Smart City Street Lighting System

An Engineering Internship at Eco-FX LED

Smarter LED Lighting Solutions

Prepared by Janarthan Sri Kantha

Submitted to the School of Engineering and Information Technology, Murdoch University

Academic Supervisor: Dr Graeme Cole

Industry Supervisor: Nigel MacKay

November 2015

This page has been intentionally left blank

Abstract

This final year honours thesis project was undertaken with Eco-FX; it involved consulting, designing and developing their new Smart City Street Lighting System.

Smart Street Lighting utilises wireless control and monitoring to produce a more energy efficient and sustainable street light system. Previously, the technology and the wider community were obstacles in its development; presently with advancement in wireless low data rate protocols and support from the Western Australian Local Government Association, the development of the system is approaching its completion.

To consult on the design and development for this project required vast amounts of research about the existing lighting technologies, public utilities and low data rate wireless protocols. The methodology was to research and evaluate all protocol and hardware technologies available. These technology options were presented to the relevant stakeholders for discussion; and then the final design specification was approved.

The ZigBee protocol met final design specifications and requirements for Eco-FX; therefore the ZigBee Alliance was contacted to find the best approach in designing to their standard. After the guidance from the ZigBee Alliance, more research was conducted on the hardware and the services required for implementing the Smart City Street Light System.

The final stage in the project was finding manufacturers and designers for the required hardware and software to develop the system in China. The previous research and evaluation provided guidance in specifying to the manufacturer and designer all the critical features required by Eco-FX in the system; and ensured all Australian and international standards were met in the manufacturing and designing process.

Acknowledgements

I would like to thank Eco-FX for providing me with opportunity to consult and design their smart street light solution as my honours project. I acknowledge that Nigel MacKay placed a great deal of trust in a graduate engineer to lead the development of this system and the guidance and support he demonstrated was next to none. I am grateful to him for the exposure to all aspects of this project. I was invaluably assisted in everyday activities in the office by Danni Yang; undoubtedly I could not have communicated with China or read certain documents without her ability to translate.

I would like to recognise the contribution and help that Anser Technical provided. Amish Sheth was a wealth of knowledge about the compliance and engineering requirements for a system to be implemented on to the Western Power and Horizon grids. Garry Chong's knowledge on business practices of the power distributors and WALGA, also assisted me in this project.

I would like to thank WALGA for assisting me in my thesis project; more importantly Andrew Blitz and Stuart Downing who explained the history and the nature of ownership of utilities in Western Australia, and the importance of asset management in local government.

Thank you to Mark Sumich from Nova Legal, whose pro bono legal advice regarding the certification, licensing and intellectual property protection of the system was greatly valued.

Thank you to Professor Graeme Cole for his time and guidance during my honours project. Regardless of his enormous workload, Professor Cole was always very accommodating to give me feedback and advice when I required it.

Finally and most importantly, I would like to thank my family; my incredible partner Debbie and beautiful daughter Addison. Their support and understanding during my degree and internship have been outstanding. My success is attributed to both of you.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

µA	Microampere
AC	Alternating Current
ADC	Analogue to Digital Converter
ADSL	Asymmetric Digital Subscriber Line
AES	Advanced Encryption Standard
APL	Application Layer
ASK	Amplitude Shift Keying
BPSK	Binary Phase Shift Keying
CAP	Contention Access Period
CCA	Clear Channel Assessment
CMS	Control and Monitoring System
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CS	Carrier Sense
CSMA-CA	Carrier Sense Multiple Access Collision Avoidance
dBm	Decibels to one milliwatt
DC	Direct Current
DLL	Data Link Layer
DSSS	Direct Sequence Spread Spectrum
ED	Energy Detection
EDGE	Enhanced Data GSM Evolution
FFD	Full Function Device
GB	Gigabyte
GPIO	General Purpose Input or Output
GPRS	General Packet Radio Service
GPS	Global Positioning Satellite
GSM	Global System for Mobile Communications
GTS	Guaranteed Time Slot
HART	Highway Accessible Remote Transducer
HSDPA	High-Speed Down-link Packet Access
HSPA+	Evolved High-Speed Packet Access

Hz	Hertz
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IoE	Internet of Everything
IoT	Internet of Things
IP	Ingress Protection
IPv6	Internet Protocol version 6
ISM	Industrial, Scientific and Medical
ISP	Internet Service Provider
kB	Kilobyte
Kbps	Kilobits per second
LED	Light Emitting Diode
LLC	Logical Link Control
LQI	Link Quality Indicator
LR-WPANs	Low Rate-Wireless Personal Area Networks
LTE	Long Term Evolution
mA	Milliampere
MAC	Media Access Control layer
Mbps	Megabits per second
MCU	Micro Controller Unit
mm	Millimetre
NBN	National Broadband Network
NWK	Network Layer
OQPSK	Offset Quadrature Phase-Shift Keying
OSI	Open Systems Interconnection
PAN	Personal Area Network
PCB	Printed Circuit Board
PHY	Physical layer
PROM	Programmable Read Only Memory
PSD	Signal Power Spectral Density
PSK	Phase Shift Keying
PSSS	Parallel Sequence Spread Spectrum
PWM	Pulse Width Modulation

QPSK	Quadrature Phase-Shift Keying
RAM	Random Access Memory
RF	Radio Frequency
RFD	Reduced Function Device
RX	Receive
SCSLS	Smart City Street Lighting System
SEA	Sustainable Energy Association of Australia
SNR	Signal to Noise Ratio
SPI	Serial Peripheral Interface
T/R	Transmit or Receive
TI	Texas Instruments
UART	Universal Asynchronous Receiver/Transmitter
V	Volts
WA	Western Australia
WALGA	Western Australian Local Government Association
WiMAX	Worldwide Interoperability for Microwave Access

1 Introduction

1.1 Project Scope

As the final component of the Bachelor of Engineering in Industrial Computer Systems and Electrical Power degree at Murdoch University, a honours thesis project is required to be undertaken in the relevant field of study. This provides students the opportunity to practically apply and demonstrate the knowledge gained during their degree. The knowledge and experience gained through undertaking the honours project provides invaluable exposure to the engineering tasks required in commercial projects, such as analysis, design, testing and management.

This project was undertaken from July to November of 2015 at Eco-FX Smarter Light Emitting Diode (LED) Lighting Solutions ("Eco-FX"), where a new smarter street lighting system was designed and developed for deployment preliminarily into Western Australia municipalities. An initial plan was generated by the student for this project indicating the tasks and scope of the project. The intern is periodically required to meet deadlines for tasks outlined in the project plan; this indicated the project progress and provided transparency of any deviations of the project plan to the supervisor. The final components of the internship were to deliver a final presentation and submit a formal report about the work undertaken by the intern during placement at Eco-FX.

1.2 Eco-FX LED Australia

Established in 2011, Eco-FX is a private Australian company in East Victoria Park that delivers innovative and sustainable lighting solutions using high quality, low energy and cost effective LED technology. Eco-FX provides lighting solutions for industrial and commercial applications such as streetscapes, landscapes, sporting, architectural and medical.

Eco-FX uses state of the art chipsets in their LED products to meet Australian standards and their products were awarded SAA certification. Eco-FX's high level of compliance has led to the company being granted membership to the Sustainable Energy Association of Australia (SEA) and listed as a preferred supplier of the Western Australian Local Government Association (WALGA) and Government of Western Australia Office of Energy.

Some of the notable projects undertaken by the company to date are WALGA head office, Kingsway shopping centre, Water Corporation, IBM centre, Shire of East Pilbara, Newton Quindalup boat ramp, Southern Metropolitan regional council and Canning waste services [1].

Eco-FX provides whole of life lighting services to meet the customer's difficult lighting needs. These services include light load survey assessments, luminaire reports, DIALux or AGI32 lighting simulations and design, installation and maintenance [1].

1.3 Smart City

Smart City solution is a worldwide paradigm for the integration of all urban infrastructures via Internet of Everything (IoE). The smart grid is a combination of wired and wireless communication networks that can control and monitor the Smart City Street Lighting System (SCSLS) and other systems. The most effective method to implement a wireless smart grid is via elevated structures that optimise the wireless signal. Streetlights are the obvious abundant elevated structures in an urban environment; additionally they are owned and operated by the government. Therefore Smart Streetlights have the ability to control and monitor all domestic and commercial residences with Smart Meters to collect power, water and gas meter readings. The system has the ability to control Smart Street Signs and monitor Smart Parking for better traffic management. Additionally, the system has the ability to update public transport users at the Smart Bus or Tram Stop about the location of their buses or trams, and connect Smart charging stations for electric cars.

The Smart City solution has the ability to connect people, data and things via one process or network. The SCSLS will be used as the information pathways of the Smart City solution; the streetlights can connect all nodes mentioned above to one or more Control and Monitoring System's (CMS) and distribute the information to the relevant organisations to disseminate to their users. The Smart City system can use existing Information and Communication Technologies (ICT) as the backbone and the Internet to transfer the collected information from the wireless smart grid to the CMS software.

Existing Smart City pilot systems for controlling street lights utilise hobby and off the shelf componentry, such as Beagle bone and Raspberry-PI to implement the control and monitoring. These microcontrollers are capable of performing the tasks, but are expensive and bulky to implement in a commercial system [2]. The Eco-FX SCSLS is the only system to integrate other services, such as surveillance, public transport and smart metering; therefore the SCSLS has an original and tailored software solution to utilise its features and meet customer solutions. Most other systems on the market have a simpler framework due to the small scale of their system [3], the SCSLS will be designed with scale in mind, it will be implementing a cloud server service that will allow for quick expansion of capacity, and remote access by multiple devices anywhere in the world.

WALGA in partnership with Eco-FX and Anser Technical are working towards providing a uniform Smart City solution for Western Australia (WA) local governments to transition from traditional to intelligent technologies. This solution will enable local government and various other organisations to utilise it to improve the transfer of information, sustainability of public, working and living spaces and energy consumption. Ultimately the benefit will be financial; as the technology has become more widespread the saving for the government organisations out strips the capital expenditure.

2 Background of WA Street Lighting Systems

One of the major hurdles in achieving a sustainable and greener future is the production of energy, especially during the periods when the sun is absent. An alternative solution to generating for the baseload demand is to reduce the baseload demand by innovative new processes and devices and altering mindset to reduce the hunger for power. SCSLS integrates new and existing technologies to provide an affordable power saving solution. SCSLSs achieve greater performance by integrating digital street lights such as LEDs with embedded control systems and a CMS. The system must have the flexibility to be adapted to new and existing deployments of grid and solar powered street lights.

The development of the SCSLS to control and monitor street lights will enable safer, efficient and more reliable street lighting. The improvement of technology will enable huge financial savings; one example is the reduction of power consumption by over 50% and in turn reducing carbon emission [4]. The system will employ low data rate technologies to keep the system true to its ethos, and to enable integration into power critical solar powered street light deployments. The system will be of capable of controlling thousands of devices using a wireless protocol standard; therefore the system will employ a standard that can provide interoperability between multiple different end devices and manufactures. The standard will provide a secure and robust platform to develop the Smart City System.

The SCSLS should retrofit the existing street poles which are more sustainable and cost effective. Using LED lights which don’t require warm up time and they are not manufactured using toxic chemicals compared to high-pressure sodium or mercury vapour lights is another benefit of the system [4]. Also LED lighting can last up to 8 times longer reducing maintenance costs and increasing the reliability of the system [5].

In addition to the environmental and financial benefits, the SCSLS will produce a more ergonomic lighting system by dimming lights remotely and independently, in turn reducing light intrusion to neighbouring properties and light pollution in the night sky. The system will allow the lighting to be tailored for other properties or areas which may require full power lighting at certain periods of the night. As the system uses LED technology, it will produce white light which is dimmable and directional and is more effective in colour discrimination and illuminating in public spaces and roads compared to its predecessors.

In most cases the existing lighting systems in WA do not meet Australian Standards as these installations were done some decades ago. Therefore the new smart lighting systems are not just nice to have, but they are a mandatory requirement in most cases. The Australian lighting standards AS/NZS 1158 stipulate good lighting is required to reduce car and pedestrian accidents on public spaces and roadways [6]; Western Australian government reports have shown that good street lighting gives reassurance to the public and reduces crime and the fear of crime in public space [7].

Due to the factors outlined above, street lighting is recognised as a core business of WALGA. Local governments require Smart City Street Lighting solutions to free up financial and maintenance resources in order to address other community needs. Street lighting consumes one third of local government's total energy expenditure. This expenditure is even more significant considering that the tariffs in Western Australia have risen by 100% since 2007/08, and it is estimated to rise again by 37% in 2015/16. The tariff is currently estimated to cost local government $40 million per annum and rise by $15 million by 2015/16 [5].

On the issue of environmental impacts of street lighting on local governments, the Shire of Capel estimated that street lights contributed as much carbon dioxide (CO_2) emissions as all of their council's facilities and fleet combined [8]. A caveat on these estimations must be disclosed and it highlights another issue local government face, all estimates on energy consumption and emissions are collected and gathered via information from the distributors. The distributors are Western Power and Horizon Power, these distributors connect and distribute electricity to businesses and domestic residents. However they aren't electricity retailers or producers; that role is filled by Synergy.

All three of these corporations are state government owned and run. Western Power has control of the South West Interconnected System (SWIS), which consists of 90% of the street lighting in WA. Horizon is in control of the North West Interconnected System (NWIS) and consists of regional and remote locality networks. The transparency of pricing, amount of the electricity used and maintenance costs to local government from these organisations is limited due to the regulatory environment in place in WA. Additionally, the non-contestability of the infrastructure in WA doesn't allow others to connect street lights to the distributor's poles. These barriers to fitting energy efficient lighting to existing assets have slowed the evolution of street lighting in WA. However, new public assets can be owned and operated by local government and these assets are the initial targets for the SCSLS deployments.

Local government are enthusiastic to deploy the SCSLS on the poles that they own and operate, as there is a slow response to their request for the LED street lighting from Western power. Western Power's response to local governments request for more sustainable lighting is the replacement of Mercury and Sodium vapour lighting with the Compact Fluorescent Lamps (CFL), which is a product that will be illegal to fit to the SWIS network according to the Minamata Convention on Mercury [9]. Western power have begun testing LED technology for street lights with a supplier, but to date have not released a LED product into their product line up for replacement of traditional street light technology. Horizon has released a LED product into their product line up and has begun retrofitting selected areas with the LED street lights.

As the distributors are moving towards LED lighting technology at varying speeds, there also exists a barrier in innovating improved energy efficient lighting with the Australian Standards, as all older lighting technology luminaries are outlined in AS/NZS 1158.6 " Lighting for roads and public spaces Part 6: "Luminaries", but LED technologies are absent. The Australian Standards have been advocated by WALGA to align closer to the International Electrotechnical Commission (IEC) standard 60598-2-3 "Luminaries for roads and street lighting" which include LED technology. Clear and defined standards are imperative for the development, design and installation of the SCSLS to be compliant.

With distributors and Standards Australia moving towards LED technology, the SCSLS must comply and meet the needs of all stake holders. The SCSLS must be at a price point that does not pose another barrier to the adoption of the technology. For instance the control and monitored LED lights and systems should be price competitive with the existing LED technology. The task is easier than expected as a reduction in maintenance cost can be offset against the price of the smarter street lighting system. The monitoring of the street lights can locate lights that are not operational and councils are not reliant on the public or contractors to find or search for unserviceable street lights. The smarter street lights can also provide the contractor with valuable information by identifying what type of fault exists on the light. Additionally the control feature can reduce the illumination level of the street lights during certain periods of the light, which will consume less energy that the conventional LED light, which also can be used to offset against the price of the SCSLS.

The monitored system lights can also provide the councils with valuable information about the consumption of energy by each light. This information produces a higher level of transparency about the cost of energy and maintenance and the emissions created due to the system. This information can be used to calculate a fairer state government tariff for LED street lights, which could be financially beneficial to local government. The information gathered by the SCSLS can be bulky and hard to decipher. Therefore the system must also incorporate an interface for the back of office use with multiple user levels for different local government departments.

The technology must also be a tested to be reliable, integrable and secure to meet the demands of a critical public utility system. The system's reliability is paramount as there is great scepticism and opposition by some organisations towards the system, methodical testing and research on the system is critical for wide spread acceptance. Security is a key issue in designing a wireless system, especially when implementing it for a public utility which may have other critical utilities sharing its smart grid. The system must be physically tamper proof and have appropriate security encryption for transmission of information over radio frequencies. An integrable system is another very tricky issue because as technology evolves, there will undoubtedly be new wireless standards and technologies that are superior in certain aspects than the chosen standard. The chosen technology and standard must be able to keep pace with the dynamic Smart City environment.

3 Project Objectives

The following project objectives were gathered from several meetings with customers, contributors and research papers. The objectives outline the features required in the SCSLS. Primarily the SCSLS must have the ability to control and monitor street lights. The key requirements of the system are:

- illumination control of the luminaire,
- incident management and
- power consumption monitoring.

Illumination control will allow the system to control the on/off state of the luminaires and the luminance level of the luminaire for peak and off-peak periods. This control should be applied to individual or sections of luminaires to tailor the most ergonomic environment.

Incident management will provide monitoring of luminaires to display which luminaires require maintenance and the type of maintenance that is required. If total communication failure has occurred, a driver or communication module may require replacement. If the power consumption of the luminaire is anomalous then the LED luminaire may require replacement or repair. If the power quality from the power grid to the luminaire has changed, then the distributor will need to be contacted to test and rectify the issue.

Power consumption monitoring will allow local governments to conduct more effective and accurate consumption audits on all or part of the street light system. The system will enable the tariffs imposed on the power to be modified by the distributor to best represent the usage by the SCSLS.

In addition to the functional requirements, the technologies employed in the system must be proven to be robust, reliable, secure, low power and affordable to carry information to and from the SCSLS and other Smart systems for other utilities.

4 Project Overview

This project was written for an audience that has knowledge of electrical, electronic and computing hardware and software. Some information about the device profiles and protocol stacks used for the microcontrollers have been omitted or limited to protect intellectual property of Eco-FX. A breakdown of the project is outlined below.

The SCSLS is designed to control street light luminaires from a remote and central position. To implement the control and monitoring on the street lights, research into the components of street lights and the SCSLS was conducted. Each section of the project will outline a component or assembly of the SCSLS and how the component or assembly effects the implementation and the requirements for effective implementation of the SCSLS.

The street light luminaires will be connected to the drivers; the drivers convert AC to DC to power the luminaires. The drivers will be controlled by a unit which includes the microcontroller and transceivers. This unit will use a low rate wireless technology to transfer data from each street light to the central point in the street. The central point will control gather data from several street lights and use a modem to connect to the internet. The data will be stored and processed in a cloud based server system for a back office system. The back of office system will be located in a remote location where different users can monitor and control the SCSLS.

Section 4 Luminaire Design - A brief explanation of the design of the LED luminaire that will be connected to the system to help understand the final design requirements of the SCSLS.

Section 5 LED Driver Specifications – A brief explanation of the critical requirements of the LED drivers used for the LED luminaire for the system such as configuration and ratings of the components.

Section 6 Low Data Rate Wireless Technology - The different wireless standards researched and analysed for the product are discussed. The evaluation process undertaken and the factors contributing to the preferred standard are outlined. Further information about the chosen standard and its governing organisation is detailed to provide a comprehensive understanding of the requirements necessary for compliance to the standard.

Section 7 Transceiver Modules - All aspects of a generic transceiver are explained in detail. Several manufacturers produce modules and transceivers of the preferred standard; a select number of these are tabulated and compared to find the most suitable for SCSLS. Additionally, the key selection factors for the preferred company and chipsets chosen are explained and justified.

Section 8 Antennas – Available antenna types for the transceivers and what factors influenced the final choice of antenna are outlined.

Section 9 Internet Access – An introduction of some of the ICTs that are available throughout WA to connect the SCSLS to the Internet.

Section 10 Modems - The modem requirements for the coordinator or master poles for different deployments is discussed.

Section 11 Cloud Based Data Management –An explanation of the data management strategies employed to connect the Smart City Street Lights to the CMS.

Section 12 Control and Monitoring Software - The CMS is discussed with the features and design suggested to the manufacturer.

Section 13 Final Design of LED Deployment - The final design of the SCSLS deployment is revealed in this section as well as alternative configurations.

Section 14 Future Works – A discussion of the next stages of the projects and the further research that will be undertaken to advance the system.

5 Luminaires

The luminaires being used in this project are proprietary products from Sansi Technologies, but most other luminaires can be used with modifications to the driver. These luminaires use multiple individual LED modules for cost effective and easy maintenance as shown in Figure 1.

Figure 1: The luminaire to be controlled and monitored by the SCSLS

Each individual module is available with several different lenses to customise the light profile of the luminaire. Each module is wired in parallel with the driver; consequently when individual module fails, the current drawn from the driver will be decreased. Sensing the current flow out of the driver will indicate the number of modules that are operating in the luminaire. As the modules fail, each individual module can be replaced without changing the entire luminaire. This is a more sustainable approach than the traditional LED technology that has all LED chips soldered to a backing Printed Circuit Board (PCB). The luminaire must also be capable of withstanding extreme temperatures and weather experienced in Western Australia. The luminaire must have an Ingress Protection (IP) 65 or IP67 rating for the maximum maintenance intervals according to the AS/NZS 1158.3.1. An ambient temperature 30^{o}C has been proven to heat an enclosure to a temperature above 75^{0}C; therefore the luminaire must also tolerate extremely high temperatures, as an ambient temperature of 40^{o}C is not uncommon in WA [10].

6 LED Driver

According to Eco-FX and Anser Technical, the LED drivers often are the first component of a lighting system to fail. Therefore they need to be researched and designed wisely for the SCSLS. The driver will be the component that absorbs any power quality issues from the grid. The nominal voltage of the grid is 240 Volts (V) Alternation Current (AC), but voltages may vary between 230V and 260V AC in some areas according to Anser technical. In some occasions the flickers, dips or harmonics (fluctuations) may occur too quickly for the tap changing transformers to react to the change. In some rural areas, where a power audit has not been conducted, the fluctuations can overwhelm the tap changing transformer due to unforeseen and unauthorised load changes [11]. Hence all drivers used for the project were specified to have an operation range between 220V and 270V AC and operating frequency of 50 and 60 Hertz (Hz). The downside of this specification is the additional cost incurred to have higher rated drivers.

6.1 Background

The driver steps down the nominal voltage to a regulated 12V or 24V Direct Current (DC) with a constant current of 0 to 2A depending on the luminaire's LED modules. The usual method of stepping down the voltage is to use a buck mode of a switch mode power supply also known as a buck converter. The buck converter provides a greater efficiency and it regulates the voltage to a higher degree at a lower cost and weight compared to a linear power supply [12]. Incorporating the converter with a transformer can reduce the stress on the semiconductive devices in the converter.

The driver must have a dimming function for the LED luminaire; as well this requires the driver to either reduce the constant current or Pulse Width Modulation (PWM) the current flow to change the state of the LED. The PWM method reduces the illuminance level by modulation of the LED, but the LED modules are still operating with the same voltage and current. The constant current reduction or analogue method reduces the voltage to the LED modules, but the current is difficult to control at the lower current levels and undesirable colour shift occurs. Both methods are acceptable, but the PWM method would be recommended to implement. Some new drivers have both dimming methods in place depending on the dimming control available.

6.2 Action plan

The wireless transceiver will control the modulation rate of the PWM or the constant current level in the driver to control the illuminance of the luminaire [13]. The transceivers required for the wireless networking of this system will either be a separate unit or integrated into the driver casing for simplicity of manufacture and power delivery. In both cases the power will need to be regulated to be stepped down to the voltage requirements of the transceiver.

The driver must have a very low standby voltage. For example, the luminaire in the 'on state' for 11 hours and then in the 'stand by state' for 13 hours. If the luminaire uses 7 W in the 'on state' and 0.5 W in the 'standby state', the power in standby is still substantial [14]. The transceiver and power regulation must be very efficient, as tasks and devices will still consume power during the 'standby state'.

Lastly the driver must be tamper and vandal proof. Even though the IP65 or IP67 rating of the drivers will provide a barrier to accessing the internal components; nevertheless it was highlighted by several local council members at the WALGA Expo that vandalism and unauthorised access into the network must be of paramount concern. Therefore, extra precautions are specified such as a secure metal casing, and including theft proof screws to prevent access to the driver internals.

7 Low Data Rate Wireless Standards

7.1 Background

The initial step in developing the SCSLS is to find a wireless technology that can support the requirements of the network. A low data rate wireless protocol is best suited to this application, as it only transfers a small amount of data and in turn uses very little power. Therefore these standards or protocols can be referred as low power or low data rate. As discussed in the objectives, the wireless standard chosen must be robust, low power, secure, reliable and interoperable.

Furthermore, the technology must support mesh topology to allow for nodes to connect to one and another without the requirement of a central node, as in the traditional star or tree topology shown below in Figure 2. If the central node becomes unserviceable then the nodes surrounding will also become unserviceable.

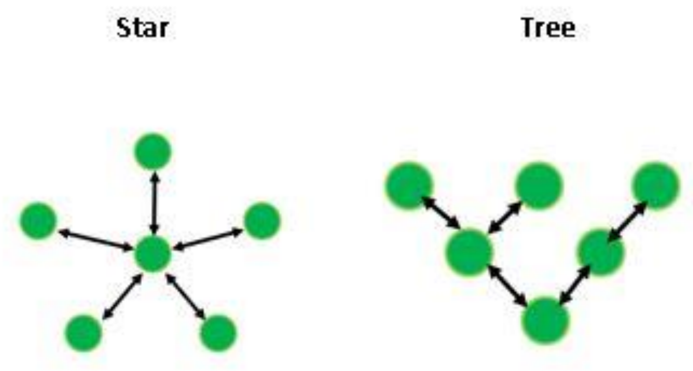

Figure 2 : Star and Tree topology

Mesh topology is recommended for urban environments, where data paths can be dynamically changed and when redundancies are desired. Mesh allows for all devices or nodes to communicate with each other to relay data within the network. This topology allows for nodes to route data by hopping from node to node. When a node becomes unserviceable, unreliable or busy on a signal's shortest data path to its destination, then the network will reconfigure to find the next shortest data path. These features result in increased reliability and capacity in high traffic networks, as multiple nodes can simultaneously communicate compared to other topologies, where only one node can communicate at a time. There are two mesh topologies that are depicted in Figure 3. In the partial mesh topology, each node is connected to some but not all other nodes. In the full mesh topology all nodes are connected to all other nodes. Partial mesh is easier to implement as nodes will only have to communicate with a one or a few of the other nodes depending on the configuration. Only partial mesh can use Reduce Function Devices (RFD) in the network to lower the cost. Full mesh network is more robust, reliable and efficient as all nodes have multiple signal path options; but the topology is harder to Implement and more costly as Full Function Devices (FFD) are used. More information about FFD and RFD is contained in Appendix B.2.

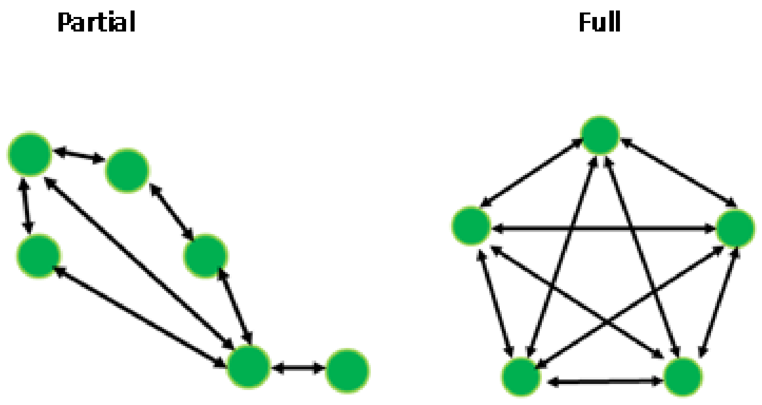

Figure 3: Partial and Full Mesh topology

7.2 Analysis

7.2.1 Unsuitable Wireless Standards

There are several wireless networking standards available, but some are not suitable for this application such as the most commonly used Z -Wave and Bluetooth. These protocols do not use the Institute of Electrical and Electronics Engineers (IEEE) 804.15.4 Low Rate-Wireless Personal Area Networks (LR-WPAN) standard [15], and as a result, they lack certain features required for this project.

The Z-wave signal has no method of mitigating interference by use of a spreading method. The spreading methods will be explained in detail in the analysis of this section. Z-Wave only supports 8 bit addressing. It limits the number of nodes that can be addressed by network to 232 nodes, and the protocol is regarded as insecure for commercial purposes, as it has an older Data Encryption Standard with a key size of 56 bits [16].

Ultra-Low Power Bluetooth also known as “Wibree” is another wireless network standard and is derived from the traditional Bluetooth. However as the name implies the power demands and data rates have been decreased to suit low power applications. This standard is not suitable, as it does not support the mesh topology [17].

7.2.2 Suitable Wireless Standards

The remaining suitable low data rate wireless standards have differing features that need to be evaluated on their suitability for the SCSLS network. All of the following standards-based network protocols are based on the IEEE 802.15.4 standard and use the 7 layer Open Systems Interconnection (OSI) model to define its networking framework. A brief explanation of the OSI model is tabulated in Appendix A if the reader is unfamiliar with the concept.

As these standard-based network protocols are based on the IEEE 802.15.4 standard, the Physical layer (PHY) and Media Access Control layer (MAC) sub layer in the DDL of these protocols will remain the same. The Data Link layer is divided into two sub layers, the MAC and the Logical Link Control (LLC) layer, but the IEEE 802.15.4 only specifies the MAC in the standard. Appendix B briefly explains the key features and requirements of the IEEE 802.15.4 standard; it is recommended reading before continuing further if the reader is unfamiliar with wireless technology.

The IEEE 802.15.4 standard also supports three forms of communication mechanisms: broadcast, multicast and unicast. A broadcast message is directed to all devices in the network, a multicast message is directed to a particular group of devices and a unicast message is directed to a single device. The standard-based network protocol will implement them using the Network Layer (NWK) data services and Application Layer (APL). The standard-based network protocol must have the ability to implement broadcast or at the least multicast; as only unicast messaging to a large network is not efficient as the same message will be sent multiple time to each individual node.

ZigBee is a low power, low cost wireless standard that was produced by the ZigBee Alliance group of companies in 1998 [18]. The standard focuses on an open global wireless language capable of connecting devices such as sensors, meters and controls. The protocol offers machine to machine connection with 128 Advanced Encryption Standard (AES) encryption security, efficiency and interoperability, allowing ZigBee to be implemented in the healthcare, commercial building automation and industrial sensor networks without integration and vulnerability issues. ZigBee is built upon the IEEE 802.15.4 standard and operates at the 868 MHz, 915 MHz and 2.4 GHz frequency band. The ZigBee OSI model includes the MAC and PHY layers of the IEEE 802.15.4 standard, together with power management implementation in its NWK, the APL of ZigBee contains several device profiles to allow remote control, input devices and any other vendor profile requirements. ZigBee devices have a very low duty cycle of below 1%, therefore they are capable of very low power consumption [19]. ZigBee mesh network is composed of a target device (Personal Area Network (PAN) coordinator, router or node) and a controller device (end device or node). The coordinator has the ability to initiate the PAN autonomously and allow controllers to pair with it or join the PAN. Multiple PANs constitute the network [20] .

MiWi is a proprietary wireless protocol designed by Microchip Technology and is built on top of IEEE 802.15.4 at the 2.4 GHz band. MiWi was developed in response to the complexity and cost of implementation of the ZigBee wireless standard. It has low power capabilities similar to ZigBee, but the protocol can only handle simple networks with a maximum of 1024 nodes. The protocol can handle a maximum of 127 nodes for 8 coordinators [21]. Even though the protocol has Personal Area Network (PAN) mesh capabilities, the information packets can only hop a maximum of 4 times from the coordinator. The other limiting factor with MiWi is that only Microchip Technologies produce the chipsets.

Wireless Highway Accessible Remote Transducer (HART) is a recent addition to the wireless communication standards with its conception in 2004 by the Hart Communication Foundation companies. The standard was developed as a process field device network for industrial sensing applications. The Wireless HART was built on the Highway Addressable Remote Transducer (Hart) open protocol used in process automation since 1986, it allows for backward compatibility. HART overlays a digital signal on a 4 to 20 mA loop current on instrument wiring or on a 2.4 GHz wireless connection. Wireless HART offers mesh topology with AES 128 block ciphers for security [22]. Wireless HART is a time division multiple access schedule communication, which defines all layers in OSI model. The PHY is IEEE 802.15.4 compatible and the standard allows channel hopping on a packet by packet basis over 15 channels, therefore providing additional reliability and data bandwidth [23]. Wireless HART can blacklist channels to avoid hopping into them. The standard also implements an assessment to determine if the channels are clear to avoid creating or experiencing interference. The nominal transmission power of Wireless Hart is 10 Decibels to one milliwatt (dBm), which is quite high for a low data rate standard. Unicast, multicast and broadcast messaging are supported [23]. This wireless standard is the superior choice for integration into existing HART networks, as the upper APL of Wireless HART is the same as HART to enable the backward compatibility.

6LoWPAN was created by the Internet Engineering Task Force and is based on the Internet Protocol version 6 (IPv6) used for wired and wireless communication. 6LoWPAN has 128 bit addressing allowing for unique addressing of all nodes [24]. The standard was designed to send IP data packets over a wireless network using the 802.15.4 format. This enables a simpler interface between the wireless network and the internet. If the system was a standalone system, then this protocol would be unnecessary. However as most commercial wireless networks are cloud based, the system is gathering momentum. The standard creates an adaption layer above the MAC layer to convert IPv6 to 802.15.4 and vice versa. Furthermore the standard defines all other layers above the MAC layer.

7.3 Evaluation and Recommendations

All of the four suitable low data rate wireless protocols discussed in the section 6.2 all have features that would be suitable for the SCSLS. However, MiWi is proprietary to Microchip Technologies and acquiring the chipsets on a large scale will be dependent on one company. Even though the protocol is simpler to implement than the other protocols, it has poor documentation and support from the company. The bargaining power after implementation of the protocol will favour Microchip, whereas an open source protocol with multiple manufacturers, will favour Eco-FX. The scale of the network will also be an issue with MiWi, as the number of children and coordinators is limited. Furthermore, when the network spreads radially from the coordinator a maximum of 4 hops will increase the number of coordinators required for a MiWi network.

Wireless HART is based on the proven HART protocol and its features are very attractive to apply to the SCSLS. It has superior interference rejection and security compared to all other protocols [25], but the cost and availability of the chipsets are an issue. The chipsets are far more expensive than other protocols at $120 compared to $20-30 for all other protocols [26]. The price and availability will render this protocol and chipset unsuitable for large scale deployments, as it is not priced competitively in contrast to traditional luminaires.

6LoPAN is a very robust protocol and allows for easy implementation to the network for transmission to the cloud based service and to the back of office servers. To date the limitation of the protocol is the slow adoption rate by the industry and the limited number of vendors offering the chipset [24]. The knowledge and market profile of the protocol is a major hurdle in vending it; it needs to be marketed further and case studies of deployments must be more readily available.

The final and most suitable protocol is ZigBee. It is secure and robust as it is based by on the IEEE 802.15.4 and the chipsets are priced well [26]. The protocol has been proven to implement well in many large scales for smart street lighting systems throughout the world [27]. Of particular note is the Victorian government has become part of the ZigBee Alliance to develop their smart metering system [28]. The ZigBee Alliance provides a high level of support to all companies developing products using the ZigBee protocol, therefore the adoption of the technology is simplified. Although once the research and development is completed, the compliance of the product can become expensive according to Vice President of Technology, Victor Berrios of the ZigBee Alliance.

7.4 Action Plan

Subsequent to ZigBee being chosen as the wireless communication standard, the ZigBee Alliance was contacted to ascertain the mandatory requirements to produce a ZigBee certified product. The VP of Technology for the ZigBee Alliance Victor Berrios was the point of contact and he instructed Eco-FX that to produce a ZigBee Certified product, the product must be constructed with ZigBee certified transceivers or module. After the research and development of the product, a working model of the product with the transceiver or module is required to be certified to ensure that the product utilises the correct transmission frequencies, applications and network programs which are specified in the ZigBee Standard. The ZigBee Alliance has developed all the necessary OSI upper layer base features and formats for the NWK and APS layers; and ZigBee allows for easy modification of the format to suit the user application. The IEEE 802.15.4 standard provides all necessary features for the PHY, MAC and DDL. The introduction of ZigBee IP will allow for the advantages of IP format with the interoperability of the ZigBee standard. The OSI model for the ZigBee Standard is shown below in Figure 4 with all application profiles and the ZigBee protocol stacks.

	RF4CE			**PRO**							**IP**	
APPLICATION PROFILE	ZRC	ZID	Z3S	ZLL	ZHA	ZBA	ZTS	ZRS	ZHC	ZSE 1.X	ZSE 2.0	
NETWORK	ZIGBEE RF4CE				ZGP		ZIGBEE PRO				ZIGBEE IP (IETF based)	Alternate IP Transport
MAC	IEEE 802.15.4 - MAC										Alternate MAC	

PHY	IEEE 802.15.4 – sub-GHz (specified per region)	IEEE 802.15.4 – 2.4 GHz (worldwide)	Alternate PHY

ZID– ZigBee Interface Device	ZLL– ZigBee Light Link
Z3S– ZigBee 3D Synch	ZBA– ZigBee Building Automation
ZIP– ZigBee Internet Protocol	ZTS– ZigBee Telecom Services
MAC – Media Access Control	ZRS– ZigBee Retail Services
PHY – Physical Layer	ZHC– ZigBee Health Care
ZGP – ZigBee Green Power	ZRC – ZigBee Remote Control
ZSE – ZigBee Smart Energy	ZHA – ZigBee Home Automation

Figure 4: OSI model for ZigBee with all the base features and formats [29]

For SCSLS, the ZigBee Pro NWK format will be utilised as it provides the most suitable application profiles, such as ZLL and ZID. The ZigBee Alliance will certify the implementation of the standard on the product. The certification is done by an independent testing laboratory in China, and Eco-FX's manufacturers will liaise with the certification laboratories to get certification before shipping to Australia.

8 Transceiver Modules

8.1 Background

8.1.1 Transceivers Units

The transceiver will allow for two nodes of a wireless network to communicate and it consists of microcontrollers, memory, Analogue to Digital Converters (ADC) and General Purpose Input or Output (GPIO) ports. Figure 5 displays a block diagram with all the key units in an IEEE 802.15.4 transceiver [30]. The transceiver has two main components the radio and the microcontroller. They can either be integrated onto one chipset or separate units. Most transceivers are matched with a 50 ohm antenna which will be covered in Section 9. The antenna signal is filtered and impedance matched by the first unit of the transceiver. This unit will improve the receiver sensitivity and eliminate out-of-band transmission using passive devices. The transceiver uses the Transmit or Receive (T/R) Switch to switch the antenna between transmit and receive modes as the transceiver can only perform one mode at a time. The crystal outside the boundary of the chip can also be incorporated on the chipset. The oscillations of the crystal are used for the reference clock generation. Some of the basic crystal operation and selection considerations are discussed further in this section.

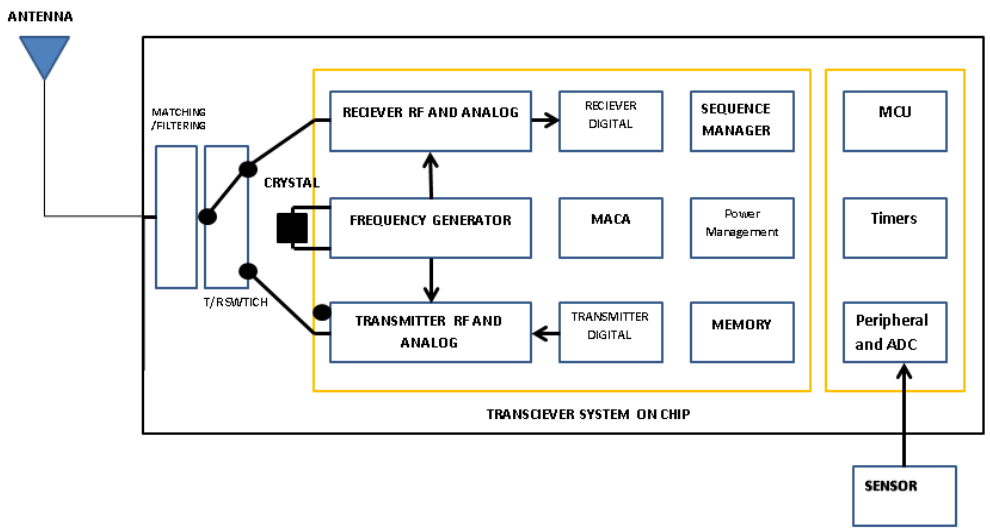

Figure 5: Block diagram of an IEEE 802.15.4 transceiver

The receiver path of the transceiver amplifies the received signal from the T/R Switch in the Receiver Radio Frequency (RF) and Analog unit, then down-converts the high frequency received signal. The lower frequency signal is then demodulated and converted to a digital binary signal in the Receiver Digital Unit and passed to the PHY layer. The Frequency Generation Unit uses the

crystal to produce the reference clock and a frequency. This frequency is used to down-convert and demodulate the received signal.
The transmission path of the transceiver performs the receiver path in reverse. The Transmitter Digital Unit modulates the digital information onto an analogue signal. The Transmitter RF and Analog Unit up-converts the modulated signal and then amplifies the signal to the specified output power to comply with the local regulations and standards.

The Sequence Manger performs the coordination of the timing, manages the priority of the events for the transceiver and tracks the state of the circuit constantly. The Universal Asynchronous Receiver/Transmitter (UART), Serial Peripheral Interface (SPI) and GPIO are used by the transceiver for communication with peripherals. The ADC's are utilised to connect to the analogue sensors. As all transceivers that support the IEEE 802.15.4 standard are built for low duty cycle and low current, therefore power management unit for the transceiver consists of voltage regulators and converters [30]. Separate regulators may be used for RF components to eliminate noise leakage.

The MACA unit, also known as the MAC accelerator, helps link the transceivers to the MAC and PHY for low level control; it may include buffers used in transmitting and receiving packets. This unit is not a mandatory requirement for a transceiver, but it will reduce the load placed on the microprocessor. Multiple timers are used in the transceivers to provide real time interrupt.

Depending on the configuration of the transceiver and the Micro Controller Unit (MCU), some of the units described above can be included in the MCU, such as the ADC's, power management unit, the communication ports, timers and the I/O ports. Ultimately, the MCU always contains the Central Processing Unit (CPU) and memory. The CPU is used to run programs from the MAC, higher level layers and user applications. The CPU may have differing amounts of volatile and non-volatile memory in the form of Flash, Random Access Memory (RAM) and Programmable Read Only Memory (PROM) depending on the model. The transceivers may also carry memory externally for the CPU.

8.1.2 Receiver Sensitivity

The IEEE 802.15.4 standard defines receiver sensitivity as the lowest received signal power to produce a 1% packet error rate. The standard defines different sensitivity levels for differing mode of operation. Mandatory modes, such as the 2.4 GHz Industrial, Scientific and Medical (ISM) band with Offset Quadrature Phase-Shift Keying (OQPSK) modulation, require a sensitivity of -85 dBm;

the 868/915 MHz band with Binary Phase Shift Keying (BPSK) requires a sensitivity of -92 dBm. The other optional modes in the 868/915 MHz band with Amplitude Shift Keying (ASK) and OQPSK modulation require a sensitivity of -85 dBm [30].

8.1.3 Receiver Interference Rejection

Adjacent channels to the desired channel have similar frequencies and therefore cause the most receiver interference. Alternate (once more removed) channels will also cause some receiver interference. This type of interference is only present on the 915 MHz and 2.4 GHz bands as the 868 MHz band only has one channel. The 2.4 GHz band has adjacent channels ±5 MHz and alternate channels ±10 MHz from the desired channel, whereas the 915 MHz band has these channels ±2 MHz and ±4 MHz from the desired channel respectively.

As the IEEE 802.15.4 standard becomes more popular for domestic and commercial devices. This interference can become an increasing issue as two or more nodse transmit signals at the same time. The receiver must be able to achieve a 1% or less packet error rate when detecting and demodulating the desired signal with the presence of adjacent and alternate channel interference to be compliant with the IEEE 802.15.4 standard. The IEEE 802.15.4 standard outlines the jamming resistance test to evaluate receiver performance. The 1% packet error rate is a minimum requirement and most commercially available receivers can far exceed this requirement [30].

8.1.4 Modulation and Spreading Method of the Transceiver

The modulation and spreading method requirements of the transceiver must meet the IEEE 802.15.4 standard; further information of the specifications is included in Appendix B.1. The QOPSK, BPSK and ASK modulation allow for a frequency band to have different data rates. ASK and BPSK are more robust as there are fewer data points to recover the original data, but it comes at the cost of the data rate.

The Direct Sequence Spread Spectrum (DSSS) and Parallel Sequence Spread Spectrum (PSSS) allow for different data rates as well. Additionally the DSSS and PSSS have a number of other advantages such as reduced cross talk interference which provides improved voice quality and data integrity. The DSSS and PSSS are affected less by multipath fading as the signal can be recovered using a despreading method at the receiver. The security of the signal is improved by mapping the symbols to the chip sequence before transmission, and only the receiver and transmitter have the chip sequence conversion tables. Consequently, the co-existence of the spread signal is much better than non-spread signals, as the signal will exist as random noise and not cause interference in other wireless devices. This non-interference nature of the signal can allow for high signal power and greater operation distance. The spreading using the chip sequence will make the signal harder to detect, intercept, demodulate or jam. The only methods of modulation and spreading that are necessary are the OQPSK and BPSK and the DSSS, Therefore all compliant transceivers must have this capability.

8.1.5 Transmitter Power

The transmitter must meet three criteria to comply with the IEEE 802.15.4 standard. First, the Signal Power Spectral Density PSD of the signal must be less than the limits in Table 1. The average PSD shall be measured using a 100 kHz resolution bandwidth. The peak power of the PSD must be measured within ±1 MHz from the carrier frequency for the 2.4 GHz band and within ± 600 KHz of the carrier for the 915 MHz band. The 868 KHz band needs only to be filtered by a raised cosine filter before transmission as it has only one channel [30].

Table 1: IEEE 802.15.4 standard PSD limits of the signal

Frequency Band	Frequency Offset	Relative Limit	Absolute Limit
2.4 GHz	$\|f-f_c\|$ > 3.5 MHz	-20 dB	-30 dBm
915 MHz	$\|f-f_c\|$ > 1.2 MHz	-20 dB	-20 dBm
868 MHz	N/A	N/A	N/A

The second criterion is that the transmission power needs to be adjustable to match the distance between the nodes.

The third criterion of the IEEE 802.15.4 standard requires the transmitter to have at least -3 dBm or 501 µW of output power and at least 30 dB of adjustable output power range. Reducing the output power to the minimum level where a reliable link is still achieved during the transmit cycle, will conserve power and minimise interference with other networks.

8.1.6 Modulation Accuracy

Modulation accuracy is measured and indicated by an error vector magnitude for all three modulation techniques. Receivers will always tolerate some quantity of modulation error. Amplitude error must first be measured and then divided by the ideal signal amplitude. It is then multiplied by one hundred to give the percentage of the error vector magnitude. The IEEE 802.15.4 standard specifies an error vector magnitude percentage of less than 35 for a transmitter [30].

8.1.7 Centre Frequency Tolerance

The transmit and receive centre frequency tolerance for all modulation methods must be a maximum of ±40 ppm to comply with the IEEE 802.15.4. The total offset between the transmitter and receiver is ±80 ppm, but the receiver can implement an automatic frequency control unit to compensate for the offset and contribute to the receiver sensitivity [30].

8.1.8 Turnaround Time

Any two wireless transceivers engaged in communicating will have to switch between transmit and receive modes many times. The time taken to make the switch between the modes is the turnaround time and it is usually measured in microseconds. However, the IEEE 802.15.4 uses symbol periods as the unit of measurement. An IEEE 802.15.4 transceiver must be able to transition between the modes in less than 12 symbol periods. A symbol period depends on the symbol rate of the transceiver; for example a 2.4 GHz transceiver with 54,500 symbols per second has a symbol period of 18.34µs. Therefore, this transceiver must have a turnaround time of less than 220µs.

8.1.9 Crystal Oscillator

A crystal is used with a circuit to generate a precise clock in the transceiver. When a voltage is applied to the piezoelectric device a mechanical vibration is produced at a constant frequency that is transferred to the electrical circuitry. As it is important for IEEE 802.15.4 transceivers to synchronise to other devices, when synchronising it may use the clock from the other device. Consequently utilising the other device's clock will eliminate the need for an additional crystal need for its own clock, therefore saving space on the PCB, simplifying design and reducing the cost of the transceiver.

8.1.10 Analog to Digital Converter

The IEEE 802.15.4 transceiver should have ADCs integrated into the circuitry. ADCs that can convert the information from the sensor and transfer it to the memory without the involvement of the transceivers processor is preferable to minimise the load on the processor. The sensing and processing of the information by the sensor should be undertaken when the transceiver is in a sleep mode to reduce the current draw by the transceiver. Even if the transceiver is not running on batteries, it is a feature that will allow the transceiver to be implemented into lower power applications in the future.

Resolution and conversion time are metrics that are important in the ADCs used in the transceiver. The resolution of the ADC is the number of bits that are available to create the analogue level in the ADC. For example, a 2 bit ADC will have 4 distinct levels of 00, 01, 10 and 11 to represent the input analogue voltage into a digital signal. The greater the resolution the better the digital representation of the analogue signal, as the resolution becomes lower, then the measurements become more susceptible to noise. However the greater resolution comes at the expense of more time to convert the signal which is known as the conservation time. The Smart Street Lighting System only requires information at a low data rate and the power measurements will not change very quickly. Therefore the ADC best suited to this application would be high resolution for better accuracy and lower conservation time as the measured quantity will not rapidly change. There are two types of ADCs distinguished by the method of sampling the incoming signal. The first is the Nyquist-rate ADC that samples the input signal at least 2 times higher than its frequency [31]. The second is the oversample ADC and it samples much higher almost 100 times the input signal; this type of ADC has the advantage for improving Signal to Noise Ratio (SNR) and resolution of the output signal. All ADCs require signal conditioning to ensure the voltage is in between 0 and the reference voltage before the analogue signal is converted to digital; this task can be achieved on the ADC or before it.

8.1.11 Other Transceiver Requirements

As discussed in Appendix B, when two nodes in a wireless network are linking, they do not necessarily have to be synchronised. If they do require synchronisation, the IEEE 802.15.4 requires that the transceiver has a timing recovery mechanism to retrieve the clock from the synchronisation header of the received pack.

Additionally, the AES 128 bit encryption must be implemented to comply with the IEEE 802.15.4 standard. The encryption and authentication of signals is done by a security coprocessor on the transceiver.

8.2 Analysis

The optimum way to display a comparison of the available transceiver ICs, MCU and transceiver modules is to tabulate them as shown in Table 2, Table 3 and Table 4. All tables were populated using datasheets from the respective companies and the transceivers are all ZigBee compliant and the modules have the ZigBee Pro protocol stack with all other required device profiles.

Table 2: The transceivers IC from some of the leading IC companies

Manufacturer and Model	Supply Voltage (V)	Sleep Current (μA)	Tx Current (mA)	Rx Current (mA)	Tx Power (dBm)	Rx Sensitivity (dBm)	Data rate (kbps)	Security	Dimensions (mm)
TI CC2420	2.1-3.6 (VREG) 1.6-3.6 (IO)	20	17.4 at 0 dBm	18.8	0	-95	250	AES 128	7x7
TI CC2520	1.8-3.8	0.3(Deep) 175(Norm)	25.8 at 0 dBm 33.6 at 5 dBm	22.3 (Norm) 18.8 (Low Current)	5	-98	250	AES 128	5x5
ATMEL AT86RF233	1.8-3.6	0.02 (Deep) 300 (Norm)	13.8 at 4 dBm	11.8	4	-101	250	AES 128	5x5
Microchip MRF24J40	2.4-3.6	2	23 at 0 dBm	19	0	-95	250	AES 128	6x6

Table 3: The CPU specification on the integrated MCU and transceiver module

Manufacturer and Model	CPU	MCU RAM Size (kB)	Flash Size (kB)	EEPROM (Bytes)	GPIO	ADC
NXP JN5168	32 bit RISC	32	256	4	20	10 bit, 4 channels
TI CC2530 (Rev. B)	8 bit EFM8	8	Up to 256	4	21	12 bit, 8 channel
AMTEL atmega128rfa1	8 bit AVR	16	128	4	38	10 bit, 8 channels

Table 4: Additional information of the integrated MCU and transceiver module

Manufacturer and Model	Supply Voltage (V)	Sleep Current (µA)	Tx Current (mA)	Rx Current (mA)	Tx Power (dBm)	Rx Sensitivity (dBm)	Timer	RF Data rate (kbps)	Antenna connection	Security	Dimensions (mm)
NXP JN5168	2.0-3.6	0.12	15.3	17	2.5	-95	16 bit	250	Yes	AES 128	7x7
TI CC2530 (Rev. B)	2.0-3.6	0.4	33.5 at 4.5 dBm	24	4.5	-97	16 bit	250	Yes	AES 128	6x6
AMTEL atmega128rfa1	1.8-3.6	0.25	18.6	16.6	3.5	-100	16 bit	250	Yes	AES 128	9x9

8.3 Evaluation and Recommendations

ZigBee modules contain both transceiver and MCU on one PCB, whereas the ZigBee transceiver IC requires an external MCU to control and process information. The benefit of having a standalone transceiver is that a more powerful MCU can be matched to the transceiver used in large, complex or demanding systems. These transceiver ICs are also used with powerful processors in the coordinators of the ZigBee network. As shown in Table 2, the main features are similar in all transceiver ICs due to the specification of IEEE 802.15.4 standard. However the efficiency, the transmit power and the receiver sensitivity of the transceivers are where the designs differ. As the SCSLS is going to be connected to mains power and not a battery, the power usage is important but not critical.

The urban environment in which SCSLS is operating will include large amounts of interference and obstacles for the RF signal, therefore the transmit power and the receiver sensitivity is critical. The Texas Instrument (TI) CC2520 chipset was chosen as it has superior transmit power with good receiver sensitivity. Although it has a high current draw in active modes, this is inconsequential due to the availability of mains power. An advantage of using TI products is that the documentation and support available about the system setup and testing are extensive [32].

Table 3 and Table 4 show the specifications of the MCU and transceiver modules available for the SCSLS. These modules are usually used in the ZigBee FFD router devices, as it is easier to implement without compatibility issues or RF losses via connections between transceiver and MCU. The modules have undergone completed testing; and the specifications for operating temperature, power usage and antenna loads of the module are available. An example of the ZigBee module is shown in Figure 6.

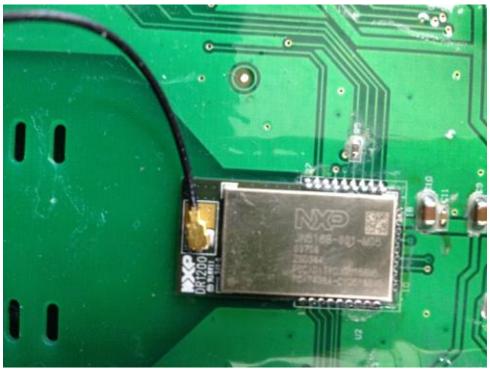

Figure 6: ZigBee module with RF connector and coaxial cable

After assessing the data available about the modules, the AMTEL module performed well in all fields, but the testing and support available through the company was lacking. TI CC2530 module is the second option because the support that the company provides to developers and designers is far better. Several documents in the antenna choice and device profile configuration are available on the internet, and once a company is registered with TI, a support line is available. The additional devices for the system are also readily available such as the power amplifier and low noise amplifier IC to improve the transmit power and the receiver sensitivity.

8.4 Action Plan

The TI CC2520 transceiver and an ARM processor are chosen for the coordinator controller. This combination can process large amounts of data from all connected devices. The TI CC2530 module are chosen for the devices or lamp controllers in the network, because the 8051 processor in TI CC2530 has enough processing power to control the transceiver and memory to store the Z–stack containing the ZigBee Pro stack.

9 Antennas

9.1 Background

The range of transceivers used in the system can be improved by various methods, but some methods can create issues with noise and interference. Increasing the receiver sensitivity and transmitting power are two methods which will increase noise in its network and interference in other networks. The best approach to improving range is to optimise RF propagation by choosing a suitable antenna design for the application. Frequency contributes to the size of the antenna; low frequencies require larger antennas, which increases the range. There are two general types of antenna and the types are differentiated by either single ended or differential connection. Single ended are easier to use and impedance match to 50 ohm, making them superior to the differential connection antennas for this application.

The best suited antennas for a mesh network are isotropic antennas. They are omnidirectional and they enable a node to connect to any nodes surrounding it. Directional antennas will only transmit in one direction in one plane and it is not suitable for a mesh network. An example of an isotopic antennas radiation pattern in shown below in Figure 7.

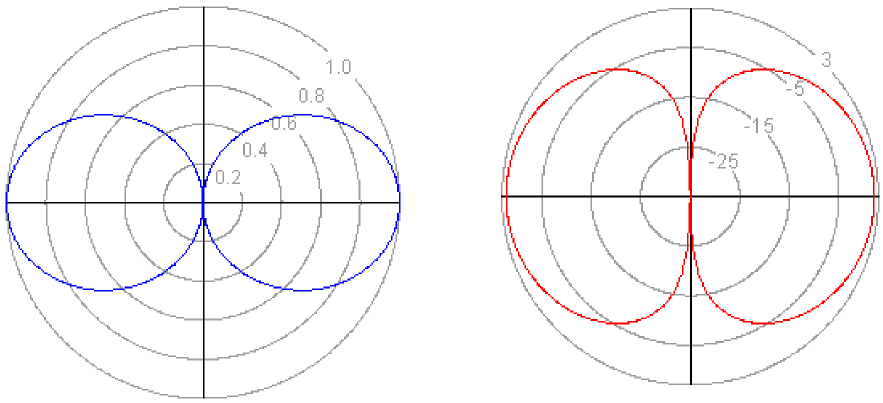

Figure 7: An Ideal isotropic antennas radiation linear and decibel pattern [33]

Antennas used in this project operate on the principal of reciprocity; therefore they will convert electrical signals from the PHY of the transceiver to the electromagnetic or RF waves for transmission into free space, and in the receive mode it will convert the RF waves to the electrical signals. Shorter wavelength RF waves can radiate better through the metal surrounds of luminaires. The antenna must also be tuned or designed to the frequency of the RF signal, for example an antenna designed for 2.4 GHz will not function well with a 915 MHz signal. Therefore, the antenna should be chosen for the primary frequency that the transceiver will utilise. All IEEE

802.15.4 transceiver manufacturers will specify the antenna impedance (usually 50 ohm) that will be optimal for their transceiver. If different impedances are specified on the transceiver and antenna, impedance matching may be required. Different antenna designs will have different characteristics, consequently a few of the antenna choices will be briefly discussed and the final antenna choice will be further explained and justified.

9.2 Analysis

9.2.1 Internal Antennas

The simplest and cheapest choice is the internal antenna; they are usually identified as separate ceramic components or as tracks on the PCB near the transceiver chip as shown in Figure 8.

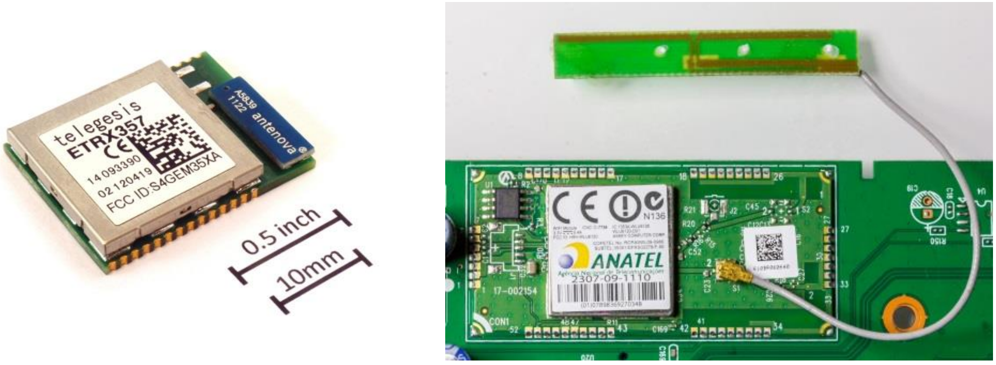

Figure 8: Surface mounted antenna chip [34]and PCB antenna [35]

These antennas require a minimum separation of 2cm from other metallic surfaces and the casing of the driver or luminaire; if metal surrounds the antenna range will be affected. Some manufacturers prefer plastic casings to be used when using an internal antenna. These antennas are good for short range applications, where the environment poses less interference and obstacles for the RF signal. Both these antenna types come in several configurations, but for simplicity sake the categories are left broad.

The internal chip antennas come in various configurations, but they are generally cheap, easy to implement and have low range. Whereas the internal PCB are also cheap and have good range, but it requires more space on the PCB and software and design tools to implement.

9.2.2 External Antenna

A half dipole whip type antenna, shown in Figure 9, has an ideal isotropic horizontal radiation pattern and a very small vertical radiation pattern. These antennas are more costly than other antennas, but theoretically have the best range and it is recommended for systems where the electronic circuits are surrounded by a metal casing. External antennas will require the transceiver to have an SMA RF connection on the transceiver PCB and a suitable RF shield coaxial cable to connect the PCB and antenna. These antennas are easily matched to 50 ohm impedance.

Figure 9: A half dipole whip antenna on top of a luminaire with coaxial cable

9.3 Evaluation and Recommendations

The external antennas were chosen to be the best fit for the SCSLS, as they allowed for greater range when nodes became unserviceable and signals have to travel a greater distance. In addition, the increased gain of the antenna can combat the interference caused by other signals, obstacles and the metal casing of the luminaire. The internal F type PCB antenna would be suitable if a UV stabilised plastic casing for the luminaire was used, as it is cheaper and the antenna is internal. External antennas are a target for birds, which may severe any cables or antennas protruding from the luminaire.

Table 5: Comparison of the antennas

Type of antenna	Range	Physical size	Cost
External Antenna	High	Large	High
Internal PCB Antenna	Low-Medium	Small-Medium	Low
Internal Antenna Chip	Low	Small	Low

9.4 Action Plan

The external antenna will be used with a plastic non-conductive casing that will protect the antenna and provide good range and sensitivity. The plastic casing must be UV stabilised and of a light colour as dark pigments in the plastic may absorb RF energy and reduce range.

10 Internet Access

10.1 Background

The system will require internet access to transfer the street level data to the cloud based server and finally to the CMS and vice versa. Several technologies were considered for their suitability for the SCSLS and the main technologies are briefly explained below. In order to keep costs down, only one technology was chosen as a preliminary design. The main factors that contribute to the final decision are outlined at the end of this section.

10.1.1 Worldwide Interoperability for Microwave Access (WiMAX)

WiMAX is a wireless broadband network based on IEEE 802.16 standard and it is offered throughout metropolitan Western Australia by Vivid and Amnet wireless broadband. Alternatively it is a private network can be implemented to service a remote locality. The customer private network can be set up to be 50 km from the SCSLS [36] and it contains a base station with connectivity to the National Broadband Network (NBN), a WiMAX transceiver and a cross polarized direction antenna.

The transmission frequencies can be between 2 to 11 GHz for the licenced or 10 to 66 GHz for unlicensed band, which poses no interference risk to the ZigBee communication of the SCSLS. The network data rate can be between 2-70 Megabits per second (Mbps) depending on the number of base stations. As WiMAX is wireless, it requires no civil work to implement. Implementation cost such as subscription to service and capital works for WiMAX is higher than cellular networks as it is for commercial use.

10.1.2 Asymmetric Digital Subscriber Line (ADSL)

The national rollout of the NBN has given the SCSLS a cheap and convenient option to connect to the web server using ADSL. The data rates of 8 to 24 Mbps [37] are within specifications but this solution requires wiring and it will involve more engineering and civil works. ADSL is available in most metropolitan areas, however rural and remote areas will require another option.

10.1.3 Global System for Mobile Communications (GSM)

GSM is the cellar telephony network such as 2G, 3G and 4G and each one has a different packet data service such as General Packet Radio Service (GPRS), High-Speed Down-link Packet Access (HSPDA) and Evolved High-Speed Packet Access (HSPA+) respectively [38]. Each one of the different packet data service has a different data rate as shown in Table 6. This data rate should be a consideration when selecting the features required in the SCSLS, for example, high definition video streaming would be better supported by 4G.

Table 6: GSM networks with data packet service and their associated data rates [38] .

GSM Network	Data packet service	Data rate
2G	GPRS & EDGE	114 & 384 Kbps
3G	HSDPA	3.1 Mbps
4G	HSPA+ & LTE	168 & 299.6 Mbps

Several companies offer GSM networks with different levels of network coverage and costs depending on the amount of data used. Most major cities will have good GSM network coverage, but remote localities will require another option as there is poor GSM network coverage.

10.1.4 Satellite Communication

Satellite communication is an option for internet access for remote localities, but the cost is high for the service, hardware and professional installation.

10.2 Modems

Every Internet Access technology will require different types of modem and converters to convert the IPv6 information to suitable format required by the differing communication technology. Additionally, the WiMAX, Satellite and GSM will require a suitable antenna or dish to be connected to the modem. Media converters may be required to convert fibre optic signals to electrical and vice versa. The ISP or telecommunication provider will be consulted on the connection to find suitable equipment. A mixture of the technologies can be used in the SCSLS to provide a flexible and adaptive solution. For instance the information from the different coordinators each utilising different internet access communication technologies will all be transmitted to one cloud server to be processed and disseminated to the back of office devices.

10.3 Action Plan

A quick comparison of the cost, range and availability of the different internet access technologies is provided in Table 7. It will be explained to the customer that cost and availability of these technologies may vary between the different Internet Service Providers (ISP) and telecommunication providers. The preliminary development option for Eco-FX due to the availability of the networks, cost and ease of implementation is the GSM network. The other communication technologies can be used in future deployments to connect the coordinator to the internet in remote area deployments and the customer will need to be informed of the associated additional costs.

Table 7 : Comparison of Internet Access technologies

Internet Access Method	Monthly Cost*	Installation and Hardware cost	Range	Availability
WiMAX	90	High to Medium	Up to 50km from Base Station	All
GSM	60	Low	Up to 5 km from Base Station	Metropolitan
ADSL	40	Low	Wired	Metropolitan
Satellite	400	Very High	Everywhere	All

*Monthly average cost based on 20 Gigabyte (GB) data for ADSL and 10 GB data for others per month from several providers

11 Data Management and Back Of Office system

11.1 Cloud Based Data Management

The cloud based data management system will use the data transmitted to the internet over the GSM network or other networks. The data will enter the cloud based server system via a firewall and a router. From the router the data will be sent to the cloud server to be stored for further processing. When the data is requested from the server by the back of office terminal or mobile device using the CMS, the data will be retrieved with additional Global Positioning Satellite (GPS) data referenced against the PAN ID number of the controller. The GPS data will position the lamp and coordinator data on the map software such as Google maps used in the CMS. The cloud based server will produce SMS and email alerts to the relevant users for any fault on the system. A block diagram of the Full SCSLS is shown below in Figure 10: The full SCSLS deploymen with the Cloud Based Data Management system.

11.2 Control and Monitoring Software

The CMS provides control and monitoring with a tailored user experience for different user levels. The CMS will be offered in full and mobile versions for the Apple, Android and Windows based operating systems. The CMS must draw the information from the SQL based database stored in a cloud server to display the information in a user friendly manner such as graphical charts; and system information overlayed onto mapping software. The user must have the ability to drill down on an individual lamp, group of lamps or coordinator on the map to produce detailed information. Information such as the power usage, operating cost and status, faults or any other user specific information will be displayed on a pop up window.

The CMS will also perform analysis on the data gathered from the SQL database; and manage user queries to the SQL database. In addition, the CMS will produce tabulated reports for operational and maintenance related tasks. The mobile version of the CMS used on any GSM capable device must be able to send a direct control SMS message to a chosen coordinator. This feature will allow for a group of lamps to be controlled without the cloud based server or full CMS version for testing and maintenance.

Janarthan Sri Kantha

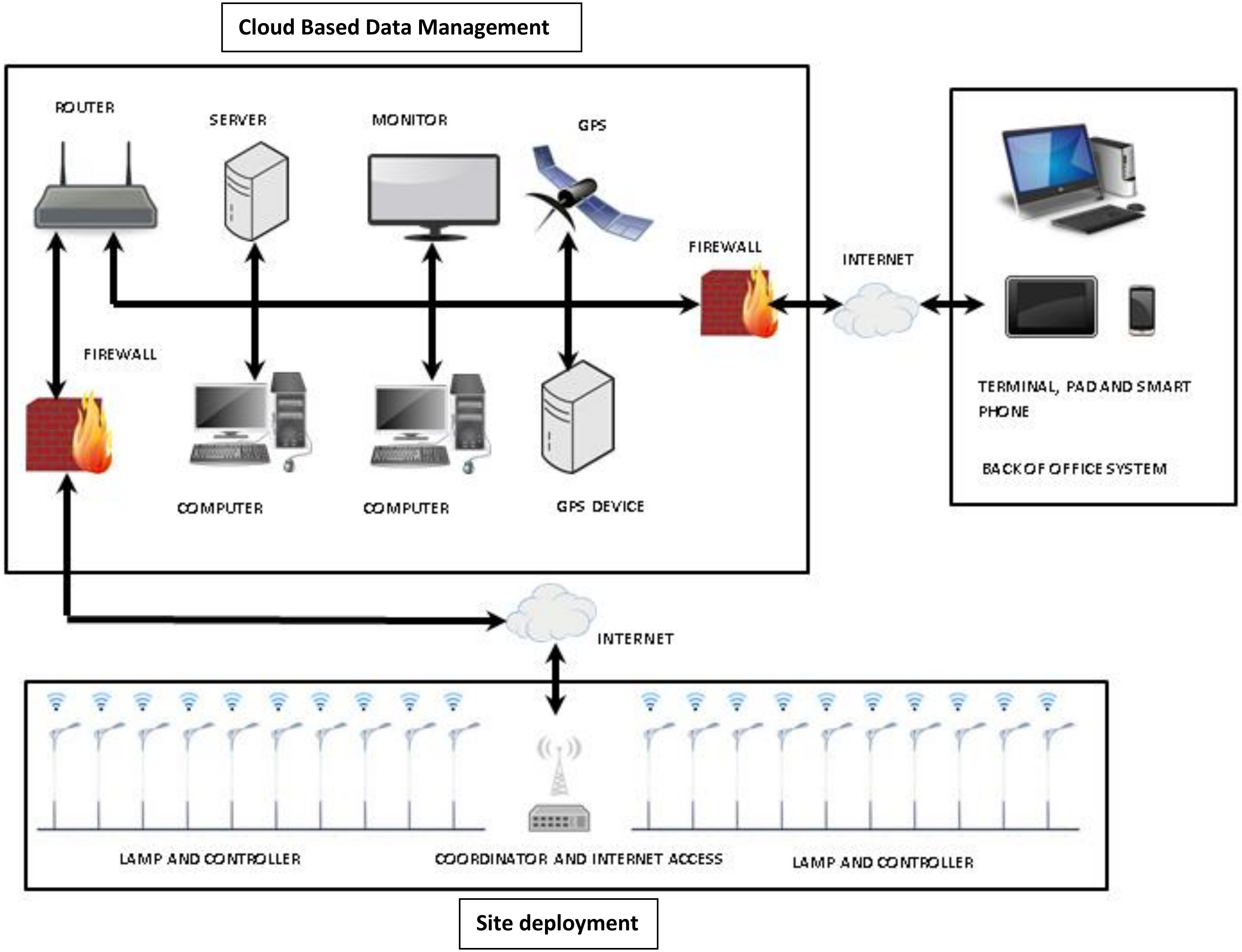

Figure 10: The full SCSLS deployment

12 Final Design of Smart Lighting System

The SCSLS final design is planned for roll out in 2016 as shown in Figure 10; and it will consist of the street lamp driver and controller either in one module or as two separate units with a half dipole antenna. These modules will be placed in the base of the pole for ease of assess with a RF cable connecting to the antenna fitted to the luminaire. If the driver cannot be placed on the bottom of the pole, then it will be fitted inside the luminaire.

A coordinator will control a maximum of 100 lamps and it will be located in a marshalling cabinet on the sidewalk. The controller in theory can connect 200 lamps; nevertheless as users add extra features to each pole in the future, the coordinator would experience difficulties in processing the increased amount of information from each pole or node.

The marshalling cabinet will also contain a main breaker and a circuit breaker for each group of 25 lamps and will be used for maintenance purposes to isolate circuits. A cloud based server service will either be subscribed or designed to provide the storage and processing capacities for the SCSLS. A central control and monitoring station will be designed for the customer and Eco-FX.

Ja

13 Conclusion

Researching, developing and consulting on the SCSLS project for Eco-FX provided a large amount of knowledge of several types of LR-WPAN; these technologies were able to be researched and evaluated against the Eco-FX and WALGA's requirements.

Outlining the needs of the company and customer was an important initial step at the infancy of the project. It provides the starting point and an initial direction for the research in the project. Company's and customer's needs were translated into system requirements before research.

Undertaking a set research methodology was critical as it allowed for all system requirements to be outlined before research was undertaken, maximising the research effort. Most of the research in this project was concentrated in two areas; the LR-WPAN and the equipment necessary to implement the network protocol.

Several of the LR-WPAN protocols were evaluated, but only ZigBee provided the features, support and price to be feasible for implementation. Even then, the hardware on the market that was stating ZigBee compliance were far from suitable or did not have the necessary compliance certificate to implement. There are several protocols that are similar to ZigBee and easier to implement. These protocols were being substituted by vendors in place of ZigBee. Therefore certification from the ZigBee Alliance became an important final step and test for the system.

The ZigBee Alliance compliance test was performed with expensive equipment and must be done in an approved laboratory. The process is costly and to ensure the final product is ZigBee compliant, all hardware used in the system must be from ZigBee compliant companies. This evaluation process was difficult with several companies producing ZigBee modules or transceivers, most transceiver features were similar as they are all based on the IEEE 802.15.4 standard. Eventually the TI ZigBee transceiver and modules were chosen due to the support TI provided and the availability of the products.

To optimise the cost and efficiency of the system, some other key elements of the system were researched and evaluated. The antenna was one of the main features evaluated, where the best theoretical choice of an external half dipole antenna posed other issues with integrity in the harsh Australian climate. A solution to cover the external antenna will be tested in the future. The CMS software design is completed, the development of the cloud server is being finalised, and the final product will be reviewed and tested in the coming weeks. Provisions are in place to subscribe to a cloud based data management service initially, and then the number of deployments will indicate if Eco-FX will invest in a designing and owning a data management service. After the visit to China, Eco-FXs SCSLS system design is complete, but there are several support elements of the system that need to be finalised in the following month before deployment in 2017.

14 Future Works

The deployment of the SCSLS is imminent and multiple municipalities in WA are interested in a small scale pilot installation. At this stage, the server solution and an agreement with an ISP for the system are in progress. Furthermore, no installation, maintenance and operating procedures have been produced for the system. The procedures are critical to commercially produce and operate a safe and reliable system. All documents will be completed by the end of 2015 and the first deployment is planned for early 2016. All component testing will be completed by the end of 2015 and the whole system test will be done after the first deployment.

The ADSL and WiMAX modem options are definitely the next development step for Eco-FXs SCSLS, as these will be required to reduce cost and allow the system to be deployed in remote areas. Furthermore Eco-FX is planning to integrate HD cameras into the SCSLS that will require a greater data rate, which can only be achieved in rural and remote localities with WiMAX or ADSL. The CMS must be modified to have camera control and monitoring capability with additional storage for steamed video footage.

Incorporating new low data rate wireless technologies into the SCSLS such as 6LoWPAN or ZigBee IP would be a natural evolution. It would reduce the requirement for conversion of protocol formats, as the IEEE 802.15.4 and internet protocols would be the same. Wireless HART may be more widely adopted in future if the cost of implementing the protocol becomes feasible; and if it is found that the SCSLS has difficulty coexisting with other wireless systems.

Finally, after the SCSLS pilot deployments have been successfully trialled and tested; the integration of all smart devices such as bus stops, traffic signs and charging stations into the Smart Grid created by SCSLS will begin. These new devices will need to be trialled and tested. Updates to the CMS, Coordinators and Cloud server will be necessary to handle the large volume of data and processing as the new systems are integrated into SCSLS.

Bibliography

[1] Eco-FX Australia, “Eco-FX LED Smart Led Lighting Solutions,” Wide Eye Production, 2015. [Online].

Available: http://www.eco-fx.com.au/. [Accessed 22 September 2015].

[2] M. C. a. D. T. Fabio Leccese, "A Smart City Application: A Fully Controlled Street Lighting Isle Based on Raspberry-Pi Card, a Zigbee Sensor Network and WiMAX," University degli Studi "Roma Tre", Roma, 2014.

[3] A. a. A. P. Fernandez, "Evaluation framework for IEEE 802.15.4 and IEEE 802.11 for smart cities," IEEE - Seventh International Conference on Innovation Mobile and Internet Services, Tokyo, 2013.

[4] P. L. Halonen, " Lighting technologies," IEA International Energy Agency, 11 October 2012. [Online]. Available: http://www.lightinglab.fi/IEAAnnex45/guidebook/5_lighting%20technologies.pdf. [Accessed 26 August 2015].

[5] Caroline Perks - climate Change Coordinator, "Energy Efficient Street Lighting - Dicussion paper," Western Australian Local Government Association - WALGA, Perth, 2014.

[6] A. Z. Standard, "Lighting for roads and public spaces," SAI Global, Sydney, 2005.

[7] Office of Crime Prevention, "Designing out crime "Designing in people" - lighting for crime prevention," Governement of Western Austrlian, Perth, 2006.

[8] Western Australian Local Government Association, "South West Country Zone - Meeting Agenda," Shire of Capel, Perth, 2014.

[9] A. G. -. D. o. t. Environment, "Invitation to comment on the proposal for Australia to ratify the Minamata Convention on Mercury," Commonwealth of Australia, Canberra , 2014.

[10] K. DOMKE, "Thermal testing of road luminaires," Poznań University of Technology, Institute of Electrical Engineering and Electronics, Poznan, Poland, 2013.

[11] W. Power, "Generator Grid Connection Guide V2 - An Introduction To Power Systems," Western Power, Perth, 2011.

[12] P. Halonen, "Lighting Technologies," 11 October 2012. [Online]. Available: http://www.lightinglab.fi/IEAAnnex45/guidebook/5_lighting%20technologies.pdf. [Accessed 26 August 2015].

Ja

[13] M. Poplawski, “LED Dimming: What you need to know,” US Department of Energy, NorthWest, US, 2012.

[14] NXP Semiconductors, “R_10018 Smart lighting: A bright idea whose time has come,” NXP Semiconductors, Netherlands, 2011.

[15] I. o. E. a. E. E. S. Association, “Part 15.2: Low-Rate Wireless Personal Area Networks (LR-WPANs) standard,” IEEE Std, New York, 2011.

[16] P. Steenkiste, “Wireless Netwroking Challenges,” Carnegie Mellon University, Pittsburgh, 2012.

[17] S. Farahani, in *ZigBee Wireless Networks and Transcievers*, United States of America, Newnes, 2008, p. 34.

[18] J. A. &. B. Heile, “IEEE Spectrum,” IEEE, 1 October 2006. [Online]. Available: http://spectrum.ieee.org/computing/networks/busy-as-a-zigbee. [Accessed 10 August 2015].

[19] Z. Alliance, “ZigBee Specification FAQ,” ZigBee Alliance, 2014. [Online]. Available: http://old.zigbee.org/Specifications/ZigBee/FAQ.aspx. [Accessed 5 August 2015].

[20] A. E. Z. &. A. Ibrahim, “Using ZigBee to Build a Web-Based DCS System,” IEEE, Egypt, 2012.

[21] L. Iacono, “Wireless Sensor Network Protocols,” Universidad De Mendoza, Mendoza, 2011.

[22] M. Nixon, “A Comparison of WirelessHART™ and ISA100.11a,” Emerson Process Management, Texas, USA, 2012.

[23] Emerson Process Management , “System Engineering Guidelines - IEC 62591 WirelessHART,” Emerson Process Management , St. Louis, Missouri, United States, 2014.

[24] J. Sarto, “ZigBee VS 6LoWPAN for Sensor Networks,” LSR, Cedarburg, Wisconsin, https://www.lsr.com/white-papers/zigbee-vs-6lowpan-for-sensor-networks.

[25] S. S. a. F. H. Tomas Lennvall, “A Comparison of WirelessHART and ZigBee for Industrial Applications,” ABB Corporate Research, V¨aster°as, Sweden, 2008.

[26] FAI Electronics , “Future Electronics,” FAI Electronics Japan, 2015. [Online]. Available: http://www.futureelectronics.com/. [Accessed 10 October 2015].

[27] SHENZHEN IOTCOMM TECHNOLOGY CO., LTD, "SEMS Smart Street Light System," XIAMEN IOTCOMM TECHNOLOGY CO., LTD, Fujian State, China., 2014.

[28] A. Government, "Smart Grid, Smart City - A new direction a energy era," Department of the Environment, Water, Heritage and the Arts, Canberra, 2009.

[29] ZigBee Alliance, "Exploring New Lighting Opportunites with ZigBee Light Link Webinar," 16 May 2012. [Online]. Available: www.zigbee.org. [Accessed 5 September 2015].

[30] IEEE, "Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area," LAN/MAN Standards Committee of the IEEE Computer Society, New York, 2011.

[31] J. F. W. S. a. T. W. Paul Flikkema, "Wireless Sensor Network Design," Multi University Systems Education, Arizona, Vermont, Hawaii and South Florida, 2012.

[32] Texas Instuments, "TI Low Power RF - Designer's Guide to LPRF," Texus Instruments, Dallas, Texas, 2010.

[33] Wikipedia, "File:RadPatt-lin.png," Wikipedia, 2006. [Online]. Available: https://commons.wikimedia.org/wiki/File:RadPatt-lin.png. [Accessed 5 November 2015].

[34] Wikipedia, "ZigBee," Wikipedia, 18 March 2013. [Online]. Available: https://upload.wikimedia.org/wikipedia/commons/2/29/ETRX357_ZigBee_module_with_size_ref.JPG. [Accessed 30 October 2015].

[35] Wikipedia, "Wi-Fi network card by Askey Computers with Wi-Fi Antenna by Amphenol-9714," Wikipedia, 17 September 2015. [Online]. Available: https://commons.wikimedia.org/wiki/File:Wi-Fi_network_card_by_Askey_Computers_with_Wi-Fi_Antenna_by_Amphenol-9714.jpg. [Accessed 17 October 2015].

[36] M. B. a. E. Grabianowski, "How stuff works," InfoSpace, 2015. [Online]. Available: http://computer.howstuffworks.com/wimax2.htm. [Accessed 15 August 2015].

[37] Access communication, "ADSL overview," Access communication, 8 May 2014. [Online]. Available: https://www.accesscomms.com.au/reference/adsl_overview.htm. [Accessed 20 July 2015].

[38] KORE Telematics, "Field Technologies Online," Jameson Publishing, 2015. [Online]. Available: http://www.fieldtechnologiesonline.com/doc/gsm-network-services-0002. [Accessed 20 September

2015].

[39] Wikipedia, “Wikipedia The Free Encyclopedia,” MediaWiki, 6 October 2015. [Online]. Available: https://en.wikipedia.org/wiki/OSI_model. [Accessed 12 October 2015].

[40] Energy Vortex, “Energy Dictionary,” © Documen Information Design, Inc., 26 September 2014. [Online]. Available: https://www.energyvortex.com/energydictionary/baseload__base_load__baseload_demand.html. [Accessed 25 August 2015].

Appendix

Appendix A – OSI Model

Table 8 is a brief explanation of the different layers of the Open Systems Interconnection. OSI allows for a system to be broken into layers. Each layer of the OSI model provides services to the layer above and uses the services of the layers below.

Table 8: OSI Model [39]

Layer	Data Unit	Function	Examples
7. Application	Data	High level API's, including resource sharing, remote file access, directory services and virtual terminals	HTTP, FTP, SMTP, SSH, TELNET
6. Presentation	Data	Translation of data between a networking service and an application, including character encoding, data compression and encryption/decryption	HTML, CSS, GIF
5. Session	Data	Managing communication sessions, i.e. continuous exchange of information in the form of multiple back and forth transmissions between two nodes	RPC, PAP, SSL, SQL
4. Transport	Segments	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing	TCP, UDP, NETBEVI
3. Network	Packet/Datagram	Structuring and managing a multi-node network, including addressing, routing and traffic control	IPv4, IPv6, IPsec, AppleTalk, ICMP
2. Data link	Bit/Frame	Reliable transmission of data frames between two nodes connected by a physical layer	PPP, IEEE 802.2, L2TP,MAC, DHCP, LLDP

1. Physical	Bit	Transmission and reception of raw bit streams over a physical medium	Ethernet physical layer, DSL, USB, ISDN, DOCSIS

Appendix B – IEEE 802.15.4 Low-Power Wireless Personal Area Network Standard

The IEEE standards are developed to assist working groups to design and maintain their own wireless and wired standards; it provides a base to build upon. The IEEE 802.15 group of standards encompasses a variety of WPAN applications; this group contains the IEEE 802.15.4 standard for the LR-WPAN, which defines the PHY and MAC sub layer of Data Link Layer (DLL) specifying the largest collection low data rate WPANs.

There are three types of data transfer in the IEEE 802.15.4; these are peer to peer, coordinator to device and device to coordinator. The data verification used by the IEEE 802.15.4 to check that bits of any packet are recovered correctly is Cyclic Redundancy Check (CRC). The addressing defined by the IEEE 802.15.4 can either be 16 bits or 64 bits, the network can specify the option used, according to the size of the network. Beaconing-enabled and nonbeaconing networking is another feature of the IEEE 802.15.4 standard, this feature outlines the methods used for channel access. If the nonbeaconing or contention-based channel access is utilised, all devices are on a first come first serve basis for frequency channels using the Carrier Sense Multiple Access Collision Avoidance (CSMA-CA). In a beacon-enabled network, the coordinator will allocate a Guaranteed Time Slot (GTS) for a device; therefore the device can transmit during its GTS without using its CSMA-CA. To allocate GTS for all devices, they must be synchronised by sending a beacon message to synchronise the clocks on all nodes in the network.

B.1 Physical layer

The PHY defines relationship between the physical device and the electrical RF transmission. This in turn directly effects the hardware requirements, which is covered in Section 4 transceiver of the thesis. But the other specifications such as channel assignment, energy detection and signal management will be briefly covered in this Appendix. When discussing Channel assignment, the channel page and numbers define the channel frequency as shown in Table 9.

Ja

Table 9: Channel Assignment of the IEEE 802.15.4 standard [17]

Channel Page	Channel number	Frequency and modulation	Bit rate (Kb/s)	Spreading Methods
0 (Mandatory)	0	868 MHz band (BPSK)	20	Binary DSSS
	1-10	915 MHz band (BPSK)	40	Binary DSSS
	11-26	2400 MHz band (OQPSK)	250	16-array orthogonal
1 (Optional)	0	868 MHz band (ASK)	250	20-bit PSSS
	1-10	915 MHz band (ASK)	250	5-bit PSSS
	11-26	Reserved		
2 (Optional)	0	868 MHz band (OQPSK)	100	16-array orthogonal
	1-10	915 MHz band (OQPSK)	250	DSSS
	11-26	Reserved		
3-31 (Future Development)	Reserved	Reserved		

A channel page distinguishes the PHY of the different editions of the standard. As the 2003 edition supports all channels on channel page 0, which are mandatory for IEEE 802.15.4 standard. The 2006 edition of the standard introduced the optional channel pages 1 and 2 and all their channels. The channel page 3-31 is for future development.

If the developer defines the frequency band of operation in PHY, then if a high level of interference exist on one channel on the band, then it is possible to change the channel to operate on an idle channel on the same band. If all channels of a frequency band are busy, then the device must have the option to dynamically change to either of the alternative operational frequencies. If the device is operating in the optional modes (Channel page 1 and 2) from the 2006 edition of the standard, 802.15.4 still requires the device to be able to revert to the mandatory channel page 0. But if the user has defined the device to operate in the mandatory channel page, there is no requirement to have the optional channel pages available to the device.

The 2.4 GHz or 2450 MHz ISM band is accepted worldwide, alternatively the low frequency channels are utilised for better signal penetrate in some application. But the lower frequencies have limited channels, 915 MHz has 10 channels and 868 MHz has only one channel. The limitation can affect the transmission of data in a high traffic area, where other 868 and 915 MHz frequency band is utilised by other networks.

B.1.1. Modulation

There are three modulation methods in the IEEE 802.15.4 standard, the only mandatory Modulation methods are BPSK for 868/915 MHz band and OQPSK for the 2.4 GHz band and the ASK and OQPSK methods are optional methods for 868/915 MHz band. Again if the optional methods are used, the device must be able to revert to the mandatory BPSK. But the reverse is not necessary as only the mandatory method needs to be offered.

The Phase Shift Keying (PSK) modulation varies the phase of the carrier single of the carrier wave, by the B-PSK uses two phases which offset by 180^{o} to transmit the digital data as shown in Figure 11. This type of modulation is more robust against noise and distortion than PSK.

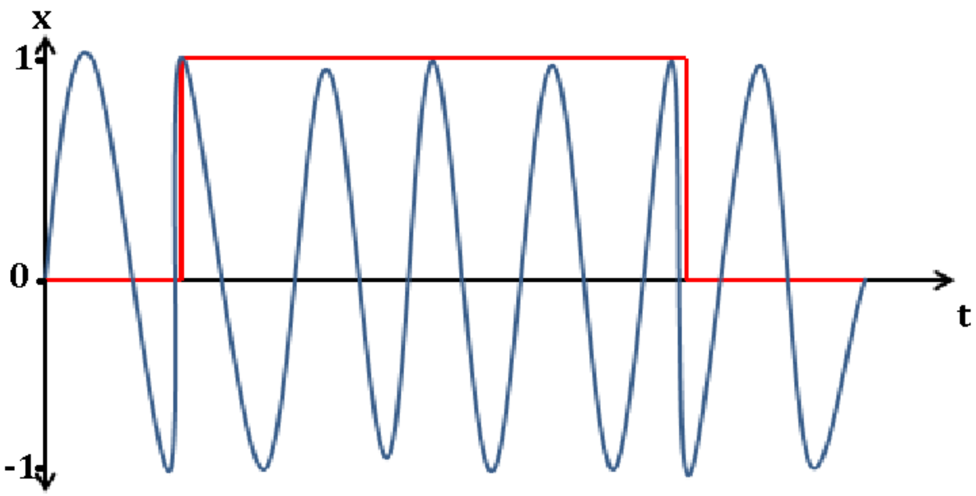

Figure 11: A pulse created using B-PSK modulation

Quadrature Phase-Shift Keying (QPSK) utilises four different values of phase of carrier wave to transmit they are separated by 90^{o}. This type of modulation doubles the data rate of B-PSK modulation. The offset in OQPSK refers to the timing offset of the odd and even bits as shown in Figure 12.

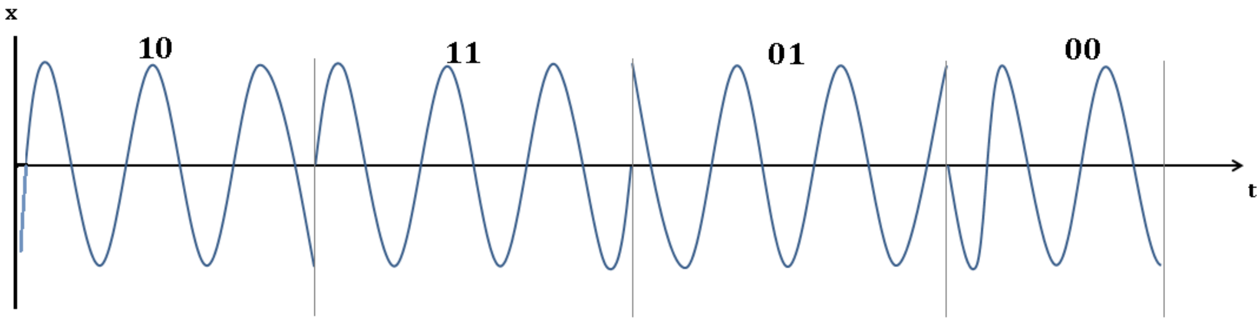

Figure 12: An OQPSK modulated signal

ASK modulation varies the amplitude of the carrier wave to transit digital data as shown in Figure 13.

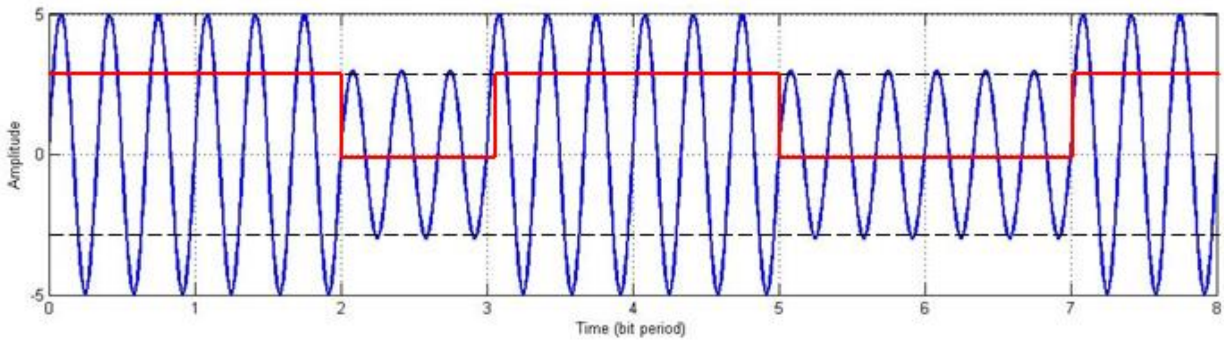

Figure 13: An amplitude modulated signal

B.1.2. Spreading Methods

Signal spreading is when the power of a signal is spread over a greater frequency range to improve performance. To explain signal spreading methods, a few new concept need to be explained. Firstly, the graph depicting the signal power versus frequency is referred to as the PSD. The PSD graph peak will be at the carrier frequency of 2.45 GHz, 915 MHz or 868.96 MHz and a majority of the signal power will be within the bandwidth on either side of the carrier. The PSD graph will include sidebands, but the receiver uses analogue and digital filtering to remove the unwanted spectral content outside the bandwidth of the signal. It produces a PSD graph similar to Figure 14 and displays the ratio of total signal power to the total noise power in the frequency band.

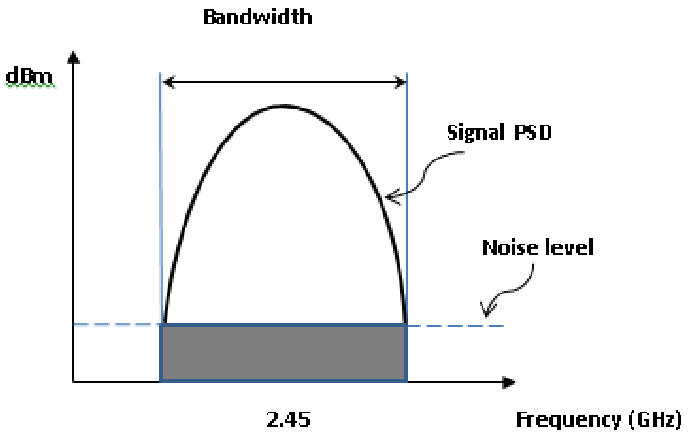

Figure 14: A filtered 2.4 GHz band PSD graph with SNR of the signal

.

The IEEE 802.15.4 Standard uses spreading methods at the transmitter and despreading methods at the receiver to improve receiver sensitivity, increase jamming resistance and reduce the effects of multipathing. Multipathing will be explain in more detail in the next section, but briefly it is a transmitted signal that splits and finds different paths to a receiver due to scattering, reflection and diffraction. Signal spreading is when a transmitter spreads a signal power over a greater bandwidth. The signal will have a lower peak on the PSD after being spread over a greater bandwidth. When the signal is travelling in free space, interference and noise can be added to it. When the signal is received it will be despread to recover only the original signal.

The original signal will be concentrated back to the original bandwidth and the noise and interference will remain spread. The original signal will regain the higher PSD peak, where the SNR will increase and improve receiver sensitivity, this process is known as the processor gain. An example of the effect on noise in the original signal due to the spreading method is shown in Figure 15.

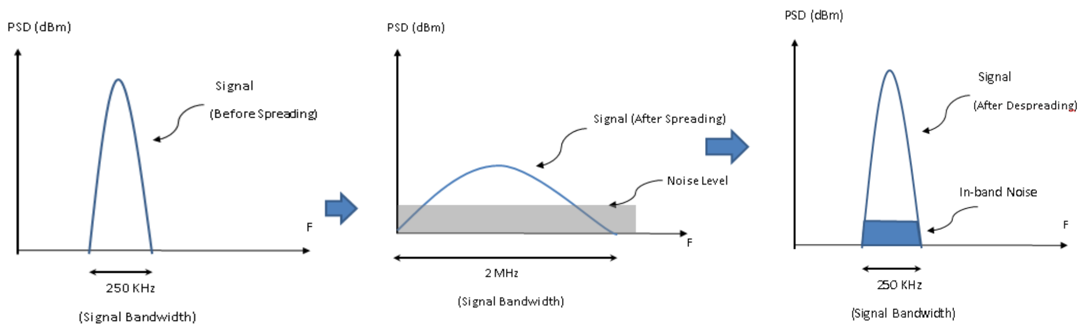

Figure 15: Effect on noise due to the spreading method

The despreading procedure can also improve discrimination between the original signal and another signal called the interferer, which has the same carrier as the original signal. The despreading procedure will concentrate the original signal to the smaller original bandwidth, but it will spread the interferer over a greater bandwidth. An example of the effect on the interferer signal due to despreading is shown in Figure 16.

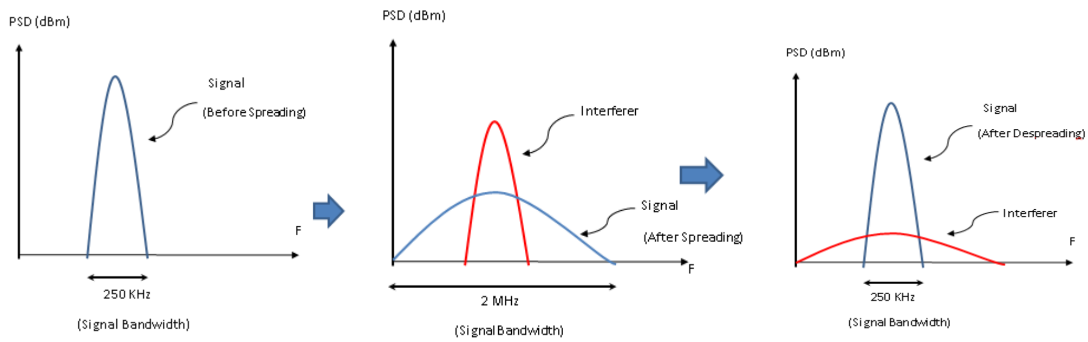

Figure 16: Effect on the interferer signal due to despreading

Different methods of modulation have different associated spreading methods as shown in Table 9. The IEEE 802.15.4 specifies that BPSK and OQPSK modulation uses DSSS, where every 4 bits or symbol of each PHY protocol data unit octet is mapped to a unique bit sequence knowns as a chip sequence. The symbol to chip mapping for the OQPSK modulation can vary depending on the frequency band used 2.4GHz and 868/915 MHz has 16 and 5 different symbols and 32 or 16 bit sequence respectively. As every 4 bits is transmitted over a 32 or 16 bit sequence, as the bit rate required to transmit the signal has increased and the bit rate is proportional to the bandwidth. The bandwidth of the signal is increased and signal is spread by the transmitter. The receiver will despread the signal by applying the same symbols to chip mapping as the transmitter to identify the original signal and concentrate it back to the original bandwidth. The BPSK modulation follows the same procedure of spreading and despreading, but for each bit it uses a 15 bit chip sequence.

PSSS method converts all data to bipolar and then multiplies the bipolar data by a unique sequence numbers; there are 20 and 5 sequence numbers for the 915 and 868 MHz bands respectively. The summation of all the multiplied data is a single sequence. As the sequences are nearly orthogonal the receiver is capable of recovering the original data from the sequence.

B.1.3. PHY Specifications

Energy Detection (ED) is a task that requires PHY to detect the signal energy level in a channel; it does not identify the signal. If the signal energy level is too low, then it may not detect it. IEEE 802.15.4 specifies that a receiver should detect a signal that has a 10dBm difference to the receiver sensitivity and the ED must have a range of 40 dBm. When the MAC requests this information from the PHY, it must have an accuracy of ± 6 dB.

Carrier Sense (CS) in contrast to ED will identify the signal to verify is the channel is available for transmission in PHY. The device will initially switch to receive mode and demodulate any signal on the channel to confirm the signal characteristics are complaint with the PHY in use by the device, the device will consider the channel busy if an 802.15.4 exist on the channel.

The Link Quality Indicator (LQI) determines the data packet quality received by the receiver. Higher LQI measurements will result in a lower error rate for the data packet and a better probability of delivering the information. The Receiver Signal Strength is the total energy of the received signal and it can be used to measure the signal quality in combination with the SNR of the signal determine the link quality. LQI is performed for each data packet to provide a quality measurement of at least 8 different increments, which is then sent through the various upper layers to the NWK layer. The NWK layer will determine which of the channels are reliable to find a suitable path for routing a signal according to LQI measurement.

Clear Channel Assessment (CCA) is the initial step of CSMA-CA process, it is where the PHY will be requested by the MAC to check the channel is not being used by other device. The CCA uses the ED, CS or both to determine the availability of the frequency channel depending on the mandatory three CCA modes offered in the IEEE 802.15.4. IEEE 802.15.4 defines constants and attributes for the PHY. These are tabulated below in Table 10 and Table 11.

Table 10: Constant of PHY in the IEEE 802.15.4

Constants	Description	Value

aMaxPHYPacketSize	The maximum allowed PSDU size (in octets)	127
aTurnaroundTime	The allowed RX to TX or TX to RX turnaround time (symbol periods)	12

Table 11: Attributes that may change during operation in IEEE 802.15.4

Attributes	**Description**
phyCurrentChannel	The frequency channel of operation
phyChannelsSupported	The array of the available and unavailable channels
phyTransmitPower	The transmitter output power in dBm
phyCCA Mode	The CCA mode of operations (1-3)
phyCurrentPage	The current PHY channel page
phyMaxFrameDuration	The maximum number of symbols in a frame (55,212,266,1064)
phySHRDuration	The duration of the synchronization header (SHR) (3,7,10,40)
phySymbolsPerOctet	The number of symbols per octet for the current PHY (0.4,1.6,2,8)

The other services that PHY provides are the PHY Data Service and the PHY Management Service. The PHY data service accepts data from the MAC and transmits the data and provides the MAC with the reports the results of the transmission or attempt. The PHY Management Service allow for commands to be sent between the MAC and PHY. The commands are for services such as ED, CCA and controlling of the transceiver.

Lastly the PHY sets the format for the data packets according to the frequency and modulation of the operating channel. The format of a PHY Protocol Data Unit (PPDU) is show in Figure 17.

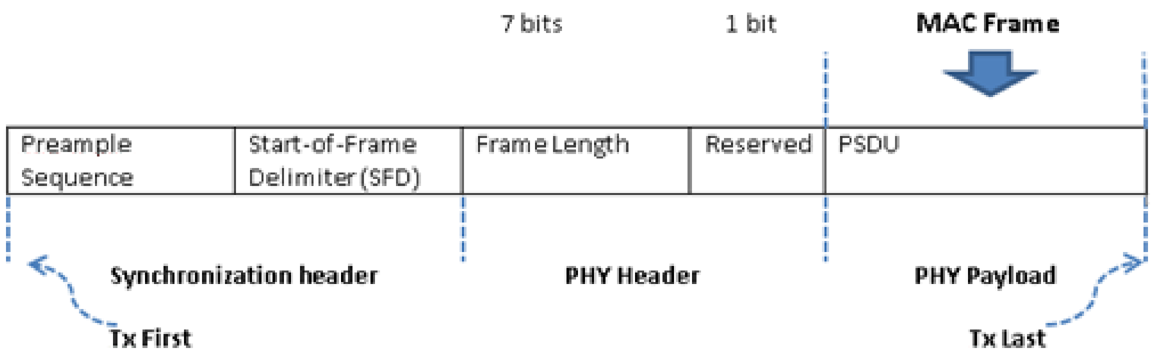

Figure 17 : PPDU format

B.2 MAC Sub Layer

MAC is a sub layer of the DLL of the OSI model. The MAC provides access to PHY for the layers above the MAC enabling the upper layers and the MAC frames to be transmitted through the physical channel. MAC provides addressing and control of multiple nodes to communicate in a multiple access network that incorporates a shared communication medium. MAC provides data and the management services; these services will be briefly discussed. Beside these services, the main other features of the MAC that will be briefly discussed are the network beaconing management, association and disassociation, interframe spacing, CSMA-CA and frame format. These are only some of the relevant features and services the MAC of the 802.15.4 provides.

The MAC uses 12 digit hexadecimal numbers for addressing devices in the network. The devices in the network specified by the IEEE 802.15.4 standard MAC are the FFD and RFD as Figure 18. The FFD can connect with any device in the network and it can be used with all topologies. Alternatively, the RFD can only connect with one FFD and it is suitable for the end device in star topology. The implementation of the RFD due to its limited functionality is much simpler. The FFD is described as a coordinator in the IEEE 802.15.4 as it can coordinate other devices about ideal channels for transmission using such ED, CS and LQI. This leads to the RFD being the slave and the FFD being master in any network. If all FFD's are used in a network there is no master/slave relation.

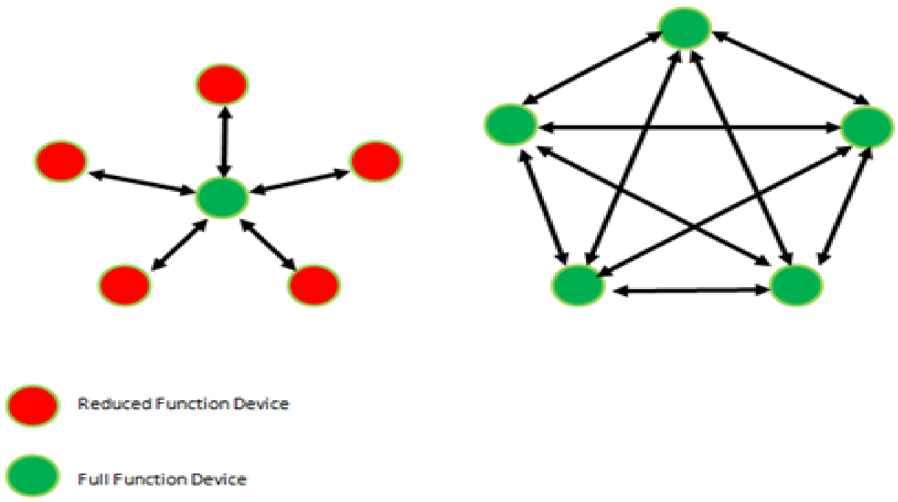

Figure 18: RFD and FFD in star and mesh topologies

MAC data services are provided to the NWK. When transmitting the data required to be transmitted by the NWK is placed in the payload of the MAC. MAC will manage all requests from the NWK for transmission and assigns a sequence numbers for each data frame. When transmitted the data frame there are three options. Acknowledge or unacknowledged transmission as the names implies the sender of the data may or may not ask for a receipt acknowledgement from the recipient device. Transmission can also be during GTS or Contention Access Period (CAP), if nonbeaconing is enabled then all transmissions are using CAP. The third option for transmission is direct and indirect, in an indirect transmission the data is not directly transmitted to the recipient. Other methods are used to store the data till recipient is ready or reroute the data to the recipient. When the device is in received mode the MAC data service provides the time stamped data and LQI to the NWK.

The MAC management services provides access to MAC for the NWK, it will provide information about the successful or invalid results of the NWK requests. In addition to the result of the request other MAC command parameters are delivered to the NWK such as the security and addresses fields.

Association and disassociation is the procedure utilised by a device to join or leave the network contained in the MAC. This service is provided to the NWK to form the network. This procedure has several steps where the coordinator and device requesting to join or leave the network communicate their identity, intentions and parameters to be allowed to join or leave the network. But ultimately the MAC provides the procedure for the NWK to make the decision. The interframe spacing by the MAC layer dictates the amount for time interval required by the recipient to process the data sent before another frame is transmitted. The period is dependent on the size of the frame, as larger frames will take longer to process.

CSMA-CA is the channel access mechanism used in the IEEE 802.15.4 MAC. Before every transmission the CCA is used to check the channel is clear before transmission, if it is clear it will transmit its signal. If the channel is not clear the device will back off for a period and try again. The devices may use two types of CSMA-CA depending on the state of beaconing, the slotted CSMA-CA is used in beacon-enabled networks as there are GTS for the algorithm to align the back off periods. The unslotted CSMA-CA is used in nonbeaconing networks when are no GTS for the algorithm to align the back off periods during contentious periods. The CSMA-CA algorithm has a number of retries before the CSMA-CA report channel access failure to the NWK. Other values CSMA-CA algorithm determines are the random back off period and contention window. The frame formats for the MAC is depicted below in Figure 19.

THE DATA FRAME

Octets	2	1	Variable	0,5,6,10 or 14	Variable	2
	Frame control	Sequence Number	Addressing Fields	Auxiliary Security HDR	Data Payload	FCS
	MHR				MAC PAYLOAD	MFR

THE ACKNOWLEDGEMENT FRAME

Octets	2	1	2
	Frame Control	Sequence Number	FCS
	MHR		MFR

THE MAC COMMAND FRAME

Octets	2	1	Variable	0,5,6,10 or 14	1	Variable	2
	Frame Control	Sequence Number	Addressing Fields	Auxiliary Security HDR	Command Frame Identifier	Command Payload	FCS
	MHR				MAC PAYLAOD		MFR

Figure 19: The data frame formats in the IEEE 802.15.4 MAC