application. Each MCU is assigned unicast addresses, a network key and a device key. Then we give them the ‘Light Control’ application key, and add them to the ‘Koules Walkway’ group address, thus subscribing all the lights on the walkway to this group. This way we can address all the lights in the walkway at the same time. The main element on all nodes is the ‘Lamppost’ element. Inside each element, the models define the behavior and communication formats of all data that is transmitted across the mesh. All mesh communication happens through models, and any application that exposes its behavior through the mesh must channel the communication through one or more models. Below we can see the model representation of the lights operation functionality, the ‘Lights’ model will have three conditions, ‘On/Off’, ‘Color’ and ‘Brightness’, and their corresponding states:

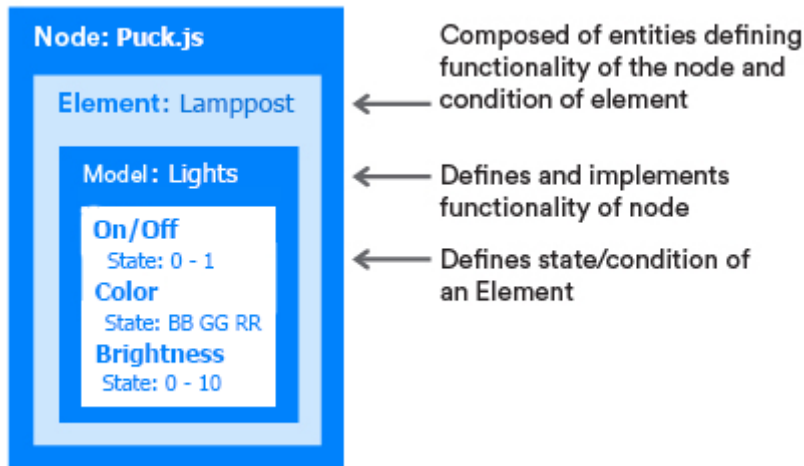


Figure 24: Lamppost element entity

Another important aspect of our smart lighting system will be the ability to report malfunctioning bulbs. To represent this ability in our nodes, we create another model called 'Health' in the same element 'Lamppost', it can automatically report when a bulb is not working or when asked to do so. The 'Health' state will be computed in relation to the 'On/Off', 'Brightness' and 'Light Level' (as perceived by the light sensor) state, if the bulb is On, Brightness is at normal level and the Light Level is low, it means that the light is malfunctioning:

```
var health = (On == 1 && Brightness > 5 && Light levels < 0.7) ? 0 : 1
```

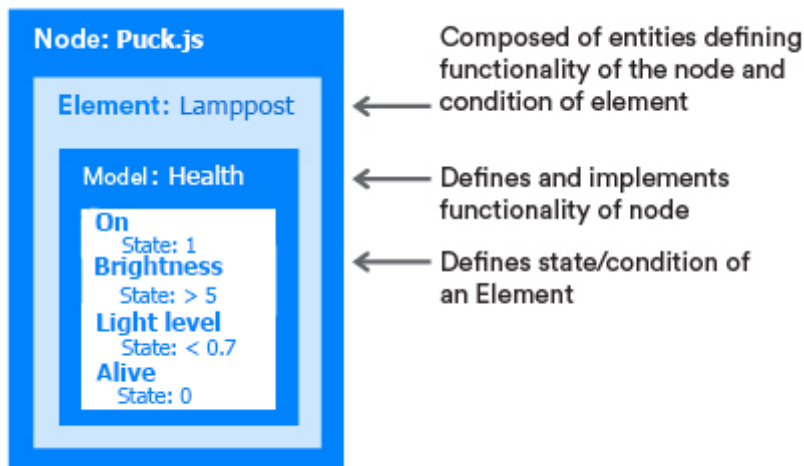


Figure 25: 'Health' model representation

Some of the nodes will act as BLE beacons, broadcasting a URL that can be seen by nearby smartphones. We define a new element called 'Beacons', which as an element

will have a unique unicast address, and in it the model 'Eddystone'. The conditions will be 'On/Off', signal 'Interval', transmission 'Tx Power' and broadcasted 'URL':

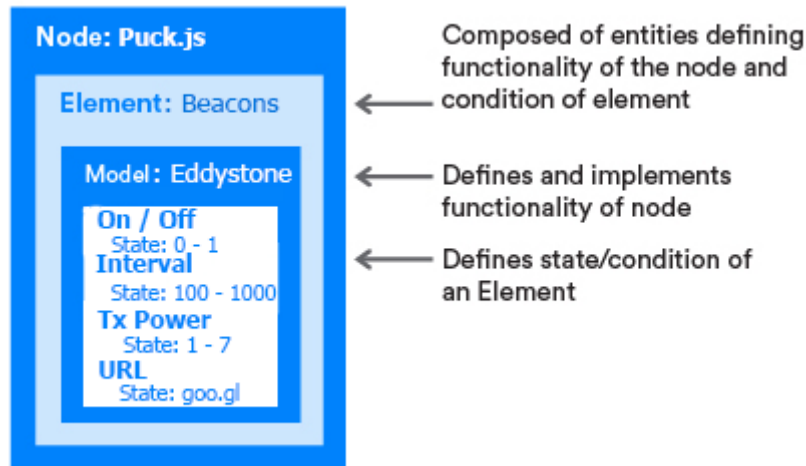


Figure 26: 'Beacons' element and model

4.3 System Architecture

The smart lighting system for public spaces that we propose is designed having in mind a three-level hierarchical model. The reason that we decided to follow this implementation is to achieve maximum system scalability and clearly define modules that can be easily modified and upgraded, without affecting the rest of the system. This structure makes it possible to be implemented on the existing power and wireless network municipality infrastructure, without the need of modifications and additional costs. Another reason for this approach is that we strive to make it possible for the whole system or parts of it to be used for other projects on the context of Smart Cities. Sensors that monitor temperature, humidity, noise, proximity based services and more, will be possible to be added to the system at a later time. Each level is responsible for its own activities and all three of them communicate information to each other.

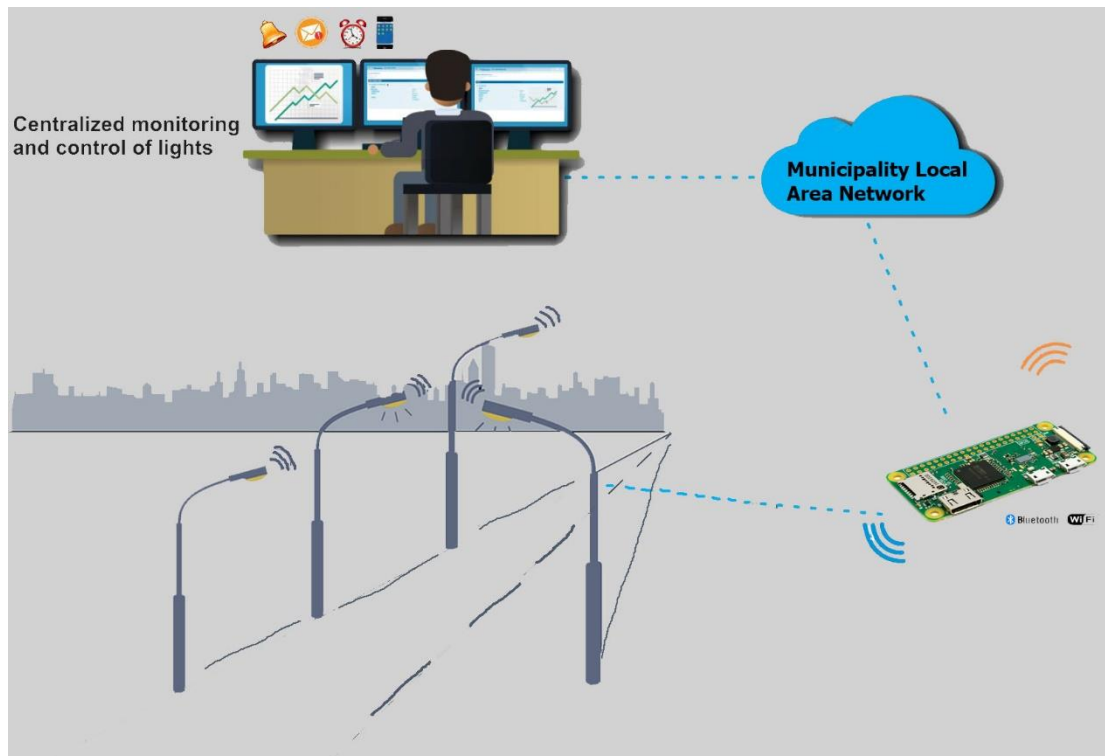


Figure 27: Smart lighting components

The three level are: (i) the lamppost level, (ii) the microcontrollers’ network and (iii) the remote control level.

4.3.1 The lamppost level

This is the simplest level to implement, since it has only one requirements, namely a light bulb that can communicate through Bluetooth. By having this simplicity, we ensure that changes that needed to be done on the existing lighting infrastructure are minimal and easy to implement. This layer will be controlled by the second level, the MCU units, which will instruct the light bulbs about when to turn on-off, the brightness level and color tuning. An especially important requirement for this layer is the ability to offer secure communication, using robust encryption methods.

4.3.2 MCUs network level

Essentially this layer is the heart of the system, enabling information to be flooded through all the MCUs in the network and controlling the light bulbs. By having the MCUs placed in a separate architecture level, we create a network of devices that can play a plethora of roles in a Smart City context. The MCUs, besides controlling the lights, can be used to enhance public transport infrastructure, with the addition of the appropriate sensors provide information about street noise levels, temperature and

humidity, air pollution information, and actually to communicate with any device that support Bluetooth. The placement of the MCU devices can be anywhere of their BLE range (for Bluetooth 5 up to 240 meters on open space) from the light bulb that it controls, but to protect it from harsh weather condition and undue removal, given the very small size of it, the best place is inside the lamppost. Even though each MCU can control more than one lamp, to give the system the ability to able to report malfunctioning lamps, we place one MCU in each lamppost. The role of each MCU, which in the Mesh context we call a *node*, is threefold.

Firstly, it acts as a controller for the Bluetooth light bulbs, with the node undertaking the ‘Central’ role and the bulb the ‘Peripheral’ role. Like every Bluetooth device, the bulbs will have what are called *services*, with each service corresponding to some function of the bulb. Peripherals, the bulb in our case, will periodically advertise what kind of services they have to offer, which can be seen by central devices, the nodes. Each service has *characteristics*, which are variables and properties, and can be read, written, or both, from other central devices. Services and characteristics are identified by a unique 16-bit (for example dd64) or 128-bit number (for example 00000000–1000–1000–9000–00735F4G34DB). Since we have all these information from the bulb manufacturer, after pairing and the authentication step, the nodes will have access to all the services of the bulb, reading and writing them.

Secondly, they are the medium of the backbone of our system, the wireless sensor network. The usage of MCU as a medium for our WSN has their own advantages and disadvantages. Some of advantages are the low cost, low energy consumption and mature software ecosystem. On the other hand, some of the drawbacks are the limited transmission power, multipath signal propagation and dispersion, fading, impulsive noise, lack of efficient medium access mechanism (Dargie & Poellabauer, 2010) (Gomez, Oller, & Paradells, 2012). There are many wireless communications protocols available that can be used for our WSN. Generally, WSN communication protocols can be classified by the utilized frequency spectrum, modulation techniques, bit rate and signal coverage (Gogic, Mujcic, Ibric, & Suljanovic, 2016). BLE is a very good choice to be used for the creation of our mesh network topology because of the good radio frequency performance, its support from many existing electronic devices (smartphones) and the very low power consumption.

The routing model we choose to use for our mesh is the flooding communication model. Flooding is one of the oldest routing algorithms proposed for WSNs, mainly due to its simplicity, low computational and memory needs, and low energy consumption. Flooding is based on each node broadcasting the messages that it receives, so they can spread into the network, without the need to know about nearby nodes or to have a routing protocol and list of nearby nodes. It does so for every new message that it receives, if a message was received already, it will not broadcast it again. This is achieved by storing messages that were already broadcasted in cache. In our case, we only need to store the last message that was received and propagated. In flooding, if there are nodes between a starting and ending destination nodes, then it is guaranteed that the message will reach the destination node, probably through many paths, and as a consequence this will be done also through the shortest path.

One downside of using the flooding algorithm in our WSN is that it will create a lot of traffic, wasted bandwidth and high congestion on our network, because of the non-directional broadcasting of the messages, but this will not be a big problem from our case, since the traffic on our network will be infrequent and the packages will be of a very small size able to fit in a single advertisement package. One way to reduce unnecessary traffic in our network will be to introduce a TTL value to our messages, but this will require relative knowledge of the position of the destination node in relation to the source node. Flooding uses the 3 primary advertising channels to broadcast messages, and with Bluetooth 5 the robustness has increased significantly, since we can use the 37 secondary advertising channels beside the primary ones. One problem that we have to face by using a flooding solution is that we cannot use Segmentation and Reassembly (SAR) mechanism to transmit large messages. In our case, this is not a problem, since all the messages we sent for the lights and the beacon functionality can fit in a 31 byte payload package.

Each node will have a virtual address assigned and also a group address so we can send commands to each node individually or to a group of nodes simultaneously. As a measure to ensure the correct propagation of messages in our network, each source node will repeat broadcasting messages for a period of time, so as to make sure that other nodes in the transmission vicinity will receive the message.

And thirdly, it act as a LBE beacon, enabling proximity-based services, which we describe in more detail in Section [4.5.1](#).

Reduction of the data that are needed to be sent through the Mesh network is very important for the optimal operation of the network, reducing latency and the need for error-corrections schemes, while keeping power consumptions to a minimum. To avoid sending large instructions for common operations, we define a conventional representation of these operations, where each operation is represented by a state. These information is stored in each node and processed by it when received. For example, in our system common operations are lights dimming levels and the color red shades used to reflect wind intensity on the walkway. We define three levels of red shades, very light red for Beaufort level of 4-5, medium red level for Beaufort level of 5-6 and dark red for Beaufort level of 7 and above. The light red (RGB : 255, 145, 164) is represented by the value '1', the medium red (RGB : 237, 41, 57) by the value '2', and so on. This way we achieve significant reduce on the information needed to be transmitted on the Mesh.

4.3.3 Remote control level

The third layer is the gateway to the local area network, collecting data coming from the Mesh and storing them in the local Municipality network (and to a cloud service if requested), and conveying instructions to the Mesh coming from the web-based management application. The layer consist of a Raspberry Pi Zero W micro-computer, connected with the Municipal wireless network.

In the heart of the third layer resides the MQTT server, in our case the Mosquitto Broker running on the Pi, which acts as the mediator for all information coming from the Mesh nodes and the ones received from the web-based management application. The Pi will run the EspruinoHub open-source software, which essentially acts as a bridge between the MCUs and the Broker on the Pi. This service is responsible for managing the BLE connection between the Pi (which has support for BLE) and the MCUs nearest to it. It also takes the BLE data flows from the MCUs and translate them to MQTT streams, and vice-versa for outgoing information flowing from the Pi to the MCUs.

All the mapping of MQTT topics from subscribing and publishing clients is done on the Node-Red instance running on the Pi. Here is defined all the logic of our system, publishing and subscribing roles are given to different parts of our system. The MCUs publish the messages in the Broker using a topic with general path */ble/advertise/de:vi:ce:ad:dr/service/characteristic*. They subscribe in the path

`/ble/write/de:vi:ce:ad:dr/service/characteristic`, from where they receive all the commands published by the web-based application.

The need for persistent storage of information about the lighting system is implemented by adding the ‘node-red-contrib-sqldb’ extension on Node-Red, which makes it easy to work with any database that can be either MSSQL, MySQL, SQLite, or PostgreSQL server. The data collected in the database, will display information on faulty light bulbs and system health, and in general can be used for statistical purposes in the Smart City ‘big data’ context.

4.4 Remote management interface

An important part of our system is the user interface (UI), which can be used by the system manager to interact with our lighting system. The UI have to be platform independent, to the end we implement a web-based application that can be accessed using any modern web-browser. One of the benefit of using Node-Red is the ability to build a live data dashboard using the Node-Red Dashboard module. The Dashboard conveniently offers all the UI components to put together IoT management interfaces, like buttons, switches, sliders, graphs, color pickers, maps, input fields and forms.

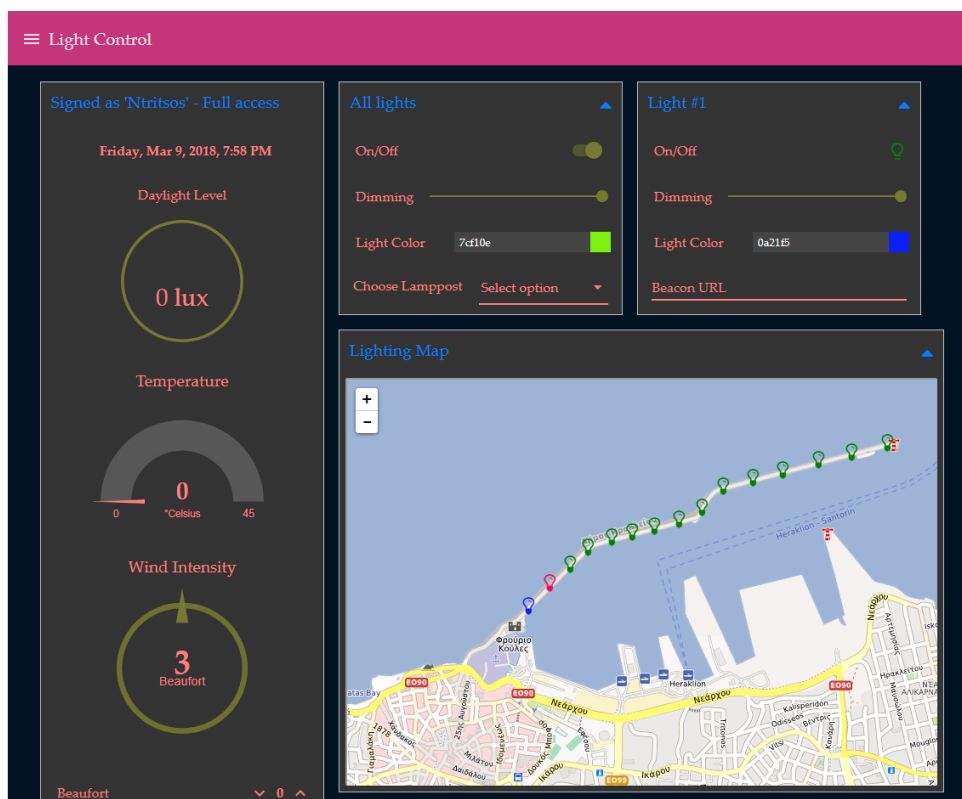


Figure 28: Node-Red Dashboard

Beside the offered components, custom UI widgets can be created to accomplish our dynamic user interface needs by using html and Angular/Angular – Material directives. The produced web-based user interface is available at <http://localhost:1880/ui> (if the default settings are used) on the same local Municipality network as the Pi running Node-Red.

Although it is possible to make our smart lighting user interface accessible from the Web, by connecting it with IoT cloud services (like IBM Watson IoT, Google Cloud IoT, AWS IoT), doing so would add unnecessary complications to our system without any immediate gain. Given the sensitive and public-related nature of our lighting system, by connecting it to third parties cloud services, all the data will be available to them to be processed in accordance to their privacy and compliance policies. Connecting to the Web will add another layer of security risks that can be exploited to gain unauthorized access to the system. Cloud server can become unavailable, due to technical reasons or maintenance, and services and API can change or terminated on short-order. Migrating to other services can be in many cases a very difficult process, and of course there is always the costs involved with the usage of cloud services, which can be significant depending on the usage. For all the above reasons, we believe that having a web-based application running on the local Municipality network is the safest and most economically advantageous solution.

4.5 Application and test case

The proposed system in this thesis is tailored for public areas where the visual requirements of pedestrians are dominant, areas like parks, walkways and in general pedestrian zones where at all time there must be a certain amount of illumination during nighttime. The city of Heraklion is the largest city and the administrative capital of the island of Crete. One of the favorite walkways of locals and visitors alike is the breakwater of the Venetian Fortress Koules. The walkway is about 2.5 km and is used for walking, jogging and cycling activities. It is accessible at all times, with most of the activities on the walkway taking place during the evening.



Figure 29: Koules breakwater walkway (© Perikles Merakos)

Although the walkway conforms to safety specifications and regulations, strong winds and large waves still pose a danger for its users, especially at certain points of the walkway. Being literally inside the sea, the wind intensity on the breakwater is in many cases totally different from that on the seaside, making it difficult for people wanting to visit it to correctly evaluate it. The smart lighting system that we propose in this thesis uses the light's color to indicate the safety level of the walkway in regard with wind and wave intensity. When strong winds are present, the lights color will change to light shades of red, depending on the intensity of the winds, with deep red meaning that it is unsafe to visit the walkway. The red color attracts the most attention from all the other colors, it can be seen from the furthest distance that other colors due to its longer wavelength, and in Western societies red acts as a sign of danger and a trigger of avoidance motivation (Maier, Elliot, & Lichtenfeld, 2008), prohibition (red traffic lights), and causes alertness and higher stress levels on the human body. So even in the case when a visitor on the walkway is not aware of the light convention, still the red light will cause psychological and physical alertness. The lights on the walkway are visible from a good part of the city, thus informing beforehand citizens who intend to visit it about the current situation. Below we go on more detail about the proposed implementation.

4.5.1 Proposed Use Case Scenarios

The breakwater walkway is illuminated at the moment by 110 lampposts placed in intervals of 15 meters along the walkway. All the bulbs used are conventional and will be needed to be replaced with Bluetooth-enabled LEDs. The existing lampposts are wide enough to accommodate inside the MCU unit (node). The Pi microcomputer will be situated at the Heraklion Central Harbormaster's Office, where power supply and Wi-Fi network are available. The distance between the Pi and the first lamppost in the breakwater walkway is about 250 meters and will be covered by 4 nodes placed in-between. The data about wind intensity will be provided by the database of the weather station situated in the Harbormaster's Office, so they be very accurate and reflect the actual condition in the walkway. Two nodes will be placed at locations that are not affected by nearby light sources to measure daylight illuminance, and the average readings of both of them will be used to decide daylight level. The system will be controllable from the web-based management application and also offer automated operations based on user's input. The use-case scenarios available are:

Use-Case: Automated regulator mode without Pi

Automated node's system mode, where two nodes (*regulator node* in this context) are placed in locations that are not affected by nearby light sources, thus measuring accurately daylight illuminance. Depending on daylight availability, one of the nodes will flood the Mesh network with instructions for every node to initially dim the lights accordingly at dusk, and turning them on fully after sunset. The same procedure will occur during sunrise, with the node passing information on the Mesh to turn the lights off. As an additional safety measure, to ensure that the system will be functional even in the case where the regulator node fails to regulate the system, each individual node will turn on automatically if it detects, through its own light sensor, that the daylight level is near zero and it have not received instructions from the Mesh to turn the lights on. Obviously in this mode the system will not be able, depending on the weather situation, to provide information, by changing the lights color to red, about the safety of the walkway to citizens, but it is still useful as a backup emergency plan if there is some kind of malfunctioning at the third level of our system architecture (as described in Section 4.3.3). The system will automatically enter this mode if the two nearest nodes to the Pi cannot establish connection with the Pi for a period of five minutes.

Use-Case: Automated mode with Pi but without Wi-Fi access

Automated system controlled by the Pi without Wi-Fi access. In this mode the Pi is the main logical control unit of the system. All the decisions regarding the operation of the lights are taken by the Pi, based on the logic of a light control scheme, which can be pre-applied through the web-based application, and external inputs from the nodes. The Pi will gather information about daylight availability from the two nearest nodes and decide the dimming agenda.

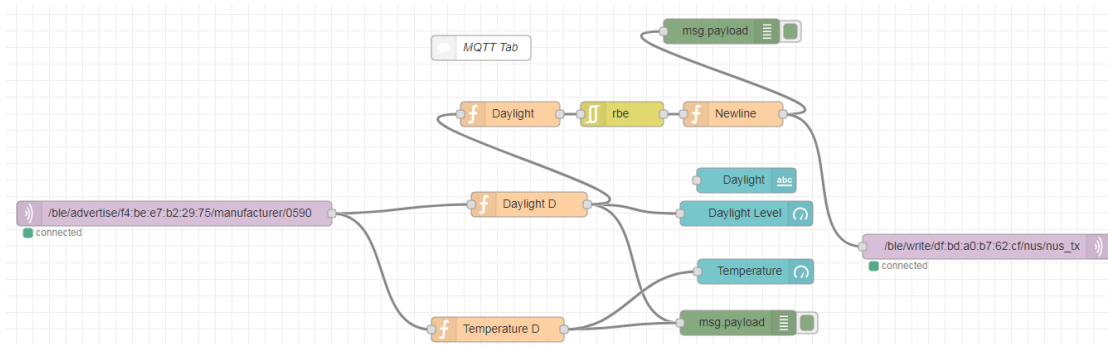


Figure 30: Daylight flow on Node-RED

This mode is useful in case the wireless network is unavailable, in which case the Pi will automatically assume the role of the moderator, which allows for more complex pre-defined scheduling scenarios, given the vastly superior computing abilities of the Pi compared to the MCUs, and the ability to store reports and analytics about the system.

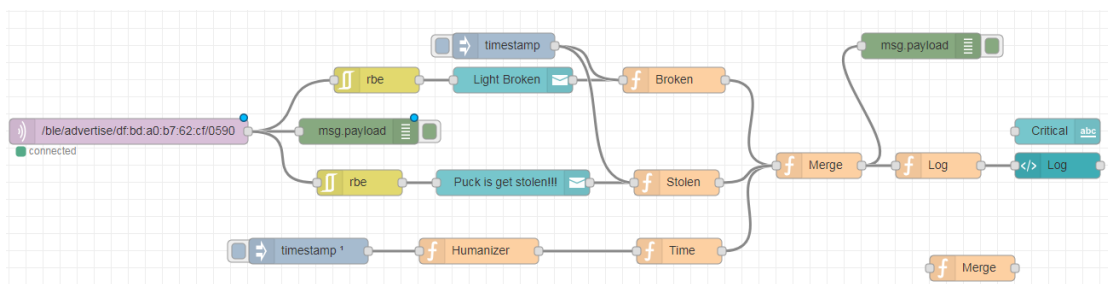


Figure 31: Reports flow on Node -RED

Use-Case: Automated mode with Pi and Wi-Fi access

Automated system control mode by Pi with Wi-Fi access. In this mode the system have full functionality, being able to access data about the wind intensity from the Harbormaster's Office database, and accordingly changing the color of the lights to communicate the situation of the weather in the walkway. The exact parameters of the control scheme can be determined through the web-based control management

application. The Pi microcomputer in this mode is able to log statistical and data from the Mesh in the local database.

Use-Case: Manual system control

Remote control management using the web-based application mode. This mode give the system moderator total control of the system. Parameters can be modified and schemes for the above automated modes defined. The data logged in the local database are available and reports from the nodes about possible problems in the system are displayed.

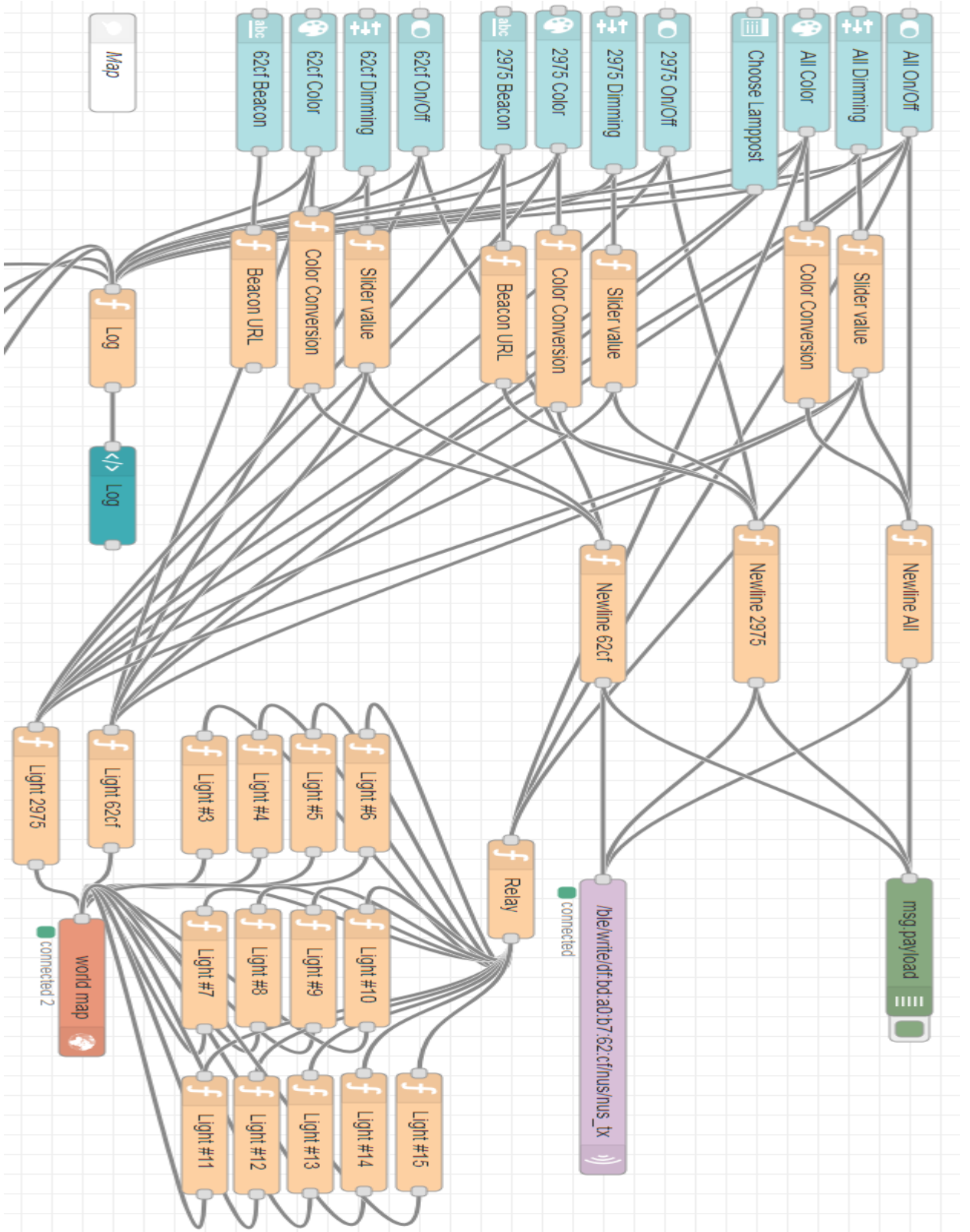


Figure 32: Manual control flow on Node-RED

Use-Case: Eddystone beacon mode

Beacon mode. This mode is not associated with the lighting control and can be used as the needs arise. Proximity-based services can have many useful applications on our walkway. The Municipality can use them to broadcast URLs in different points of the walkway, providing news about city's current affairs, cultural events and happenings in the city. In case of open exhibitions or art installations on the walkway, the beacons can be used to provide information about the displayed pieces. The beacons can also be used by smartwatches and smartphone apps targeting joggers and cyclist on the walkway to display information about the distance covered and related information. The beacon characteristics for each node can be modified directly from the web-based application.

5 Experimental validation

Following the theoretical and technical implementation presented in the previous chapter and in order to validate the overall functionality of our smart lighting system, we engaged in several experiments who were realized in a simulated environment⁶. We used two Bluetooth light bulbs that were controlled by two Puck.js microcontrollers. One of the microcontrollers was in the BLE range of the Pi and acted as a contact point between the Pi and the rest of microcontrollers. The two nodes were located about 15 meters from each other on open space, without obstacles between them.

All the system modes that we described in Section 4.5.1 were tested multiple times. Below we list the findings for each of them.

Test-case: Mesh transmission failure

To test the simplest backup plan we have in place for the case where multiple node in our Mesh system fail to transmit instructions to the next nodes, we did not sent any instruction to all the nodes to turn on the lights. As expected, when the light sensor in each node measures brightness intensity of daylight below 10 lux (near dark), and that node had not received an instruction to turn on the light from the Mesh, then each node automatically turns on its light. When the lux level measured is above 400 lux, which means that there is natural light present, the nodes did again successfully turned off the light. All the test in this mode were successful, and this is very important as we ensure that the system will always work even if there are problems in the Mesh transmitting chain. Unfortunately in this mode, as shown by our tests, it is not possible to achieve a uniformity as to the exact time each node turns on/off its light, as each node rely on its own light sensor. The average time deviation between the two nodes was about 3 seconds, with the maximum deviation observed being 15 seconds until all two lights were turned on. In real life situations, these variations in the time that each node will turn on its lights, are expected to be even larger as factors like the location of the node, dirt and dust on the lamppost can affect differently the readings of each light sensor.

Test-case: Automated regulator mode without Pi

The second automated mode we tested is when one of the microcontroller acts as a regulator for all the nodes on the Mesh, in case that the nearest MCU to the Pi cannot

⁶ <https://drive.google.com/open?id=1Ml94jVOxf8Z65mQ3ZNFV2b7uH5G8quOJ>

Test-case: Automated mode with Pi but without Wi-Fi access

In the next mode we tested, the Pi is part of our smart lighting system without it being connected to the Wi-Fi network, and is in control of the functionality of our system. All the logic controlling the lighting system on the Pi is defined on the Node-Red flows running on the Pi. The Pi decides dimming levels and on/off states for the lights based on the readings of the light sensor on the nearest MCU. All the tests were successful, the system correctly adjusts dimming levels and on/off light states. In a real site deployment of our system, it would be best practice to have two MCU that will relay information between the Pi and the rest of the Mesh, so as to avoid a single point of failure. Another test we conduct is the ability of the Pi to store information regarding the health status of each light bulb.

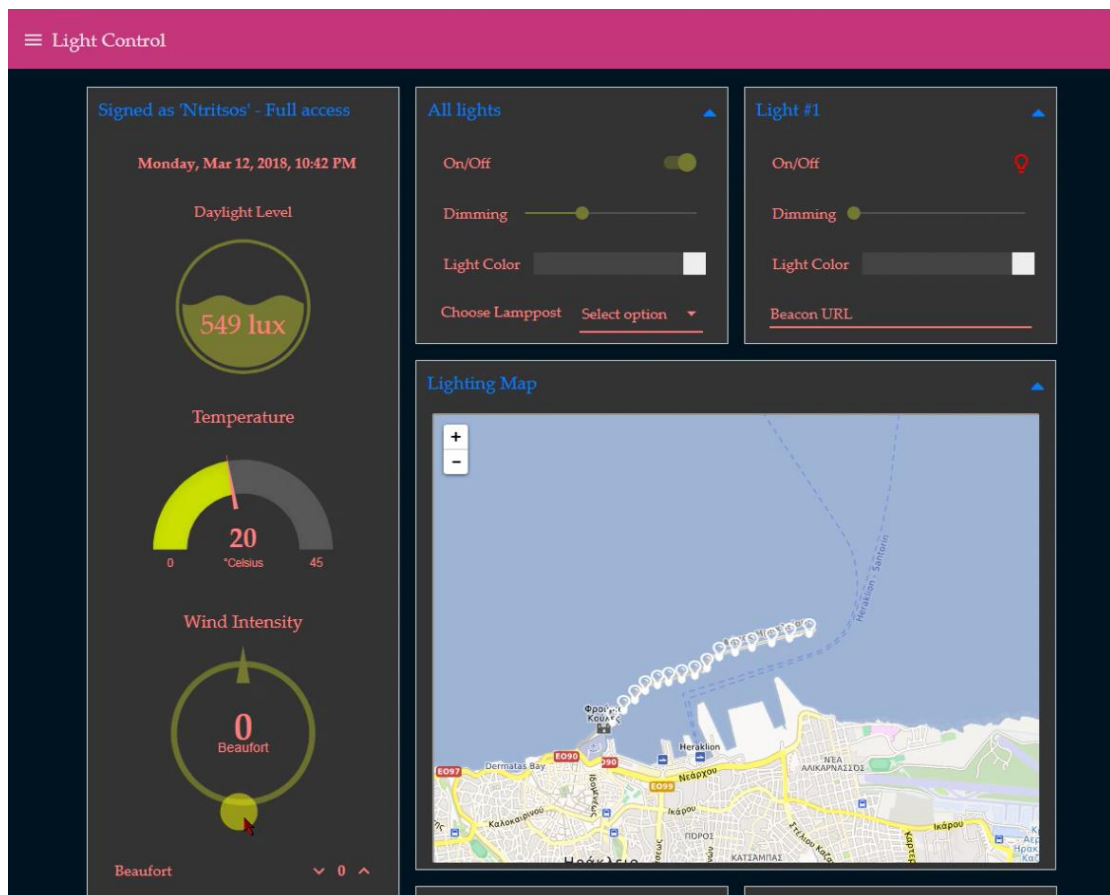


Figure 34: Wind intensity is not available

To that effect, we turn on all the lights and remove a bulb from one of the lampposts. Since the light is ON but the light sensor on that lamppost's MCU will detect no light, the MCU correctly reports the problem, information that is successfully stored in the Pi. One issue that we run into during testing in this mode is that the Pi has not a Real

Time Clock (RTC) module, so it cannot keep date and time without a power source. In our system design the Pi will be always powered-on, but power blackouts can make it display the wrong time. This was a problem for our initial design, as we had in place scheduling tasks during which the Pi would only monitor light levels from the MCU only during certain hours (5 p.m. – 7 a.m.), and this was done so as to avoid battery drain on the MCU during the day. We solved this by having the Pi asking for light measures from the MCU every 3 minutes at all times, but a better solution would be to add a RTC module in the Pi, which would keep the clock on power breakouts and would allow for scheduling tasks.

Test-case: Automated mode with Pi and Wi-Fi access

Testing the mode where the Pi is connected to a Wi-Fi network gave the same successful results as above. In this case the Pi would monitor the wind intensity every five minutes using the DarkSky API, and based on that input decided if it should instruct the Mesh nodes to switch the light color to red.

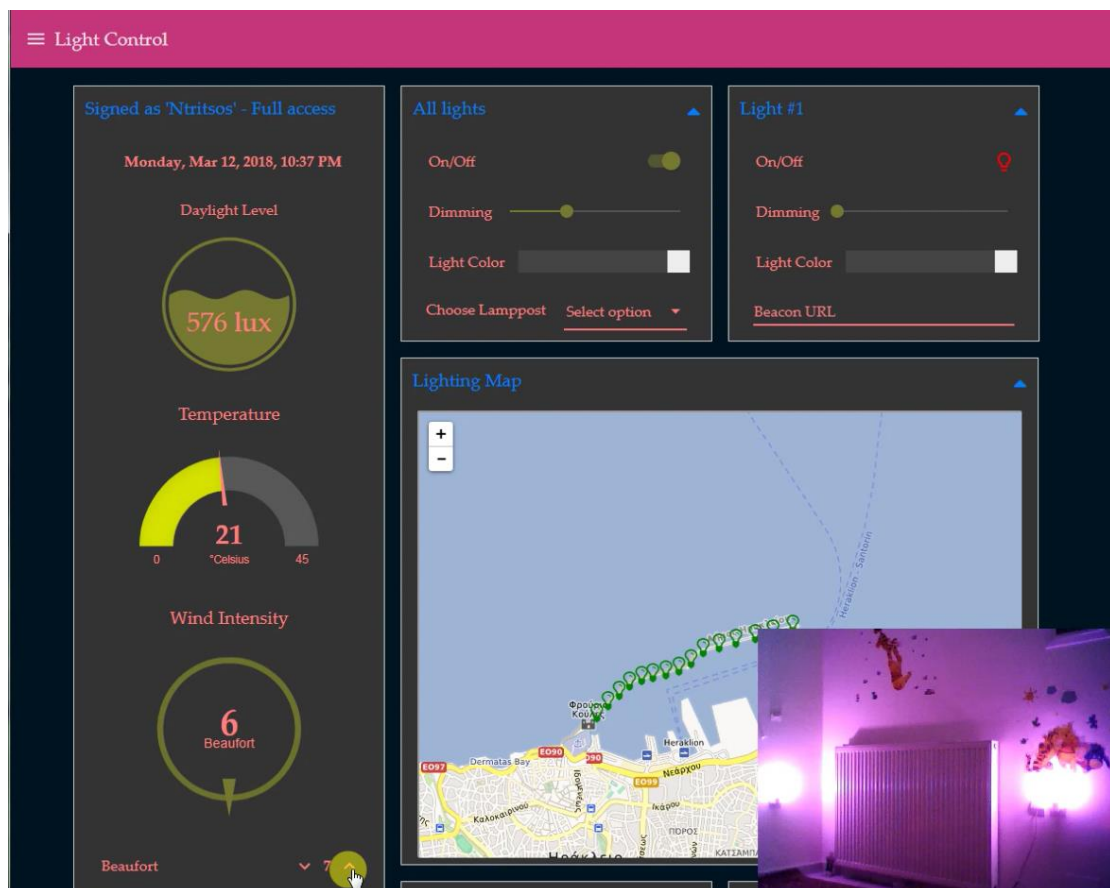


Figure 35: Full functionality

During testing, we came across the scenario where the wind intensity was very high and the lights were in a dimming phase (at dawn or dusk). Since displaying the red color

is an important feature of our system, we decided to tweak our design to skip the dimming phase when the lights must be red, and instead go straight to full lighting so as to increase their visibility. Since the lights would be turned off during the day, we had to consider possible solutions that can be used to inform the visitors at the entrance of the walkway about the safety situation on the length of the walkway. At this stage we experimented with the idea of having one of the lampposts that are at the walkway entrance pulsing at fixed interval with red color when it is not safe to visit the walkway. Even in sunlight the pulsing light was visible in our tests, so this a solution that can be mobilized in the real life application of our system.

Test-case: Eddystone beacon mode

To test the beacon (Eddystone) mode, we enter the desired URL from our web-based management interface. The only restriction here are the usual ones, that the URL must resolve to an https URL and it is not larger than 17 bytes, in which case we used Google URL Shortener⁷.

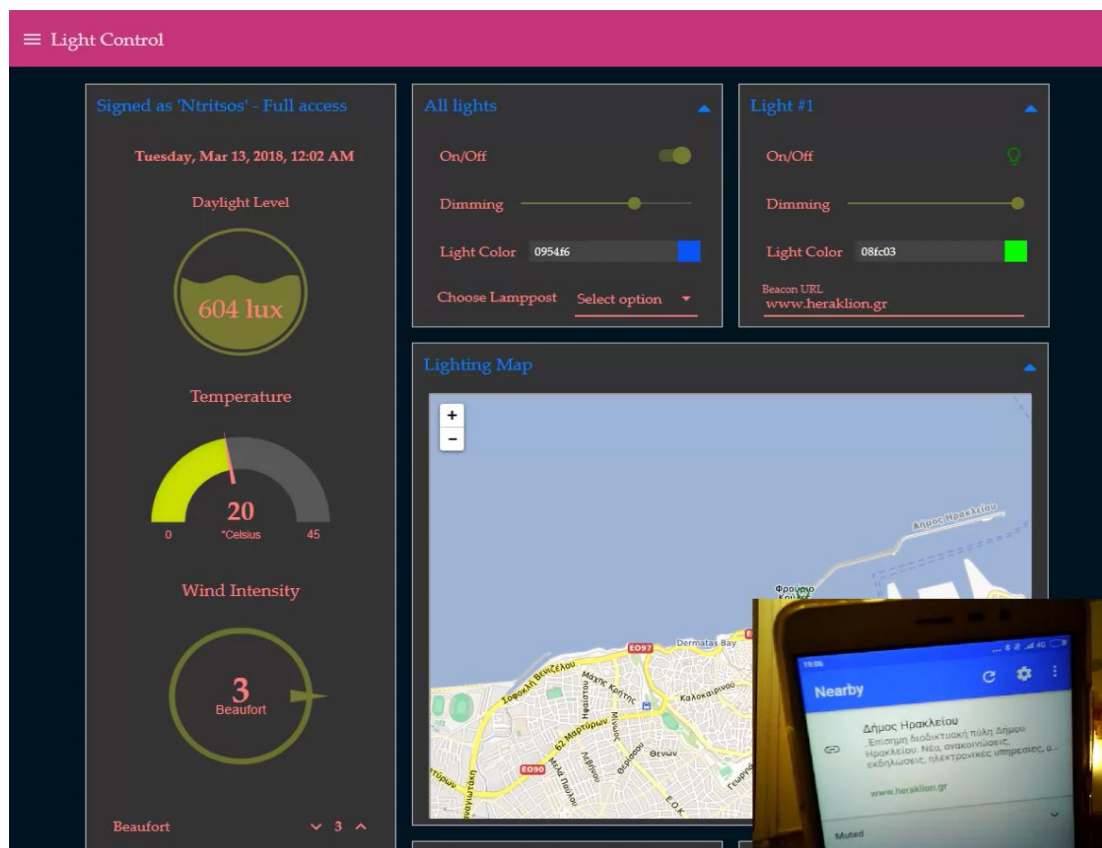


Figure 36: Beacon mode

⁷ <https://goo.gl/>

6 Discussion

In this thesis from the beginning we set out to design a smart public lighting system that would be implemented entirely on open source or open standard technologies. We followed this approach because despite the many smart lighting solutions that are available at the moment on the market, Municipalities around the world are still struggling to find the right solutions to fill their needs, in terms of being economical, easy to deploy and offer interoperability with their existing infrastructure.

Our proposed system offers a well-rounded solution that can be used to offer safety information to pedestrians and cyclist visiting Koules walkway. It is designed combining color-tunable LED bulbs, a Mesh network of microcontrollers deployed in each lamppost, and an intelligent management system running on a microcomputer (Raspberry Pi). This modularity in design makes it possible to use each layer for other Smart City's initiatives as well. The microcontrollers on our system function effortlessly as beacons, offering opportunities to provide contextual information, local-based navigation and precise wayfinding solutions. Adding additional sensors to the microcontrollers to overcome challenges and needs of modern cities is possible, noise and sound detectors, air quality sensors, the Mesh MCUs network can become the backbone of the city network information infrastructure.

The software components used to implement our system are proven solutions on building IoT applications and are open-source and open-standards initiatives. Bluetooth Mesh is the latest mesh networking player, offering a low-power mesh network with the potential to interconnect different Smart City's initiatives and offer varied added value services. The MQTT protocol is ideally suited for situations where a "small code footprint is required or the network bandwidth is limited". Node-Red visual development is fast and offers a quick way to wire together hardware devices, APIs and online services components of our system. Using Javascript as our developing language ensures that our system can be expanded and debugged easily at a later time, and open many possibilities for interactions with existing web-based infrastructure.

Despite the successful results during the testing of our system in a simulated environment, it is imperative that our proposed system is tested in real life situation over an extended time period. This way safe conclusions could be drawn about the power consumptions savings of using LEDs lights, the life expectations of the battery

powered microcontrollers, and possible latency issues in the Bluetooth Mesh network. Especially latency issues can pose a problem to our system design, as it is important that all the lights are turned on at the same time. One possible solution to achieve this is to add a five second delay to the timestamp of the initial instruction issued by Pi, so that every MCU turns on the light at the same time.

Comparing our initial design goals and the results we got from our testing phase, we can say that our system met all of those objectives. An implementation on-site would offer concrete data and reveal possible iterations needed for optimal results.

7 Conclusions and future work

Smart lighting solutions have seen a rapid growth and innovation during the last years, both on indoor and outdoor environments. Beside the huge savings on power consumption and maintenance costs, the very high life expectancy, the improved quality and uniformity of the light, the use of color can be used to provide safety information and to increase the standards of quality of life in modern smart cities.

In this thesis we proposed an effective public lighting system to be used on the breakwater walkway in the city of Heraklion. Depending on the wind intensity on the walkway, the lighting color changes so as to alert visitors on the walkway of the safety status. The system has been implemented using a networks of microcontrollers connected on a Bluetooth Mesh implementation, with a Raspberry Pi microcomputer acting as the gateway to the Municipality local area network. The system can automatically moderate the lights, allowing dawn and dusk light dimming, real-time monitoring with reports of malfunctioning bulbs and collection of data that can be used for statistical purposes and further system optimization. The web-based management application provided can be used to change schemes, update parameters and review system reports and statistic. We believe that the combination of open-source and open-standards solutions, the simplicity and the low-cost component used, together with the very positive and reliable results we observed during our testing phase, makes our proposed system a promising candidate for actual deployment on the walkway.

A future improvement of our system hardware-wise would be the integration of the microcontroller inside the light bulb, so that the microcontroller is powered directly from the mains, without the needs for batteries. We did not integrate motion sensors in our microcontrollers, doing it would enable occupancy-based schemes to be added to our system, offering bigger savings on power consumption. Our implementation of the Mesh was done in the most basic form, proper integration of the Bluetooth Mesh on Espruino would boost security and offer the full set of capabilities that it can offer.

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