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Distributed Communication for Streetlight Systems

A decentralized solution

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**Abstract**

Streetlights are usually lit during all dark hours even though vehicles or other objects are not using the road. Instead of wasting energy on keeping the streetlights lit when no vehicles are using the road, the streetlights should be lit whenever vehicles are in proximity of the streetlights and turned off otherwise. A distributed network can be used to handle the communication between streetlights for sharing information about vehicles in proximity. There are streetlight systems that adapt from the environment and handles communication but are still not optimized for country roads with low frequency of vehicles. Therefore, distributed communication for streetlight systems is implemented, by letting the streetlights be a part of a distributed system. Each streetlight is represented with a Zolertia RE-Mote, a sensor for detecting objects and an LED. The representation of the streetlights are wirelessly connected as a mesh network where they can communicate with each other and forward data packets to nodes more far away in the network. The concept of having the streetlights in a distributed system is believed to work and can be considered to be applied on streetlights at country roads to save energy.

**Keywords**

Streetlights, Distributed system, Decentralization, Internet Of Things

**Abstract**

Gatlyktor är oftast tända under alla timmar då det är mörkt ute, även fast det inte är något fordon eller annat objekt som använder vägen. Istället för att slösa energi på att ha gatlyktorna tända när det inte är några fordon som använder vägen, bör gatlyktorna vara tända när fordon är i närheten av dem och släckta annars. Ett distribuerat nätverk kan användas för att hantera kommunikationen mellan gatlyktor till att dela information om fordon i närheten. Det finns gatlyktsystem som anpassar efter miljön och hanterar kommunikationen, men är inte optimerat för landsvägar med låg trafik. Därför är distribuerad kommunikation för gatlyktsystem implementerat genom att låta gatlyktorna vara en del av ett distribuerat system. Varje gatlykta är representerad med en Zolertia RE-Mote, en sensor för detektering av objekt och en LED. Representationen är trådlöst kopplat som ett mesh- nätverk där de kan kommunicera med varandra och skicka vidare datapaket till noder längre bort i nätverket. Konceptet att ha gatlyktorna i ett distribuerat system tros fungera och kan tänkas att appliceras på gatlyktor på landsvägar för att spara energi.

**Nyckelord**

Gatlyktor, Distribuerat system, Decentralisering, Internet Of Things

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# Introduction

Streetlights exist along roads to give a good visibility for vehicles and people. The lights are usually lit during all dark hours consuming energy unnecessarily when no one is using a road. A streetlight system can be created for lowering the amount of energy consumed on roads with low frequency of vehicles. There are streetlight systems used in the real world for lowering the energy consumption. One streetlight system is used for changing the intensity of the light depending on the weather and vehicle frequency [1]. This means that a lower frequency of vehicles will get less light than a high frequency of vehicles. A vehicle should get the same amount of light independent of the amount of vehicles using a road, to ensure driver safety.

The technique of changing the light intensity can instead depend on the position, direction and speed of a vehicle, by giving more light in proximity of vehicles and lower the intensity or turn off the lights where there are no vehicles. To determine a vehicle's position, direction and speed, a Vehicular Ad-hoc Network (VANET) [2] can be used. A VANET is a network where the vehicles and streetlights can interact with each other [2]. The problem with a VANET is that it carries sensitive data from vehicles and people, which can violate personal integrity if it ends up in the wrong hands.

## Background

Streetlight communication is normally done as a mesh network [3], where each streetlight has a direct connection with its nearest neighbors. The reason why a mesh network is used in a streetlight system is that the wires or the wireless signals do not need to have that long range. Most of the existing streetlight systems use a central control unit for distributing light information to the streetlights. The central control unit monitors like power consumption or to find out if a lamp is broken, from the sensors at each light [4][5][6][7].

Instead of having a centralized solution the communication can be decentralized to avoid the communication from going through a central unit. A decentralized solution means there is communication directly between streetlights which removes the single point of failure from the central unit and adds scalability to the system [8]. The scalability property means it should be easy to expand with new streetlights and lower the consequence of a broken one. A decentralized system would be optimized on country roads with low frequency of vehicles, to let the data packets flow in proximity of a moving vehicle.

## Problem

The main focus will be to create distributed communication for handling the distribution of data packets between the streetlights, so that there is a structure for sending and receiving data packets. Distributed communication can either be done in a centralized or a decentralized manner. Each streetlight has to know which data packets to ignore, read and forward. The distributed

communication also have to have some sort of fault tolerance, because the visibility for drivers is important for their and others safety.

To handle communication between the streetlights, a data transmission medium have to be used which either can be done by wire or wireless. If wired communication is used, the existing power line can be utilized together with hardware for sending and receiving data packets [9]. If instead wireless communication is used, the important thing to consider is that the transceiver at least needs to handle the range of 30-40 meters, which is the normal distance between the streetlights in Sweden [10]. A programmable device needs to be used at each streetlight for implementing the distributed communication.

How should the distributed communication be implemented for streetlight systems?

## Purpose

The purpose of the thesis is to present distributed communication for streetlight systems, where each streetlight can communicate directly with its neighbors and forward data packets from other streetlights. The idea is to let the data packets flow in proximity of the vehicles, and light up enough visibility for drivers. The streetlight system is supposed to mainly work for vehicles but also pedestrians. The research is aimed on country roads with low frequency of vehicles. Distributed communication will be implemented to evaluate and see if the concept could be considered to be applied in the real world.

## Goals

The goals of the project are to create effective communication for streetlights that saves energy. Effective in the sense that it distributes the data packets only to the streetlights that needs the information about a moving object. At the same time, the data packet needs to consist of enough information for each streetlight itself to decide whether to lit or not. The distributed communication should be able to maintain the same flow in the traffic and try to keep the same level of safety for a driver. The deliverable will be a communication structure applied on hardware to represent a streetlight system. The focus is to prove the concept of distributed communication for streetlight systems.

### Benefits, Ethics and Sustainability

The benefit that people can get from the written thesis is the structure of distributed communication between objects connected to the internet. The structure can be used for streetlight systems or other Internet of Things (IoT)

[11] applications where scalability and flexibility are the main goals. The benefit that cities and municipality gets from a potential end-product is lowering their energy consumption from streetlights when no vehicles or other objects are using a road.

The ethical aspects concerning distributed communication for streetlight systems are that it must be reliable. The distributed data packets must reach the incoming streetlights so that there is enough light for a driver, to ensure safety for the drivers. The data packets distributed between the streetlights should not violate personal integrity, by avoiding gathering and sending of sensitive information.

The sustainability factors in the project is mainly the environment and investment cost. The purpose with the project is to lower the amount of consumed energy from streetlights. The problem is that hardware is needed to make this streetlight system work and the hardware needs production and development. This gives a negative effect on the environment, but the idea is that the environment will be better in long-term due to the lower amount of energy consumed by the streetlights.

The economic issues are that the streetlight system needs hardware, that the municipalities will need to invest in. The idea is the same as mentioned above that in long-term the municipalities will benefit on it. Also, in large orderings a quantity discount is usually given.

## Methodology / Methods

The types of research methods used in a project is commonly Quantitative or Qualitative [12]. A Quantitative research method often uses large data sets to falsify or verify a hypothesis [12]. A Qualitative research method on the other hand is to understand a behavior to reach a theory or develop a computer system [12]. A Qualitative research method commonly has small data sets [12].

This thesis will use a Qualitative research method to develop distributed communication for streetlight systems. The project is mainly about implementing distributed communication on an experimenting hardware to see if it could be considered to be implemented for streetlight systems in the real world. The hardware may not be the specific to use in the real world and therefore this will be using more of a Qualitative research method.

### Philosophical Assumption

The philosophical assumption is the perspective of the project [12]. It consists of the paradigms: Positivism, Realism, Interpretivism and Criticalism [12]. Positivism is usually about experiments and tests. It assumes an objective reality and is independent of the observer and material [12]. Positivism is suited for performance tests [12]. Realism is about observing phenomena to provide credible data and facts [12]. It is suited for an interdisciplinary research [12].

Interprevitism is about peoples' opinions, perspective and experiences to a phenomenon [12]. It is good for developing computer systems [12]. Criticalism is about how people affect the society. It focuses on finding and eliminating alienations [12]. This thesis will use an interprevitism assumption to see what

people have experienced when they are developing a streetlight system. This experience will be used to learn from and avoid common mistakes.

### Research Methods

There are different research methods, the most common are: Experimental, Non-experimental, Descriptive, Analytical, Fundamental, Applied, Conceptual and Empirical research [12]. The Experimental research method is a quantitative method that studies causes and effects of different variables [12]. This method is suited for evaluating performance of a system [12]. The Non- experimental research method is a qualitative method that consists of three different designs: relational, comparative and longitudinal research [12]. It can be used for testing users' experiences when they are experiencing for example a new User Interface (UI) [12]. The descriptive research method is a method for learning more about an existing environment [12]. It is used for finding new information from already existing data [12].

The Analytical research method also uses existing data, but uses it to test it against a pre-planned hypothesis. An analysis is done to evaluate the existing data [12]. The method can be used when designing a product [12]. The Fundamental research method is a method that uses theories and known problems to find new solutions [12]. It is suited for all kinds of investigations [12]. Applied research is a method that is similar to Fundamental research, but is focused on solving one specific problem [12]. Conceptual research is a method that uses literature to establish a concept in an area or to interpret an existing concept [12]. Empirical research uses experiences, observations or experiments to gain knowledge from real people and situations [12]. This knowledge is used for evaluating relationships between technologies [12].

This thesis will be using a fundamental research to solve the problem of how to design good communication for streetlights. This research will include a literature study of looking on related streetlight systems to get knowledge how other have designed their communication. The research is supposed to lead to a new and hopefully better way of structuring the communication than the existing solutions.

### Research Approaches

To draw conclusions from the project there are different research approaches: inductive, deductive and abductive [12]. The Inductive approach analyzes the data collected from a qualitative method [12]. The analysis is for understanding phenomenon like behaviors, opinions and patterns [12]. The deductive approach analyzes the large data sets gained from a quantitative method [12]. The approach uses the data to get causal relationships between variables [12]. It also verifies or falsifies hypotheses [12]. The abductive approach is a combination of inductive and deductive. It is used when there are incomplete data sets and uses preconditions to explain conclusions [12].

In this thesis an inductive approach is going to be used, because it will be a qualitative study to analyze existing streetlight systems' qualities and

properties. This analyze will help in the development of the distributed communication.

## Stakeholder

The project is carried out at Syntronic AB [13]. Syntronic is a company that has competence in electronics and software development [13]. The company was founded in 1983 in Stockholm, Sweden, by two master's thesis students from the university college KTH [14]. In 1985, did a head office for the company open in Gävle, Sweden, and today the company is also located at Malaysia, China, Indonesia and Canada [14]. Syntronic has around 500 employees working in the areas: telecom, defence, industrial, medtech and automotive [13].

## Delimitations

The project is divided into two parts. This project focuses on the distributed communication between the streetlights, while K. Andersson's [15] project focuses on the system functionality, calculations and detection of vehicles.

Streetlights at cities are excluded in this thesis, because of the complexity to implement a distributed system at a city and that a city has a lot of inconsistent movement. Also, that there already exist good solutions for city lights. The thesis aims on country roads with low frequency of vehicles. The security of a streetlight system is important, so that people not are be able to manipulate the data, but security is a quite large area and will therefore be excluded in this thesis. Reliable transmission is also excluded in this thesis. The distributed communication will not be tested on real streetlights.

## Outline

Chapter 2 presents the theory and related work according to distributed streetlight systems which then is used as a foundation for the thesis. Chapter 3 explains what theoretical methods are going to be used for the process of the project. Chapter 4 presents the different network models the distributed communication needs to handle. Chapter 5 shows the software implementation of the distributed communication used on the hardware. Chapter 6 shows results from the evaluation. Chapter 7 concludes the thesis and suggestions for future work is made.

# Communication in streetlight systems

This chapter introduces with section 2.1, by explaining what a distributed system is and what kind of distributed systems there exists. The term Internet of Things (IoT) [11] is presented in section 2.2 and explains why it concerns a streetlight system. Section 2.3 describes how to find out a vehicles position. Section 2.4 explains a wireless mesh network. Then there is a discussion about wired and wireless transmission mediums in section 2.5. After this, section 2.6 presents related research work with its advantages and disadvantages. To end the chapter, section 2.7 looks at fault tolerance, and section 2.8 explains the hardware and software that is going to be used.

## Distributed system

Streetlights consume energy unnecessarily when there are no vehicles or objects using a road. The streetlights can instead form a distributed system, where each node can communicate with its neighbors, to share information about a moving object. A distributed system [16] is defined as a system consisting of several computers connected as a network. The computers are working together to solve a problem [16]. In this thesis the streetlights should be a part of a distributed system, where the streetlights are the computers, which are supposed to share information about moving objects. By sharing the information between streetlights, electrical energy can be saved by dimming or turn off a light, when there are no moving objects in proximity. A distributed system can either use centralized communication which is shown in section 2.1.1 or decentralized communication, which is shown in section 2.1.2.

### Centralized communication

Communication to a central unit is called centralized communication and means that there is a leader that has control and makes the decisions [8]. There are a lot of streetlight systems that have a central unit, one is for deciding if the lights should turn on or off, or just change the level of light intensity [7]. M. Mendalka et al. aimed their centralized system for a group of lights like a parking or a gas station [7]. A centralized solution is good in the case of a small sized group like a parking or a gas station, because then all the lamps can be adapted to the same level of light. The problem with a centralized solution is that it can become a single point of failure and will therefore not be used in this thesis.

### Decentralized communication

Decentralized communication is communication directly between nodes and means that all nodes have the same authorities and responsibilities [8]. The same authorities and responsibilities gives that streetlights can determine by their own if they should lit or not, depending on the received information from the other streetlights. Decentralized communication will be used in this thesis so that the data packets can flow in proximity of a vehicle, and it adds scalability and flexibility to the system [8].

## Internet of Things

To form a distributed system the streetlights needs to be able to communicate with each other, which means they need to be connected to some sort of network. Connecting physical objects and people to the internet, so that they can communicate with each other is called Internet of Things (IoT) and the term was first used by Kevin Ashton [11] in 1999. The idea with IoT is to create an intelligent world with smart environments where everything should have its own Internet Protocol (IP) address [17]. The IP addresses are used for objects and people to communicate, by sending and receiving data packets between each other [17]. The objects and people that are connected to a network can be exposed of sensitive data, by attacks from unauthorized people [11]. The attacks can be done by connecting to a device to get data or by reading data streams in a network [11]. To prevent the data from being exposed, security and privacy must be concerned when developing IoT applications [11].

An example of an IoT application for streetlights is Vehicular Ad-Hoc Network (VANET) [2], where the vehicles interact with the streetlights. By using VANET, information about location, direction and speed could be used to let the lights bright before the vehicle is reaching them [2]. A VANET uses Road- Side Units (RSU) [2] for interaction between streetlights and vehicles. The problem of using a VANET is that all vehicles and other objects using a road, will need a programmable device, also known as a microcontroller, with a wireless transceiver for sending information about their appearance [2]. Another problem is that it may violate personal integrity by carrying sensitive information about a driver's exact location and direction that can be exposed by attacks from unauthorized people.

## Vehicles' positions

Instead of using a VANET, a sensor can be used for detecting nearby vehicles. A sensor can be placed before a section of lights to send information about incoming vehicles to the streetlights [4]. Having a sensor before a section of lights is a quite simple solution, but it is not a good solution for energy efficiency and it may not provide enough light for a driver. The problem with the solution is that a vehicle may use another path than the lit section and that there have to be a communication between the sensor and the lights. To prevent a streetlight system from violating personal integrity and reduce the communication amount, it can use a sensor that anonymously only detects an object's appearance and not what kind of object. A microcontroller with a transceiver can be used at each streetlight to process and send the produced data.

## Wireless Mesh Network

The distribution of the data packets in a streetlight system is usually done as a wireless mesh network [4][5][6][7]. A wireless mesh network [3] is meant that there are connections between the geographical closest nodes. To communicate with nodes more far away, the nearest nodes have to forward a

data packet until it reaches its destination [3]. Depending on the range of the wireless transceiver the signal can reach the nearest or even to a further streetlight. By using the mesh topology, the data packets are forced to visit every incoming streetlight, which is good because all incoming lamps in proximity have to light up for the driver.

## Transmission medium

The streetlights need to communicate with each other in order to share information about incoming or passed vehicles, for the streetlights to know when to illuminate or not. The communication is done by sending data packets, either with a wired or wireless connection between the streetlights. If the communication is done by wire, the streetlights' existing power line can be used for sending and receiving data packets. The power line is the energy source for the lamps. SA-50 [18] is an example of a module that can be used for sending data packets and interpreting data packets from the power line. It consists of 1 master module and up to 254 slave modules, where the master module can either broadcast information or communicate to a specific slave module [18]. The problem with using the communication through the power line is that some kind of filtering is needed for noise and interference [9]. Noise and interference occur due to the activity of other devices using the power line [9].

The communication can be done wireless with techniques like Bluetooth, WiFi, ZigBee [19] or “IPv6 over Low-Power Wireless Personal Area Network” (6LoWPAN) [20][19]. Those techniques works in the 2.4 GHz frequency band [19], which is a part of the Industrial, Scientific and Medical band (ISM). ISM is license free world wide [21]. Bluetooth is created for short-range communication to replace cables for example headsets and keyboards [19]. WiFi is also a network with limited range but with high speed and bandwidth as a trade-off, often used for homes or offices [19]. ZigBee and 6LoWPAN are more optimized for a streetlight mesh network, because they have longer range, are cheaper in price and consumes less energy [19]. Low energy consumption is a requirement for a battery device, but in the case of a streetlight system, the existing power line can be used for giving power to the wireless transceiver.

The disadvantage of using a wireless technique is that the data packets can be affected by other signals using the same bandwidth and obstacles can lower the signal range [22]. The advantage is that it is cheaper and more scalable to use a wireless transceiver like ZigBee or 6LoWPAN than the modules for power line communication [22]. Wireless communication will be used in this thesis because it makes the streetlight system easier to expand with other IoT applications.



Figure 1. The protocol stack of ZigBee and 6LoWPAN. Source of figure: [23].

The majority of wireless streetlight mesh systems are using ZigBee for the communication [4][24][5][25]. Only one streetlight system has been found that uses 6LoWPAN [26]. As can be seen in Figure 1, is that ZigBee only uses 3 layers of the protocol stack while 6LoWPAN uses all the layers. 6LoWPAN has the protocol IPv6 which means that it can communicate with a WiFi network [20]. On top of that layer it also has the Transmission Control Protocol (TCP), which is a protocol that uses acknowledge-messages for reliable transmission [27]. Reliable transmission is a key property for a system that lights up a road for vehicles. If ZigBee is used, there exists something called ZigBee IP [28] that provides IPv6 communication. ZigBee IP also includes TCP [28].

## Related work

There is a related research on a streetlight system using the existing power line for communication [29]. It has a master-slave model, where the slaves are the streetlights and the master has control over the streetlights [29]. The master can turn the lights on/off, dimming lamps and monitor the lamps to see their status and statistics [29]. The master also has a connection to the internet for human interaction [29]. The system turned out to be fault tolerant because if one streetlight fails the master will use another routing path to reach a slave [29]. This master-slave system will not be used in the thesis because it may not work well on country roads due to that all communication have to go through the master that decides whether or not to turn on/off a light.

There are some related streetlight systems using a wireless mesh network. One is for monitoring and control in a city [6] using ZigBee for communication. It is complex to implement an optimized solution for streetlights in a city because there is a lot of movement that streetlights will register. Due to the

large movement frequency there will also be a lot of communication flooding the streetlight network and ZigBee is constructed for low data rate [19]. This streetlight system is created for monitoring and central control, which will not be considered in this thesis because there exist a lot of equal solutions [4][5] [6][7].

Another related streetlight system is using the mesh topology together with a centralized base station for control [5]. The system is using a unique address for each streetlight and the communication is done point-to-point between the base station and the streetlights [5]. To handle failures, each streetlight has the possibility to communicate with its second nearest neighbors [5]. The system has a Graphical User Interface (GUI) for managing statistics stored at each streetlight and the ability to turn them on or off [5]. Statistics are easily obtained from the GUI which is an advantage for the maintenance but it is not scalable because the GUI has to be configured if new streetlights are added. The communication in this thesis will use the idea of communication to second nearest neighbors for fault tolerance.

There is a research on a streetlight system using 6LoWPAN for point-to-point communication [26]. Each streetlight has a unique IPv6 address and a unique IEEE 802.15.4 address [26]. The IPv6 address is for the communication between the streetlights [26]. The IEEE address is for the communication from the streetlights via a gateway router to reach a control center [26]. The control center is used for gathering information about each individual streetlight and decides when to turn on or off lights [26]. Parts of those ideas of a streetlight system will be used in the project. First of all 6LoWPAN will be used, because it is developed for IoT applications [20] and it is not that frequently used in streetlight systems [26]. The distributed communication will use IPv6 addressing for direct communication with neighbors. The control center will not be used because there exist a lot of equal solutions to centralized communication already [4][5][6][7].

Those related streetlight systems presented have one thing in common and that is centralized communication. All data packets have to go through a central device for determining what to do with a light or a group of lights [4] [5][6][7]. Central controlling is not a good way of handling the communication in large scale streetlight systems on country roads, because the central will need to handle all the data packets which make it a single point of failure. Instead, this thesis will consider a decentralized solution, so that the communication can be in proximity of a moving vehicle.

## Fault tolerance

When creating a streetlight system that will control the lights it is important to keep the same level of safety at the same time as lowering the energy consumption. To keep the level of safety, fault tolerance has to be taken into account. In a mesh network the connection is between the closest nodes, to make the system more robust it could also have a connection to the second closest streetlights [5]. The distance between streetlights is usually around 30-

40 meters [10] and ZigBee was tested at 100 m with a wired antenna [5]. The test gave the result 99.96 % in reliability with a hill as an obstacle and it was raining [5]. 99.96 % is a good result because the distance of 100 m only needs to be used when a node failure occurs. 6LoWPAN will get the same result because it uses the same standard (802.15.4) as ZigBee for the physical layer, see figure 1, page 9.

If two nodes in a row are broken the communication will not work in F. Leccese's streetlight system [5], because the range is maximum 100 m for ZigBee and the distance between the working streetlights will be longer. When two nodes are not working the communication is broken [5], which is not good for a streetlight system. In this thesis a decentralized architecture will be considered, for it to become two separate streetlight systems instead of not working.

## Hardware and software for the distributed communication

Distributed communication will be developed for a streetlight system as a proof of concept. The distributed communication will be implemented on a programmable hardware called Zolertia RE-Mote [30] that uses 6LoWPAN for wireless communication. Five Zolertia RE-Motes are given by Syntronic for testing the complete streetlight system, where one RE-Mote will be used at each streetlight to represent the distributed communication for a streetlight system. Section 2.8.1 explains the hardware that is going to be used and section 2.8.2 explains the software that is going to be used.

### Zolertia RE-Mote

Zolertia RE-Mote is a microcontroller with a built-in wireless transceiver for 6LoWPAN [30]. The range of the wireless transceiver is 100 meters [31] and it has a transfer rate of 250 Kbps [32]. Zolertia is developed for IoT applications like smart cities, lighting and industrial projects [31]. The microcontroller has a Security Digital (SD) card for storing to and retrieving information from [31]. Existing commercial sensors can be connected and used on the microcontroller [31]. Also, the batteries can run for years [30]. Zolertia is compatible with an operating system called Contiki [30].

### Contiki

Contiki is an operating system that is open source for both commercial and non-commercial use [33]. It is written in the programming language C and has an active community [34], where the latest release was in august 2015 (version 3.0) [35]. Encryption is also included in Contiki which is important for IoT applications [35]. Contiki has a graphical network simulation tool called Cooja

[36] that allows the developer to compile and test their code before uploading it to the hardware. Cooja also makes it possible to simulate large scale networks of the developed application [36]. The operating system Contiki together with Cooja will be used for developing the software for the distributed communication in the project.

The RE-Mote is initialized with a predefined Internet Protocol version 6 (IPv6) [20] address in Contiki. The IPv6 address is created through the mac address, where the mac address is pre-loaded in the RE-Mote's internal flash memory [17]. The IP address is needed for communication between the RE- Motes.

# Methodologies and Methods

This chapter presents the theoretical research methods and methodologies that can be used in the project and which ones that are going to be used in the project. Section 3.1 presents the research strategies, section 3.2 explains the data collection methods, section 3.3 shows the data analysis methods and section 3.4 presents quality assurance of a project. The development method that will be used is presented in section 3.5. The chapter ends with section 3.6 by explaining the working method.

## Research strategies

The research strategies used in a project normally depends if it is a Quantitative or a Qualitative research [12]. The research strategies used in a Quantitative research are normally: Experimental, Ex post facto, Surveys and Case Study [12]. Experiments are used for verifying or falsifying hypotheses, usually done with large data sets [12]. Ex post facto is like experiments, but uses already collected data sets, to verify or falsify hypotheses [12]. Surveys are a descriptive method that finds relationships between variables [12]. Case Study investigates a phenomenon in real life, by an empirical investigation [12].

The research strategies used in a Qualitative research are normally: Surveys, Case Study, Action research, Exploratory research, Grounded Theory and Ethnography [12]. Action research is a cyclic method that consists of planning, taking action, observing, evaluating and reflecting [12]. It often studies restricted data sets from like a community [12]. Exploratory Research is about finding as many relationships between variables as possible [12]. The method often uses surveys to get an insight of a problem [12]. Grounded Theory is used for collecting and analyzing data, to establish a theory grounded in data [12]. Ethnography is for studying people about their social and cultural context [12].

This thesis will use grounded theory to come up with the foundation for the distributed communication for streetlight systems. The foundation will be created through related work according to streetlight systems that the authors have suggested for their solutions.

## Data collection

To collect data for the research, data collection methods are used [12]. The data collection methods used in a quantitative research are normally: Experiments, Questionnaire, Case Study and Observations [12]. Experiments are used for collecting large data sets [12]. Questionnaire collects data through questions, either open or closed [12]. Case Study uses a small number of participants to find in-depth data [12]. Observations, is focused on observing situations or culture [12].

The data collection methods used in a qualitative research are normally: Questionnaire, Case Study, Observations, Interviews, and language and text [12]. Interviews are used for getting participants' point of view on a specific problem [12]. Language and text are for interpreting conversations and meanings in texts [12].

There will be informal interviews, meetings, with the Company Syntronic once a week, for them to give their opinion during the project. The interviews are used to get a different point of view on the project and for them to give their ideas and feedback.

Observations will be used for the data collection when the distributed communication is implemented. Observations mean to observe a behavior in real situations [12]. Observations will be used to observe different network scenarios and vehicle scenarios with the distributed communication for a streetlight system. Network scenarios will be observed to see which streetlights are lit, which are turned off and that light is given in the same direction as the object is moving. Vehicle scenarios will be observed to see that all the sent data packets are reaching their destination. The scenarios will represent different situations that can occur on a road with a streetlight system.

## Data analysis methods

The data collected from the data collection needs to be analyzed [12]. The data analysis methods used in a quantitative research are normally: Statistics and Computational Mathematics [12]. Statistics are used for analyzing data, which includes calculating results for a population [12]. “Computational Mathematics is used for calculating numerical methods...” [12].

The data analysis methods used in a qualitative research are normally: Coding, Analytic Induction, Grounded Theory, Narrative analysis, Hermeneutic and Semiotic [12]. Coding analyzes transcriptions from interviews and observations [12]. It turns qualitative data into quantitative data [12]. Analytic Induction and Grounded Theory are a combination which alternates between them two [12]. The methods are used for iterating until a valid theory is established [12]. “Narrative analysis concerns literary discussion and analysis“[12]. Hermeneutic and Semiotic is for finding traceability by analyzing texts and documents [12].

This thesis will use usability as the data analysis method. Usability will be used to analyze the observations, to find out how good the interaction is between the streetlights and a vehicle. The interaction can tell if the distributed communication could be considered to be implemented in the real world on a streetlight system.

## Quality assurance

To verify and validate the research material, there have to be a quality assurance [12]. To assure quality of a quantitative method, one has to show:

validity, reliability, replicability and ethics [12]. Validity means that the tools for measuring actually are measuring what is expected to be measured [12]. Reliability is about the stability of the measure [12]. Replicability means that the author of the thesis has to describe the procedures well, in order for another researcher to reach the same results [12]. Ethics is for the moral of the project [12].

To assure quality of a qualitative method, one has to show: validity, dependability, confirmability and transferability [12]. Validity in this case is about following existing rules, when doing the project [12]. Dependability corresponds to reliability, the correctness of the conclusions [12]. Confirmability is to confirm that the research has been performed without affect from personal judgement [12]. Transferability is about delivering material which can be used by other researchers [12].

Validity will be achieved by following a set of requirements, when creating the structure and the implementation. To assure dependability, the structure will be followed when creating the implementation of the distributed communication. An expert in the area can be used to correct that the implemented distributed communication is based on the structure. For confirmability, a design will be used for creating the distributed communication, the design will be based on facts to avoid personal judgement. Transferability in this thesis will be the structure and the implementation, where a reader can recreate and understand the implemented distributed communication.

## Software development method

A software development method is used for structuring the process of developing an information system [37]. There are different methods that can be used for software development, like Extreme programming, Prototyping, Iterative Model and Rapid Application Development.

Extreme programming (XP) [37] is a method that is suited for software development in an unstable environment. In XP it is good to have interaction with a customer on site for fast feedback when questions arise [37]. The work is done in pairs of two developers on one computer, for one to write the code and the other to review the code [37]. XP uses tests to confirm that a created component is complete, which it is when it passes all the tests [37]. When the tests are done refactoring is done to remove complexity in the written code [37]. XP will not be used due to that it is supposed for pair programming.

Prototyping [38] is a method that consists of identifying requirements, developing initial prototype, review of the prototype and improvement of the prototype. Prototyping is a method that lets the user to test prototypes during the development, in order to give the developer feedback in an early state [38]. The early feedback gives the developer an opportunity of changing the implementation earlier. Prototyping will not be used because the distributed

communication is hard to be tested and evaluated by short releases to a user. User tests are best suited on the end product in this case.

The Iterative model [39], as can be figured out by the name, uses iterations to implement software, where the iterations continue until a complete system is created. The iterative model is a combination of iterative and incremental development [39]. It starts with implementing a small subset of the requirements and in each iteration the implementation is expanded with new functionality according to the requirements [39]. During each iteration, the software is tested and verified, to see that it works as the requirements are specified [39]. Due to that the software evolves in each iteration means that tests have to be repeated and also extended to verify the newly extended functionality [39]. When all the iterations are done and all the requirements are tested and verified, the system is complete [39]. This thesis will use the Iterative model because requirements will be stated and the components that will be implemented will build upon each other.

Rapid Application Development (RAD) [40] is a method that uses prototyping and iterative development as a base. The method uses minimal planning; instead the requirements are gathered through workshops, for customers to try out prototypes in an early state. The minimal planning and feedback from the customers makes the development easier to change. RAD will not be used because the requirements will be gathered before starting the implementation.

## Working method

The working method will be the iterative model combined with meetings with Syntronic once a week during the implementation of the distributed communication. There will be four iterations of the iterative model, where each iteration will last for 1-2 weeks. Every iteration will end with a meeting with Syntronic for discussion about the current iteration with suggestions for changes in the work and how to continue with the next iteration. The meetings will give the developer weekly feedback on the work.

The project is divided into two parts of a streetlight system, where this thesis presents distributed communication and K. Andersson [15] presents the system functionality, calculations and object detection. The development is done in the same room for constant communication. When all the iterations are done, the project will end with assembling the distributed communication and the system functionality for the streetlight system.

# Communication design

This chapter shows the structure of the communication that is going to be used for the iterative model shown in chapter 5. Chapter 4 starts with showing the design choices that are made in section 4.1 and the architecture of the complete streetlight system in section 4.2. Section 4.3 starts with the basics of the communication structure. Then different network scenarios are considered in section 4.4. Section 4.5 explains when to turn on a streetlight. Section 4.6 shows the different vehicle scenarios that can occur and the chapter ends with section 4.7, by showing what kind of content the data packets will need to consist of.

## Design choices

A literature study have been done by looking at related work and structures of distributed communication. Grounded Theory has been used for analyzing the written materials gathered from the literature study. Analyzing the written materials' properties and qualities of streetlight systems to get a theory of how a streetlight system could work. The established theory is mostly used as a foundation for the design choices: it should be wireless communication, it should use wireless mesh networks, the communication should be decentralized, fault tolerance is needed, and the development will be done in Contiki, which will be applied on Zolertia RE-Mote (see chapter 2).

From the theoretical foundation, there are own ideas of how to define the communication in more detail to achieve the goals of the distributed communication in section 1.4 and the purpose in section 1.3. All the ideas are discussed and configured together with K. Andersson [15] and also with informal meetings with Syntronic. The ideas are then formed as requirements for the distributed communication. The requirements are established as:

* + - Nodes should be able to communicate directly with each other
		- Nodes should be able to leave the distributed system without making a large impact on the rest of the system
		- Nodes should be able to forward data packets to the right neighbors in the right direction
		- Communication to the streetlights in range of the wireless transceiver, on the same road as a streetlight
		- Handling of different network scenarios
		- Handling of different vehicle scenarios
		- A data packet should consist of enough information for a streetlight by itself to determine whether or not to lit

The following sections are the structure for the distributed communication in order to meet all the requirements.

## Architecture of the complete streetlight system

The setup of the project will look like the sketch that can be seen in figure 2, where each streetlight will be represented by a Zolertia RE-Mote [32], together with an attached sensor for detecting objects. The RE-Mote also has an LED which will be used in the implementation to represent a lit streetlight [32].



Figure 2. The supposed setup of the chosen hardware. Drawing by author.

Zolertia RE-Mote is chosen because it uses 6LoWPAN as the standard for wireless communication (section 2.8), and it is compatible with the operating system Contiki (section 2.8.2). Wireless communication makes it possible to expand the distributed streetlight system with other IoT applications (section 2.5). The sensor for detecting objects will be provided by K. Andersson [15]. The RE-Motes will use wireless communication to communicate with each other in order to provide the driver with a lighted road.

## Communication basics

The distributed communication will be structured as a wireless mesh network, because it will be using wireless communication with the Zolertia RE-Mote. Each RE-Mote is going to have a unique node ID, that is based on a node's position on a road. The ID will be used to distribute data packets in the right direction, which is a requirement mentioned in section 4.1. The nodes should

store information about their closest neighbors, to be able to communicate and forward data packets to them.

The communication structure is supposed to be a node sending a data packet in both directions, the receivers will in turn forward it. Forwarding will be needed for the sent data packets to reach the nodes more far away in the wireless mesh network, as mentioned in section 2.3. Each node will determine by their own whether or not to lit, due to that a decentralized solution will be used (see section 2.1.2). A node will determine if it should lit by the received data packets. The communication should be in proximity of where a vehicle is located, so that the communication is effective, which is a goal described in section 1.4.

## Network structure

The basic network of streetlights will be at a straight road without intersections. The network can be seen in figure 3. Each streetlight has connections to their neighbors within 100 meters, because the range of the Zolertia RE-Motes wireless transceiver is 100 meters [31]. The distance between two streetlights is normally 30-40 meters in Sweden [10] and the range of 100 meters is enough for each node to have a connection to its four closest neighbors. The normal communication will be through the two closest connections and the other two connections will be used if a node failure occurs. The idea of the communication to bypass a broken node is taken from

F. Leccese's streetlight system as mentioned in related work [5].



Figure 3. The mesh network in a simple scenario of streetlights. Drawing by author.

Another scenario is when there is an intersection or a roundabout, see figure

4. When a vehicle is reaching an intersection or a roundabout, the streetlights will not know in which direction the vehicle will go. Due to the unknown direction, there have to be light in all directions, to provide good visibility for the driver. When a data packet reaches an intersection streetlight, the data packet needs to be forwarded to all the other streetlights in the intersection, to be able to get light in all directions. When the data packet is received by another streetlight in the intersection, it has to be forwarded to the streetlights belonging to that exit of the intersection.

Figure 4 shows an example of how the network will look like in an intersection. For the data packet not to be forwarded between the intersection

streetlights forever, the intersection streetlights have to look at the data packet to see if it is a newly forwarded data packet. The communication in an intersection is supposed to work in the same way as a roundabout.



Figure 4. The mesh network in an intersection. Drawing by author.

The streetlights need something unique in their data packets to represent a road, because there are scenarios where the streetlights can send the data packets to streetlights which does not belong to the same road. Examples of roads where the data packets can end up to the streetlights on wrong roads are a viaduct which is going over a road or two parallel roads. A viaduct and two parallel roads are two scenarios where the streetlights can be close enough to send data packets to the streetlights at a road where a vehicle is not driving. By a road id, the nodes can simply ignore not expected data packets.

If one streetlight failure occurs, the streetlight system should not be affected, the data packet should by pass the failed node. If two nodes in a row fail, the communication will be broken, because the range of the transceiver is 100 m (see section 2.8.1) and that will not be enough for reaching beyond two streetlights.



Figure 5. Network scenario if two nodes in a row fails. Drawing by author.

The scenario of two broken nodes can be seen in figure 5. The streetlight system will be broken into two parts (1-2 and 5-6-7), which separately are supposed to work, because it should be a decentralized system (see section 2.1.2).

## When to turn on a light

Each node itself, should determine whether or not to lit, either if there is a vehicle in proximity that is heading towards it or if the direction of a close vehicle is unknown. The decision of when to lit will be done in the other part of the project by K. Andersson [15]. K. Andersson will also calculate the velocity of a vehicle by the time difference between two streetlights, in order to optimize the number of nodes to lit in front of the vehicle.

## Vehicle scenarios

Vehicle scenarios also have to be taken into account when developing distributed communication, due to that it can affect the light provided for the vehicles. Some vehicle scenarios are acceleration, deceleration, vehicles passing each other, two cars driving in different directions and traffic congestion. To handle different vehicle scenarios, each vehicle can have its own section of streetlights. The size of the section can be fixed and all the streetlights in a section are communicating with each other, for each streetlight to know where a vehicle is.



Figure 6. Streetlight sections for vehicles. Drawing by author.

In figure 6, there are sections marked for each vehicle, which are of a fixed size. The sections are the ellipses, the vehicles are the arrows and the small circles are streetlights and a lit streetlight is represented with the yellow color. The number of lit lights will be a variable that can depend on the speed and direction of a vehicle. Every time a vehicle passes a streetlight, the streetlight will send a data packet in both directions to the closest streetlights about a

detection of a vehicle. The receiving streetlights will in turn forward the data packet to the streetlights depending on the fixed length of a vehicle's section. In other words, for every streetlight a vehicle passes, a new streetlight will be included in the section and an old will be excluded from the section.

A special case is if a car is reaching its first streetlight, then the streetlight will not know in which direction the vehicle is heading. To handle this situation the streetlight will communicate with its supposed section to light up in both directions, to give the driver a good visibility in both directions. When the driver is reaching the next streetlight, the data packets can still be sent in both directions and forwarded, but with the information about the direction and speed for the other streetlights to determine if they should lit or not. The number of lit lights always has to be lower than the length of the section, otherwise a streetlight can be leaved lit outside of a vehicle's section.

## Data packet content

The data packet needs to consist of enough information for each streetlight itself to determine whether or not to lit, which is a requirement mentioned in section 4.1. Apart from determining whether or not to lit, the data packet also need to consist of information to handle different network scenarios discussed in section 4.4 and vehicle scenarios discussed in section 4.6. The data packet needs to consist of the following:

* + - an ID to the creator of the data packet
		- an ID from the sender of a data packet
		- an ID to the receiver of a data packet
		- a road ID
		- the speed and direction of a vehicle
		- a distance of how many lights to lit
		- a distance of the number of nodes that will exist in a section

All the data packets that are transmitted will consist of the parameters shown in the list. All the parameters may not be used, the number of parameters used depends on how much information a streetlight has that it can send or forward. The creator ID is needed for each streetlight to know where a vehicle is detected. The node ID from the sender of a data packet is needed for the streetlight to know in which direction a packet is heading. The ID of the receiver of a data packet is for a node to know if the data packet is for it. The road ID is needed to know if the received data packet is belonging to the node's road. The speed and direction of a vehicle is needed to know if a vehicle is heading towards that streetlight, to know if it should lit or not.

The distance of how many lights to illuminate is a counter that should lower for every streetlight that receives the data packet. When the counter reaches zero means the end of the light. There will also be a counter for the number of streetlights consisting in a section. When the section reaches zero means the end of the section and the data packet should no longer be forwarded. The reason why there will be two counters (lights to lit and section), is because the number of lights to lit will be calculated from the velocity. By having a

separate parameter for the number of lights to lit gives that the parameter do not need to be recalculated at each nodes. It is important that all data packets have the same transmission time, because the speed of a vehicle is calculated from the amount of time between a received data packet from a neighbor until a vehicle passes the streetlight [15].

# Distributed communication for streetlight systems

This chapter explains what is implemented in the Contiki OS for the programmable platform Zolertia RE-Mote (see section 2.8), which are the software and hardware used in the project. The chapter starts with section 5.1, by showing how the structure of the development is done. Section 5.2 shows the basic implementation for the distributed communication between two RE- Motes, and then section 5.3 shows how the nodes establish a connection to their neighbors.

The chapter continues with section 5.4 by showing an example of a vehicle triggering a data packet to be sent and how the forwarding works. The implementation of the special scenarios of an intersection and a roundabout are shown in section 5.5. Section 5.6, explains how the implemented fault tolerance works and section 5.7 presents the structure of a data packet. Section 5.8 summarizes the implemented distributed communication.

## Developing structure

The development of the distributed communication is following the iterative model described in section 3.5. Chapter 4 shows the communication structure that is used together with the iterative model for the implementation. There are 4 iterations, where every iteration consists of a planning part of looking at a subset of the design in chapter 4, implement the subset, test it and discuss it. In each iteration the implementation will expand with new functionality which will require a test of the previous implemented components and also the newest implemented component. The previous implemented components have to be tested, because most of the parts in the implementation builds upon each other.

The tests will be performed with the simulation tool Cooja (see section 2.8.2), to see that the implementation is working as expected. In the end of every iteration a meeting is held with Syntronic for discussion of the implementation and the upcoming iteration. When all the iterations are done the implementation of the distributed communication is considered ready to be assembled to a streetlight system, together with the system functionality created by K. Andersson [15].

The first iteration is to establish a network between the nodes, the second is to send and forward data packets to the right nodes and in the right direction. The third iteration is the implementation of a node inside an intersection or a roundabout, the fourth is for the nodes to handle node failure and recovery. The data packet is created during the development, until all the needed information is included in it.

## Communication between RE-Motes

Existing functions in Contiki have been used for sending and receiving data packets when developing the communication. Simple\_udp\_register [41], is an

existing function used for listening to a specified port for incoming data packets. When a data packet is received, a callback is done to a receiver function [41]. To send a data packet, the function Simple\_udp\_sendto [41] is used. It uses the User Datagram Protocol (UDP) [27], to send the data packet to a neighboring node by a specified IP address and port [41]. UDP's routing is not used, instead the routing is own implemented, which is shown in section

5.3. As mentioned in section 2.5, reliable transmission is a key property for a system that lights a road. Reliable transmission is left for future work, because it makes implications with the velocity calculations between the streetlights.

A function called uip\_create\_linklocal\_allnodes\_mcast [42] is used for communicating with all the neighbors in a range of 100 m. Simple\_udp\_register, Simple\_udp\_sendto and uip\_create\_linklocal\_allnodes\_mcast are located in the file uip.h provided by Contiki.

## Establish connection

The first iteration in the project was to establish a network between the neighboring nodes. To know which neighbors each node have, a node is specified with an ID depending on the geographical location of the node, for it to know in which direction to forward data packets. To establish a connection to the closest neighbors, each streetlight broadcasts [43] a data packet containing their node ID, IPv6 address and road ID. The broadcast is done by first creating a link to all the neighboring nodes with the Contiki function uip\_create\_linklocal\_allnodes\_mcast (see section 5.2).



Figure 7. Broadcast of each node to tell their appearance. Drawing by author.

Figure 7, shows a broadcast with seven nodes on a straight road. The data packet reaches the neighbors within a distance of 100 m, which is the maximum range of the Zolertia RE-Mote transceiver, as mentioned in section

2.8.1. The range is for example, enough for node 3 to reach node 1, 2, 4 and 5, on a straight road without obstacles, as can been seen in figure 7. From the broadcast, all streetlights store their neighbors' IPv6 address and associating node ID, to know where to send and forward data packets through the streetlight system.

|  |
| --- |
| Node 3 - Neighbors |
| **ID** | **IPv6 address** | **Road ID** |
| 1 | fe80::c30c:0:0:1 | 1 |
| 2 | fe80::c30c:0:0:2 | 1 |
| 4 | fe80::c30c:0:0:4 | 1 |
| 5 | fe80::c30c:0:0:5 | 1 |

Table 1. Node 3, storage of its neighbors' IDs, IPv6 addresses and road IDs.

Table 1 shows an example of that node 3 will store the IDs, IPv6 addresses and road IDs of node 1, 2, 4 and 5, from the broadcast in figure 7.

## Sending and forwarding

The second iteration was to send and forward data packets. Sending and forwarding were supposed to be direct to the stored IPv6 address, but the data packet never reached its destination when it was tried out. Instead the broadcast function uip\_create\_linklocal\_allnodes\_mcast was used for each node to look at its received data packet to see if it is for its own ID. The intended solution using the IP address can be found in future work.

When a vehicle passes a streetlight, a sensor provided by K. Andersson [15] detects the object and sends two data packets, one for each of the two closest neighbors. The two closest nodes, finds out that the data packet is for them and reads it. They lower the counter for the light and the vehicle section, and forwards the data packet. When a node receives a counter for the section which is zero, it stops forwarding the data packet and knows that it is in the end of a section of a vehicle. Each node itself determines in which direction to forward a data packet. The direction is determined by comparing a node's own ID with the sender's ID, by the comparison it knows in which direction the data packet is heading.



Figure 8. Data packet distribution when a streetlight detects a vehicle.

Drawing by author.

In figure 8, a scenario of a vehicle passing the node 5 is shown. When the vehicle passes node 5, it sends data packets to both node 4 and 6. Node 6 forwards the data packet to node 7, which forwards it to node 8. Node 4

forwards the data packets to node 3, which in turn forwards it to node 2. The current section is from node 2 to node 8; the definition of a vehicle section is described in section 4.6. When the vehicle passes the next node which is 4, the same procedure is done and node 1 is included in the section and node 8 is excluded.

## Intersection and roundabouts

The third iteration was to handle communication in an intersection and roundabout. Intersection and roundabout nodes are special in the sense that as soon as they receive a data packet, they will forward it to the other nodes belonging to the same intersection or roundabout. When the intersection or roundabout nodes receive the data packet, they will forward it to all the exits, as mentioned in section 4.2. In the implementation all the intersection nodes in the same intersection are given the same node ID. The amount of roads that are belonging to an intersection or roundabout, defines the number of IDs that an intersection or roundabout node needs. An intersection or roundabout node needs multiple IDs to forward data packets in all directions of an intersection.

In figure 9 there is an intersection where the intersection nodes have the IDs 3 and 9, and road ID 1 and 2 for example. Both of the node IDs and road IDs are needed for forwarding data packets to node 2 and 4, and also node 8 and

10. In the scenario shown in figure 9, a vehicle is detected by node 2. Node 2 will forward a data packet to the intersection node 3,9 about an incoming vehicle. When the intersection node receives the data packet it will start with forwarding it to its own ID, which includes the other intersection nodes. The next step is that the intersection node will receive a data packet from a node with the same ID, which will result in both forwarding to itself and forwarding to all the exits. Then the node will start a timer when the next forwarding of a data packet is allowed, to avoid the intersection nodes from forwarding the same data packets forever.



Figure 9. Forwarding data packets in an intersection. Drawing by author.

A roundabout is working in the same way as an intersection. The only difference is that there may be a streetlight located in the middle of the roundabout that provides light. If there is a streetlight in the middle of a roundabout, it will not be using a sensor, it just forwards data packets from the other streetlights.

## Fault tolerance

The fourth iteration was to create fault tolerance for the nodes. Every node is storing their neighbors' IDs and IPv6 addresses from the network establishment as mentioned in section 5.3. Apart from the ID, IPv6 address and road ID of each neighbor, each node also stores a parameter for suspection, suspection time and death for every neighbor. The suspection parameter is needed for a node to suspect that another node is dead. The whole process can be seen in figure 10. For a node to suspect another node, it needs to look it up in its stored neighbors. The node sends a data packet to the node that it is suspecting, which it expects a response on. The node that sends the heartbeat message starts a timer and expects a response within a specified time, which is set to 2 seconds. While the timer is running the program will continuing with detecting vehicles and forwarding data packets. If a response from the suspected node is received, it is considered alive. Otherwise, if the

timer is more than the specified time, it considers the node dead. If a node is considered dead, the communication is going by pass it, to avoid the communication from a stop.



Figure 10. Sequence diagram of the suspection mechanism. Drawing by author.

A dead node can always be restored by sending a data packet to its neighbors, and then its neighbors will realize that it is alive and the communication will pass through the node again. If two nodes in a row is dead, the communication will break in that point, because the range of the RE-Mote is only enough for a node to reach beyond one node. The problem of two dead nodes in a row is solved by the fact that this streetlight system is a decentralized system, where each streetlight handles itself. By each streetlight handling itself, gives that the streetlight system divides into two streetlight systems when two nodes are dead, as mentioned in section 4.4.

## Data packet structure

The data packet has the structure as mentioned in section 4.7. Figure 11 shows the data packet in more detail. Each data packet is using the data type char array with the size 24, which corresponds to 24 bytes [44].



Figure 11. Data packet size. Drawing by author.

Message type is the only parameter not discussed in section 4.7, that parameter describes what kind of data packet it is. There are three different message types: a data packet that should be forwarded, a heartbeat message or an alive message. The velocity parameter has one position for a sign, from the sign the direction of a vehicle is determined.

## Complete streetlight system

From all the steps of the iterating model, the distributed communication was implemented with the establish phase, sending and forwarding data packets, intersection and roundabout nodes, fault tolerance and a data packet consisting of all the needed information. The distributed communication is assembled with the system functionality for the streetlights created by K. Andersson [15], for the evaluation of the distributed communication in a complete streetlight system.

# Evaluation

The implementation of the distributed communication is shown in chapter 5. In this chapter the distributed communication is evaluated with different scenarios to see how good the interaction is between a moving object and the streetlights. Section 6.1, describes that different scenarios is tested and observed. In section 6.2, the results from the communication time are shown.

The evaluation is done in small scale due to that there are only five Zolertia RE-Mote provided. Contiki came with a simulation tool called Cooja, as mentioned in section 2.8.2. Cooja was not used in the evaluation because the simulation did not have support for Zolertia RE-Mote, it only had Zolertia Z1, which is a bit different. The LED attached to the RE-Mote was used for representing a lit streetlight. All the tests were performed on the distributed communication, together with the functionality for the streetlight system created by K. Andersson [15]. A human hand was used as the moving object, to see if the RE-Motes could provide the needed light. All the tests were performed indoor with a distance around 0,3 m between the RE-Motes. The section and light distance were of fixed sizes for testing.

## Observations

Observations were used on the distributed communication for the streetlight system. The distributed communication was observed in the different network scenarios: a straight road, a broken streetlight on a straight road, an intersection and a roundabout. It was also observed with the vehicle scenario of two vehicles driving towards each other to see how the distributed communication was behaving. The network scenarios are used to see which streetlights are lit, which are turned off and that light was given in the same direction as the object was moving. The vehicle scenarios are used to see if all the sent data packets are reaching their destinations.

Section 6.1.1, shows the result of the scenario of an object moving on a straight road, section 6.1.2 shows the result of the scenario of a broken streetlight, section 6.1.3 shows the result of the scenario of an intersection and roundabout, and section 6.1.4 shows the result of how the communication is affected by two vehicles driving towards each other.

### An object moving on a straight road

The first scenario test was performed with 5 Zolertia RE-Motes as a straight road. The section distance used was 3 and the light distance was 2, where the section distance is the number of nodes that should receive the data packet. Figure 12 shows an illustration of how the nodes were communicating and giving the object a lit road in the direction as it was heading.



Figure 12. Flow of light at a straight road. Drawing by author.

If an object is detected by a streetlight for the first time, the direction is unknown. An example of when a vehicle is detected for the first time is when it is joining a road from a parking. The tested scenario used the same setup as the previous test and can be seen in figure 13.

Figure 13. Flow of light at a straight road with unknown direction of a vehicle.

Drawing by author.

The moving object was detected by node 3, which spread the knowledge about the newly joined object and all nodes around it were lit. When the moving object was detected by the next node, the direction was known and the lights did turn off behind it.

### Broken streetlight and recovery

The fault tolerance mechanism was tested, to see that it worked as expected. In the test all five Zolertia RE-Motes were used, where one node was faulty. The section distance was 4 and the light distance was 3. The test can be seen in figure 14.



Figure 14. Flow of light at a straight road with a broken node. Drawing by author.

The test was performed by first letting the nodes establish a connection to each other (see section 5.3). When the connection was established, node 3 was shut down and its neighbors sent a suspection data packet, to see if it was alive. The neighbors of node 3 did not get a response in time and therefore declared node 3 as dead. The suspection mechanism can be seen in section

5.7. A moving object joined the road and the interaction between it and the nodes can be seen in figure 14, where Node 2 and 4, forwards their data packets beyond the dead node 3.

When node 3 was restarted, it sent a broadcast to its neighbors 2 and 4. Node 2 and 4, declared node 3 alive again and sent a data packet consisting of their information for node 3 to establish a connection to them again. The setup then worked as a normal straight road, which can be seen in section 6.2.1.

### Distributed communication in an intersection and roundabout

The distributed communication in an intersection were also tested with the five Zolertia RE-Motes on the complete streetlight system. The setup of the test can be seen in figure 15, where there were two intersection nodes and three normal nodes. The intersection nodes belonged to both road 1 and road

2. The normal node 1 and 3, belonged to road 1 and the normal node 8, belonged to road 2. The section distance used was 2 nodes and the light distance was 1 node, which are both of a low size in order to see how the lights did interact in the intersection.



Figure 15. Flow of light at an intersection. Drawing by author.

When the moving object in the figure was approaching to the intersection, both of the intersection nodes were lit. When the moving object then reached an intersection node, all the exits in the intersection were lit, while node 1 which was behind the moving object, was turned off. When node 8 detected the moving object, all the other nodes were turned off, due to that the direction of the moving object was known.

### Two vehicles driving towards each other

The distributed communication in the complete streetlight system was tested with the scenario of two vehicles driving towards each other and reaching one neighbor node each, at the same time. The idea of the test was to see how many of the data packets that did get lost, when sending and receiving were performed almost at the same time. The scenario was tested by using two Zolertia RE-Motes and letting them detect objects at the same time. The distance between the RE-Motes was around 0,3 m to avoid data packet loss from other sources. The test can be seen in figure 16.

Figure 16. Sending and receiving at the same time. Drawing by author.

In the test, the RE-Motes sent 1 data packet each at the same time. 600 data packets were sent in total, which are 300 data packets per node. From the sent data packets, 16 were lost, which corresponds to a loss rate at around 2.6 %. From the 16 losses, 8 data packets were not received by either node and 8 data packets were only received by one node.

The other test performed was to see how many of the data packets that did get lost, when a single node did receive from two of its neighbors at the same time. This scenario was tested with 3 Zolertia RE-Motes, two for sending data packets and one for receiving the sent data packets. The scenario can be seen in figure 17.

Figure 17. Receiving two data packets at the same time. Drawing by author.

In this test, the RE-Motes sent 1 data packet each at the same time, with the difference of one node to receive both of those data packets. 600 data packets were sent in total, where 14 data packets were lost. The loss rate was around

2.3 %, where all of the data packet losses were a single data packet. Both of the data packets were never lost at the same time.

## Communication Time

Apart from the different scenarios that can occur on a road between a vehicle and streetlights, the communication time was also measured. The communication time was measured to see how responsive the communication between the streetlights were, which also affects the interaction between a vehicle and the streetlights. Two Zolertia RE-Motes were used for finding out the communication time, where one of them was measuring the time. The time was measured by one node, because each RE-Mote has its separate clock.

The measure was done by one node, from building the data packet and sending it, for the other node to receive it and build a new data packet to send it back to the first node. The measure corresponds to figure 8, page 26, for example node 5 to send the data packet and for node 7 to receive the data packet. The measure was done 30 times, where the minimum value was 158 ms and the maximum was 533 ms. The resulting mean of the measure was around 326 ms, see appendix A, table 2, for all the results. 326 ms corresponds to a vehicle driving in 883 km/h, by using the assumed distance of 80 meters between one streetlight and a third streetlight.

## Energy consumption

From the scenarios tested in section 6.1.1 – 6.1.3, less energy will be consumed compared to a road where all the streetlights are lit, by turning off streetlights if there are no vehicles in proximity. No calculation have been done to see how much energy the communication and the calculations are consuming, but the Zolertia RE-Motes are said to hold for years on batteries (see section 2.8.1). The energy consumption depends on the amount of objects using a road, which road it is, which type of lamps, how many lamps, which day it is and how the objects are moving on the road. To make an estimation worth mentioning on how much energy the streetlight system will consume, it has to be implemented on a road or simulated as a specific road to find an average result.

# Conclusions

This chapter starts with concluding the thesis and the work that have been done. Section 7.1 discusses the distributed communication. In section 7.2, future work is suggested.

Streetlights consume energy during the dark hours to provide the drivers and people with a good visibility. The streetlights are lit even though there are no vehicles or objects using a road, which makes the energy consumption unnecessary. This thesis presented distributed communication for streetlight systems, to see if it is a good way for saving energy from the streetlights on country roads. No real test or calculation have been done to show how much energy the complete streetlight system saves energy. The thing that have been shown though is that only the lights on a road where an object was in proximity were lit, instead of having all the lights lit. Lowering the amount of lit streetlights should lower the amount of energy consumed on a road. A road with constantly moving objects may not lower the energy consumption, but a road with low frequency of vehicles will.

The research question used during the project was: how should the distributed communication be implemented for streetlight systems? This is more of a general question for the whole thesis, which is overall answered in chapter 4 and 5. The research question is more specified through the goals, purpose and requirements of the distributed communication.

The purpose of the thesis was fulfilled by presenting the idea of distributed communication and implement it on a streetlight system. The communication was supposed to be effective in the sense that it distributes the data packet only to the streetlights that needed the information. The problem is that every data packet is now broadcasted in every transmission, instead of sent to the actual receiver. Broadcast was used because communication directly to an IP address was never solved. Even though a broadcast is used, the data packets will only be received by the neighbors in range of 100 m, which restricts the amount of data packets to read. The data packet is also immediately discarded if it is for another node. The intended solution of the transmission is described in future work.

The ethical aspects concerning distributed communication, is that it needs to be reliable and not violating personal integrity. Reliability was not achieved due to that there is no retransmission and data packets can be lost in the transmission. Why retransmission is not used is because it would have complicated the implementation quite a lot, which is described further down. The data packets sent in the communication is not violating personal integrity, because all data packets containing information about passing vehicles are anonymous. The information only says that it is an object, not which or what kind of object.

The methods used for the literature study was of a qualitative approach. A Qualitative research did best fit due to that qualities and properties of the communication in existing streetlight systems were most interesting to look at. Grounded Theory was used for conducting the foundation for the distributed communication. During the development, the iterative model was used together with meetings with Syntronic. Observations and Usability were used for observing and analyzing the interaction between a moving object and the streetlights. Overall, the chosen methods did fit for this thesis.

To prove the concept of distributed communication it was implemented on a streetlight system represented by Zolertia RE-Motes, sensors and LEDs. The implementation was done on the RE-Motes to form a distributed system, where they could share information about moving objects in proximity of the streetlights.

The requirements of the communication structure included that nodes should be able to handle direct communication with neighbors, forward data packets from neighboring streetlights in the right direction and leave the system without making a large impact on the rest of the distributed system. Direct communication and forward data packets from neighboring streetlights were solved by using an ID on each node, which is specified depending on a node's geographical position to the other nodes on a road. It is a quite simple solution, but worked well during the development of the distributed communication.

The requirement: leave the distributed system without making a large impact on the rest of the system, was solved through the suspection mechanism (see section 5.6). If two nodes in a row are leaving, the decentralized manner will solve the problem by dividing the distributed system into two separately working parts. The distributed communication was implemented to handle different network scenarios like a straight road, an intersection, a roundabout and broken streetlights. The data packet was the last part to be implemented, to be sure that all needed information was included.

From the results in the evaluation chapter, the distributed communication in the streetlight system seemed to work properly with all the different network scenarios tested. The scenarios that were tested were a straight road, a broken node at a straight road and an intersection, by using the five provided Zolertia RE-Motes. The moving object was given light in all directions when it was detected for the first time. When the object passed another node, the direction was known and the lights behind it were turned off while the lights in front of it were lit. From those scenarios it can be concluded that the distributed communication seems to work good and the data packet is consisting of enough information for each streetlight itself to determine whether or not to lit.

The distributed communication was also evaluated with two tests of the vehicle scenario of two objects moving towards each other, to see if the

distributed communication was affected. In both the tests, some of the data packets were never read, which probably was when a send operation was done at the same time as a receive operation or if two receive operations was done at the same time. The scenario of two cars passing two neighboring streetlights at the same time may not be happening that often, but have to be taken into consideration if distributed communication for streetlight systems is going to be used in the real world.

Apart from the scenarios, the communication time was also tested. The result of the communication time was longer than expected, but it is still enough for giving fast driving vehicles a lit road. The conclusion from the project is that the concept of distributed communication for streetlight systems could be considered to be applied on the streetlights on country roads. Before the distributed communication is applied on the streetlights on country roads, it needs some adjustment, further development and more tests.

## Discussion

The implementation of the intersection turned out to be better than expected. Having the same ID made that all the nodes neighboring an intersection node, are able to talk to all intersection nodes. If an intersection node is dead, the data packet will still be received by the other nodes in the intersection. The trade-off is that the same data packet will be forwarded by all intersection nodes. An implication is that an engineer has to define that the streetlight is in an intersection and that it has multiple roads and node IDs.

Apart from that sending and receiving can cancel out each other is that wireless communication itself has a data packet loss rate, tested by F. Leccese [5]. The most obvious solution to data packet loss is acknowledgment and retransmission. The problem with retransmission is that it will affect the velocity calculation between two streetlights. Another problem is if the acknowledge-message is lost, then a retransmission will be done and the receiving node will think that it is another moving object incoming. Also, if a node is dead, the retransmission will go on forever.

The Zolertia RE-Mote is supposed to be powered by the existing power line if it is applied on real streetlights. Due to that the RE-Mote uses wireless communication and can use batteries will make that the distributed communication will still work even if there is some problem with the power line. If there is some problem with the power line, the RE-Mote can be used for detecting it and distribute the information to an engineer for maintenance.

The related work according to communication in streetlight systems can be found in section 2.6. All of the related work are centralized systems where a central device determines whether or not a light or a group of lights should lit. This thesis contributes with a decentralized solution where each streetlight individually makes the decision if it should lit or not. The decentralized structure makes the communication and lit streetlights, only to be in

proximity of the moving objects. It also adds scalability and flexibility to the system.

The complete streetlight system additionally contributes with an indication of movement, by lighting a part of a road. The indication can warn a driver about that an object have been using the road, like an animal, a human or another vehicle, but the object have to pass a sensor for the streetlight system to detect it. The streetlight system will also warn a driver about an approaching vehicle, which the driver can see by light approaching from behind. Some parts of a road may be good to always lit, like a pedestrian crossing for keeping the level of safety for pedestrians.

## Future work

When creating distributed communication for streetlight systems, there are a lot of scenarios which can happen, that needs to be considered if it is going to be used in the real world. The distributed communication needs to be tested in a larger network to see if there are cases where the communication will not work. Apart from the tests, there are things that also need to be implemented if it is going to be used in the real world. First of all, a suggestion is to implement the intended solution of direct communication between neighbors. A data packet is now broadcasted every time a node is sending, because there was a problem with receiving the sent data packets in direct communication. The intended solution was to send directly to a stored IP address. When sending to the intersection nodes, the broadcast should still be used, so that all the nodes in the intersection get the data packets. Secondly, could be to add a way for nodes to easily join the distributed system. If nodes can easily join the distributed communication, less work is needed for the engineers that have to setup the system, so they do not have to predefine all the road and node IDs.

In the conclusion, data packet loss is discussed to be a problem at the same time as retransmission is a problem. If the distributed communication is going to be used in the real world, message-acknowledgment and retransmission is needed for reliable streetlights. Retransmission of a data packet would need something to tell that it is a retransmission and also how many retransmissions that have been done, for the velocity calculation to be correct. If a sent data packet is received and the acknowledge-message is lost, the receiving node needs to know that it is a retransmission of a data packet that it already has read. This is needed so that it do not read and forward a data packet which is already read and forward. Forever data packet sending will arise if a node sends a data packet to a dead node. To avoid a data packet from being forever sent, the node needs to know when to suspect the dead node to find out that it is dead.

When developing the distributed communication, the hardware Zolertia RE- Mote was used. Zolertia RE-Mote is a microcontroller developed for experimenting with and maybe not optimized to be used for the end-product in the real world. The hardware cost may be lowered if a more optimized

microcontroller for a streetlight system is produced without unnecessary components.

Security was delimited in this thesis, which is an important aspect to look at if the distributed communication is going to be used in the real world. Otherwise, there may be a problem of people manipulating the streetlights. The streetlight system can also be extended with other functionality like maintenance and storing of statistics. A central server can be used for storing information from the streetlights, without being dependent on the rest of the system. If a streetlight declares another streetlight dead, the server can get that information and a maintenance person may see it. If there is traffic congestion, the streetlights gets the information and sends it to the server. The streetlights get the information about speed of vehicles, which can be used for calculating the average speed on a road. The number of moving objects using a road can also be interesting.

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**Appendix A**

Communication time (ms)

|  |  |  |
| --- | --- | --- |
| 273 | 265 | 292 |
| 306 | 458 | 533 |
| 378 | 255 | 249 |
| 475 | 246 | 158 |
| 333 | 333 | 318 |
| 235 | 286 | 460 |
| 239 | 453 | 336 |
| 340 | 233 | 158 |
| 235 | 315 | 336 |
| 475 | 506 | 302 |

Table 2. Results of the communication time.

[www.kth.se](http://www.kth.se/)