Smart LED Street Lighting

http://www.ee.ic.ac.uk/niccolo.lamanna12/yr2proj/

Feasibility Report

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Abstract

Urban areas in the entire world are dealing with increasing energy consumption and carbon emissions, a known contributor to climate change. Due to inadequate dimming control and low efficiency, current street lighting is wasteful in terms of energy spending, accounting for a major part of governmental electricity costs. Therefore, it has become desirable and of great importance to design a new smart lighting system that is more efficient and environmentally friendly.

The main aim of a new smart street lighting system is to control energy efficient LED street lights to turn on only when needed and to remain in a dim state otherwise. The system integrates technologies such as: Passive Infrared (PIR) sensor, ZigBee wireless network and dimmable LEDs.

This report aims to illustrate an evaluation and analysis of the proposed system. The feasibility study done by the team details the requirements and constraints considered in the design of the system, as well as a technical overview of the solution. Additionally, the successful implementation of a prototype further supports a possible large-scale development of the project. Finally, it aims to present an overview of a profitable and green solution to the energy consumption problem imposed by street lighting.

1. Problem Analysis

Energy Prices and Carbon Emissions

Conventional street lighting systems use constant illumination lighting which leads to high energy consumption accounting for up to 60% of a municipal government's total electricity expenditure [1]. Furthermore, forecasts show that the energy spending for street lights is likely to increase over the next few years as the demand and price for electricity increase [2].

Many urban areas are currently facing high carbon emissions due to public lighting, which are a known contributor to climate change. For example, in Harrow, street lighting consumes 6,551,500 kWh of electricity, which leads to emissions of around 3900 tons of carbon annually [3].

Inadequate Dimming Control

The current street lighting policy requires all lights to be fully operational during the entire night, due to security reasons and inadequate dimming technology. This leads to unnecessary energy use, lowers the lamps' life and causes significant light pollution.

Considering the above problems of conventional lighting methods, it has become increasingly important to develop a radically new system that is both environmentally friendly and cost effective.

2. Current Solutions

There are 3 options available to reduce energy use caused by conventional street lights. These are: Variable Lighting, Part Night Lighting, and Light Trimming [3].

2.1. Variable Lighting

This method ensures that the lights remain lit during the night. However, the intensity level of lights will be dependent on the level of use of the streets: for example, the lights on a main road will have increased brightness, while the lights in a remote area will have reduced brightness.

Limitations: The brightness of the lamps is fixed and cannot deal with unpredictable changes in traffic statistics.

2.2. Part Night Lighting

This method involves switching the lights off completely during certain time intervals, from 12:00am to 5:00am.

Limitations: Due to security reasons, this could be used only for sparsely populated areas and thus could not be widely applied for residential areas.

2.3. Trimming

Trimming relates to decreasing the total night period during which the lights are on, by delaying the lighting up time in the evening, as well as bringing forward the switching off in the morning by up to 30 minutes.

Limitations: The energy savings are limited to around 3-4%, which does not provide significant cost and carbon emission reduction.

3. Our Proposed Solution

3.1. Design Specifications

Our proposed design aims to reduce the carbon footprint and the overall costs of street lighting by integrating dimmable light-emitting diodes (LEDs) and wireless technology. The principle of operation is to efficiently control the intensity of the streetlights to respond to the needs of road users. The following is a list of requirements our system aims to fulfill such to solve the problems that the current lighting system presents:

1. **Motion Detection**: A motion detection sensor will ensure that the lights only brighten when motion is detected.
2. **Wireless Communication:** The network will enable the lights to transmit and receive data between each other. This ensures that when motion is detected near one light, the adjacent lights will turn on, therefore providing enough light for pedestrians or cars.
3. **Microcontroller:** The microcontroller will act as the processing unit. It will have the following functions:
   - **a. Process Data**: It must process the data received from the sensor.
   - **b. Control Output**: This output controls the intensity of the light according to the results of data processing.
   - **c. Communication with wireless interface**: It must be able to receive and send control signals through the network.
4. **Dimming:** This involves adjusting the lighting levels of LEDs such that lower lighting levels are used when there are no pedestrian or cars on the streets.
5. **Control:** Intelligent algorithms will be used to smartly control the lights to quickly respond to the needs of road users.
6. **Even Power Consumption:** Adjusting the brightness level of lights introduces a problem of uneven power consumption which adversely affects power companies' carefully forecasted usage. This is required in order to produce the right amount of power such to avoid overproduction or shortages.
   Our solution aims to account for this by implementing an algorithm which dynamically controls the network such that an even power usage is maintained.

3.2. Modular Overview of the System

The diagram below illustrates the modules of the system and the communication between them.

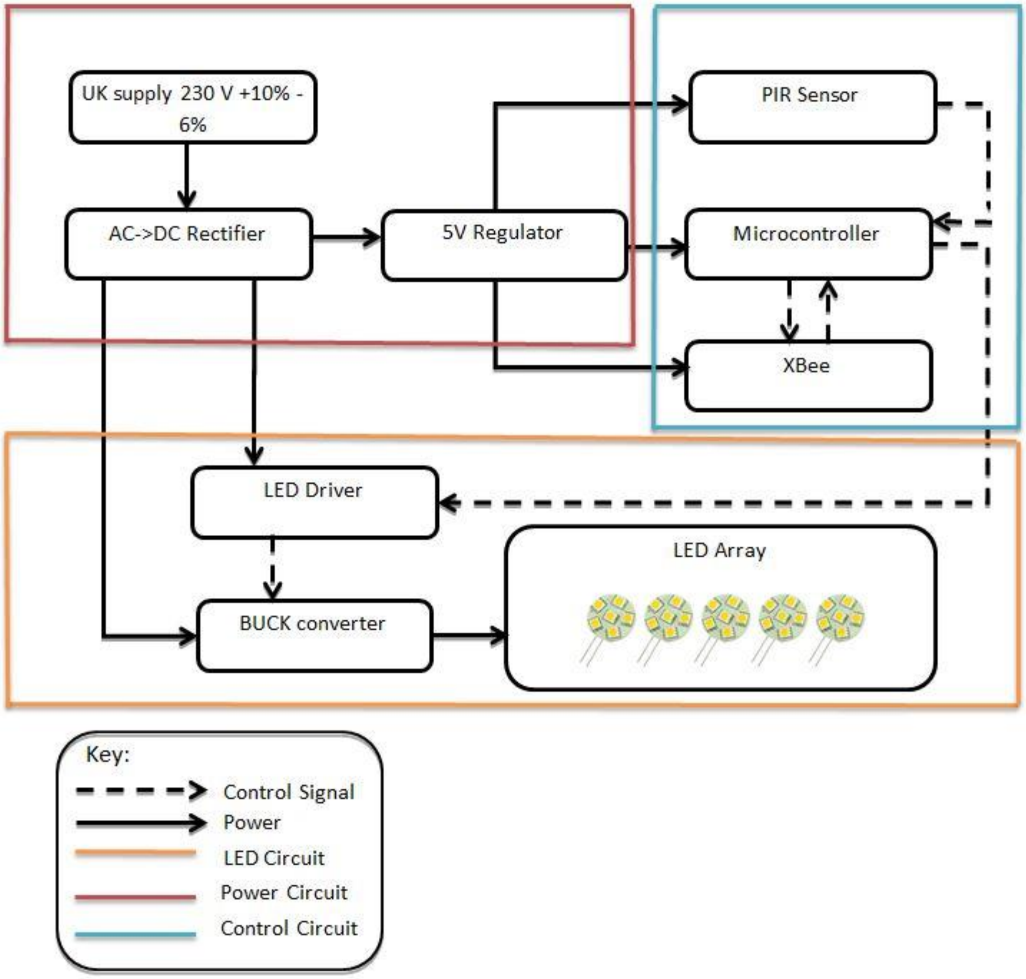

Figure 1. Modular Overview of Design

The Power Circuit provides the necessary voltage levels needed to power the modules. A rectifier converts the AC mains voltage to a DC voltage which will be used to power the LED driver, as well as the BUCK converter circuit. A regulator steps down this voltage to a 5V level, used to power the PIR sensor, the microcontroller and XBee Pro module.

The LED Driver is required to control the light intensity by applying a dimming method. It takes an input pulse-width modulated signal (PWM) from the microcontroller and outputs a higher frequency PWM signal to the MOSFET of the BUCK converter, which will control the current through the LEDs accordingly.

The Control Circuit is composed of the passive infrared **(**PIR) sensor, the microcontroller and the XBee module. The sensor will send a control signal to the microcontroller. The microcontroller will process and forward this to neighbour XBee devices and additionally, output the PWM signal for the LED driver.

Other additional modules that could be integrated in the design are:

- Temperature Module: This would prevent the temperature of the components to get too high and affect their performance.
- Light Sensor Module: The current design uses the microcontroller as a timer, which activates the street lights only at night. Future development includes adding a photocell to give optimal turning on times.

4. Technical Design

4.1. Sensors

In the proposed solution, a motion detector sensor is required in the system in order to detect pedestrians, vehicles and cyclists within the range of each lamp post, and then signal to the microcontroller accordingly.

Requirements and constraints

Our system is currently designed for a residential area where the lights are on average 15-45m apart [3]. The widths of the roads are on average 10-15m wide. Therefore the sensors are required to have a range greater than 15m, and a viewing angle as close to 180 as possible, to provide adequate coverage of the road.

The casing for the sensor will need to be tamper proof and resilient to all weather conditions. The minimum Ingress Protection (IP) rating required is 65, which means the casing must be dust tight and resilient to water jets. The IP rating applies to all parts of the lamp [4], [5].

Another requirement is for the lights to only function at night. This can be achieved by using existing methods present in the current system such as timers or photo-detectors. These detect light and turn on the lights when it is dark.

Comparison of Sensors

The table below compares the two main types of sensors which could be suitable for our design specification. In order to construct a fair comparison we analyse sensors available on the market at a similar price [6], [7].

	PIR	**Ultrasonic**
Coverage	• Line of sight • Field of view can be adjusted by user via a Fresnel lens • Range of 6-40m	• Covers entire space (volumetric) • Field of view cannot be adjusted by user • Coverage area of 50-200m^2
Highest sensitivity	Motion lateral to the sensor	Motion to and from the sensor
Indoor/Outdoor use	Indoor and outdoor	Indoor
Compatible applications	• Smaller enclosed spaces • Spaces where the sensor has a view of the activity • Outdoor areas	• Typically ceiling mounted • Open spaces • Spaces with obstacles • Spaces with hard surfaces
Incompatible application characteristics	Low motion levels by occupants, obstacles blocking sensor view, within 2-3m from HVAC air diffusers or other heat sources	High ceilings, high levels of vibration or airflow, open spaces that require selective coverage

Table 1. Comparison of Sensors

We consider PIR technology to be most suitable for our application. Although ultrasonic sensors are more sensitive and have greater coverage and range, they are not suited for outdoor applications and will consequently have a high false detection rate. The false detection rate explains why we did not consider dual technology (both PIR and Ultrasonic) sensors. The suitability of the chosen sensor (Honeywell 8IR103) is discussed in the sections below with respect to the requirements and constraints.

The chosen sensor is packaged for indoor use and so the casing needs to be modified for outdoor applications. Another alternative for future development is to design the whole casing including the Fresnel lens from scratch. This would allow us to optimise detection for cars and people while meeting the required regulations for ingress protection.

Further details about the sensors and their mounting positions can be found in Appendix E.

4.2. Communication Network

In the proposed solution, a control system is required to certify that the system operates correctly and safely. To ensure safe road conditions, the street lights at the current position of a driver/ cyclist, as well as the lights relatively further ahead must provide the correct brightness. Therefore, a network is required to send and receive control signals between street lights.

Requirements

The following requirements must be fulfilled by the network in order to meet the objectives above. Firstly, a wireless transmission range of at least 40m is essential to ensure data packets can be successfully communicated between two street lights. Secondly, low power consumption is desired. Another key requirement is for the network to have low set up and maintenance costs which is a direct objective of this project.

Comparison of Wireless Technologies

Table 2 below compares Wi-Fi, Bluetooth and ZigBee wireless technologies in terms of transmission range, power usage, network topologies and other factors [8].

	ZigBee	**Bluetooth**	**Wi-Fi**
Data Rate	20, 40 and 250 Kbps	1 Mbps	11 and 54 Mbps
Range	60m	10m	50-100m
Topology	Ad-hoc, peer to peer, mesh or star (max 65000 devices)	Ad-hoc, very small networks	Point to hub
Frequency	868 MHz (Europe), 900-928 MHz (NA), 2.4 GHz (others)	2.4 GHz	2.4 GHz and 5 GHz
Power Consumption	Very low	Medium	High
Security	128-bit AES plus application layer security	64 and 128 bit encryption	WEP, WPA and WPA2

Table 2. Comparison of Wireless Technologies

From Table 2 above, it can be deduced that Bluetooth is not suitable for this application because of its short range of only 10m. Although Wi-Fi is a suitable choice in terms of data rate and security, it has extremely high power consumption and its centralised nature requires all devices to be in a range of up to 100m. This makes it am inappropriate medium for this network where devices can be up to hundreds of metres apart.

On the other hand, ZigBee has a decentralised nature meaning that data can be transmitted from one device to the next until it reaches its end destination, essentially allowing data to be transferred across long distances. Additionally, this wireless standard has low power consumption as compared to Wi-Fi and its maximum data rate of 250Kbps is more than enough for our system. Therefore, it can be concluded that ZigBee closely meets the requirements of this project by offering a cheap, easy to setup, secure and low power solution.

ZigBee Network

An XBee device can be configured as one of the following [9]:

- **Coordinator** – Creates a PAN[1] and allows other devices to join the network. It is responsible for routing data and maintaining network security. Each PAN can have only one coordinator that selects a unique PAN ID and a channel to operate on.
- **Router** – Allows other routers and end devices to join the PAN. It may also assist in routing data.
- **End-Device** – Must associate itself with a ZigBee PAN before it can transmit or receive data. It cannot route any data and must always communicate with the rest of the PAN through its parent.

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[1] A ZigBee network is called a PAN, Personal Area Network.

In the proposed design, each street light has an XBee[2] module attached to its microcontroller for transmitting and receiving control signals. The nodes (lights) on a road are divided into clusters each consisting of routers and end devices. For example, a cluster formed under Router 1 is shown in Figure 2.

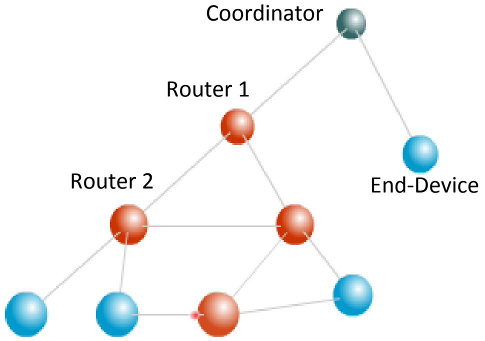

Figure 2. The mesh network

As a vehicle moves along the road, entire clusters respond by adjusting their brightness as opposed to controlling individual lights. Hence, this makes the implementation of the network easier because only a single control signal must be sent to head of the cluster which in turn forwards it to all the devices in the cluster. The cluster size is flexible and may contain any number of devices that have joined the PAN.

As shown in Figure 2, the XBee modules are connected in a mesh network topology to provide alternate routes for data packets in case of any node failure.

Security

The ZigBee standard offers security by encrypting application data packets using 128-bit AES[3] encryption and a network key chosen by the coordinator. The coordinator also acts as a trust centre that is responsible for authenticating devices that join a network.

Further details about the ZigBee network standard can be found in Appendix D.

4.3. Power

In the proposed solution, a power supply module is necessary to provide the appropriate DC voltage levels for the circuit modules. In addition, a driver circuit is required in order to power and control the dimmable LEDs through PWM.

Requirements and constraints

LEDs satisfy the general requirements for street light sources: Colour Rendering Index (CRI) [4] of 85-90, colour temperature of 6400K. In addition, it is important to note that any changes of street lamps, lighting levels and type of technology should agree with the British Standards for Road Lighting (Appendix B).

Mains electricity is an AC electric power supply. Since the LEDs are current operated devices, power needs to be supplied to them by a DC current source. A 230V/50HZ AC/DC converter is required to rectify the AC mains to DC and in addition, an LED driver is needed to provide the DC current source for the LED lamps.

Comparison of Light Sources

Regarding street lighting, the energy spending is proportional to the energy consumption and efficiency of the lamps. Therefore, we could reduce the energy consumption by replacing the current street light sources with more efficient LEDs and by controlling them dynamically. Table 3 compares three common light sources used in Harrow.

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[2] An XBee module is a product of Digi International Inc. that provides the ZigBee Network Standard 802.15.4

[3] AES - Advanced Encryption Standard

[4] Colour Rendering Index measures how faithfully a light source reveals the colours of various objects, as compared to an ideal light source.

	Harrow		
Type of Lamps	**High-Pressure Sodium (SON)**	**Low-Pressure Sodium (SOX)**	**LEDs**
Lights Quantity	9704	2950	2968
Typical Rated Life (hours)	12,000-24,000	10,000-18,000	50, 000- 100,000
Lumens per Watt[5]	70-120	80-180	120-150
Watts per bulb[6] (W)	50-400	20-180	<30
CRI	25	0	85-90
Ability to dim	No	No	Yes

Table 3. Features of Different Light Sources Predominantly Used for Street Lighting in Harrow [10], [11]

SOX and SON lamps have an average lifespan and high energy efficiency. However, a poor CRI is a significant disadvantage and may raise safety concerns. Moreover, the higher power consumption compared to LEDs (lower efficiency) and the limited dimming control makes it inadequate to integrate in modern systems that use dimming control.

As compared to sodium lamps, the main advantages of LEDs are: the low energy consumption, the higher efficiency, the extended life span (more than 12 years) and a higher CRI. Moreover, LED lamps could be integrated in a modern smart network due to their dimming abilities. The overall result is that electricity consumption, and therefore costs and carbon emissions are vastly reduced.

Other advantages of LED lamps are illustrated in Appendix C.

Power Conversion Stages

Firstly, the conversion from AC (mains) to DC is implemented using a full-wave rectifier, which can be implemented by four diodes in a bridge configuration. In general, the output voltage required for the LEDs is lower than 230V, and so a step down converter is needed which can be realized with a buck converter.

A more constant DC output at the rectifier can be achieved by adding a combination of a resistor capacitor (RC) low pass filter. An active power factor correction (PFC) unit can also be added to the circuit in order to improve the power factor close to one, therefore reducing the reactive power consumption.

Frequency locking PFC converter and the LLC[7] converter is used in order to reduce noise and eliminate electromagnetic interference. Increasing the PFC frequency in synchronization with the LLC at light load[8] will increase the continuous mode operation range of the PFC buck converter (by reducing the current at which this enters discontinuous mode). Therefore, it provides the following advantages: improved light load operation, and reduced distortion [12].

LED Driver

The LED driver takes constant DC voltage as input and outputs variable DC current depending on logic control. Different dimming methods can be applied, such as analogue dimming or PWM. For our purposes, PWM control seems the best option in this case, since a fixed switching frequency can then be selected which optimizes efficiency of the rest of the driver circuit (See appendix G for more details on how the driver works). LEDs are controlled by the logic commands sent from the microcontroller to the LED driver.

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[5] Lumens per Watt represent an indication of efficiency of the light bulbs. Lumens are a measurement of the amount of light that the human eye perceives.

[6] Watts per bulb represent an indication of the electrical power.

[7] LLC is a converter composed of two inductors and a capacitor.

[8] Light load means high output resistance, and low current.

5. Evaluation

5.1. Maintenance

Initial and Maintenance Costs

A disadvantage of using LED lamps concerns the implementation costs, which are higher compared to other lighting methods. Nevertheless we expect that the initial capital costs will be considerably reduced as the technology is improved and popularity increases. In addition, the long lifespan and decreased maintenance costs will lead to increased overall profitability (see Appendix A).

Lifespan

The table below shows the lifetime of the major electrical components:

Component	Mean Time To Failure(MTTF)/Comments
LED Driver (HV9910B)	25+ years. Some higher quality drivers have a MTTF which is 250+ years.
High power White LED	Useful life (until lumen output reaches 70% its initial value) is approximately 35000 – 50000h
Electrolytic Capacitors	8000h at 85^o, approximately 32000h at 60^o. Lifetime is approximately doubled for every 10^o drop in operating temperature.
Inductor	25+ years provided recommended operating conditions are met
Power MOSFET	15+ years provided recommended operating conditions are met
PIR sensor module	10+ years provided adequate protection from the elements (ip65 package)
Microcontroller (ATmega48)	Data retention: 15 years at 85^o, 100 years at 25^o Failure can occur much earlier if input pin and power spikes are not filtered
XBee module	10+ years

Table 4: Lifespan of Components [7], [9]

In summary, the main life limiting component is the electrolytic capacitor. Therefore, regular maintenance should be conducted approximately every 3 years. The cost of the replacement capacitors is negligible (<2£), but the labour costs could be significant, so it could be worthwhile to replace other components during these routine maintenances. For example, every other time the capacitors are changed, the sensor module, MOSFET and LEDs could also be changed. Although ceramic capacitors have a larger lifetime, it has been estimated that the additional cost of these outweigh the advantages.

5.2. Fault Tolerance

We aim to design a system that is able to continue to operate properly in the event when one or more components fail to work. The following characteristics of the system ensure that increased fault tolerance is achieved:

a. **Mesh Network**: A mesh topology and the sufficient transmission range of XBee modules ensure that if any XBee device fails, information can still be transmitted within the network.
b. **Sensors**: PIR sensors are located on every street light pole. This, as well as the sufficient range of the sensor ensure that in the case a sensor is damaged, motion can still be detected by neighbouring sensors (on the same side or on opposite side of the road).
c. **Mains Supply:** This ensures a reliable voltage supply for the circuits as power outages rarely occur in the grid.

6. Further Development

Even Power Usage

This section proposes a method to dynamically control the network such that a constant power usage is maintained within the network. The ultimate purpose of this dynamic network control is to eliminate fluctuations in the power grid due to load changes due to the street lighting.

Different algorithms could be integrated in order to achieve constant power consumption within the network. One of these is illustrated in Appendix F. In brief, when a set of lights are brighten a request to dim the same number of lights is forwarded to the closest neighbors, and is spread outwards until it is met.

Server and Statistical Data

Information will be gathered from the lamps and sent to a main server connected to the ZigBee network. The server stores statistical data that could enable a more efficient control of the network. The statistical data could include the following: average energy consumption and dimming time of the lights. Based on these statistics, the requests mentioned in the even power usage section can be forwarded to the appropriate regions with higher probability of success.

Feedback and Control

The current LED driver can be replaced with one which utilizes feedback to enhance the control of the output current. Although this is more expensive, it could provide more stable and allow more control over the intensity, and hence be advantageous to our system.

7. Conclusion

The fundamental aim of this project is to find a cost-effective and energy efficient replacement for the current street lighting systems. By identifying the causes of energy waste of lamps during night and investigating the requirements needed for the residential area chosen, we were able to develop a design that provides an efficient solution.

In order to reduce the energy spending, our design integrates highly efficient and smartly controlled modules. In brief, the design utilizes dimmable LEDs and wireless technology in order to activate the street lighting in the required area only when motion is detected. The design consists of three main parts which are: motion detection sensors, wireless communication and power control for the LEDs.

In our design, we have included components with desirable features such as low cost, low power consumption and long lifespan. Using appropriate design techniques, we have integrated these components in a system that is reliable, fault tolerant and cost effective. Moreover, the low maintenance costs support the profitability of our design. In addition, the successful implementation of a demonstrator shows that our solution is feasible from the technical point of view (See Appendix G). Further research is currently being conducted on more advanced ways to control the system such to maintain an even power usage within the network.

Overall, the proposed system solves energy spending problems (lower power consumption of street lights) and environmental issues (lower carbon emissions).

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Appendices

Appendix A: Feasibility Analysis

Costs

Table 5 below shows the maintenance costs and Figures for savings of different lamps over a 12 year period. It is illustrated that the maintenance costs for LED lamps are considerably reduced compared to other lamps. [13]

The calculations are based on a 10m wide road and a 6m height of the luminaire [3]. In addition, the calculations refer to a Lower Lighting Level (S4), which is the corresponding level for residential areas.

Lamp Type	No of Columns	Energy Cost	Maintenance	Indicative Installation Cost/ Column	Total Installation Cost
Sodium Lamp	52	24,299.81	576.77	550.33	28,617.16
LED Lamp	43	15,182.17	476.94	855.35	36,780.05

Table 5. Operating Costs for Street Lights

Energy Consumption and Estimated Savings using LEDs

Reducing energy consumptions and therefore, carbon emissions due to street lighting is an important aspect of the Climate Change Strategy of Harrow Council [3].

Table 6 below shows the typical annual energy consumption in Harrow Borough, for a Km of residential lighting. In addition, it presents an estimated energy spending if the street lights were replaced by smart LEDs.

Lamp type	**No of Columns**	**Energy (kWh)**
SON	52	237,744
LED	48	148,539

Table 6. Energy Consumption in Harrow Borough in UK

In addition, it is assumed that using dimming control, there is a potential to save up to 6.6% of existing consumption [3]. (This figure would be much higher in less densely populated areas).

Overall, the energy using dimming control with LEDs will be around 138, 735 kWh. Therefore, the energy savings would be around 41.6% if current street lamps would be replaced by dimmable LEDs.

Options to reduce energy

The development of new Street Lighting Policies is a major contributor to the Climate Change Strategy of the Harrow Council and is aiming at reducing the council's electricity consumption, reducing in the same time the annual carbon emissions.

A new Street Lighting Policy proposes different options to reduce energy. These are: Variable Lighting, Part Night Lighting, Light Trimming, and Light Dimming.

1.1. Variable Lighting

This method ensures that the lights remain lit during the night. However, the intensity level of lights will be dependent on the level of use of the streets. The level of brightness will therefore be adjusted according to traffic statistics: for example, the lights on a main road will have increased brightness, while the lights in a remote area will have reduced brightness.

1.2. Part Night Lighting

This method involves switching the lights off completely during certain time intervals, from 12:00am to 5:00am.

1.3. Trimming

Trimming relates to decreasing the total night period during which the lights are on, by delaying the lighting up time in the evening, as well as bringing forward the switching off in the morning by up to 30 minutes.

1.4. Dimming

The dimming solution is the preferred option in what lighting of Harrow's Residential Areas is concerned. This involves adjusting the lighting levels of LEDs such that lower lighting levels are used when there are no pedestrian or cars on the streets. A survey has been taken in order to determine the public opinion regarding these methods of street lighting and therefore, to help evaluate the system. The following table illustrates the results of the survey.[5]

	Option 1 Decrease Lighting Levels	Option 2 Light Trimming	Option 3 Light Dimming	Option 4 Part Night Lighting
1st Preference	45%	23%	47%	14%
2nd Preference	26%	17%	37%	11%
3rd Preference	19%	43%	14%	12%
4th Preference	10%	16%	2%	63%

Table7. Statistics regarding options to reduce street lighting energy consumption

These results show that Light Dimming is the most favorable options. This can be achieved using a Smart LED Street Lighting Network, where the dimming level of LEDs can be adjusted, leading to significant energy savings in time.

Appendix B: British Standards

British Standards for Road Lighting

The British Standards for Road Lighting are, BS 5489 2003 and BS EN 13201 2003.

The BS 5489 2003 Standard gives recommendations on the design of the lighting of tunnels and takes into account aspects related to traffic safety such as: arrangement of lighting poles, levels of light intensity etc.[1] In order to account for safety policies and to comply with lighting requirement, the dimming option for the lights will not be implemented in road tunnels.

The BS EN 13201 2003 Standard considers the following aspects of road lighting: visual needs of road users and environmental aspects. Different light intensity classes have been designed will be considered.

1. **Reduction of Obtrusive Light**

   In what the Reduction of Obtrusive Light is concerned, there are 4 main zones [14]:

   a. Zone E1 – National Parks, Areas of Outstanding Natural Beauty, Sites of Special Scientific Importance and other Dark Area
   b. Zone E2 - Areas of Low District Brightness (Rural Location outside Zone E1)
   c. Zone E3 - Areas of Medium District Brightness (Urban Location)
   d. Zone E4 - Areas of High District Brightness (Urban Centers with high night time usage)

Harrow District is an urban area of Medium District Brightness. Therefore, policies concerning Zone 3 should be studied in the purpose of implementing the proposed system in this area.

The relevant types of highways for Zone E3 Category are:

a. primary routes
b. district distributors
c. local distributors
d. access roads
e. shared access roads
f. secondary access roads

Categories d), e) and f) roads will generally be considered as residential and lit accordingly. Glare shall be restricted to CEN Luminous Intensity Class G2/3.

In what the footpaths and cycle tracks are concerned, these should be permanently lit if they have a high night time use. If they are located in a remote area with no important night traffic, dimming options should be taken into consideration.

2. **Lighting of pedestrian crossings**

The lighting of pedestrian crossings takes into account two main important factors:

a. Pedestrians should be able to clearly judge traffic conditions
b. Drivers should be able to correctly interpret the visual scene
c. If the use of the crossing is high during night, direct and permanent illumination over the full crossing should be considered.

Therefore, in order to comply with safety policies regarding the lighting of crossings, the proposed system will provide a higher intensity level of lights located at pedestrian crossings.

3. **Light sources**

The British Standards allow using LEDs where appropriate. Several advantages of LED lamps are illustrated, such as: low maintenance implications and energy use, extensive lamp life, white light source.

The specific manufacture standard for lantern is BS EN 60598-2-3 1994 (BS4533). The specific manufacture requirements include the following aspects:

a. All component parts should be easily recyclable
b. The constituent parts should be weather and dust-proof (IP65)
c. The downward light output ratio shall be a minimum of 70%[9]

LED Requirements

According to the investigation on the existing LEDs street lamps, specific requirements for the LED lamps are shown in the following table.

Characteristics		**Typical Values**	**Comments**
High Brightness LEDs	Colour Rendering Index (CRI)	70	This is generally required for most of lighting applications.
	Colour Temperature (CT)	4000K & 5700K	Cool white and daylight
	Initial Lamp Lumen	5000-15000 lumens	This will be specified further according to the local lighting policy.
Approximate Power Consumption		50W-250W	High energy efficiency is also required.
System Power Factor		>90%	
Other requirements		Operating temperature	From -40˚C to +50˚C
		Programmable dimming options	Adequate for our system
Ingress Protection Rating (IP) requirements	Optical	IP65	N/A
	Electrical	IP44	N/A
	Electronic driver	IP66	N/A

Table 8. LED Requirements

---

[9] From the International Electro Technical Commission, the definition for downward light output ratio is:
Downward light output ratio: ratio of the downward flux of the luminaire to the light energy absorbed in luminaire.

Appendix C: LED Advantages

Several advantages of implementing a New Modern Street Lighting System using LEDs are illustrated below: [6]

1. Faster repair timescales

A remote operating system will be used to detect any broken or faulty lights, providing more reliable street lighting. Other maintenance methods such as on night time scouting regimes to find faults become unnecessary.

2. Improvements in road safety

LEDs produce a more natural white light, which provides better facial recognition helping people feel safer at night.

Research carried out during the 1990s showed that criminals take account of security levels such as visibility to witnesses. Therefore, use of white light sources has a positive impact on the crime rate, reducing the risk of night crimes. In addition, due to good colour rendering, white light sources such as LEDs have a significant role to play, particularly when introduced into residential areas.

3. Reduction in energy consumption

The system will use dimming levels of street lights between the hours of 11pm and 5.30am subsequently reducing the energy consumption.

4. Energy Conservation

The UK Government set a target of reducing carbon dioxide emissions by 12.5% on 1990 levels by the year 2010. However, the corporate target is 40% by 2015.

Centrally managed systems shall be considered the preferred option for all existing and proposed street lighting systems. This will give the ability to have complete control over street lights and help reduce energy usage and therefore carbon emissions. In addition, the lights used should be capable of dimming and switching off, should have a high energy efficiency, should support the application of electronic ballasts (lower energy consumption, near unity power factor), should provide lower wattage white light.

LEDs are the most suitable lamps which can meet the above targets.

5. Reduction in light pollution

LEDs can be directed more easily such that light is only shone where needed, e.g. pavement or road. This leads to significant reductions in light pollution in the sky.

Appendix D: ZigBee Network

Addressing

Every ZigBee device has a 64-bit address assigned to it when manufactured. This is called the extended address and is unique to each device.

In addition, the device is assigned a randomly generated 16-bit address (network address) by the co-ordinator or router when it joins a network. When transmitting it is common to include the 64-bit address of the destination to ensure data reaches the correct device because the network address is not static and is therefore not reliable.

Each module also maintains an address table that maps the network address to the extended address. This is useful for unicast transmission as described below [15].

Topologies

	Topology	**Advantages**	**Disadvantages**	**Comments**
Tree	Top node with a branch & leaf structure	• The structure is simple and easy to configure.	• If one 'branch' is disabled, its 'leaves' can't communicate with other devices. • Two nodes close to each other can't communicate directly.	For communication, the signal must go up the tree until the nearest common point and then down the tree.
Mesh	Tree-like structure in which some leaves are directly linked	• Adding or removing a device is easy. • It can eliminate dead zones. • It can provide alternative routes in the case of failure.	• It uses a more complex routing protocol. • It requires greater overhead.	For communication, the signal route can be quite flexible, depending on the configuration of the network.

Table 9. Network Topologies

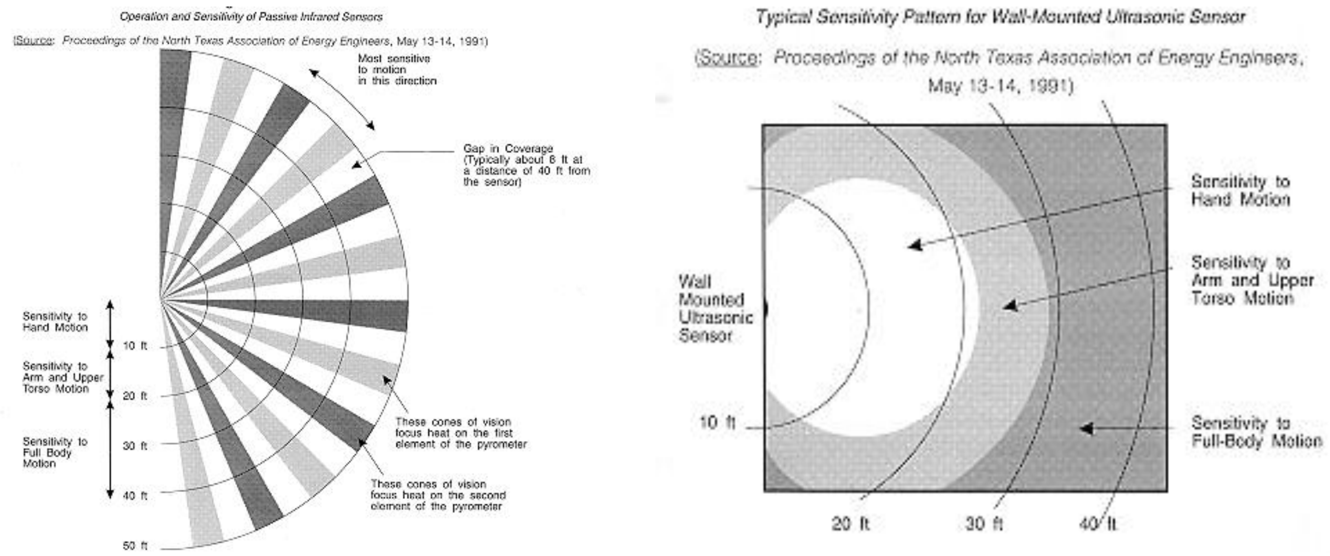
Regarding our application, we have decided that a Mesh Network would be more suitable. The reason is that we wish to provide, in the future, a reliable lighting algorithm for public roads. Hence, taking into consideration safety reason, our network has to deal effectively with the failure of a device. In addition, the routing should be efficient, since our aim is to reduce power consumption. Mesh topology has these attributes, therefore we will use it. Even if it requires more overhead and the routing is more complex, we believe that the positive aspects make it desirable.

Appendix E: Sensors

How PIR Sensors Work

Ultrasonic sensors use the Doppler Effect to detect occupancy. An ultrasonic frequency is emitted and the frequency of the reflected signal is detected. Any difference between these two is interpreted as motion in space. [2]

Passive Infrared (PIR) sensors react to infrared energy emitted by objects. They are passive in the sense that they only detect infrared; they do not emit any. The sensor contains consists of two detectors configured as differential inputs. When a warm object enters the field of one detector, there is a positive differential change. As the object moves to the next field, there is a negative change. These change pulses are detected and interpreted as motion. [3]



Operation and Sensitivity of Passive Infrared Sensors

(Source: *Proceedings of the North Texas Association of Energy Engineers*, May 13-14, 1991)

Typical Sensitivity Pattern for Wall-Mounted Ultrasonic Sensor

(Source: *Proceedings of the North Texas Association of Energy Engineers*, May 13-14, 1991)

Figure 3. PIR Coverage Area

The two Figures above [5] summarise the sensitivity of both these sensors. Although they both lose sensitivity with distance, this shouldn't be a problem for our application since we do not need to detect minute movements. In the PIR case, detection ability is reduced since the width of the 'gap in coverage' increases with radius. In the ultrasonic case, there are no blind spots.

Position of street poles

In general, there are two main positions of street poles: some are placed between the sidewalk and road, and others are placed behind the sidewalk. For the latter, it is possible to use one sensor to detect both vehicles on the road and pedestrians on the sidewalk since both the road and sidewalk are in front of the pole and hence in view of the sensor.

For the previous case, we could use two complimentary sensors pointing in opposite directions, each one focused on detecting motion either on the road or on the path. However, this complicates the design and increases installation costs.

In order to keep the design more flexible, we chose to use one sensor with the largest possible range, within reasonable price. Therefore, even if the pole is placed in-between the road and sidewalk, the sensor has sufficient range to detect objects on the road, as well as on the opposite side of the road. Because there will be poles on both sides of the road, both paths are effectively covered. This also reduces the potential blind spots caused by trees and parked cars.

Position of sensors

The range is 18m and the horizontal viewing angle is 60deg. Since the sensor is most sensitive to lateral motion, it should be placed perpendicular to the pole. The manufacturer recommends installation 1.8 -2.4m above the ground, and Figure 1 shows the detection characteristics for a 2.1m installation. We estimate an installation 2.5-3m above the ground to best satisfy our requirements.

Therefore, there should be sufficient coverage even in cases where cars are parked directly in front of the senor.

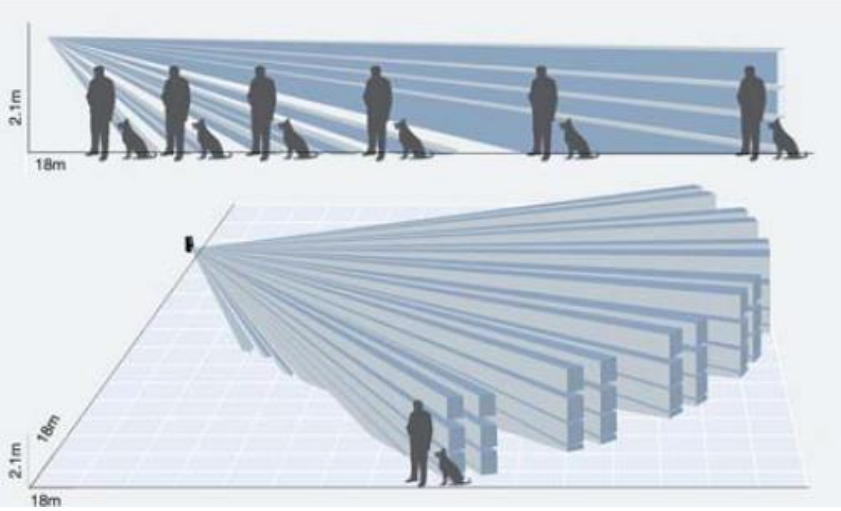


Figure 4. PIR sensor detection type [16]

Algorithm to Control the Lights

The algorithm proposed is referring to the control of the lamps placed in the cluster located at position N. For simplicity, we will assume that in our design, a cluster is composed of 2 devices: a router and an end device. These will be located on opposite sides of the road.

The following assumptions are made:

1. The distance between the street lamps is typically 15-45 m.
2. The range of the motion PIR sensor used is typically 16m and the view angle is 60deg.
3. The algorithm will affect all the street lights, except the ones located at crossroads, which should remain in a permanent bright state.
4. The lights will be off during the day and will be set to a dim state at night. The exact times to turn on the lights at night will be set taking into account different factors such as: location, season, government policies etc. This can also be controlled through the use of an additional photocell which detects ambient lighting levels.
5. The number of neighbour clusters which are lit when a sensor located in the N-th cluster detects motion will be set according to governmental and safety policies. This algorithm presents the situation when the lights located in the 2 adjacent clusters are used. Therefore, whenever motion is detected in one cluster, both the previous and the next clusters will turn on.
6. The difference in intensity between the dim and the bright state will be set according to governmental or safety policies, as well as taking into account extra functionalities of the network (even power usage).
7. The delay time T will be set taking into account the human speed and the distance between the street lights. We consider a minimum walking speed of 5km/h. As the maximum distance between street poles is 45m, the maximum time required for a pedestrian to move from one street pole to another is around 35 seconds.

How the algorithm works:

a. As the range of the sensors is limited to around 18m, which is much lower than the distance between street lights, motion detection could be affected when the object is moving between two adjacent lamp posts. Issues might occur when the object is moving between the two poles, but is neither in the range of the first sensor, nor the second sensor. As the object is not detected in this case, there is no signal to tell the lamps to turn on.

   We could solve this issue by trying to improve the current design of the PIR sensors by enlarging the detection range. However, the sensing might still be affected by other factors such as differences in weather conditions, temperature, humidity etc. [2]

   Therefore, in order to provide a more accurate operation of the lamps and to ensure that the lights turn on at the right time, additional features are added to the algorithm. By using a variable x, we could determine when the lamp has stopped detecting motion, i.e. we could determine when a person has moved out of the detection range of the sensor, but is still moving on the path and thus the lights should be kept on. The variable x will become 1 whenever the lamp detects motion and 0 when the lamp does not detect motion or after it has stopped detecting.

b. When the N-th sensor detects motion, its microcontroller sends a control signal through ZigBee, to the 2 routers located at neighbouring clusters and thus, increasing the intensity of lamps located in those clusters. Moreover, the light intensity of the lamps in the N-th cluster is increased and the variable x is set to 1.

c. If none of the sensors located in the N-th cluster detect motion, we need to check whether they have just detected motion or on the other hand, if they were in a dim state for a very long time. This is done by checking the variable x.

   - If x=1, the sensor has just detected motion, which means that the object is still moving towards an adjacent street pole. Thus, the lamps in the N-th cluster, as well as the lamps in the adjacent clusters should be kept bright for a certain time T.

     The time T was set to 35 seconds, which is an approximation of the maximum time for a pedestrian to travel between two adjacent street poles. A delay time solves the problem when object is moving along the path between two street poles, but it is not detected by either of the sensors located on these poles.

   - If x=0, the sensor has not detected motion, and therefore we need to check whether the lamps in the adjacent (N-1) or (N+1) clusters detect motion. This is illustrated in step d.

d. If any of the adjacent lamps starts detecting motion after the delay time T, it means that the object is moving alongside the detection range of the (N-1) or (N+1)-th clusters. As the N-th cluster is adjacent to these clusters, it should be kept on to ensure enough surrounding light for the moving object.

e. Otherwise, we assume that there is no moving object on the path and therefore, the N-th cluster lamps should go in a dim state. In addition, the variable x should be reset to 0, showing that the N-th cluster lamps go in a dim state.

   The flowchart in Figure 5 below illustrates how the algorithm to control the light works.

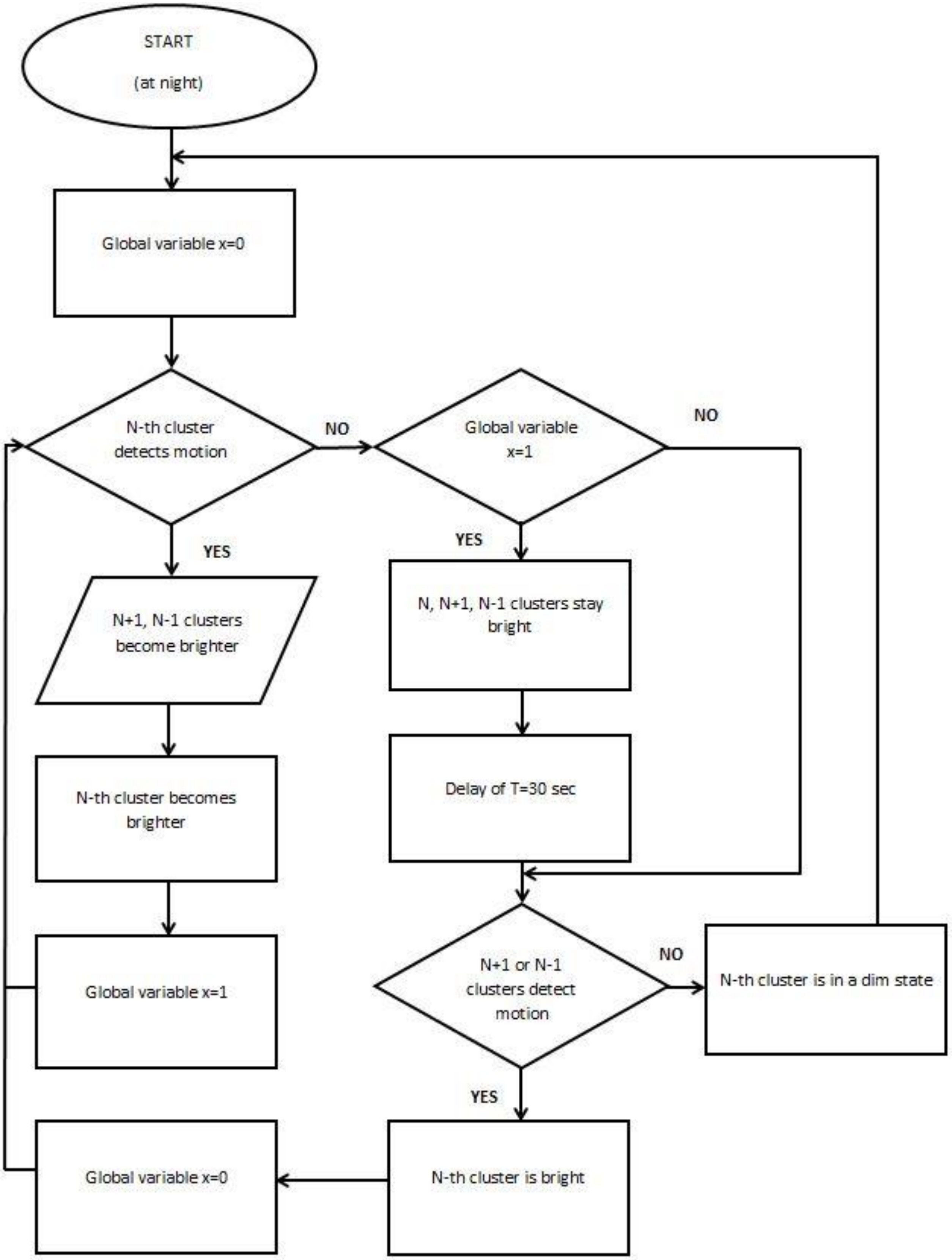


Figure 5. Algorithm to control the sensors

Appendix F: Further Development

Algorithms for Even Power Usage

Network Design

The Street Lighting System can be represented as a complex network, that can be modeled by a graph whose nodes are routers and edges indicate the communication between these routers. For simplicity, we will assume that each lamp in our system is a router, and is therefore able to communicate to other lamps.

An important feature of this network is that it is composed of interconnected sub-networks, which are groups of nodes with common properties. These sub-networks will have similar functions within the graph. For the purpose of our design, the sub-networks will be represented by lamps which are not required to light up at a certain moment in time (we will call these OFF sub-networks), or on the other hand, by lamps which must remain on for a certain period of time (we will call these ON sub-networks).

We are interested in developing an algorithm which could automatically detect such communities and use this information in order to dynamically control the network. Therefore, whenever the lamps in a sub-network turn on, we are trying to find the closest sub-network containing lamps which do not have to turn on at that moment in time. We will dim these lights to a lower brightness level. By doing so, we cancel the effect of lights turning on in the first sub-network and therefore, maintain a constant power consumption.

The algorithms presented below illustrate ways to find the closest OFF sub-network of lights from the current ON sub-network [17].

In this purpose, an offline list of neighboring lamps should be created.

Algorithms for the identification of sub-networks

1. **Depth-first search**

Network Topology

Using this algorithm, we aim to return the node of interest (light that does not have to turn on) closest to the query point (light that turned on).

Algorithm

The depth-first search could be illustrated by the following algorithm:

a. Start from a node which detects motion, which we will call **node M**. This represents the **current node**
b. Push all the neighbors of the current node which have not been visited yet onto the stack containing nodes which are going to be visited.
c. Each neighboring node which does not represent a solution will be added to a list of visited nodes, which we will call Visited
d. If a node is part of the Visited list, we will not check it again. This is to ensure that a node is not visited more than once.
e. For each neighbor of the current node, repeat steps b-d, until we find a solution.

Limitations: A tree topology is more suitable for the implementation of this algorithm, which is not the preferred network topology for our system. In addition, using a depth-first search, we might explore infinitely long paths without being able to find a node with the required properties, when there is in fact a solution of one or a few steps. Therefore, the algorithm might be less appropriate if we are looking for the shortest path solution.

A more suitable algorithm could be Dijkstra's Algorithm. However, this algorithm should be modified in order to return the sub-network of interest closest to the query sub-network [17].

Appendix G: Demonstrator Hardware and Software

Introduction:

The demonstrator model aims to help visualise the concept of the smart LED lights and demonstrates the technical feasibility. It consists of 4 small scale battery powered street lights approximately 1.5m tall. The basic principles to demonstrate include; detecting road users, communication between lamps and dimming the LED's. For demonstrative purposes, we choose to only fit one lamp with a motion sensor. This master lamp then communicates to the subsequent lamps via XBee wireless communication modules. The lamp brightness is controlled by the microcontroller which provides PWM output. The block diagram below shows the main functional modules of the demonstrator.

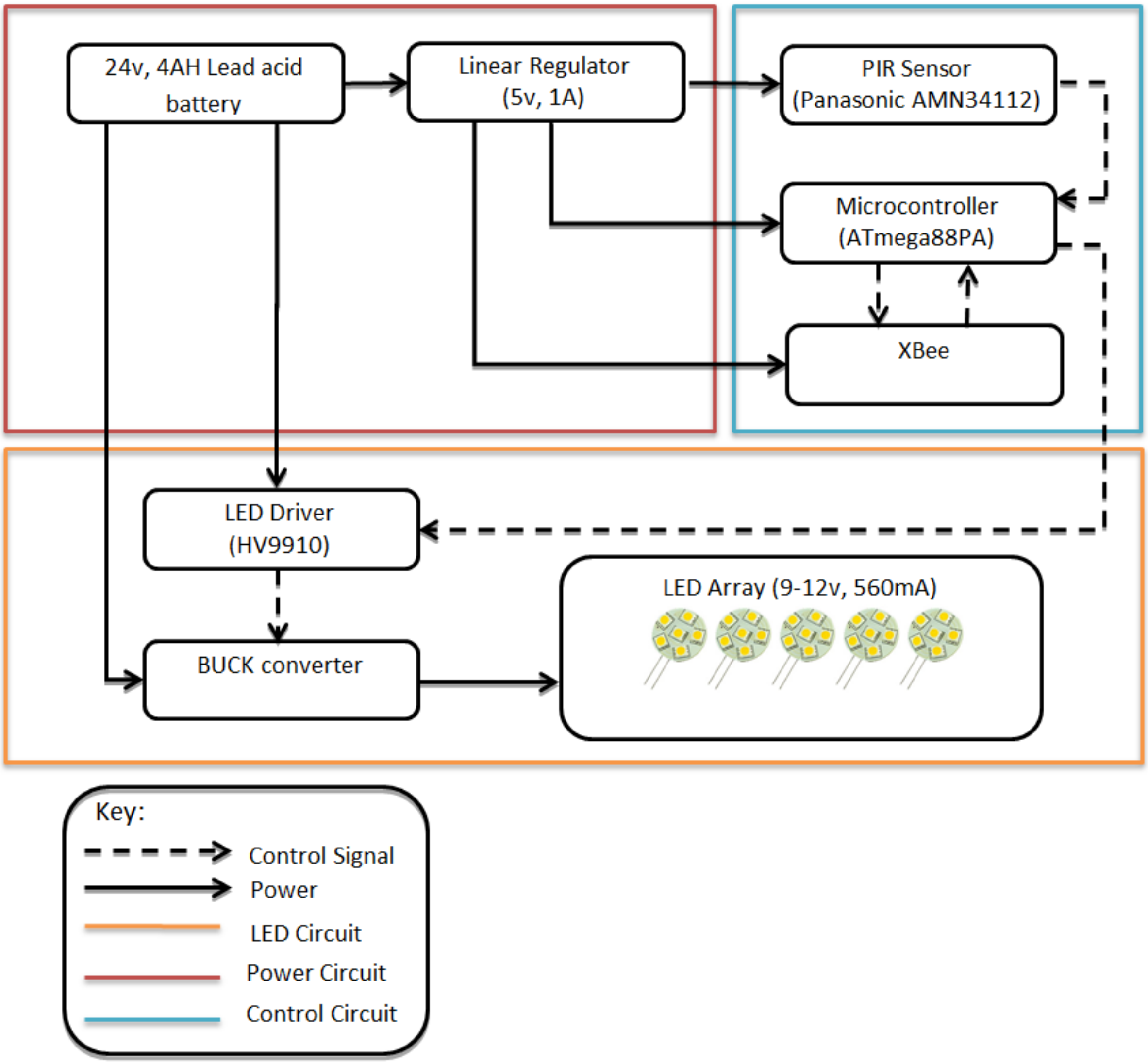


Figure 6. Modular overview of demonstrator

Modules/components explained:

PIR sensor:

A Panasonic AMN34112 digital PIR senor is used to detect the oncoming car on the road. The sensor has 10m range and 110^0 detection angle and provides logic output (5V when active). This was chosen to give wide detection area and to ease of interface with the microcontroller.

Microcontroller

An ATmega88PA microcontroller was chosen because it has Programmable PWM output and it has the required serial interface to communicate with the XBee module. It operates from 5V, the same as the PIR sensor and XBee.

XBee

This offers all the ZigBee network standards, and is power efficient. It has enough range for the prototype (40m).

Regulator

A 5V linear regulator powered from 24Vis used to power the XBee module, the microcontroller and the PIR sensor

LEDs

The LED's were chosen with the following considerations. High brightness is required so that when dimmed we can see the difference easily. The working voltage and current should be relatively low to since the power is supplied from batteries. Therefore, we chose to use 2 x 3 Watt high brightness LED modules per lamp. The nominal ratings are 9-12V for the voltage and 260-280mA for the current. The maximum illumination output of each module is 300-330LM. A heat sink is attached to each LED board to ensure they will not become too hot.

LED driver and buck converter:

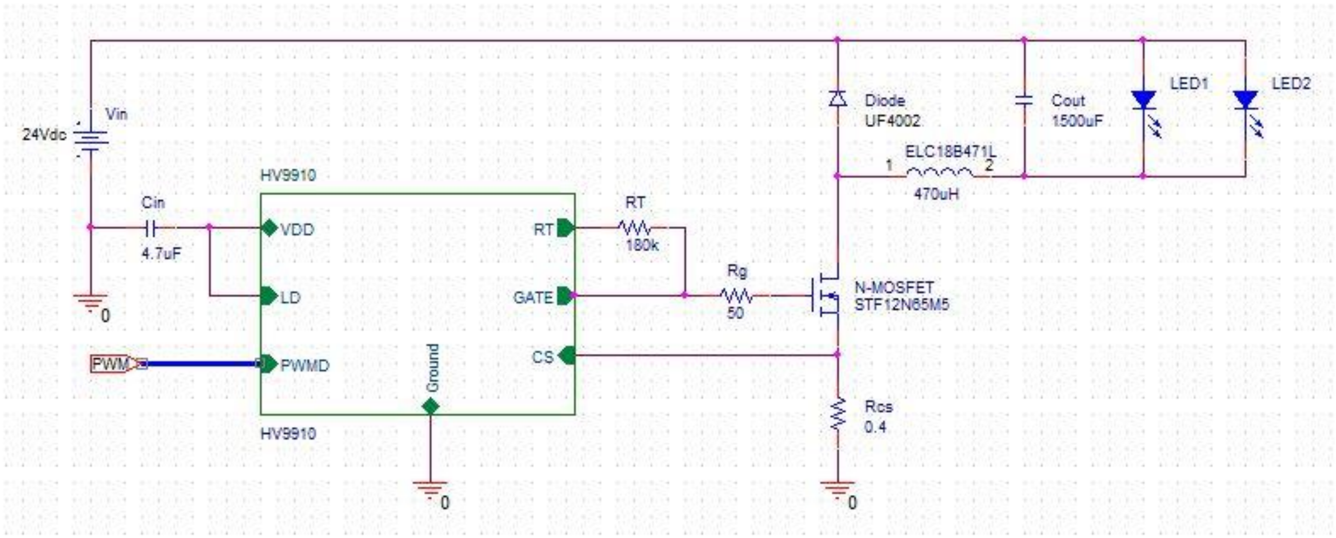


Figure 7. Schematic for the LED driver and buck converter

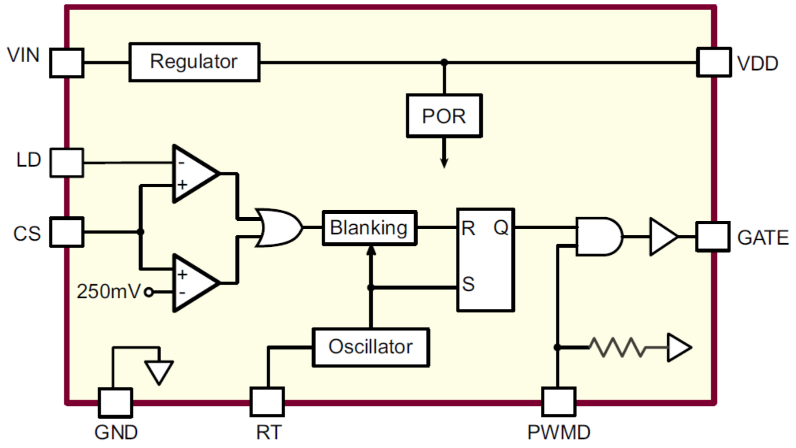


Figure 8. Modular overview of LED Driver (HV9910) [18]

Overview of the driver

The HV9910B is a high brightness LED controller which drives the MOSFET of an external buck converter. The output current can be controlled by either a linear dimming input, or PWM dimming input applied at PWMD pin. It can give good output current regulation in open loop mode and a low cost driver circuit can be implemented with very few external components [18]. With a buck converter, the desired output voltages and currents can be obtained with efficiency exceeding 90%. The input voltage range is from 8V to 450V which is desirable for both demonstrator and final large scale implementation.

Detailed operation of the LED driver

The pulse width modulation dimming (PWMD) input pin of the driver is driven by a PWM signal form the microcontroller at around 500Hz. When the PWMD input is Low, the gate driver of the MOSFET is disabled. When PWMD input is high, the MOSFET is dynamically controlled by internally generated higher frequency PWM signal and a reasonably constant current flow through LEDs. Therefore, average current flowing through LED is linearly proportional to the duty cycle of the PWMD input.

The constant current is achieved by the comparators connected to the current sense (CS) pin (Figure 8). While the MOSFET is on, the current through the inductor and hence the LEDs and CS resistor is increasing linearly. As a result the voltage across the CS pin is increasing linearly. When this reaches 250mv, the reset-set (RS) flip flop is reset and the MOSFET is turned off. Hence the current starts decreasing linearly. It is 250mV in our case because we connected the linear dimming (LD) to VDD. After some time (the switching frequency explained in the following sections), a new cycle is initiated by the internal oscillator which sets the RS flip flop high and everything repeats. If this ripple is fixed in amplitude, and the peak is fixed by the driver chip, then the average current must be constant.

VDD provides the power for the internal circuitry, and the GATE is driven with the equivalent voltage. The LD pin is for the linear dimming input which is not used in our case, and so set to VDD. This pin can be used to override the internal 250mv threshold on the CS pin to lower values.

Notes on the buck converter circuit:

The N channel Enhancement MOSFET is controlled by the driver chip. A 50 Ω resistor is added between the GATE output pin and the gate of the MOSFET. This limits the maximum current from the gate driver to maximum of 150mA since the driver can only source and sink 165mA. The recommended total gate charge of this MOSFET is less than 25nC for switching frequencies smaller than 100 kHz and less than 15nC for switching frequencies larger than 100 kHz. The gate voltage from the chip is 7.5V so the threshold voltage should be smaller than this value. Therefore, we chose which has the typical threshold voltage 4V and total gate charge 20nC. Additionally, the maximum drain source voltage is 650V and the maximum continuous drain current is 8.5A, which is more than sufficient for our demonstrator.

The diode was chosen such that it doesn't break down at -24V, and it can handle the maximum LED current of 500mA and have sufficient recovery time to be able to operate at 80 kHz. The device chosen is UF4002, 100V, 1A and has a reverse recovery time of 50 nanoseconds.

The inductor and the capacitor ensure the current through the LEDS is reasonably constant. In actual fact, the current through the inductor is a DC current with triangular ripple, but this ripple is necessary for the internal operation of the driver chip. For best results, it is recommended that the ripple current through the inductor is around 30% the total output current. Additionally, the inductor must not saturate at 500mA, and must have a small series resistance for high efficiency. Based on our switching frequency of around 80 KHz (this decision is explained below), and equation 1, we chose a 470μH Inductor, with a saturation current of 1.6A, and 210mΩ resistance.

$$L = \frac{V_{in} - V_{LED}}{f_{switching} \Delta I} \frac{V_{LED}}{V_{in}} \quad \textit{(eq.1)}$$

The switching frequency will have an impact on both the MOSFET and the inductor. If the switching frequency is very high, MOSFET will dissipate too much power. On the other hand, if the switching frequency is too small, we then need larger inductor and output capacitor. Considering the above two constraints, we chose a moderate switching frequency of 80 KHz. We decided to use the driver in constant off time mode since this allows for better current regulation and stability [2, p1]. The following equation gives the value of the constant off time required for this desired frequency. Note that the frequency varies based on input and output voltages, but this is tolerable since the input voltage and the output are reasonably fixed in our case.

$$t_{OFF} = \frac{1}{f_{switching}} \left(1 - \frac{V_{out}}{V_{in}}\right) \quad \textit{(eq.2)}$$

The off time is then set by the resistor R_T, and is given by equation 3. From this, 180kΩ is required.

$$t_{OFF}(\mu s) = \frac{R_T(k\Omega) + 22}{25} \quad \textit{(eq.3)}$$

While the driver is enabled, the peak current is set by the CS resistor and is given by equation 4. ΔI is the ripple current in the inductor as a fraction of the average (assuming continuous conduction operation), and in our case $(1 + \Delta I)$ is 1.15 since we have a 30% ripple. For 500mA, we used a 0.4 Ω resistor.

$$R_{cs}(\Omega) = \frac{0.25(v)}{(1 + \Delta I)\, I_{LED(A)}} \quad \textit{(eq.4)}$$

Figure 9 shows the implementation of this circuit on a bread board. Note that because R_{cs} is so small, and the resistance of the tracks in the breadboard are greater than this, we had to mount the resistor directly onto the PCB on which the driver is mounted.

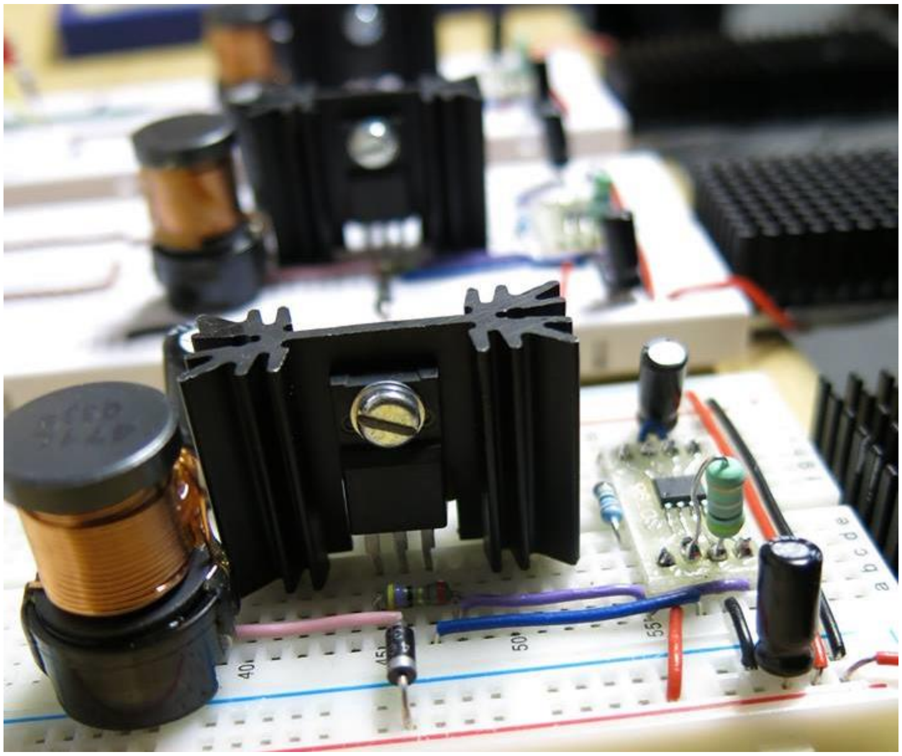
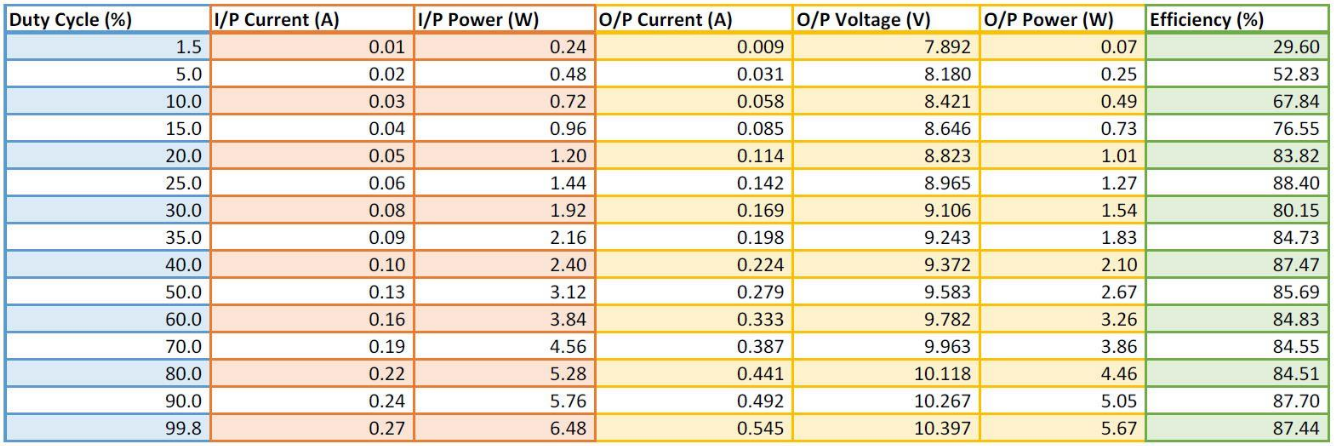


Figure 9. Implementation of the power circuit

Power Circuit Test

Test Conditions

The input voltage is 24V from the power supply unit [19]. To simulate the PWM signal from the microcontroller, we used a signal generator to send a 500Hz square wave with amplitude 5V into the PWM pin of HV9910B. The test results are shown in the Table 10.



Duty Cycle (%)	I/P Current (A)	I/P Power (W)	O/P Current (A)	O/P Voltage (V)	O/P Power (W)	Efficiency (%)
1.5	0.01	0.24	0.009	7.892	0.07	29.60
5.0	0.02	0.48	0.031	8.180	0.25	52.83
10.0	0.03	0.72	0.058	8.421	0.49	67.84
15.0	0.04	0.96	0.085	8.646	0.73	76.55
20.0	0.05	1.20	0.114	8.823	1.01	83.82
25.0	0.06	1.44	0.142	8.965	1.27	88.40
30.0	0.08	1.92	0.169	9.106	1.54	80.15
35.0	0.09	2.16	0.198	9.243	1.83	84.73
40.0	0.10	2.40	0.224	9.372	2.10	87.47
50.0	0.13	3.12	0.279	9.583	2.67	85.69
60.0	0.16	3.84	0.333	9.782	3.26	84.83
70.0	0.19	4.56	0.387	9.963	3.86	84.55
80.0	0.22	5.28	0.441	10.118	4.46	84.51
90.0	0.24	5.76	0.492	10.267	5.05	87.70
99.8	0.27	6.48	0.545	10.397	5.67	87.44

Table 10: Power Test Results

It can be seen from Figure 10 that the LED current and the duty cycle have the linear relation. Since the lumen of LED is also linearly dependent on the current (Figure 12), the brightness of LEDs can be controlled by the PWM on almost full duty cycle range. From observation, the brightness of LEDs is increasing as the duty cycle increases.

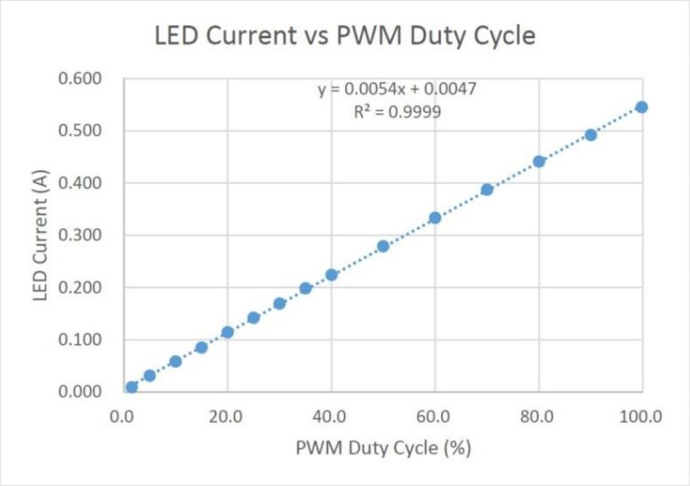


Figure 10. Graph of LED current against PWMD

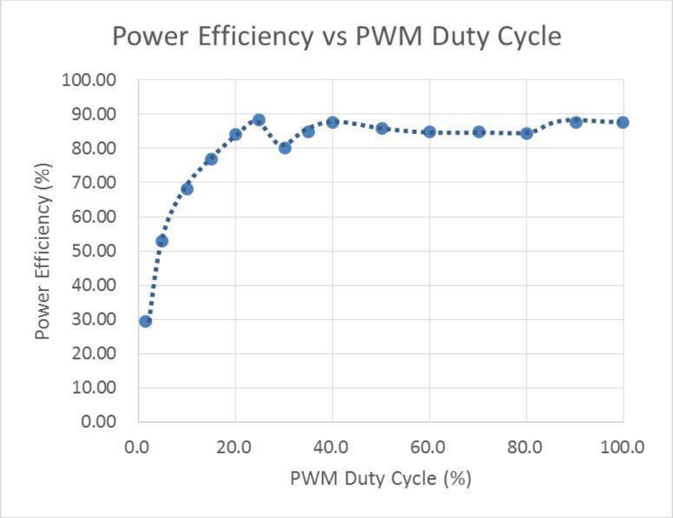


Figure 11. Graph of efficiency against PWMD

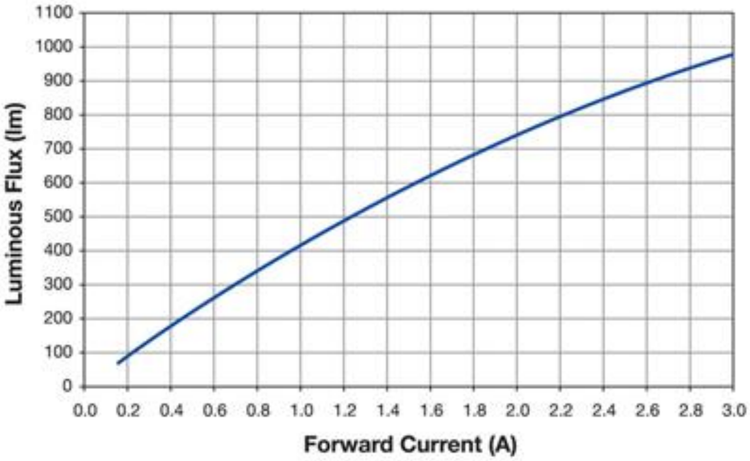
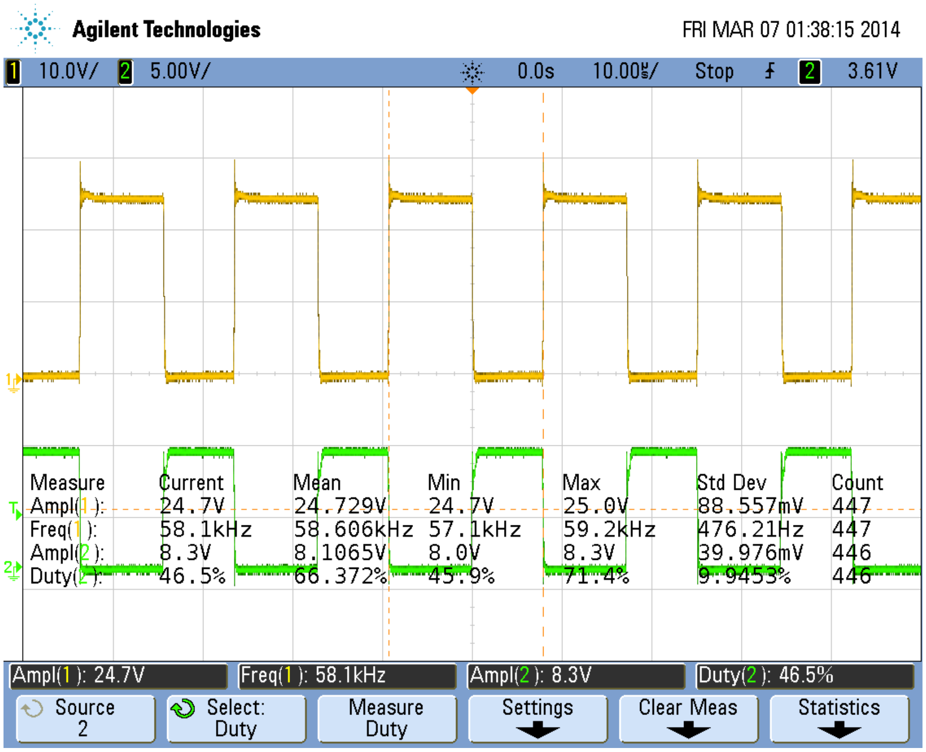


Figure 12. Graph of lumen output against LED current

From Figure 11, the efficiency of our driver circuit can be up to around 90% when the lights are fully on. From a duty cycle of 30% to 100%, the efficiency is also very stable.



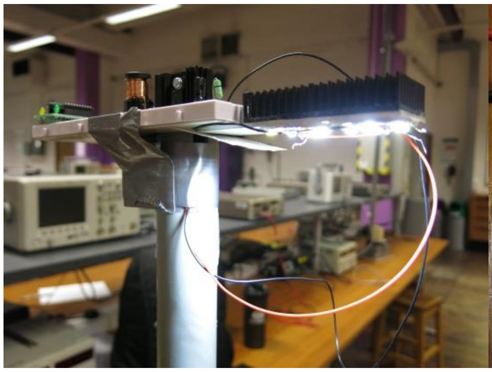
Measure	Current	Mean	Min	Max	Std Dev	Count
Ampl(1):	24.7V	24.729V	24.7V	25.0V	88.557mV	447
Freq(1):	58.1kHz	58.606kHz	57.1kHz	59.2kHz	476.21Hz	447
Ampl(2):	8.3V	8.1065V	8.0V	8.3V	39.976mV	446
Duty(2):	46.5%	66.372%	45.9%	71.4%	9.9453%	446

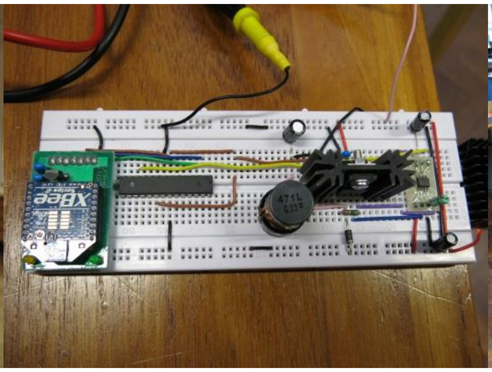
Figure 13. MOSFET gate and drain waveforms

Figure 13 shows the wave forms of MOSFET gate voltage (yellow) and the drain voltage (green). It can be clearly seen that they are well-controlled by the PWM signal. It also shows that the real switching frequency (57 kHz) is smaller but close to the selected value (80kHz).

According to our test results, it can be concluded that our driver circuit operates well to control the brightness of LEDs, which is highly desirable in our design case.

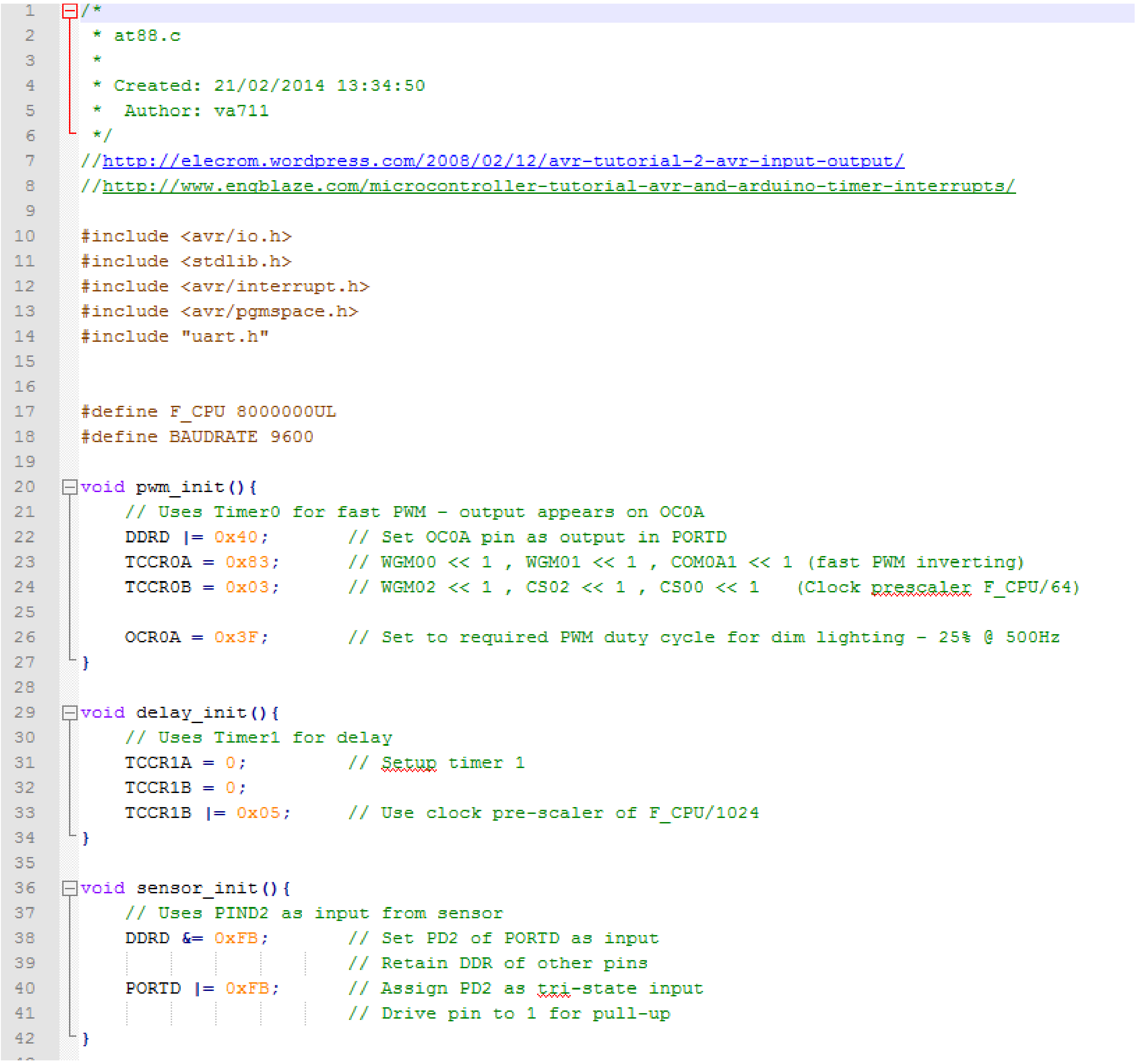
Below are some images of the hardware demonstrator (still in construction):



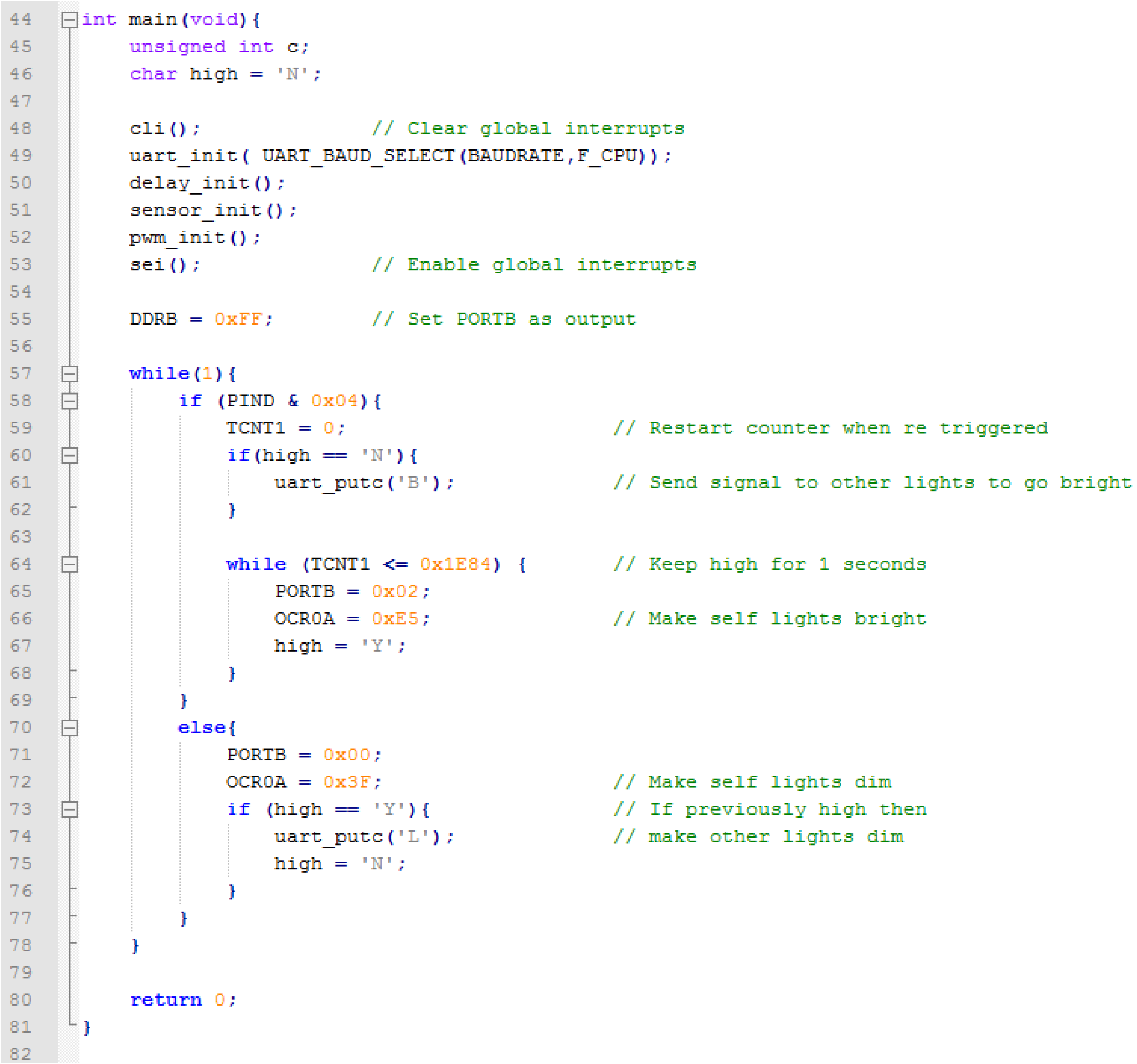


Software:

Code for the Coordinator:

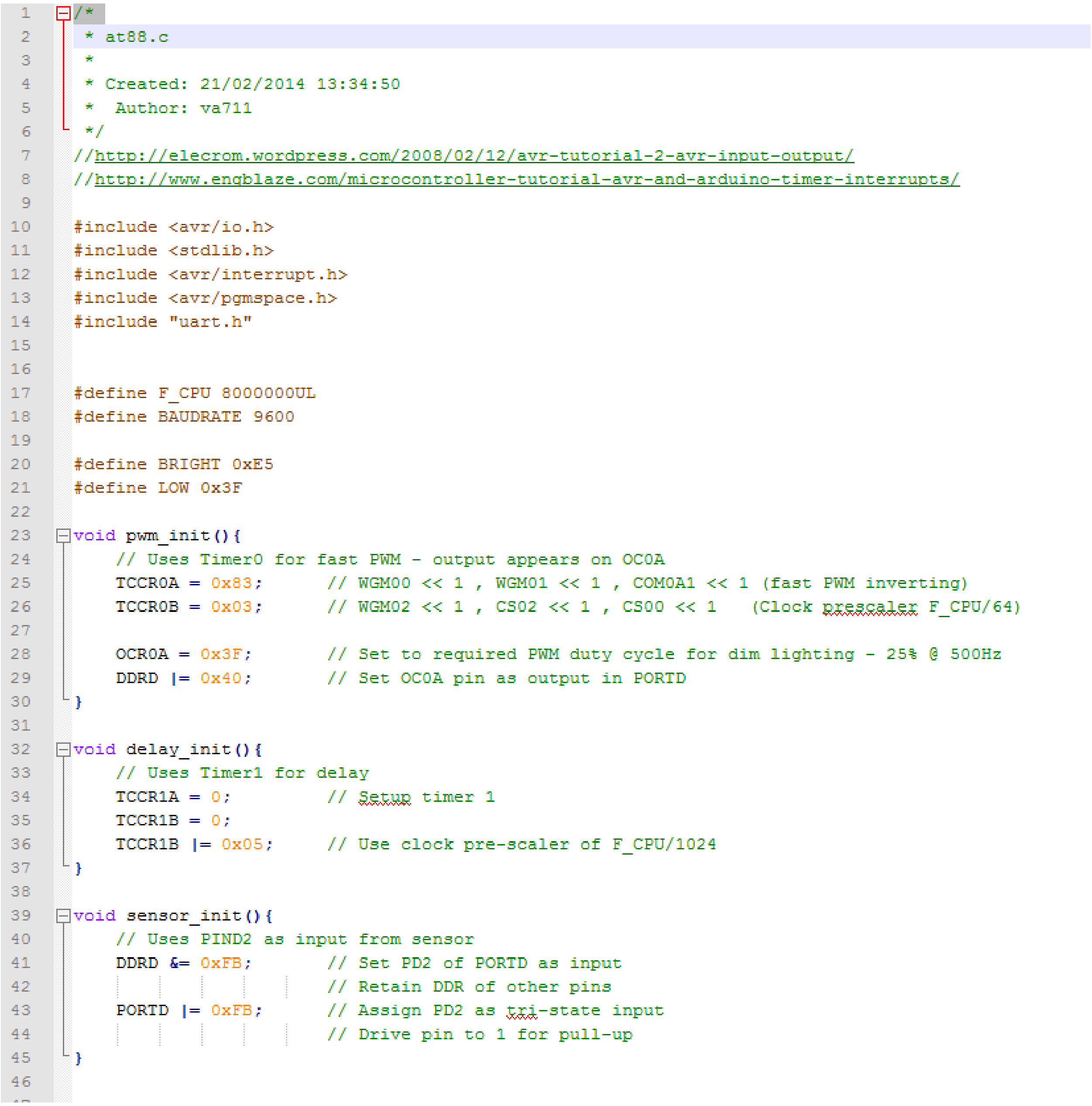


```c
/*
 * at88.c
 *
 * Created: 21/02/2014 13:34:50
 *  Author: va711
 */
//http://elecrom.wordpress.com/2008/02/12/avr-tutorial-2-avr-input-output/
//http://www.engblaze.com/microcontroller-tutorial-avr-and-arduino-timer-interrupts/

#include <avr/io.h>
#include <stdlib.h>
#include <avr/interrupt.h>
#include <avr/pgmspace.h>
#include "uart.h"


#define F_CPU 8000000UL
#define BAUDRATE 9600

void pwm_init(){
    // Uses Timer0 for fast PWM - output appears on OC0A
    DDRD |= 0x40;       // Set OC0A pin as output in PORTD
    TCCR0A = 0x83;      // WGM00 << 1 , WGM01 << 1 , COM0A1 << 1 (fast PWM inverting)
    TCCR0B = 0x03;      // WGM02 << 1 , CS02 << 1 , CS00 << 1   (Clock prescaler F_CPU/64)

    OCR0A = 0x3F;       // Set to required PWM duty cycle for dim lighting - 25% @ 500Hz
}

void delay_init(){
    // Uses Timer1 for delay
    TCCR1A = 0;         // Setup timer 1
    TCCR1B = 0;
    TCCR1B |= 0x05;     // Use clock pre-scaler of F_CPU/1024
}

void sensor_init(){
    // Uses PIND2 as input from sensor
    DDRD &= 0xFB;       // Set PD2 of PORTD as input
                        // Retain DDR of other pins
    PORTD |= 0xFB;      // Assign PD2 as tri-state input
                        // Drive pin to 1 for pull-up
}
```

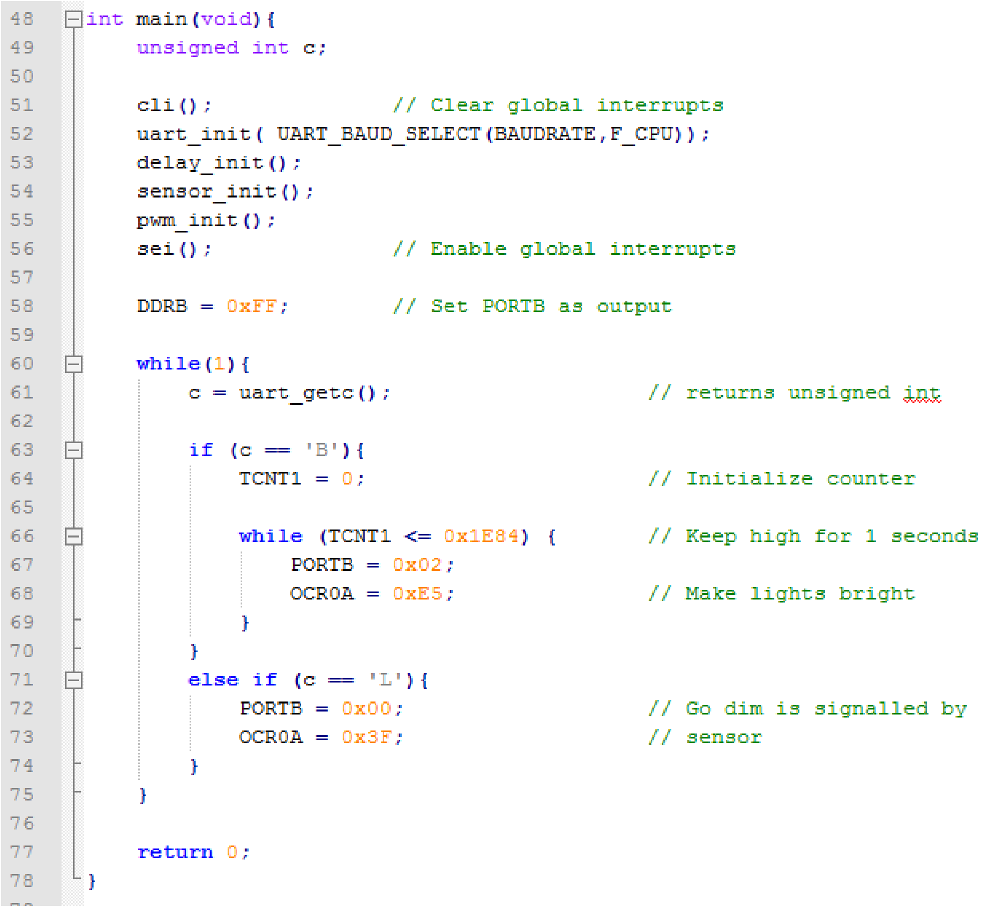


```
int main(void){
    unsigned int c;
    char high = 'N';

    cli();              // Clear global interrupts
    uart_init( UART_BAUD_SELECT(BAUDRATE,F_CPU));
    delay_init();
    sensor_init();
    pwm_init();
    sei();              // Enable global interrupts

    DDRB = 0xFF;        // Set PORTB as output

    while(1){
        if (PIND & 0x04){
            TCNT1 = 0;                      // Restart counter when re triggered
            if(high == 'N'){
                uart_putc('B');             // Send signal to other lights to go bright
            }

            while (TCNT1 <= 0x1E84) {       // Keep high for 1 seconds
                PORTB = 0x02;
                OCR0A = 0xE5;               // Make self lights bright
                high = 'Y';
            }
        }
        else{
            PORTB = 0x00;
            OCR0A = 0x3F;                   // Make self lights dim
            if (high == 'Y'){               // If previously high then
                uart_putc('L');             // make other lights dim
                high = 'N';
            }
        }
    }

    return 0;
}
```

Code for the Router:



```c
/*
 * at88.c
 *
 * Created: 21/02/2014 13:34:50
 *  Author: va711
 */
//http://elecrom.wordpress.com/2008/02/12/avr-tutorial-2-avr-input-output/
//http://www.engblaze.com/microcontroller-tutorial-avr-and-arduino-timer-interrupts/

#include <avr/io.h>
#include <stdlib.h>
#include <avr/interrupt.h>
#include <avr/pgmspace.h>
#include "uart.h"


#define F_CPU 8000000UL
#define BAUDRATE 9600

#define BRIGHT 0xE5
#define LOW 0x3F

void pwm_init(){
    // Uses Timer0 for fast PWM - output appears on OC0A
    TCCR0A = 0x83;      // WGM00 << 1 , WGM01 << 1 , COM0A1 << 1 (fast PWM inverting)
    TCCR0B = 0x03;      // WGM02 << 1 , CS02 << 1 , CS00 << 1   (Clock prescaler F_CPU/64)

    OCR0A = 0x3F;       // Set to required PWM duty cycle for dim lighting - 25% @ 500Hz
    DDRD |= 0x40;       // Set OC0A pin as output in PORTD
}

void delay_init(){
    // Uses Timer1 for delay
    TCCR1A = 0;         // Setup timer 1
    TCCR1B = 0;
    TCCR1B |= 0x05;     // Use clock pre-scaler of F_CPU/1024
}

void sensor_init(){
    // Uses PIND2 as input from sensor
    DDRD &= 0xFB;       // Set PD2 of PORTD as input
                        // Retain DDR of other pins
    PORTD |= 0xFB;      // Assign PD2 as tri-state input
                        // Drive pin to 1 for pull-up
}

```



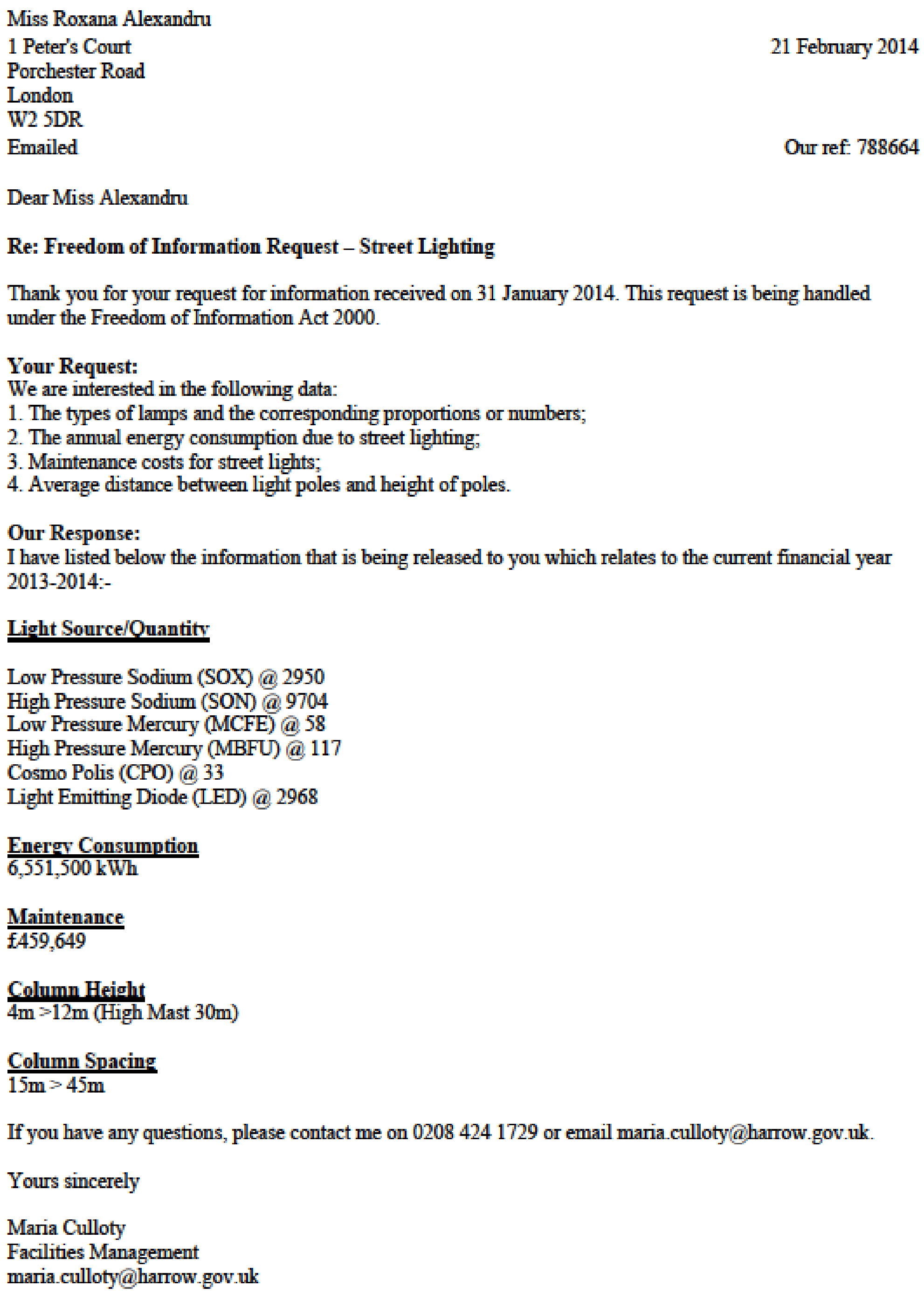
```c
int main(void){
    unsigned int c;

    cli();              // Clear global interrupts
    uart_init( UART_BAUD_SELECT(BAUDRATE,F_CPU));
    delay_init();
    sensor_init();
    pwm_init();
    sei();              // Enable global interrupts

    DDRB = 0xFF;        // Set PORTB as output

    while(1){
        c = uart_getc();                    // returns unsigned int

        if (c == 'B'){
            TCNT1 = 0;                      // Initialize counter

            while (TCNT1 <= 0x1E84) {       // Keep high for 1 seconds
                PORTB = 0x02;
                OCR0A = 0xE5;               // Make lights bright
            }
        }
        else if (c == 'L'){
            PORTB = 0x00;                   // Go dim is signalled by
            OCR0A = 0x3F;                   // sensor
        }
    }

    return 0;
}
```

Appendix H: Requested Information from Councils

The information provided by several Boroughs of London clearly illustrates the following:

a. Old street light technologies are predominantly used such as sodium lamps;
b. The maximum column spacing is 45m;
c. The energy consumption due to street lighting is important and leads to significant carbon emissions.

Harrow Borough



Miss Roxana Alexandru
1 Peter's Court
Porchester Road
London
W2 5DR
Emailed

21 February 2014

Our ref: 788664

Dear Miss Alexandru

Re: Freedom of Information Request – Street Lighting

Thank you for your request for information received on 31 January 2014. This request is being handled under the Freedom of Information Act 2000.

Your Request:
We are interested in the following data:
1. The types of lamps and the corresponding proportions or numbers;
2. The annual energy consumption due to street lighting;
3. Maintenance costs for street lights;
4. Average distance between light poles and height of poles.

Our Response:
I have listed below the information that is being released to you which relates to the current financial year 2013-2014:-

Light Source/Quantity

Low Pressure Sodium (SOX) @ 2950
High Pressure Sodium (SON) @ 9704
Low Pressure Mercury (MCFE) @ 58
High Pressure Mercury (MBFU) @ 117
Cosmo Polis (CPO) @ 33
Light Emitting Diode (LED) @ 2968

Energy Consumption
6,551,500 kWh

Maintenance
£459,649

Column Height
4m >12m (High Mast 30m)

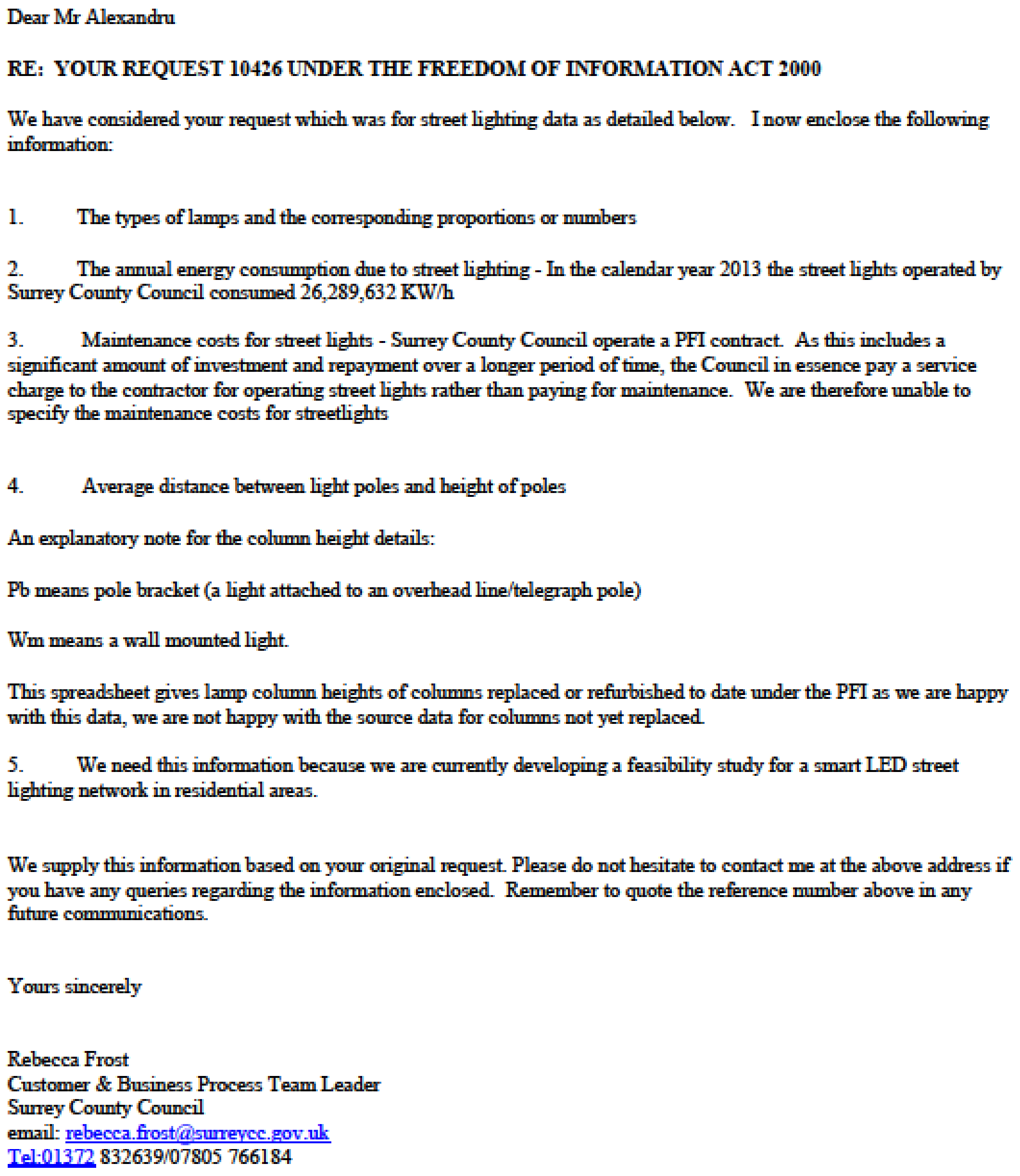
Column Spacing
15m > 45m

If you have any questions, please contact me on 0208 424 1729 or email maria.culloty@harrow.gov.uk.

Yours sincerely

Maria Culloty
Facilities Management
maria.culloty@harrow.gov.uk

Surrey Borough



Dear Mr Alexandru

RE: YOUR REQUEST 10426 UNDER THE FREEDOM OF INFORMATION ACT 2000

We have considered your request which was for street lighting data as detailed below. I now enclose the following information:

1. The types of lamps and the corresponding proportions or numbers

2. The annual energy consumption due to street lighting - In the calendar year 2013 the street lights operated by Surrey County Council consumed 26,289,632 KW/h

3. Maintenance costs for street lights - Surrey County Council operate a PFI contract. As this includes a significant amount of investment and repayment over a longer period of time, the Council in essence pay a service charge to the contractor for operating street lights rather than paying for maintenance. We are therefore unable to specify the maintenance costs for streetlights

4. Average distance between light poles and height of poles

An explanatory note for the column height details:

Pb means pole bracket (a light attached to an overhead line/telegraph pole)

Wm means a wall mounted light.

This spreadsheet gives lamp column heights of columns replaced or refurbished to date under the PFI as we are happy with this data, we are not happy with the source data for columns not yet replaced.

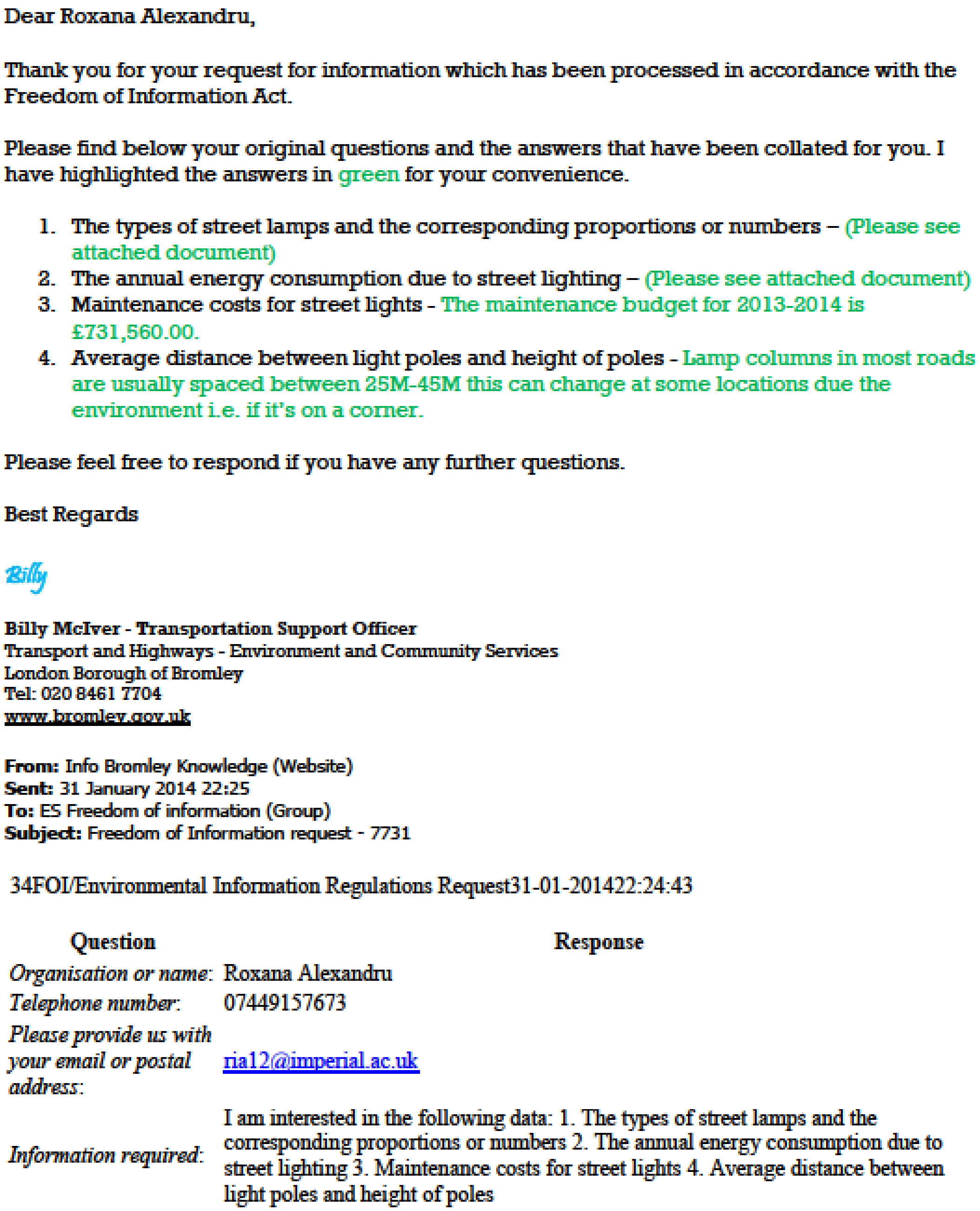
5. We need this information because we are currently developing a feasibility study for a smart LED street lighting network in residential areas.

We supply this information based on your original request. Please do not hesitate to contact me at the above address if you have any queries regarding the information enclosed. Remember to quote the reference number above in any future communications.

Yours sincerely

Rebecca Frost
Customer & Business Process Team Leader
Surrey County Council
email: rebecca.frost@surreycc.gov.uk
Tel:01372 832639/07805 766184

Bromley Borough



Dear Roxana Alexandru,

Thank you for your request for information which has been processed in accordance with the Freedom of Information Act.

Please find below your original questions and the answers that have been collated for you. I have highlighted the answers in green for your convenience.

1. The types of street lamps and the corresponding proportions or numbers – (Please see attached document)
2. The annual energy consumption due to street lighting – (Please see attached document)
3. Maintenance costs for street lights - The maintenance budget for 2013-2014 is £731,560.00.
4. Average distance between light poles and height of poles - Lamp columns in most roads are usually spaced between 25M-45M this can change at some locations due the environment i.e. if it's on a corner.

Please feel free to respond if you have any further questions.

Best Regards

Billy

Billy McIver - Transportation Support Officer
Transport and Highways - Environment and Community Services
London Borough of Bromley
Tel: 020 8461 7704
www.bromley.gov.uk

From: Info Bromley Knowledge (Website)
Sent: 31 January 2014 22:25
To: ES Freedom of information (Group)
Subject: Freedom of Information request - 7731

34FOI/Environmental Information Regulations Request31-01-201422:24:43

Question	Response
Organisation or name:	Roxana Alexandru
Telephone number:	07449157673
Please provide us with your email or postal address:	ria12@imperial.ac.uk
Information required:	I am interested in the following data: 1. The types of street lamps and the corresponding proportions or numbers 2. The annual energy consumption due to street lighting 3. Maintenance costs for street lights 4. Average distance between light poles and height of poles