Optimised Protocols for Time-Critical Applications and Internetworking in Vehicular Ad-Hoc Networks

by
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Statement of Originality

I hereby certify that to the best of my knowledge, the intellectual content of this thesis is the product of my own work and that all material in this dissertation which is not my own work has been properly acknowledged.

Abstract

Vehicular ad-hoc networks (VANETs) that enable communication among vehicles and between vehicles and unmanned aerial vehicles (UAVs) and cellular base stations have recently attracted significant interest from the research community, due to the wide range of practical applications they can facilitate (e.g., road safety, traffic management and rescue missions). Despite this increased research activity, the high vehicle mobility in a VANET raises concerns regarding the robustness and adaptiveness of such networks to support time-critical applications and internetworking.

In this thesis, as a first step toward the design of efficient MAC protocol to support time-critical applications and internetworking, we show that it is indeed possible to follow the dynamics of a network and consequently adapt the transmission probability of the Aloha protocol to reduce the interference and maximise the single-hop throughput between adjacent nodes. Extensive simulation validates the proposed analytical model, which thus can serve as a promising tool to improve VANETs performance.

By exploiting the parallel between the CSMA/CA and Aloha performance models, the optimal transmission probability for the Aloha protocol as a function of estimated vehicular density is derived. This probability is then used to obtain the optimal maximum CW that can be integrated in an amended CSMA/CA protocol to maximise the single-hop throughput among adjacent vehicles. We show by means of simulation that the beneficial impact the proposed protocol is increased channel throughput and reduced transmission delay when compared with the standardised protocol CSMA/CA in IEEE 802.11p. These results reveal the applicability of the new, optimised protocol to safety applications and clustering techniques with stringent performance requirements.

Lastly, we propose a Stable Clustering Algorithm for vehicular ad-hoc networks (SCalE) internetworking. The exchange of the necessary status information to support the efficient clusters formation can firmly relay on the support of our optimised CSMA/CA protocol. The SCalE algorithm makes use of the knowledge of the vehicles behaviour (explained in Chapter 5) for efficient selection of CHs, and selects a backup CH on top of the CH to maintain the stability of cluster structures. The increased stability and improved performance of the SCalE algorithm is studied and compared with existing clustering algorithms.

Acknowledgment

I would like to spend my first words of acknowledgment to especially thank my supervisor Prof. Kin K. Leung. The guidance he has provided me with during my PhD has not only helped me learn how to do research but also its true value. The lessons I have learnt from him are invaluable, as are the skills acquired over these years, which have made me the person I am today.

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I am especially grateful to my parents for always being by my side. Their constant love and support has given me the strength to accomplish all I have done over these years. Lastly, I would like to acknowledge all my dear colleagues and friends who have supported me whenever I needed them and brightened up my days during the PhD.

Considerate la vostra semenza:

fatti non foste a viver come bruti,

ma per seguir virtute e canoscenza.

[Dante Alighieri, *The Divine Commedy*, *Canto XXVI*]

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List of Notation

λ	Poisson arrival process rate
v	vehicle speed
ζ	vehicular density
n_i	the ith node (or equivalently vehicle)
P_t	transmission power
α	path loss exponent
P_r	received power
d_{ij}	distance between a transmitter and a receiver
I_k	transmission indicator
p_t	probability of transmission
$SIR_{i,j}$	signal to interference ratio at node n_j when n_i is transmitting
β	SIR threshold
R_c	communication range
R_f	interference range
$P[\cdot]$	probability of a predefined event
E	(3.13) is valid
F_k	condition in (3.18) is satisfied for a given interfering node n_k
A	event that node n_k is located outside the interfering range R_f of node n_j
S_l	left segment of the road
L_s	(3.18) is satisfied for all S interfering nodes n_k located in the road segment S_L
S_r	right segment of the road

R_q	(3.18) is satisfied for all S interfering nodes n_k located in the road segment S_R
G_{ij}	event of meeting all of the interference conditions in (3.17) or (3.18) for transmission from node n_i to n_j
T_h	throughput
W	maximum contention window size
b_k	probability of state k
b_0	probability of transmitting in an arbitrary free slot time
T	CAM message transmission time
T_H	MAC header payload
E_P	packet payload
r_d	data rate
c	vehicle size
$\bar{k}$	estimated number of neighbouring vehicles
CH	cluster head
CM	cluster member
$\mathrm{CH}_{\mathrm{Bkp}}$	backup cluster head
ξ_k	CH selection index of vehicle k
γ_k	ID of vehicle k
Φ_k	set of all cars within range of vehicle k
(x_k, y_k)	position coordinates of vehicle k
B_k	vehicle behaviour of vehicle k
S_k	relative mean speed of vehicle k
D_k	relative mean distance of vehicle k
S_k	mean relative speed of vehicle k
Ω_k	set of all the vehicles speed differences $\lvert v_k - v_n \rvert$ within the set Φ_k, provided the vehicles are moving ($v > 0$)
D_k	mean relative distance of vehicle k

Z_k	set of the all the Euclidean distances between vehicle k and all its N neighbouring vehicles
Ψ_k	The set of all ξ for every neighbour's set Φ_k
Θ_i	ith cluster
C_k	cardinality of vehicle k
α_m	ID of vehicle in cluster Θ_i
Γ_{Ac}	set of all the cardinality values $C(\alpha_m)$ of the CMs in Θ_i
A_C	ordered set of CM IDs with respect to the cardinality C_k of each node in the cluster
β_m	ID of vehicle in cluster Θ_i
Ξ_{As}	set of all the cardinality values $\xi(\beta_m)$ of the CMs in Θ_i
A_S	ordered set of CM IDs with respect to the cardinality ξ_k of each node in the cluster
$\xi_T h$	CH selection index threshold

Abbreviations

ACK: Acknowledgement

AICC: Autonomous Intelligent Cruise Control

AIFS: Arbitration Inter-Frame Spacing

CACC: Cooperative Adaptive Cruise Control

CAM: Cooperative Awareness Message

CAV: Cooperative Awareness Message

CCH: Connected and Autonomous Vehicles

CCI: Control Channel Interval

CH: Cluster Head

CM: Cluster Member

CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

CW: Contention Window

DARPA: Defence Advance Research Projects Agency

DSRC: Dedicated Short-Range Communication

EDCA: Enhanced Distributed Channel Access

ETSI: European Telecommunications Standards Institute

FANET: Flying Ad-Hoc Network

GloMo: Global Mobile Information Systems

ICT: Information and Communication Technologies

ITS: Intelligent Transportation System

MAC: Medium Access Control

MANET: Mobile Ad-Hoc Network

PPP: Poisson Point Process

PRNET: Packet Radio Network

RSU: Road Side Unit

SDMA: Space Division Multiple Access

SCalE: Stable Clustering ALgorithm for vEhicular ad hoc networks

SCH: Service Channel

SCI: Service Channel Interval

SI: Synchronisation Interval

SIR: Signal to Interference Ratio

SURAN: Survivable Adaptive Network

TDMA: Time Division Multiple Access

UAV: Unmanned Aerial Vehicle

V2V: Vehicle-to-Vehicle

V2I: Vehicle-to-Infrastructure

V2X: Vehicle-to-Everything

VANET: Vehicular Ad-Hoc Network

WLAN: Wireless Area Network

List of Publications

Publications arising directly from this thesis

1. **G.V. Rossi** and K.K. Leung, "Optimal CSMA/CA Protocol for Safety Messages in Vehicular Ad-Hoc Networks", IEEE Symposium on Computers and Communications (ISCC) 2017, 3-6 July, Heraklion, Greece.

2. **G.V. Rossi** and K.K. Leung, "Optimised CSMA Protocol to Support Efficient Clustering for Vehicular Internetworking", IEEE Wireless Communications and Networking Conference (WCNC) 2017, 19-22 March, San Francisco, US.

3. **G.V. Rossi**, Zhong Fan, Woon Hau Chin and K.K. Leung, "Stable Clustering for Ad-Hoc Vehicle Networking", IEEE Wireless Communications and Networking Conference (WCNC) 2017, 19-22 March, San Francisco, US.

4. **G.V. Rossi** and K.K. Leung, "Connectivity Optimisation for Vehicular Ad-Hoc Networks", Autonomous Systems Underpinning Research (ASUR) Conference 2015, 17 June, Basingstoke, UK.

5. **G.V. Rossi**, K.K. Leung and A. Gkelias, "Density-Based Optimal Transmission for Throughput Enhancement in Vehicular Ad-Hoc Networks", IEEE International Conference on Communications (ICC)

2015, 8-12 June, London, UK.

Other Publications

1. **G.V. Rossi** and K.K. Leung, "Performance tradeoffs by power control in wireless ad-hoc networks", International Wireless Communications and Mobile Computing Conference (IWCMC) 2013, 1-5 July, Cagliari, Italy.

2. **G.V. Rossi** and K.K. Leung, "Performance tradeoffs by power control in wireless ad-hoc networks", National PhD Scheme Conference 2013, 27 February, Oxford, U.K.

Chapter 1

Introduction

Overlooking the bright colours of the city at night. The aeroplane is cutting through an uncommonly clear sky for this time of the year. Foreheads are pushed against small windows as passengers, returning from Christmas holidays abroad, admire the welcoming and spectacular show of lights just beneath, outside in the cold. Foreheads are pushed against the small windows to improve the limited view. Staring at the warm, colourful lights in the dark, inquisitive eyes begin to recognise familiar places with excitement, and instinctively start following the slow movement of these tiny lights in their intricate geometries.

Then, a sudden realisation that the marvellous shining spectacle beneath us is merely the accidental combination of individual drivers travelling to their final destination. Each one of them, down below, is likely listening to the directions from a mobile phone while their vehicle is cleverly looking after the safety of its passengers within by monitoring and eventually amending the driver's behaviour.

What not long ago seemed a distant hope for the future is slowly becoming a tangible reality. We are building smart cities, immersing ourselves in a technology now felt so vital, a glimpse of which is glowing right now in front of us. Smart phones, smart cars, smart drones, everything is interconnected and alive; a thick web has blossomed and through it a dense stream of information can flow restlessly in a continuous, infinite cycle that has improved and continues to improve our lives.

1.1 Overview

In the last few decades an exponential advancement in wireless technologies has been witnessed. This increasing development has been led by the rising need for flexibility. In fact there is a demand, especially in military operations, to support communications in mobile environments, possibly in a distributed fashion to enhance the deployability of the networks. This is because communication infrastructure in battlefields or areas of military operations are seldom available or usable. Therefore, wireless communications infrastructure are required to be transported and configured on site. By following the aforementioned requirements research efforts have converged on a new network paradigm able to handle more challenging scenarios: Mobile Ad-Hoc Networks (MANETs).

In the 70's the Defence Advance Research Projects Agency (DARPA) initiated research on the feasibility of packet switching technology to be employed for mobile wireless networks. The DARPA Packet Radio Network (PRNET) provided packet exchange by broadcasting over a common channel, and multi-hop connectivity [1, 2]. To extend the work carried out in the PRNET and investigate open issues such as scalability and network security, DARPA established a new program called Survivable Adaptive

Network (SURAN). This mainly focused on the design of network algorithms able to deal with large networks (thousands of nodes) [3]. Later on, the Global Mobile Information Systems (GloMo) program, started in 1994, supported several research projects with the final aim of addressing the problems arising from defence requirements [4, 5].

Despite the initial development due to military interest, MANETs have gained additional momentum in the research community because of their applicability to commercial uses as they can rapidly assist the setup of network services in areas not supported by pre-existing communications infrastructure. This could be the case, for instance, when a natural disaster causes the disruption of all communication infrastructures and coordination of the rescue mission is of vital importance to help the survivors.

The definition of MANETs includes a broad range of different network typologies, mostly based on the node's mobility. A specific class of MANETs, called Vehicular Ad-Hoc Networks (VANETs), has recently succeeded in attracting significant research and industrial attention. As the name suggests, the peculiarity of these wireless networks is that communication devices are placed on vehicles. Hence, VANETs are defined as highly mobile wireless networks of vehicles. These are able to communicate with each other by exploiting a multi-hop ad-hoc connection. The integration of communication technology with transportation systems creates a self-organising and rapidly deployable network that ultimately does not require a permanent infrastructure [6,7]. Additional subsets of VANETs can be further defined. For instance, a network supporting communication amongst aerial vehicles is called as a Flying Ad-Hoc Network (FANET) [8].

Whilst VANETs are individually able to support a multitude of applications in a wide range of contexts, cooperation between vehicles and Unmanned Aerial Vehicles (UAVs) or cellular base stations can be extremely beneficial. For instance, a hybrid network formed by vehicles and UAVs or cellular base stations can assist in holding the connection stable even in the event of disruptions due to obstacles, poor weather conditions or natural disasters that may have destroyed existing communication infrastructure.

Road safety can also drastically be improved. By periodically exchanging status information, each vehicle can continuously monitor the surrounding vehicles and infrastructure, allowing them to become aware of possible imminent threats, and to take rapid countermeasures such as sending warning messages to the drivers and neighbouring vehicles in such scenarios.

The relevance of these kind of networks has been confirmed by the development of a specific IEEE standard, purposely adapted to vehicular characteristics and operating scenarios. In particular, the IEEE 802.11p is a wireless area network (WLAN) standard for dedicated short-range communication (DSRC) among vehicles [9–11]. In regards to road safety, the European Telecommunications Standards Institute (ETSI) has even designated a specific type of broadcast message known as Cooperative Awareness Messages (CAMs), containing information relevant to safety related applications (e.g. vehicle speed and position) [12–14].

1.2 Motivation and Aims

Although the potential applications of VANETs has led to a surge of interest and activity within the research community, many challenges remain due to the high mobilities that characterise vehicles. The rapid change in network topologies is difficult to handle because it significantly affects the performance of the network as well as the frequent fragmentation that usually takes place in vehicular traffic scenarios. Thus, VANETs are expected to properly enable communications among vehicles under various conditions of vehicular density.

In fact, both dense or sparse vehicle density scenarios can represent challenging situations to handle. For instance, if vehicles are waiting at a red traffic light the vehicular density can quickly increase. Vehicle-to-vehicle (V2V) communication in the aforementioned situation (i.e., a dense network) can incur disruptions as communication needs cannot be met due to the limited network capacity. Sparse networks, on the other hand, may be characterised by the lack of connectivity due to fragmentation generated by the great distance amongst the vehicles. Therefore, it would be beneficial to design MAC protocols able to adjust to different vehicular density conditions in order to efficiently allocate resources (e.g., right to transmit) [15] .

Regrettably, the medium-access-control (MAC) protocol in the IEEE 802.11p still makes use of indirect mechanisms through carrier sense. Specifically, the standard uses Enhanced Distributed Channel Access (EDCA) that employs Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The latter, in broadcast based applications to support road safety, is characterised by the lack of acknowledgment (ACK) packets required to identify a transmission collision and consequently adapts the maximum contention window (CW), which is doubled following each unsuccessful transmission attempt, and has to rely on a fixed, maximum CW size instead. The need to support distributed communications and dynamic topology requires improvement of the classical protocols adapted to the dynamics of highly mobile networks [15].

Implementation of time-critical applications such as safety systems or clustering techniques to support vehicular internetworking, can impose additional limitations in VANET scenarios due to low latency requirements. In fact, the exchange of status information embedded in CAMs is bound to happen periodically under stringent time requirements (100 ms as defined in the IEEE 802.11p standard). More specifically, it is expected that the co-operative awareness messages coming from all neighbouring vehicles can all be successfully exchanged, within the pre-established time period of 100ms. Therefore, it becomes imperative to maintain the network connectivity in order to achieve reliable communication across all of the nodes.

Network fragmentation can be the result of low vehicular density or disruptions due to external agents such as poor weather conditions or natural disasters. A possible solution to hold the network connected is the formation of hybrid networks where vehicles are allowed to establish communications with UAVs or cellular base stations as well as other vehicles. Nevertheless, the direct communication between every vehicle and UAV or base station, can generate serious resource issues related to bandwidth, processing, and power consumption.

Clustering techniques, which aim to partition the ground network vehicles into virtual groups known as clusters, can provide an effective solution for the aforementioned problems. A vehicle is selected to be a Cluster Head (CH) to manage the communication amongst its Cluster Members (CM) as well as interacting with other layers of a cooperative network (e.g. unmanned aerial vehicles, road side units or cellular base stations). Therefore, clustering algorithms are particularly effective in limiting the channel contention, assuring fair channel access to vehicles within the cluster. Moreover, by limiting the number of vehicles that can connect to UAVs or cellular base stations, clustering techniques can provide spatial reuse of resources such as the bandwidth. Despite the potential advantages, the main problem arising in the design of clustering techniques is dealing with the mobility of the vehicles that deeply affect the stability of the newly formed clustered structure. Hence, it is important to reduce changes in the structure of the clusters (e.g., reconfiguration and Cluster Head changes) in light of the fluctuation of the vehicular density.

1.3 Contributions

The growing interest in the development of greener, safer and more efficient cities, broadly referred to as smart cities, has driven technological improvement in numerous fields and disciplines. V2V communication represents one of the fundament pillars on which smart cities will be built, given the high number of potential applications they could support, many of which would directly enable the realisation of smart cities. As most applications in VANETs are of a time-critical nature and require internetworking with other infrastructures, many practical issues and challenges in VANET design exist, as explained in the previous section. In light of this, it is the belief of the author that the main contributions of this thesis is the proposal of a new MAC protocol and a clustering algorithm, which enable the design of VANETs better able to fully support time-critcal applications and internetworking, when compared to existing approaches.

As a first step in devising efficient MAC protocols for VANETs, we focus on optimising the transmission probability in the Aloha protocol to enhance the single-hop throughput for connection between adjacent nodes, in order to keep the network connected (i.e., maintaining minimally connected [16]). To this end, in the first part of this thesis the work is focused on the derivation of a throughput model.

Firstly, when considering a VANET, a Poisson Point Process (PPP) is considered to be a good representation for vehicle arrival at the entrance of a single lane road section [17–21]. In a network supported by Aloha protocol it is also important to introduce the concept of capture effect. The latter states that a packet can still be received even in the case of simultaneous transmission as long as the Signal to Interference Ratio (SIR) at the receiver is greater than a certain threshold. By further integration of the SIR constraints into the model a closed form solution for the network throughput is obtained and in turn exploited to derive the optimal transmission probability. The validity of the model is proved by means of extensive simulation, showing that the proposed model can be a powerful tool to improve the performance of a vehicular ad-hoc network, enabling the nodes to follow the highly changing network conditions and adapt accordingly [21].

According to the current IEEE 802.11p standard [12–14], communication in VANETs depends on CSMA/CA, that differently from Aloha can enable channel sensing before transmission to avoid collisions. In light of this, performance enhancement of V2V communication hence requires an amendment to the existing mechanism. Despite the differences that characterise the two MAC protocols, under specific circumstances it has been shown, by means of simulation and analysis, that the sensing mechanism advantages of CSMA broadcast can be reduced to the point of degrading to a Aloha-like behaviour [22]. It follows that by exploiting the Aloha-like behaviour of the broadcast CSMA/CA, we are able to extend the proposed model by integrating the optimal transmission probability into the CSMA/CA protocol. Additional constraints are also taken into account, such as the introduction of the size of the car c in the PPP that describes the vehicular flow, that would otherwise assume dimensionless points. On the importance of point, further explanation will be given in Chapter 4. Furthermore, to relate the optimal transmission probability to the denoting feature of CSMA/CA, a (fixed) maximum CW, a new model is used to describe the behaviour of vehicles exchanging CAM safety messages. The integration of the optimal CW in our proposed CSMA/CA protocol shows improved performance of the amended protocol based on vehicular density when compared with the original IEEE 802.11p MAC protocol [23].

Moreover, this thesis presents a new protocol with improved performance in relation to throughput and delay that can therefore be an indispensable tool to support time-critical application such as safety messages exchange or clustering techniques for vehicular internetworking [24]. In fact, time-critical applications have stringent requirements of low latency to collect the necessary status information from all neighbouring vehicles. The results shown in this thesis work illustrate the decreased packet transmission delay when our proposed MAC protocol is used instead of the standard CSMA/CA.

As a final step toward the development of hybrid networks able to support heterogeneous internetworking, this thesis presents a clustering technique able to maintain cluster stability in light of vehicle mobility and radio fluctuation [25]. The stability of the network is, in fact, a major challenge to overcome in designing clustering mechanisms and has to be therefore carefully approached. The traffic flow, and consequently the communication amongst vehicles, is heavily influenced by vehicles behaviour. This means that the stability of the network depends on the vehicles behaviour and it would be therefore beneficial to record and include behaviuoral information in the design of the cluster, or equivalently the clustering process. By introducing the driver's behaviour as an additional feature in the clusters formation and cluster head election it is indeed possible to group vehicles into more stable clusters. To further maintain the newly formed network structure over time we also integrate the concept of a backup cluster head (CH_{Bkp}) that will be properly presented in Chapter 5 . This enable the cluster to remain active even in the case of sudden loss of the original CH, that is promptly substituted by the appointed backup. Thus, our proposed Stable Clustering Algorithm for vehicular ad hoc networks (SCalE) shows promising results in addressing the aforementioned stability issues and facilitate the networking between clustered VANETs and UAVs or cellular base stations.

Key contributions of this work can be summarised as follows:

- In Chapter 3: Optimisation of the transmission probability for Aloha protocol to enhance the single-hop throughput for connection between adjacent nodes, in order to keep the network connected.

- In Chapter 4: Enhancement of the communication model with realistic constraints such as the vehicle size (instead of treating each vehicle as a dimensionless point) in modelling vehicular flows and estimated vehicular densities.

- In Chapter 3 and 4: Derivation of a closed form solution for the throughput expression, achieved under some assumptions that help to handle the complex interference scenario that characterise VANETs.

- In Chapter 4: Estimation of the optimal maximum CW size to be used in CSMA/CA broadcast based on vehicle density by exploiting the parallel between CSMA and Aloha protocols, while considering the signal-to-interference ratio (SIR) and capture effect at receiving vehicles.

- In Chapter 4: Integration of the optimal maximum CW with the CSMA/CA protocol to enhance the delay and throughput performance for time-critical applications (e.g., CAM safety messages, clustering techniques).
- In Chapter 5: Addressing the problem of improving the reliability of the network architecture in order to facilitate the networking between VANETs and UAVs or cellular base stations.
- In Chapter 5: Presentation of a stable cluster head selection scheme that is achieved using the knowledge of the vehicle's behaviour.
- In Chapter 5: Presentation a stable cluster maintenance scheme by introducing the concept of a backup cluster head (CH_{Bkp}).

1.4 Thesis Organisation

In Chapter 2 a detailed literature review is provided. The concept of VANETs and their applications is described. Furthermore, the challenges to overcome in designing efficient vehicular ad-hoc networks are explained and several examples of proposed solutions are described to highlight and put into context the contributions of this thesis.

Chapter 3 shows our first approach to the problem of devising a MAC protocol that can adapt to the changing conditions of the road, specifically the vehicular density. The derivation of a model to describe the throughput of the slotted Aloha protocol for VANETs is described. Extensive simulation shows the validity of the model derived. Finally, using the model the optimal transmission probability to maximise the throughput for different values of vehicular density is calculated.

In Chapter 4 we extend the results of Chapter 3 to optimisise the broadcast CSMA/CA protocol, since this is the one currently designated to operate in the IEEE 802.11p standard and has to support the exchange of CAM safety messages in vehicular communications. The relation between the maximum (fixed) CW size and the transmission probability is determined in order to integrate the optimised CW value in the proposed CSMA/CA.

Chapter 5 addresses the problem of interconnecting VANETs with other networks and consequently form hybrid networks with UAVs or cellular base stations. As clustering techniques can support the formation of hybrid networks, a new clustering algorithm is presented in Chapter 5. The main objective of the proposed technique is to overcome the stability issues related with the formation and maintenance of clusters in VANETs. Performance comparison with existing techniques highlights the merits of the algorithm presented in this thesis in terms of several metrics.

The thesis ends with Chapter 6 containing the final remarks and conclusions regarding the work presented. Additional issues yet to be addressed are also presented as possible future extensions.

Finally a description of the mobility model, developed for the simulations presented in Chapter 5, is included in the Appendix.

Chapter 2

Literature Review

2.1 Applications

The recent interests of the research community have focused on the smart cities. In fact, the exponential growth of Information and Communication Technologies (ICTs) has led to their employment in most city activities with a consequent performance improvement [26]. This naturally includes smarter urban transport networks with the development of Connected and Autonomous Vehicles (CAV) and reliable Autonomous Intelligent Cruise Control (AICC) [27]. ETSI defines the Intelligent Transportation System (ITS) as advanced applications able to integrate telecommunications and information technologies to improve transport systems [28]. This means the range of ITS application can be very diverse relatively to their specific purpose. For instance important contributions can be made to improve road safety and efficiency as well as environmental performance. Vehicles are expected to communicate to each other and with Road Side Unit (RSU), enabling V2V communications. Different ITS application, on the other hands, might require additional support. Hence, vehicles should also be able to establish connections with other infrastructures (V2I), such as with base stations of cellular networks, and ultimately enable vehicle to everything communications (V2X).

VANETs have been employed in many scenarios and their applications can be divided into two main categories: civilian and military. The former class includes a wide range of applications [29, 30], for instance, to overcome safety related issues [31–33].

Key applications in the civilian domain are as follows (Figure 2.1) [29, 30]:

- Collision warning, where the objective is to prevent imminent car accidents through coordination between vehicles when visual range is limited by conditions such as rain or fog, ultimately limiting situational awareness.

- Traffic information systems to help reduce road congestion. This can increase the road capacity and enhance the journey experience for drivers.

- Cooperative Adaptive Cruise Control to assist the driver on the road by automatically controlling the vehicle speed.

- Entertainment applications such as streaming, content downloading, gaming, video/voice conferencing or other real-time systems can be supported by the internet access provided by vehicle-to-vehicle communications.

The following outline summarises the main application vehicular adhoc networks have in military operations [34–37]:

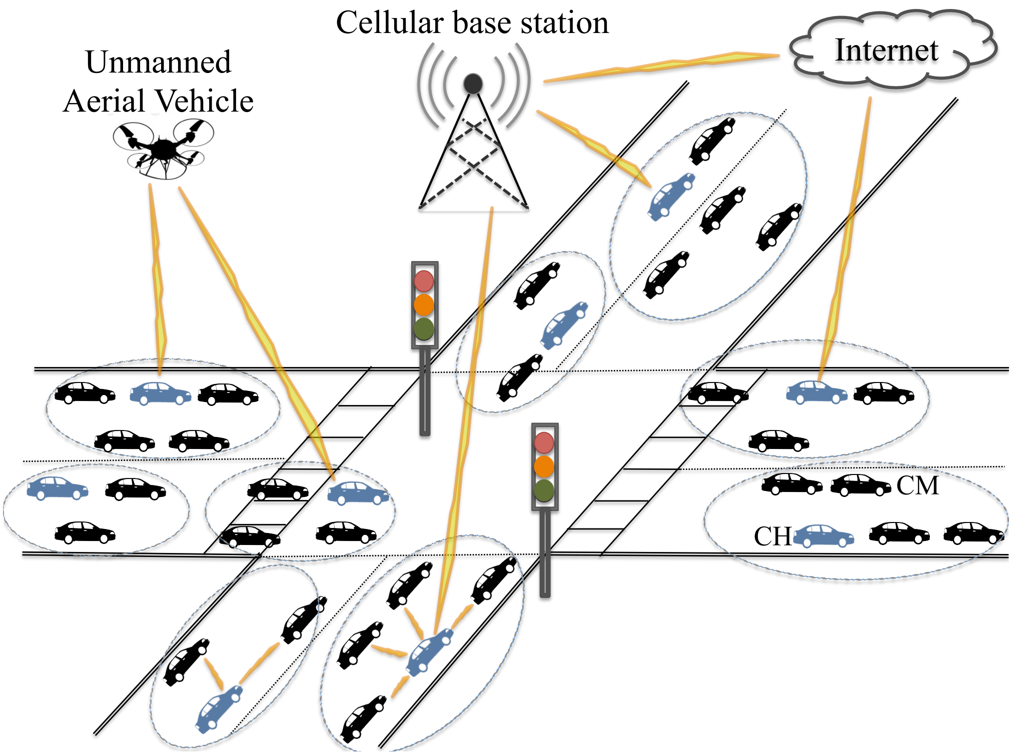

Figure 2.1: Clustering scenario: vehicle cluster (circle dashed line) with cluster head (faded blue), grouping all cluster members (black) within range. For networking with UAVs or cellular base stations only CHs are allowed direct communication.

- Maintaining stable communication between soldiers, vehicles and headquarters regardless of possible disruptions due to the unfavourable terrain wherever the network is deployed (Figure 2.2).

- Rescue missions requiring the cooperation of the team involved in such tactical operations, when it is not possible to access the current infrastructure (e.g., in enemy territory) for communications. Additionally, this challenging scenario can also arise as the result of natural disasters.

- Target tracking operations that often include the combined use of Unmanned Aerial Vehicles in addition to the traditional ad-hoc net-

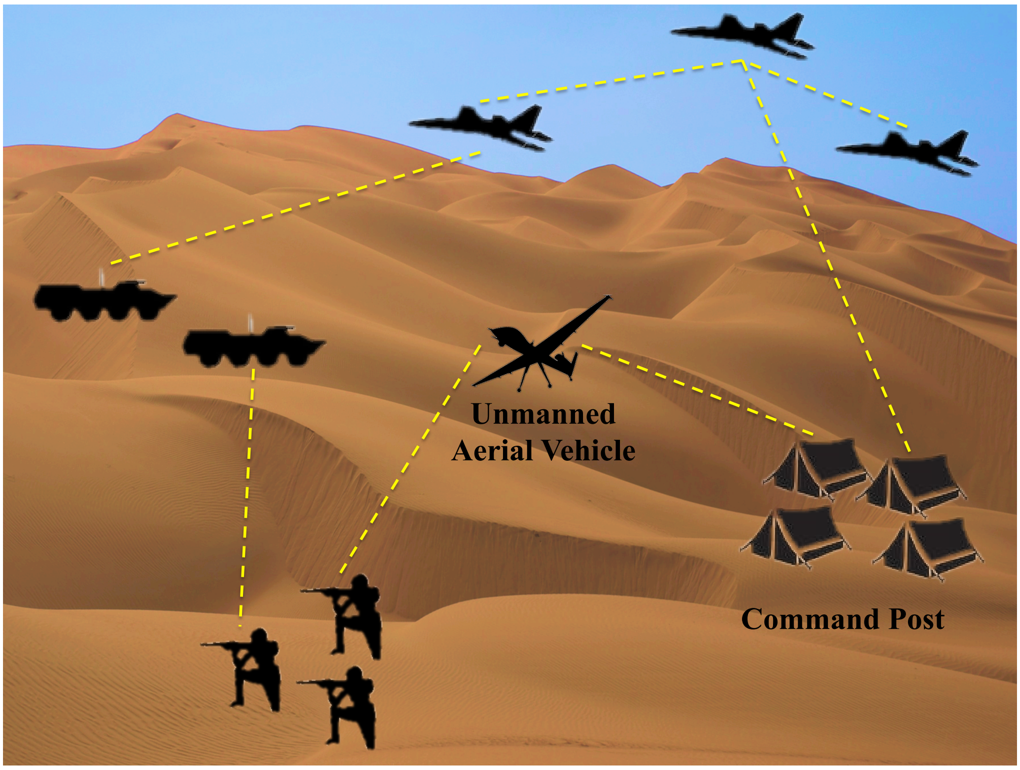

Figure 2.2: Military application of VANETs in a battlefield scenario.

work [38–40].

2.2 MAC protocols for ad-hoc networking

The Aloha mechanism was proposed in the 1970s as the first protocol designed for packet radio networks [41–43]. In the attempt to efficiently share the medium this random access process provides a resource allocation (e.g., access to the medium) in a distributed manner. In fact, if a vehicle has a packet to send over the shared channel it will immediately start the transmission and then wait to check if a collision has occurred. A new retransmission is attempted after a random time, if no acknowledgement packet has been received after the initial transmission (e.g., the packet suffered a collision). Unfortunately, the Aloha protocol provides very small throughput. Therefore, a slotted version of the Pure Aloha was proposed. By dividing the channel into time slots of the same size, and provided that all the vehicles are synchronised, it is indeed possible to improve the throughput performance of the Aloha protocol.

Regrettably, as we have previously stated, it is extremely challenging to deal with the dynamic nature of vehicles and the consequent density changes. Hence several approaches to enhance the performance of the Aloha protocol have been proposed. For instance, a thorough study over the challenging problem of improving the packet progress has been carried out. The authors in [19,20,44] investigate the aforementioned issues by incorporating in their model the assumption of Poisson distribution of the vehicles.

The CSMA/CA protocol represents the evolution of Aloha, as it adds a sensing mechanism to the original random access process. In fact, before initiating any communication a vehicle willing to send a packet has to listen to the channel in order to verify that the medium is indeed free of other ongoing transmissions that could prevent the packet from being successfully received [45,46]. It has been observed that increasing vehicular density corresponds to decreasing performance of [47,48]. More specifically, the feasibility of the current broadcast CSMA/CA protocol to support time-critical applications has been studied and it has been shown that the single-hop throughput performance still needs further improvement [49].

Various solutions have hence been proposed to overcome the issues related to reliable broadcasting in VANETs. For example, Space Division Multiple Access (SDMA) protocols assign different time slots relative to the vehicle location [50–53]. This implies that roads must be divided into segments, yet fairness can be difficult to maintain under fast changing vehicular densities that may characterise different road segments at the same time.

Another approach exploits the Time Division Multiple Accessccess (TDMA) mechanism that assigns a transmission slot to a vehicle [54–56]. Originally designed to be used in a centralised fashion, vehicular networks require TDMA protocols to act in a distributed manner, which unfortunately is still not completely immune to the contention problem and can only accommodate a limited number of vehicles, given that the time slot will not be released as long as the vehicle has to transmit a packet (i.e., CAM messages have to be transmitted periodically from each vehicle). Hence, it seems reasonable to efficiently allocate transmission rights to various vehicles based on the current IEEE 802.11p MAC protocol, by optimising the network performance according to the changing vehicle density.

A mechanism to adjust the optimal value of CW is presented in [57], which although gives good results, requires a centralised approach that is not suitable for dealing with vehicular ad-hoc networks. On the other hand, the authors in [58] address the problem of optimising the minimum contention window size for CSMA/CA in a distributed fashion, although without considering the signal-to-noise ration constraint.

2.3 Internetworking

Networking between vehicles and UAVs or cellular base stations can keep the network connected in the event of disruptions due to obstacles, poor weather conditions or natural disasters that have destroyed existing communication infrastructure.

Unfortunately, concerns on the robustness and adaptiveness of such networks to support system applications arise in light of the the high mobility that characterises the nodes in a vehicular ad-hoc network. A main challenge is handling the rapid changes in the network topology and vehicular density, which significantly affects the performance of the network [16, 21].

Despite the potential advantages of utilising clustering techniques for internetworking applications, maintaining cluster stability in light of vehicle mobility and radio fluctuation remains a major issue. The first clustering algorithms were initially designed for Mobile Ad-Hoc Networks (MANETs) [59–62]. Of these, Lowest-ID [62] is a well-known algorithm, in which the vehicle with the smallest ID in its neighbourhood becomes cluster head. Although initially designed for MANETs, it has been shown that it can also be employed in a vehicular environment [63]. Among these MANET clustering algorithms, the Highest-Degree [61] requires the vehicle with the highest nodal degree in the neighbourhood to undertake the role of cluster head. A combination of these two popular techniques, k-ConID, was proposed in [64] that as well as the original algorithm Highest-Degree is characterised by a longer cluster lifetime and smaller number of clusters.

Many clustering techniques designed for VANETs have also been proposed [65–73]. A fast clustering algorithm that focused mostly on the rapid construction of the cluster is described in [71]. Nevertheless, the stability of the cluster head selection is not assured due to the rapidity of the decision making process and this negatively affect the stability of the clustered structure of the network.

A different approach has been adopted in [69, 72, 73] in order to make the cluster heads selection more reliable and maintain the clusters stable. Several mobility metrics are widely introduced to select a stable CH. The authors in [69] propose a clustering approach based on affinity propagation.

The metrics used are a combination of current and future positions. Each node makes its clustering decision every clustering interval (CI). Depending on the length of the CI, which is arbitrary, the performance may rapidly diminish and hence not always stable. The VMaSC algorithm, presented in [72], employs the average relative speed amongst neighbouring vehicles as a mobility metric, to select the CH.

None of the above mentioned clustering algorithms account for the behaviour of the vehicles in the course of the decision making process to select a stable CH. In fact, information regarding the future behaviour of a vehicle (e.g. if a vehicle is about to leave the network) might prevent an erroneous CH selection that can in turn incur in the collapse of the cluster.

In [70] the stability of the cluster head is improved in due to lane detection. The possible behaviour of vehicle is accounted for by the detection of the lane they are travelling on (e.g. if a vehicle is on a side lane will probably leave the system). Specifically, every lane is assigned a different weight based on the traffic flow, which in turn will help evaluate the decision metric to elect the CH. However, lane detection is not always feasible, because it requires specific equipment and the weight assignment for the lanes is not always straightforward. Furthermore, no countermeasures are taken, for the maintenance phase, to prevent the clusters from falling apart when the CH looses connection.

Chapter 3

Optimised Aloha Protocol for Density-Based Throughput Enhancement in VANETs

Communication in vehicular ad-hoc networks are subjected to the highly mobile nature that characterised the vehicles. Despite the advantageous wide range of application the infrastructureless architecture of this wireless networks can support, many issues arise due to the high mobility of nodes (vehicles) within VANETs. The rapid change in the network topology is difficult to handle because it significantly affects the performance of the network as well as the frequent fragmentation into multiple clusters that usually takes place in vehicular traffic scenarios. An additional limitation of the VANETs is related to the low latency that is often required by many applications, especially for the implementation of safety systems. Ergo, it becomes imperative to maintain the network connectivity in order to achieve reliable communication across all of the nodes. Connectivity and capacity are very important issues that have been widely investigated in [16–18, 74, 75] and both connectivity and capacity are closely influenced by vehicular density.

VANETs are expected to properly enable communications among vehicles under various conditions of vehicular density. As a result, efficient resource allocation (e.g., right to transmit) should strike a balance for the optimal network performance by directly considering vehicle density. The need for distributed communications and dynamic topology requires improvement of the classic protocols adapted to the dynamics of highly mobile networks. In [18] , for instance, the problem of choosing the transmission power to reduce the network interference is investigated. Optimisation of VANETs performance is also performed and analysed in [19, 20, 76]. In [76], the authors derive the best transmission range to minimise the energy usage over uniformly distributed networks. Authors of [19] investigate the optimal transmission radius to enhance the packet progress, assuming a Poisson distribution of the terminals to derived an improved model. The work considers two MAC protocols: slotted ALOHA and CSMA. It is note worthy that the model does not take into account VANET scenario with highly mobile nodes. In [20] the matter of position-related optimal transmission probability for packet progress enhancement is investigated. Unfortunately, due to the high mobility of nodes, vehicular density can change rapidly creating heterogeneous scenarios. Hence, it is not always possible to have a priori knowledge of the density distribution based on vehicles locations as it is assumed in [20].

As a first step to devise efficient MAC protocols for VANETs, we focus in this chapter on optimising the transmission probability to maximise the single-hop throughput for connection between adjacent nodes, in order to keep the network connected (i.e., maintaining minimally connected [16]). A closed form solution is indeed achievable under some assumptions that help to handle such a complex interference scenario. As a proof of the model validity, extensive simulations are compared with it, showing that the proposed model can be a powerful tool to improve the performance of a vehicular ad-hoc network, enabling the nodes to follow the highly changing network conditions and adapt accordingly. To gain the design insights, a simple VANET is considered here, which consists of a single-lane road with one traveling direction where vehicles arrive according to a Poisson process at the entrance point of the road and move at a constant speed on the road. Vehicle movement can be characterised by a fluid mobility model. It is assumed that all vehicles use the slotted Aloha protocol with a uniform transmission probability to control their channel access. Using the information from the mobility model, the expression for the network throughput is derived analytically. Consequently, the optimal transmission probability can be evaluated and obtained based on the vehicle density. This result reveals that it is possible to improve VANET performance by adapting the transmission probability depending on the vehicular density. This work represents our first step toward the design of an efficient MAC protocol specifically tailored for VANETs, in contrast to the CSMA protocol in the 802.11p, to adjust the backoff window according to vehicle density.

3.1 System model

3.1.1 Mobility Model

We characterise the traffic source and its underlying assumptions. An infinite single lane, one direction road is considered in this work, as shown in Figure 3.1. The one-dimensional scenario can be helpful to give a good insight into more complex scenarios.

As in [17–20], a Poisson arrival process with an integrable rate function

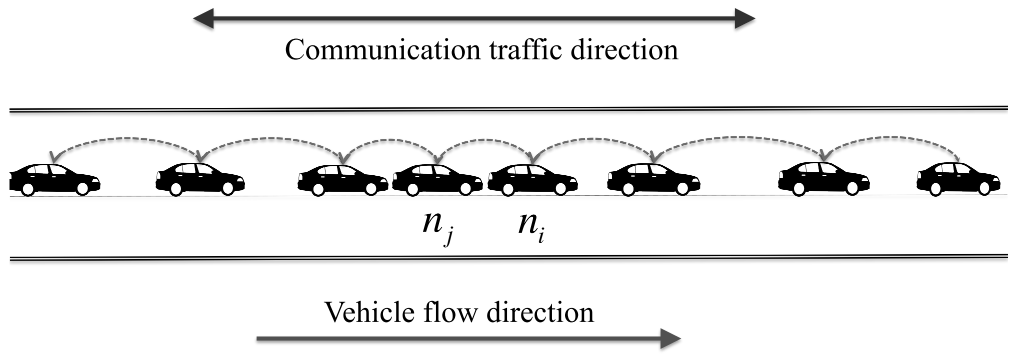

Figure 3.1: One-dimension vehicular ad hoc network, with single-hop connectivity

$\lambda(t)$, is considered to be a good traffic generation model in order to describe the approaching vehicles distribution at the entrance of the road section in a free flow state scenario. Vehicles can join the network only through the main entrance (located at the far left hand side) as in Figure 3.1, and they are not supposed to enter or leave the network along the road. After entering the network, vehicles proceed from left to right as shown in Figure 3.1 and maintain a constant velocity v during the time interval $(0, t]$.
Finally, no interactions between vehicles are taken into account, as a result the locations of every node depend only on vehicle arrival times.

By assumption of Poisson arrival process, the expected value of the number of vehicles entering the road in the time interval $(a, b]$ is:

$$E[V(t)] = \int_a^b \lambda(t)dt. \quad for \;\; t \geq 0 \tag{3.1}$$

To describe vehicle movement on the road, a fluid model is used. This means that vehicles are macroscopically treated as continuum fluid characterised by the constant flow rate λ, the velocity v and the vehicle density ζ.

If there are no interactions among vehicles, the flux is defined as

$$\lambda = v\zeta. \tag{3.2}$$

By assuming that vehicles move at a constant velocity v it follows that the vehicles entering the road with a Poisson arrival process of rate λ will be spread on a road following a Poisson Point Process (PPP) with rate, or equivalently vehicular density, $\zeta = \lambda/v$. This is because vehicles entering the road at different times t, under the assumption of proceeding with constant velocity v, will be found at positions $x = vt$ on the street. From (3.2), and with the knowledge of the flow rate λ used to inject the vehicles in the street and speed v of the vehicles, it is possible to mathematically derive the vehicular density ζ that characterised the Poisson spacial distribution of the vehicles in the road.

Note that this thesis work presents a one-dimensional scenario to be analysed, as shown in Figure 3.1. Nevertheless, the model and results shown can be extended to multiple lanes scenario under the assumptions of independent Poisson point processes for each parallel lane of the road. This is because, independent PPP can be combined into a single PPP (for a one-dimensional scenario) with coefficient given by the combination of those of the independent processes.

Let's now define x_j the position of vehicle n_j in the road and x_i the position of the adjacent vehicle n_i as in Figure 3.1, where $i = j + 1$. The distance between adjacent vehicles n_i and n_j is then formalised as $d_{ij} = d_{j+1,j} = |x_{j+1} - x_j|$. From the Poisson arrivals process assumption it follows that distances between adjacent vehicles are identical and independent random (iid) variables exponentially distributed with probability density function (pdf)

$$f_{d_{ij}}(d_{ij}) = \zeta e^{-\zeta d_{ij}} \qquad x \geq 0. \tag{3.3}$$

Let us now define the distance between a vehicle n_j and a non adjacent vehicle n_k as $d_{kj} = |x_k - x_j|$. If $k = j + 2$ then the distance becomes $d_{kj} = d_{j+2,j} = |x_{j+2} - x_j|$ and its pdf can be obtained by convolving the densities of the 2 random variable $d_{j+2,j+1}$ and $d_{j+1,j}$ (representing distances between consecutive adjacent vehicles n_j n_{j+1} n_{j+2}) given in (3.3). The resulting pdf is hence

$$f_{d_{j+2,j}}(d_{j+2,j}) = \int_0^{+\infty} f(d_{j+2,j} - d_{j+1,j}) f(d_{j+1,j})\ dd_{j+1,j}. \tag{3.4}$$

By inserting (3.3) in (3.4) we obtain

$$f_{d_{j+2,j}}(d_{j+2,j}) = d_{j+2,j}\zeta^2 e^{-\zeta d_{j+2,j}}. \tag{3.5}$$

It follows that when $k = j + 3$ the pdf of the distance $d_{kj} = d_{j+3,j} = |x_{j+3} - x_j|$ can be found as

$$f_{d_{j+3,j}}(d_{j+3,j}) = \int_0^{+\infty} f(d_{j+3,j+2} - d_{j+2,j+1}) f(d_{j+2,j+1})\ dd_{j+2,j+1}, \tag{3.6}$$

and using (3.3) and (3.5) into (3.6) we have

$$f_{d_{j+3,j}}(d_{j+3,j}) = \frac{\zeta^3}{2} d^2_{j+3,j+2} e^{-\zeta d_{j+2,j}}. \tag{3.7}$$

Generally, the pdf of the distance d_{kj} between 2 random non adjacent vehicles n_k and n_j can be found with the k-fold convolution that leads to

$$f_{d_{kj}}(d_{kj}) = \frac{\zeta^k}{(k-1)!} d_{kj}^{(k-1)} e^{-\zeta d_{kj}}. \tag{3.8}$$

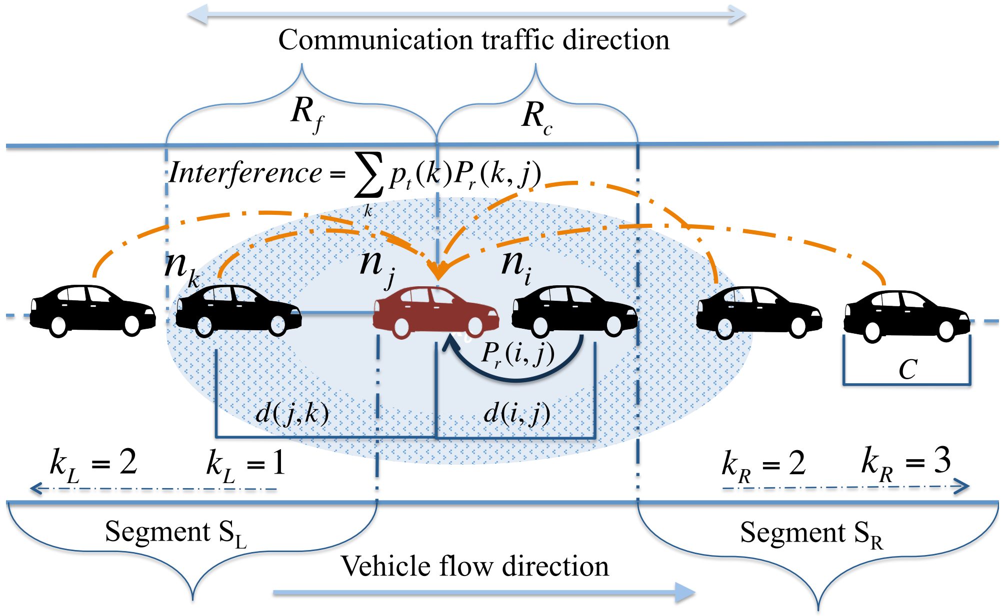

Figure 3.2: Road configuration and assumptions for the analytical model

The expression in (3.8) is known as Erlang distribution and has parameter ζ, the vehicular density, and k. In the scenario under consideration in this thesis, the value k represents the number of vehicles within distance d_{kj} while $k-1$, that appears in (3.8), represents the number of vehicles located between the two non-adjacent vehicles n_k and n_j.

3.1.2 Interference Model

The analysis of the co-channel interference requires the consideration of the following assumptions. To consider the characteristics of certain applications, let us focus on data transmission from a vehicle to another vehicle that is traveling right next to the former one. Specifically, data communication can flow both directions and we consider that the transmission is established between adjacent nodes, as to maintain the connectivity of the network and reduce the interference simultaneously. For example, node n_i

is transmitting towards the receiving node n_j, while an arbitrary node is denoted by n_k, as shown in Figure 3.2.

The transmission power P_t is set to be identical on every node. Signal attenuation is assumed solely due to distance with a power exponent $\alpha > 2$ in the operating environment.

Slotted Aloha protocol is used to allow channel access for analytic simplicity, rather than the more sophisticated CSMA required in vehicular standard 802.11p. In fact, this work is only a first step with the sole purpose of proving that it is indeed possible, under certain circumstances, to find a closed form solution to optimise network parameters, i.e the transmission probability, based on system density dynamics; hence at this stage of the research Slotted Aloha protocol is adopted for analytic simplicity. Finally, half-duplex communication is considered such that each node can either transmit or receive signal, but not both, at any given time.

The received power P_r at a node depends on the transmission power P_t of the transmitted packet and the path loss γ from the transmitting node to the receiving one as follows

$$P_{r(i,j)} = P_t \left(\frac{1}{d_{ij}} \right)^{\alpha} \quad with \;\; \alpha > 2, \tag{3.9}$$

where d_{ij} represents the distance in metres between a transmitter the adjacent receiver. The signal-to-interference ratio (SIR) at the receiving node, for M interfering nodes is

$$SIR = \frac{P_{r(i,j)}}{\sum_{k=1}^{M} I_k P_{r(k,j)}}, \tag{3.10}$$

where the denominator is the total interference received at the receiving vehicle and I_k is an indicator that reflects whether vehicle k is allowed to transmit according to the slotted Aloha protocol under consideration. Therefore, I_k is a random variable with only 2 possible outcomes, $I_k = 1$ if the vehicle is transmitting and $I_k = 0$ if it is not transmitting. The former occurs with probability p_t whilst the latter with probability $1-p_t$. Formally, I_k has a Bernoulli distribution with pdf

$$f_{I_k}(I_k) = \begin{cases} p_t & for\ \ I_k = 1 \\ \\ 1 - p_t & for\ \ I_k = 0. \end{cases} \tag{3.11}$$

Inserting (3.9) into (3.10) we obtain the general expression for SIR at n_j when n_i is transmitting

$$SIR_{i,j} = \frac{P_t \left(\frac{1}{d_{ij}}\right)^{\alpha}}{\sum_{k=1}^{M} I_k P_t \left(\frac{1}{d_{kj}}\right)^{\alpha}}. \tag{3.12}$$

3.1.3 Connectivity and Throughput Model

The following assumptions are used in order to evaluate the connectivity of the system. Although data packets can be transmitted and forwarded from one vehicle to another via multi-hops, we focus on the connectivity between any two adjacent (neighbouring) vehicles. That is, we consider whether a packet can be received by the vehicle immediately in front of or behind a given transmitting vehicle.

For any two adjacent nodes n_i and n_j, Figure 3.2 shows two separate segments of the road, namely S_L and S_R, where possible interfering nodes are located that can interfere with transmission between n_i and n_j.

Let us introduce the notion of communication range R_c. This is defined as the distance from a given reference vehicle within which a signal from a transmitting vehicle can be received at a power level greater than a specified threshold (referred to as the receiver sensitivity) as illustrated in Figure 3.2. In this work, the communication range R_c is set to be identical for all vehicles within the network, as was done in [19, 21, 75, 76].

Connectivity Requirements

Two adjacent vehicles n_i and n_j are considered to be connected if two conditions are fulfilled. Firstly, the vehicles have to be located within each other's communication range R_c, which is referred as the event E. This condition follows from the receiver sensitivity requirements, defined earlier in terms of R_c, that have to be fulfilled and it is expressed as

$$d_{ij} \leq R_c. \tag{3.13}$$

In addition, a second condition is needed. In fact, the communication link between vehicles n_i and n_j can be affected by the interference from other vehicles accessing the channel at the same time. Consequently, the signal to interference ratio (SIR) has to exceed a prefixed threshold β related to the data rate and the particular coding scheme used. It follows that the second condition is

$$SIR_{i,j} \geq \beta. \tag{3.14}$$

Given the exponential distribution for distance between two adjacent vehicles in (3.3), the probability of event E, that (3.13) is valid, is given by

$$P[E] = 1 - e^{-\zeta R_c}. \tag{3.15}$$

By the definition of SIR in (3.12), the threshold in (3.14) can be expressed as,

$$P_{r(i,j)} \geq \beta \sum_{k=1}^{M} I_k P_{r(k,j)}. \tag{3.16}$$

Where $P_{r(i,j)}$ denotes the received power at node n_j from n_i. Unfortunately, to determine whether the condition in (3.16) is satisfied requires complicated calculation because of the random variables involved, including the transmission indicators I_k and the distribution of distance between the vehicles. As a result, it is not possible to obtain closed-form expression for the performance metrics of interest.

Note that in a one dimensional topology (or equivalently a single lane or a combination of PPP as earlier explained), like the one studied in this thesis, vehicles tend to spread along the roads (a line). Therefore, due to the deterministic path loss in (3.9) (because fading is not included in our analysis), the further is the k interferer the smaller the received power at the receiver, especially when considering scenarios with high path loss exponent, $3 \leq \alpha \leq 5$, as we find in urban areas, to the extent that for $k \rightarrow \infty \quad P_{kj} \rightarrow 0$. This means that due to the deterministic path loss, that is solely dependent on the distance, only some vehicles, placed within a certain radius (interference range R_f in Figure 3.2) from the receiver n_j, will be able to transmit a signal powerful enough to interfere with the communication between vehicle n_j and n_i. Moreover, from (3.9) it follows that even if a single vehicle n_k within the interference range R_f is transmitting (that is $I_k = 1$), it is already enough for the SIR requirement in (3.16) not to be met regardless what other interfering vehicles are doing. In light of this, we propose to replace the connectivity requirement in (3.16) by a set of single-interferer conditions. That is, the SIR at the receiving node n_j, associated with a transmission from node n_i, satisfies the following expression for every interfering vehicle n_k

$$\begin{cases} P_{r(i,j)} \geq I_k \beta P_{r(1,j)} \\ P_{r(i,j)} \geq I_k \beta P_{r(2,j)} \\ \vdots \\ P_{r(i,j)} \geq I_k \beta P_{r(k,j)} \end{cases} \tag{3.17}$$

Clearly, replacing the requirement in (3.16) by a set of conditions in (3.17) represents an approximation, which is intuitively reasonable for VANETs under deterministic path loss conditions as explained above. Extensive simulation in a later section validates this approximation. By using the path loss formula in (3.9), (3.17) can be expressed as,

$$\underbrace{P_t \left(\frac{1}{d_{ij}}\right)^{\alpha} \geq I_k \beta P_t \left(\frac{1}{d_{kj}}\right)^{\alpha}} \rightarrow \quad d_{kj} \geq I_k \beta^{1/\alpha} d_{ij} \quad \forall k. \tag{3.18}$$

The above inequality represents that the distance d_{kj} between node n_k and node n_j exceeds the distance d_{ij} by a factor of $\beta^{1/\alpha}$. This condition needs to be verified for every possible interfering kth node in the network in order to guarantee a successful reception in terms of SIR in (3.17).

Let us now define an event F_k where the condition in (3.17) or equivalently (3.18) is satisfied for a given interfering node n_k. Clearly, the event F_k occurs when either node n_k is not transmitting (i.e., $I_k = 0$) or if it does, $d_{kj} \geq \beta^{1/\alpha} d_{ij}$. Therefore, we have

$$P[F_k] = P\{I_k = 0 \vee (I_k = 1 \wedge d_{kj} \geq \beta^{1/\alpha} d_{ij})\}. \tag{3.19}$$

Evaluating the probability in (3.19) again requires complicated calculation because distances between two vehicles are random variables. Consequently, it is impossible to obtain a closed-form expression for the probability. To overcome the difficulty, we observe that the random distance between node n_i and n_j, d_{ij}, is characterised by (3.3). In order to meet the requirement of receiver sensitivity as defined for the communication range, d_{ij} has its maximum value of R_c, as shown in (3.13). Replacing d_{ij} by R_c in (3.19) provides the approximate probability as

$$P[F_k] = P\left\{(I_k = 1 \wedge d_{kj} \geq R_c \beta^{1/\alpha}) \vee I_k = 0\right\}. \tag{3.20}$$

For convenience, we set $R_f = R_c \beta^{1/\alpha}$. If node n_k is located beyond R_f from the receiving node n_j, the interference condition in (3.17) is satisfied for node n_k. Therefore, R_f is referred as the interference range below. As a first step towards the evaluation of such probability in (3.20), we need information regarding the density dynamics, in term of ζ, that can be evaluated through the fluid model shown in (3.2).

As the next step, let us determine the probability of an event A that node n_k is located outside the interfering range R_f of node n_j. As shown in Figure 3.2, any interfering node n_k can be located in road segments, S_L and S_R, to the left and right of node n_j. Given the Poisson vehicle arrivals, the distance between any two adjacent nodes (vehicles) is exponentially distributed as given in (3.3). Therefore, the distance between two non-adjacent nodes has an Erlang distribution in (3.8) where the value of k-1 represents the number of nodes between the non-adjacent nodes. Combining this fact with the indexing scheme k for interfering nodes as shown in Figure 3.2, the probability that node n_k lies beyond R_f from node n_j is

$$P[A] = \sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f} \tag{3.21}$$

As the access protocol assumption in (3.11), the probability that node n_k does not transmit is

$$P[I_k = 0] = 1 - p_t. \tag{3.22}$$

Substituting (3.21) and (3.22) into (3.20) yields

$$P[F_k] = 1 - p_t[1 - (\sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})], \tag{3.23}$$

It is worth noting that the probability in (3.23) is that for satisfying the single-interferer SIR condition in (3.17) or equivalently (3.18) for node n_k. The probability of event L_s, of satisfying (3.18) for all S interfering nodes n_k located in the road segment S_L is thus given by

$$P[L_s] = \prod_{k=1}^{S} 1 - p_t[1 - (\sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})] \tag{3.24}$$

because all nodes transmit or not independently. Similarly, the corresponding probability of event R_q, that all Q interfering nodes n_k in the road segment S_R satisy (3.18) is

$$P[R_q] = \prod_{k=2}^{Q} 1 - p_t[1 - (\sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})]. \tag{3.25}$$

Using (3.24) and (3.25), the probability of meeting all of the interference conditions in (3.17) or (3.18) for transmission from node n_i to n_j (defined as the event G_{ij}), despite of all possible interfering nodes n_k, is given by

$$P[G_{ij}] = P\left\{R_q \wedge \, L_s\right\} \tag{3.26}$$

By directly inserting (3.24) and (3.25) in (3.26) the probability of event G_{ij} becomes

$$P[G_{ij}] = \prod_{k=1}^{S} 1 - p_t[1 - (\sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})] \cdot \prod_{k=2}^{Q} 1 - p_t[1 - (\sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})]. \tag{3.27}$$

If the number of vehicles in region S_L is the same as in region S_R, that is $S = Q = M$, with few rearrangements of (3.27), the probability $P[G_{ij}]$ becomes as follows

$$P[G_{ij}] = \frac{\prod_{k=1}^{M} \left[(1 - p_t) + (p_t \sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})\right]^2}{(1 - p_t) + p_t e^{-\zeta R_f}}. \tag{3.28}$$

Optimal Throughput

Data throughput from node n_i to its adjacent node n_j is defined as successful reception subject to satisfying conditions in (3.13) and (3.18). This definition also include that node n_i is transmitting while its adjacent node n_j is not transmitting (i.e., receiving). Combining all these factors, the throughput from node n_i to n_j is given by

$$T_h = P\left\{E \wedge \, G_{ij} \wedge \, I_i = 1 \wedge \, I_j = 0\right\}. \tag{3.29}$$

Substituting (3.15), (3.22) and (3.28) into the above yields the single-hop throughput from node n_i to its neighboring node n_j as

$$T_h = p_t(1 - e^{-\zeta R_c})(1 - p_t) \cdot \frac{\prod_{k=1}^{\infty} \left[(1 - p_t) + (p_t \sum_{n=0}^{k-1} \frac{(\zeta R_f)^n}{n!} e^{-\zeta R_f})\right]^2}{(1 - p_t) + p_t e^{-\zeta R_f}}. \tag{3.30}$$

It is important to note from the above equation that the only control variable is the transmission probability, p_t , and all other variables are constants for a given network and communication equipment. Naturally, it is useful to maximise the throughput with respect to p_t by the first derivative of (3.30). In terms of protocol operations, the optimal p_t can be determined from (3.30) as a function of the vehicle density, ζ , which can be estimated by vehicles.

3.2 Numerical Results

Simulations are used to validate the proposed analytical model. In this work, it is assumed a one-lane and single-direction road with 5 Km in length, and data packets can travel in both directions, as shown in Figure 3.2. Furthermore, it is assumed that vehicles arrive and join the network only at the entrance (located at the far left hand side) of the road with a constant arrival rate $\lambda(t)$. All vehicles move forward on the road with a constant velocity v. The fluid model provides the vehicle density information in the network, which is then used as an input parameter in the analytical model. The communication range is assumed to be $R_c = 100\,m$, the path loss exponent $\alpha = 4$ (as in urban areas can assume values in range $3 \leq \alpha \leq 5$) and $\beta = 4$. The value of the SIR threshold can largely vary [44]. In this thesis β has been chosen relatively to the fact that broadcasted messages sent at low data rate do not required high thresholds [77, 78]. However, a different value would simply scale the values of R_f by multiplying R_c for a new value of $\beta^{1/\alpha}$.

Figure 3.3 shows the probability $P[G_{ij}]$ of meeting all of the interference conditions in (3.17) or (3.18) for a single-hop transmission. The simulation

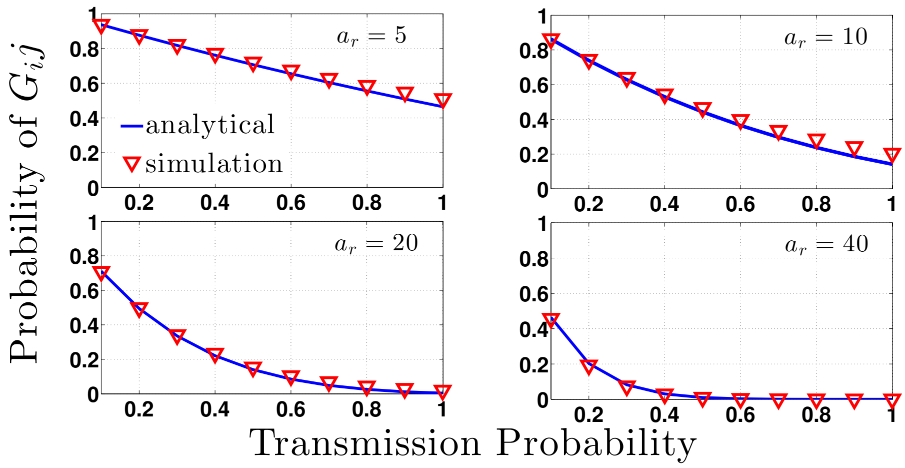

Figure 3.3: Probability of connection for different values of arrival rates: $a_r = 5, 10, 20, 40$ **cars/min**

results, design to meet the SIR condition in (3.16) and obtained by carrying out 100,000 Monte Carlo simulation, are compared with the analytical model in (3.28). Four cases are considered with different vehicle arrival rates: 5, 10, 20 and 40 *vehicle/min*, respectively. It is important to note that the curves in Figure 3.3 show a close match between simulation and analytic results, validating the approximations used in the model proposed in this work. It can be observed that the $P[G_{ij}]$ decreases when the probability of packet transmission p_t increases. This is so because a higher transmission probability causes more interference. Moreover, the performance in terms of SIR in (3.17) or (3.18), tends to be better in situations with a smaller vehicular density, as there are less vehicles able to interfere.

Figure 3.4 shows how the model presented in (3.30) generates curves with global maximum each, where every line describes a single event of a different vehicles arrival rate. Therefore, it is possible to find the value of p_t for different densities ζ by finding the probability of transmission corresponding to the pick of the curve under investigation.

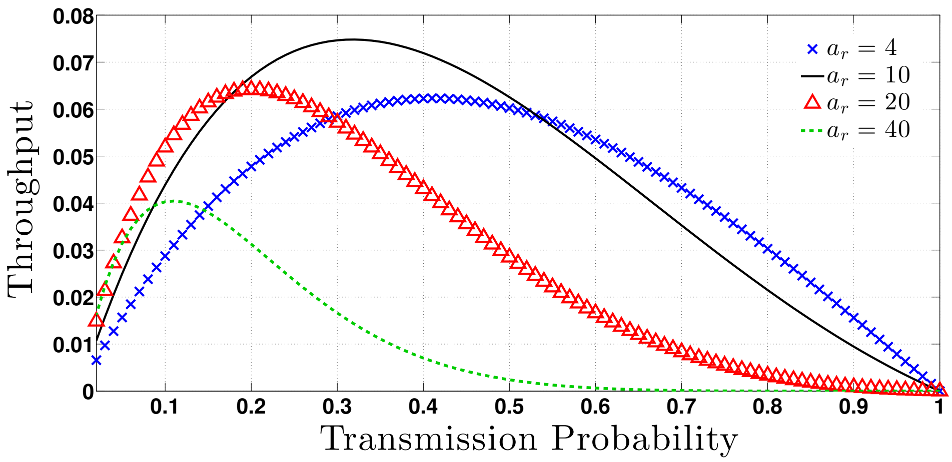

Figure 3.4: Throughput for different values of arrival rates: $a_r = 5, 10, 20, 40$ **cars/min**

From (3.30) the optimal transmission probability p_t to maximise the network throughput on a single-hop connection can be evaluated. The result is displayed in Figure 3.5 as a function of the increasing arrival rate of vehicles at the entrance of the network. The optimal transmission probability p_t decreases as the vehicle arrival rate increases. This is due to a higher node density and thus more interfering vehicles. Consequently, the high chance of collisions can be decreased by reducing the transmission probability at every node.

Finally, Figure 3.6 shows the maximised throughput obtained from the previously chosen values of transmission probability. It can be observed that the throughput reaches a maximum at a certain value of transmission probability. Throughput does not depend only on the transmission probability, but is also influenced by the vehicular density and the average distance between vehicles that affect whether vehicles can properly communicate. Fortunately, all these parameters have been included in the throughput expression (3.30). The plot also shows that the analytical and

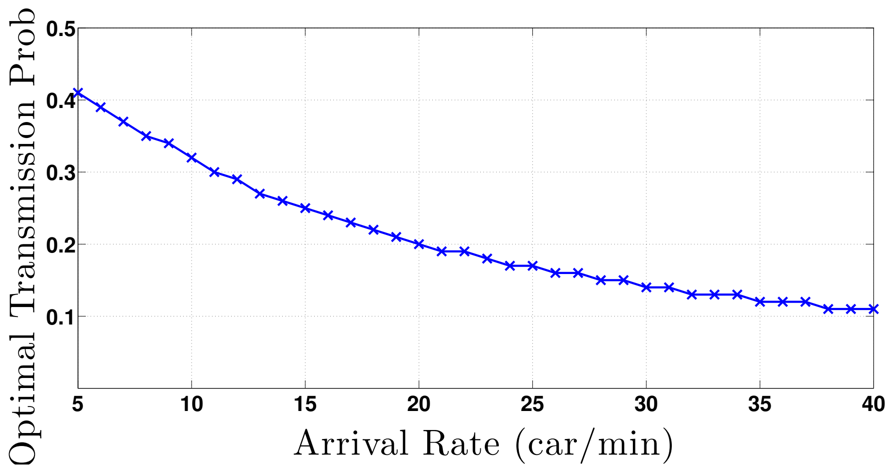

Figure 3.5: Optimal transmission probability to maximise throughput for different car arrival rates

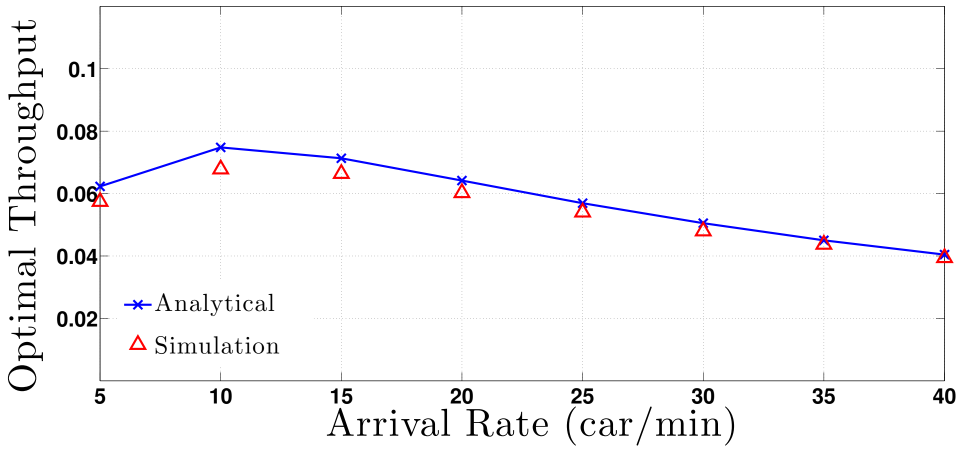

Figure 3.6: Maximum Throughput for different car arrival rates

simulated results are very close, revealing the possibility of adapting the optimal transmission probability p_t from the proposed analytic model to enhance the network performance, according to the estimates of vehicle arrival rate or equivalently the vehicle density.

3.3 Concluding Remarks

In this chapter we have investigated the problem of dealing with the rapid mobility of the vehicles that causes the degradation communication performance. As a first step toward the design of efficient MAC protocol tailored for VANETs, we have investigated whether it is possible to adapt the transmission probability for the MAC layer depending on vehicle density in order to reduce the interference and maximise the single-hop throughput between adjacent nodes (vehicles). To gain initial insights, a simple roadway scenario with one lane and one single travel direction has been considered. By considering SIR expressed as a set of pairwise conditions, connectivity among vehicles in the network can be determined and an expression for network throughput for one-hop communications has been obtained. This closed form expression is then exploited to determine the optimal transmission probability and hence maximise network throughput. The accuracy of the analytic approximation approach has also been verified with extensive simulations.

In the following chapter we show that the optimal transmission probability can be integrated into the CSMA/CA protocol. In fact, the current IEEE standard for VANETs uses CSMA/CA protocol. Thus, the results shown in this work can be incorporated in the design of a new CSMA/CA protocol that makes use of the optimal transmission probability for throughput enhancement.

Chapter 4

Optimal Broadcast CSMA Protocol for Time-Critical Application in VANETs

One of the most attractive benefits of VANETs is their capacity to support time-critical applications, for instance, by enabling efficient vehicle internetworking or by drastically improving road safety, by means of exchanging safety information. In light of this, the European telecommunications standards institute designated a specific type of message based on the IEEE 802.11p, to be broadcasted in a single hop employing the CSMA/CA protocol. Known as cooperative awareness messages, they contain information relevant to safety related applications (i.e., speed and position), and are broadcasted as frequently as ten times per second to provide reliable support for safety applications that usually require low latency (as low as 100 ms) [12–14]. This is so each vehicle can constantly monitor the surrounding vehicles and infrastructure, allowing them to become aware of possible imminent threats, and to take rapid countermeasures such as sending warning messages to the drivers and neighbouring vehicles in such scenarios.

In this chapter we focus on designing a MAC protocol to support time-critical applications that otherwise rely on the IEEE broadcast CSMA/CA. The latter, does not enable the detection transmission collisions due to the lack of acknowledgment ACK packets and therefore the consequent adaptation of the maximum contention window is not possible. This means that instead of doubling the maximum contention window every time a collision occurs, the broadcast CSMA/CA is characterised by a fixed, maximum CW size instead.

In light of this, VANETs may be particularly vulnerable to performance degradation due to the vehicular density changes. Consequently, it is questionable whether the networks are robust enough to support the particularly stringent performance requirements for safety applications. Hence, it seems reasonable to efficiently allocate transmission rights to various vehicles based on the current IEEE 802.11p MAC protocol, by optimising the network performance according to the changing vehicle density.

In that regard, the CSMA/CA performance and its behaviour under different scenarios has been investigated in [22, 79–81]. The authors in [79,80] observe, by means of extensive simulation, that the IEEE 802.11p MAC tends to behave like the Aloha protocol as the vehicular density rises, meaning that the benefits of the sensing mechanism diminishes and the transmission process merely behaves like a random transmission technique. A more formal approach to the problem is used in [22,81], in which stochastic geometry is employed to prove that slotted CSMA/CA for broadcast application can be approximated by slotted Aloha under the assumption that the vehicles in transmission form a Poisson point process (PPP). In the Chapter 3 [21] we presented an approach to choose the optimal transmission probability for the slotted Aloha based on the vehicular density in networks where vehicles arrive and are distributed according to a PPP.

By exploiting the Aloha performance behaviour of the broadcast CSMA/CA, we are in this chapter able to integrate the optimal transmission probability into the CSMA/CA protocol. As a first step, to devise efficient MAC protocols for time-critical applications in VANETs, we establish the relation between the (fixed) maximum CW and the transmission probability. Following the model presented in [21], the density-based optimal transmission probability to enhance the network throughput is evaluated and the optimal maximum CW is found. Finally, we integrate our results with the CSMA/CA protocol and show improved performance of the proposed protocol based on vehicular density when compared with the original IEEE 802.11p MAC protocol.

4.1 System model

4.1.1 CSMA/CA broadcast model

The IEEE 802.11p MAC protocol is designed to work over a synchronisation interval (SI) of 100 ms, during which every vehicle switches between the control channel (CCH) and service channels (SCHs) for a CCH interval (CCI) and a SCH interval (SCI), respectively, such that SI = CCI + SCI . Specifically, the broadcast CSMA/CA for CAMs (i.e., safety messages) requires a 100 ms latency as well as a periodic message (packet) generation of 10 Hz for each vehicle. This means that a new packet is generated in every CCI (100 ms) for transmission.

Before continuing let us briefly describe the backoff procedure of broadcast CSMA/CA in 802.11p as described by ETSI in the european standard of access layer specification for ITS [14]:

1. select a random integer from the uniform distribution within the contention window (CW) range, [0,W-1];
2. decrement the backoff counter only when the channel is sensed idle, one decrement per slot time;
3. when the backoff counter reaches 0, transmit. Transmission in a broadcast fashion do not allow a vehicle to invoke the backoff procedure more than a single time since no ACK is sent to assure the successful trasmission.

The states associated with the channel contention protocol over a single CCI are described in Figure 4.1. The lack of any ACK means that vehicles cannot account for any collision and try to send again the same packet. Hence, the model presented in this thesis does not account for packet collisions. In light of the backoff procedure just described and the assumptions of the scenario investigated in this thesis the Markov chain in Figure 4.1 can be explained as follows. At the beginning of every CCI, all vehicles generate a new CAM (packet) for broadcast. For each packet, a backoff time is randomly selected from a fixed contention-window (CW) range of 0 to W - 1 slot times, as in point 1. The backoff time (counter) is then decremented every slot time when the channel is sensed idle, as expressed in point 2. When the counter reaches 0, the vehicle transmits the packet. From point 2 of the backoff procedure above it follows that if the channel is determined to be busy, the counter is frozen (because the counter is decremented only when the channel is free). From the Markov model in Figure 4.1 and assuming that vehicles are able to carry out the

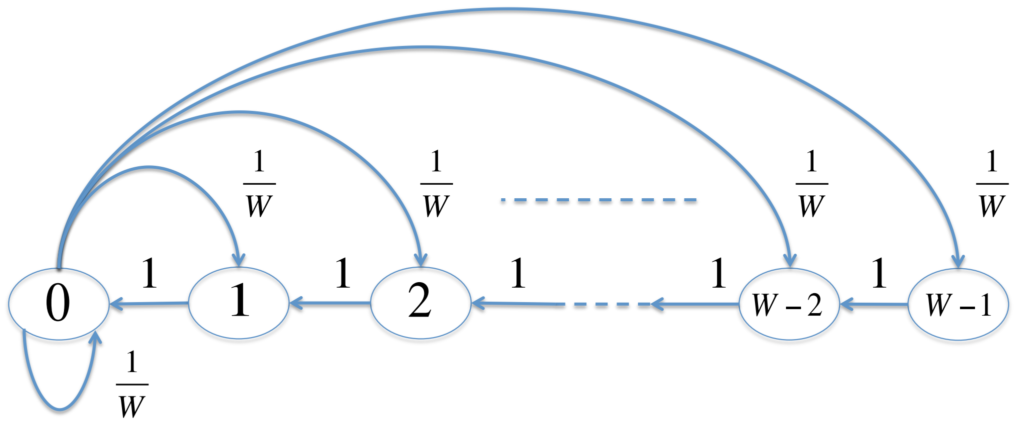

Figure 4.1: Markov model of CSMA/CA Broadcast in 802.11p for every CCI interval

backoff process correctly (e.g., no hidden node problem), the state transition probabilities are given by

$$\begin{cases} P\{k|0\} = \frac{1}{W}, & \text{for } k \in [0, W-1] \\ \\ P\{k-1|k\} = 1, & \text{for } k \in [1, W-1] \end{cases} \tag{4.1}$$

where state k represents the current value of the backoff counter on a vehicle. Let us now introduce a new variable b_k representing the probability that a vehicle has a backoff value of k or equivalently it is found in state k. Figure 4.1 illustrates that every k state can be directly selected with probability $\frac{1}{W}$, as shown in the first line of (4.1). It is additionally possible to reach a state k by sequentially decrementing the counter with probability 1, as in (4.1), after the selection of a higher backoff value (Figure 4.1). In light of this, with reference to Figure 4.1, we can evaluate the probabilities of each state as follows

$$\begin{cases} b_{W-1} = \frac{1}{W} b_0 \\ b_{W-2} = \frac{1}{W} b_0 + b_{W-1} \\ \vdots \\ b_{W-i} = \frac{1}{W} b_0 + b_{W-i+1} \end{cases} \tag{4.2}$$

where b_0 represent the probability that the backoff counter is zero and consequently it represents the probability that a vehicle transmits in an idle slot. By introducing the change of variable $W - i = k$ we can eventually express the probability b_k as

$$b_k = (W - k)\frac{b_0}{W} \tag{4.3}$$

The sum of all possible states probabilities has to be equal to 1. That is,

$$\sum_{k=0}^{W-1} b_k = 1. \tag{4.4}$$

By substituting (4.3) into (4.4) and rearranging we obtain

$$\sum_{k=0}^{W-1} (W - k) = \frac{W}{b_0}. \tag{4.5}$$

Let us focus on the first summation of (4.5). The nth partial sum is given by

$$\sum_{n=1}^{N} n = \frac{N(N+1)}{2}, \tag{4.6}$$

By using (4.6) and applying the change of variable $n = W - k$ the summation index in (4.5) for $k = 0$ becomes $n = W$ and for $k = W - 1$ is $n = 1$. From the commutative property of the sum follows that (4.5) becomes

$$\sum_{k=0}^{W-1}(W-k) = \underbrace{\sum_{n=W}^{1} n = \sum_{n=1}^{W} n = \frac{W(W+1)}{2}} = \frac{W}{b_0}, \tag{4.7}$$

the relation between the CW size and the probability b_0 can be expressed as

$$W = \left\lfloor \frac{2}{b_0} - 1 \right\rfloor, \tag{4.8}$$

where b_0 is the probability that a vehicle starts transmitting in an arbitrary free slot time and the flooring operation is applied because the CW must be an integer value, as specified in the protocol standards.

4.1.2 Equivalence of the CSMA/CA Broadcast to Slotted Aloha

To consider the CAM safety messages exchanged based on the ETSI standardisation, we focus on the MAC protocol operation over a single CCH interval, where the messages are generated once every CCI of 100 ms for each vehicle. In fact, each vehicle generates a CAM packet synchronously at the beginning of every CCI, resulting in a saturated traffic condition (i.e., every vehicle has a packet ready for transmission). According to the CSMA/CA protocol depicted in Figure 4.2, each vehicle selects a random backoff period from the contention window (CW) range of 0 to W-1. When a vehicle senses the channel idle during a slot time, its backoff counter is decremented by one. On the other hand, if the channel is sensed busy, due to either successful transmission or collision, the counter remains unchanged. When the backoff counter reaches zero for a vehicle, it will start to transmit

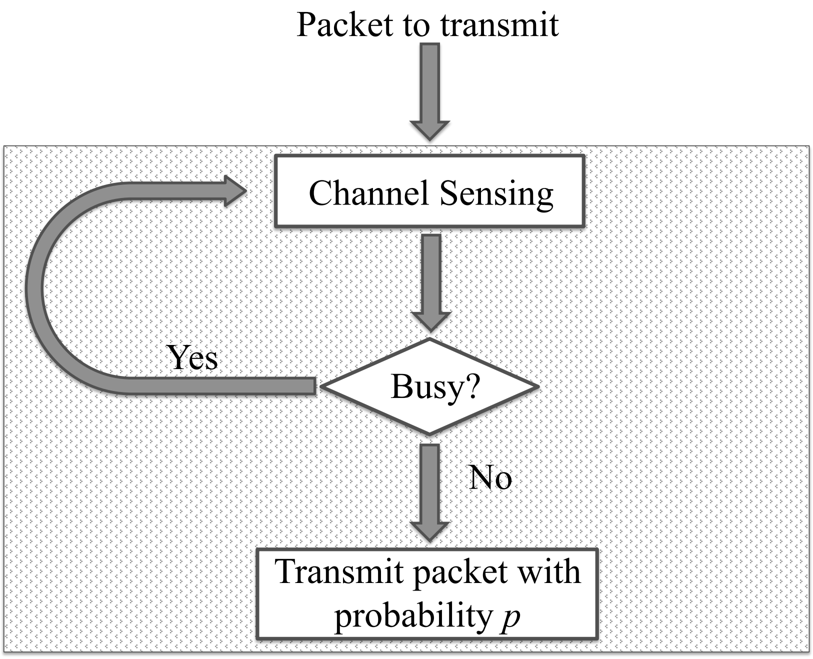

Figure 4.2: CSMA/CA p-persistent algorithm

its packet at the beginning of next slot time. Due to the random selection of the backoff period and assuming perfect channel sensing by all vehicles, each vehicle that has a CAM packet to transmit, has the probability of b_0 to transmit in an arbitrary idle slot time following the beginning of the CCH interval, as illustrated in Figure 1. When the channel is occupied by any transmission, either successful or collided, the busy channel does not change any backoff counter. Consequently, by focusing only on the idle slot time, the CSMA/CA for CAMs behaves in a way identical to that of slotted Aloha protocol, where a transmitter has a corresponding probability $p_t = b_0$ to transmit in an arbitrary time slot.

Let us evaluate the expression for the success probability in Aloha and CSMA/CA for broadcasting safety messages. We consider a fixed number of contending vehicles n, each one within each others transmission range.

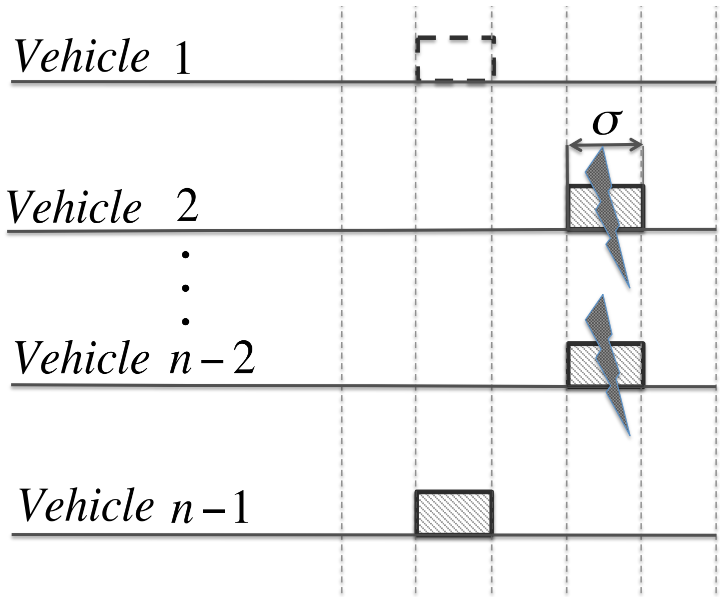

Figure 4.3: Aloha MAC protocol behaviour for successful reception

Hence, we assume that simultaneous transmissions of packets will always cause collisions, whilst a transmission over a slot time is successful if no collisions occur over the slot time, and every vehicle has a set transmission probability b_0 that random variable I_k described in Chapter 3 in (3.11) has a Bernoulli distribution with the following pdf

$$f_{I_k}(I_k) = b_0^{I_k}(1 - b_0)^{1-I_k}, \qquad \text{for } I_k \in \{0, 1\}. \tag{4.9}$$

Firstly, we focus on the Slotted Aloha. This protocol requires the time to be divided into slot, σ, of a fixed length, that is the length of a single packet transmission. The packets size is, then, always the same and the transmission is only allowed at the beginning of a slot time. Therefore, if a vehicle has a packet to send, it has to delay the transmission until the beginning of the next slot. In contrast, for pure Aloha, a packet transmission can begin at any time. We define a transmission of a safety message, or CAM, to be successful if while a vehicle is sending its packet the other $n-1$

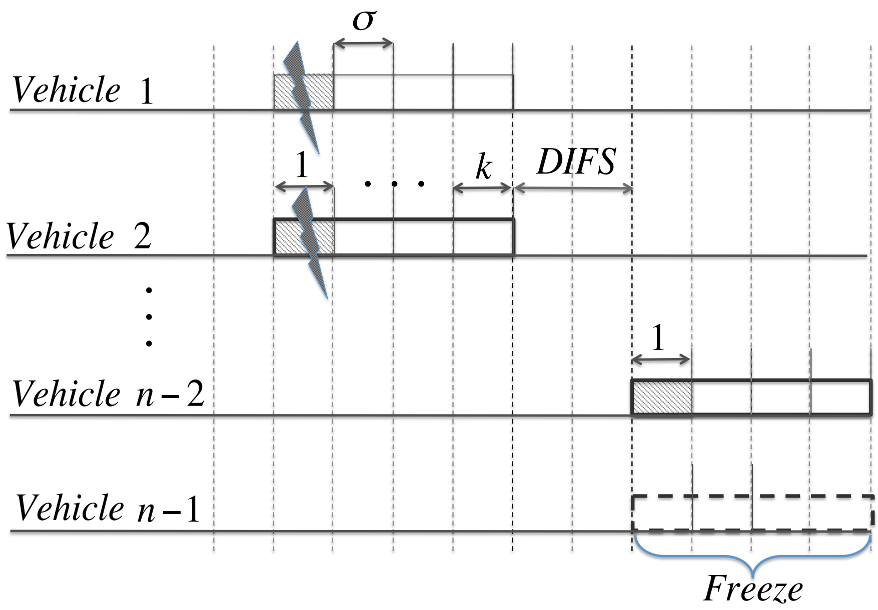

Figure 4.4: CSMA/CA MAC protocol behaviour for successful reception

neighbouring vehicles are not attempting to access the channel during the same slot time as shown in Figure 4.3. Or expressed mathematically:

$$P_{success\,Aloha} = b_0(1 - b_0)^{n-1}. \tag{4.10}$$

Secondly, we investigate the scenario of Slotted CSMA/CA when it is used in a broadcast fashion. The slot time size, σ , in this protocol is set to be equal to the time a vehicle needs to detect an ongoing transmission over the channel (e.g, channel busy). A single packet is not required to have always the same size, as shown in Figure 4.4. It also assumed that the backoff process is correctly performed, that is, the vehicles are able to detect the channel busy within the first slot time of the transmission as depicted in Figure 4.4. By including the aforementioned assumption, we can define that a vehicle can successfully send a packet if during the first slot time of the transmission the other $n-1$ surrounding vehicles are not attempting a transmission. Expressed mathematically:

$$P_{success\,CSMA} = b_0(1-b_0)^{n-1}. \tag{4.11}$$

Note that equations (4.10) and (4.11) have the same structure, meaning that under specific circumstances both Slotted Aloha and Slotted CSMA/CA for broadcast may indeed behave in the same way.

In the following, we shall derive the optimal value of b_0 based on the vehicular density λ. This means that the optimal transmission probability can be expressed as a function of the density as $b_0(\lambda)$, and by substituting it in (4.8) we obtain the optimal maximum CW, W-1, to maximise the CSMA/CA throughput based on the vehicular density

$$W = \left\lfloor \frac{2}{b_0(\lambda)} - 1 \right\rfloor. \tag{4.12}$$

Before continuing, we note that the transmission time T for a CAM is assumed to be constant, regardless of whether the transmission is successful (collision-free) or not, as given by

$$T = \frac{T_H + E_P}{r_d} + AIFS + \delta, \tag{4.13}$$

where T_H stands for the MAC header and E_P is the packet payload of the CAMs transmitted at a data rate r_d. The signal propagation delay is denoted by δ, while the arbitration inter-frame spacing (AIFS) is the initial waiting period following every transmission.

4.1.3 Inter-Vehicles Distance Distribution Model

Let us consider the traffic source and its assumptions. A single-lane road with one traveling direction and infinite length is considered, as shown in Figure 4.5. This one-dimensional case can be helpful in obtaining valuable insight into increasingly complex scenarios. Vehicles are assumed to be located on the road according to a Poisson point process (PPP) with rate λ, which has been considered to be a good model to describe the physical distribution of vehicles on a road [18, 19, 21].

A limitation of a simple PPP is, however, the unrealistic assumption of vehicles as dimensionless points. In fact, the received power P_r is a function of the distance between a transmitter and a receiver and, hence, the dimension of the vehicles in the network clearly plays an important role in accounting for the signal and interference value. Therefore, in this paper we present a model that accounts for the size of the vehicles. Let us assume the vehicles have the same size c, then by the assumption of PPP, the random distance $d_{ij} = d_{j+1,j} = |x_{j+1} - x_j|$ between receivers mounted on adjacent vehicles n_j and n_i where $i = j + 1$ has a shifted exponential distribution with a probability density function (pdf)

$$f_{d_{ij}}(d_{ij}) = \begin{cases} \lambda e^{-\lambda(d_{ij}-c)}, & x \geq c \\ \\ 0, & x < c \end{cases} \tag{4.14}$$

Note that the due to the Poisson arrival process, distances between every two adjacent (neighbouring) vehicles are independent and identically distributed (i.i.d.) random variables.

Using (4.14) and following the same process shown in Chapter 3, the distance between any two non-adjacent vehicles n_k and n_j can be modelled as the sum of shifted exponentially distributed random variables. Therefore, the distance between any two non-adjacent vehicles has pdf

$$f_{d_{kj}}(d_{kj}) = \frac{\lambda^k}{(k-1)!}(d_{kj} - kc)^{k-1} e^{-\lambda(d_{kj} - kc)} \quad d_{kj} \geq kc, \tag{4.15}$$

The expression in (4.15) is known as shifted Erlang distribution and has parameter λ, the vehicular density, the size of the vehicle c and k. In the scenario under consideration in this thesis, the value k represents the number of vehicles within distance d_{kj} while $k-1$, that appears in (4.15), represents the number of vehicles located between the two non-adjacent vehicles n_k and n_j.

Let us now assume that a reference vehicle n_j has range $r/2$ (for instance communication range, sensing range or cluster range). This means n_j can sense other vehicles within $r/2$ metres in front and behind it. Hence, the reference vehicle n_j covers a total distance, or range, r. Let $N(r)$ be the random number of vehicles located within r. From (4.15), we have the pdf

$$f_r(r) = \frac{\lambda^{N(r)}}{(N(r)-1)!}(r - N(r)c)^{k-1} e^{-\lambda(r - N(r)c)} \quad r \geq N(r)c, \tag{4.16}$$

By integrating (4.16), the mean value of the range r is obtained as

$$r = \frac{N(r)}{\lambda} + N(r)c. \tag{4.17}$$

From (4.17) the mean number of vehicles $N(r)$ within distance r (i.e., at the back and front of the reference vehicle) can be finally obtained [66]

$$\bar{k} = N(r) = \frac{\lambda r}{1 + \lambda c}, \tag{4.18}$$

where $\bar{k}$ represents the number of neighbouring vehicles that can be estimated by the reference vehicle through sensing. The value of λ, which will be needed in determining the optimal probability $b_0(\lambda)$ and CW parameter in the following section, can hence be evaluated using (4.18) based on the estimation of the average number of neighbouring vehicles.

4.1.4 Throughput Model

VANETs can enable data packets exchange from one vehicle to another in a multi-hop fashion. However, in this work we focus on communication between two adjacent (neighbouring) vehicles traveling in the same direction, as this scenario is most relevant in the context of safety applications. Hence, we focus on whether the vehicle immediately behind the transmitting vehicle can receive a packet.

Let us introduce the notion of communication range R_c. This is defined as the distance from a given reference vehicle within which a signal from a transmitting vehicle can be received at a power level greater than a specified threshold (commonly referred to as the receiver sensitivity) as illustrated in Figure 4.5. In this work, the communication range R_c is set to be identical for all nodes within the network, as was done in [19, 21, 75, 76].

The scenario illustrated in Figure 4.5 is the same of Chapter 3 and shows that for every pair of adjacent vehicles n_i and n_j in the network, we can identify two separate road segments, namely S_L and S_R. They represent regions where it is possible to find other vehicles that can interfere with the transmission between n_i and n_j.

By following the connectivity requirements extensively described in (3.13) and (3.14) of Chapter 3 and given that the distance between two adjacent vehicles is described by a shifted exponential distribution as seen in (4.14), the probability of event E, that 2 vehicles are within each other's communication range R_c, becomes

$$P[E] = 1 - e^{-\lambda(R_c - c)}. \tag{4.19}$$

From (3.9), the SIR requirement in (3.14) and its definition in (3.12) yields

$$\frac{P_t}{d_i j^{\alpha}} \geq \beta \sum_{k=1}^{M} \frac{I_k P_t}{d_{kj}^{\alpha}}, \tag{4.20}$$

The expression in (4.20) does not allow a closed-form expression to be obtained for the performance metrics of interest. Nevertheless, in Chapter 3 [21] it has been shown, by means of extensive simulation, that (4.20) can be effectively approximated by a set of M pairwise conditions for each kth vehicle, when analysing a vehicular scenario. By applying the same approximations presented and validated Chapter 3 [21], (4.20) becomes

$$d_{kj} \geq I_k R_f \quad \forall k, \tag{4.21}$$

where R_f represents the interference range within which vehicles may still interfere with the communication between n_i and n_j; it is expressed as $R_f = \beta^{1/\alpha} R_c$.

The condition expressed in the above inequality means that the distance d_{kj} between the interfering node n_k and the reference node n_j exceeds the distance between nodes n_i and n_j (that at most can be as large as the communication range R_c) by a factor of $\beta^{1/\alpha}$. The requirement in (4.21) can guarantee the successful reception of a packet in terms of SIR, when it is satisfied for all possible interfering k nodes located in the network, or

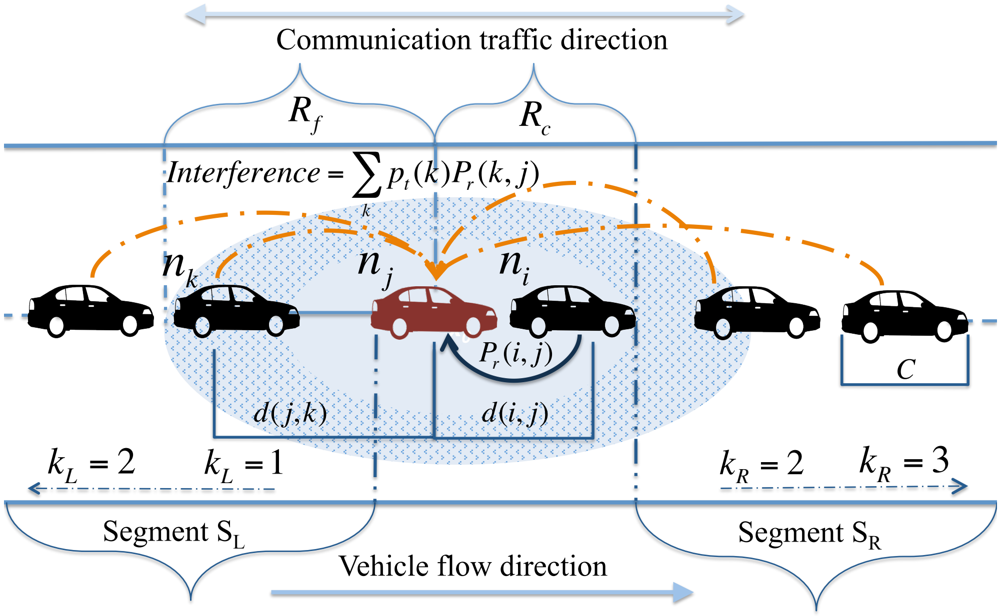

Figure 4.5: Road configuration and assumptions for the analytical model

equivalently in segments S_L and S_R.

We consider now the event F_k that a single interfering node n_k satisfies the condition in (4.21). F_k can only occur if either the node n_k is not transmitting (i.e., $I_k = 0$) or if it is true that $d_{kj} \geq \beta^{1/\alpha} R_c$. Consequently, we obtain

$$P[F_k] = P\{(I_k = 1 \wedge d_{kj} \geq R_f) \vee I_k = 0\} . \tag{4.22}$$

Therefore, the interference condition in (4.21) is fulfilled for node n_k when the latter is located outside the interference range R_f from the receiving node n_j. To evaluate the probability in (4.22), we require information regarding the vehicle density in the vicinity, which can be estimated from the average number of neighbouring vehicles from (4.18).

Next, let us define the event A that node n_k is located outside the interfering range R_f of node n_j. As given in (4.14), the distribution of the distances between adjacent nodes is shifted exponential. The distance between two non-adjacent nodes is consequently described by a shifted Erlang distribution (4.15), where $k-1$ represents the number of nodes between the non-adjacent nodes. Combining this fact with the indexing scheme k for interfering nodes as shown in Figure 4.5, the probability of event A occurring is

$$P[A] = \sum_{n=0}^{k-1} \frac{(\lambda(R_f - kc))^n}{n!} e^{-\lambda(R_f - kc)} \quad \forall k. \tag{4.23}$$

As a result of the access protocol assumption in (4.9), the probability that node n_k does not transmit is the same as presented in Chapter 3 in (3.22). Inserting (4.23) and (3.22) into (4.22), the probability of event F_k occurring becomes

$$P[F_k] = 1 - b_0[1 - (\sum_{n=0}^{k-1} \frac{(\lambda(R_f - kc))^n}{n!} e^{-\lambda(R_f - kc)})]. \tag{4.24}$$

The expression in (4.24) represent the probability of satisfying the interferer SIR condition (4.21) for a single node n_k. The scenario illustrated in Figure 4.5 shows that for every pair of adjacent vehicles n_i and n_j in the network, we can identify two separate road segments in front and behind the receiving vehicle n_j, namely S_L and S_R. They represent regions where it is possible to find other vehicles that can interfere with the transmission between n_i and n_j.

Let us define the event L that the requirement in (4.21) is verified for all possible interfering vehicles n_k in the road segment S_L, while R is the event that (4.21) is verified in region S_R. By using (4.24), the probability of L is expressed as follows

$$P[L_s] = \prod_{k=1}^{S} P[F_k], \tag{4.25}$$

because nodes either transmit or do not independently. Note that the same probability for the road segment S_R is computed in a similar manner.

Let us now find the probability of the event G_{ij},already defined in (3.26) Chapter 3, that the interference condition in (4.21) is satisfied for all possible interfering nodes n_k located on both road segments S_R and S_R, for the transmission from node n_i to n_j. The probability that event G_{ij} occurs, by using (3.26), (4.25) and by following the same process presented in (3.27) thus becomes

$$P[G_{ij}]=\frac{\prod_{k=1}^{\infty}\left[(1-p_t)+\left(p_t\sum_{n=0}^{k-1}\frac{1}{n!}(\lambda(R_f-kc))^n e^{\lambda(R_f-kc)}\right)\right]^2}{(1-p_t)+p_t e^{\lambda(R_f-c)}}. \tag{4.26}$$

Optimal Throughput

We define the data throughput T_h, from the transmitting node n_i to its adjacent node n_j, as successful reception subject to satisfying the conditions expressed in (3.13) and (4.21), as was done in Chapter 3 [21]. Note that due to the half-duplex mechanism assumption, this definition additionally includes the fact that node n_i is transmitting while its adjacent node n_j is not (i.e. it is receiving). The combination of all these factors yields to the expression presented in (3.29) in Chapter 3. Substituting (4.19), (3.22) and (4.26) into (3.29), and expressing the interference range R_f in terms of communication range R_c as $R_f = \gamma^{1/\alpha} R_c$, the single-hop throughput from node n_i to its neighbouring node n_j becomes

$$T_h = \prod_{k=1}^{M} \left[1 - b_0 \left(1 - \sum_{n=0}^{k-1} \frac{(\lambda(\beta^{1/\alpha} R_c - kz))^n}{n!} e^{\lambda(\beta^{1/\alpha} R_c - kz)} \right) \right]^2 \cdot \frac{(b_0 - b_0^2)(1 - e^{-\lambda(R_c - z)})}{(1 - b_0) + b_0 e^{\lambda(\beta^{1/\alpha} R_c - z)}}. \tag{4.27}$$

Note that in this equation the transmission probability, b_0 is the only control variable, whilst all other variables are constants for a given network. As described in Algorithm 1, it is possible to evaluate the value of λ from the estimated number of neighbouring vehicles $\bar{k}$. The optimal b_0 can then be determined from (4.27) as a function of λ, that is $b_0(\lambda)$, and by using (4.12) the optimal maximum CW size, W-1, can be evaluated based on the vehicular density.

Algorithm 1 Optimised CSMA

1: **for each** vehicle **do**
2: periodically monitor the radio channel in order to estimate the number of surrounding vehicles $\bar{k}$
3: calculate λ from the estimated number of neighbouring vehicles $\bar{k}$ in the interfering range R_f by using (4.18)
4: pick the optimal CW size (obtained from (4.27) and (4.12)) for the current value of λ
5: execute CSMA/CA procedure with optimised CW
6: **end for**

Algorithm 1 shows the steps of the proposed (optimised) CSMA/CA protocol for broadcast. In the following section, we will present the results of the protocol proposed in this paper, in comparison with the standard IEEE 802.11p MAC protocol.

4.2 Numerical Results

Simulations are used to validate the proposed CSMA/CA protocol which is adaptive to vehicle density, and to compare performance with the standard one. In this section, a one-lane, single-direction road that is 5 km in length is simulated. Furthermore, it is assumed that vehicles are able to estimate the number of neighbouring vehicles in the range R_f. The values of simulation parameters are the same as in Chapter 3. The transmission range is assumed to be $R_t = 100$ m, $\beta = 4$ and the path loss exponent $\alpha = 4$. The values for the broadcast CSMA/CA can be found in Table 4.1.

Table 4.1: Simulation Parameters

Mac Layer Parameters	Values
aSlotTime σ	$13\mu s$
AIFS	$58\mu s$
Propagation delay δ	$1\mu s$
MAC header T_H	50Bytes
Packet payload E_P	500Bytes
Data rate r_d	6Mbit/s

Using (4.27), Figure 4.6 shows how the channel throughput changes as the transmission probability p_t varies for a set of vehicle arrival rates, which influences the corresponding vehicle density in the network. As shown in the figure, for a given vehicle density (as reflected by the average number of vehicles located within R_f), there exists the optimal transmission that maximises the channel throughput.

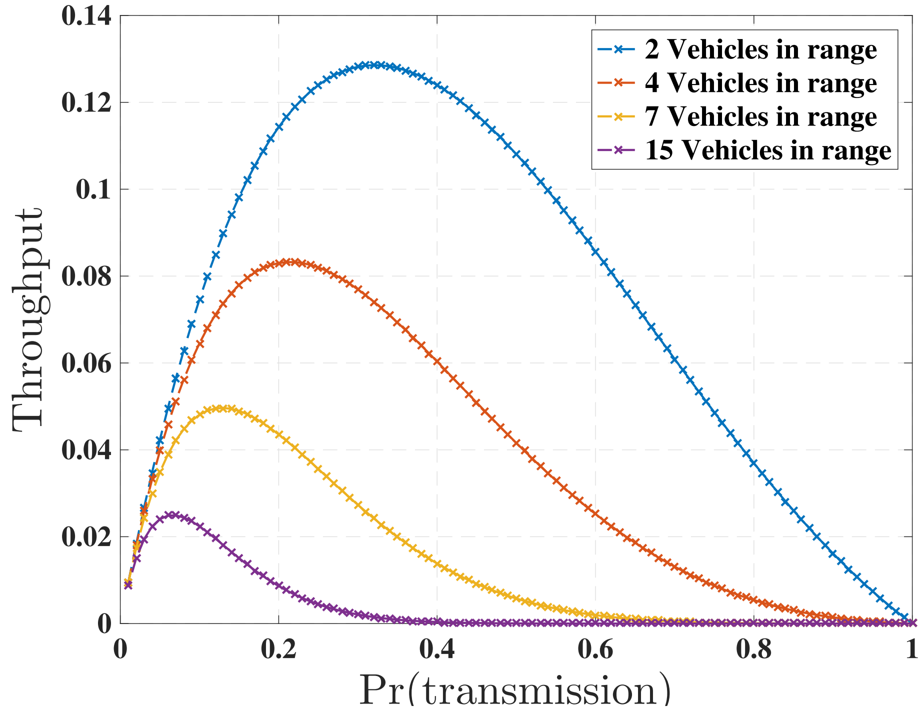

Figure 4.6: Throughput as a function of the probability of transmission p_t

Substituting the optimal transmission probability b_0 in (4.12), the optimal maximum CW, W-1, to maximise the single-hop throughput can be evaluated.

The optimal maximum CW is displayed in Figure 4.7 as a function of the average number of estimated neighbouring vehicles within the interference range R_f of an arbitrary vehicle. The linear behaviour of the plot in Figure 4.7 can be explained by noticing that the values of b_0 at the denominator in (4.12) are always smaller than 1. In particular, from Figure 4.6 it can be observed that b_0 tends to become very small with increasing vehicular density. This means that the hyperbole described by the expression in (4.12) has a trend that is almost linear within the small range of b_0 values. Furthermore, it can be observed that W-1 increases with the vehicle density

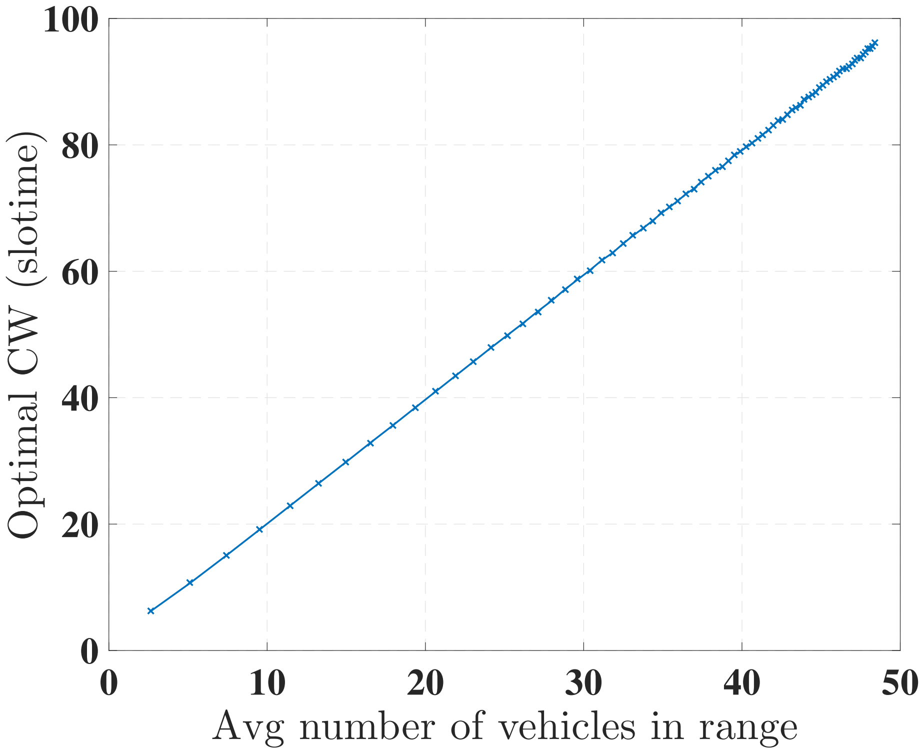

Figure 4.7: Optimal maximum CW, W-1, to maximise the single-hop throughput as a function of the average number of estimated neighbouring vehicles within the interference range R_f of an arbitrary vehicle

because a higher density increases the likelihood of transmission collision. Consequently, in these situations, it is advisable to choose a bigger CW to reduce collision, as suggested in Figure 4.7. As intuitively expected, these results also confirm that a fixed maximum CW without considering the vehicle density, as specified in the ETSI protocol standard, cannot yield the best achievable throughput.

The average transmission delay as a function of the average number of neighbouring vehicles within the interference range R_f is depicted in Figure 4.8. The delay is defined from the time a vehicle generates a CAM packet at the beginning of the CCI of 100 ms until the packet is transmit-

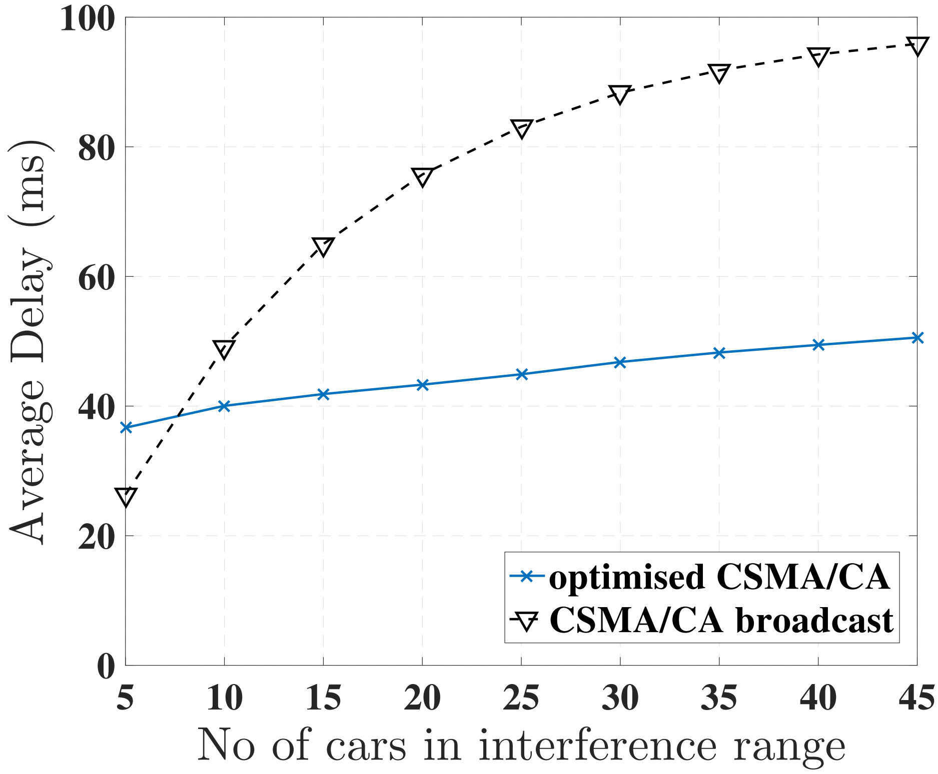

Figure 4.8: Average transmission delay per CCI as a function of the number of neighbouring vehicles within the interference range R_f

ted. Each vehicle is assumed to have a buffer for one packet. Due to the safety application under consideration, each CAM packet is expected to be transmitted with a delay less than 100 ms; that is, before the end of the corresponding CCI. So, if a second packet has been generated at the beginning of the next CCI before the first packet is transmitted, the second packet is assumed to overwrite the first one still in the buffer (e.g., to replace the obsolete information). In this case, the delay for the first packet that has missed the latency requirement is assumed to be 100 ms in the simulation. Figure 4.8 depicts the average packet delay in a CCI for the standardised CSMA/CA broadcast protocol and our proposed protocol with the optimised CW as a function of vehicle density. As shown in the figure, the new

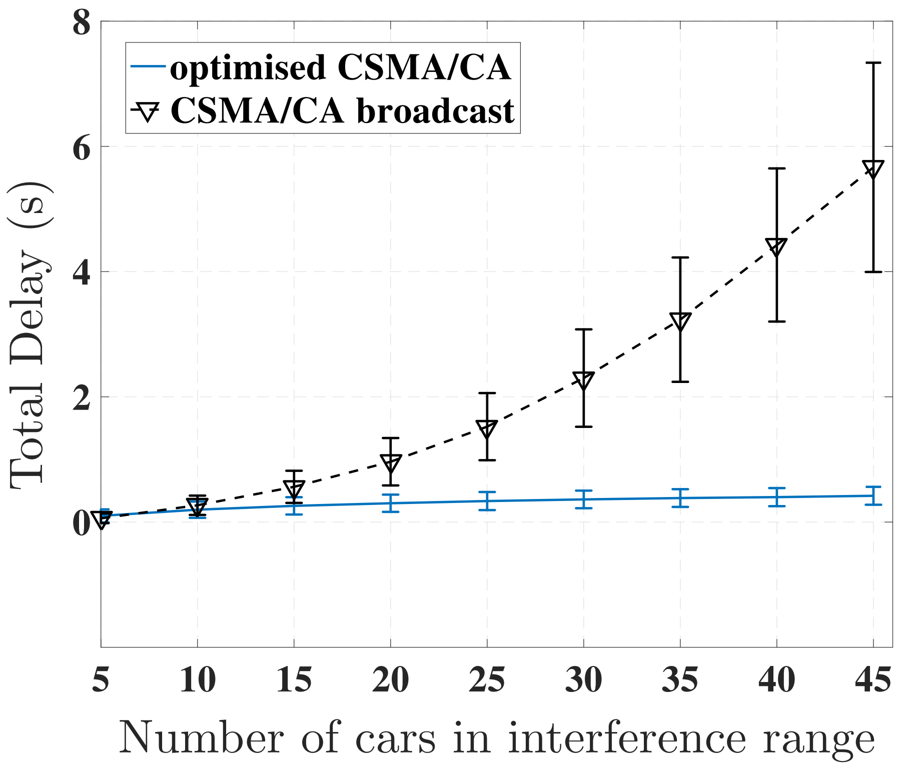

Figure 4.9: Average total delay for a vehicle to collect all CAM messages from its neighbours as a function of the number of neighbouring vehicles within the interference range R_f.

protocol offers much lower delay than the standardised protocol because the CW is optimally selected according to vehicle density by the new protocol to avoid transmission collision.

Figure 4.9 depicts the average total delay for the proposed (optimised) and standard protocol as a function of the average vehicular density. The vertical bars in the figure represent one standard deviation around the average delay. The total delay metric is defined as the average amount of time that a vehicle waits before CAMs from all its neighbours are received. As shown in the figure, the proposed protocol offers much lower delay than the standard protocol because the CW is optimally selected according to

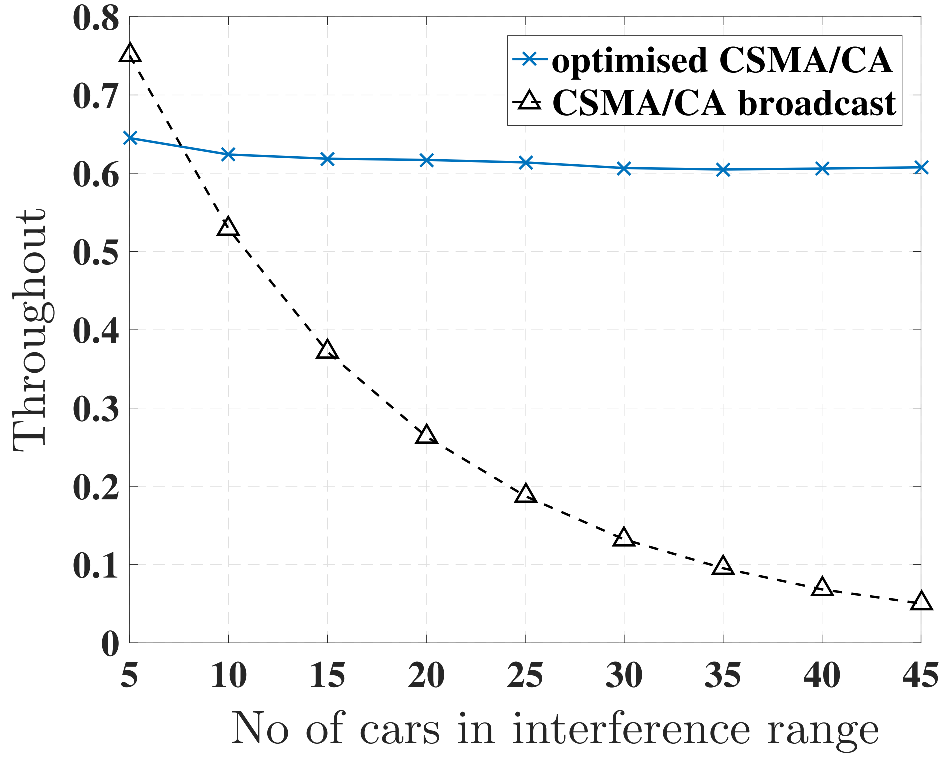

Figure 4.10: Throughput for the standardised as a function of the number of neighbouring vehicles within the interference range R_f

vehicle density by the new protocol to avoid transmission collision. In fact, each time a collision occurs, the packets involved are not received and new transmissions can be possible in the next CCI. This increases the total delay to receive all CAMs packet from the neighbours. Vehicle clustering mechanisms for internetworking and road-safety applications strongly rely on the timely reception of accurate status information from neighbouring vehicles. Hence, by offering low latency, the optimised protocol can support such real-time applications.

Finally, the throughput for the standardised and the new protocol is compared in Figure 4.10. By adapting the CW as a function of vehicle density, the proposed protocol is clearly able to maintain throughput performance despite increasing density. By contrast, since the standardised CSMA/CA protocol has a fixed maximum CW, a greater number of collisions occur when as the number of vehicles on the road increases.

4.3 Concluding Remarks

As a step toward the design of efficient MAC protocol tailored for VANETs, we have established the relation between the maximum CW size and the transmission probability. By exploiting the equivalence between the slotted Aloha and the broadcast CSMA/CA protocols, we have enhanced the stochastic model developed in Chapter 3 [21] for the Aloha protocol to derive the optimal transmission probability and the optimal maximum contention-window size based on the vehicle density, in order to reduce co-channel interference and maximise the single-hop throughput among adjacent vehicles. Furthermore, the optimal maximum contention-window size is integrated into the amended CSMA/CA protocol. Results from extensive experimental simulations have revealed significant performance improvement in terms of channel delay and throughput when compared with the standardised protocol over a wide range of vehicle densities.

Chapter 5

Stable Clustering Technique for Efficient Vehicular Internetworking

5.1 Introduction

Cooperation between vehicles and UAVs or cellular base stations, as depicted in Figure 5.1, can be extremely beneficial. For instance, road safety can be drastically improved.

Networking between vehicles and UAVs or cellular base stations can keep the network connected in the event of disruptions due to obstacles, poor weather conditions or natural disasters that destroyed existing communication infrastructure.

Unfortunately, concerns on the robustness and adaptiveness of such networks to support system applications arise in light of the the high mobility that characterises the nodes in a vehicular ad-hoc network. A main challenge is handling the rapid changes in the network topology and vehicular

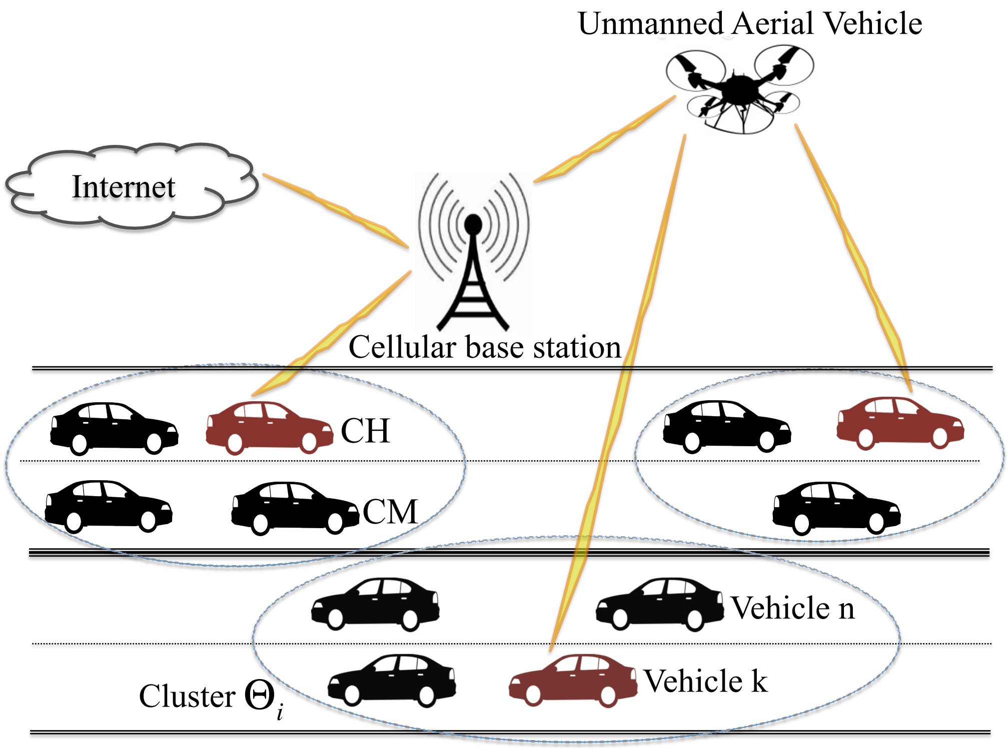

Figure 5.1: Clustering scenario: vehicle cluster (circle dashed line) with cluster head (faded red), grouping all cluster members (black) within range. For networking with UAVs or cellular base station only CHs are allowed direct communication.

density, which significantly affects the performance of the network [16, 21]. Furthermore direct communication between every vehicle and UAV or base station, can generate serious resource issues related to bandwidth, processing, and power consumption. Clustering techniques, which aim to partition the ground network vehicles into virtual groups known as clusters (Figure 5.1), can provide an effective solution for the aforementioned problems. The communication amongst the cluster members within the cluster is managed by cluster head can additionally interact with other layers of a cooperative network (e.g. unmanned aerial vehicles, road side units or cellular base stations) as in Figure 5.1. By providing fair channel access to vehicles within the cluster, clustering algorithms can reduce the channel contention.

Furthermore, by limiting the number of vehicles that can able to interact with UAVs or cellular base stations, clustering techniques can support the spatial reuse of resources such as the bandwidth.

Despite the potential advantages, a challenging issue to overcome, is to provide cluster stability in highly mobile vehicular networks. In this chapter we propose a Stable Clustering Algorithm for vehicular ad hoc networks (SCalE), in order to address the aforementioned issues and facilitate the networking between clustered VANETs and UAVs or cellular base stations.

To this end we introduce new features in the clustering process. The knowledge of the vehicle's behaviour is exploited for the selection of a stable cluster head, whilst the election of a backup cluster head (CH_{Bkp}) can help prolong the cluster life and consequently maintain the network structure.

5.2 Cluster Head Election

Algorithm 2 summarises the CH election process and cluster formation. Through periodical exchange of CAM messages every k vehicle can acquire information to calculate the CH selection index ξ_k. The vehicle with the lowest ξ will then be selected to be the CH, whilst all its free neighbours will become CMs.

5.2.1 CAM packet structure

The structure of the CAM used is depicted in Figure 5.2. It contains the following embedded information field of every vehicle k: vehicle state, vehicle ID γ_k, cluster ID (that is the cluster head ID), average speed v_k over time

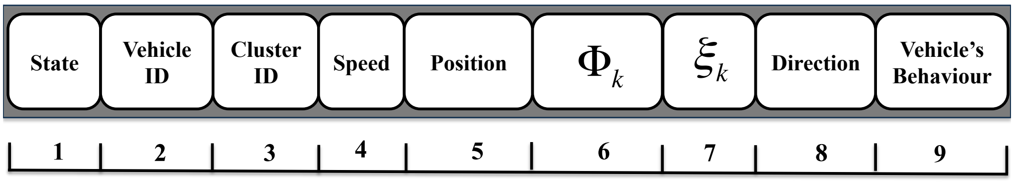

Figure 5.2: Cooperative awareness messages (CAMs) structure of the information embedded. For simplicity every entrance is numbered.

step T ($T = 1$s in this work and simulation), position (x_k, y_k) (expressed as GPS coordinates), Φ_k defined as the set of all cars within range of vehicle k, flow direction and vehicle behaviour B_k. For the sake of brevity, every data entry is henceforth denoted by a number as shown in Figure 5.2.

The vehicle state (field number 1 of the packet structure), can assume two different values: cluster head (CH) and cluster member (CM). Note that the vehicle's behaviour B_k, field number 9 in Figure 5.2, represents a piece of information newly introduced in this work. This is a single bit of information (0/1) which indicates whether the vehicle will leave the system (i.e. road way) at the next side exit. Obtaining such information is fairly straightforward since the vehicle itself can easily record this information either when it decides to take a turn or by combining input from the steering wheel and GPS tracking.

5.2.2 Cluster Head Selection Index

The CH selection index, ξ, is a parameter periodically calculated by every vehicle for the purposes of CH election. It is defined as a combination of different metrics, which are categorised as follows. The value of B_k, vehicle's behaviour in field number 9 in Figure 5.2, is set to 1 if the vehicle intends to leave the system and to 0 otherwise, as expressed in (5.1). The information

Algorithm 2 Cluster Head Election

Require: $\forall k$ in the system that do not belong to a cluster yet
for each kth vehicle **do**
  Evaluate ξ_k using (5.2), (5.6) and (5.8)
end for
for each kth vehicle **do**
  if k is in range of a CH_i **then**
    k$\leftarrow CM_i$
  else
    Start CH election process:
    Eliminate unstable vehicles with (5.1)
    if (5.10) **then**
      k$\leftarrow CH_i$
    end if
  end if
end for
go to CLUSTER MAINTENANCE

can improve the decision making process with regards to the election of a stable CH and backup CH ($\mathrm{CH_{Bkp}}$). A vehicle willing to leave the system at the side exit cannot act as a stable CH, therefore the vehicle in question will be excluded from the election procedure. It represents the first step in the CH election, as it is used to filter out unstable candidates for the role.

$$B_k \doteq \begin{cases} 1, & \textit{if } k \textbf{ is } \textit{leaving the road way} \\ \\ 0, & \textit{if } k \textbf{ is not } \textit{leaving the road way.} \end{cases} \tag{5.1}$$

The stability of the clusters can degrade rapidly in a highly mobile environment. Hence, the relative speed, that is the difference $|v_k - v_n|$ of the speeds of vehicles in range, is an important metric widely used in clustering algorithms [66,70,72,82]. In particular by evaluating the mean of the relative speeds for a vehicle k with all its N neighbours (i.e. those belonging to the set Φ_k), the mean relative speed S_k is obtained, as in [66, 72]. This represents a good measure of the stability of a vehicle in a VANET because the lower the value of S_k, the less mobile vehicle k is when compared to its neighbouring vehicles. The mean relative speed is thus expressed as

$$S_k \doteq \frac{\sum_{n=1}^{N} |v_k - v_n|}{N \cdot max\left\{\Omega_k\right\}}, \tag{5.2}$$

where the normalising factor is the maximum value of the set Ω_k. This is defined as the set of all the vehicles speed differences $|v_k - v_n|$ within the set Φ_k, provided the vehicles are moving ($v > 0$), and is formally expressed as

$$\Omega_k \doteq \left\{|v_k - v_n| \;\; | \; \forall n \in \Phi_k\right\}. \tag{5.3}$$

Another metric that can be used to identify a stable CH is related to the vehicle position relative to its neighbours. A smaller normalised relative mean distance D_k indicates that the neighbouring vehicles are closer to the potential CH. Given the GPS coordinates of two vehicles k and n, we can write the x and y distance between the two at an arbitrary time as

$$\Delta x_{k,n} = |x_k - x_n|, \tag{5.4}$$

$$\Delta y_{k,n} = |y_k - y_n|. \tag{5.5}$$

Consequently, the mean relative distance D_k of vehicle k is defined as the mean Euclidean distance. Furthermore, normalising by the maximum value of the set Z_k, as shown in (5.6), makes S_k and D_k comparable:

$$D_k \doteq \frac{\sum_{n=1}^{N} \sqrt{\left[\Delta x_{k,n}\right]^2 + \left[\Delta y_{k,n}\right]^2}}{N \cdot max\left\{Z_k\right\}}. \tag{5.6}$$

Z_k is the set of the all the Euclidean distances between vehicle k and all its N neighbouring vehicles, that is all the vehicles belonging to the set Φ_k.

Therefore,

$$Z_k \doteq \left\{ \sqrt{[\Delta x_{k,n}]^2 + [\Delta y_{k,n}]^2} \;\middle|\; \forall n \in \Phi_k \right\}. \tag{5.7}$$

Finally the CH selection index is evaluated as the sum of the normalised values of the mean relative speed and distances,

$$\xi_k \doteq S_k + D_k, \tag{5.8}$$

and as such will always fall in the range $[0, 2]$.

Upon periodical exchange of CAMs amongst all the vehicles in the system, the kth vehicle can record a list of all CH selection indexes ξ belonging to every nth vehicle in its neighbour's set Φ_k. The set of all ξ for every neighbour's set Φ_k is therefore defined as:

$$\Psi_k = \{\xi_n \mid \forall n \in \Phi_k\}. \tag{5.9}$$

Denoting γ_k as the ID of the vehicle k, the vehicle will be elected CH if its CH selection index ξ_k is found to be smaller than ξ_n, the selection index of any other vehicle n in range, that belongs to the set Φ_k:

$$CH = \{\gamma_k \mid \xi(\gamma_k) \leq min\{\Psi_k\}\} \tag{5.10}$$

5.3 Cluster Maintenance

5.3.1 Backup CH selection

After cluster formation, a maintenance phase comes into effect that aims to maintain cluster structure (Algorithm 3). To this end, another novel contribution of this work is introduced: the backup CH (CH_{Bkp}). This is defined as the most suitable CM to become CH (without re-starting the CH election) if the current head is forced to resign from its role. The choice of a stable $\mathrm{CH_{Bkp}}$ is based on CH selection index ξ, and on the coverage that a vehicle has over its existing cluster. In choosing a stable $\mathrm{CH_{Bkp}}$, it is important that the vehicle selected will have the smallest repercussions in terms of losing CMs, and resulting reaffiliations. Consequently an additional metric, called cardinality (5.11), is introduced to take the vehicle coverage into account. Let us define the ith cluster Θ_i as the set of all vehicles that belong to the same cluster and share the same CH. The CH keeps record of CMs in Θ_i and of the neighbours set Φ_k for every CM in Θ_i, as shown in Figure 5.2. We can now define the cardinality degree index as

$$C_k \doteq |\Theta_i \cap \Phi_k| \qquad \forall\, k \in \Theta_i\,, \tag{5.11}$$

where $\Theta_i \cap \Phi_k$ denotes the set of neighbours of vehicle k that are also part of the cluster Θ_i. Hence, C_k represents a measure of the coverage that vehicle k has over the cluster Θ_i, where a higher value means better coverage.

Let's call α_m the ID of a vehicle within a cluster Θ_i, with m representing an additional ordering index. The set Γ_{Ac} contains all the cardinality values $C(\alpha_m)$ of the CMs in Θ_i as shown in (5.12).

$$\Gamma_{Ac}=\{C(\alpha_1), C(\alpha_2), ..., C(\alpha_N)\}\,. \tag{5.12}$$

The CH sorts the CM IDs in descending order with respect to their cardinality; as the ordering index m increases the cardinality related to the vehicle with ID α_m decreases. The ordered set of CM IDs, A_C, is formally

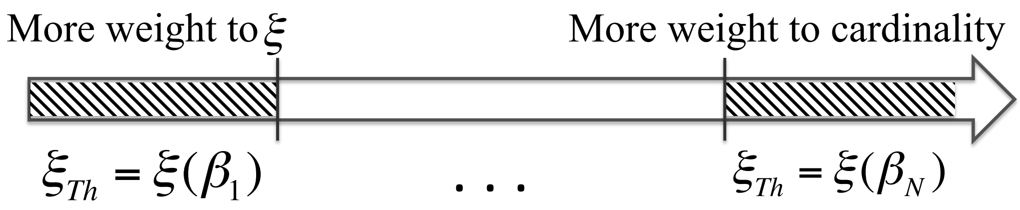

Figure 5.3: How to choose ξ_{Th}

expressed as:

$$A_C \doteq \{\alpha_1, \alpha_2, ..., \alpha_N \mid C(\alpha_m) \geq C(\alpha_n), \forall\, m < n\}\,. \tag{5.13}$$

To select most suitable backup, the CH needs to acquire and store some additional information. Firstly, the CH needs a list Ξ_{As} of all CH selection indexes $\xi(\beta_m)$ belonging to every vehicle, or CM, in its cluster Θ_i, where β_m denotes the personal ID of a CM within a cluster Θ_i. The set Ξ_{As} is therefore:

$$\Xi_{As} = \{\xi(\beta_1), \xi(\beta_2), ..., \xi(\beta_N)\} \tag{5.14}$$

The cluster member IDs are then sorted in ascending order with respect to their CH selection index ξ; as the ordering index m increases the ξ of the vehicle with ID β_m increases. The ordered set A_S of cluster member IDs is hence formalised as follows:

$$A_S \doteq \{\beta_1, \beta_2, ..., \beta_N \mid \xi(\beta_m) \geq \xi(\beta_n), \forall m > n\} \tag{5.15}$$

Finally, the new CH_{Bkp} will be the first CM in the cluster Θ_i with the highest cardinality degree (from set A_C) whose ID is recorded in α_m, to simultaneously fulfil the requirement of having its CH selection index $\xi(\alpha_m)$

smaller than a set threshold ξ_{Th}. That is,

$$CH_{\text{Bkp}} = \underset{k \in \Theta_i}{\arg\min} \{\alpha_m \mid \xi(\alpha_m) \leq \xi_{Th}\} \tag{5.16}$$

With reference to (5.14) and (5.15) the threshold ξ_{Th} can be established. In (5.16) the threshold is selected amongst values recorded in set Ξ_{A_S}, depending on the choice of cluster member ID β_m, as

$$\xi_{Th} \doteq \xi(\beta_m) \quad m = 1, ..., N. \tag{5.17}$$

From Figure 5.3 it is important to notice how the choice of the threshold can drastically influence the terms under which the CH_{Bkp} is selected. Picking the cluster member ID β_m with small ordering index m, will result in adding more weight to the CH selection index ξ during the selection, because the resulting threshold will be very small. On the other hand, by employing a higher threshold, that is choosing a β_m with a large ordering index m, the weight of the decision making process is shifted to the cardinality degree. In this work a higher threshold ξ_{Th} is chosen to minimise the repercussions in terms of losing CMs after changing from CH to CH_{Bkp}.

5.3.2 Cluster Maintenance

The rest of the maintenance phase is described in Algorithm 3, which is designed to minimise cluster changes for every possible event, namely for the following situations:

- The CH leaves the network, that is the vehicle will turn at the next intersection.
- The CH is within the communication range of at least another CH.

- A CM loses connection with the CH.
- A new vehicle joins the network.

Algorithm 3 Cluster Maintenance

for each CH_i **do**
    CH_i chooses the CH^i_{Bkp} using (5.16) and (5.17)
end for
if CH_i leaves system **then**
    $CH^i_{Bkp} \leftarrow CH_i$
end if
if CH_i is in range of another CH_j **then**
    if CH^i_{Bkp} is not in range of CH_j **then**
        $CH^i_{Bkp} \leftarrow CH_i$
    else
        merge cluster Θ_i and Θ_j
    end if
end if
if CM_i is not in range of CH_i **then**
    go to CLUSTER HEAD ELECTION
end if
if new vehicle k enters the system **then**
    go to CLUSTER HEAD ELECTION
end if

If a CH leaves the system, it will put its $\mathrm{CH_{Bkp}}$ in charge of the cluster. All the CMs in cluster Θ_i can therefore still hold onto the original cluster structure and avoid going through the clustering process again. In the case a $\mathrm{CH_i}$ can hear at least another $\mathrm{CH_j}$ but the backup cluster head of cluster Θ_i, $\mathrm{CH^i{}_{Bkp}}$, is not in range of the other $\mathrm{CH_j}$, then the $\mathrm{CH^i{}_{Bkp}}$ will become the new $\mathrm{CH_i}$, without the need of a new election. On the other hand, if both the $\mathrm{CH_i}$ and its $\mathrm{CH^i{}_{Bkp}}$ lie within $\mathrm{CH_j}$ transmission range, the two CHs will merge. The CH with more CMs in its cluster will maintain its role whilst the other (with the minimum number of CMs) will become its CM. Lastly, if a new node joins the network or loses connection with the reference CH, it will undergo the CH selection procedure already explained in Algorithm 2.

5.4 Performance Evaluation

Experimental simulations were conducted to assess the performance of our proposed clustering algorithm, SCalE. The performances of our proposed method are compared with the Highest-Degree and VMaSC methods. The former is commonly used for comparative purposes in the literature [70, 83, 84], it selects the vehicle with greater number of neighbours as CH. Therefore, this algorithm is characterised by a smaller number of CH and bigger cluster size. The VMaSC algorithm was proposed in 2016 in [72], it selects the vehicle with the lowest average relative speed in range as CH.

5.4.1 Mobility model

A Matlab implementation of the Gipps car following model and the Gipps lane-changing model [85–87] (also used in the AIMSUN simulator) is employed in this work. The behaviour of each vehicle, in terms of speed or lane changing decision, is determined using information such as vehicle dimensions, current traveling speed, distance to the leading vehicle, acceleration and deceleration.

A highway scenario of 8 lanes, 4 in each direction is implemented. The highway section is 6 km long and an additional side exit is placed at the 3 km mark for both directions, as seen in Figure 5.4. The side exit is accessible only to vehicles driving on or that move to (due to the lane changing model) the side lane. Vehicles are injected in the system, at either end of the highway in Figure 5.4, following a Poisson process with arrival rate λ =30 veh/min. A network of 560 cars is monitored for 350 s. The probability that a vehicle on the side lane leaves the network at the side exit is set to $p = 0.7$. Vehicles can assume different sizes from 2 m to 7 m

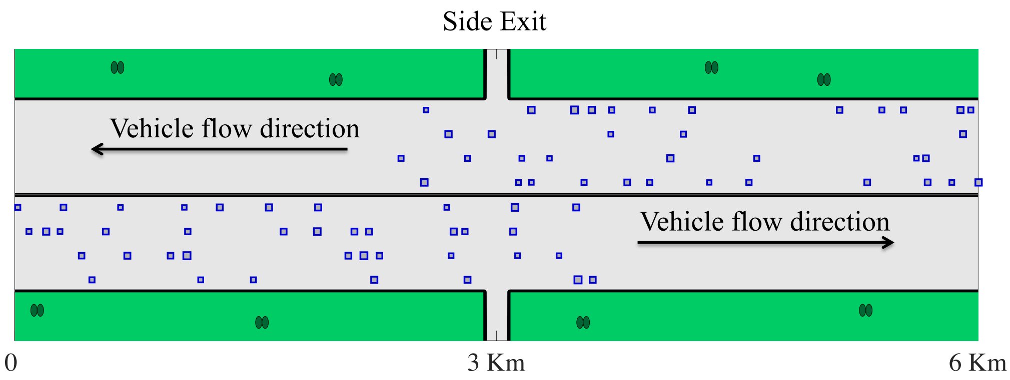

Figure 5.4: Simulations scenario. Highway of 4 lanes for each moving direction. Length of road section is 6Km and 2 side exits are placed at 3Km to allow vehicles driving on or moving to (using the Gipps lane changing model) the side lane to leave the highway. Arrival rate of λ =5car/min for illustrative purpose only.

and their speed can vary in the range of 22 - 33 m/s.

5.4.2 Clustering performance criteria

The performance of a clustering algorithm can be measured by several metrics. In this work the following are used:

- *Average CM Lifetime* represents the average time a vehicle spends as a member of the same cluster and it is an important measure of the cluster stability.
- *Number of Leaving CHs* counts how many CHs leave the system at the side exit during the simulation time. Cluster stability is directly influenced by this metric since every time a CH leaves the system its CMs have to undergo a new CH election process. It is normalised by the highest value to allow relative comparison.
- *Number of CH Re-elections* is the total number of new CH elections that take place during the simulation. It represents the cluster stabil-

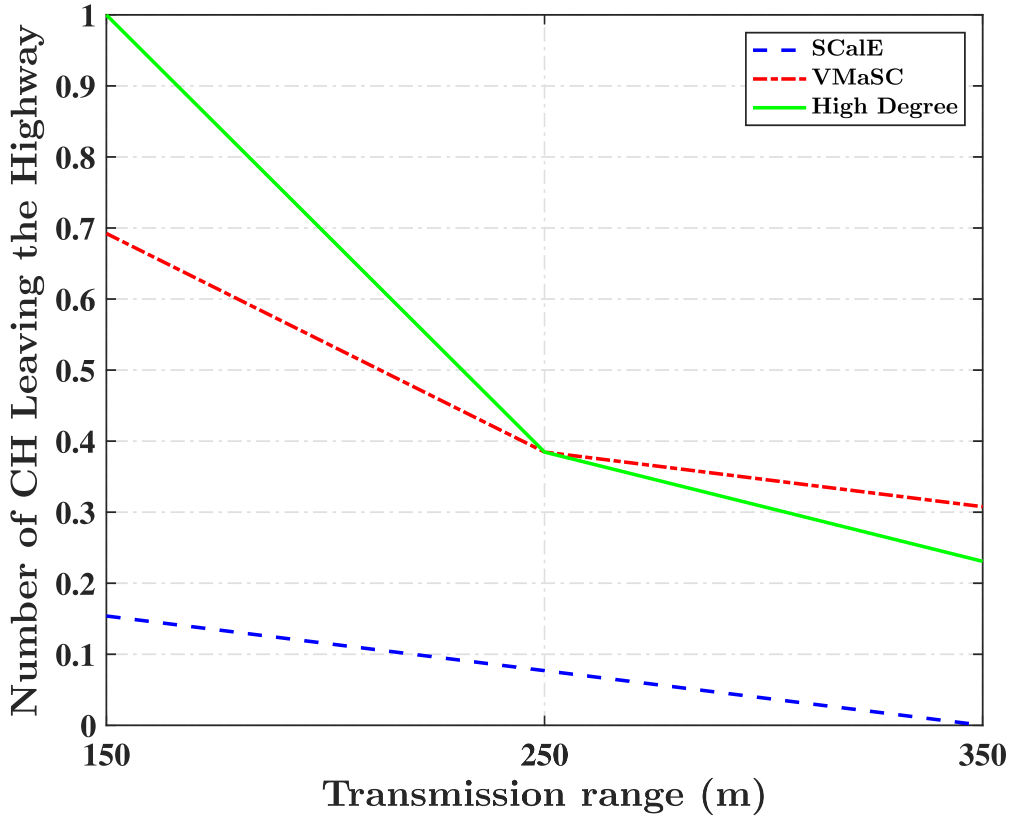

Figure 5.5: Normalised number of CHs leaving the highway at the side exit

ity and the additional delay suffered by vehicles due to re-elections. This metric is also normalised by the highest value.

- *Average Number of Reaffiliations* per vehicle is defined as the average number of times a vehicle starts or join a new cluster due to one of the following reasons: 1) a CH gets detached from its cluster, 2) a CM gets detached from its cluster, 3) a CH merges with a second CH. The value is an additional criteria used to establish the reliability of the cluster structure. This metric is then normalised by the highest value to allow relative comparison.

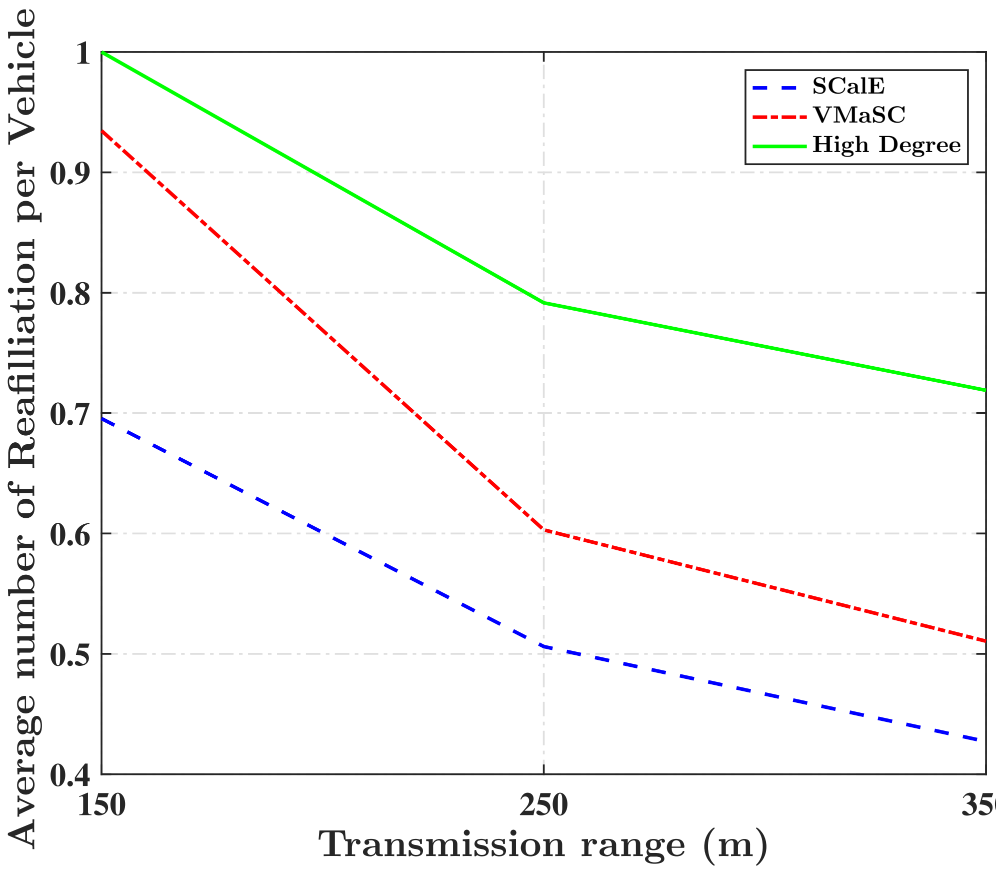

Figure 5.6: Normalised Average number of cluster reaffiliations per vehicle

5.4.3 Performance Analysis

The number of CHs leaving the system at the side exit decreases with the communication range as shown in Figure 5.5. The graph shows that SCalE has the best performance, due to the tailored selection of the CH using the vehicle's behaviour information B_k. Furthermore, the use of a stable $\mathrm{CH}_{\mathrm{Bkp}}$ with high coverage over the cluster can help reduce the number of vehicles losing contact with their CH, meaning the number of reaffiliations can be reduced as Figure 5.6 indicates. Consequently the number of CH re-elections is also diminished as observed in Figure 5.7, allowing SCalE to outperform the Highest-Degree and VMaSC algorithms. Finally, Figure 5.8 shows that

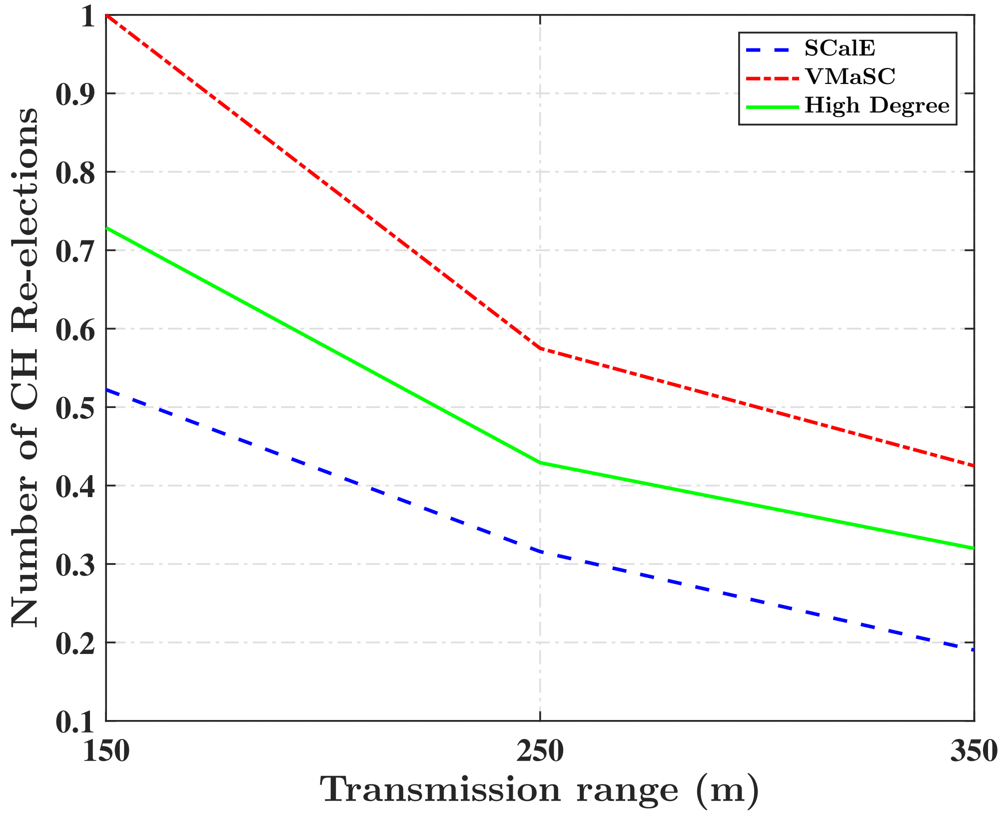

Figure 5.7: Normalised average number of CHs re-elections

the average lifetime of a CM decreases with the vehicle's transmission range. It can be noticed that the proposed algorithm has better performance. This is demonstrated by the fact that the SCalE algorithm can select a stable CH and CH_{Bkp} capable of maintaining the cluster structure for longer than other algorithms.

Lastly, a brief discussion on the overhead is due. An important issue in clustering is the reduction of overhead that is introduced in the CH election and cluster maintenance phase. Hence, efficient clustering is to maintain the stability of the clustered structure of the network to minimise the overhead. Packets overhead in clustering algorithms is defined in [72] as the percentage of the number packets directly related to the clustering

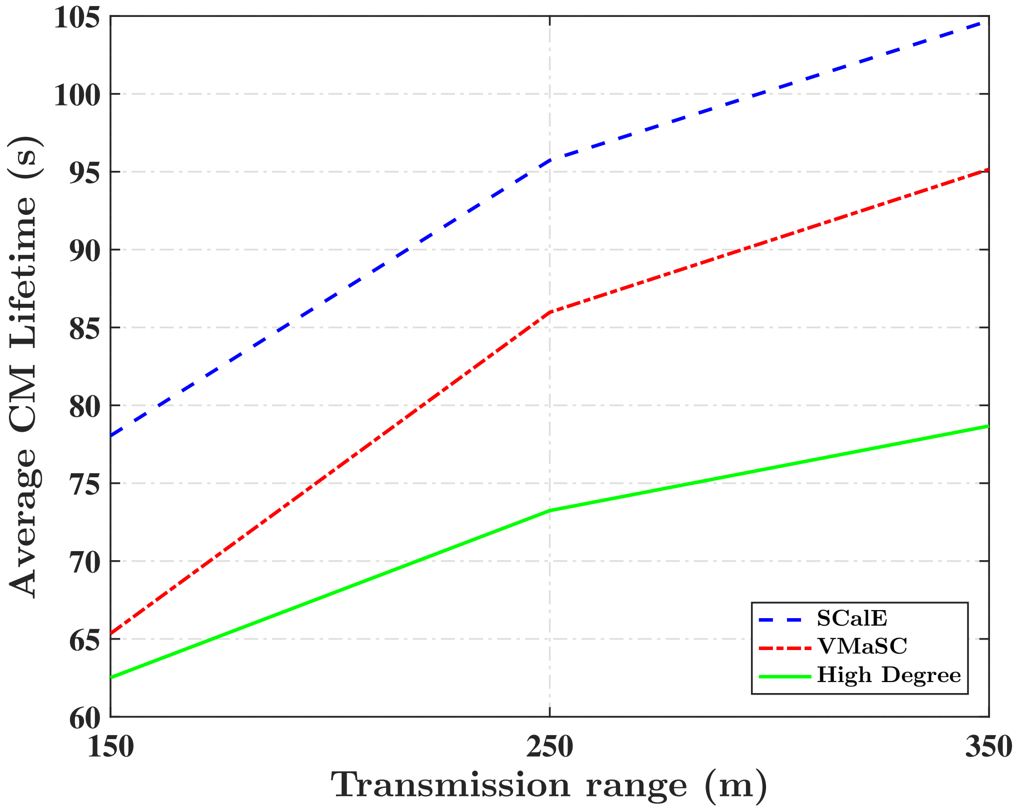

Figure 5.8: Average cluster member lifetime

process compared to the total number of packets exchanged in the network. In the clustering technique presented in this thesis, clustering information used for the cluster formation and maintenance is embedded in vehicles periodic status (CAM) messages [66]. Therefore, the overhead is greatly reduced. Another mean of lowering the overhead is the adoption, in our proposed algorithm SCalE, of a backup CH, that being directly selected by the CH to take over its responsibilities, makes the cluster more stable. This, in turn, increases the lifetime of the cluster members and reduce the overhead related to re-clustering process.

5.5 Concluding Remarks

In this chapter, we have proposed a Stable Clustering Algorithm for vehicular ad-hoc networks (SCalE), in order to improve the stability of the communication vehicles and facilitate efficient networking between vehicles and UAVs or cellular base stations. The clustering algorithm groups neighbouring vehicles into a cluster and selects two of them as the cluster head and backup cluster head, respectively. The stability of the cluster structures is achieved by the use of knowledge of the vehicle's behaviour in the cluster-head selection as well as the use of the backup cluster head to enable efficient maintenance of the cluster structure.

Simulation results presented in this chapter validate the SCalE algorithm under the challenging circumstances of working in a highly mobile environment. A performance comparison with Highest-Degree and VMaSC algorithms shows that SCalE is able to enhance the cluster stability in various performance metrics such as the average cluster member lifetime, the number of cluster heads leaving the system, the number of cluster head re-elections and the number of reaffiliations per vehicle.

Chapter 6

Conclusion and Future Work

The organisation of this chapter is as follows. Firstly, a condensed but comprehensive outline of the methodologies and results presented in this thesis is provided. As further extensions to this research work are still possible, this chapter additionally includes suggestions for future work in the field of vehicular communication technology.

6.1 Conclusion

In this thesis we have addressed the challenging issue of devising MAC protocols able to handle the highly mobile nature of vehicles in VANETs, specifically for time-critical applications (e.g., road safety) and to ultimately provide a reliable support for efficient vehicular internetworking.

Initially, we approached the problem of adapting MAC protocol transmission probabilities based on vehicular density, in order to diminish the negative effect of interference and eventually maximise the single-hop network throughput. To pursue the aforementioned goal, initial understanding of the issue is obtained through the study of a single lane scenario when the Aloha protocol is adopted in the network. Chapter 3 demonstrated that it is indeed possible to enhance Aloha protocol performance by following the changing traffic conditions in VANETs. In fact, a stochastic model to express the network throughput over a single-hop communication is derived.

Towards the development of such a model the throughput formulation is obtained under the assumption of a poisson point process representing the vehicular traffic arrival at the entrance of the network (e.g., road section) [17–21]. Furthermore, the capture effect is also accounted for by introducing the signal-to-interference ratio (SIR) constraint. This is because, despite the presence of interfering signals from other neighbouring vehicles, the reference signal can still be successfully received if its strength exceeds the interference by a certain threshold. By additionally approximating the SIR constraint as a set of pairwise conditions the derivation of a closed form expression for the single-hop throughput is achieved. Finally, this expression is exploited to calculate the optimal transmission probability to maximise the throughput based on vehicular density. The results generated by extensive simulation confirms the validity of the presented model, showing that is possible to overcome the shortcomings of the current Aloha protocol in dealing with the range of vehicular density conditions found within networks.

In fact, the rapid density fluctuation in a VANET can deeply influence the network connectivity supported by the Aloha protocol and cause a drastic degradation in communication performance. Dense vehicular networks, for instance, may not be able to support a stable communication for all vehicles due to network capacity limitations.

Despite results obtained from this novel approach, the current IEEE standard for vehicle-to-vehicle communication is based on carrier sensing mechanism using a CSMA/CA protocol. Chapter 4 is hence focused on incorporating the model described in Chapter 3, developed for Aloha, to design an amended CSMA/CA protocol that can select the optimal transmission probability needed to improve the network throughput with regards to the vehicular density. In particular, the case of optimising the broadcast CSMA/CA protocol is studied. The transmission of information in a broadcast fashion is, in fact, needed for time-critical applications such as providing reliable support for road safety or for efficient vehicle internetworking. The parallel between Aloha and broadcast CSMA/CA is introduced in Chapter 4 first, and later exploited to integrate the optimal transmission probability, estimated for Aloha, into the CSMA/CA broadcast protocol. In fact, it has been observed, by means of analysis and simulations, that CSMA/CA can tend to Aloha-like behaviour [22, 79, 80].

Upon establishing that the single-hop throughput model derived in Chapter 3 for Aloha can be used for broadcast CSMA/CA, the model is extended to include more realistic constraints, as outlined in Chapter 4. The assumption of dimensionless points in the poisson point process describing the vehicular arrival at the road entrance is relaxed to include the vehicles size. Moreover, we have introduced the notion and formulation of the estimated number of neighbouring vehicles in contrast to the more theoretical value of vehicular density previously assumed. Under the aforementioned extensions to the original model, the optimal transmission probability is evaluated. By establish the relation between the maximum CW size and the transmission probability it is possible to adapt optimal maximum contention-window size based on the vehicle density. Finally, also described in Chapter 4 is the integration of the optimised contention-window size into the broadcast CSMA/CA protocol. Simulations confirmed that the proposed MAC protocol improved performance, in terms of delay and throughput, in comparison to the current IEEE standard. In particular, the delay improvement means that the amended broadcast CSMA/CA is well suited to support time-critical applications where a rapid reception of status information from the neighbouring vehicles is vital, for example for road safety applications or efficient internetworking.

The significant contributions provided in Chapter 4 can hence play an important role in supporting clustering techniques for vehicles internetworking. Consequently, as a final step of the work presented in this thesis, the problem of designing a stable clustering mechanism to facilitate an efficient vehicle internetworking is addressed. To this regard, in Chapter 5 we propose a Stable Clustering Algorithm for vehicular ad-hoc networks (SCalE), to maintain the communication stability and enable internetworking between vehicles and UAVs or cellular base stations. A new key feature was introduced in the cluster head selection process: the vehicles behaviour. Compared to cluster head elections solely based on current mobility and position information, the knowledge of vehicle behaviours is important in helping choose a stable cluster head because it gives additional insight on the future movements of the vehicles (e.g., if a vehicle will turn at the next crossroad and leave the system). Furthermore, after the cluster formation phase, the SCalE algorithm is able to maintain the network structure regardless of the highly mobile nature of the vehicles. By selecting a backup cluster head, in fact, the stability of a cluster can be prolonged since the backup can promptly substitute the original cluster head when it has to resign from its role. The results shown in Chapter 5 illustrate the enhanced performance of the SCalE algorithm when compared to Highest-Degree and

VMaSC algorithms. Our proposed clustering mechanism can indeed increase the cluster stability and hence represents a valid support for efficient internetworking.

The main contributions introduced in this thesis can be summarised as follows:

- Derivation of a model able to follow the highly mobile nature of vehicles and to optimally adapt the transmission probability of Aloha protocol based on the vehicular density in the network.
- Vehicular density-based optimal maximum CW estimation for CSMA/CA broadcast protocol by exploiting the Aloha-like behaviour of CSMA, whilst including realistic constraints such as the vehicle size in vehicular flows and estimated number of neighbouring vehicles. Moreover, the signal-to-interference ratio (SIR) capture effect is considered at the receiving vehicles.
- Proposed amendment of the current CSMA/CA protocol for vehicular communications by integrating the optimal maximum CW. This new MAC protocol can consequently enhance the delay and throughput performance for time-critical applications (e.g., CAM safety message exchanges or clustering techniques for efficient internetworking) as shown by extensive simulation.
- Presenting a stable clustering algorithm to tackle the issue of forming a reliable network structure able to facilitate the internetworking between VANETs and UAVs or cellular base stations. This major challenge is addressed by introducing two key contributions: knowledge of the vehicles behaviour and the selection of a backup cluster head (CH_{Bkp}), that is the most suitable candidate to become CH in case

the current head has to resign from its role. The driver's behaviour is a new piece of information used for selecting a stable cluster head whilst the backup cluster head enables a stable cluster maintenance scheme.

6.2 Future work

Despite the contributions presented in this thesis, challenges and opportunities for further research remain. The following are avenues for future work.

The throughput model derived in Chapters 3 and 4 is based on a one-dimensional one-way road system. In spite of the significant insight gained by the investigation of this particular scenario, vehicular networks architectures are more often described by a two-dimensional scenarios, for instance when vehicles are operating in a urban environment. In light of this, by relying on the fundamental research we have conducted over a one-dimensional system, an extension of the throughput model can be investigated in order to become applicable to more complicated traffic scenarios (e.g., two-dimensional networks).

Additionally, in devising the throughput model used to optimise MAC protocols for vehicular communications, the connectivity analysis is solely based on the deterministic path loss. Nevertheless, fluctuations in the radio signals may change the conditions under which the connection between two vehicles is established. Thus, future extensions of this PhD work can also include the analysis of more challenging fading scenarios, such as log-normal shadowing or Rayleigh fading.

In Chapter 4 we have introduced the concept of estimated number of neighbouring vehicles since this is a more realistic value to obtain rather than the theoretical vehicular density that cannot be known a priori. In the work presented in this thesis we have merely assumed that the vehicles are able to estimate the number of the neighbouring vehicles. Therefore, a possible extension to this work can focus on the derivation of an accurate estimation mechanism of the vehicle density by sensing the number of neighbouring vehicles. Since the performance of the CSMA/CA protocol proposed in Chapter 4 depends on the density estimate, its accuracy is important.

Furthermore, the performance study the work described in Chapter 4 regarding the design of a optimised CSMA/CA protocol essentially assumes that every vehicle in the network has a buffer for one single packet, which is reasonable for the CAM or certain safety applications with periodic packet generation. Another area of extension is, hence, to consider multiple buffers for other time-critical applications where packet generation can be bursty.

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Appendix A

Mobility Model

The Matlab implementation of the mobility model used for the simulation in Chapter 5 is based, as previously mentioned, on the Gipps car following model and the Gipps lane-changing model [85–87]. In the following we will simply illustrate the main equations that constitute the body of the model that we have implemented.

The model developed by Gipps has been designed to be able to operate under different density conditions. Therefore, for each vehicle two speeds are calculated: the free flow state $u_n^a(t+\tau)$ (e.g., for lower vehicular densities) in (A.1) and the car following speed $u_n^a(t+\tau)$ (for dense networks) given in (A.2). Finally, the speed of the vehicle is then chosen to represent the most limiting constraint, that is the lowest value between the two speeds as in (A.3).

$$u_n^a(t+\tau) = u_n(t) + 2.5 a_n \tau \left(1 - \frac{u_n(t)}{U_n}\right) \sqrt{0.025 + \frac{u_n(t)}{U_n}} \tag{A.1}$$

$$u_n^b(t+\tau) = b_n\tau + \sqrt{b_n^2\tau^2 - b_n\left[2[x_{n-1}(t) - s_{n-1} - x_n(t)\tau] - u_n(t)\tau - \frac{u_{n-1}(t)^2}{\hat{b}}\right]} \tag{A.2}$$

$$u_n(t+\tau) = \min u_n^a(t+\tau), u_n^b(t+\tau) \tag{A.3}$$

where:

- a_n is the maximum acceleration which the driver of vehicle n is willing to undertake.
- b_n is the most severe deceleration that the driver of vehicle n wishes to undertake.
- $\hat{b}$ is the most severe deceleration of vehicle $n-1$ as estimated by the driver of vehicle n.
- s_{n-1} is the effective size of vehicle $n-1$. This includes the physical length of vehicle $n-1$ and a safety margin, into which the driver of vehicle n is not willing to intrude even at rest.
- U_n is the desired speed of vehicle n.
- $x_n(t)$ is the location of the front of vehicle n at time t.
- $u_n(t)$ is the speed of vehicle n at time t.
- τ is the reaction time, which is constant for all vehicles and equal to the simulation step.