Bio-Inspired Fuzzy-Causal Communication Protocol for Vehicular Ad-Hoc Networks

Grigory Evropeytsev, Dr. Saúl Eduardo Pomares Hernández,
Dr. José Roberto Pérez Cruz

Laboratorio de Cómputo y Procesamiento Ubicuo.
Coordinación de Ciencias Computacionales.
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), México.

Technical Report No. CCC-17-001
February 27, 2017

Luis Enrique Erro 1
Sta. Ma. Tonantzintla,
72840, Puebla, México.

Abstract

Intersection management is one of the most challenging problem in the traffic control. The most common way of managing the intersection is the traffic lights. The main challenge in optimizing the traffic flow is the traffic light adjustments. One of the way to configure traffic lights is by analysing the traffic statistics, but this solution does not adapt to the real world traffic and can possibly reduce the traffic efficiency. With the availability of cheap transceivers the vehicles and road infrastructure can communicate with one another. But this type of communication differs from the traditional models in several aspects making the traditional solutions inefficient. In this work, we present the communication protocol designed for the vehicular network architecture. The proposed solution does not require any communication infrastructure and ensures that messages are ordered according to the spatial-temporal relation, that ensures that only the most recent information is available.

Contents

Chapter 1

Introduction

The volumes of vehicle traffic has grown beyond the capacity of road system infrastructure. This firstly have been noted in 50ties [3]. But unlike 50ties it is not possible to increase the road infrastructure to accommodate the increased traffic flow [8].

Intersection management is one of the most challenging problem within the transport system. All of the intersections represent the small part of road system but they represent the bottlenecks in the traffic flow [1] and accounts for a majority of incidents [1]. And thus, it is important to manage intersections to increase traffic flow and reduce incidents rate.

The most common way of managing the intersection is the traffic lights. They provide a way of controlled intersections crossing. But as mentioned in [1] the effect of traffic lights on the traffic efficiency is far from explored.

Several works exist that try to optimize the traffic flow by adjusting the signals based on traffic statistics. The statistics are analysed and the corresponding times for signals are determined, and then programmed into the traffic lights installed at the intersections. As a main disadvantage, these works cannot adapt to the real world traffic flow as it changes. And also it has been show that the incorrect signal setting can drastically reduce the traffic efficiency as compared to the uncontrolled intersections.

To adjust to real world conditions each traffic light must have the ability to estimate the traffic flow and to communicate with other traffic lights installed at the neighbour intersections. But the implementation of this communication is very expensive in terms of implementation and maintenance as it requires the connection of each traffic light to the global communication network.

Recent advancement in communication have enabled the development of cheap transponders and the creation of communication capable vehicles and road infrastructure elements. With these cheap transceivers a vehicle can communicate with other vehicles and road infrastructure using the WAVE protocol [6] that does not require the existence of the global communication infrastructure. These systems are named VANET (Vehicle Ad-Hoc Network). As a result of this, the communication between vehicles and road infrastructure can be implemented without significant increase of the system cost.

VANET is a type of Mobile Ad-Hoc Network, but it is very different from traditional systems and produce many challenges in the communication implementation. Main challenges for communication are:

- High vehicle mobility.
- High vehicle density.
- Radio obstacles.

As the result of this, the traditional communication protocols for Ad-Hoc networks cannot be used to achieve the communication in a vehicular network as they are designed for static or slow moving low density networks.

Several works exist to account for these challenges [2] [4] [5] [7] [10] [11] [13] [16] [17] [19] [20] [21] [22]. They provide protocols for communications that are adapted to the communication challenges mentioned above. But the main disadvantage is that they are required to know the message destination or the physical location of the message receiver. While the logical address of messages destination (such as process identifier or IP address) can be known, the knowledge of the physical location of the receiver is a great challenge in the communication protocol implementation as it changes with time. And due to high node mobility it can become outdated during the message transmission (ex. a message is send to receiver at location A, but when message arrived the receiver already moved to location B).

Also for several types of application (Traffic efficiency and Infotainment applications) [6] the participants who can benefit from the information are not known a priori. In other words, when the information is generated the message destination is not known. (ex. the information about traffic flow at a particular intersection is useful for vehicles that will pass throw this intersection, but there is no way to know vehicles that are planning to pass at this intersection). These systems require a new communication protocol that can deliver messages when the destination is not known to the sender.

The traffic conditions can change rapidly and they are also localized to a particular region of space [1]. In other words, the traffic flow information at intersection A at 6:00 can be very different from traffic information at the same intersection at 6:30 or at the intersection B. This also applies to the infotainment applications (such as available parking space information). For these applications the information is localized in a particular region of space at a particular moment of time and it can be outdated or irrelevant at another region of space or at another moment of time. For these applications the spatial-temporal communication model is required.

The main aim of this research work is the design and development of the spatial-temporal communication protocol for the traffic efficiency applications such as the intelligent traffic lights. The designed communication protocol will be based on the WAVE communication stack (it will not require the existence of the global communication infrastructure). The proposed protocol will deliver messages in a vehicular network when the nodes that require the information are not known to the sender. The spatial-temporal properties of the proposed solution will be modelled by fuzzy-causal relation. Also the proposed solution will contain mechanisms to detect the outdated or irrelevant information in the system and remove it.

This document is divided into 8 chapters. The chapter 1 offers an introduction to this work. Also it includes the short definition of the problem of this work and a short description of the proposed solution for the problem. In chapter 2 the background concepts and definitions used for this work are present. Chapter 3 presents a detailed problem description. In chapter 4 the overview of the state of the art is present. Chapter 5 describes the research proposal to resolve the problem described in chapter 3. In chapter 6 the work plan is present. Chapter 7 present the preliminary results of this investigation. And chapter 8 described the conclusions from this work and also marks the ways for future works.

Chapter 2

Background

2.1 Causal ordering in distributed systems

2.1.1 Causal ordering

Time is an important theoric construction to understand how the transactions are developed in a certain system [9]. A practical way to achieve such construction, is recording the time when certain events happen to create a temporal ordering of events. Unfortunately, there are some environments that lack of a global time reference, as a physical clock, where it is difficult to establish such ordering. An example is a distributed system.

A distributed system is composed by different processes spatially separated, that communicate with each other by exchanging messages. In a distributed system each process has its own physical clock that may have a certain time difference with each other. In the absence of a global physical time in a distributed system, it is impossible to determine if an event has happened before other, in other words, it is impossible to determine the systems causal order.

A causal order establish a precedence relation between two events in the following way: let a and b two events causally related:

1. It is said that a *happened before* b if there are information flow from a to b.

2. Given the relation, a must be processed before b.

2.1.2 *Happened before* relation

Causal ordering was developed to remove inconsistencies in message delivery, which is produced by an unpredictable delay in the communication channels. Causal order is based on the *happened before* relation defined by Lamport [9]. This relation is denoted by $\rightarrow$ as follows.

Definition 1. *Definition 1. The relation $\rightarrow$ on the set of events of a system is the smallest relation satisfying the following three conditions:*

1. *If a and b are events in the same process, and a comes before b, then $a \rightarrow b$.*
2. *If a is the sending of a message by one process and b is the receipt of the same message by another process, then $a \rightarrow b$.*
3. *If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$.*

Two distinct events a and b are said to be concurrent $a \parallel b$ if $a \nrightarrow b$ and $b \nrightarrow a$.

This relation can be extended to messages in the following form: message $m \rightarrow$ message m' if and only if $send(m) \rightarrow send(m')$ where send is the message sending event.

2.1.3 Immediate Dependency Relation

The Immediate Dependency Relation (IDR) [15] is the propagation threshold of the control information, regarding the messages sent in the causal past which must be transmitted to ensure a causal delivery. IDR is denoted as "↓" and its formal definition is as follows.

Definition 2. *Two messages m and m' form an IDR $m \downarrow m'$ if and only if $m \rightarrow m'$ and m'' such that $m \rightarrow m''$ and $m'' \rightarrow m'$ does not exist.*

Thus, a message m directly precedes a message m', if and only if no other message m'' exists in a system, such that m'' belongs at the same time to the causal future of m, and to the causal past of m'.

This relation is important since if the delivery of messages respects the order of their diffusion for all pairs of messages in IDR, then the delivery will respect the causal delivery for all messages.

Causal information that includes the messages immediately preceding a given message is sufficient to ensure a causal delivery of such message [15].

2.1.4 Fuzzy causal relation

The fuzzy-causal relation (FCR) relates the logical/temporal domain with the spatial domain. According to [14], it is necessary to define three linguistic variables:

1. Causal Distance (CD), it is the variable whose universe of discourse is the logical/temporal domain. It is defined as the difference between the creation of two events.

2. Physical Distance (PD), whose universe of discourse is the spatial domain, refers to the distance between two regions of space.

3. Fuzzy-causal closeness (FCC), whose universe of discourse is the degree of closeness among events considering both logical/temporal and spatial domains.

Definition 3. *The FCR over a set of events must satisfy:*

1. $a \overset{\lambda}{\rightarrow} b$ *If* $a \rightarrow b$ *and* $0 < FCC < \phi_s$

2. $a \overset{\lambda}{\rightarrow} b$ *If* $\exists c : a \overset{\lambda}{\rightarrow} c \overset{\lambda}{\rightarrow} b$ *and* $0 < FCC\phi_s$

where FCC is the degree of fuzzy-causal closeness between a and b.

2.1.5 Causal distance

Let e_1 and e_2 be two events where $e_1 \neq e_2$. The causal distance is the number of events that occur between e_1 and e_2.

2.1.6 Causal history

Causal history, in general, the set of events that happened before a specific event. We denote the causal history by Π.

2.2 Traffic flow modeling

Modeling traffic flow allows a great variety of different model approaches for two reasons [8]. First, the details of traffic flow can be resolved to different extents, ranging from the dynamics of averaged quantities down to individual vehicle motion. Secondly, no first principles of traffic flow are known, from which models of different resolution could be derived, so the field of traffic flow dynamics leaves room for a lot of substantially different ideas.

The classification of the models with respect to their resolution is quite straightforward and unequivocal. In general three classes of models can be distinguished.

1. Microscopic models, which address the subject by describing individual vehicle dynamics.

2. Macroscopic models, which are based on equations for averaged quantities like vehicle density and average flux, are distinguished.

3. Mesoscopic models, that describes the vehicles using a mixture of macroscopic and microscopic dynamics.

This work considers the individual vehicles, as a result it is based on the microscopic traffic flow model.

2.2.1 Microscopic traffic flow modeling

The idea of microscopic modeling of traffic flow is to describe the dynamics of each individual vehicle as a function of the positions and velocities of the neighboring vehicles. The main assumption of this model is the fact that in general vehicles move without colliding [8].

Two types of dynamical processes are considered in the microscopic traffic modeling:

1. Car-following
2. Lane-changing

Car-following process describes the changes of vehicle velocities in the same line. The change of the velocity is performed, if the momentary velocity does not coincide with some desired velocity, which is determined by safety considerations, legal restrictions and so on.

Line-changing process describes the lane changing event that is performed by a car on a two or more lane street.

2.2.2 Spatial discretization of the traffic model

In the discrete traffic flow model the space is divided into the cells of length l that corresponds to the space occupied by a car in a dense jam and the time is also divided in the time steps of Δt [8]. The model is characterized by four parameters l, V_{max}, a and b. l corresponds to the length of the space occupied by a car in a dense jam, V_{max} is the maximum allowed speed, a is the maximum acceleration and b is the maximum deceleration. V_{max}, a and b are the integer number and are expressed as the number of cells.

The update rules of the model will be given by the following equations:

$V_{des} \leftarrow min[V_{max}, V(t)+1, V_{safe}]$

$V(t+1) \leftarrow max[0, rand(V_{des}-a, V_{des})]$

This function calculates the velocity of a vehicle at the next time step. $rand(x, y)$ is the random number between x and y and represents the imperfections in the driving such as overestimation of the other participants speeds.

The safe velocity can be calculated from the assumption that vehicles drive without collisions by using the following equation:

$V_{safe} = V_l + \Delta V(g - V_l, V_l + V_s)$

where

$\Delta V(x, y) = \frac{x}{\frac{y}{2b}+1}$

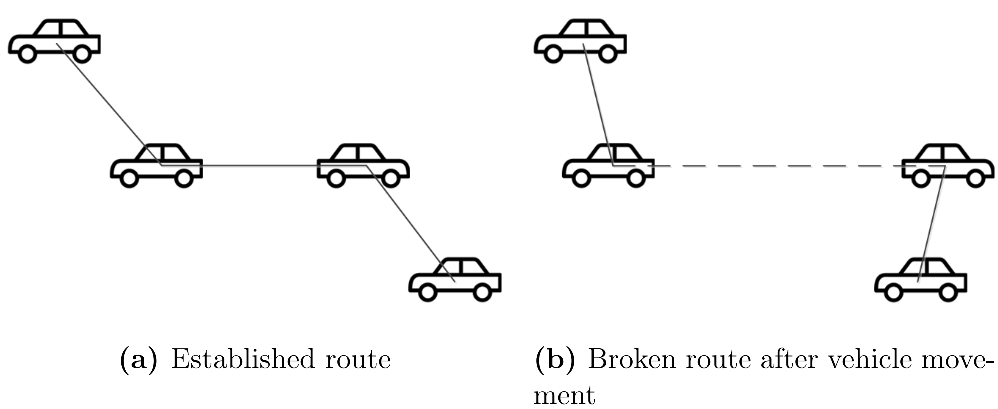
In this equation g corresponds to the space between the leading and following vehicles, V_l is the speed of the leading car and V_s is the speed of the following car.

Chapter 3

Problem description

New advances in the area of wireless communication allowed a new tendency of developing vehicular networks to exist. These networks are formed by vehicles and road infrastructure elements communicating among each other using the extension of the Wi-Fi protocol defined by 802.11p standard. The usage of communication can improve drivers experience but at the same time these systems have several challenges [6] [18].

Vehicles can be characterized by high mobility that provokes rapid dynamic topology changes. The algorithms for ad-hoc networks assume a static nodes or nodes with low mobility. One of the reasons these algorithms cannot be applied in vehicular networks is that the selected route can be broken after the message was send from source but before it arrives to its destination. Due to high mobility of nodes in a vehicular network the probability of this to happen is high.



(a) Established route **(b)** Broken route after vehicle movement

Figure 3.1: Link breaking due to high mobility

Another challenge is that there are a lot of obstacles that degrade radio performance like buildings, tunnels, bridges and even other vehicles. Also in urban areas the high densities of vehicles are present. These two reasons can significantly reduce the signal range and increase the error rate due to degradation of radio signal and interference from other participants.

Also the existing networks are based on logical addressing where the address defined a resource but not a physical location. But a vehicular networks require a geographical addressing scheme. This addressing mechanism is based on the physical position of the participants of the communication. One type of this addressing is geo-cast (send a message to all vehicles in a specific area). This form of communication is primarily required for active safety and traffic efficiency applications, but the existing underlying network structure does not support this form of addressing.

The area of traffic efficiency and management require a communication between vehicles and the road side units (RSU) like traffic lights. The communication between RSU can be very useful. For example, so that traffic lights can better adapt for traffic condition or the information about traffic jam can be delivered to vehicles that they can choose alternative routes.

Another challenge in the area of traffic efficiency and management is that in some cases the participants who can benefit from the information are not known to the sender. For example, a vehicle that is reporting a traffic flow at the intersection A cannot know vehicles that will pass at the intersection A sometime later and take advantage of the provided information. In this case the indirect communication model can be used to deliver messages to nodes that can benefit from it.

Another benefit from the message diffusion when the destination is not known is that a message can be delivered to participants that are located in a specific region at a specific time. In other words, the message will be delivered based on the physical location instead of logical addresses.

The communication in a vehicular networks is very important to improve the traffic efficiency and to deliver useful information to drivers and road infrastructure element to increase traffic flow. A lot of research has been done in the area of data routing in vehicular networks, but this type of communication require that the destination is known before sending the message. But in many cases the destination cannot be known beforehand. The development of communication mechanisms that can deliver messages in this case is required to improve the traffic efficiency and driving experience.

Chapter 4

Related work

This chapter presents a detailed description of related works that propose protocols to offer the communication services in vehicular networks. These protocols can be divided based on 3 parameters:

1. The system architecture they are designed for.
2. The message delivery strategy used.
3. And routing type used.

The taxonomy of related work is presented in the Figure 4.1.

4.1 Protocols designed for ad-hoc network topology

This section presents an overview of the protocols designed for the network topology that does not have any infrastructure elements e.g. it consists only of moving vehicles. This group can be further divided based on the message delivery strategy used.

4.1.1 Protocols designed to use the data mulling strategy

The protocols from this category are primarily based on the MULEs [16] model. This model is designed for sensor networks where sensor does not have capability

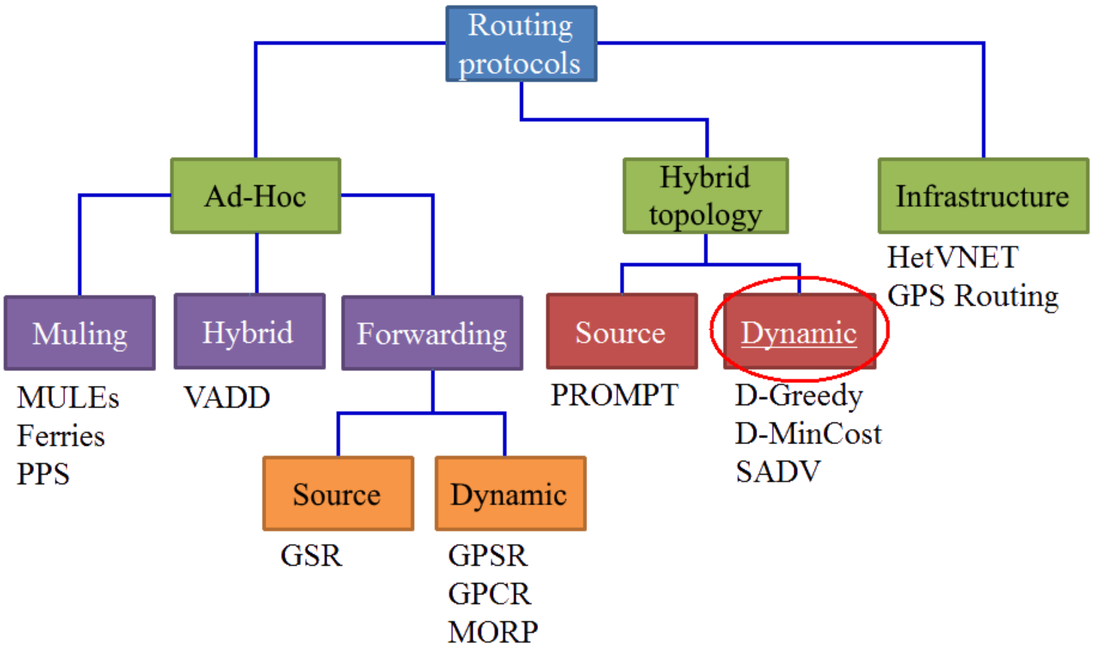


Figure 4.1: State of the art taxonomy

for direct communication. The system also contains randomly moving nodes denoted as MULEs (Mobile Ubiquitous LAN Extensions) to transmit data. When the MULE enters in the vicinity of a sensor, the sensor transmits data to the MULE. And when a MULE enters in the vicinity if an access point, it dumps all of the recollected data. This model is energy efficient (in terms of battery life of sensors) but introduces high latency.

To resolve the high latency of data delivery the Ferry approach was introduced [21]. Instead of random movement of MULEs, a Ferry moves along the predefined route. When a node wants to send a message it moves to meet up with the ferry and transmits data using the low power transmitter. This model decreases the latency comparing to MULEs protocol, but requires the movement capability of sensors.

To further decrease the latency of data delivery a ferry model was modified [19]. In the modified model the ferry selects the next destination node randomly. If the node has any data to transmit, on the next cycle the probability to visit this node is increased. If no data is available the probability returns to its predetermined default value. As the result of this, the latency of data from several nodes can increase, but the average latency of messages in the system is decreased.

4.1.2 Protocols designed to use the hybrid strategy

The hybrid strategy is a routing strategy that combines elements of multipoint routing with mulling. The protocols from this category alternate between these strategies to use the available resources in an efficient manner.

The main protocol from this category is a VADD [20] protocol. It uses this store and forward technique by routing the messages via road segments with high vehicular density. With few messages this work provides good results, but when the number of messages increase the road segments with high vehicle density get saturated which decrease data delivery rate.

4.1.3 Protocols designed to use the forwarding strategy

The protocols in this category are inspired by the Greedy Perimeter Stateless Routing (GPSR) [7]. In this protocol the nodes maintain only the information about its immediate neighbors. The forwarding decision is taken based on the position of the neighbors to reduce the distance to the destination. As a shortest path can lead to a dead end the recuperation algorithm is introduced to recover from this.

To address the issues of the GPSR in urban areas such as obstacles several solutions GSR [10] and GPCR [11] were introduced. In GSR when a node send a message it determines the location of the destination using the location services and then with the information provided by the city map it can calculates the shortest route that is embedded in the message header. As a main disadvantage this work requires city map information to be available at all times and the message route is determined at the sender, so this algorithm cannot adapt to changing traffic conditions.

When a map is not available GPCR [11] algorithm can be applied. This algorithm uses several heuristics to detect junctions without the use of external information. With the junction location information GPCR takes decision about message forwarding at each junction on greedy basis. But this heuristics reduce the delivery rate compared with the GSR.

To prevent the situations when the link breaks during the packet transition a MORP [13] protocol was designed. It uses the information about vehicles position and velocity to determine the route with lowest probability of rupture during the message transmission. But as a disadvantage it drastically increases the bandwidth usage by the vehicles.

4.2 Protocols designed for hybrid network topology

This section presents an overview of the protocols designed for the network topology that contains infrastructure elements and moving vehicles. The communication in the category is achieved by cooperation between vehicles and road infrastructure elements.

4.2.1 Protocols with source routing

A source routing is a type of routing where the message route is determined by the sender. A main representative of this category is a PROMPT [5] protocol. In this protocol the base station sends beacon frames that are retransmitted by vehicles to determine the fastest route between vehicle and base station. As a result of this, the protocol adapts to the changing traffic conditions, but as a disadvantage it does not work in sparse networks.

4.2.2 Protocols with dynamic routing

To reduce the bandwidth usage D-Greedy and D-MinCost protocols [17] were proposed. Both of these protocols based around the idea of combining data mulling and forwarding to reduce the bandwidth usage but at the same time achieve lower transmission delays. But as a disadvantage they require a network to be dense so that the message can be forwarded at any moment.

To address the issues of VADD, D-Greedy and D-MinCost protocols a SADV [2] protocol was developed. It introduces a static nodes at each intersection to act as a message buffer when the network is sparse. But this protocol requires the precise city map with traffic statistics information.

4.3 Protocols designed for infrastructure network topology

This category elaborates the protocols that are designed for an infrastructure based system. In this type of system each vehicle is capable of global communication with the help of the provided infrastructure.

Several authors investigate the possibility to use 4G LTE [22]. In this approach instead of direct communication between vehicles the cellular network infrastructure is used. This approach is attractive because cellular networks are designed with mobility of nodes in mind. But they have several disadvantages when applied to vehicular networks. The main disadvantages are that the peer discovery is a long process, high interference when vehicle density is high and the requirement to have a global coverage of cell service.

To address the issue of data routing for vehicular networks over an existing infrastructure several approaches were defined [4]. The application or DNS approach consists of a data base where the logical addresses are mapped to GPS coordinates. When a node moves it updates its location in the centralized database and thus, it is discoverable by its GPS coordinates.

In the multicast approach nodes enters multicast groups to receive messages based on location. When node moves to a different location it enters another group to receive notification for this location. But each node requires the knowledge of region-to-group mapping to be able to enter correct group. Both of this approaches defines how the messages can be routed by using the existing Internet infrastructure for vehicular networks, but they require vehicles to be always connected to the Internet.

4.4 Comparison of the analyzed protocols

All of the analyzed protocols are analyzed in several different aspects.

The first aspect is whether a mobility of nodes can be controlled or not. In other words whether the communication protocol can influence the direction a node moves based on the information received.

Another aspect is the implementation and maintenance cost. How much the implementation of a particular solution will require to implement (installation/equipment cost) and how much the proposed solution will require to maintain (monthly/periodical costs).

The third aspect is whether the protocol considers a dynamic environment where it is not known where a message can be generated and where it is need to be delivered.

The last aspect is whether the protocol requires to know the destination before sending the message or it can handle messages when the destination is not known.

The results of the comparison are presented in the table 4.1.

Table 4.1: Comparison of the analyzed protocols

Title	Mobility	Implem. cost	Maint. cost	Dynamic env.	Unknown destination
MULEs [16]	Random	Low	Low	✗	✓
Ferries [21]	Controlled	Low	Low	✗	✓
PPS [19]	Controlled	Low	Low	✗	✓
VADD [20]	Uncontrolled	Low	Low	✓	✗
GSR [10]	Uncontrolled	Low	Low	✓	✗
GPSR [7]	Uncontrolled	Low	Low	✓	✗
GPCR [11]	Uncontrolled	Low	Low	✓	✗
MORP [13]	Uncontrolled	Low	Low	✓	✗
PROMPT [5]	Uncontrolled	Medium	Medium	✓	✗
D-Greedy [17]	Uncontrolled	Medium	Medium	✓	✗
D-MinCost [17]	Uncontrolled	Medium	Medium	✓	✗
SADV [2]	Uncontrolled	High	Low	✓	✗
HetVNET [22]	Uncontrolled	High	High	✓	✗
GPS Routing [4]	Uncontrolled	High	High	✓	✗
Proposed solution	Uncontrolled	Low	Low	✓	✓

Chapter 5

Research proposal

The design and development of the fuzzy-causal protocol is divided into eight phases. The first one is the modeling of the vehicular network environment. The second one consists of development of the system model based on the road intersections. The third phase includes the design of the causal ordering protocol for the designed system. During the fourth phase the protocol is extended for spatial-temporal relation. In the fifth phase the methods to estimate data relevance are developed. The sixth phase extends the designed protocol for cooperative navigation scenarios. The protocol is further extended to incorporate the direct communication model in the seventh phase. During the last phase the protocol is validated to ensure its correctness and simulated to measure its characteristics to be compared with the state of the art.

Phase 1. Environment modeling.

During this phase the environment (roads, infrastructure elements and vehicles) are modeled for the following phases. This model is used to represent the environment, its state and state transitions.

Phase 2. System model for vehicle communication.

During this phase the model to represent the communication in a vehicular network movement is developed. This model is based on the road infrastructure instead of vehicles. This approach is scalable because it does not depend on the number of vehicles in the system but instead on the road infrastructure that is static.

Phase 3. Spatial causal order protocol for vehicular network.

In this phase, the system model from phase 2 is used to develop the protocol that ensures causal ordering in a vehicular network. This protocol is also based on the road intersections to remove the scalability issue of the traditional systems based on vehicles.

Phase 4. Spatial-temporal protocol extension.

The protocol from phase 3 is extended to use the spatial and temporal data to identify causal message relation in the vehicular network.

Phase 5. Data relevance estimation.

During this phase the rules to estimate data relevance are developed. These rules are used to remove data that is not relevant for a particular situation and also to remove outdated information from the system.

Phase 6. Cooperative navigation extension.

In this phase the protocol from phase 4 is extended to incorporate data generated and consumed by vehicles in a cooperative navigation scenario. This extension provides the cooperation between vehicles and infrastructure to improve the traffic efficiency.

Phase 7. Direct communication extension.

The protocol from previous phase is further extended to incorporate the direct communication between participants in a vehicular network. This extension is aimed to further improve the characteristics of the proposed solution.

Phase 8. Protocol validation and simulation.

In this last phase the developed protocol is formally validated to ensure its correctness. Also the protocol is simulated to measure its characteristics that cannot be calculated mathematically.

5.1 Research question

How can a scalable spatial-temporal communication be achieved among entities of a vehicular network without a global communication infrastructure?

5.1.1 Particular research questions

1. How can a communication among vehicles and road infrastructure be modeled?

2. How can the exchanged data, transmitted in a vehicular network, be organized into a timeline?

3. How can the spatial information be associated with the temporal information to identify cause-effect message relations?

4. How can a spatial-temporal communication be achieved among fixed and mobile entities in a vehicular network?

5.2 Objectives

5.2.1 Overall objective

To design and to develop the bio-inspired communication protocol for the vehicular networks to provide communication capabilities for vehicles and road side units.

5.2.2 Particular objectives

1. To design a communication model among vehicles and road infrastructure.

2. To design an algorithm to ensure the causal message ordering in the system based on the intersection road side units.

3. To design a mechanism to order messages according to the spatial-temporal relation.

4. To develop a set of rules to estimate the data relevance to make decisions about data retransmission.

5. To design an extension for the cooperative navigation systems.

6. To extend the proposed protocol to incorporate direct communication aspects.

5.3 Hypothesis

Communication among the entities of a vehicular network can be achieved through a bio-inspired spatial-temporal communication protocol.

Chapter 6

Work plan

Table 6.1: Schedule of activities

Activity	Year/Month															
	2016				2017				2018				2019			
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Review of related work	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		
Environment model design			🟩	🟩												
System model design			🟩	🟩	🟥											
Causal flooding protocol design				🟩	🟥	🟥										
Causal flooding protocol validation						🟥	🟥									
Spatial-temporal protocol extension							🟥	🟥								
Spatial-temporal protocol validation								🟥	🟥							
Design of data relevance estimation rules									🟥	🟥						
Extension for cooperative navigation										🟥	🟥					
Cooperative navigation extension validation											🟥					
Direct communication extension											🟥	🟥				
Communication protocol validation													🟥			
Communication protocol simulation													🟥	🟥		
Thesis writing					🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
Thesis defense																🟥
Publications							🟥			🟥				🟥		

Chapter 7

Preliminary results

7.1 System model

We define the system model in order to describe and represent our system.

- Processes: Each road entity, mobile and fixed is represented as an individual process. Hence, a vehicular network can be seen as a set of process $P = \{p_1, p_2, \ldots, p_n\}$ that communicate with each other. A set of processes can be seen as a union of mobile and fixed road infrastructure elements: $P = V \bigcup I$. V and I will be defined in a continuation.

- Mobile road entities: Each mobile entity in a vehicular network belongs to the set $V = \{v_1, v_2, \ldots, v_m\}$. A mobile entity $v_i \in V$ represents a mobile entity (like vehicle) equipped with a transceiver moving throw the road infrastructure.

- Fixed road entities: Communication capable fixed road infrastructure elements (like traffic lights) form a set $I = \{i_1, i_2, \ldots, i_k\}$. Each road infrastructure element $i_j \in I$ represent a road infrastructure element equipped with a transceiver and a message buffer.

- Events: An event represents an instant execution performed by a process. In a distributed system, a process only can execute two kind of events: *internal events* and *external events*. An internal event is an action that change the

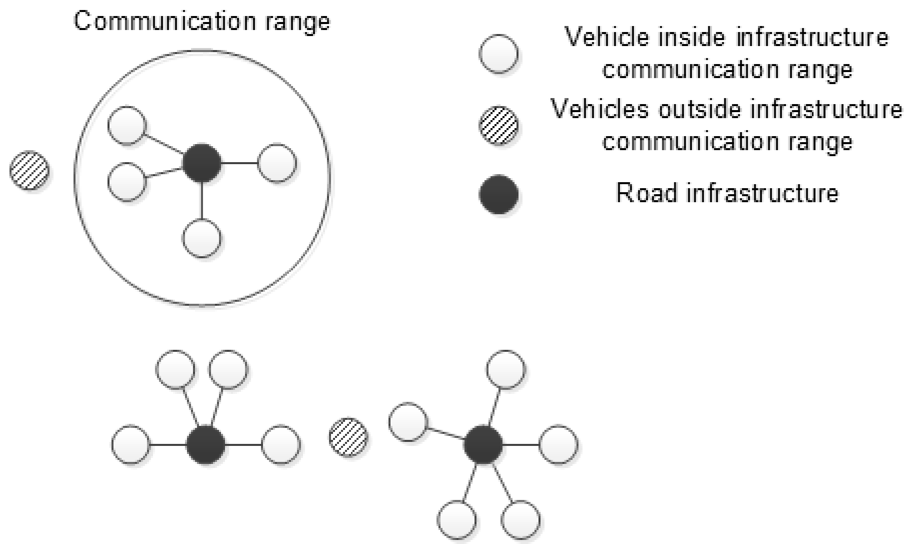


Figure 7.1: System model

state of a process. An external event is also an action in a process, but, unlike the internal event this action is seen by other processes, affecting the global or system state.

In this work two types of internal events (*create* and *delete*), two atomic external events (*send* and *receive*) and three composite external events (*commit*, *push* and *peek*) are considered:

- The create internal event refers to the action of the process that creates a new message to be transmitted to other processes.
- The delete internal event refers to the action of the process when data is considered to be no longer relevant and is removed from buffer.
- The send event is an atomic event representing the message sending by one participant to another.
- The receive event is an atomic event representing the message receipt by a participant of a vehicular network.

– The commit external event refers to the action when the message created by the create event is associated with the road infrastructure element and deposited in its buffer.

– The push external event refers to the action when the message already associated with the road infrastructure element by commit event or peeked from its buffer is deposited to the buffer of the other road infrastructure element.

– The peek external event refers to the action when a vehicle receives a message deposited by the commit or push events without removing it from the infrastructure.

7.2 Environment modeling

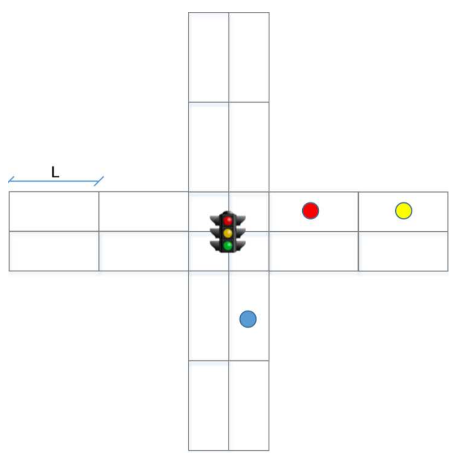


Figure 7.2: Environment modeling

- Road graph: Based on the discrete model described by [Stefan Krauß, 1998] the roads in a specified region can be represented as a directed graph $G =< U, C >$. $U = \{u_1, u_2, \ldots, u_p\}$ represents all of the cells that divide the road in the given geographical region. Each element $u_i \in U$ represents a single cell from the road discretization as described below.

The road between intersections is discretized in segment that occupy one line and have a length of L. L is chosen such that it is equal to the length of a car occupied in a dense jam (for a passage car it is usually equal to 5-7 meters).

The intersection is discretized in segments that are formed by intersection of lines. Each segment have a height and width of exactly one traffic line [as shown in Figure 7.2].

C represents all of the possible directions that a vehicle located in this cell can move to. If $< u_i, u_j > \in C$ that a vehicle can move from cell u_i to u_j.

Other types of intersections can be modelled in the similar way. A roundabout can be modelled as consecutive intersections for each entry/exit point.

At any moment each vehicle v_i is located inside a road infrastructure cell $\forall v_i \in V \exists u_j : v_i \in u_j$ but each cell can contain at most one vehicle: $u_i \in v_j \Rightarrow \nexists v_k : v_k \in u_i$.

- Regions: The system is divided into regions that are formed by communication capable fixed road infrastructure elements. Each region r_j is formed by exactly one fixed road infrastructure element i_j and each fixed road infrastructure element i_j forms exactly one region r_j.

  Each region belongs to the set $R = \{r_1, r_2, \ldots, r_k\}$. A region represents a communication range covered by fixed road infrastructure element i_k and have a finite size: $r_i = \{u_1, u_2, \ldots, u_n\}$. The regions do not overlap: $\forall u_i \in r_j \nexists r_k : u_i \in r_k$. Also the regions R do not cover the whole road graph U ex. several areas exists that are not covered by any region: $\exists u_i \in U : \nexists r_k : u_i \in r_k$ or $R \subset U$.

  If a vehicle v_i is found in a cell u_j belonging to the communication range r_k than a vehicle v_i belong to the communication range $r_k : v_i \in u_j \bigwedge u_j \in r_k \Rightarrow v_i \in r_k$. As the vehicle move they can leave and enter another communication region ex. if at time t a vehicle $v_i \in r_j$ that at time moment $t+p$ a vehicle $v_i \in r_k$. Alternatively a vehicle can move to an area $u_i \in U : \nexists r_k : u_i \in r_k$ not covered by any region in this case a vehicle does not belong to any communication region as well $\exists r_k : v_i \in r_k$.

7.3 Pheromon abstract data type

- Pheromones: Since each vehicles movement is independent and unpredictable the communication between them is realized by the use of pheromones F. In this work, a pheromone is defined as an abstract data type as follows. A pheromone $f \in F$ is defined by the tuple $f = \{id, region, payload\}$ where id is a unique identifier of a pheromone inside a $region$, $region$ is the unique identifier of the region where the pheromone was initially generated. The $id-region$ pair uniquely identify the pheromone in the system. The $payload$ represent the additional data used for fuzzy-causal message ordering and contains application data.

  A pheromone can be transferred from region r_i to the region r_j by vehicles. In this case a new pheromone is created in the region r_j.

7.4 Causal flooding protocol description

In a vehicular network no stable transmission link can be achieved due to high vehicle mobility and the implementation and maintenance of the global communication is expensive. Thus, the messages can not be passed directly between the participants.

To achieve the communication the indirect communication model is implemented, where the messages is stored by the fixed road infrastructure elements until it is picked up by a mobile entity.

When an infrastructure requires to communicate information to the other road infrastructure elements it generates a messages and stores it in the buffer using the commit operation [see Figure 7.3].

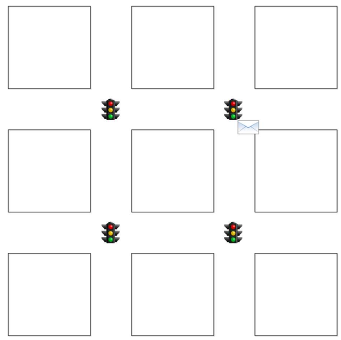


Figure 7.3: Message is generated by the road infrastructure

When a vehicle enters the communication range of the road infrastructure element that have information stored in its buffer it can receive it using the peek operation. During this operation road infrastructure transmits messages stored in its buffer to the vehicle and vehicle stores them inside its buffer for delivery [see Figure 7.4]

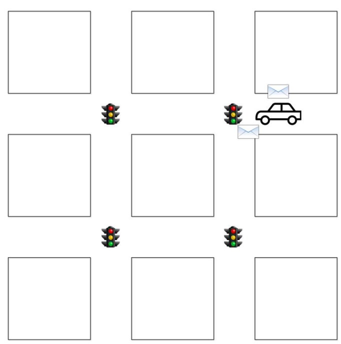


Figure 7.4: Vehicle receives message from the road infrastructure

Vehicle with message stored moves to the communication range of another infrastructure element. When it detects that it has entered the communication range of another road infrastructure element it can store this message using the push operation [see Figure 7.5].

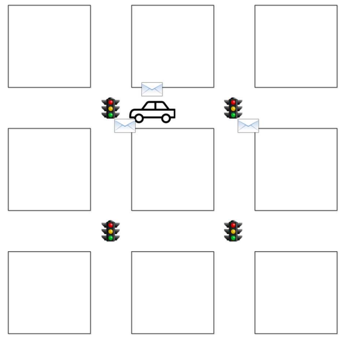


Figure 7.5: Vehicle stores the message in another road infrastructure

After the push operation the messages copy is stored in the road infrastructure, waiting for other vehicle to puck it up using the peek operation [see Figure 7.6].

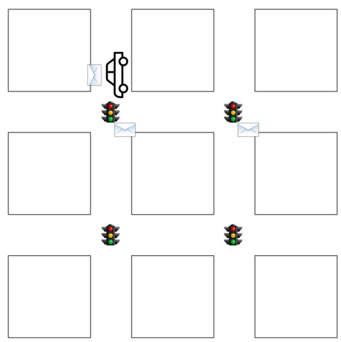


Figure 7.6: Message is received by another vehicle

After the message is picked up by the vehicle the process is repeated until the message is diffused to the participants in the specified geographical area.

7.5 Causal flooding protocol specification

Fixed road infrastructure elements manages in a local fashion the following information:

- $VT(r_k)$ are the vector timeclocks. The size of the vector is equal to n, where n is the number of regions in the the system. It is here that we keep track of the number of messages diffused by the participant.

- The structure of a message $m_{r_k,tk}$, is a tuple $m_{r_k,tk} = (r_k, t_k, payload)$, where r_k is the region identifier, $t_k = VT(r_k)$ is the value of vector clock at region r_k and $payload$ is the message content.

- Each fixed road infrastructure entity are equipped with buffer. This buffer contains messages with the format described above.

Mobile vehicular network elements manages in a local fashion the following information:

- Each mobile vehicular network entity is also equipped with a buffer to store messages described above.

As a part of the initialization process, each fixed road infrastructure element initializes its variables as described in Table 7.1.

1	$VT(r_k)[j] = 0 \; \forall j : 1 \ldots n$

Table 7.1: Fixed road infrastructure initialization

When a road infrastructure element wants to send a message to other participants in the systems, it constructs it using the procedure described in Table 7.2.

1	$m = (0, \emptyset, payload)$
2	commit(m)

Table 7.2: Message generation by fixed road infrastructure element

The commit function is used by road infrastructure element to assign unique identifiers for the new message and is defined in Table 7.3.

When a vehicle enters the communication range of a road infrastructure they can exchange messages stored in the buffers. The message from vehicle to road infrastructure is send by push operation, and the message is retrieved from road

	function commit(m)
1	$VT(r_k)[k] = VT(r_k)[k] + 1$
2	$m' = (r_k,\ VT(r_k),\ m.payload)$
3	Store m' in the message buffer

Table 7.3: The commit operation

infrastructure by peek operation. Both operations do not modify the internal structure of the message.

When a vehicle receives a beacon frame from the road infrastructure it executes the push operation described in Table 7.4. The push operation is only initiated when a vehicle have messages in the buffer to deliver.

	Vehicle		Road infrastructure
1	$\forall m$ in buffer		
2	Vehicle sends a message m from buffer	$\rightarrow$	Road infrastructure receives m from vehicle
3			if $VT(r_k)[j] \geq VT(m)[j]$
			$\forall j : 1 \ldots n$
4			discard(m)
5			else if $VT(r_k)[r(m)] =$
			$VT(m)[r(m)] + 1$ and
			$VT(r_k)[j] \geq VT(m)[j]$
			$\forall j : 1 \ldots n, j \neq r(m)$
6			deliver(m)
7			else
8			buffer(m)

Table 7.4: The push operation

The peek operation is also initiated by vehicle when in detects that it enters the communication range of road infrastructure element by receiving the beacon frame using the algorithm described in Table 7.5.

	Vehicle		Road infrastructure
1	Vehicle sends a peek request	$\rightarrow$	Road infrastructure receives a peek request
2			$\forall m$ in the message buffer
3	$\forall m$ received from road infrastructure buffer(m)	$\leftarrow$	Road infrastructure sends m to vehicle

Table 7.5: The peek operation

If the message m satisfies the delivery condition, then it can be delivered by road infrastructure element. The delivery process consists of the algorithm presented in Table 7.6.

1	$VT(r_k)[r(m)] = VT(m)[r(m)]$
2	Store m in the message buffer

Table 7.6: Message delivery to fixed road infrastructure element

After the message is delivered, the process should revalidate delivery conditions of all messages in the delivery buffer. If any message satisfies the delivery condition it should be delivered using the procedure described in Table 7.6.

We demonstrate that out protocol delivers messages to all participants of the vehicular network without causal ordering violations with the following sketch of proof.

First, we demonstrate that every message is delivered to all reachable entities in a vehicular network.

Let a and b be two neighbor intersections and there is a road leading from a to b (vehicles can move from intersection a to b). Then eventually a vehicle will pass that peeks messages stored at the road infrastructure associated with the region a (Table 7.5) and will push them at region b (Table 7.4). Thus, every message generated at any region a, will be eventually delivered to all neighbor regions that have a road leading to them. After the message is pushed at region b, it is available for other vehicles to be peeked and delivered to neighbor regions of region b. Thus, after some time a message generated at any region a, will be delivered to all regions that are reachable from region a.

Now we demonstrate that no causal violations are present in the system. To demonstrate this, we use a fact that if m_1 and m_2 have the same vector clocks $VT(m_1) = VT(m_2)$ then $m_1 = m_2$ and vice versa [12].

When a message m is pushed at region b there can be three different cases:

- A message m has been already received at region b.
- A message m can be delivered at region b.
- A message m cannot be delivered because it have a causal dependency on message m' that was not yet delivered at region b.

If message m was already delivered at region b, this means that m had its FIFO and causal conditions satisfied in the past: $VT(r_k)[r(m)] = VT(m)[r(m)] + 1$ and $VT(r_k)[j] \geq VT(m)[j] \forall j : 1 \ldots n, j \neq r(m)$ (Table 7.4, Line 5) and the message was delivered executing the $VT(r_k)[r(m)] = VT(m)[r(m)]$ (Table 7.6, Line 1). Thus, after a message m is delivered $VT(r_k)[j] \geq VT(m)[j] \forall j : 1 \ldots n$. When a message m is received a second time, condition $VT(r_k)[j] \geq VT(m)[j] \forall j : 1 \ldots n$ (Table 7.4, Line 3) is satisfied and the message is discarded.

Considering that a message is delivered to all entities of the vehicular network, the last two cases are exactly as described by the vector clock protocol [12], and therefore, are also satisfied.

Thus, the proposed protocol delivers messages to all participants of the vehicular network without causal order violations.

7.5.1 Message ordering

All of the messages in the system can be ordered using the following rule. Let m_1 and m_2 be two messages received by fixed or mobile road infrastructure element.

1. If $VT(m_1)[j] \leq VT(m_2)[j]\ \forall j : 1 \ldots n$ than $m_1 \rightarrow m_2$
2. If $VT(m_1)[j] \geq VT(m_2)[j]\ \forall j : 1 \ldots n$ than $m_2 \rightarrow m_1$
3. If $\exists j, k : VT(m_1)[j] < VT(m_2)[j]$ and $VT(m_1)[k] > VT(m_2)[k]$ than $m_1 \| m_2$

7.6 Causal flooding protocol simulations

The proposed causal flooding protocol is simulated to measure the message diffusion time in a region. In each simulation a square diffusion region with sizes from 3x3 to 9x9 is modelled. Each region contains a fixed number of vehicles and this number does not change during the simulation. At each intersection a vehicle chooses its direction randomly (ex. A vehicle have equal chances to move forward, turn right or turn left).

At the beginning of each simulation the road infrastructure located at the center of the region generates and commits a message. The simulation is finalized when all fixed road infrastructure nodes receive the message.

The first experiment measures the message diffusion time depending on the number of vehicles in the region [see Figure 7.7].

From the results of the experiment we can observe that the diffusion time decreases as the number of vehicles increases. For a 100 vehicles in a region the diffusion time is 45 seconds for 3x3 region, 106 seconds for 5x5 region, 220 seconds for 7x7 regions and 330 seconds for 9x9 region. As we can notice that the decrease is not infinite and after a certain point, increasing the number of vehicles in the system does not introduce a significant decrease in the message diffusion time.

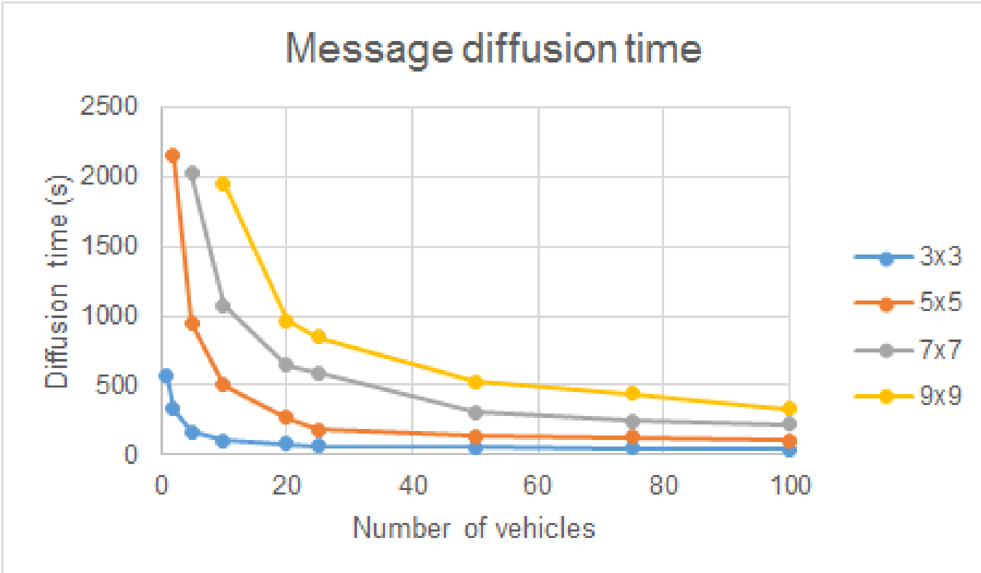


Figure 7.7: Message diffusion time for different vehicle count

The second experiment is performed to measure the message diffusion time depending on the region size with the fixed number of vehicles [see Figure 7.8].

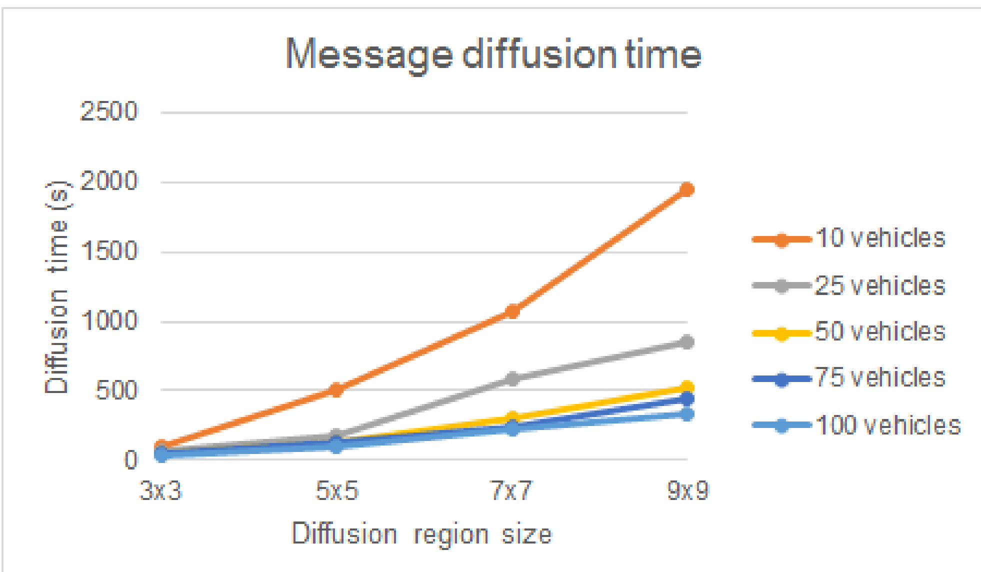


Figure 7.8: Message diffusion time for different region size

From the results of the second experiment we can observe that the message diffusion time increases with the region size. For a 9x9 region the message diffusion times are 1952 seconds for 10 vehicles, 846 seconds for 25 vehicles, 528 seconds for 50 vehicles, 440 seconds for 75 vehicles and 330 seconds for 100 vehicles. From the results we can notice that with sufficient number of vehicles the growth of diffusion time is linear, but with fewer vehicles the growth becomes quadratic.

The last experiment aims to measure the message diffusion time dependency of the vehicle average speed [see Figure 7.9].

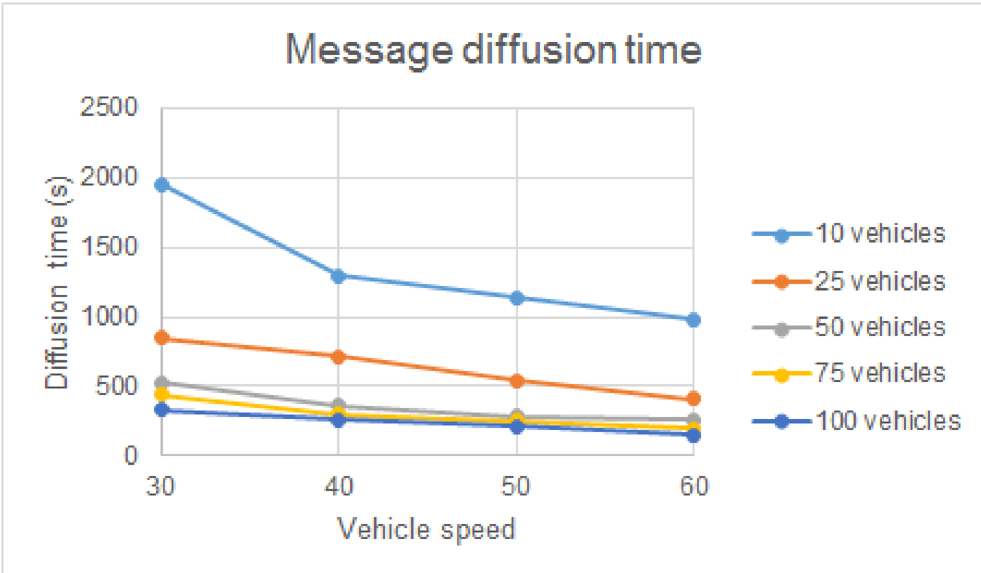


Figure 7.9: Message diffusion time for different vehicle speed

The results shows that the message diffusion time have a linear dependency on the vehicle average speed except for the case of 10 vehicles. But in this case the message diffusion time is composed mostly of the time that the message is buffered by the road infrastructure element waiting for the vehicle to be delivered to another infrastructure element.

Chapter 8

Conclusions

This work presents a causal flooding protocol for vehicular networks. The presented protocol provides the causal communication mechanism for fixed and mobile entities without the need of a global infrastructure. The efficient communication is achieved using the fixed road infrastructure nodes like traffic light to store messages that are transported between them by moving road entities like vehicles.

The main advantage of the proposed solution over the traditional solutions, is that the amount of required control information depends on the number of regions (intersections) and not on the number of vehicles in the system.

One of the possible extensions of the proposed solution is to include the redundant in message sending to ensure the communication when the communication channels are not reliable. But at the same time the protocol should be analyzed to reduce the number of unnecessary messages.

The presented protocol considers only the communication where messages are generated and consumed by fixer road entities. Another possible extension is to include messages generated and consumed by mobile road entities.

Another possible improvement is to extend the proposed solution to use spatial-temporal communication. This communication will ensure that only the relevant information is delivered to the participants.

Bibliography

[1] Lei Chen and Cristofer Englund. Cooperative intersection management: A survey. *IEEE Transactions on Intelligent Transportation Systems*, 17(2):570–586, 2016.

[2] Yong Ding, Chen Wang, and Li Xiao. A static-node assisted adaptive routing protocol in vehicular networks. In *Proceedings of the Fourth ACM International Workshop on Vehicular Ad Hoc Networks*, VANET '07, pages 59–68. ACM, 2007.

[3] Harold Greenberg. An analysis of traffic flow. *Oper. Res.*, 7(1):79–85, February 1959.

[4] Tomasz Imieliński and Julio C. Navas. Gps-based addressing and routing. RFC 2009, November 1996.

[5] Boangoat Jarupan and Eylem Ekici. Prompt: A cross-layer position-based communication protocol for delay-aware vehicular access networks. *Ad Hoc Netw.*, 8(5):489–505, 2010.

[6] Georgios Karagiannis, Onur Altintas, Eylem Ekici, Geert Heijenk, Boangoat Jarupan, Kenneth Lin, and Timothy Weil. Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *IEEE Communications Surveys & Tutorials*, 2011.

[7] Brad Karp and H. T. Kung. Gpsr: Greedy perimeter stateless routing for wireless networks. In *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking*, pages 243–254. ACM, 2000.

[8] Stefan Krauß. *Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics*. PhD thesis, Deutsches Zentrum für Luft–und Raumfahrt Hauptabteilung Mobilität und Systemtechnik, 1998.

[9] Leslie Lamport. Time, clocks, and the ordering of events in a distributed system. *Commun. ACM*, 21(7):558–565, 1978.

[10] Christian Lochert, Hannes Hartenstein, Jing Tian, Holger Fußler, Dagmar Hermann, and Martin Mauve. A routing strategy for vehicular ad hoc networks in city environments. In *Intelligent Vehicles Symposium, 2003. Proceedings. IEEE*, pages 156–161, 2003.

[11] Christian Lochert, Martin Mauve, Holger Fußler, and Hannes Hartenstein. Geographic routing in city scenarios. *SIGMOBILE Mob. Comput. Commun. Rev.*, 9(1):69–72, 2005.

[12] Friedemann Mattern. Virtual time and global states of distributed systems. In *Parallel and Distributed Algorithms*, pages 215–226. North-Holland, 1989.

[13] Hamid Menouar, Massimiliano Lenardi, and Fethi Filali. A movement prediction-based routing protocol for vehicle-to-vehicle communications. In *V2VCOM 2005, 1st International Vehicle-to-Vehicle Communications Workshop*, 2005.

[14] Jose Roberto Perez Cruz and Saúl Eduardo Pomares Hernández. Temporal alignment model for data streams in wireless sensor networks based on causal dependencies. *International Journal of Distributed Sensor Networks*, 2014, 2014.

[15] Saúl Eduardo Pomares Hernández. The minimal dependency relation for causal event ordering in distributed computing. *Applied Mathematics & Information Sciences*, 9(1):57–61, 2015.

[16] Rahul C. Shah, Sumit Roy, Sushant Jain, and Waylon Brunette. Data mules: modeling and analysis of a three-tier architecture for sparse sensor networks. *Ad Hoc Networks*, 1(2–3):215–233, 2003.

[17] Antonios Skordylis and Niki Trigoni. Delay-bounded routing in vehicular ad-hoc networks. In *Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, MobiHoc '08, pages 341–350. ACM, 2008.

[18] Xinzhou Wu, Sundar Subramanian, Ratul Guha, Robert G. White, Junyi Li, Kevin W. Lu, Anthony Bucceri, and Tao Zhang. Vehicular communications using dsrc: Challenges, enhancements, and evolution. *IEEE Journal on Selected Areas in Communications*, 31(9-Supplement):399–408, 2013.

[19] Xiwei Zhang and Jia Yu. Probabilistic path selection in mobile wireless sensor networks for stochastic events detection. In *Proceedings of the 8th International Conference on Ubiquitous Intelligence and Computing*, pages 52–63. Springer-Verlag, 2011.

[20] Jing Zhao and Guohong Cao. Vadd: Vehicle-assisted data delivery in vehicular ad hoc networks. *IEEE Transactions on Vehicular Technology*, 57(3): 1910–1922, 2008.

[21] Wenrui Zhao, Mostafa Ammar, and Ellen Zegura. A message ferrying approach for data delivery in sparse mobile ad hoc networks. In *Proceedings of the 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, pages 187–198. ACM, 2004.

[22] Kan Zheng, Qiang Zheng, Periklis Chatzimisios, Wei Xiang, and Yiqing Zhou. Heterogeneous vehicular networking: A survey on architecture, challenges, and solutions. *IEEE Communications Surveys Tutorials*, 17(4):2377–2396, 2015.