Intersection Traffic Control System for Autonomous Vehicles

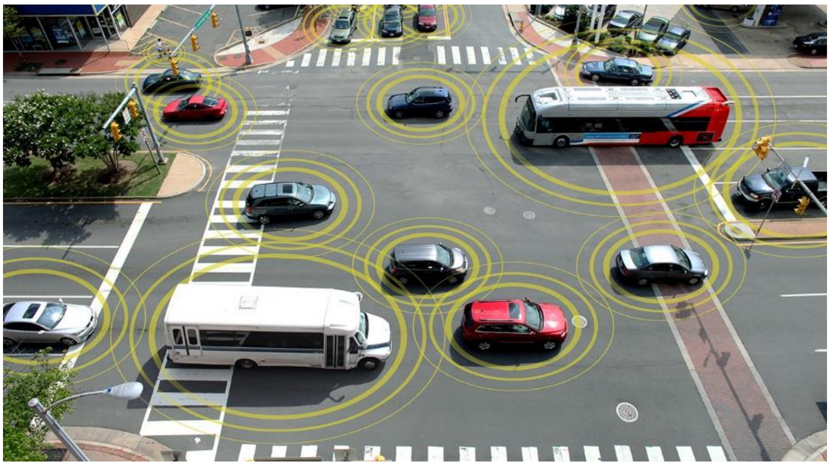

Figure 1: A future where vehicles and static road entities inter-communicate.

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1 Abstract

Imagine a future where the world's motor industry is dominated, if not exclusively inhabited, by autonomous vehicles. A traffic system in which these vehicles are to exist presents many challenges, and introduces new possibilities for improvement in traffic control and safety. Among one of the important areas to address is intersection management. At present, intersection traffic is managed using traffic lights. However, this is neither the safest solution nor the most efficient, with a large number of road accidents happening at intersections [1], and many drivers being forced to wait for redundant periods of time to ensure order is maintained. There is one common factor in both these cases: the human factor. Humans are prone to error and therefore leeway must be given to them. Humans are also blind to that which they cannot directly see or hear and therefore it is not possible for them to predict how safe it is to cross an intersection. In a world where machines operate our cars however, it might be possible to push efficiency and safety levels up by allowing vehicles to communicate with each other, which would optimise the flow of traffic.

2 Introduction

2.1 Background

A node is defined to be a specific point in a network that can store, process and exchange data between other nodes or a main entity such as a central hub [2]. In traditional network design, all nodes report directly to a central hub. On the contrary, a mesh network does not require a central hub to function. It enables the transmission of data over a large topology by 'hopping' packets from one node to the next, reducing data loss, noise and overall transmission power. Mesh networks are also resilient to node failures since multiple paths to connect two nodes can exist. This is in contrast with the use of a central hub where a failure in the hub will result in no communication with all the nodes reporting to that particular hub.

2.2 Initial Proposal

The group's original proposal was to create a mesh network protocol for low-powered IoT (Internet of Things) devices that would enable sensor data-logging and real-time application control with a distributed set of nodes. However, after conducting research on existing solutions it was realised that well-defined solutions exist such as ZigBee [3], which is the most popular wireless specification for mesh networks using low-powered radio modules that complement IoT devices. It was realised that to make the project unique, an application of a mesh network had to be specified.

2.3 Revised Proposal

After carrying out further research (and discussing the feasibility of possible applications with academics), the group decided to focus on transportation and identified a possible shortcoming: V2V (vehicle-to-vehicle communication). This is an active area of research but as of now, no commercial applications exist in the market. Several different research topics [4] branch out of V2V communications but they all have one major goal: to reduce fatal road accidents.

The group therefore decided to build a mesh network, based on the ZigBee/IEEE 802.11 architecture, for modules that would be used in the envisioned future of autonomous cars.

This network shall be used to control and navigate cars at intersections without collisions. To do this it is necessary to build a combined module that is capable of transmission and reception of information (communication with other modules), processing and sensing relevant information (such as position and speed of the vehicle) as well as sensing relevant information (such as speed and position of the vehicle). We also needed to research algorithms for path management and optimisation and packet routing in mesh networks.

The network may also extend to the roads leading to the intersection, to control the speed (or even route) of cars heading towards the intersection in order to further improve fuel efficiency. Traffic control requires real-time V2V communication between all nodes at all times. It is for this reason a mesh network will be used to enable communication between the nodes.

3 Design Criteria

The following are seven criteria that will help team members decide on what ideas to implement, trade-offs to consider and how to select the most effective design choices.

3.1 Reliability

Primarily designed to reduce fatal accidents, the system will first need to demonstrate a high level of credibility to be safe and legal to install on vehicles as well as function properly when it is required the most. The design also needs to have a reliable connection between all nodes of the network. This means that the number of data packets lost or corrupted should be kept to a minimum.

3.2 Performance + Response

An important requirement for collision prevention is for each node to be updated with real-time data regarding the velocity and position of all other nodes in the network. This will ensure that the nodes are always able to respond to any changes in the network. The mesh network should also be able to provide a quick-connect interface for the nodes as well as rapid processing speed at the hardware level. These features will ensure the network will respond in real time to any changes.

For example, if node A is navigating the junction and suddenly brakes, node A would have to send data notifying node B (traveling behind node A). Node B would need to be able to receive this data with minimal delay and process it immediately in order to make an early decision to slow down – preventing a collision.

3.3 Adaptability

The whole idea of a mesh network is that the network can scale to virtually any size within performance and other constraints. A V2V mesh network will exist in a rapidly changing environment. Traffic can vary by large amounts during the day depending on rush hours and hence at times the mesh network would hold eight or more nodes at a time. The mesh network should also have a termination mechanism to allow it to dissolve itself if, for example, no cars exist near a given junction.

3.4 Cost Effectiveness

The product is required to be affordable primarily to make it accessible to a large majority of the public who drive cars, which would eventually lead to a high percentage of the public endorsing the technology. It may also be impossible for the network to operate safely, say, if just one car were not to have the communication capabilities, since collisions or at best erroneous optimisations could occur due to incomplete information about all vehicles, which might actually make traffic worse. It is also important that all components used fit within the allocated budget to ensure the final product is of reasonable cost

3.5 Self-sufficiency

An important aspect of any product released for the first time in the market is the fact that it does not ask the consumer to buy additional components/parts for proper functioning. As long as the product is used for its intended purpose and in the intended environment, it should work ‘out-of-the-box’. The same criteria will be considered for the final prototype.

3.6 Reproducibility + Manufacturability (Design)

Having a good source of documentation is critical for exact reproduction of the design. This will allow for smoother upgrades to the design as well as facilitate the process of shifting from prototype to production. Furthermore, component availability is important in any electrical design. A lack of steady, wholesale supply could hinder large-scale production and as a result, make it difficult for the mass deployment of the final product.

3.7 Unique Selling Point

Like any new product in the market, it is essential for the product to have a USP to persuade customers to integrate the product into future autonomous cars. The USP of this project it that it is self-sufficient and integrates the physical, network and application layer into one package. It is also different from currently researched systems, as it does not require a central hub.

A further description of the primary and secondary objectives for this project (which reflect upon the aforementioned criterion) can be found in the Appendix (Section 8.1 & 8.2).

4 Concept Designs

Current intersection management solutions rely of traffic lights – a system that uses various coloured lights to act as a controller for traffic and thus prevent accidents. Another way to do this would be to encode information through the traffic lights through a technology such as LiFi. The group decided to go one-step further and remove the need for a central traffic light at all by using ad hoc vehicle mesh network, which has the benefits of reducing infrastructure, and enabling efficiency optimisations. As shown in the diagram on the next page, the overall design of system is a mesh network. The overall design of system is a mesh network. Since the design of a mesh network is predefined, the team decided to focus on the subsystems and modules that make up each node of the mesh network. Here are the proposed concept designs.

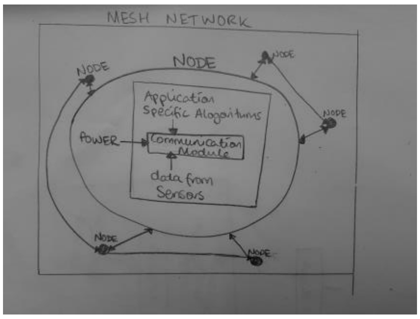


Figure 2: The overall top-level design of the network

4.1 Hardware

4.1.1 Processing Unit

Due to the high availability of the ARM mbed-010.2 development boards, it has been decided to use the ARM Cortex–M0 based microcontroller (LPC11U24 NXP) as it can be easily programmed using the ARM mbed-010.2 development boards.

The benefits of the LPC11U24 include the fact that it has two SPI channels and a single I2C channel, which can be used to communicate with multiple modules using only one microcontroller. Another advantage is that the microcontroller is a surface mount device, which is much cheaper to manufacture for mass-production as compared to a 32-pin through-hole microcontroller.

The considered alternative was the ATMEGA, which has a significantly lower clock speed (48MHz vs 20MHz) and much less RAM (8kB vs 2kB) for through-hole MCUs of a comparable price point (£2-3). However, the advantage to the ATMEGA is that it has a more manageable amount of pins and that it would have been through-hole, which would have made it easier to work on a prototype. The group had also briefly considered using a Raspberry Pi Zero; this would have been a fantastic option for the modules were it not for the fact that the cost of each Pi would have been roughly £9 with the required SD-card.

4.1.2 Communication

The Communicator Modules will form a vital part of the network, being used to transmit information between nodes. There are numerous various units available on the market, with the main difference being the level of implementation of the transmission protocol. The simplest consist only of simple modulator, demodulator and amplifier; requiring encoding and data validation to be done by user's device. On the other side of the range are advanced modules equipped with advanced MCUs, which can be easily configured and then become transparent to the cooperating device, making the communication as simple to implement.

After some considerations and market analysis, it was decided that RFM12B [5] transceivers are a good choice for the application. Belonging to a low-cost range, they use an SPI communication protocol for configuration and data transfer. The modules require the system to configure them (i.e. set frequency and modulation type, among other parameters) and send appropriate instructions to send or receive data (thus being non-transparent). However, they are equipped with FIFO buffer and interrupt generator, handling the low-level aspects of data transmission/reception. This way, the group can focus of implementing mesh network algorithms instead of managing basic communication protocols (which would require time and resources). In general, the market analysis results can be summarised as below:

- All the available radio modules can be separated into a few categories, ranging from cheap and simple (requiring much processing power to drive) to advanced and expensive (being simple to use and almost transparent)
- The simplest modules would require too much time to implement, while the advanced ones do not always provide required flexibility in use
- The chosen module handles low-level aspects of transmission (resulting in saved time) while allowing for flexibility in building a network

4.1.3 Sensors: Accelerometer & Magnetometer

To predict the trajectory of nearby vehicles, some physical quantities will need to be continuously measured accurately. For traffic intersection management, the physical quantities are position, orientation/direction (NSEW), velocity and intended direction (check bibliography for relevance). Although the first two quantities can be found by integrating, the second quantity can also be found using a dedicated compass. This improves the accuracy of the readings as well as reduces the amount of computational required by the main microcontroller.

After researching about several different sensor options, the team decided to use an accelerometer and a magnetometer for direction information. The accelerometer was chosen because no practical embedded sensors exist that are natively designed for velocity measurement. Although this can be calculated using speedometers or GPS, these devices are generally expensive and do not include serial link. Certain devices such as the velocimeter [6] could possibly be used but they are meant for fluid velocity measurement and are not design for the purpose of this product.

The team has agreed to use the 'LSM303DLHC eCompass', which has a built-in 3D accelerometer and 3D magnetometer [7]. Using a single module allows savings on space, wiring and communication channels whilst staying within budget. Since the information will be delivered using a single I2C link with both sensors acting as slaves, pins are conserved on the MCU. This in effect reduces total power consumption, cost as well as the overall dimensions of the final product. The chip uses an I2C interface for serial communication and this can be found on the main MCU as well so there should not be any connection issue.

4.1.4 Power

Supplying power to the chip from inside the car can most easily be accomplished by using batteries with a switch mode power supply, as it is one of the most efficient ways to convert DC power from one voltage to another. Supplying straight from batteries will not ensure a stable enough supply accounting for the sudden voltage and current drops and draws.

The car's cigarette lighter can also be used to power the chip but since the car battery works with fuel supply, the voltage fluctuates widely and this could damage the chip or inadvertently cause it to turn off. Therefore, a possible use for this is to charge the device's batteries, but this will be a factor that will be considered if there is time left over at the end.

Short summary of the DC power circuit:

- 3.3 Volt rails as all the chips can use it and it is a logic level as well.

- Estimates for current draw:
    - ARM mbed Processor LPC11U24 runs at 50 MHz (draws 7mA) [8].
    - Communication module runs on the setting for transmitting and receiving 400 MHz, drawing 22 to 24 mA [5].
    - Sensor draws 0.1 mA when sensing and 0.002 mA otherwise [7].
- Estimates for power usage:
    - All of the above operating at 3.3 Volts, so power usage respectively is 23.1 mW, 79.2 mW and 0.3 mW.
- Designing for four AA batteries (using Duracell power plus as a reference)
    - Four AA batteries for higher pool of power, so less battery changing, and also for a lower battery cut-off voltage, as using lower voltages in batteries yields a better power output.
    - ~0.8V from each battery used, and yields about 2600 mWh from each battery.
    - Estimated Lifetime is 104 hours [9].

- Buck converter to convert 6 volts to 3.3 volts.
- Regarding voltage ripple, the sensor and the ARM mbed chip both have a maximum value of 3.6V, the closest values to 3.3V, so the maximum voltage ripple allowed will be 9%.
- Regarding current ripple, the sensor and the ARM mbed chip both have a nearly constant current value of 7mA, while the communication module can vary by 1mA either higher or lower, so the maximum current ripple allowed will be 11%.
- The duty cycle will be 55% to achieve an output voltage of 3.3V from a supply voltage of 6V
- The inductor value chosen is 100mH.
- Switching frequency is 35064 Hz ~ 35 kHz
- Maximum effective capacitor series resistance is 385.7 ohms, which is more than most capacitors ESRs, so a capacitor can be picked purely on the voltage and current draw expected, while going for the least ESR to ensure minimal voltage ripple.

4.2 Software

4.2.1 Application Layer Module Description

The following list describes potential software modules/functions to be considered for the preliminary design.

1. Node Priority - A function to assign node priority based on distance from the intersection, a given node’s destination and existing traffic rules and regulations.
2. Instruct – A function to broadcast various high priority instructions to nearby nodes such as stopping in case of an emergency.
3. Verify – A function to determine whether a module needs to remain connected to the mesh network. If the module is found to have left an intersection and has travelled at least 10m, it should be disconnected from the mesh network to prevent over-crowding. In turn, this should increase the connection speed of the network.
4. Data Processing – This function will use data gathered from all connected nodes to develop a 'virtual map' of each car position and destination.
5. Decision - This function will use the information given by the data processing function to decide the best possible/safest course of action for the current vehicle (e.g. stop, instruct, warn, or reduce speed).

4.2.2 Network Layer Module Description

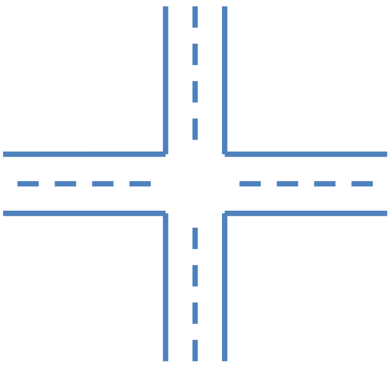
The basis of all V2V communication is to form a mesh network representing each car as a node in the network. Two main functions will allow for communication of nodes across the network:

- Communicate – A function to allow a given node to communicate with its neighbouring nodes. It will either receive data from different nodes and broadcast it or send the data for analysis to the relevant function if the current node itself was the recipient.
- Path – A function, which calculates the shortest path to connect to nodes. This will allow any two nodes in the mesh network to communicate (relevant algorithms can be discussed in the design concept section)

4.2.3 Demonstration

For proof-of-concept demonstration, a number of assumptions have been made:

1. A maximum of five cars can navigate the intersection at any time.
2. The



3. intersection layout is as shown:
4. All vehicles are fully autonomous which means that they can be controlled wirelessly and without the need of human input.

For the purpose of demonstration, the project will be modelled using an intersection of lane length 10m and lane width 1.5m. The cars will be replaced with the nodes of the network (made up of communication modules running algorithms developed by the team). Finally, the team will employ the use of various coloured LEDSs that will emulate a certain output or process.

1. Red LED x 5 – Used to indicate that a node is receiving an instruction to stop.
2. Green LED x 5 - Used to indicate that a node is receiving an instruction to accelerate.
3. Yellow LED x 5 – Used to indicate that a node is receiving an instruction to slow down.
4. Blue LED x 5– Used to indicate that a node is transmitting data.
5. White LED x 5 – Used to indicate that a node is receiving data.
6. Power supply circuit x 5 – This limits the power supplied to the modules and ensures a stable power supply.

5 Discussion

5.1 Possible Obstacles/Problems

5.1.1 Problem: How to determine node locations

1. Use GPS modules/ GPS functionality of phones
    - Advantage: GPS is what would be used in the full-scale implementation of intersection management.
    - Disadvantage: Modules are outside the project budget range. GPS has a best-case accuracy of 2.168m [10]. This is not appropriate for scale used for the model, as it requires accuracy in the order of cm.
2. Dead Reckoning. This method can be used to estimate the relative positions of the nodes by using information on the nodes' displacement. This data can be obtained from a magnetometer and accelerometer.
    - Advantage: Simple to understand
    - Disadvantage: The further the distance travelled, the greater the error. However, as dead reckoning would be used to determine position on a small scale, the position error should not be significant.

5.1.2 Problem: How to determine a communication path between two nodes

1. Determine the connections and distances between the nodes
    - Connections can be determined using a known algorithm such as Dijkstra's, Prim's or Kruskal's [11]
    - Distances between nodes can be calculated in relation to received signal strength or time for data to be received.
    - Alternatively, distances between nodes can be derived from positional data.
2. Use connection and distance information to create a routing table. Every node will have a copy of this table.

5.1.3 Problem: How to fix a broken path

1. Message – Response system:
    - If a node receives a message destined for it, it sends a confirmation message back to the transmitting node. Until the transmitting node has received this confirmation, it will stall. Upon successful transmission, the message will continue to propagate through the network.
    - If the transmitting node does not receive a response for a certain amount of time, it will propagate a message to all other node to delete the 'receiving' node from the routing table.
    - The routing table will then be reconstructed by sending a test packet to all nodes.

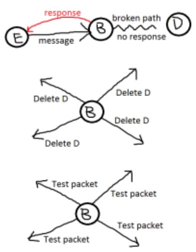


Figure 3: Reconstructing a routing table

Node	Routing address
A	F
B	B
C	B
D	B
E	THIS NODE
F	F

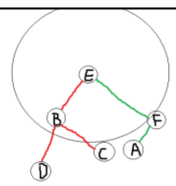


Figure 4 Example of Routing Table

6 Conclusion

6.1.1 Future Work

In order to select the preliminary design, testing for some of the subsystems will need to be conducted as follows:

- To determine distance between nodes, these tests would need to be conducted before reaching a final decision:
    - Correlation between signal strength and distance between nodes.
    - Correlation between τ = (time received – transmission time) and distance between nodes
- To determine the criteria for node priority
    - Tests investigating which ranking of the variables: time of arrival at junction, route (straight path or turn), speed allow the nodes to safely navigate the junction
- Tests to judge the reliability and accuracy of using dead reckoning to determine the position of the nodes
- Tests to define a time-period (T) within which the system should respond to changes. One possibility for calculating T is:
    - $P(X|T) < 0.05$ Where X is the event of a collision between 2 nodes
    - In words: The probability of 2 nodes colliding given the system delay is T is less than 5%

6.1.2 Deliverables

Below is a table outlining the main deliverables of the project and expected finishing times.

Deliverable	Deadline:
Working prototype for Mesh network	25th February
Final prototype design for Application layer	29th February
Working prototype for Application layer	8th March
Final Report outlining project implementation	13th March
Website	13th March
Presentation and Demo	21st March

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8 Appendix

8.1 Primary Objectives

1. To leverage radio technology and existing radio communication modules for the creation of an economical and scalable wireless mesh network that is software configurable for a variety of applications.
2. To establish a reliable, robust and real-time vehicle-to-vehicle (V2V) communication framework that will form a mobile ‘mesh-network’ with rapidly connecting and disconnecting nodes.
3. To design a fully autonomous intersection management (IM) system for crossroads without traffic lights in order to assist driverless vehicles in using appropriate approach speeds and managing a mutual priority service.
4. To use a broad-range of sensors including gyroscope, accelerometer and magnetometer in order to determine the position, speed, orientation (NSEW plane) and intention of other road users.
5. To create a virtual map of nearby road-users using information received from such sensors and then perform speed adjustments as well as provide warning messages as necessary.
6. To demonstrate the aforementioned objectives using standalone modules held by humans acting as “self-driving cars” in a closed environment. The modules will have LEDs that would substitute as warning messages if the user were required to stop.
7. To create a website that promotes our product while explaining how the module was created as well as providing information about the team.

8.2 Secondary Objectives

These optional objectives are to be considered only if they are no time constraints and the team has managed to achieve all primary objectives.

8. To produce low-powered modules that have optional tethered and untethered power supply unit that do not affect the performance of the vehicle in any way if plugged-in.
9. To incorporate a road-type detection algorithm that could make use of road widths or other sources of information to judge the type of road and then adjust the priority management scheme accordingly (e.g. major road users have higher priority).
10. To demonstrate the consistency of the intersection management system by using a large number of nodes (i.e. 5 or more) and create and test out various different scenarios.
11. To consider managing the speeds and routes of cars approaching the junction from a distance to minimise either fuel consumption or time waiting or a balance.
12. To consider the large-scale management of traffic in a hierarchal mesh network (of servers at each junction).

8.3 Team Management

- Used Slack for communications.
- Met regularly to discuss ideas.
- Created meeting agendas for each meeting to ensure efficient use of time.