Wireless sensor network for smart street lighting

Aleksandar Kospenda

Faculty of Electrical and Computer Engineering
University of Iceland
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WIRELESS SENSOR NETWORK FOR SMART STREET LIGHTING

Aleksandar Kospenda

20 ECTS thesis submitted in partial fulfillment of a
Baccalaureus Scientiarum degree in Mechatronics Engineering Technology

Advisor(s)
Krista Hannesdóttir
Þórður Halldórsson

Faculty of Electrical and Computer Engineering
School of Engineering and Natural Sciences University of Iceland
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Keilir Institute of Technology
Faculty of Electrical and Computer Engineering
University of Iceland
Grænásbraut 910
235 Reykjanesbær, Iceland

Telephone: 5784000

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Abstract

This thesis discusses the design of a Wireless Sensor Network (WSN) for smart city street lighting, a system that automates street lighting by detecting traffic and controlling lights with wireless radio frequency modules. The system is designed to be compatible with preexisting lighting infrastructure and is easy to install and maintain.

Top down design approach is used in the creation of the system, the overall architecture is defined as well as following sub-systems that make up the network. Wireless nodes on street lamps form modular networks that use sensors to detect vehicles and illuminate the road while there is traffic. In the first part, reasons for the need of such a system is presented as well as an introduction to the project. Secondly, individual components are compared and analyzed to find which best suits the design. Lastly, the system was contrived, and a prototype is put together that simulates functionality in parts of the system. Design aspects and possible future developments are discussed.

Útdráttur

Í þessari ritgerð er fjallað um hönnun á þráðlausu skynjaraneti fyrir 'Smart city' götulýsingu, sjálfvirkt kerfi sem stýrir götulýsingu eftir umferð með þráðlausum einingum á ljósastaurum. Kerfið er hannað til að vera í samræmi við fyrirliggjandi grunnvirki fyrir götulýsingu og er auðvelt að setja upp og viðhalda.

Stigveldis hönnunarnálgun var notuð við stofnun kerfisins, heildar arkitektúr var skilgreindur sem og síðari undirkerfi sem gera upp skynjaranetið. Þráðlausar nóður á ljósastaurum mynda öreiningakerfi sem notar skynjara til að greina ökutæki og lýsa veginum svo lengi sem það er umferð. Í fyrsta hluta er kynnt ástæða fyrir þörf slíks kerfis. Næst var gerð þarfagreining íhluta sem leiddi í ljós þá íhluti sem hentaði kerfinu best. Að lokum var hönnun rituð og frumgerð sett saman sem hermir virkni kerfisins. Hönnunarþættir og hugsanleg framhaldsþróun eru rædd.

Preface

The idea of a dynamic street light system came to me on an evening walk when I strolled down an illuminated road with no vehicles, it was nice having an entire street illuminated, but I could not help to feel that it was a waste of energy. I decided that it would be a suitable project for this thesis. It has evolved from a concept to an idea to hopefully later on a realistic product that is used.

I have to credit many of the ideas I had about the project to my classmates and colleagues as they have helped me get a different perspective on many aspects of the design of this project.

I hope this project opens up the possibility of further research and development of similar ideas.

Lastly, I want to thank my instructors, Krista Hannesdóttir and Þórður Halldórsson for their guidance and advice in making of this thesis.

Aleksandar Kospenda

Contents

List of Figures

List of Tables

Abbreviations

AC Alternating current

AES Advanced Encryption Standard

AIE Electronic Industries Alliance

AIR Active Infrared sensors

API Application Programming Interface

BLE Bluetooth low energy

CE Conformité Européene

CP Communication protocol

DALI Digital Addressable Lighting Interface

DC Direct current

DoS Denial of Service

DSP Digital signal processing

FFD Full-function devices

FMCW Frequency modulated continuous wave

HPS High-Pressure Sodium

IC Integrated circuit

IDE Integrated development environment

IEEE Institute of Electrical and Electronics Engineers

I^{2}C Inter-integrated circuit

IoT Internet of Things

IP Internet protocol

ISM Industrial scientific and medical

LAN Local area network

LED Light Emitting Diode

LoRa Long Range Radio

LR-WPAN Low-rate wireless personal area network

M2M Machine-to-machine

MAC Medium access control

MCU Microcontroller unit

MISO Master in slave out

MOSI Master out slave in

MPU Microprocessor unit

NPN Negative-Positive-Negative

OS Operating system

PAN Personal area network

PCB Printed circuit board

PIR Passive infrared sensor

NPN Positive-Negative-Positive

RF Radio-frequency

RFD Reduced-function devices

RoHS Restriction of Hazardous Substances

SCL Serial Clock Line

SCLK Serial clock

SDA Serial Data Line

SOC System-on-chip

SPI Serial peripheral interfac

SS Slave select

SSH Secure Shell

SSL Solid State Lighting

SSR Solid state relay

SWAP Simple Wireless Abstract Protocol

UART Universal asynchronous receiver/transmitter

USB Universal serial bus

VIP Video image processing

WLAN Wireless local area network

WSN Wireless Sensor Network

1. Introduction

Ever since the rise of sedentary human civilization, people have had to apply urban planning for major infrastructure. In modern times, infrastructure such as water, electrical, transport and even communication between people have all been focal points. Minute improvements in infrastructure can lead to a considerable impact on the environment and a better quality of life for inhabitants. In the early days, urban planning was done with convenience and comfort in mind, today's prime influence is the sustainability of resources while maximizing social health and interconnectivity between both people and systems that govern organizations of people and commodities. With the emergence of electricity, the possibility of controlling more and more components of the infrastructure, such as radar technology for aviation and traffic lights for road-bound transportation has resulted in higher efficiency systems and better overall experience for individuals.

The smart city concept is built on the idea that information and communication technology should be combined to control buildings, transportation, utilities and many more community assets with the ultimate goal of improving the quality of life, decreasing resources and increasing security.

The proposed design in this thesis is intended to increase efficiency in street lights, decrease light pollution and open up the prospects of implementing traffic control by sensing cars and their direction. The system works by detecting cars, communicating wirelessly to the next light post and turning on lights for a set amount of time. Wireless communication between light posts makes use of nodes that are commonly used in wireless sensor networks. Having the system wireless would save on construction costs, it would also remove constraints regarding upgradeability of the system.

There have been projects that are similar in nature to the design in this report. WSNs have been used as an intelligent control for street lights such as the Light-Grid system by General Electric [1]. This system monitors the condition of street lighting, continuously monitors power consumption and can be programmed to turn lights on and off depending on sunrise and sunset times.

Street lighting system based on a WSN by Rodrigo Pantoni, Cleber Fonseca and Dennis Brandão aspires to monitor (mainly power consumption) the condition of street lamps and control public street lighting in Brazil [2].

1.1. Street lighting

Lighting had existed in its current form since incandescent bulbs took over from candle lighting in the 1800's when Russian inventor Pavel Yablochkov developed the arc lamp by exciting two carbon rods with an inert material between them, this produced an incandescent light source for two hours. The arc lamp would later be developed into the first system of electrical lighting [3, p. 282]. Modern street lighting adopted the concept in the modernized arc lamps such as high-pressure sodium (HPS) lights. High-pressure sodium and other varieties of similar bulbs have drastically affected the way civil engineers design roads, pathways, and facilities where lighting is requisite.

Engineers have tried to control street lighting in a cost beneficial way by either dimming the lights when it is bright outside or turning them completely on and off by way of sunrise and sunset timing tables. These methods increase efficiency and add substantial value for future smart technology where we want to control most aspects of our surroundings. By using the latest advancements in light sources and Internet connected wireless devices, one can open up the possibility of taking the next progressive step in the technological evolution of infrastructure. Smart control for street lighting could result in the integration of many different discrete elements that make up the smart city framework.

High-pressure sodium lights are the most common way of lighting up streets and industrial settings [4]. Typical power consumption for a HPS bulb is 150-200 W which delivers approximately 15 000 lm, often in a yellow hue given off by the sodium. These bulbs last an estimated 20 000 hours [5]. Their fundamental problem is that there is a delay between being able to turn them on again if they have been turned off recently and they take minutes to warm up to full brightness after being turned on [6]. This hinders them unusable and uncontrollable in the modern context where most residential light fixtures allow both rapid termination and dimming.

Light emitting diodes (LEDs) also known as solid state lighting (SSL) can be manipulated in ways that HPS lights cannot. LEDs have the ability to turn on and off without delay whereas HPS bulbs can take minutes to cool down enough to be switched on again. LEDs can be dimmed precisely to any output strength necessary, LED street lights also have the ability to use many low powered LEDs instead of one bulb like HPS. Going from the current state of street lighting to modern LED lights opens up the opportunity of controlling street lighting in an unprecedented way. This realization was the inspiration for the design presented in this thesis.

1.2. Problem Statement / Design goals

The feasibility of such a system is not in question as the capabilities of each element is clear and combining them is possible. On the other hand, it is uncertain how one should go about designing such a system, its capacity and how it should be implemented.

The main objective of this thesis is to design a WSN which detects vehicles, relays information between nodes or wireless radio frequency modules to ultimately turn on and off street lights by the flow of traffic.

A solution for the design will be researched in this thesis and will be composed of:

- Low overall cost for the system.
- Energy efficient wireless transmission.
- Comparative analysis of wireless nodes and sensors used to detect vehicles.
- Design of 230 V alternating current (AC) trigger circuit for LED drivers.
- A construction of a simple prototype that illustrates the basic functionality inside the system.
- Cost analysis will not be done for the system.

1.3. Thesis overview

The audience of this thesis is fellow engineering peers and professionals and other science-interested communities and individuals.

Summary of chapters that gives a brief overview of this thesis is as follows:
Chapter 1 serves as an introduction to the project and the faced design problem.
Chapter 2 presents the relevant literature used in the design process.
Chapter 3 presents requirement analysis and hardware selection of suitable components used in the design.
Chapter 4 goes over the network topology and design methodology used. It also describes the overall design structure.
In Chapter 5 a prototype is developed and a simple prototype is put together.
Chapter 6 goes over some of the problems faced with the design, builds a discussion around them along with possible future work related to similar ideas. Finally, Chapter 7 is a short conclusion for the thesis.

Additional supporting literature, datasheets, and work schedule for this thesis can be found in Appendix A.

2. Background

At the core of the design is the wireless node which is comprises a processor, a transmitter, a battery power supply and sensors along with serial communication peripherals. Such a contraption is often a part of an embedded system, an organized framework where many individual components work together and have a dedicated function. In the case of this device, the embedded systems sole purpose is to control LED street lights.

Background information describing parts of the embedded system needed for this thesis is presented in this Chapter along with an explanation of communication protocols and sensor technologies used to detect vehicles in traffic control situations.

2.1. Wireless sensor networks

Wireless sensor networks are a relatively new but emerging technology that makes it possible to address various industrial and environmental problems where spatial monitoring is required, as opposed to a singular or one-dimensional measurement. Spatial monitoring can give a clearer perspective on the overall conditions of that which is being measured. A wireless sensor network's ultimate goal is an acquisition of data and delivery of measured data to a central gateway, from there, data can be extracted to the Internet where it can be combined and processed.

Wireless sensor networks are made up of nodes that make up an autonomous collective, each has a role in making up an embedded system. Coordinator nodes also known as full-function devices (FFD), are always singular and have unique roles in WSNs. They are responsible establishing the network size, the personal area network (PAN) wireless nodes work on, it gives other nodes unique addresses which make them identifiable and addressable by wireless communication. Overall wireless network health is monitored by coordinator nodes, if any node disconnects from a network, the coordinator node chooses an alternative routing path for data[7]. Figure 2.1 portrays an example wireless sensor network. The three types of nodes as defined by the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard [7, p. 4] and ZigBee protocol [8, p. 219] that make up a WSN are:

- The coordinator node is the pathway for the WSN to the Internet. These nodes are the busiest nodes in the network as they are the only connection to the outside world and receive and send more data than any other node. They are therefore often connected to mains electricity for stability.

- Routing nodes are the workhorse of a WSN. They both measure by their own sensors if they have one, and route incoming data from nodes in their vicinity. Routing nodes do not physically differ from coordinator nodes but they have no authority when it comes to WSN framework or configuration.

- End nodes or reduced-function devices (RFD) are nodes that take measurements and pass their data to routing nodes nearby. They do not have the ability to communicate with other end nodes. They are physically indistinguishable from routing and coordinator nodes.

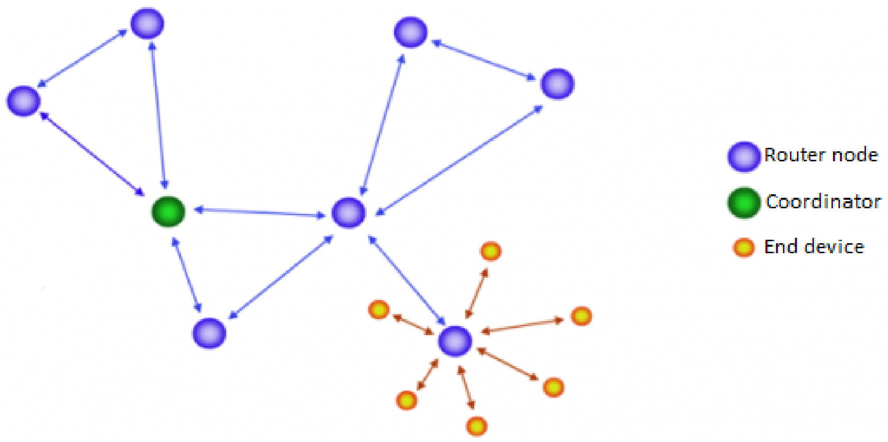

Figure 2.1: Example of a wireless sensor network and explanations of node types and their roles. Each dot represents a wireless node. The arrows show which direction communication is allowed between nodes in a WSN. Source: `https://cdn2.episensor.com/wp-content/uploads/docs/docs-sensor-network-513x250.png` (Accessed May 10, 2017)

2.1.1. Wireless sensor network topologies

Wireless sensor networks can consist of anywhere from few to thousands of nodes. How they are set up to communicate with each other is regulated by two types of topologies, Star topology, and Peer-to-Peer topology. Each topology has its own contributing attributes and handles some situations better than others. Nodes in a defined topology network are given a unique address which they use to communicate within their own PAN set up by the coordinator [7, pp. 8-9].

Star topology is a single-hop system where a single coordinator node communicates with any number of router nodes and end devices in a bidirectional way both short and long range. The router nodes, however, do not speak to each other or pass information to other router nodes. This kind of system is often used in home automation applications where the coordinator node is placed in the center of the homes and router nodes control relays, solenoids, and other control equipment. It is recommended to have the PAN coordinator connected to mains electricity power because of the frequency of communication requests [7, p. 15] and the routing algorithms used while in this topology [9].

Peer-to-Peer topology has a PAN coordinator, but unlike Star topologies, router nodes can freely communicate with each other to relay both data and commands from other router nodes and the coordinator as long as they are in range of each other. It can be recognized that Peer-to-Peer topologies are more complex in nature as they allow for bigger network topologies where routing algorithms dictate the direction and which nodes route data to the PAN coordinator and ultimately to the Internet through a Gateway. The Peer-to-Peer or mesh topologies are used in monitoring agricultural environments, inventory tracking in automated warehouses and security and military settings where large amounts of nodes work together [10]. Figure 2.2 depicts the two types of WSN topologies.

Full function devices in a Peer-to-Peer topology can act as a self-organizing device for the system in case some nodes malfunction and break communication pathways. Automatic routing can be helpful when batteries die in WSN nodes or if there are problems with delivering data between nodes. Any wireless communication device can experience faults in data transfers, for instances such as these, nodes can work together to either skip the affected node or retry sending the desired packets.

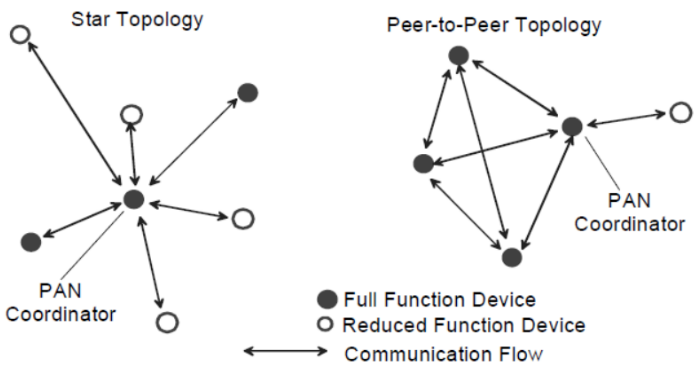

Figure 2.2: Wireless sensor network topologies as per definition by IEEE *802.15.4-2011 standard on Low-Rate Wireless Personal Area Networks. Source:*`http://ecee.colorado.edu/~liue/teaching/comm_standards/2015S_zigbee/802.15.4-2011.pdf` *(Accessed May 10, 2017)*

2.1.2. Wireless sensor network nodes

Wireless sensor network nodes first application was found in a military context, surveillance of areas was done by motion detection sensors [11]. Nodes were larger in those times, but they are still made up the same or similar electrical components. Today's nodes have a dedicated microprocessor (MPU) or microcontroller unit (MCU), a radio device which has a transmitter and receiver for wireless communication and depending on the device, either a sensor interface or built-in sensors. Nodes are in most cases deployed in rural environments where they are left for a long period and are thus powered by batteries.

Radio transceivers for WSNs can be designed with both range and power consumption in mind, while long range communication can be aided with high gain antennas, long range nodes require substantially more power than nodes designed for low range. Typical transmit and receive actions use close to 20 mA, this value fluctuates a lot depending on which wireless nodes are used. Along with sensing and data processing a node with average power consumption can be powered for many days[1] with decent capacity batteries. There are also wireless nodes which can be charged with the help of harvested energy for alternative energy sources such as solar [12]. Presented in figure 2.3 is a diagram of a emblematic WSN node.

[1]`https://www.digi.com/pdf/ds_xbee-s2c-802-15-4.pdf` (Accessed on 10.05.2017)

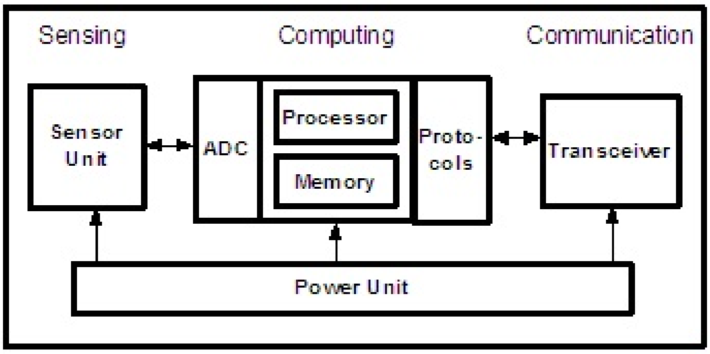

Figure 2.3: Wireless sensor network node diagram. The diagram shows the peripherals on a wireless node as well as the direction of communication between sensor, processor and radio frequency transceiver. The nodes are powered by power unit which in most cases is a battery. source:`http://www.scielo.edu.uy/img/revistas/cleiej/v14n1/1a09f3.gif` *(Accessed May 10, 2017)*

2.1.3. Node microprocessor

The microprocessor unit or microcontroller used on nodes controls the functionality needed to operate the node. Some nodes have a MPU capable of performing digital signal processing (DSP), these nodes contain a power efficient processor that does all the calculations needed and controls the link between modules on the node by serial communication. These processors often host a specially built operating system (OS) such as TinyOs [13], which is broadly used in the scientific and research community. The MPU has a memory peripherals where program memory for the OS and memory for sensed data is kept, the data memory is however not intended as a long-term storage device as they are often limited in size. Other nodes might include a MPU that controls all peripherals but does not have any capability of programming logic other than setting digital outputs high or reading analog input.

2.1.4. Node wireless transceiver

A transceiver is a device that includes a transmitter and a receiver for wireless communication. Transceivers are put on an integrated circuit (IC) that includes system-on-chip (SOC) which integrates both a transmitter and receiver. Transceivers are manufactured with the architectures required by the relevant wireless protocols. Transmitter and receiver in most cases share the same antenna. Logic switching dictates whether the device is transmitting or receiving. [14, pp. 20-23].

Sensor nodes that are used in an application where secret broadcasting is not a priority make use of open and unlicensed industrial, scientific and medical (ISM) radio-frequency (RF) bands. The most common frequencies are; 433 MHz, 900 MHz and 2.4 GHz. The exact frequencies are region dependent and they have a tolerance span. There are few frequencies outside these three and they each have their own features which make them more suitable for different applications [15, p. 88]. Bluetooth low energy (BLE), ZigBee, WiFi, 6LoWPAN and WirelessHART protocols and frequencies are often used on transceivers.

The different frequency ranges have their own attributes, for example, the 433 MHz is most often used in long range wireless, whereas 2.4 GHz can be used to transfer a greater amount of data over a short distance [16, pp. 24-31].

Transmit power required for low range spans from 1 mW to 10 mW for sub 100 m range, for long range transmission with antennas, 50 mW to 100 mW is common, these numbers are however also dependent on the communication protocol used and whether or not the node is a coordinator node, a routing node or an end device [17]. This kind of power is however not used continuously because transceivers have the ability to idle or sleep when they are not being used.

2.1.5. Node sensor interaction

Some nodes have a dedicated function and utilize built-in sensors that are directly connected to a MCU or MPU. There are a wide variety of sensors available such as:

- Chemical sensors.
- Electrical current and voltage sensors.
- Moisture, humidity, wind and temperature sensors.
- Acoustic, vibration, pressure and optical sensors.
- Displacement, distance, accelerometer, velocity and presence sensors.

External sensors can be used through serial interfaces a MPU or MCU provides. The four most common serial interfaces used for communication between sensors and the controller are Inter-integrated circuit (I^2C), Serial peripheral interface (SPI), Universal asynchronous receiver/transmitter (UART) and universal serial bus (USB). For each of these interfaces, there are certain rules or protocols that have to be followed for the device to function properly [18]. The first three protocols mentioned above are discussed in section 2.3.

2.1.6. Node power sources

WSN nodes serve many purposes and come with many different options that add to their capabilities. Some are intended to be disposable as they are either placed in hazardous locations or in places where human interaction is unfavorable.

Some wireless nodes require a mains power source as they are always on and a battery would be impractical. Most nodes use either 1.5 V AAA or 3.7 V 18650 batteries that can power nodes anywhere between weeks to years depending on battery capacity, the function of the node and conditions the battery and node are in [17]. Most nodes are powered by logic level voltages, i.e., 3.3 V or 5 V, connecting batteries in series is required in most cases.

Wireless nodes can use external voltage supervisors that it interacts with through serial communication much like any sensor it can be connected to. Voltage supervisors can monitor battery voltages and notify other nodes if the batteries run low. Additional wireless nodes can also act as monitors for a WSN, these nodes can monitor abnormal communication between nodes (i.e. packet loss due to loss of power) and report it to a PAN coordinator [19]. Solar chargers have also been used to charge batteries for prolonged monitoring [12].

2.2. Communication protocol

Every computer or electronic device that needs to communicate with other devices follows a communication protocol (CP), these protocols come in varying sizes and complexities. Some protocols are specifically made for one way communication, some are designed for high-speed communication whereas others are set up to deliver high amounts of data reliably. What these protocols have in common is that they format either digital or analog signals into messages in an organized way so devices can have standardized rules when it comes to speaking to each other. CPs deploy authentication mechanisms so two devices can identify each other and know who they are communicating with. Error detect messages are used to be certain they have received the entire message and many more features that are different from protocol to protocol.

Communication protocols can be implemented both in software, hardware or a combination of the two. Most devices that follow protocols develop states that devices can be set as, they can be set to be masters, which in most cases control the communication or slaves which do not possess as much control over the communication between devices. Many protocols deploy acknowledging tests that make sure devices are ready to start receiving or transmitting, once both parties agree on which way the data or header stream is going they send packets also called frames, often in a predetermined size, depending on the communication syntax for the protocol. Within a frame of data, a whole set of instructions can be carried out, these instructions are determined by the protocol syntax much like syntaxes for programming languages.

Layering communication protocols involve designing protocols such that it is divided into layers where each layer accomplishes a task or specified function to keep it simple and allowing it build additional layers to adapt to its use and applications. For simple CPs such as SPI or I^2C, layering of the protocol might not be needed since peripherals in most cases are simple devices.

2.3. Serial communication

I^2C is a two wire serial bus communications protocol where devices are split into two classes, masters and slaves. The two bidirectional signal wires between every device are serial data, and serial clock often denoted as SDA and SCL. They are connected to a supply voltage with a pull-up resistor between them. The data transmission or messages, in the from of a 7 or 10-bit address space which is synchronized to a clock oscillator. Messages are framed in such a way that there is a start command at the beginning of the frame and a stop command at the end of it. Data and other error checking and acknowledgment features are sandwiched in predefined bits. Data rates can be set at 0.1, 0.4, 1 and 3.4 Mbit/s [20].

SPI is also a synchronous serial bus, it uses four wires opposed to the two used by I^2C. The four signal wires are; master out slave in (MOSI), master in slave out (MISO), serial clock (SCLK) and slave select (SS). Unlike that half-duplex (non-simultaneous bi-directional communication) system used by I^2C, SPI uses unidirectional synchronized data travel through the MOSI and MISO lines. The slave devices are selected with SS so only two devices are ever in communication with each other, a drawback over I^2C because dedicated lines must be used to select which slave is being communicated with. SPI can be used with many different transmission speeds or baud rates [21].

UART communication can be full duplex, half duplex same as SPI and simplex (one-way communication) these methods depend on the hardware implementation of the device that is using it. UART is a circuit that implements serial communication, the two serial wires that act as output and input are RX (for receive) and TX (for transmit). Devices talking through serial must have a synced baud rate. The serial data is sent in 5 to 9 bits at a time in a formatted data frame. Each frame has a start bit and stop bit, they signal to start and end of a data packet. (seen in figure 2.4). UART can be found in few different voltage levels, RS-232 (+3 to +15 or -3 to -15) and RS-422 (-6V to +6V) are versions developed by Electronic Industries Alliance (AIE), each has its own characteristics and functions.

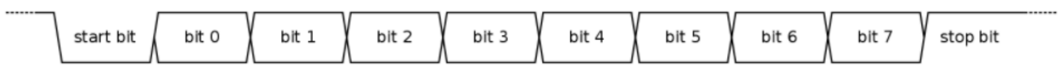

Figure 2.4: Example UART *data frame in serial communication. source:*`https://upload.wikimedia.org/wikipedia/commons/thumb/2/24/UART_timing_diagram.svg/1920px-UART_timing_diagram.svg.png?1494583090316` *(Accessed May 12, 2017)*

2.3.1. IEEE 802.15.4 wireless communication protocol

While some older WSN nodes used 802.11 wireless local area network (WLAN) communication protocol used by most 2.4 GHz devices. It became apparent that the power demand and data transfer rates were excessive for wireless nodes. For reasons, including the one mentioned above, a low power wireless communication was developed. Institute of Electrical and Electronics Engineers (IEEE) define the 802.15.4 protocol which is the most commonly used WSN protocol as:

> A low-rate wireless personal area network (LR-WPAN) is a simple, low-cost communication network that allows wireless

> connectivity in applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol [22].

Some of the current (2015 revision) characteristics of the 802.15.4 protocol are:

- Data rates are 20, 40, 100 and 250 kbit/s
- 16 channels on 2.4 GHz band
- 10 channels on 900 MHz band
- Dynamic addressing
- Unique 64-bit extended address or allocated 16-bit short address
- Star or Peer-to-Peer operation
- Support low latency devices
- Handshake protocol
- Low power consumption
- Fully acknowledged protocol for transfer reliability

Different application layers can be built upon the physical and medium access control (MAC) layers of the 802.15.4 protocol stack, this allows the communication protocols to have different profiles and different characteristics [23, p. 11]. Some of these application-specific layers include ZigBee, WirelessHart, LoRa or even compressed IPv6 protocol such as 6LoWPAN.

2.3.2. Internet gateway for wireless sensor networks

Internet gateways, sometimes called sinks, provide wireless sensor networks the capability of extracting acquired data to a format or protocol which is understood by the Internet protocol (IP) which is used by most personal computers. These gateways make use of open source programming environments so users can structure applications that format extracted data in a way that is desirable, whether that is to store raw data on a server or modify to use inside cloud computing.

There are two methods of achieving IP data extraction by a gateway. One uses a dedicated gateway node (often the coordinator) connected to a personal computer as demonstrated by Leon du T. Steenkamp, Shaun Kaplan and Richardt H. Wilkinson [24] with an AT91RM9200-EK evaluation board with TinyOS.

The second method uses machine-to-machine communications, abbreviated as (M2M), to connect the gap between mobile networks such as the ones that use the 802.15.4, LoRa [25] or ZigBee protocol. M2M was developed from telemetry, an automated system of sensor measurements where a central host analyzes data sent to it. M2M uses the same concept with present-day networking technology, essentially bringing together wireless sensors, the Internet, and personal computers. M2M is one of the backbones in the Internet of Things (IoT) initiative [26].

2.3.3. Communication encryption and WSN security

Security threats and security protection are continuously evolving, security measures and protocols take up more and more resources as they grow in size. Asymmetric cryptography such as the ones used in local area networks where there is a set of paired keys, one public key and one private key are used to form secure communication.

The main objectives of cryptography are twofold, authentication and encryption. Authentication is done by checking the validity of the private key to public key where only one solution to mathematical algorithm presents the right answer, an example of protocols that use such algorithms are Secure Shell (SSH) [27]. Encryption is a mechanism of handling communication data and encoding it a way that illegitimate or unwanted users can't read it. The keys are again used to decrypt the messages sent between the two parties that hold the keys.

Symmetric cryptography algorithms use only one shared key to encrypt and decrypt encrypted messages. This means that when the keys are shared between devices, they need to be secure in the first place. For this reason, asymmetric and symmetric are often used in combination with each other, one example is openPGP [28].

Hardware limitations of wireless nodes and the capabilities of WSN prevent such systems from using asymmetric cryptography because of the computational complexity of solving algorithms continuously [29, pp. 592-595]. For that reason, most WSN today use lightweight shared key cryptography such as advanced encryption standard (AES) encryption. The IEEE 802.15.4 protocol uses 128-bit AES.

These encryption processes are used to secure communication between wireless nodes. Data confidentiality of sensitive information that is sent between devices and protection from outside attacks are a priority as they can reduce the performance of a WSN and cause faults or failures.

Some of the attacks on WSNs are: Jamming, where a lot of data is intentionally sent to disrupt data flow. Tampering, where change the nodes are altered to gain information or access to a WSN. Collision, where outside frequency sources try to replicate the frequency inside the WSN to disrupt them. Exhaustion, where a communication request is continuously sent on nodes to deplete their battery power. Sinkhole attack, where one node requests data from neighboring nodes to disrupt routing of data. Sybil attack, where one node replicates its own identity at different locations in the WSN so to create confusion and communication faults [30]. Flooding or denial of Service (DoS) attacks, where a WSN is flooded with a vast amount of fake requests that overloads the system and prevents normal function [31]. Some of the techniques and mechanisms used to battle these attacks and keep WSNs healthy and secure are:

- Confidentiality: Unwanted intruder could read communication between nodes if the data isn't encrypted.

- Integrity checks: Message integrity checks ensure that data isn't being altered while it is transmitted between nodes.

- Authentication: Authentication signals can be sent between wireless nodes to make sure the received message was from a trusted source.

- Timestamp: Data can be implemented with a timestamp, so copies of old messages between nodes are not retransmitted again by an external source [30].

2.4. Vehicle detection with sensors

There is wide range of sensors that can be used to detect movement, or the presence of vehicles or pedestrians, the sensor technologies relevant to this project will be presented in this section. Some sensor technologies will be discussed but excluded as they do not fit the WSN criteria as of now, however, if the design allows for it, later on, it could be implemented.

For this design, the vehicle detection could be done in one of few different ways, by mounting the sensors high up on the lamp posts and using remote sensing, by mounting the sensors low on lamp posts and use remote sensing, this would allow for cheaper sensors than if mounted far away because of difference in distance, sensors would require less detection range if they were mounted close to the vehicles. Finally, some sensors can be installed underground and can detect traffic, this method has been utilized effectively before in traffic light systems. The combination of two different detection technologies can increase the accuracy of vehicle detection to make it more reliable, this has been done to achieve vehicle detection and tracking with WSNs [32]. Overview of the different types of sensor technologies can be seen in Table 2.1.

Communication bandwidth between sensor and processor or microcontroller is considered low if only commands are transferred between them. The cost comparison is relative to each sensor technology and is not based on real figures, included in the cost is the method of installation which differs from underground and overground sensors. More detailed price comparison will be presented in chapter 3. One of the sensor technologies will be used and unique sensors will be compared.

It would be beneficial to the capabilities of the system to detect both presence and the velocity of a vehicle. Microwave vehicle detection seems to be the way to go as they are both simple and power efficient. Table 2.1 was made with the aid of 'The Vehicle Detector Clearinghouse[6] report on Vehicle Detection and Surveillance Technologies used in Intelligent Transportation Systems.

[6]https://www.fhwa.dot.gov/policyinformation/pubs/vdstits2007/vdstits2007.pdf(Accessed March 23, 2017)

Table 2.1: Overview for sensor technology used in vehicle detection. Comparison of cost, ability to detect vehicles, their speed and communication bandwidth for each sensor. Source: `https://www.fhwa.dot.gov/policyinformation` *(Accessed March 23, 2017)*

Sensor Technology	Cost	Detect Presence	Detect Velocity	Communication Bandwidth
Microwave	Low to moderate	✓[4]	✓	Low to moderate
Photoelectric	Low	✓	✓[2]	Low to moderate
Ultrasonic	Low	✓	✓[3]	Low
Acoustic	Moderate	✓	✓[5]	Low to moderate
Inductive loop	Low	✓	✓[2]	Low to moderate
Magnetic	Low to moderate	✓[4]	✓[2]	Low
Video image processing	High	✓	✓	High

[2] Requires two sensors in sequence
[3] If facing target directly
[4] Requires signal processing
[5] With array of sensors. Average speed can be obtained.

2.4.1. Microwave sensors

Microwave sensors also known as radar sensors, detect by sending out electromagnetic waves by a transmitter and listening to a reflected signal with a receiver [33, s. 5-13]. By timing detection signals it can detect objects direction and velocity. These kinds of detectors are commonly used in security systems and automatic lighting. These sensors can cover multiple lanes if placed accordingly. False positives readings can occur during bad weather or radio frequency radiation from electronic devices. Filters that help the sensor ignore weather can be implemented in software [17].

There are two types of microwave detectors currently used in vehicle detection practice, a continuous wave which does not change with respect to time and a sawtooth wave where changes time result in a change in amplitude of the emitted signal. The continuous wave type can only measure the velocity and presence of an object if it is not stationary, whereas the sawtooth type, also known as frequency modulated continuous wave (FMCW) microwave sensors can detect stationary objects and the distance from the sensor to the object [33, sec. 5-13].

2.4.2. Photoelectric sensors

There are two types of photoelectric or infrared sensors, active and passive. Active infrared sensors (AIR) are similar to microwave detectors, they instead send out an infrared signal with a transmitter and detect reflections with a receiver. Passive infrared sensors (PIR) detect heat radiation emitted from any object above absolute zero [33, sec. 5-17].

Differences in body temperature from vehicles and pedestrians can be used to have different characteristics of the output signal from the sensor. Neither AIR or PIR should have trouble with detecting in bad weather conditions. The sensor can be placed both above the road and alongside it.

2.4.3. Ultrasonic sensors

Ultrasonic sensors use sound or pressure waves which are produced by a pulse transmitter. The sound wave propagates through the air at the speed of sound. When it reaches a target that has a higher density than air it reflects or scatters sound waves back towards the sensor. A transducer picks up the sonic energy that reaches it, with this method, both range and speed of a vehicle can be determined. Optimal placement for vehicle detection of ultrasonic sensors are directly above the road pointing downwards or slightly inclined [33, sec. 5-25].

2.4.4. Acoustic wave sensors

A piezoelectric material is used to detect mechanical vibrations (i.e. sound) given off from passing vehicles or pedestrians. This sort of sensor is passive, meaning they do not transmit anything outwards from the sensor. Typically an array of sensors is placed to increase the accuracy of the sensor system as environmental noise can effect the output from the sensors. These sensors can be programmed to ignore sounds produced by undesired objects that are not to be detected [33, sec. 5-28].

2.4.5. Inductive loop sensors

An inductive loop is a system which uses oscillating wires buried underground to detect a magnetic body. Wires are excited with an electric signal when a vehicle passes over the wires, and it decreases the inductance in the wires which in return makes the wire oscillate faster. This change in frequency can be read and processed. This sort of sensors is often used around traffic light controlled intersections. Unless more than more than one of these sensors are used in succession, the speed of a vehicle can not be determined [33, sec. 4-4].

2.4.6. Magnetic sensors

There are both active and passive magnetic sensors, Both passive and active magnetic sensors work much like inductive loop sensors. Passive magnetic sensors measure changes in the earth magnetic field which is attenuated by a passing vehicle. Active magnetic sensor often called a magnetometer, induces currents in a wire coil wrapped around a magnetic core. Changes in the magnetic field which are caused by a vehicle can be detected by the sensor. Both of these sensors can be placed underground. This sensor technology will not work for pedestrian detection [33, sec. 4-6].

2.4.7. Video image processing

Video image processing (VIP) is when a video cameras data source is intertwined with mathematical algorithms in software to analyze every frame of video sensor. Depending on the algorithm used, the output of such a sensor can be either an image which depicts information or parameters that describe the image. With this sensor technology, one can distinguish between vehicles and pedestrians. As an added benefit speed could also be calculated which could aid the capabilities of the system [33, sec. 5-1]. Since the image sensor can be mounted high above the road, it can monitor multiple lanes and sidewalks simultaneously. Weather can have a big impact on the effectiveness of the sensor if it blocks the line of view. All these capabilities come with a cost, the power needed to keep the sensor running and decoding the images in real time is high. However, research is being done on compressed video algorithms for WSNs in environmental monitoring [34] and video surveillance [35].

3. Requirement analysis and hardware selection

For the case in which a wireless sensor network is used in an environment such as the design in this thesis, there are a number of things that have to be taken into consideration. The requirement analysis presented in this chapter will quantify the relevant features used for the design of the WSN architecture and components in this design. Users and authority on current street lighting infrastructure are not involved in the presented analysis, further iterations of the design might include input from external sources.

The requirements analysis is split into two sides, one where the design requirements for the whole system is set forth, and another one for specific components that make up the system. Wireless nodes and vehicle detection sensors are compared to pick out the ones which meet the design requirements and best suit the design.

The overall requirement for the system are, in no particular order:

- Cost: The objective of the design is to lower cost of street lighting, the total cost of the system must remain low. This is done to present a lucrative return of investment and increase the validity of the design from a practical standpoint.

- Low power consumption: One of the ways the system decreases street lighting costs is by reducing the time lighting is powered on. Low power components will aid in lowering the overall cost.

- Robustness: If the design is used in public infrastructure, it needs to be reliable and easily maintained.

- Secure: The design shouldn't be vulnerable to outside attacks or interferences. This will be done by encrypting messages and using methods mentioned in section 2.3.3.

- Simple installation: The design should be able to be easy to set up and implement in a preexisting utility system.
- Reliability: Data transfer between nodes should be as reliable as possible, wireless CP message acknowledgment scheme will be used.
- Small form factor: The enclosure used for the wireless units should be small.
- Scalability: Scaling up the size of the system network should be easy and straight forward.

For the system to follow these constraints, each component must follow the requirements mentioned above if it applies to them. The next sections will go through each component if it warrants a requirement analysis.

3.1. Wireless node requirement analysis

In the heart of this design are the wireless nodes which relay information between them and act upon it, whether that is to turn on lights or report a status back to a control station. Picking the most suitable nodes for the intended design is important.

Presented in Table 3.1 are the items which define the features of wireless nodes and why it matters to this project, such as cost, size, range, data rates, power consumption, security options, the types of serial interfaces, which frequency they use and their capabilities to fit the requirements.

Table 3.1: Overview for WSN *nodes with explanations for features and their purpose in the design.*

Feature	Comment
Cost	As the purpose of the design is to cut cost by power saving, the devices must be inexpensive.

WSN topology	For this project, it is not vital to have a self-discovering topology as the system will work in a point-to-point or daisy chain arrangement where nodes only talk to neighboring nodes.
Wireless protocol	The way the design is set up it WSN only sends simple commands between nodes and a non-commercial wireless protocol could suffice but with more complex data structures this could be a problem, so standardized protocols are suitable and recommended.
Frequency	Some WSN require data to be sent over great distances and some frequencies are more fitting than others, for instance, 900 MHz frequency bands' dB loss over distance compared to 2.4 GHz is lower. However, they also require high gain antennas. 2.4 GHz band should be more suitable for this design as the wireless units will in most cases be in line-of-sight of each other.
Power consumption	Most current WSN nodes are very energy efficient and can be put into sleep mode where they only transmit data when they are interrupted or scheduled to do so. Distance is also a concern as longer distance transmission requires more power. Less power consumption equals to higher cost savings in most cases.
Range	Street light posts have a varying distance between them depending on if they are used in residential areas or outside urban settings. For this design, it would be good for one node to be within the range of two or three other neighboring nodes. Line-of-sight range is expected to be over 100 m.
Power source	Two parallel connected Lithium-ion 18650 batteries with a capacity of 5000 mAh can power most nodes for a sufficiently long period until the batteries need to be recharged. Coordinator nodes should be permanently connected to mains electric.
Data rate	It seems most nodes today work within the ISM 2.4 GHz frequency and are limited to low data rates. This is perfectly fine for this design since only commands are conveyed between them and not high bandwidth data streams.

Size	Todays LED or SSL lights do not require bulky electronic ballasts and are therefor much smaller in size. The nodes could be mounted either in the light housing or clamped on a light post or the structure they are installed on inside an enclosure.
Encryption	If the WSN is in public use and are used to control important infrastructure it is critical that strong encryption is used. Some wireless protocols include built in communication encryption.
Serial interface	The wireless node should be able to communicate with sensors or a microcontroller. Most nodes should have either I^2C, SPI or Software/hardware based UART. One of these CPs is enough.

It should be remarked that some features are not discussed in Table 3.1, such as temperature range, whether or not the nodes are RoHS compliant or have Conformité Européene (CE) marking approval or not. It is assumed the wireless nodes meet the relevant agency approvals and work in both cold and warm weather climates.

In Table 3.2 some wireless node criteria are looked at and given a grade based on performance which benefits this design. Features with higher grading is considered more important. The baseline of each feature is established on overall system requirements.

Table 3.2: Wireless node features and baseline grading scale.

Feature	Comment	Grade
Cost	The baseline price for each node intended for use in this design is \$30. Three points are given for a device that meets the baseline, two points for nodes under \$50 and 1 point for any price over \$50.	1,2,3
Size	Two points are awarded for nodes smaller than 50×50 mm, one point for nodes bigger than that.	1,2
Range	Three points are given to nodes that can transmit data over 200 m, 2 points for over 100 m and 1 point for under 100 m. 0 points if the range does not exceed 50 m in outdoor line-of-sight conditions.	0,1,2,3
Wireless protocol	One point is given to nodes that follows a standardized commercially used protocol such as IEEE 802.15.4 or BLE. For other non-standardized protocols, a grade of 0 is given.	0,1
Frequency	Nodes using open and unlicensed frequencies such as 900 MHz, 2.4 or 5 GHz are awarded two points while nodes using frequencies outside those do not get points.	0,2
Power consumption	Power consumption for transmitting data is graded as follows: Three points for nodes that use less than 100 mA and can be put to sleep. Two points for nodes that use less than 100 mA and are not able to go into sleep mode and one point for nodes that use more than 100 mA in transmission. The idle current draw is not a part of the grading scale.	1,2,3
WSN topology	As the focus is placed on delivering the data sequentially and no order is kept in the system, no grade is assigned for this feature. No point reduction is given even if the nodes are not capable of forming a mesh network.	(N) No grade

Power source	Having a safe power source is vital. A grade will be given for the convenience of the power source. The baseline is having a power source not much bigger than double lithium-ion 18650 batteries will reward 3 points. Two points for a power source four times the size of an 18650 battery. One point is rewarded for a battery source with bigger than four 18650 batteries connected to the device.	1,2,3
Data rate	The data rate is not very important for this project at this time, no points are rewarded for data rate under 100 kbit/s and one point for more than 100 kbit/s.	0,1
Serial interface	If nodes support one of the serial interfaces mentioned in Table 3.1, a point is given, otherwise none.	0,1
Encryption	Encryption can always be added afterward, but it is very handy to have built in encryption for nodes. Two points are awarded nodes that have secure encryption. Zero points for nodes without it as it adds overall cost of a system	0,2

3.1.1. Wireless node selection

There are many different manufacturers of wireless nodes, in the current market there seems to be an emphasis on having an operating system which allows for complex network topologies and functions. For this design there is no need for such operating systems as the simple behavior of the system does not require it.

The wireless nodes presented in Tables A.1 - A.6 in Appendix A adhere to the requirements outlined in Table 3.1.

The nodes chosen for comparison are all of the garden variety, produced by known manufacturers, some are open source and can be modified under free use licenses while others are proprietary. Finally to summarize the selection, Table 3.3 shows an overview for the WSN node selection matrix.

Wireless nodes for selection :

- XBee S2C by Digi[7]
- XBee pro 900HB by Digi[8]
- NRF2401 module by Nordic semiconductor[9]
- .NOW mote by Samraksh company[10]
- AS-XM1000 by Advanticsys[11]
- AVR 2 by panStamp[12]

Datasheets for the wireless nodes and modules can be located in Appendix A if applicable, else in the footnotes.

3.1.2. Wireless node selection results

The decision matrix indicates that the XBee S2C is the best choice when the specifications of the wireless nodes are graded. It is most suitable for the system as it stands, it is not out of the question to use other nodes if any insurmountable problems are confronted in the design process. The XBee Pro came in second and a shared third to fourth place by NRF2401 and AVR 2. The AS-XM1000 and .NOW mote could be too expensive for this project as things stand.

[7] `https://www.digi.com/pdf/ds_xbee-s2c-802-15-4.pdf`(Accessed May 10, 2017)
[8] `https://www.digi.com/pdf/ds_xbeepro900hp.pdf`(Accessed May 10, 2017)
[9] `https://www.nordicsemi.com/eng/Products/2.4GHz-RF/nRF2401A` (Accessed May 10, 2017)
[10] `https://samraksh.com/files/products/DotNOW/emote-spec-sheet.pdf` (Accessed May 10, 2017)
[11] `https://www.advanticsys.com/shop/asxm1000-p-24.html`(Accessed May 10, 2017)
[12] `https://github.com/panStamp/panstamp/wiki/panStamp-AVR-2.-Technical-details`(Accessed May 10, 2017)

Table 3.3: *Selection matrix overview for wireless nodes - Table A.*

Specification	**XBee S2C**	**XBee 900HB**	**NRF-2401**	**.NOW**
Cost	\$17.5 Grade:3	\$28.5 Grade:3	\$1.0 Grade:3	€125.0 ≈\$140 Grade:1
Size	<50 × 50 Grade:2	<50 × 50 Grade:2	<50 × 50 Grade:2	>50 × 50 Grade:1
Range	>200 m Grade:3	>200 m Grade:3	>200 m Grade:3	>100 m Grade:2
Protocol	802.15.4 Grade:1	802.15.4 Grade:1	No protocol Grade:0	802.15.4 Grade:1
Frequency	ISM Grade:2	ISM Grade:2	ISM Grade:2	ISM Grade:2
Power consumption	<100 mA +sleep Grade:3	>100 mA +sleep Grade:1	<100 mA +sleep Grade:3	>100 mA +sleep Grade:1
Topology	N	N	N	N
Power	18650x2 Grade:3	18650x2 Grade:3	18650x2 Grade:3	18650x2 Grade:3
Data rate	>100 kbit/s Grade:1	>100 kbit/s Grade:1	>100 kbit/s Grade:1	>100 kbit/s Grade:1
Serial interface	SPI,UART Grade:1	SPI,UART Grade:1	SPI Grade:1	SPI,UART, USB, I^2C Grade:1
Encryption	128-bit AES Grade:2	128-bit AES Grade:2	No encryption Grade:0	No encryption Grade:0
Sum	Grade: 21	Grade: 19	Grade: 18	Grade: 13
Rank	**1**	2	3-4	6

Table 3.3: Selection matrix overview for wireless nodes - Table B.

Specification	**AS-XM1000**	**AVR 2**
Cost	€95 ≈\$106 Grade:1	€15.33 ≈\$17 Grade:3
Size	>50 × 50 Grade:1	<50 × 50 Grade:2
Range	>100 m Grade:2	<100 m Grade:1
Protocol	802.15.4 Grade:1	SWAP protocol Grade:0
Frequency	ISM Grade:2	ISM Grade:2
Power consumption	<100 mA +sleep Grade:3	<100 mA +sleep Grade:3
Topology	N	N
Power	18650x2 Grade:3	18650x2 Grade:3
Data rate	>100 kbit/s Grade:1	>100 kbit/s Grade:1
Serial interface	SPI,UART, USB, I^2C Grade:1	SPI,UART, I^2C Grade:1
Encryption	No encryption Grade:0	128-bit AES Grade:2
Sum	Grade: 15	Grade: 18
Rank	5	3-4

3.2. Vehicle detection sensor requirement analysis

Equally as important to the system is the sensor used to detect passing vehicles. Requirement analysis for the sensors will not be as extensive as the ones for wireless nodes as the sensors are simpler devices and not as many specifications or features matter.

Microwave sensors were picked for this design as they can be inexpensive and they detect both presence and velocity of vehicles.

Presented in Table 3.4 are the important features and some of the minimum requirements for the microwave vehicle detection sensors which will be used to detect incoming vehicles.

Table 3.4: Overview for vehicle detection sensors with explanations for features and their purpose in the design.

Feature	Comment
Cost	The vehicle detection sensors are as many as the WSN nodes, and in some cases, there might be two sensors per node. This may depend on which situation or modular design they are placed in. Each microwave sensor must be inexpensive.
Power source	It would be both beneficial and practical if the sensors could use the same voltage as the wireless nodes or components that are connected to the sensor. If not, a separate high-efficiency power supply or DC-DC converter must be added where the sensors are needed. The sensors must also be low power devices.
Range	If the sensors are mounted high up on lamp posts, sensors must be capable of having a range of at least 12 m, 7 m vertical and 10 m horizontally away from a light post in either direction.
Data rate	A microcontroller will read the status of the sensors, it has to be able to read the data coming from the sensor quickly, so it has time to send commands to the wireless nodes that turn on the LED lights.

Size	It is not ideal to connect big and bulky equipment high up in lamp posts in the weather conditions that can occur. Wireless node and sensor can be placed together in a small form factor box or enclosure clamped or fixed to the outside of a light post. The microwave sensors can be placed inside a locked enclosure.
Interference	The sensors must work regardless of weather conditions, they should work independent of temperature, humidity, lighting, etc.
Serial interface	A MCU has to be able to read the signal coming from the sensors. Sensors can have I^2C, SPI or UART protocols. If the sensor has a current loop mechanism such as 4-20 mA, it has to be converted to a convenient signal such as 0-5 V DC. Logic level voltage changes acting as interrupts are also acceptable.

In Table 3.5, sensor features are looked at and given a grade based on performance and their ability to follow the requirements. The baseline of each feature should follow the requirement outlined in Table 3.4 and the overall system requirements.

Table 3.5: Microwave sensor features and baseline grading scale.

Feature	Comment	Grade
Cost	Each sensor under the price of $50 is awarded three points and prices over it are given one point.	1,3
Power source	Two points are awarded for sensors that use either 3.3 V DC or 5 V DC, one point for sensors that use over 5 V DC and no points if it uses 12 V DC or above. No points for AC voltage inputs.	0,1,2
Range	Three points are given to sensors that can detect vehicles over 30 m away in any direction, one point for sensors that reach 15 m and zero points if the sensor does not reach 15 m.	0,1,3

Data rate	One point is given for sensors that can set sample rates less than 100 samples per second (SPS), no points for sample rate above 100 as this can waste excessive power.	0,1
Size	Two points are awarded for sensors under $100 \times 100 \times 100$ mm in size, one point for sensors over it	1,2
Weather interference	Interference from weather that causes regular false positives, results in -2 points. Senors that ignore weather and are reliable are awarded two points.	-2,2
Serial interface	If nodes support one of the serial interfaces mentioned in Table 3.4 or approved features, a point is given, otherwise none.	0,1

3.2.1. Vehicle sensor selection

Until recently the vehicle detection market was a closed market dedicated for traffic management systems where robust design is required along with very high accuracy and reliability and thus bear a high price. The price of these sensors is too high for the requirements of this project. However, lower grade microwave sensors will be looked at and compared.

The sensors presented in the Table A.7 - A.11 in Appendix A adhere to most of the requirements sent forth in Table 3.4. Both ready made sensor solutions and modules that might require additional circuitry or digital logic are looked at for this thesis. Table 3.6 shows an overview of the selection matrix for the microwave sensors.

Microwave sensors for selection :

- Herkules 2 microwave motion detector by Bircher[13]

[13]`http://reglomat.bircher.com/en/detectors-and-switches-from-bircher-reglomat-\delivered-worldwide/herkules-2-microwave-motion-detector-from-bircher-\reglomat/`(Accessed May 10, 2017)

- QT50R-EU-AFHQ by Banner[14]
- CDM324 - Open source modification on IPM165 microwave sensor[15]
- Lumewave MWX-LVE-180U Microwave Sensor by Echelon[16]
- SEN0192 by DFRobot[17]

Datasheets for the sensors in this requirement analysis can be located in Appendix A if applicable, else in the footnotes.

[14] https://www.bannerengineering.com/us/en/products/part.25370.html (Accessed May 10, 2017)

[15] http://www.limpkin.fr/index.php?post/2017/02/22/Making-the-Electronics-for\-a-24GHz-Doppler-Motion-Sensor(Accessed May 10, 2017)

[16] http://www.echelon.com/products/lumewave-mwx-lve-180u-microwave-sensor\-by-echelon(Accessed May 10, 2017)

[17] https://www.dfrobot.com/wiki/index.php/MicroWave_Sensor_SKU:_SEN0192 (Accessed May 10, 2017)

Table 3.6: Selection matrix overview for microwave sensors - Table A

Specification	**Herkules 2**	**QT50R-EU-AFHQ**	**CDM324**
Cost	\$465 Grade:1	\$702 Grade:1	<\$50 Grade:3
Power source	$\geq$12 V DC Grade:0	$\geq$12 V DC Grade:0	5 V DC Grade:2
Range	<15 m Grade:0	>30 m Grade:3	>30 m Grade:3
Data rate	<100 SPS Grade:1	<100 SPS Grade:1	<100 SPS Grade:1
Size	Over size Grade:1	Under size Grade:2	Under size Grade:2
Weather interference	Ignores weather Grade:2	Ignores weather Grade:2	Interferes Grade:-2
Serial interface	No serial Grade:0	No serial Grade:0	Serial Grade:1
Sum	Grade: 5	Grade: 9	Grade: 10
Rank	5	4	2-3

Table 3.6: Selection matrix overview for microwave sensors - Table B

Specification	**MWX-LVE-180U**	**SEN0192**
Cost	>\$50 Grade:1	\$13.9 Grade:3
Power source	≥12 V DC Grade:0	5 V DC Grade:2
Range	>30 m Grade:3	>15 m Grade:1
Data rate	<100 SPS Grade:1	<100 SPS Grade:1
Size	Under size Grade:2	Under size Grade:2
Weather interference	Ignores weather Grade:2	Ignores weather Grade:2
Serial interface	Serial Grade:1	Serial Grade:1
Sum	Grade: 10	Grade: 12
Rank	2-3	**1**

3.2.2. Microwave sensor selection results

The results indicate that the SEN0192 sensor by DFRobot to be best suited for the requirements in Table 3.4. While the sensor has some drawbacks with regards to detection range, it outperforms most of the other sensors in the most crucial aspects, price, size, that it ignores the weather and its connectivity, for this reason, the SEN0192 will be used in the design.

However, no sensor will be used in the physical prototype of the system to prove the design concept as it only requires a state change. A further test of the efficacy of the sensor is done at a later time.

3.3. Microcontroller and microprocessor requirement analysis

The microcontroller will be central to all the communication between a sensor and wireless node. All logic, excluding the one programmed for the WSN will be on a MCU, it will dictate how much sensor information is read and when it sent to the wireless nodes, this would be done in code inside the MCU. The microcontroller should follow the overall system requirements.

Requirement for a MCU are:

- Small size.
- Low cost.
- Energy efficient.
- Multiple serial interfaces.
- Analog to digital converter.
- Works with XBee S2C.
- Works with SEN0192.

Some candidates include the Arduino R3, other smaller variants of that microcontroller architecture such as Arduino Nano, Arduino Pro Mini, and Teensy series microcontrollers. A dedicated microcontroller such as 8 and 16-bit PIC series MCU are also included. What it comes down to is adaptability of the microcontroller.

Teensy 3.2[18] development board comes in a small package, it requires a modest amount of power and it can be programmed to run on multiple different core clock speeds. It has UART, SPI and I^2C serial protocol options and it includes analog inputs which can be programmed and converted to digital signals. For that reason, the Teensy 3.2 is chosen to be in the design.

Each Teensy microcontroller development board unit is $19.95.

3.4. Power supply requirements

Logic level voltage power supply will provide power to the microwave sensor or sensors, the microcontroller, the RF module (wireless node) and it will be used to supply enough current to turn on the solid state relay (SSR) on a relay module. The current used by the entire wireless unit is relatively small, the microcontroller and XBee module can be put into sleep mode while they are not communicating or working.

The SEN0192's normal working current is 37 mA, this can be much lower when the sensor is not being activated or interrupted periodically, a peak value of 60 mA may also be encountered.

The power required by the Teensy 3.2 microcontroller is dependent on temperature, the voltage it is being powered with, how intensive the programming is, which clock speed it is set to and whether or not it is put to sleep while it is idle. Test should be done for the Teensy current draw when in use in a wireless unit, for now, a 30 mA current at 5 V DC input running at 24 MHz will be assumed, this number is based on a test[19] from other users running the Teensy on 72 MHz with a 5 V DC input.

The XBee S2C operational current is 33 mA @ 3.3 V DC, this current is however only used when transmitting. The module can be put to sleep, and it uses less

[18] `https://www.sparkfun.com/products/13736`(Accessed May 12, 2017)
[19] `https://github.com/duff2013/Snooze/issues/14`(Accessed May 12, 2017)

than 1 microampere while in such a mode.

The relay module uses almost no current while not conducting through the SSR. The AQG12205[20] solid state relay requires a 4 to 6 V DC input voltage and has an impedance of approximately 300 Ω , this equates to 16 mA load while the relay is conducting.

See table 3.7 for a summary of current requirements for the power supply and battery charger.

Table 3.7: Current draw for devices in a wireless unit

Device	Current draw
SEN0192	37 mA - 60 mA peak
Teensy 3.2	30 mA
XBee S2C	33 mA
SSR Relay	16 mA

This totals to 116 mA average current draw when all the components are working, this can be easily supplied by an 18650 battery bank and charger. If the battery capacity of the power bank is 10 000 mA ∗ h, the expected battery life is 86 hours in worst case conditions. This allows for plenty of time to recharger the batteries while the lights are powered by mains electricity.

The price allocated for a battery and charger pack is $20.

The physical prototype will not include three individual energy sources, but rather one that powers the prototype.

3.5. Enclosure requirements

Three main specifications must be satisfied for the enclosure the wireless units are put in. The wireless units should be able to withstand any weather conditions, for this to apply, both waterproof and dust-proof enclosure must be used. European standard EN 60529[21], for international protection marking indicates that an IP

[20] `http://www.mouser.com/ds/2/315/aq-g-catalog-1075862.pdf` (Accessed May 12, 2017)
[21] `http://sst.ws/downloads/Ingress-Protection-iss-4.pdf` (Accessed May 12, 2017)

rating of 66 should suffice. IP 66 is a complete safeguard against contact dust and resistant to water projected in powerful jets.

The enclosure must not be made out of metal or contain any metal meshing, that might diminish the range capabilities of the wireless modules. Lastly, it should have mounting brackets that support straps that are used to fix it to round objects such as lamp posts.

There need to be two holes for cable glands, one for incoming power cables to power the battery charger and one outgoing to the LED driver in the light fixture. The cable glands should face downwards to avoid rain or ice building up and leaking inside. A hole for an external antenna could be added on if it is needed. From an aesthetic side, a white or gray colored box should blend into the environment it is fixed to. The physical prototypes will not be placed inside an enclosure.

The price allocated for an enclosure is $20.

4. Design

In this chapter, a development of the overall system design will be presented. A top-down design approach will be used, where the complete system and its functions are defined, without delving into details. Further components or subsystems are described such that their objective is made clear in the overall design.

The overall purpose of the design is to automate street lights, and the design is implemented in such a way that it could be combined with a preexisting traffic or electrical utility control stations where each wireless unit could be checked on and controlled remotely through either Internet cloud computing or a local area network. This would allow the design to be scalable to any size as the modular wireless sensor networks are independent of each other. The overall system network topology for the design is depicted in figure 4.1.

The system is made up of modular networks that are connected to the Internet. These modular networks can have anywhere between one and 65536 wireless units. The networks are distinguishable from the next by an identification number given to the wireless nodes when they are configured. They can be configured not to interact with other modular networks that are inside their broadcasting range. The modular networks can have any network shape or topology as they are set and initialized to the environment they are used in. This limits the complexity of the entire network and reduce errors if nodes fail as they do not depend on neighboring nodes from different modular networks.

This project calls for the design to be used on conventional roads where street lights are placed in a sequential order. The wireless units are put on every street lights as they control whether the lights are turned on or off. Figure 4.2 shows an example of how a modular networks' wireless units are set up and the communication between other units in its range.

The communication between wireless units overlaps so any unit can speak to the next three units, allowing units to speak to other nearby nodes in case of incomplete communication between nodes, power failure of nodes and individual component

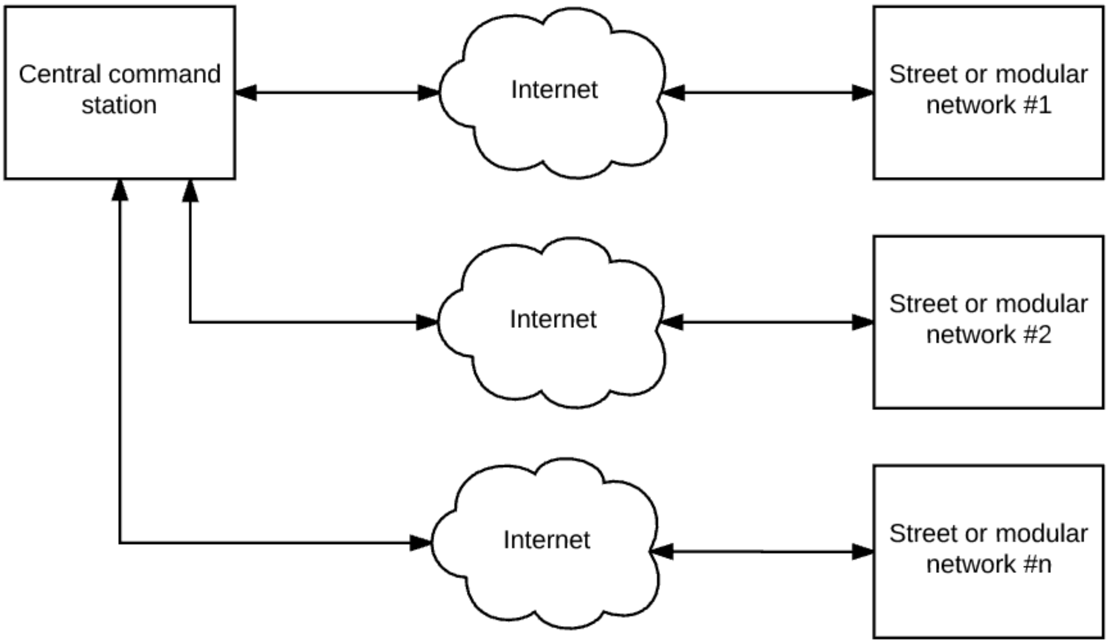

Figure 4.1: Network topology for the overall design. The modular networks are made up of wireless nodes that communicate with each other. The lines in the figure depict communication pathways and their direction. The communication between the command station and the modular networks is done by IP *through Ethernet gateways which work with the XBee* WSN *platform.*

failure in a wireless unit. This technique should improve the reliability of the modular networks as the communication inside the modular network does not break if a unit goes down. Other units can also report back to a control station if they notice a neighboring node is not sending acknowledgment messages when talked with.

The wireless units consist of a microcontroller, a radio frequency module, one or two microwave sensors, a relay circuit to turn power on and off to the LED lights and a battery power source and charger to power up the DC voltage peripherals. The units are placed in rain and dust proof enclosure close to the top of street light posts or any structure elevated above roads. The enclosure is placed such that the microwave sensor or sensors are directed towards incoming traffic. Figure 4.3 shows an emblematic wireless unit, its components and how they connect to each other.

Once all the components that make up a wireless unit have been accounted for, a price for each can be established. The cost for the components are:

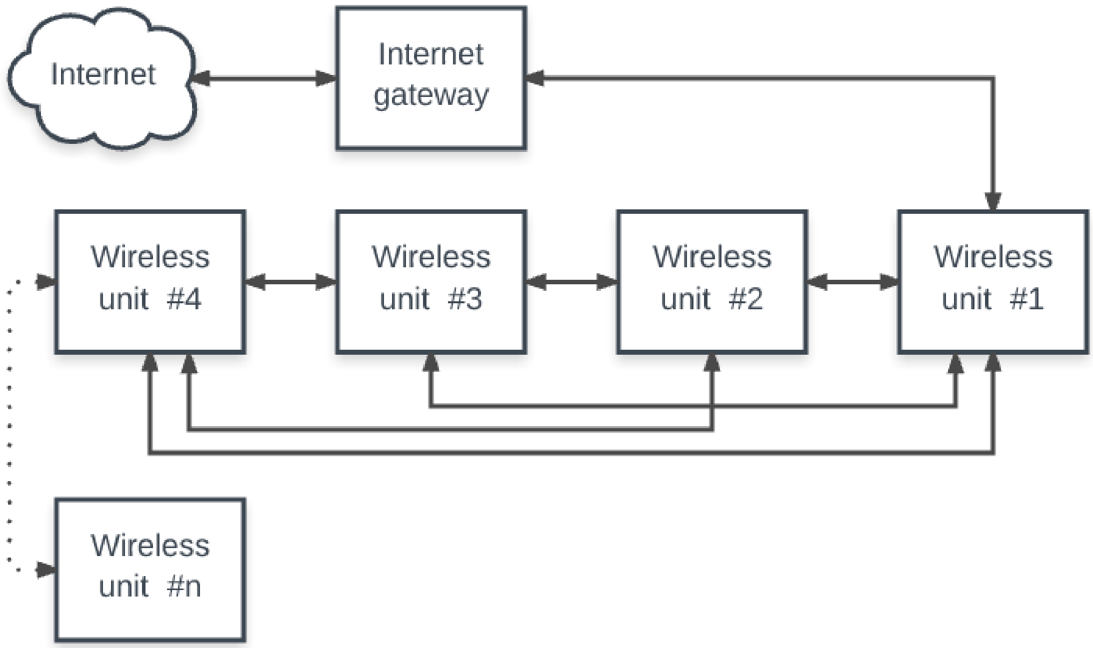

Figure 4.2: Diagram of wireless units in a modular network. Lines show communication pathways between wireless units and Internet gateway. All the communication is bi-directional, the wireless signal range extends to the nearest three wireless units. The only wired connection is between the Internet and Internet gateway.

- Teensy 3.2 microcontroller: $19.95
- XBee S2c and development board: $29.66
- SEN0192 sensor: $13.90
- Relay board: $8.06
- Estimated cost - Power bank and charger: $20.00
- Estimated cost - Enclosure: $20.00

The total price for a wireless unit with one sensor comes out to $111.57.

The wireless units are powered by batteries when the light posts are not powered by mains electricity. Batteries allow the unit to measure traffic presence during

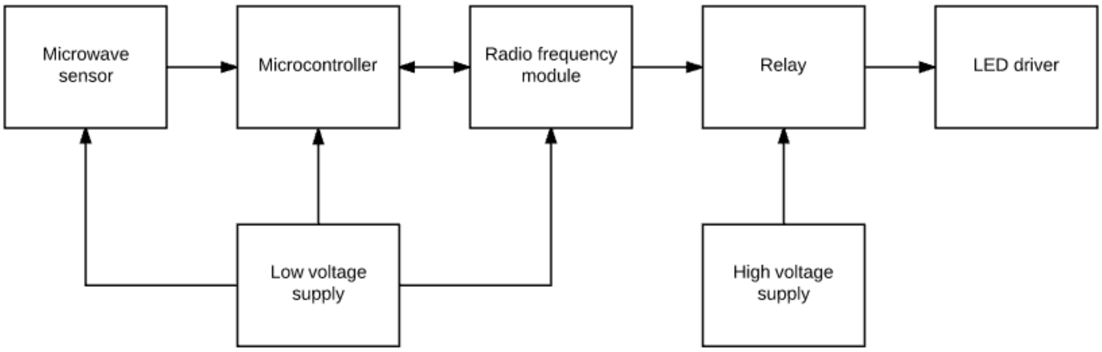

Figure 4.3: Diagram of a wireless unit in modular networks. Lines from the power supplies represent voltage lines and their respective inputs, for the low voltage side, 5 V DC *input is used, for the high voltage side, a* 230 V AC *input to the positive side of the* SSR. *Line between the sensor and microcontroller is unidirectional signal line. Line between* MCU *and XBee* RF *module is bidirectional* UART *signal line. The output to the* RF *module is a* DC 2 mA *signal line that drives the* NPN *transistor on the relay board.*

the daytime when lights are not turned on and recharge the batteries once the electricity is back on.

Only the placement of the sensor is critical in the construction of a wireless unit as it is used to detect vehicle and pedestrians. The sensor should therefor be placed either directly facing the vehicles coming towards it or at an incline tilted downwards as depicted in Figure 4.4.

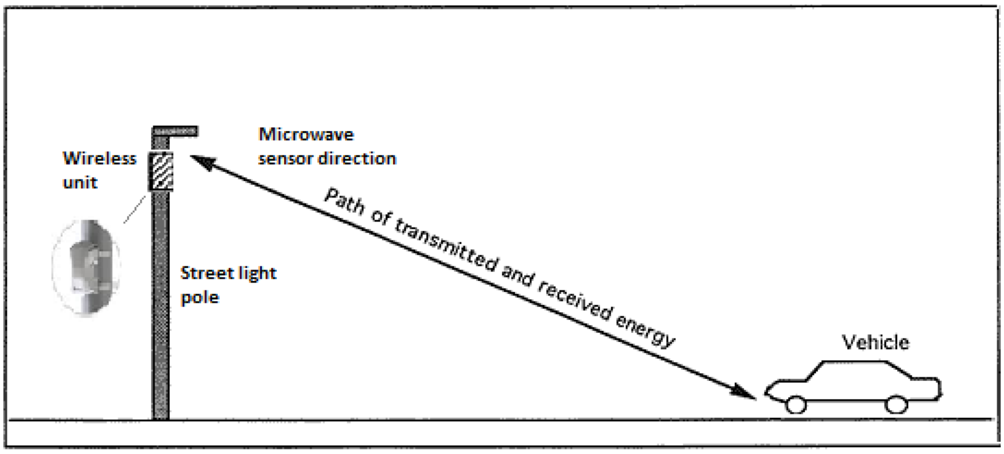

Figure 4.4: Wireless unit mounting placement and microwave sensor signal direction. Source: `https://www.fhwa.dot.gov/policyinformation/pubs/vdstits2007/vdstits2007.pdf` *(Accessed May 11, 2017)*

4.1. Data extraction from modular networks

Communication between the modular networks, the Internet gateway, and the control station are bi-directional. Permitting communication both ways supports extraction of information from the modular networks. The information that could be taken from the networks is subject to the capabilities of the components used in the network. At the current state of this project, vehicle presence could be obtained. The data could be processed once it has been gathered and used to support road traffic control.

Since information can be extracted throughout the system, it can be processed and worked with on the Internet to minimize power consumption inside each modular network. Information such as the amount of traffic and single vehicle speed can be output from the system if it is configured to do so. This will however not be a priority for this design.

4.2. XBee internet gateway

Each modular network has to have one and only one coordinator node. This node is the network's connection to both the Internet and any control station that it could be a part of.

Digi, the producers of the XBee products provide two different options when it comes to Internet-connected gateways, either Ethernet/WiFi gateway which connects a coordinator node directly to the Internet or a cellular network gateway which connects to a cellular network such as 3G or 4G.

The Ethernet-connected gateway suits this project because in most cases there are Internet service providers junction boxes in most streets, allowing a short connection for a gateway. However, a gateway will not be used in the constructed physical prototype. Figure 4.5 shows ConnectPort X2 Ethernet gateway.

Each gateway costs $158.5 from Digi-Key.

Figure 4.5: XBee ConnectPort X2 Ethernet gateway. Source: `https://writelatex.s3.amazonaws.com/wybrnmynsfrx/uploads/8235/12096220/1.PNG` *(Accessed May 15, 2017)*

4.3. Electrical connections between XBee, Teensy, SEN0192 and relay circuit

This section goes over the electrical connections between each component in a wireless unit that makes up a modular network. Depicted in figure 4.6 are the electrical connections between modules that make up a single wireless unit. The modules are not to size, and the figure is modified to show connections clearly as possible.

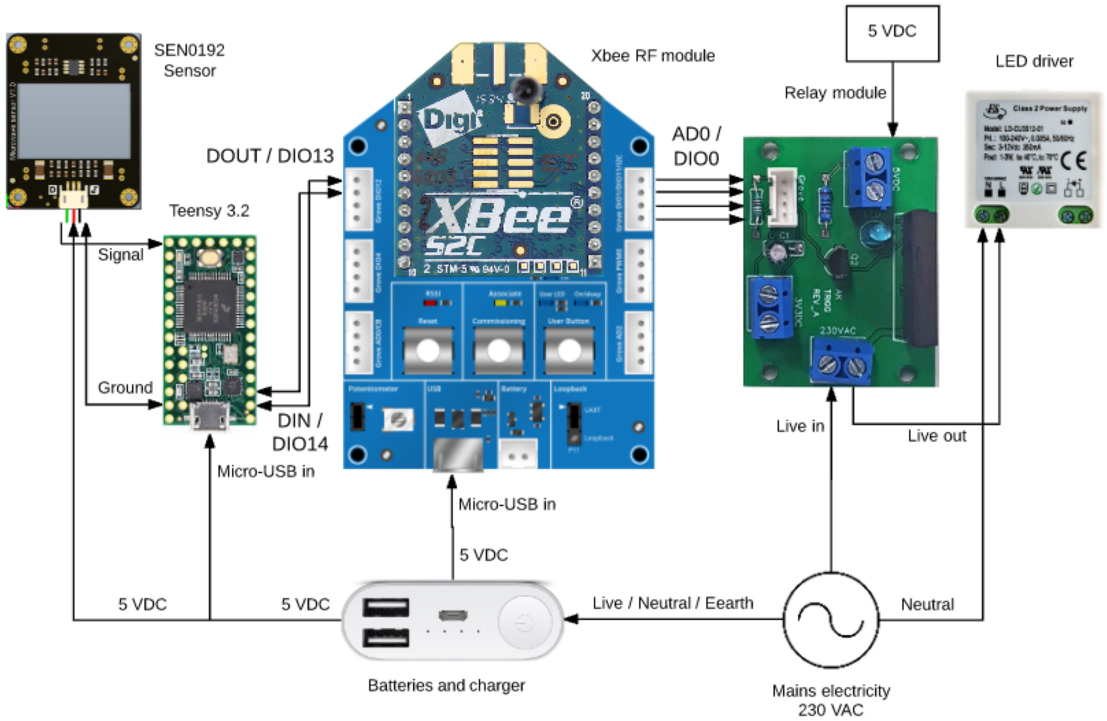

Figure 4.6: Electrical connections between modules that make a wireless unit in a modular network.

After each component of the system has been laid out, communication between the components will be outlined and illustrated. Flowcharts will aid in the flow of communication between devices.

The connections are split up as:

- Mains electricity:

  1. The entire unit is powered up by incoming 230 V AC mains electricity.
  2. The neutral line is connected to the LED driver. The live wire is connected to the input of the relay circuit
  3. Live, neutral and an earth wire are connected to a power bank that contains 18650 batteries. This gives the ability to charge those batteries and receive a regulated 5 V DC on a USB cable.

- Low voltage:
  1. These USB cables are connected to both the Teensy 3.2 microcontroller and the XBee development board, from there they are regulated to 3.3 V DC which is used by the processing units on the modules.
  2. The microwave sensor requires 5 V DC, so the direct 5 V DC output from the power bank is used.
  3. Common low voltage ground is shared by the modules and a high voltage ground is shared by the mains electricity input and the LED lamp housing.
- SEN0192 sensor: The output of the SEN0192s Schmitt trigger is treated as a digital logic voltage and acts as an input to the Teensy digital pin 13 (see figure 5.1). If more than one sensor is used, digital pin 14 is available.
- Teensy/XBee:
  1. Bidirectional serial communication is done between the Teensy microcontroller and the XBee module.
  2. RX1 (see figure 5.1) is the first of five software serial communication inputs to the Teensy development board. The serial interface pins connect to the XBee development board groove connector on the left side (see figure 5.4).
  3. These two groove pins are attached to the XBee serial pins. RX1 from the Teensy connects to DOUT/DIO13 pin, which acts as UART data out on the RF module. TX1 from the Teensy connects to DIN/CONFIG/DIO14 which serves as UART data in on the Xbee module.
  4. The XBee AD0/DIO0/CB pin is connected via groove connector to the relay module. This pin is plugged to the gate of BC547A NPN transistor (see figure 5.7), this transistor works as a switch to close the solid state relay (figure 5.8) which delivers the mains live wire to the LED driver which turns on the LED lights.

High voltage cables should be thick enough to carry the current needed[22] to drive

[22] `https://www.cse-distributors.co.uk/cable/technical-tables-useful-info/`

the LED driver and battery power bank&charger, 1.5 mm^2 should suffice. All other cables are $0.4 - 0.75mm^2$, they carry either low voltage signals or low current supply voltage.

4.4. Digital signals and serial communication pathways

Four signal wires have to do with digital logic and software. They are:

- The connection between the microwave sensor and Teensy microcontroller, from the standpoint of the Teensy, the wire is connected to digital pin 13 which can detect two states, high and low. The SEN0192 datasheet indicates that the output of the sensor is active low, when it detects an object it changes its output from high to low, the high-level output should be close to 5 V DC.

- The two output wires connected to pin RX1 and TX1 are the UART serial connection used to instruct the XBee RF module through API (Application Programming Interface) commands. These wires are the only connection between the microcontroller and XBee module. The microcontroller sends the serial communication to the XBee when the microwave sensor changes states. Once the Teensy has read the status of pin 13, if the pin has gone from high to low, instruction are sent to the XBee and neighboring wireless unit or units. A counter that counts up to a predetermine amount of time is initialized when pin 13 changes states, this allows the user to set the time which the LED lights are supposed to be on.

- The Xbees' D1O0 pin changes state from low to high which turns on a transistor and in return the SSR on the relay module. If the counter is not reset by a second detected object it makes D1O0 pin low which turns off the LED driver.

table-4e1a/(Accessed May 19, 2017)

4.5. Wireless communication between nodes

Once a network has been defined, the IEEE 802.15.4. protocol is in effect. There are two types of commands that the 802.15.4 offers, AT commands and API commands. This project can use both. However, API frames have a structure that is more suitable for this project. By default, the wireless nodes come in transparent operation or AT mode. This means any data that comes into the UART DIN (DI014) pin is sent straight to the RF buffer where it is queued for transmission. The data can be sent once the buffer is filled up or a when it passes a preset threshold.

The API mode is based on framed or structured communication packets and is specially made for host application so that outside hosts can interact with the wireless nodes or the network. A host application for this project would be a traffic control center or a cloud-based online accessible interface.

When the wireless node is in API mode, all incoming and outgoing data is encapsulated in frames that define operations or events that the RF module is capable of. These API frames allow the network to report receive success/failure status of each transmitted packet, identify where the transmission came from and send frames to multiple destinations or nodes. The configurable settings on the wireless nodes can also be changed through API frames. Figure 4.7 depicts an API frame.

If any two nodes send data between them, they can send acknowledge messages to confirm the message was delivered. The acknowledge does not indicate whether the contents of the message are correct or if any action was taken based on the data that was sent. The acknowledgement can be done in two ways, direct transmission where a data frame is forwarded to a target node and the target node responds with an acknowledgment or Indirect transmission or polling is done slightly differently. One wireless node sends a request for data to the next node, it then receives a confirmation that it is ready to send data, once the data has been delivered, a secondary acknowledgment is sent, completing the communication.

All communication between wireless nodes should use API frames.

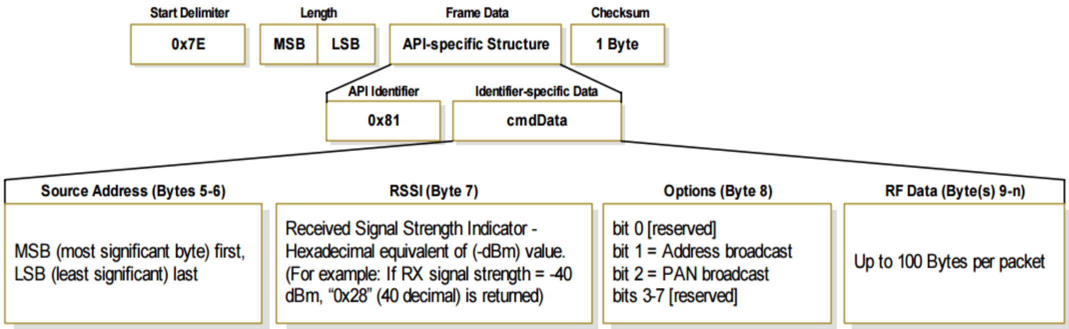

Figure 4.7: An example packet would consist of : 7E 00 0A 01 01 50 01 00 42 63 6A 6A 5F B8. Where 7E is the start frame or Start delimiter. 00 0A is the length of the frame in bytes. 01 and 01 are the API identifier and data identification number. 50 01 Is the addressable destination, i.e. where the data is supposed to go. 00 is option or status byte. The data which is sent by the frame is 42 63 6A 6A 5F, this can represent and number or ASCII characters, up to 100 bytes per packet. B8 is used for error checksum. Source: `https://www.sparkfun.com/datasheets/Wireless/Zigbee/XBee-Manual.pdf` *(Accessed May 15, 2017)*

4.6. Microcontroller and radio frequency module software

The flowchart in figure 4.8 describes the software initialization for the XBee RF modules.

The XBee can set three distinctive communication parameters that characterize its network span, they are:

1. 2.4 GHz channel it uses, by setting channel 25, which works on 2.475 GHz one can avoid any interference with WiFi used by internet service providers' Ethernet modems.

2. The PAN identification number (ID) mentioned in process number three in figure 4.8 is the personal area network identifier which the XBee RF module is part of. There are both 16-bit and 64-bit PAN IDs, these are used in conjunction to avoid any conflict between nodes in the vicinity of each other. For this project the PAN ID is configured to be matching between all the systems RF units, this would allow any unit to be detectable in the network.

3. The network can then be split into smaller modular networks that only communicate among themselves by the network ID also referred to as MY address, a 16-bit value which decides which set of wireless units the configured node can speak to.

The overall network type is a common bus topology as the networks are all connected to the Internet, the network topology in the modular networks is line or Peer-to-Peer. All the structured API frames sent between nodes are encrypted by AES 128-bit encryption.

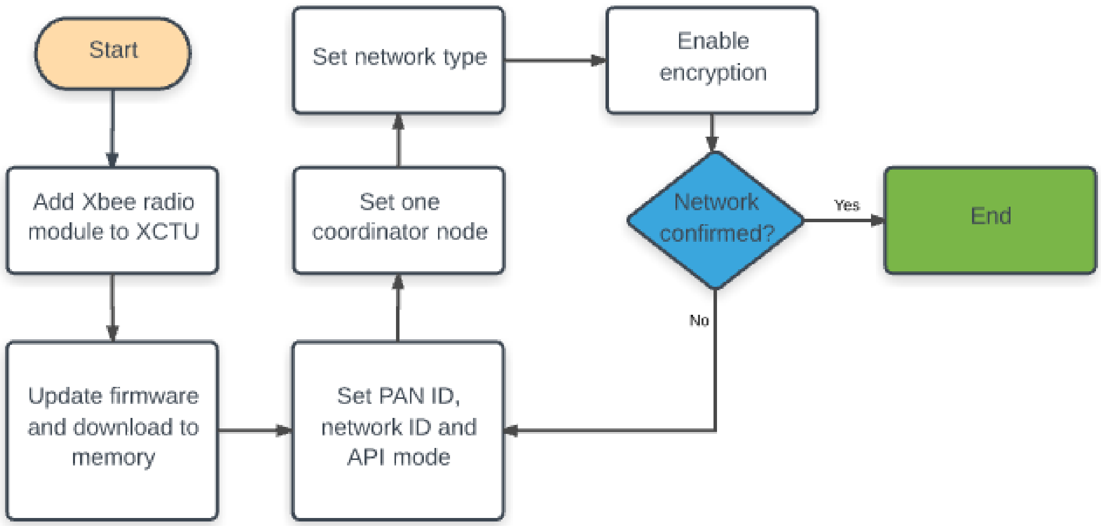

Figure 4.8: Flowchart explaining initialization of XBee nodes

Once the RF modules have been set up they can be put into any unit containing a sensor, microcontroller, relay board and relevant peripherals used to power the unit within the specified network.

Figure 4.9 describes the program flow on the Teensy microcontroller. The Teensy is configured to operate at 24 MHz which is the lower end of the settings as this will save power by running at slower than default processing speed. The serial communication between the Teensy and XBee is set to operate at 9600 baud. This baud rate is sufficiently fast enough for this design, as only commands are sent between the XBee and Teensy. A timer or counter is initialized and held in an integer variable, this value represents the amount of time a light is held on until it is turned off.

Once the XBee nodes have been initialized, they can be programmed through

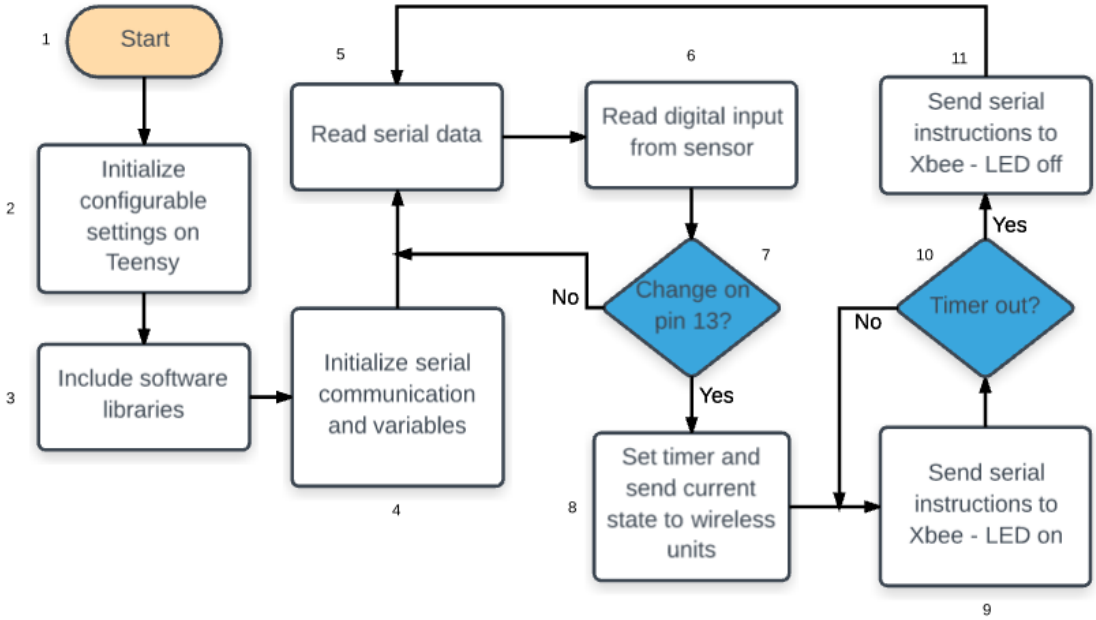

Figure 4.9: Flowchart of Teensy initialization and main loop.

serial communication with the Teensy microcontroller by API frames. Figure 4.10 explains the functions the XBee goes through once it has been addressed to a network.

This case is only for independent nodes, working alone without any algorithm dictating whether the next lights should turn on or not. The algorithms used to automate sequential initiation of lights will be injected into this loop at the process which the XBee is instructed to activate the light it is installed at, meaning that the same process that governs each light is the used as a part of the algorithm.

When wireless units have been defined, a network topology can be determined which suits this system.

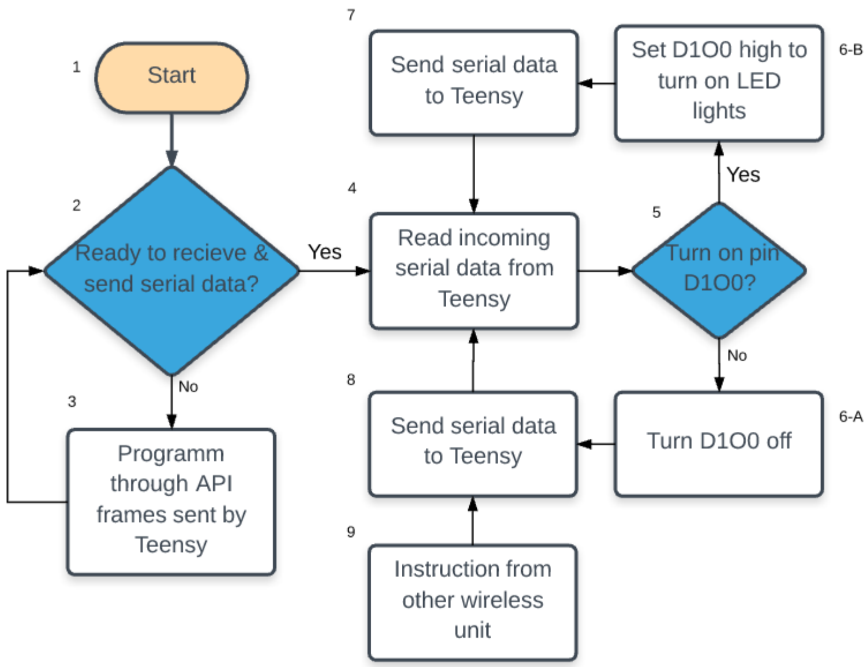

Figure 4.10: Flowchart of a single XBee loop process.

4.7. Modular network light progressing algorithm

Since the design is done such that all the modular networks have a unique identification, all the wireless units in each network can be identified. The wireless units can be programmed to have an order in the way they are installed. If an arbitrary wireless unit has the identification number n, the next node can have an identification number of n+1, where n is a 16-bit integer. This way any wireless unit knows which wireless units are in its vicinity and, therefore, it can send instructions to the relevant units. With this method a light progressing algorithm can be implemented, figure 4.11 illustrates how the algorithm works.

Figure 4.12 depicts the method behind the algorithm as well as the six different states possible. It works as follows:

- Prefix S is given to a wireless unit in this example, the number describes which number the unit is. The current status of the light is denoted by an on or off. Detected vehicle or object, indicated with (d) describes where the vehicle is in each state.

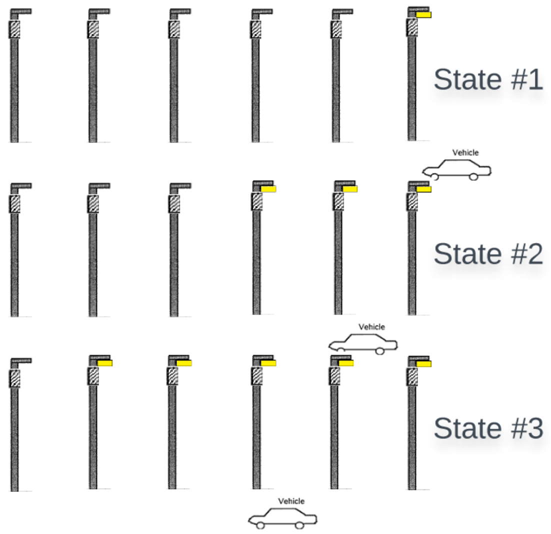

Figure 4.11: Illustration of light progression algorithm in a modular network.

- Lights are progressively turned on ahead of the vehicle such that once the vehicle has been sensed six times, six lights ahead of the vehicle are turned on, the light that the vehicle is under and three lights behind it.

- Once lights have been turned on they start a timer, denoted by (t). The timer can be programmed to be any amount of time. Some modular networks might require shorter duration timers, while others need longer. In the situation that a secondary object is detected and the timer has not ceased, it is reset to its predetermined value. If an object is ever not detected or does not follow the path it was previously going, the process resets and starts over. Once a detected target has achieved the fourth step in the algorithm in the example in figure 4.12, timer on unit 7, denoted by S7 appointed a timer with a scalar that should prevent the unit from turning off before a vehicle or object is sensed.

Each process in figure 4.12 is associated with a state, a state that can be stored in a variable on the Teensy microcontroller. This variable has to be sent along with the instructions sent to the neighboring nodes, so it knows which state it is currently in, this variable can determine whether the process continues or not.

The timer is stored on the Teensy microcontroller since XBee does not include a timer that can be used in a situation like this. Once the timer runs out, it sends serial instructions inside the wireless unit it is a part of to turn off the lights.

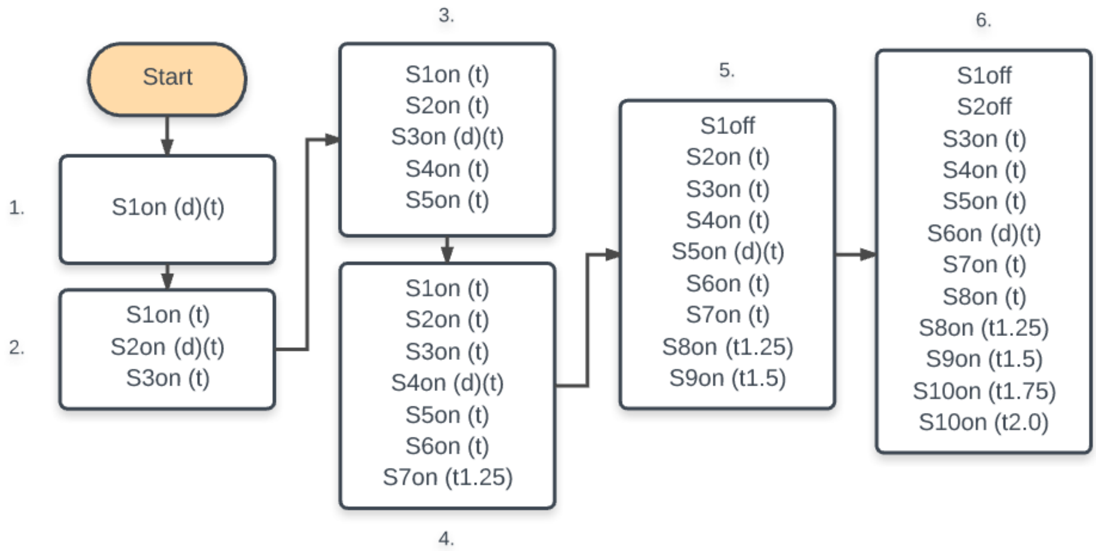

Figure 4.12: Diagram of light progression algorithm states and their change.

Figure 4.13 depicts the first three states and how the current state needs to be held at each step of the process. The current state also needs to be sent to the neighboring node, so it knows how to progress the algorithm once its sensor senses an object and pushes the whole process to the next step. The figure shows the first three states of the algorithm.

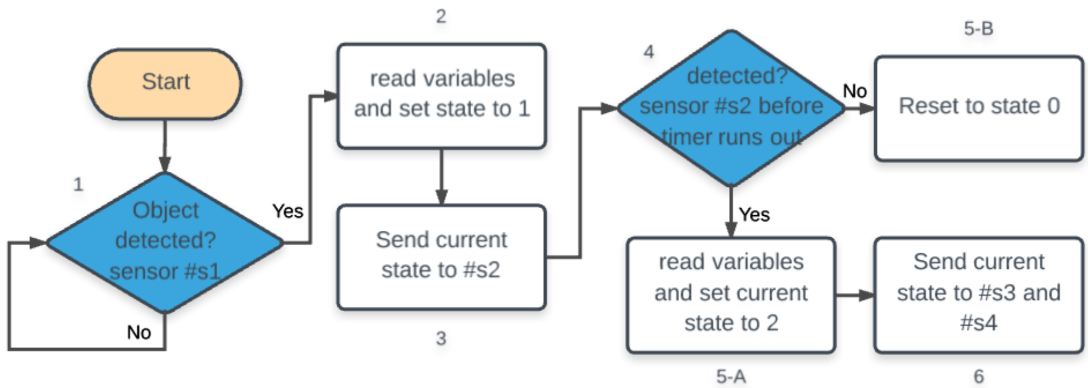

Figure 4.13: Diagram for example street where the first three states are sent between wireless units in the light progression algorithm.

5. Prototype development

This chapter goes over the preliminary version of a wireless unit design proposed in chapter 4. It will begin with listing up each component and their specific role in the prototype. Each step will have electrical drawings if they are convenient in portraying the design or function inside the design. Diagrams characterize the activity of components and their relation to other elements within the design.

5.1. Teensy development board

The Teensy is development board is a powerful and flexible board that offers many different features packed in a small form factor design. To power up the board, a micro-USB cable is connected directly to the Teensy. It can also be powered through separate wire connections to Vin and common ground. The micro-USB connector is also used as a serial interface to program the microcontroller. The microcontroller can be programmed through Arduino integrated development environment (IDE) with Teensyduino plug-in. The Arduino IDE accepts both C and C++ code with object oriented capabilities. Core clock speed can be set on the Teensy, with 2 MHz being the lowest setting and 96 MHz being the highest. At the highest setting, a heat sink directly on the core is recommended.

None of the pins from the Teensy will provide a current to drive anything in the prototype. PIN 13 will act as an input and RX1&TX1 as UART signal lines.

Figure 5.1 shows the pin-out and peripherals pins of the Teensy 3.2 development board. Figure 5.2 is the underside of the same board.

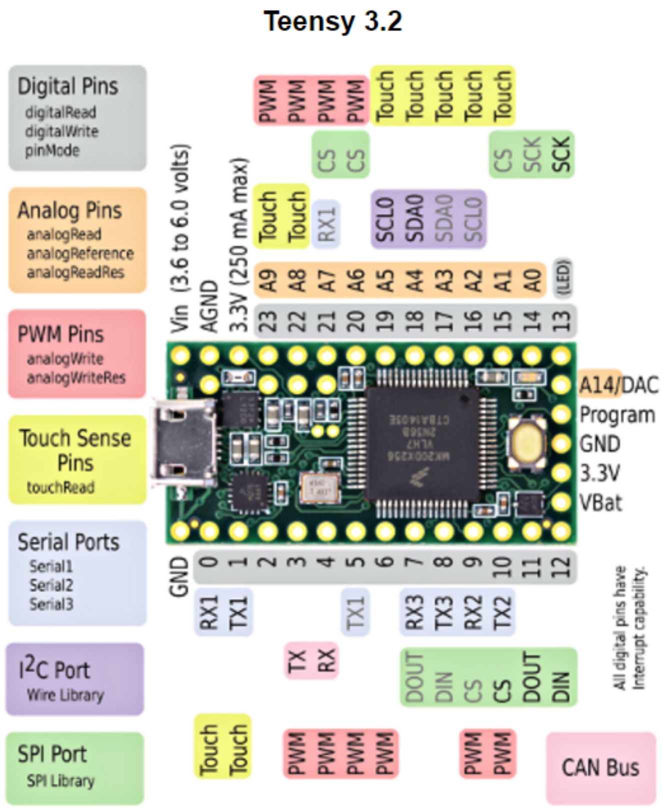

Figure 5.1: Overview of Teensy 3.2 Development board. Source: https://www.pjrc.com/teensy/card7a_rev1.png (Accessed May 15, 2017)

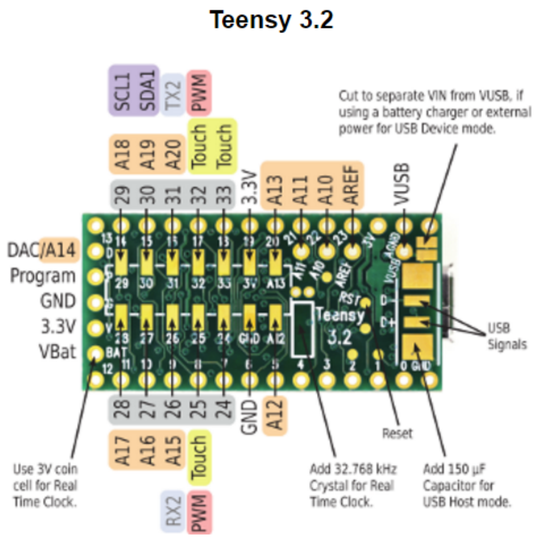

Figure 5.2: Underside of Teensy 3.2 Development board. Source: https://www.pjrc.com/teensy/card7b_rev1.png (Accessed May 15, 2017)

5.2. XBee S2C radio frequency module

The XBee S2C radio frequency module provides wireless connectivity between two wireless nodes. The modules are powered by connecting a regulated 2.1-3.6 V DC into the Vin pin and a common ground pin, the module can also be powered by a development board that allows for easier access to output pins, reset circuitry and serial interfaces. The S2C has a circuit board antenna, both on through hole and surface mount models. The through hole type allows for the addition of a pigtail antenna via an extruded antenna connector.

Figure 5.3 depicts the stand-alone RF module while Figure 5.4 shows the development board the XBee is plugged into.

The development boards for the RF module allows the XBee to be powered by a micro-USB. The microcontroller on board the RF modules can be programmed and configured by the same micro-USB connector.

In XCTU, a free software application developed by Digi is used to initialize all relevant settings before putting them into the unit they are in. Settings that are configurable on the XBee RF include which PAN ID the node joins, it's unique identification address, whether the node is used as a coordinator node or not, if communication is encrypted or not, whether the node is in transparent mode (AT) or API operation mode and any setting having to do with network topology and their role in it.

A full list of configurable parameters can be located in Appendix A.

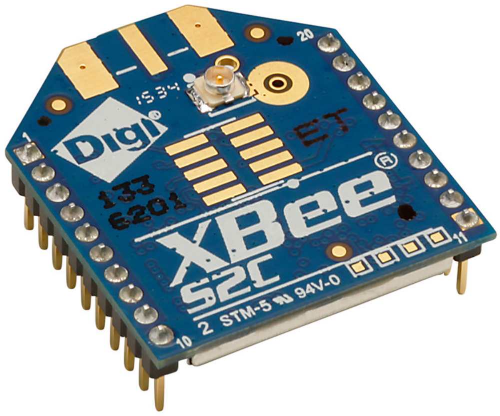

Figure 5.3: XBee S2C RF module. Source: `https://www.digi.com/products/models/XB24CDMPIT-001/product-images/xbee-s2c-th-pcb` *(Accessed May 15, 2017)*

Figure 5.4: XBee development board. Source: `https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRO_Ge7AnTgWBmGpw180lCraT7QYt6PN1RNKgyMu6wSxRLpYZV5` *(Accessed May 15, 2017)*

5.3. SEN0192 microwave sensor

SEN0192 microwave sensor is developed and sold by DFRobot, this microwave sensor can detect objects, it does not have the necessary logic circuitry to measure velocity.

The module has a supply that emits frequency at 10.525 GHz which amounts to a wavelength of close to 10 cm. These frequency waves permeate through both solid and gaseous objects. A small portion of the waves deviate from the target object and are radiated backward towards the sensor where a receiving antenna detects and processes them. Since the signal is sparse, it is magnified by an operational or conditional amplifier. It is passed through a Schmitt trigger conditioning circuit that is activated when the signal goes above a certain preset threshold, and the signal can be latched or processed as a pulse width modulated signal for digital logic.

Figure 5.5 shows the appearance of the SEN0192 sensor with signal indicators and range adjustment. Two input wires to the sensors are:

- Red as voltage in (VCC)
- Black as ground (GND)
- The green output is the digital signal line that indicates a detected vehicle or object with a voltage change.

The detection range in front of a sensor is 72 degrees parallel to the sensor and 36 degrees vertical (seen in figure 5.6).

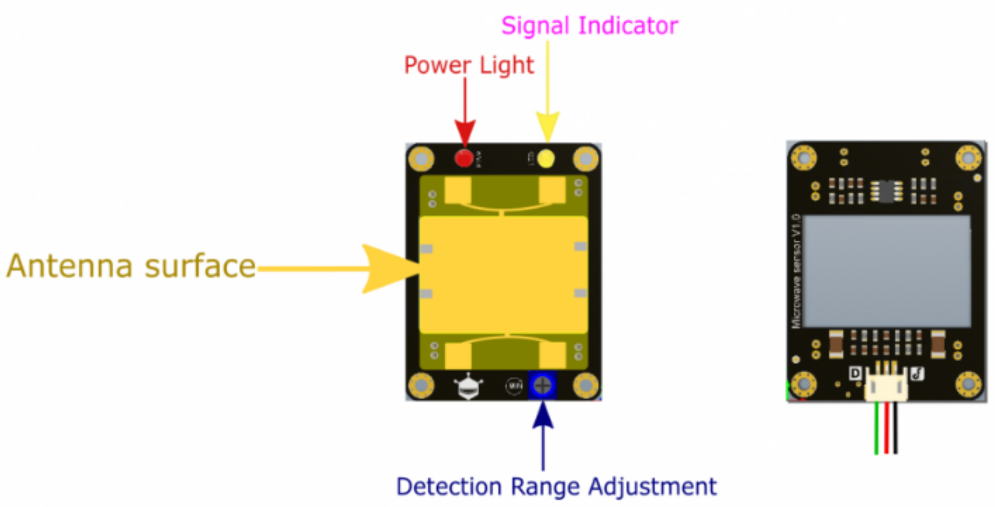

Figure 5.5: SEN0192 microwave sensor. Source: `https://www.dfrobot.com/wiki/images/thumb/2/26/SEN0192-LINE.png/600px-SEN0192-LINE.png` *(Accessed May 15, 2017)*

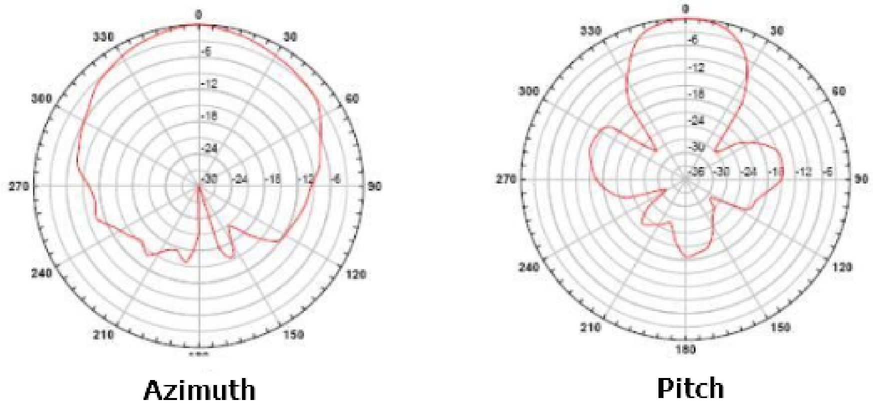

Figure 5.6: SEN0192 microwave sensor signal detection range. Source: `https://www.dfrobot.com/wiki` *(Accessed May 20, 2017)*

5.4. Relay module printed circuit board

To activate the LED lights, a relay circuit is used to switch the high voltage mains electricity. The XBee RF module's microcontroller can provide 2 mA from digital output pins, while this current is not enough to turn on a relay it could reliably be used to saturate an NPN transistor which acts as a switch for a higher current supply that in return triggers a SSR. Figure 5.7 depicts the electronic schematic for the circuit, while figure 5.8 is the physical circuit on a printed circuit board.

This relay circuit requires an external 5 V DC power supply to supply enough current to drive the 16 mA diode inside the SSR. Groove connectors are used as the XBee development board uses them for all their output and input pins.

The complete bill of materials for the relay circuit is:

- 1 x Relay PCB.
- 3 x Terminal block 5.08 mm pitch.
- 1 x AQG12205 SSR
- 1 x Resistor 1200 Ω 1/4 W

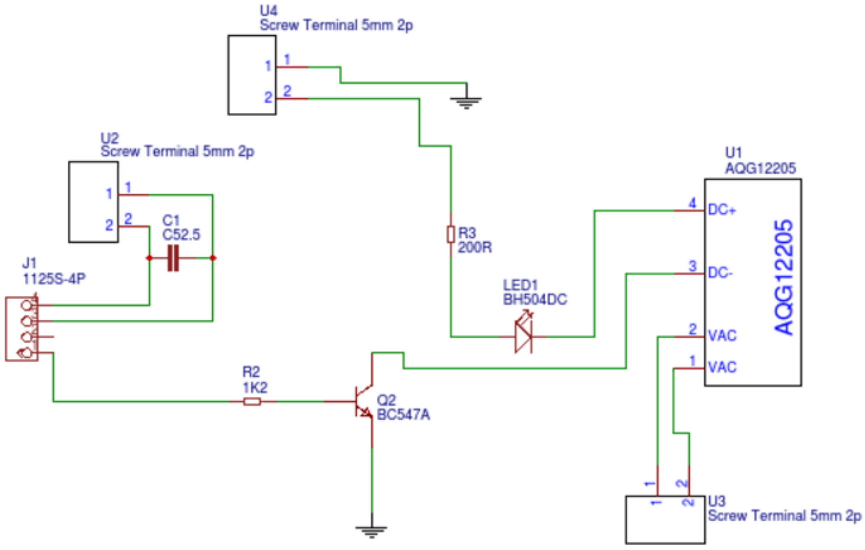

Figure 5.7: Electrical schematic of relay circuit

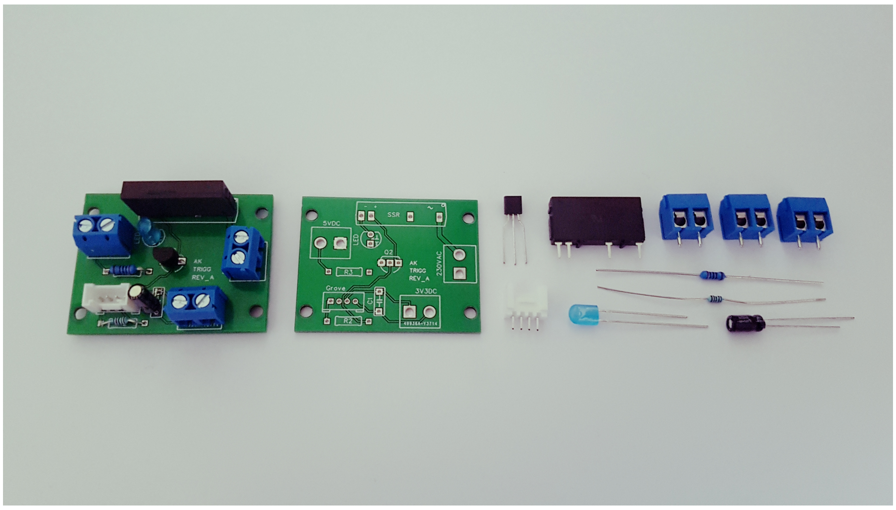

Figure 5.8: Relay PCB with components.

- 1 x Resistor 200 Ω 1/4 W
- 1 x NPN transistor BC547BTA.
- 1 x 5 mm LED.

- 1 x 10 microF electrolytic capacitor.
- 1 x Groove connector.

The total price for each relay board, including the manufacture of the PCB is \$8.06.

5.5. Enclosure and battery bank&charger

Prices for an enclosure and battery power bank and charger were allocated in Chapter 3, these two items are open to alteration as modular networks might require different specifications. This section serves to provide an idea as to how these items might be.

The enclosure needs to have an IP66 rating, and this helps to protect the vulnerable electronic components from moisture and dust derbies which could lead to short circuit faults. It has to be big enough to encompass all the modules mentioned in this Chapter (see figure 4.6, excluding the LED driver).

Tamper proofing could be achieved by adding intelligent monitoring with sensors that the Teensy could control. Other alternatives include a simple key lock or security screws. See figure 5.9 for a possible enclosure.

Figure 5.9: Plastic enclosure with cable glands. Source: `https://writelatex.s3.amazonaws.com/wybrnmynsfrx/uploads/17908/12806155/1.jpg` *(Accessed May 20, 2017)*

The battery power bank and charger need to be connected to mains electricity as this will provide the batteries with charge. It has to provide the modules in a wireless unit with power while the mains electricity is not connected. It has to couple to whichever state is needed at each time, charging or discharging.

Figure 5.10 shows a power bank&charger with USB outputs.

Figure 5.10: Example power bank and charger. Source: `https://writelatex.s3.amazonaws.com/wybrnmynsfrx/uploads/17918/12806290/1.jpg` *(Accessed May 20, 2017)*

5.6. Physical prototype construction

This section will present a short description of a physical prototype which stimulates the light progression algorithm. The prototype will be constructed with what amounts to three wireless units. The wireless units in this prototype will not include all the parts mentioned in the previous sections. The physical prototype will have one Teensy microcontroller, four XBee S2Cs on a development board and the power circuitry to power them up. Instead of a microwave sensors, buttons will simulate either 3.3 V DC as high or 0 V DC as low or ground. This will give the same effects as if a sensor was connected to the prototype. Figure 5.11 shows the setup of the physical prototype.

5.6.1. XBee physical prototype configuration

The XBee S2C RF modules are connected to a personal computer, they are added to the XCTU software application (seen in figure 5.12). Once they have been added, each node is configured to the appropriate configurable settings.

The configurations of the XBee modules can be seen in Table 5.1,

Along with all networking configurations, the serial communication baud rate is

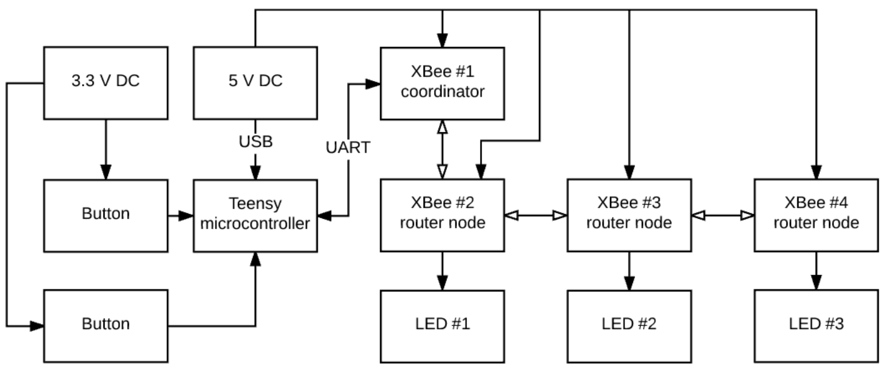

Figure 5.11: Diagram of the physical prototype. The 5 V DC power supply powers all the Teensy microcontroller and XBees. 3.3 V DC is used for PIN 13 and PIN 14 on the Teensy. Wireless communication is depicted by hollow arrows. Lines between Teensy and XBee are UART *signal lines. Digital output pins on the XBee units will power up a small LED light.*

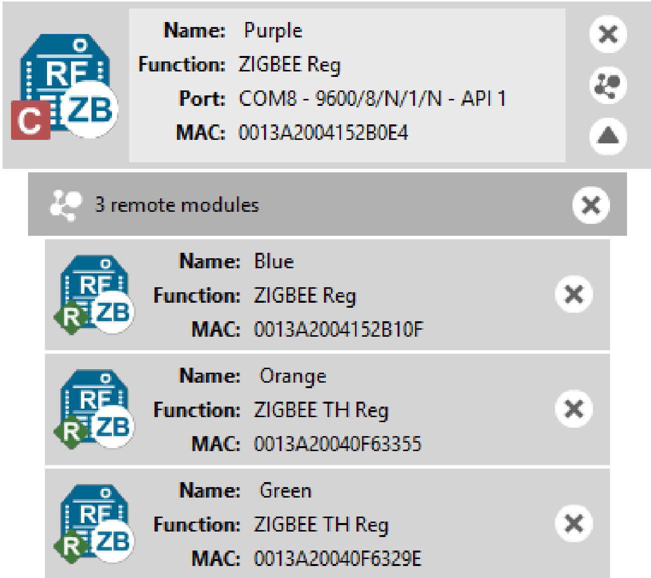

Figure 5.12: Forming a wireless sensor network with XCTU. Figure shows a coordinator node, marked with c, has two router nodes in it's network.

set to 9600, and same shall be fixed on the Teensy. Communication encryption is turned off. Transmission power levels are set to low as the prototype portray three wireless units close to each other.

Table 5.1: XBee configurable settings for physical prototype.

Setting	Data type	Value
ID: Pan ID	Hex	4C8
JV: Channel verification	Bit	1
CH: Operating channel	Dec	10
CE: Coordinator enable	Bit	1/0
TX: Power level	Int	0
PM: Power mode	Bit	0
EE: Encryption	Bit	0
BD: Baud rate	Int	3
AP: Api enable	Int	1

All pin input/output settings are left default as they will be configured through API frames by the API generator, see figure 5.13. The frames are sent by the Teensy UART connections.

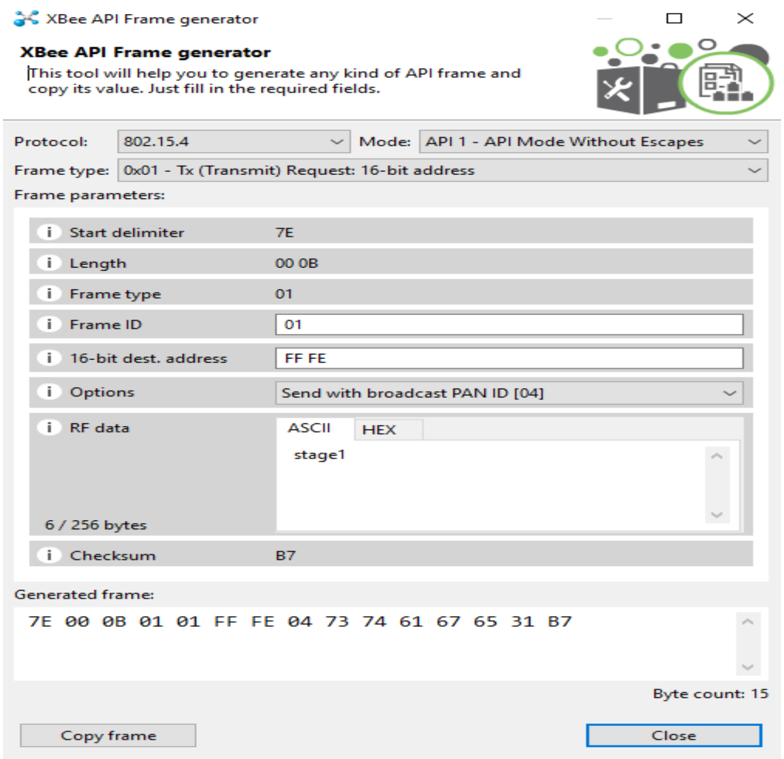

Figure 5.13: API frames are generated to send a string value to other nodes.

The XCTU software can monitor serial communication so it can confirm if right API data is being transmitted.

5.6.2. Teensy physical prototype configuration

Teensy 3.2 can be programmed in Arduino IDE. Teensyduino plug-in for the Arduino IDE can be downloaded from PJRC, the makers of the Teensy development boards. The programming language used to in the physical prototype is C++.

The Teensy microcontroller is connected to a personal computer so it can be configured and programmed. See table 5.2 for configurable settings.

XBee software library file is included to make the programming convenient, this

Table 5.2: Teensy 3.2 configurable settings for physical prototype.

Setting	Data type	Value
Board:	N/A	Teensy 3.2/3.1
USB type:	N/A	Serial
CPU speed:	N/A	24 MHz

library file has shortcuts and defined variables such as API packet sizes (so it does not go over the 100-byte limit), packet acknowledgment, baud rate and various functions that help with communication.

A link to the library file in its entirety can be located in Appendix A.

5.6.3. Physical prototype test

Figure 5.14 shows the first state in the algorithm, the first button (sensor 1) has been pressed. The teensy microcontroller is connected to the XBee coordinator via UART lines, RX on the Teensy connects to TX on the XBee and TX from Teensy to RX on XBee.

Router nodes use DI04 pin when they are instructed to do so by API frame sent by the coordinator. Figure 5.15 shows the second state once the second button (sensor 2) has been pressed.

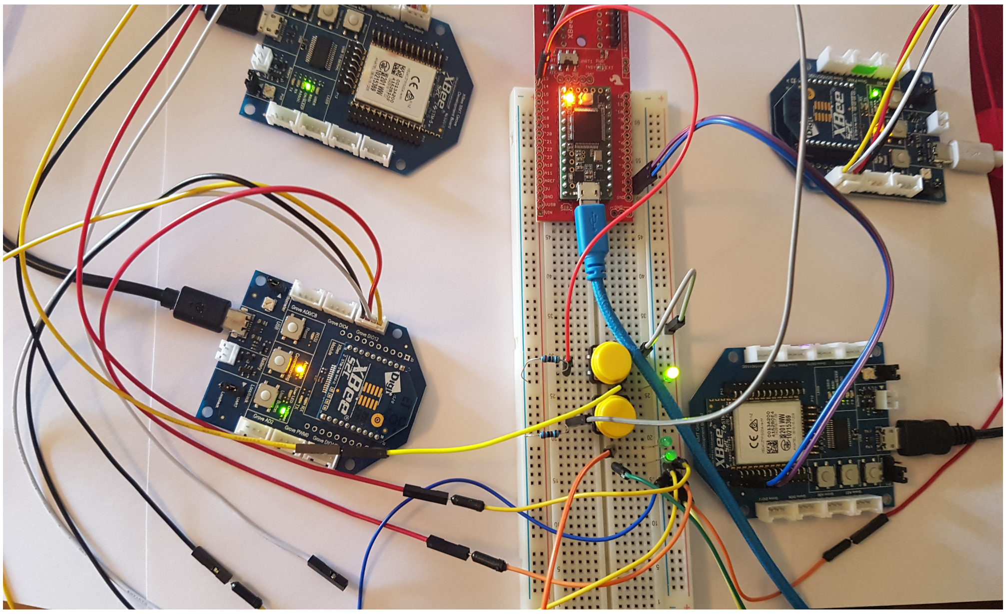

Figure 5.14: Construction of physical prototype, figure shows first state in light progression algorithm.

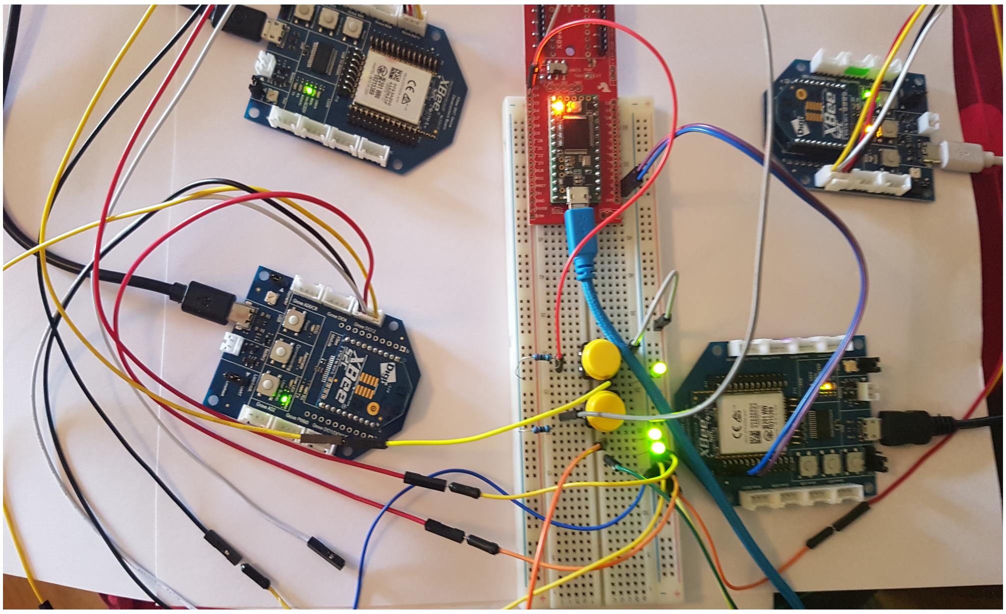

Figure 5.15: Construction of physical prototype, figure shows the second state in light progression algorithm.

6. Discussion

Regardless how the overall structure of the sensor network is set up, the best feature which could be implemented in such a design is having each wireless unit unique and addressable remotely. This expands the capabilities of the systems more than anything else, and it also serves as a gateway to further expansion of other further development ideas which could improve the system. If any wireless nodes relied on more than their nearest neighboring nodes to relay information or data to a particular point, it would both increase complexity in setting up the system and lower its stability and reliability. Few wireless nodes could malfunction and leave whole small scale networks offline.

As stated previously, the feasibility of such as system is not in question, but the way it is designed and implemented is. With the aid of iterative design process, I came up with more ways of optimizing the system to the requirements that I set. Throughout this chapter, I want to address to some of my findings which might open up this project to further research and development in the future.

6.1. LED lighting for street lights

It is currently unclear how cheap the overall price for such a system would need to be so that it would be worth the investment in it. Cost analysis could shed light on the uncertainty, this is however not in the scope of this project. The installment of LED lighting strengthens the validity of the investment as these lights have a far better expected lifetime than current high-pressure sodium light-bulb technology.

Market research in the development of LED lighting for street lighting indicates that there are currently 315 million streetlights worldwide, it is expected to grow to 359 million by 2026 [36]. A Study on SSL expresses the importance of replacing traditional sodium streetlights with solid state LED streetlights. The study estimates that 261 terawatt hours would be saved by 2030 in the U.S. compared to a "no-LED" scenario [37]. It is estimated that currently a lighting fixture uses approximately 1000 kWh/year and produces CO2 which contributes to climate change.

If the electricity consumption decreased because of this system, it follows that the light pollution from said system should also decrease. This is true for the average user as they would experience a decrease in total on time for street lights in most cases. The perception of light is also different from HPS to LED, individuals report that objects and colors are more evident in LED lighting [38]. For this reason a LED light can output less lm to achieve the same perceived luminosity. Figure 6.1 shows a comparison of a street under HPS lighting and LED lighting under similar conditions and with a similar lm output[23].

Figure 6.1: Difference in HPS and LED lighting luminosity in Sunset Drive, Miami. Source: `https://www.cob.org/gov/projects/Pages/Public%20Works/led-streetlights.aspx` *(Accessed May 15, 2017)*

High-pressure sodium light up objects with a yellow hue which makes it difficult to observe which color an object has under such lighting. There are however unexpected problems that arise when dealing with LED lighting. Presented in figure 6.2 and figure 6.3 is a comparison of the two electromagnetic spectra in the visible range for humans.

Sodium street lights have a distinct peak at around 590 nm, this makes the light pollution from such as system easily avoidable by filtering out light from a narrow span in wavelength. Such filters are often used in optical telescopes in astronomy observations with significant effect and little to no downsides. With LEDs, the spectrum encompasses a greater span, and thus a larger number of wavelengths have to be filtered out. Observatories are now faced with a big problem when it comes to how to filter out the emerging LED light pollution from this new

[23] `https://www.cob.org/gov/projects/Pages/Public%20Works/led-streetlights.aspx`(Accessed May 12, 2017)

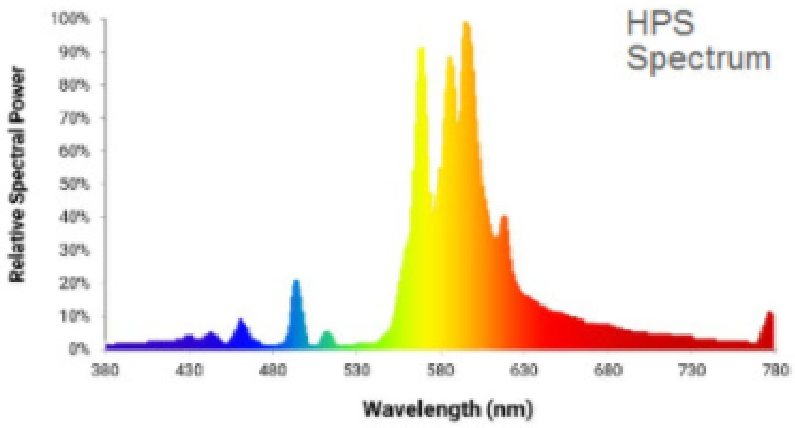

Figure 6.2: High pressure sodium electromagnetic spectrum. Source: `https://writelatex.s3.amazonaws.com/wybrnmynsfrx/uploads/9781/12325555/1.PNG` *(Accessed May 15, 2017)*

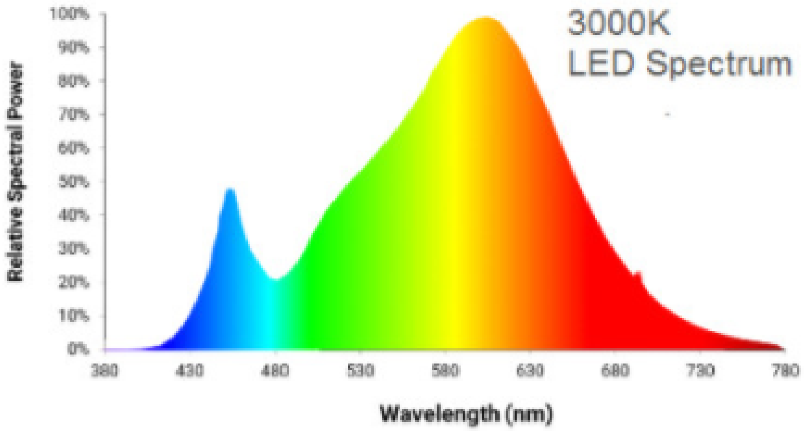

Figure 6.3: 3000K light emitting diode electromagnetic spectrum. Source: `https://writelatex.s3.amazonaws.com/wybrnmynsfrx/uploads/9781/12325555/2.PNG` *(Accessed May 15, 2017)*

technology. They cannot filter out all different wavelengths as it would eliminate the possibility of observing celestial bodies in the visible wavelengths. What makes it worse is the fact that there are many different colors of LED available, each with their unique characteristics outputs on the electromagnetic spectrum.

With the emergence of controllability of LED lighting this might become a much bigger problem for observatories and other remote sensing systems that rely on little light pollution in their surroundings. One way would be for LED lighting manufacturers to come together and work with the relevant agencies to produce the LED or SSL products which benefit both parties.

6.2. Importance of WSNs in the future

While working on this thesis and reading about the many different projects that are currently being developed, I have seen that wireless nodes or sensor networks will be in most of the devices we interact with daily. I can foresee that WSNs will be compatible with some of the platforms currently in use, such as Android and IOS products.

Wireless nodes could be made on single integrated circuit chips and put into every device we desire to control or interact with. Much like Bluetooth is today but on a much wider scale, where devices are not confined to their broadcasting range. Devices could communicate intelligently with each other and monitor and treat almost any aspect of day to day life.

Public WSNs such as the one designed in this thesis could relay information on a separate application stack to other WSNs. There are however many problems on how to implement such systems, one of the strongest points would be security and privacy.

6.3. Security vulnerabilities in WSNs

Every device that is connected to the Internet is in some way vulnerable in some way. We have seen IP cameras attacked and intruders gaining access to personal and private information through snooping on video feeds the cameras provide[24].

WSNs are especially vulnerable as they can't rely on the typical methods used to secure internet connected devices. There are studies researching methods that can be used in WSN, in 2006 an attempt was made to break the 128, 196 and 256-bit AES encryption, Seven of the ten keys were broken off the 128-bit encryption [39]. A vast amount of resources were used to get to that point, it is not unreasonable

[24] `https://pierrekim.github.io/blog/2017-03-08-camera-goahead-0day.html` (accessed on 17.05.2017)

to assume that a wireless sensor network should be safe to most if not all attacks when it comes to communication.

There are however more aspects of security that need to be considered, such as when these devices are installed publicly, there needs to be tamper proofing to the physical device, protocols in place for power outages where wireless nodes need to rely on battery power for some time and many more features.

6.3.1. Data routing in a daisy chain WSN

The entire system network topology is a typical hierarchical network while each modular network is a flat network, this means a high load is set on the coordinator node and the nodes nearest to it for the same reason mentioned in 2.1.1, this might open up the vulnerabilities as these nodes can be targeted. If information extraction is requested from a modular network, the coordinator node will always have to wake up from a sleep cycle as it is the first point of contact to the outside world (i.e. the Internet).

Every node away from the coordinator would then use less energy, and ultimately, the last node in the sequential line would use considerably fewer resources than the routing nodes close to the Internet gateway. There are also delays in communication as data from a node close to a coordinator would take considerably less time than nodes further away from it, as each transmission takes a discrete amount of time.

For bigger modular networks, two Internet gateways could be implemented so the system could choose from which side information is extracted, this is however not a possibility as XBee gateways do not have this capability.

6.4. Wireless unit development

The approach that was used in the design process of the wireless units in this project could have been improved. Both the price of each unit and the capabilities of those units could have been improved by designing the units from square one instead of puzzling together ready-made development or circuit boards. It is reasonable to place all the individual components on a single PCB, this would add to the feasibility of the project as it would lower the price for each unit considerably.

This would, however, take much longer to complete as the design process would be much more demanding. For now, the prototype that was developed should suffice for a test which could shed light on the performance of the modular networks and the entire system.

6.5. Light progression algorithms

Algorithms can be implemented in small networks where street lights are in an ordered manner. This could be applied in few different ways. By knowing the number of nodes in the street and keeping a count of how many nodes are left until the street ends. When the counter hits zero, it would be known that there are no more nodes in the street and the information isn't sent any further. Since the modular networks are configured before installation, the number of nodes in any street or design should be known.

The second option would be to send information to neighboring nodes with acknowledgments until one is not sent, meaning that the street or network size is irrelevant. This could result in problems with false termination if the same principal used in error detecting methods inside the network.

I can imagine that lights turning on and off ahead of you while driving could be bothersome or quite possibly infuriating. Test need to be carried out to see how it would be best to implement an algorithm which suits each situation. SSL lighting have control circuitry that takes 0-10 V DC as an input and dims the output of the LED light. The lowest voltage turns off the light, and any value between 0 and 10 equates to 0-100% of possible strength.

A slow ramp up to to the strength needed might be easier to look at when driving down a road.

6.6. Future work

The following list includes some of the things I recommend implementing in future projects that are related to this design.

- Design of proprietary wireless units that are designed on a single PCB. Specifications of the wireless units could then be determined based on input from experts in the field of street light infrastructure.
- Implement modular network in a real-life situation as a test.
- Measure power consumption.
- Implement video image processing to a WSN to track vehicles and report traffic in real time.
- Implement velocity measurement of vehicles.
- Add weather monitoring capability.
- Extensive research and comparison of different sensor technologies that could improve the accuracy.
- Develop a web-based control system for the modular networks.
- Add control circuitry for dimming LED lights (0-10 V DC).
- Test the security vulnerabilities of the design.
- Connect street light WSN and vehicle wireless nodes to form a traffic avoidance system.

7. Conclusion

This thesis introduced a design of a wireless sensor network used to automate street lighting.

Wireless nodes and microwave sensors were analyzed to meet requirements to fit in a design that incorporates low power wireless communication and vehicle detection. XBee S2C radio frequency module, SEN0192 microwave sensor, Teensy 3.2 microcontroller and a relay module that was designed specifically for this design were the four main components in a wireless unit, one of many wireless units that make up a modular network in the system. Each of these wireless units has the capability to turn on or off a LED street light, and together they work to illuminate roads for vehicles.

Price per unit was estimated and a simple prototype was constructed to show some of the functionality of the system.

Finally, some of the concepts and ideas are discussed to address some of the problems faced and to lay a foundation for possible extensions of this project and other possibilities of wireless sensor network related designs.

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A. Appendix A

A.1. Wireless node requirement analysis selection tables

The following tables are tables mentioned in section 3.1.1.

Table A.1: Wireless node - XBee S2c by Digi.

Specification	Comment	Grade
Cost	The Xbee S2C wireless node can be bought from few different distributors. The individual node price is $17.5 from Digikey.	3
Size	The Xbee S2C can be bought both as a stand alone chip which is 24×27 mm or with a development board which increases the size to 40×60 mm but eases connectivity to the output/input pins and adds a voltage regulator so a USB connector can be used.	2
Range	The Xbee S2C has indoor range of 60 m and outdoor range of 1200 m with antenna, 200 m without one.	3
Wireless protocol	The Xbee S2C uses the IEEE 802.15.4 (Zigbee) protocol.	1
Frequency	The 2SC uses the ISM 2.4 GHz frequency band.	2
Power consumption	The Xbee S2C uses 33 mA @ 3.3 V DC while transmitting and receiving, it can be powered down to save power.	3
WSN topology	Xbee products can produce mesh/star WSN topologies	N
Power source	Sufficient voltage input for the node is 3.3 V DC. One series connected 18650 battery is enough to power it, two can be connected in parallel to add battery runtime. 5 V DC is required if the node is used with a development board.	3
Data rate	Maximum data rate for Xbee S2C is 250 kbit/s. lower configurations are available.	1
Serial interface	Has SPI and hardware or software UART.	1
Encryption	Built in 128-bit AES encryption can be enabled.	2
Sum		21

Table A.2: Wireless node - Xbee pro 900HB by Digi.

Specification	**Comment**	**Grade**
Cost	Xbee pro 900HB by Digi node can be bought from few different distributors. The individual node price is $28.5 from Digikey.	3
Size	The Xbee pro 900HB can be both as a stand alone chip which is 24×33 mm or with a development board which increases the size to 40×60 mm but eases connectivity to the output/input pins. Same development board as the one used by Xbee S2C.	2
Range	The Xbee pro is used for long range communication it has a range of up to 3200 m outdoors or in line-of-sight.	3
Wireless protocol	The Xbee pro uses the IEEE 802.15.4 (Zigbee) protocol.	1
Frequency	The Pro 900HB uses the ISM 900 MHz frequency band.	2
Power consumption	The Xbee pro uses 120 mA @ 3.3 V DC while transmitting. It can be powered down to save power.	1
WSN topology	Xbee products can produce mesh/star WSN topologies.	N
Power source	Sufficient voltage input for the Xbee pro is 3.3 V DC, One series connected 18650 battery is enough, two can be connected in parallel to add capacity. 5 V DC is required if the node is used with a development board.	3
Data rate	Maximum data rate for Xbee pro is 250 kbit/s. lower configurations are available.	1
Serial interface	Has SPI and hardware or software UART.	1
Encryption	Built in 128-bit AES encryption can be enabled.	2
Sum		19

Table A.3: Wireless module - NRF2401 by Nordic semiconductor.

Specification	Comment	Grade
Cost	NRF2401 module by Nordic semiconductor can be bought from few different distributors. From Chinese distributors they can be bought for as low as $1.0 each	3
Size	The NRF2401 can be found in many different printed circuit board (PCB) layouts. Most of them are smaller than 50 × 50 mm.	2
Range	The NRF2401 is used for short range communication. High gain antennas can help with that. Up to 1000 m with PCB antenna, 30 m without one.	3
Wireless protocol	No protocol built in.	0
Frequency	The NRF2401 uses the ISM 2.4 GHz frequency band.	2
Power consumption	The NRF2401 uses 18 mA @ 3.3 V DC and it can be put into ultra low power mode with limited data transfer (10 kbit/s).	3
WSN topology	Nordic have implemented limited mesh topologies for NRF2401	N
Power source	Sufficient voltage input for the NRF2401 is 3.3 V DC. One series connected 18650 battery is enough, two can be connected in parallel to add capacity.	3
Data rate	Two data rates can be set, 1 Mbit/s and 250 kbit/s.	1
Serial interface	Has SPI serial interface.	1
Encryption	No built in encryption on wireless communication.	0
Sum		18

Table A.4: Wireless node - .NOW mote by Samraksh company.

Specification	Comment	Grade
Cost	.NOW mote (node) by Samraksh company can be bought directly from the producers for 125 euros each. It has a built in programmable microcontroller.	1
Size	The .NOW PCB is 50 × 85 mm.	1
Range	.NOW is used for short range communication, 100 m outdoors with standard parts.	2
Wireless protocol	The .NOW mote uses the IEEE 802.15.4 (Zigbee) protocol or 6LoWPAN.	1
Frequency	The .NOW node uses the ISM 2.4 GHz frequency band.	2
Power consumption	The mote uses 105 mA peak current @ 3.3 V DC and it can be put to sleep.	1
WSN topology	The mote uses TinyOS which can implement a mesh network.	N
Power source	Sufficient voltage input for the .NOW is between 1.8 V DC and 6 V DC. One series connected 18650 battery is enough, two can be connected in parallel to add capacity.	3
Data rate	Normal operation data rate for .NOW mote is 250 kbit/s, up to 2 Mbit/s can be selected.	1
Serial interface	Has USB, SPI, I^2C and UART.	1
Encryption	No built in encryption on wireless communication.	0
Sum		13

Table A.5: Wireless node - AS-XM1000 by Advanticsys.

Specification	Comment	Grade
Cost	AS-XM1000 by Advanticsys can be bought directly from the producers for 95.0 euros each. It comes with a programmable MSP430F2618 MPU.	1
Size	The AS-XM1000 PCB is 32.5 × 82 mm in size.	1
Range	AS-XM1000 is used for short range communication (30 m indoor) and 100 m outdoors with standard parts.	2
Wireless protocol	The AS-XM1000 uses the IEEE 802.15.4 (Zigbee) protocol.	1
Frequency	The AS-XM1000 uses the ISM 2.4 GHz frequency band	2
Power consumption	The node uses 18.8 mA @ 3.3 V DC and it can be put to sleep to save power.	3
WSN topology	AS-XM1000 uses TinyOS or ContikiOS which can implement a WSN.	N
Power source	Sufficient voltage input for the AS-XM1000 is between 2.1 V DC and 3.6 V DC. One series connected 18650 battery is enough, two can be connected in parallel to add capacity.	3
Data rate	Normal operation data rate for AS-XM1000 is 250 kbit/s.	1
Serial interface	Has USB, SPI, I^2C and UART.	1
Encryption	No built in encryption on wireless communication.	0
Sum		15

Table A.6: Wireless node - AVR 2 by panStamp.

Specification	Comment	Grade
Cost	AVR 2 by panStamp can be bought directly from the producers for 15.33 euros each. It has a built in Atmega328p MCU.	3
Size	The AVR 2 PCB is 16×22 mm.	2
Range	AVR 2 is used for short to medium range communication. Outdoor range is 200 m with an added antenna.	1
Wireless protocol	The AVR 2 uses SWAP open source protocol stack	0
Frequency	The AVR 2 uses the ISM 900 MHz frequency band.	2
Power consumption	The node uses between 24 and 36 mA @ 3.3 V DC and it can be put to sleep.	3
WSN topology	AVR 2 uses Arduino IDE which can implement a WSN by programmed software.	N
Power source	Sufficient voltage input for the AVR 2 is between 2.5 V DC and 3.6 V DC. One series connected 18650 battery is enough, two can be connected in parallel to add capacity.	3
Data rate	Normal operation data rate for AVR 2 is 1 Mbit/s, 2 Mbit/s can be selected.	1
Serial interface	Has SPI, I^2C and UART.	1
Encryption	128-bit acaes Security Encryption	2
Sum		18

A.2. Microwave sensor requirement analysis selection tables

The following tables are tables mentioned in section 3.2.1.

Table A.7: Microwave sensor - Herkules 2 motion detector by Bircher.

Specification	**Comment**	**Grade**
Cost	The Herkules 2 can be bought online and the price is $465. It is often used in car detection for automatic garage doors.	1
Power Source	Operating Voltage is 12-28 V AC or 12-36 V DC.	0
Range	The Herkules 2 can be mounted from 2-7 m in height and has a range of 10 m.	0
Data rate	The Herkules two has two output relays which change from open to closed when motion is detected. These status changes can not be implemented in logic level voltages that a MCU needs.	1
Size	The outside dimensions of the sensor unit is 150 mm long, 75 mm wide and 75 mm tall.	1
Interference	The sensor can be programmed to ignore false positive readings.	2
Serial interface	The sensor only two outputs are two electric relays.	0
Sum		5

Table A.8: Microwave sensor - QT50R-EU-AFHQ by Banner.

Specification	Comment	Grade
Cost	QT50R series sensors can be bought from Brammer. Few different sensors with different outputs and ranges are available. The list price of each unit is $702.	1
Power Source	The supply voltage is 12-30 V DC.	0
Range	QT50R series sensors have a range from 2-100 m.	3
Data rate	QT50R series sensors have two different transistors, one NPN and one NPN. They can drive a 150 mA load.	1
Size	The outside dimensions of the sensor unit is 74.1 mm by 66 mm.	2
Interference	The sensor can be programmed to ignore false positive readings such as wind, rain and bright lights.	2
Serial interface	The sensor only two outputs are transistors.	0
Sum		9

Table A.9: Microwave sensor - CDM324 Doppler Speed Sensor.

Specification	**Comment**	**Grade**
Cost	CDM324 module is a single channel microwave sensor modification of the IPM-165 module by InnoSent. Numerous open source adaptations of the module can be found online. Prices very from $10 to $36.	3
Power Source	The supply voltage is 4.75-5.25 V DC. 5 V DC is a typical input voltage to the sensor. It requires 30-40 mA for normal operation.	2
Range	No official numbers are in the database of the module, users have reported over 30 m range.	3
Data rate	The output from the sensor is a square wave, it can be read by a microcontroller. The frequency of the signal indicates the velocity the target object is traveling at. Frequency is between 3 Hz and just under 1 kHz, sampled few times a second.	1
Size	The outside dimensions of the sensor module is 50×50 mm.	2
Interference	The sensor can read false positive readings. Filter circuitry might help.	-2
Serial interface	The sensor has two outputs, frequency and voltage. It can be enabled via enable pin. Data from the unit can be teated as serial or logic level signal.	1
Sum		10

Table A.10: Microwave sensor - Lumewave MWX-LVE-180U by Echelon.

Specification	**Comment**	**Grade**
Cost	The Lumewave MWX-LVE-180U is a very long range radar-based microwave sensor. Prices are estimated to be over \$100.	1
Power Source	The supply voltage 12 V DC. It requires 60 mA for a single sensor and 120 mA for dual direction.	0
Range	Can detect pedestrians 30 m away, big trucks can be detected more than 100 m away. Varying results can be found on different angles to the detection object.	3
Data rate	The output is a simple transistor switch. Additional modules can be added on to control a 0-10 V DC digital addressable lighting interface (DALI) system dimmer.	1
Size	The sensor is smaller than 50×50 mm.	2
Interference	The sensor can be programmed to a certain threshold so it can ignore weather effects and disturbances.	2
Serial interface	The sensor unit is only a presence detector and does not measure or calculate velocity. The outputs of the sensor could be connected to a microcontroller circuit.	1
Sum		10

Table A.11: Microwave sensor - SEN0192 by DFRobot.

Specification	**Comment**	**Grade**
Cost	The SEN0192 is a digital microwave sensor. Prices per unit are \$13.90 and lower if bought in a larger quantity.	3
Power Source	Working Voltage is 4.75V-5.25 V DC. It requires 60 mA peak current, 37 mA for typical operation.	2
Range	The detection distance can vary from 2-16 m depending on how it is mounted.	1
Data rate	The digital output from the sensor can interrupt a microcontroller interrupt pin with pulse width of 5 microseconds, this equals to roughly 200 times a second. A delay can be programmed for more manageable timescales.	1
Size	The size of the sensor unit is comparable to an Arduino R3, smaller than 100 × 100 mm.	2
Interference	The sensor can be programmed to a certain threshold so it can ignore weather effects and disturbances.	2
Serial interface	The sensor unit is only a presence detector and does not measure or calculate velocity. The outputs of the sensor could be connected to a microcontroller circuit.	1
Sum		12

A.3. XBee S2C, XBee PRO 900HB, nRF2401A and .NOW wireless modules datasheets

The following datasheets are datasheets for the wireless nodes mentioned in section 3.1.1.

DIGI

EMBEDDED RF
MODULES FOR OEMS

XBEE® S2C 802.15.4 RF MODULES

Low-cost, easy-to-deploy modules provide critical end-point connectivity to devices and sensors

XBee RF modules provide OEMs with a common footprint shared by multiple platforms, including multipoint and ZigBee/Mesh topologies, and both 2.4 GHz and 900 MHz solutions. OEMs deploying the XBee can substitute one XBee for another, depending upon dynamic application needs, with minimal development, reduced risk and shorter time-to-market.

XBee 802.15.4 RF modules are ideal for applications requiring low latency and predictable communication timing. Providing quick, robust communication in point-to-point, peer-to-peer, and multipoint/star configurations, XBee 802.15.4 products enable robust end-point connectivity with ease. Whether deployed as a pure cable replacement for simple serial communication, or as part of a more complex hub-and-spoke network of sensors, XBee 802.15.4 RF modules maximize performance and ease of development.

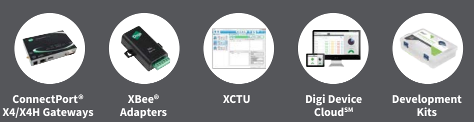
XBee 802.15.4 modules seamlessly interface with compatible gateways, device adapters and range extenders, providing developers with true beyond-the-horizon connectivity.

The updated XBee S2C 802.15.4 module is built with the SiliconLabs EM357 SoC and offers improved power consumption, support for over-the-air firmware updates, and provides an upgrade path to DigiMesh® or ZigBee® mesh protocols if desired.

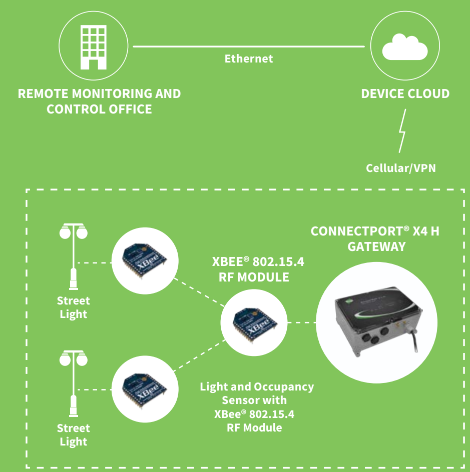
BENEFITS

- Simple, out-of-the-box RF communications, no configuration needed
- Point-to-multipoint network topology
- 2.4 GHz for worldwide deployment
- Common XBee footprint for a variety of RF modules
- Industry leading sleep current of sub 1uA
- Firmware upgrades via UART, SPI or over the air
- Migratable to DigiMesh and ZigBee PRO protocols and vice-versa

RELATED PRODUCTS



APPLICATION EXAMPLE



SPECIFICATIONS	XBee® S2C 802.15.4	XBee-PRO® S2C 802.15.4
PERFORMANCE		
TRANSCEIVER CHIPSET	Silicon Labs EM357 SoC	
DATA RATE	RF 250 Kbps, Serial up to 1 Mbps	
INDOOR/URBAN RANGE	200 ft (60 m)	300 ft (90 m)
OUTDOOR/RF LINE-OF-SIGHT RANGE	4000 ft (1200 m)	2 miles (3200 m)
TRANSMIT POWER	3.1 mW (+5 dBm) / 6.3 mW (+8 dBm) boost mode	63 mW (+18 dBm)
RECEIVER SENSITIVITY (1% PER)	-100 dBm / -102 dBm boost mode	-101 dBm
FEATURES		
SERIAL DATA INTERFACE	UART, SPI	
CONFIGURATION METHOD	API or AT commands, local or over-the-air (OTA)	
FREQUENCY BAND	ISM 2.4 GHz	
FORM FACTOR	Through-Hole, Surface Mount	
HARDWARE	S2C	
ADC INPUTS	(4) 10-bit ADC inputs	
DIGITAL I/O	15	
ANTENNA OPTIONS	Through-Hole: PCB Antenna, U.FL Connector, RPSMA Connector, or Integrated Wire SMT: RF Pad, PCB Antenna, or U.FL Connector	
OPERATING TEMPERATURE	-40° C to +85° C	
DIMENSIONS (L X W X H) AND WEIGHT	Through-Hole: 0.960 x 1.087 in (2.438 x 2.761 cm) SMT: 0.866 x 1.33 x 0.120 in (2.199 x 3.4 x 0.305 cm)	Through-Hole: 0.960 x 1.297 in (2.438 x 3.294 cm) SMT: 0.866 x 1.33 x 0.120 in (2.199 x 3.4 x 0.305 cm)
NETWORKING AND SECURITY		
PROTOCOL	XBee 802.15.4 (Proprietary 802.15.4)	
UPDATABLE TO DIGIMESH PROTOCOL	Yes	
UPDATABLE TO ZIGBEE PROTOCOL	Yes	
INTERFERENCE IMMUNITY	DSSS (Direct Sequence Spread Spectrum)	
ENCRYPTION	128-bit AES	
RELIABLE PACKET DELIVERY	Retries/Acknowledgements	
IDS	PAN ID and addresses, cluster IDs and endpoints (optional)	
CHANNELS	16 channels	15 channels
POWER REQUIREMENTS		
SUPPLY VOLTAGE	2.1 to 3.6V	2.7 to 3.6V
TRANSMIT CURRENT	33 mA @ 3.3 VDC / 45 mA boost mode	120 mA @ 3.3 VDC
RECEIVE CURRENT	28 mA @ 3.3 VDC / 31 mA boost mode	31 mA @ 3.3 VDC
POWER-DOWN CURRENT	<1 μA @ 25° C	<1 μA @ 25° C
REGULATORY APPROVALS		
FCC, IC (NORTH AMERICA)	Yes	Yes
ETSI (EUROPE)	Yes	No
RCM (AUSTRALIA AND NEW ZEALAND)	No (Coming soon)	No (Coming soon)
TELEC (JAPAN)	No (Coming soon)	No (Coming soon)

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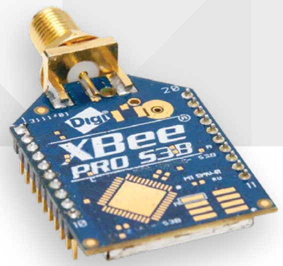
LONG-RANGE 900 MHZ
OEM RF MODULE



XBEE-PRO® 900HP

Best-in-class range RF module features software-complete mesh or multipoint topologies with advanced sleep modes

XBee-PRO 900HP embedded modules provide best-in-class range wireless connectivity to devices. They take advantage of the DigiMesh® networking protocol, featuring dense network operation and support for sleeping routers, and are also available in a point-to-multipoint configuration. Supporting RF line-of-sight ranges up to 28 miles (with high-gain antennas), and data rates of up to 200 Kbps, these modules are ideal for extended-range applications requiring increased data throughput.

The XBee-PRO 900HP requires no programming and can be configured easily using Digi's free XCTU software or via a simplified AT command set. XBee® modules are pre-certified for use in multiple countries, further reducing development costs and time to market.

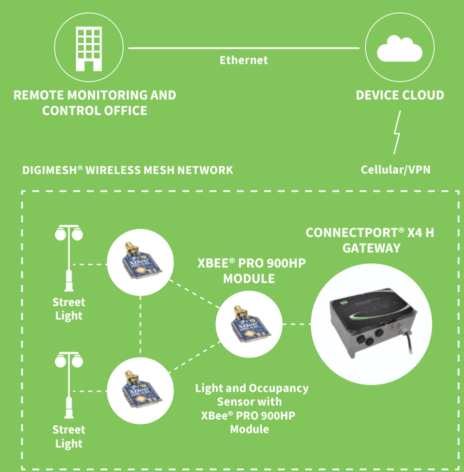
The programmable version of the XBee-PRO 900HP module makes customizing long-range wireless applications easy. Programming directly on the module eliminates the need for a separate host processor. Because the wireless software is isolated, applications can be developed with no risk to RF performance, security or additional certifications.

BENEFITS

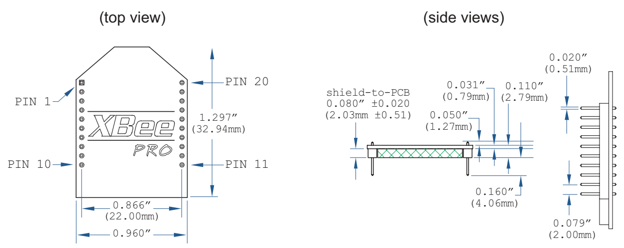
- Superior outdoor LOS range of up to 28 miles with high-gain antenna
- Over-the-air firmware updates via other XBee-PRO 900HP modules or Digi Device Cloud[SM]
- Software-selectable channel mask for interference immunity
- Programmable versions of the XBee-PRO 900HP enable custom application development
  - 8-bit Freescale™ S08 microprocessor brings custom intelligence to the module
  - XBee-specific CodeWarrior® development tools for easy programming
- RF data rate up to 200 Kbps
- Patented channel selectivity algorithm allows for more dense networks

RELATED PRODUCTS

APPLICATION EXAMPLE



SPECIFICATIONS	XBee-PRO® 900HP	Programmable XBee-PRO® 900HP
HARDWARE		
PROCESSOR	ADF7023 transceiver, Cortex-M3 EFM32G230 @ 28 MHz; Programmable includes: Freescale MC9S08QE32	
FREQUENCY BAND	902 to 928 MHz, software selectable channel mask for interference immunity	
ANTENNA OPTIONS	Wire, U.FL and RPSMSA	
PERFORMANCE		
RF DATA RATE	10 Kbps or 200 Kbps	
INDOOR/URBAN RANGE	10 Kbps: up to 2000 ft (610 m); 200 Kbps: up to 1000 ft (305 m)	
OUTDOOR/ LINE-OF-SIGHT RANGE	10 Kbps: up to 9 miles (15.5 km); 200 Kbps: up to 4 miles (6.5 km) (with 2.1dB dipole antennas)	
TRANSMIT POWER	Up to 24 dBm (250 mW) software selectable	
RECEIVER SENSITIVITY	-101 dBm @ 200 Kbps, -110 dBm @ 10 Kbps	
FEATURES		
DATA INTERFACE	UART (3V), SPI	
GPIO	Up to 15 Digital I/O, 4 10-bit ADC inputs, 2 PWM outputs	
NETWORKING TOPOLOGIES	DigiMesh, Repeater, Point-to-Point, Point-to-Multipoint, Peer-to-Peer	
SPREAD SPECTRUM	FHSS (Software Selectable Channels)	
PROGRAMMABILITY		
MEMORY	N/A	32 KB Flash / 2 KB RAM
CPU/CLOCK SPEED	N/A	HCS08 / Up to 50.33 MHz
POWER		
SUPPLY VOLTAGE	2.1 to 3.6 VDC	2.4 to 3.6 VDC
TRANSMIT CURRENT	215 mA	229 mA
RECEIVE CURRENT	29 mA	44 mA
SLEEP CURRENT	2.5 uA	3 uA
REGULATORY APPROVALS		
FCC (USA)	MCQ-XB900HP	
IC (CANADA)	1846A-XB900HP	
C-TICK (AUSTRALIA)	Yes	
ANATEL (BRAZIL)	Yes	
IDA (SINGAPORE)	Yes	



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PRODUCT SPECIFICATION

Single chip 2.4 GHz Transceiver **nRF2401A**

FEATURES

- True single chip GFSK transceiver in a small 24-pin package (QFN24 5x5mm)
- Data rate 0 to1Mbps
- Only 2 external components
- Multi channel operation
  - 125 channels
  - Channel switching time <200µs.
  - Support frequency hopping
- Data slicer / clock recovery of data
- Address and CRC computation
- DuoCeiver™ for simultaneous dual receiver topology
- ShockBurst™ mode for ultra-low power operation and relaxed MCU performance
- Power supply range: 1.9 to 3.6 V
- Low supply current (TX), typical 10.5mA peak @ -5dBm output power
- Low supply current (RX), typical 18mA peak in receive mode
- 100 % RF tested
- No need for external SAW filter
- World wide use

APPLICATIONS

- Wireless mouse, keyboard, joystick
- Keyless entry
- Wireless data communication
- Alarm and security systems
- Home automation
- Surveillance
- Automotive

- Telemetry
- Intelligent sports equipment
- Industrial sensors
- Toys

GENERAL DESCRIPTION

nRF2401A is a single-chip radio transceiver for the world wide 2.4 - 2.5 GHz ISM band. The transceiver consists of a fully integrated frequency synthesizer, a power amplifier, a crystal oscillator and a modulator. Output power and frequency channels are easily programmable by use of the 3-wire serial interface. Current consumption is very low, only 10.5mA at an output power of -5dBm and 18mA in receive mode. Built-in Power Down modes makes power saving easily realizable.

QUICK REFERENCE DATA

Parameter	Value	Unit
Minimum supply voltage	1.9	V
Maximum output power	0	dBm
Maximum data rate	1000	kbps
Supply current in transmit @ -5dBm output power	10.5	mA
Supply current in receive mode	18	mA
Temperature range	-40 to +85	°C
Sensitivity	-93	dBm
Supply current in Power Down mode	900	nA

Table 1 nRF2401A quick reference data

Nordic Semiconductor ASA - Vestre Rosten 81, N-7075 Tiller, Norway - Phone +4772898900 - Fax +4772898989

eMote Summary Specs

Dimensions	8.5cm by 5cm (not including battery)
Processor	32-bit Cortex M3
	1Mbyte Flash Program Memory
	96 Kbyte SRAM
	8 MHz – 60 MHz
RF	AT86RF231 chip
	2.4 GHz ISM Band
	Zigbee, 802.15.4, 6LoWPAN
	Receive Sensitivity -101 dBm
	Chip antenna or SMA for external antenna
Memory	256 Mbit NOR Flash (XIP capable)
Interface/Features	USB, SPI, I2C, UART
	1x 12-bit 2V DAC
	3x 12-bit 200 kHz ADC, 5V or 3.3V input
	Up to 8 interrupt capable GPIOs @ 10 MHz
	MicroSD, Hardware CRC
	Unique 96-bit read-only hardware ID
	16-bit Timers, 32 kHz crystal and RTC with backup registers
	JTAG available
	12-channel DMA
	Independent and Window watchdog timers
Supported Software	.NET MicroFramework 4.0
	TinyOS 2
Power	3 Low Power Sleep modes

eMote MCU

- STM32F103 (144-pin package)
- Cortex M-3 (Thumb2 instruction set)
- 8 MHz to 60 MHz run clock configurations (48 MHz only when using USB)
- 1 MByte onboard Flash for program and data storage
- 96 kB SRAM

Further Reading

STM's Product Page:

http://www.st.com/internet/mcu/product/247490.jsp

Reference Manual (User Guide):

http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/REFERENCE_MANUAL/CD00171190.pdf

Datasheet:

http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/DATASHEET/CD00253742.pdf

Programming Manual:

http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/PROGRAMMING_MANUAL/CD00228163.pdf

Flash Programming Manual:

http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/PROGRAMMING_MANUAL/CD00264852.pdf

Sleep Modes

The STM32 supports three sleep modes with varying levels of energy savings and wakeup requirements, listed below from the datasheet.

- Sleep - 1.8µs wakeup
- Stop - 5.4µs wakeup
- Standby - 50µs wakeup (wakeup source limited to RTC and external WKUP pin).

For more information see the STM32F103 Datasheet section 5.3.7, and Reference Manual section 5.3.

Run Modes

At startup the default operating frequency for the system clock and all busses is 8 MHz sourced from an internal RC oscillator (HSI). Using the internal PLL as a clock source, operation up to 60 MHz is allowed. When using USB, the PLL output must be 48 MHz.

See Reference Manual section 7.2 and 7.3 for more information.

Real Time Clock, Backup, Watchdogs

Additionally, a 32.768 kHz crystal is provided on the mote. In conjunction with the included CR2032 lithium coin battery, the eMote can continue to keep accurate and long-term time (32 bit) time and allows for backup registers in the event of main battery loss.

Two watchdog timers are included in the MCU, the IWDG (independent watchdog) and WWDG (windowed watchdog). The independent watchdog is a totally independent process outside the main application but has lower timing constraints than the WWDG.

See Reference Manual sections, 6 (backup registers), 18 (RTC), and 19-20 (Watchdog Timers).

eMote Power

The eMote is optimized for low-voltage battery chemistries (alkaline, NiCd, NiMH) using only a single cell.

Input Requirements

- 0.68 volt minimum for startup
- 1.8 volt maximum for best efficiency
- 6 volt absolute maximum (not recommended)
- 100mA peak current (typically <15mA)

Voltage Domains

- 2.0 volt (main, "always on")
- User controlled and user exposed:
  - 3.3 volt (I/O for MicroSD, NOR Flash)
  - 5.0 volt (USB[1])
- 3.0 volt backup domain (backup registers and RTC only)

Except for the backup domain, all domains are sourced using high efficiency boost converters.

[1] 5.0v domain not available in revision 0.

Power Profiles

- 16.3mW @ 8 MHz (busy loop)
- Others TBD

eMote Flash Memory

In addition to the 1 MByte of flash memory onboard the MCU, external flash is provided:

- 256Mbit external NOR Flash
- 70 ns
- Interfaced to MCU FSMC (Flexible Static Memory Controller)

See the M29W256G datasheet for more information:

http://media.digikey.com/pdf/Data%20Sheets/Micron%20Technology%20Inc%20PDFs/M29W256GH,GL.pdf

For more information on the FSMC, see the MCU Reference Manual Section 21.

eMote RF

RF functionality uses the Atmel AT86RF231 RF chip interfaced with a dedicated SPI bus.

Max output power	3 dBm
Receiver Sensitivity	-101 dBm
Link Budget	104 dB
Sleep Current	0.02 µA
RX Current	12.3 mA
TX Current	14 mA
Data Rates	250 kb/s to 2 Mb/s
Hardware AES Module	
2.4 GHz	
802.15.4, Zigbee, 6LoWPAN	
Antenna	SMA connector or built-in Chip Antenna
Chip Antenna Test Range	TBD
SMA (“rubber duck”) Antenna Test Range	TBD

For more information see the AT86RF231 datasheet:

http://www.atmel.com/dyn/resources/prod_documents/doc8111.pdf

A.4. Microwave sensor datasheets

The following datasheets are datasheets for the microwave sensors mentioned in section 3.2.1.

298687D
04/16

BIRCHER Reglomat

ENGLISH

Herkules 2

Microwave motion detector for industrial doors

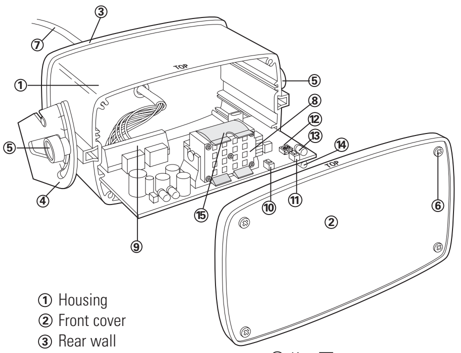
Translation of the original operation instruction

1 Safety instructions

The unit may only be operated from a protection low-voltage system with electrical separation. The unit may only be opened and repaired by the supplier.
Never touch any electronic components of the detector

2 Description of the detector

Herkules 2
Microwave motion detector
for industrial doors



① Housing
② Front cover
③ Rear wall
④ Mounting bracket
⑤ Fastening
⑥ Cover screws
⑦ 8-pin cable
⑧ Microwave planar module
⑨ Screw terminal
⑩ Key X
⑪ Key Y
⑫ Switch addressing
⑬ LED red
⑭ LED green
⑮ Clip

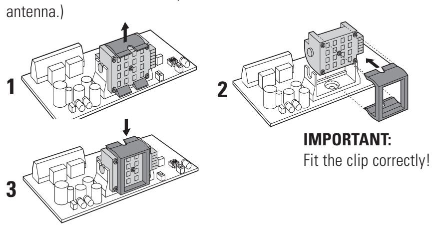
3 Mounting

3.1 Before Mounting

People/Vehicle Identification: Choose whether differentiation between people and vehicles is desired. If so, the minimum mounting height of the sensor is 3 meters!

Field geometry: Select whether a narrow or wide field geometry should be used. The clip must be used for the wide field.

Note:The clip can be used for mounting heights up to max. 4 m. It is not mounted on delivery. (However, it is stuck onto the rear of the antenna.)

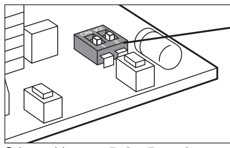


IMPORTANT:
Fit the clip correctly!

4 If the device is already connected, interrupt the power supply for 5 seconds.

5 After mounting, activate the wide field with the remote control (B+1).

Addressing: Each detector can be assigned an address (1–4 with DIP switch and 5–7 with remote control). Different addresses are necessary when several detectors are within the range of a remote control.



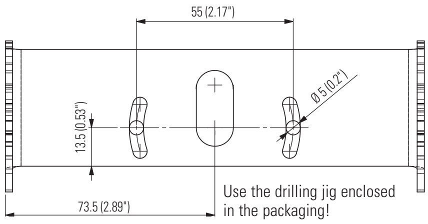
Adress 1*	ON 1 2
Adress 2	ON 1 2
Adress 3	ON 1 2
Adress 4	ON 1 2

* Factory setting

Other addresses 5, 6 + 7 can be set using the remote control (F+8+5…7)

3.2 Mechanical mounting

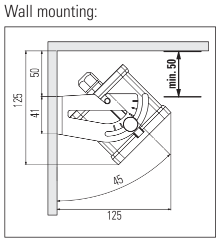
- The detector must be firmly mounted on a flat surface. (Avoid vibrations)
- Objects such as plants, flags, fans etc. must not protrude into the detection area.
- The detector must not be obscured by covers/signs
- Fluorescent lamps should not be placed in the immediate vicinity of the detection area
- Mount the device in the middle above the industrial door



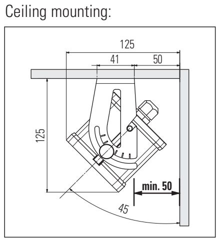
Use the drilling jig enclosed in the packaging!

1. Affix drilling jig to wall or ceiling and drill holes according to values given.
2. Route cable through opening provided in mounting bracket and make sure length is sufficient for wiring.
3. Screw mounting bracket on tightly
4. Hook detector into mounting bracket and set detector to required angle. Standard angle: 30°
5. Connect cable according to type plate.

Wall mounting:



Ceiling mounting:



Page 1

6 Troubleshooting

Symptom	Possible cause	Remedy	Refer to chapter
Industrial door reverses	Detector detects industrial door	Change the inclination angle of the microwave module	4.4
Industrial door opens – false tripping	Interference source affects microwave field (e.g. fluorescent tubes)	Activate the interference suppression filter (F6+1)	5.17
Late detection or non-detection of persons	Field is too small, incorrect mounting height set	Check the field size (D1…9). Set the correct mounting height (F4+1…7). Check setting for wide field.	5.10 5.8 5.15
P/V identification does not function	Incorrect mounting height entered	Set the correct mounting height (F4+1…7). Check setting for wide field.	5.8 5.15

7 Technical data

Technology	Doppler radar with planar module
Transmitting frequency	24.05 – 24.25 GHz
Transmitting power	< 20 dBm
Operating voltage	12–28 VAC, 12–36 VDC
Operating current	max 75 mA
Mains frequency	50 Hz
Temperature range	–30° bis 60° C
Air humidity	0% to 95% relative, without condensation
Mounting height	2.0 bis 7 m
Relay outputs	Potential-free changeover contacts
Switching voltage	max 48 VAC/DC
Switching current	max 0.5 A AC

Housing	Aluminium black anodized, Cover Polycarbonat
Dimensions	134 x 82 x 75 mm
Weight	720 g incl. cable
Protection class (EN 60529)	IP 65
Max. detection speed	25 km/h for vehicles
Cabel	Length 5 m, 8 x 0.14 mm^2
Suitable for the following countries	EU, EFTA, US, CA
Field dimensions with 30° inclination	from 2.5 m x 3 m (WxD) height 2 m to 5 m x 7 m (WxD) height 7 m

8 Conformities

8.1 EC-Declaration of Conformity

Manufacturer:	Bircher Reglomat AG, Wiesengasse 20, CH-8222 Beringen
Authorised rep:	Bircher Reglomat GmbH, Robert Bosch Strasse 3, D-71088 Holzgerlingen
Following directives have been observed:	RoHS 2011/65/EU, R&TTE 1999/5/EC until 12.06.2016, RED 2014/53/EU starting 13.06.2016
Signee:	Head of Sales & Marketing Damian Grand / Head of Operations Daniel Nef, CH-8222 Beringen
Product variant:	Herkules, Herkules 2, Herkules 2S

8.2 FCC approval

This device meets the requirements of Part 15 of the FCC regulations and the RSS-210 standard of Industry Canada.

Warning: Changes or modifications made to this equipment not expressly approved by Bircher Reglomat AG may void the FCC authorisation to operate this equipment.

9 Warranty and liability

1. The warranty and liability of Bircher Reglomat AG are based on the sales contract.
2. The warranty and liability shall expire prematurely, should the client or third parties not use and/or operate the product in compliance with existing operating instructions, should incorrect changes or repairs be made by the client or third parties, should the client or third parties, when a fault has occurred, not take suitable steps at once for a reduction of possible damage/losses and offer Bircher Reglomat AG a chance for remedying the said fault.
3. The warranty and liability shall exclude any damage for which there is no proof that it is due to poor materials, faulty construction, poor workmanship, and any damage caused by other reasons, for which Bircher Reglomat AG cannot be held liable.
4. No liability can be assumed for any consequential damage, provided this is not governed otherwise by applicable product liability laws and regulations.
5. Warranty claims made against the seller on the basis of the sales agreement are not affected by these regulations.
6. For the benefit of its customers Bircher Reglomat AG constantly develops its products further. Bircher Reglomat AG reserves the right to make changes to any of the products described in this document without prior notice.

10 Contact

Bircher Reglomat AG
Wiesengasse 20
CH-8222 Beringen
www.bircher-reglomat.com

Certified Management System SQS ISO 9001

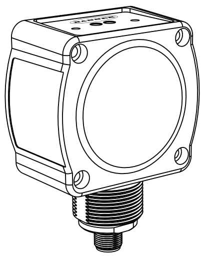
Page 8

R-GAGE® QT50R-AFH Sensor

more sensors, more solutions

Datasheet

Radar-Based Sensors for Detection of Moving and Stationary Targets



- FMCW (true-presence) radar detects moving and stationary objects
- Higher sensitivity and longer range
- Adjustable sensing field — ignores objects beyond setpoint
- Easy setup and configuration of range, sensitivity, and output with simple DIP switches
- Sensing functions are unaffected by wind, falling rain or snow, fog, humidity, air temperatures, or light
- Sensor operates in Industrial, Scientific, and Medical (ISM) telecommunication band
- Rugged IP67 housing withstands harsh environments

Protected by US patents

CAUTION: Make No Modifications to this Product

Any modifications to this product not expressly approved by Banner Engineering could void the user's authority to operate the product. Contact Banner Engineering for more information.

WARNING: Not To Be Used for Personnel Protection

Never use this device as a sensing device for personnel protection. Doing so could lead to serious injury or death. This device does not include the self-checking redundant circuitry necessary to allow its use in personnel safety applications. A sensor failure or malfunction can cause either an energized or de-energized sensor output condition.

Models

Models[1]	Maximum Range	Connection	Supply Voltage	Telecom Approval[2]	Output
QT50R-US-AFH	24 m (78 ft)	5-wire 2 m (6.5 ft) Integral cable	12 to 30 V dc	Telecom approved for US, Canada and Brazil	Bipolar NPN/PNP DIP-switch-selectable N.O. or N.C.
QT50R-EU-AFH				Telecom approved for Europe, UK, Australia, New Zealand, China, and Japan	
QT50R-KR-AFH			12 to 24 V dc	Telecom approved for South Korea	
QT50R-TW-AFH			12 to 30 V dc	Telecom approved for Taiwan	

[1] Cabled models only are listed. For integral 5-pin Euro-style (M12) quick-disconnect fitting, add suffix "Q" to the model number (e.g., QT50R-xx-AFHQ). QD models require a mating cordset; see *Quick Disconnect (QD) Cordsets* on page 6.
[2] For additional countries, contact Banner Engineering.

Original Document
162359 Rev. G

17 August 2016

162359

Specifications

Range
The sensor is able to detect a proper object (see Detectable Objects) from 1 to 24 m (3.3 to 78.7 ft), depending on target

Detectable Objects
Objects containing metal, water, or similar high-dielectric materials

Operating Principle
Frequency modulated continuous-wave (FMCW) radar

Operating Frequency
US, TW Models: 24.075–24.175 GHz, ISM Band
EU, KR Models: 24.050–24.250 GHz, ISM Band

Maximum Output Power
ERP: 3.3 mW, 5 dBm
EIRP: 100 mW, 20 dBm

Supply Voltage
12 to 30 V dc, less than 100 mA, exclusive of load
For KR models: 12 to 24 V dc, less than 100 mA exclusive of load

Supply Protection Circuitry
Protected against reverse polarity and transient overvoltages

Delay at Power-up
Less than 2 seconds

Output Configuration
Bipolar NPN/PNP output, 150mA; DIP switch 6 selects N.O. (default) or N.C. operation

Output Protection
Protected against short circuit conditions

Response Time
DIP switches 7 & 8 select ON/OFF response time

Indicators
Power LED: Green (power ON)
Signal Strength LED: Red, flashes in proportion to signal strength. Steady on at 4x excess gain. Only indicates signal amplitude, not target distance.
Output LEDs: Yellow (output energized) / Red (configuration)
See *Figure 2* on page 2

Adjustments
DIP-switch-configurable sensing distance, sensitivity, response time, and output configuration

Construction
Housing: ABS/polycarbonate
Lightpipes: Acrylic
Access Cap: Polyester

Operating Temperature
−40 °C to +65 °C (−40 °F to +149 °F)

Environmental Rating
IEC IP67

Connections
Integral 5-wire 2 m (6.5 ft) cable or M12 Euro-style QD fitting. QD models require a mating cordset

Certifications
CE
ETSI/EN 300 440
FCC part 15
RSS-210
ANATEL Category II
CMIIT Category G
ARIB STD T-73
KC mark - MSIP/RRA
NCC
for others, contact Banner Engineering
Country of Origin: USA

FCC ID: UE3QT50RUS—This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) this device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

IC: 7044A-QT50RCA—This device complies with Industry Canada license-exempt RSS standard(s). Operation is subject to the following two conditions: (1) this device may not cause interference, and (2) this device must accept any interference, including interference that may cause undesired operation of the device.

Cet appareil est conforme aux CNR exempts de licence d'Industrie Canada. Son fonctionnement est soumis aux deux conditions suivantes:(1) Ce dispositif ne peut causer des interférences; et(2) Ce dispositif doit accepter toute interférence, y compris les interférences qui peuvent entraîner un mauvais fonctionnement de l'appareil.

Modelo: QT50R*****(*)
0385-11-4042
ANATEL

Este equipamento opera em caráter secundário, isto é, não tem direito à proteção contra interferência prejudicial, mesmo de estações do mesmo tipo e não pode causar interferência a sistemas operando em caráter primário.

SRD24-IO3B24100.2TR0.1 South Korea Class A Certification
A 급 기기 (업무용 방송통신기자재)

이 기기는 업무용 (A 급) 으로 전자파적합기기로
서 판매자 또는 사용자는 이 점을 주의하시기
바라며 , 가정외의 지역에서 사용하는 것을 목
적으로 합니다 .

Operating and Control Function Specifications

Note: When using the MWX-LVE180U with the Lumewave TOP900 Wireless Lighting controller, access to many Bluetooth controlled functions are limited as the Lumewave TOP900 controller handles these functions. In this case, the MWX-LVE180U is a long range motion sensor and active functions are highlighted below.

- Operating Voltage: 12Vdc (To be powered by UL listed Class 2 Power Source)
- Current: 60ma single sensor, 120ma dual direction
- Set Sensor Sensitivity: Direction A and/or B = High, Med, Low, Disable (individually)
- Set Motion Filter: Pedestrian and Vehicle
- Set Low Level Output: 5% – 50% (.50 – 5.0V)
- Select High Level Output: 50% – 100% (5.0 – 10V)
- Set Bi-Level timeout: 2, 5, 10, 15, 20, 25, 30 minutes
- Tri-level timeout: (Cutoff) 30, 60, 90, 120minutes
- Photo cell control: Enable/Disable, Dual light detectors. Automatic differentiation between sensors
- Neighbor Control Enable/Disable: Shares motion detection with other units within range for neighbor control
- Mechanical Noise Cancellation: Signal analysis cancels out non adar (mechanical) movement signals
- Test Enable/Disable Test function with automatic timeout
- Inactivity Timeout 5, 10 minutes
- Environmental: IP 65
- Certifications: FCC
- 5-year limited warranty*

Detection Range at 20’ or 30’ Mounting Height

- Range dependent on size and speed of target
- Pedestrian: 100’
- Small Vehicle: 165’
- Full size SUV: 200+
- Truck or Bus 400+

Microwave (FFT Doppler based) Sensor

- Radar frequency: X Band, 10.250Ghz
- Power Output/Direction +17DBM, 50mw
- Power at 12Vdc 60ma/sensor/direction. 120ma when 2 sensor directions are active
- Detection Direction Single or Dual
- Filters/ Detects pedestrian and traffic movement together or individually (Selectable)
- Detection processing FFT simultaneously detects speed of pedestrian and traffic in real-time

MWX Power Pack

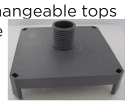
- Operating Voltage: 120 – 277Vac 50/60Hz
- Power switching: 10A, 277V General Purpose or Ballast
- Dimming Control: 0-10V (Sink or source)
- Size 3.50”X 2.50” x 1.00”
- Plastic UL 5VA Flame Retardant ABS, 3mm
- IP 65
- UL Listed

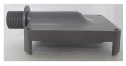
Control Configurations

- MWX-LVE-180U (2-Way) Microwave Sensor w/4-wire interface to Lumewave Controllers
- MWX-LVE-180U (2-Way) Microwave Sensor + MWX-PP (Smart Power Pack)
- Use Smart Power Pack for stand-alone fixture control

Sensor Mounting Configurations

- Mounting: 2 interchangeable tops supplied to provide multiple mounting configurations
- Mounting via vertical NTP 1/2” threaded nipple
- Mounting via right angle NTP 1/2” threaded nipple





A.5. Application software for XBee and Teensy

Full manual for XCTU can be found at: `https://www.digi.com/resources/documentation/digidocs/PDFs/90001458-13.pdf`(Accesed May 13, 2017)

Manual for Arduino IDE can be found at: `https://www.arduino.cc/en/guide/environment`(Accesed May 20, 2017)

XBee API mode library file for Arduino IDE: `https://github.com/andrewrapp/xbee-arduino`(Accesed May 20, 2017)

A.6. Project management - work schedule

This is a tentative work schedule; all dates are subject to change other than project hand in on May 22 and project presentation date on May 29-31. Table A.12 provides a schedule for the project. More details can be found on the Gantt chart in figure A.1

Table A.12: Time schedule

Task	Duration	Start	Finish
Wireless protocol research	15 days	02/01	17/01
WSM research	10 days	18/01	28/01
Buying nodes	2 days	29/01	31/01
Programming	50 days	01/02	22/03
Trigger circuit design	10 days	23/03	02/04
Testing and optimization	10 days	03/04	13/04
Project report	41 days	14/04	19/05
Total	138 days	02/01	19/05

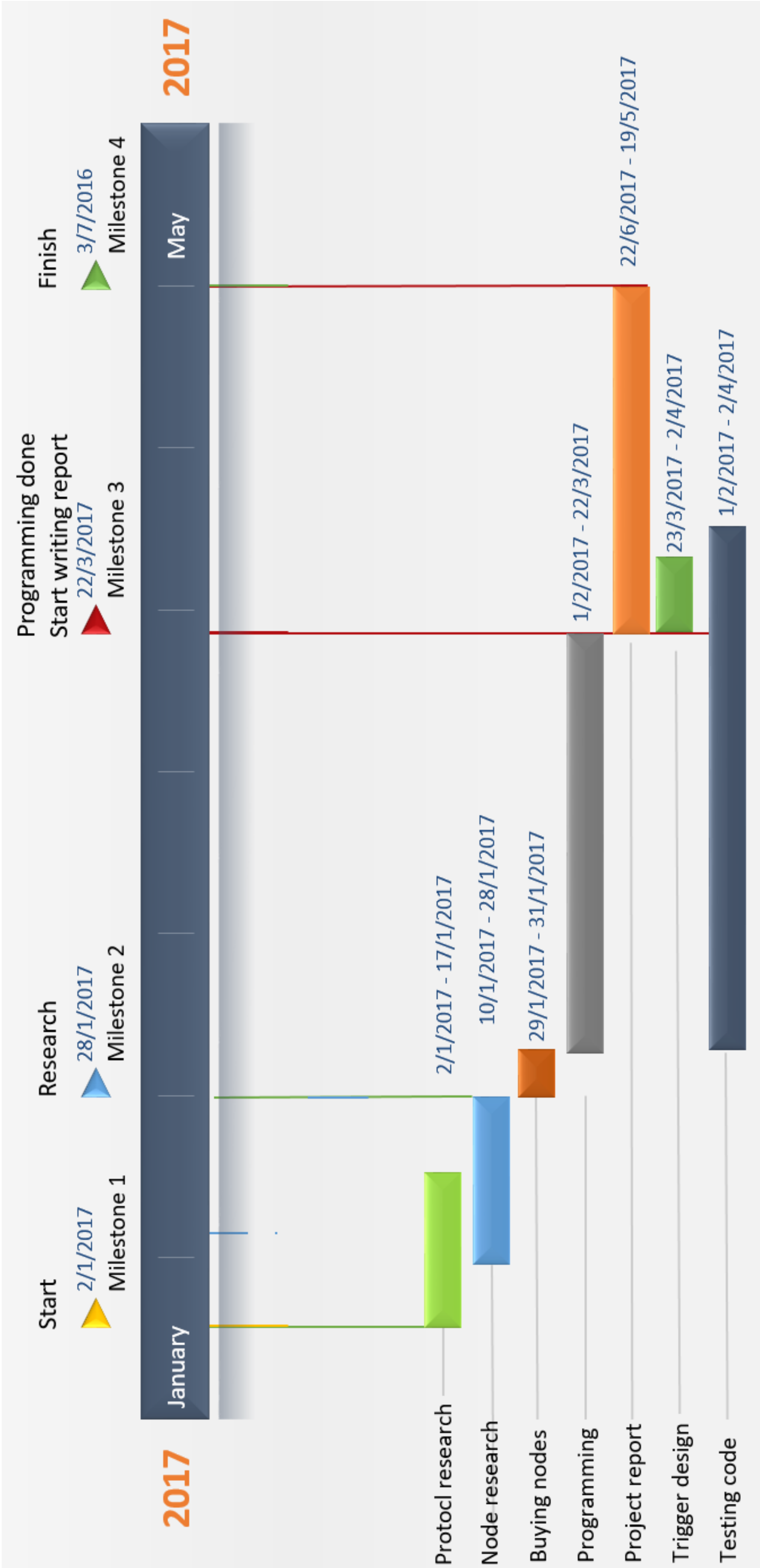


Figure A.1: Gantt work schedule