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A Scalable Communication Protocol for Vehicles Platooning

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"To my parents and family"

Resumo

O congestionamento do tráfego rodoviário está a tornar-se uma questão inconveniente, aumentando os acidentes rodoviários, o consumo de combustível e afetando a saúde dos viajantes. As redes ad-hoc veiculares (VANETs) permitem que os veículos troquem informações sobre condições de tráfego, status dinâmico e localização, suportando uma infinidade de aplicações que podem potencialmente melhorar a segurança rodoviária e a eficiência do transporte. Entre essas aplicações, *platooning* (que organiza o tráfego em pelotões) é frequentemente mencionada como uma das mais inovadoras. Esta aplicação pode tirar proveito da troca de informações sobre velocidade, direção e posição para permitir maior conforto do condutor e distâncias menores entre veículos sem comprometer a segurança. No entanto, o desempenho da aplicação de *platooning* depende drasticamente da qualidade do canal de comunicação, que por sua vez é altamente influenciado pelo protocolo de controlo de acesso ao meio (MAC).

Atualmente, existem dois standards para o Sistema de Transporte Inteligente (ITS), um proposto nos EUA, nomeadamente IEEE WAVE, e outro na Europa, nomeadamente ETSI ITS-G5. Ambos os standards usam as camadas PHY e MAC do protocolo MAC IEEE 802.11p. Este protocolo é totalmente distribuído e baseado em acesso múltiplo por detecção de portadora com prevenção de colisões (CSMA / CA), mas não é completamente isento de colisões. Esse facto motivou propostas recentes de protocolos de sobreposição baseados em TDMA que sincronizam as mensagens *beacon* transmitidas periodicamente pelos veículos numa ronda cíclica para evitar ou reduzir ainda mais as colisões. Contudo, estes protocolos requerem sincronização complexa e levam frequentemente a significativas limitações de escalabilidade.

Nesta tese, concentramo-nos em cenários de pelotões em auto-estradas e propomos o protocolo de sobreposição RA-TDMAp que combina as propriedades de dois trabalhos anteriores, levando a um método novo e mais eficaz de sincronizar veículos em pelotões. Por um lado, este protocolo permite que os veículos num pelotão permaneçam sincronizados mesmo na presença de tráfego interferente, por exemplo, de outros veículos ou pelotões, adaptando a fase da ronda TDMA para evitar interferências periódicas. Por outro lado, o protocolo reduz a ocupação do canal fazendo com que apenas o líder transmita com alta potência, para alcançar todo o pelotão de uma só vez, enquanto os seguidores transmitem com baixa potência. A ordem de transmissão é tal que o líder reúne informação de todo o pelotão apenas numa ronda.

A eficácia do protocolo RA-TDMAp é analisada minuciosamente e comparada com o protocolo de base CSMA/CA e com outro protocolo de sobreposição, nomeadamente PLEXE-slotted.

A comparação é realizada por meio de extensas simulações com diferentes tamanhos de pelotão, número de faixas ocupadas e potência de transmissão. Este estudo de simulação permite-nos deduzir modelos empíricos que fornecem estimativas do número médio de colisões por segundo e da taxa média de ocupação do canal. Em particular, mostramos que estas estimativas podem ser obtidas observando o número de vizinhos de radiofrequência (RF), ou seja, o número de fontes distintas dos pacotes recebidos por cada veículo por unidade de tempo. Estas estimativas podem permitir uma melhor adaptação on-line de aplicativos distribuídos, em particular o controlo do pelotão, para diferentes condições do canal de comunicação.

Em seguida, mostramos como reconfigurar o protocolo RA-TDMAp para lidar com a dinâmica do pelotão, considerando as múltiplas manobras longitudinais que podem ocorrer num ambiente de tráfego real numa autoestrada, como ingressar, sair, juntar ou dividir. Apresentamos uma máquina de estado de controlo de admissão adequada, validada inicialmente no mesmo ambiente de simulação já usado anteriormente.

Por fim, esta dissertação também inclui uma validação experimental com extensos testes de pequena escala, usando nós providos de interfaces IEEE 802.11p.

Keywords: TDMA, protocolo MAC de sobreposição, VANETs, platoonig, escalável

Abstract

Road traffic congestion is becoming an inconvenient issue, increasing road accidents, fuel consumption and affecting travelers health. Vehicular ad-hoc networks (VANETs) enable vehicles to exchange information on traffic conditions, dynamic status and localization, supporting a myriad of applications that can potentially enhance road safety and transportation efficiency. Among these applications, platooning is often mentioned as one of the most innovative. It can take advantage of exchanging information on speed, heading and position to allow higher driver comfort and shorter inter-vehicle distances without compromising safety. However, the platooning performance depends drastically on the quality of the communication channel, which in turn is highly influenced by the Medium Access Control (MAC) protocol.

Currently, there are two standards for Intelligent Transportation System (ITS), proposed in the USA, namely IEEE WAVE, and in Europe, namely ETSI ITS-G5. Both standards use the PHY and MAC of IEEE 802.11p. This MAC protocol is fully distributed and based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), which is not collisions-free. This fact has motivated recent proposals for TDMA-based overlay protocols that synchronize vehicles' beacons in a round to prevent or further reduce collisions, but leading to complex synchronization and scalability limitations.

In this thesis, we focus on highway scenarios and propose the RA-TDMAp overlay protocol that combines the properties of two previous works leading to a novel and more effective way of synchronizing vehicles in platoons. On one hand, it allows the vehicles in a platoon to remain synchronized even in the presence of interfering traffic, e.g. from other vehicles or platoons, by adapting the phase of the TDMA round to escape periodic interference. On the other hand, it reduces channel occupation by having just the leader transmitting with high power, to reach all the platoon at once, while the followers transmit with low power. The order of transmission is such that the leader gathers information from the whole platoon in just one round.

The effectiveness of RA-TDMAp is thoroughly analyzed against the base CSMA/CA and another TDMA-based overlay protocol, namely PLEXE-slotted, by means of extensive simulations with varying platoon sizes, number of occupied lanes and transmit power. This simulation study allows us to deduce empirical models that provide estimates of average number of collisions per second and average busy time ratio. In particular, we showed that these estimates can be obtained from observing the number of radio-frequency (RF) neighbors, i.e., the number of distinct sources of the packets received by each vehicle per time unit. These estimates can enhance the online

adaptation of distributed applications, particularly platooning control, to varying conditions of the communication channel.

We then showed how to reconfigure the RA-TDMAp protocol to cope with platoon dynamics, handling the multiple longitudinal maneuvers that can occur in a real traffic environment on a highway, such as joining, leaving and merging. We present an adequate admission control state-machine validated initially with the same simulation framework used before.

Finally, this dissertation also includes an experimental validation with extensive tests on a small scale testbed using IEEE 802.11p-enabled nodes.

Keywords: TDMA, overlay MAC protocol, VANETs, platoonig, scalable

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Aqsa Aslam

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List of Abbreviations

AcS	Acceptance of Services
AnS	Announcement of Services
ACC	Adaptive Cruise Control
AIFS	Arbitration Inter-Frame Spaces
BCH	Basic Channel
BSM	Basic Safety Messages
BSS	Basic Service Set
CAMs	Cooperative Awareness Messages
CCH	Control Channel
CAMBADA	Cooperative Autonomous Mobile roBots with Advanced Distributed Architecture
CWs	Contention Windows
CEN	European Committee for Standardization
CALM	Communications Access for Land Mobiles
CACC	Cooperative Adaptive Cruise Control
CRP	Contention-based Reservation Period
CRD	Cluster Range Data
CBT	Cluster-Based TDMA system
CH	Cluster Head
COTS	Commercial Off-the-Shelf
C-ITS	Cooperative Intelligence Transport Systems
CBMAC	Cluster Based Medium Access Control
CBMMAC	Clustering-Based Multichannel MAC
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CDMA	Code Division Multiple Access
DENMs	Decentralized Environmental Notification Messages
DCC	Distributed Congestion Control
DynBs	Dynamic beaconing
DMMAC	Dedicated multi-channel MAC protocol
DCH	Data Channel
DTMAC	Distributed and infrastructure free TDMA based MAC protocol
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standard Institute
EEBL	Emergency Electronic Brake Lights
FCW	Forward Collision Warning
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
GPS	Global Position System

ISI	Inter Symbol Interference
IMA	Intersection Movement Assist
IEEE	Institute of Electrical and Electronics Engineers
IVHS	Intelligent Vehicle Highway Systems
IVC	Inter-Vehicle Communications
ICC	Inter-Cluster Control
ICD	Inter-Cluster Data
MSL	Middle-Size League
MAC	Medium Access Control
MSDU	MAC Service Data Unit
MSE	Mean Square Error
MAC	Medium Access Control
NAHSC	National Automated Highway System Consortium
NHTSA	National Highway Traffic Safety Administration
NFC	Near Field Communication
PHY	Physical
Plexe	The Platooning Extension for Veins
PHY	Physical Layer
PDR	Packet Delivery Ratio
RA-TDMA	Reconfiguration and Adaptive TDMA
RSU	Road Side Unit
RF	Radio Frequency
RA-TDMAp	Re-configurable and Adaptive TDMA for platooning
SCH	Service Channels
SUMO	Simulation of Urban MObility
STDMA	Self-organized time-division multiple access
TIS	Traffic Information Systems
VANETs	Vehicular Ad Hoc Networks
VLC	Visible Light Communication
UMTS	Universal Mobile Telecommunications System
VeSOMAC	Vehicles Self-Organizing MAC protocol
VeMAC	Vehicular Ad Hoc Networks MAC
Veins	Vehicles in Network Simulation

Chapter 1

Introduction

Increasing road accidents and traffic congestion in the road environment have motivated Intelligent Transportation Systems (ITS) and collaborative applications to improve road efficiency and safety. These applications are becoming a reality as emerging Vehicular Ad Hoc Networks (VANETs), also known as Inter-Vehicle Communication (IVC), in the forms of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, are widely deployed to obtain and share data on traffic, safety, or other generic information (plenty of applications examples given in [1]). The challenge is to develop vehicles that relieve humans from the driving duty in an efficient, smart, and safe way. Among these applications, vehicles *platooning* addresses traffic congestion, fuel-saving, and safety, and it is expected to make for a considerable share of highway traffic, given its benefits. It has been investigated since the eighties, for example within the California projects Partners for Advanced Transit and Highways (PATH) [1] and SAfe Road TRains for the Environment (SARTRE) [2], but due to the challenging problems it raises, it is still an active research topic. One of the core reasons behind such a large interest is the benefits that platooning could provide once widely deployed. We can envision that, in the near future, a subset of highway lanes (or even entire highways) can be fully dedicated to platoons. VANETs will play an important role in leveraging platooning and its safety features, e.g., members coordination and collision avoidance, but also intelligent transportation management, e.g., intersection management, and infotainment, e.g., video streaming [3, 4].

Many operators, researchers, and governments all over the world are devoting significant resources to the deployment of VANETs to have a safer transportation system. VANETs are important components of an ITS that enable communication among vehicles, in which all vehicles are equipped with wireless devices that support collaborative applications. The paradigm of sharing information among vehicles and infrastructure enables a wide range of applications for safety such as driver assistance, collision avoidance, hazardous situation warning, but also non-safety uses such as infotainment and urban sensing. In the literature, there are different studies addressing different aspects of VANETs from their own design to collaborative applications, routing, etc.

In this thesis, we focused on communication to share safety information among vehicles, particularly in the scope of platooning applications for highways. The platooning application comprises two main different parts, namely the control system, which autonomously drives the vehicles, and the V2V communication, which provides data to the control system and to the platoon management. Our work focuses on the communication, only.

1.1 Communication in VANETs

VANETs are a vital enabling innovation for future ITS, smart vehicles and smart infrastructure. The approach of VANETs consists of vehicles provided with wireless communication capabilities that can self-organize into a cooperative mesh to share information, thus enabling a myriad of applications to make road travel safer, by avoiding/reducing collisions, more efficient, by decreasing travel time, avoiding traffic congestion, thus increasing road capacity, and more satisfying to the travelers. On the other hand, the wireless medium is known to suffer from issues that can affect timeliness and reliability of communications, potentially jeopardizing VANETs safety applications. For instance, the mesh network topology changes rapidly because of the high degree of mobility of the vehicles, also leading to high variability of channel load and interference patterns, increasing the potential for collisions in the medium, and resulting in limited and variable bandwidth.

Therefore, a significant research effort was needed to make collaborative safety-critical applications a reality. These applications require a reliable communication channel with few access collisions, low latency and high throughput, properties that call upon an adequate Medium Access Control (MAC) protocol. Such a protocol for VANETs needs to support those properties while coping with a highly dynamic configuration and high scalability.

The MAC protocol is, thus, a key component in defining the level of Quality of Service (QoS) that the network can offer. Generally, a MAC protocol must cater for a number of, often contradictory, requirements such as: promoting efficient use of the medium, providing fair and balanced access to all nodes, adjusting to varying densities of vehicles and supporting the changes in VANETs topology. The objective of the MAC protocol is to arbitrate the access to the shared medium, which in this case is the wireless channel. If no mechanism is in place to organize the transmission of information, then a large number of collisions could occur and a significant part of the transmitted information would be lost. The ideal MAC protocol would allow ad-hoc nodes to transmit immediately once they have a communication trigger, but preventing different nodes within transmission range of each other from transmitting at the same time, thus avoiding collisions.

The most established standard for vehicle-to-vehicle (V2V) communication is IEEE 802.11p / Dedicated Short Range Communication (DSRC). Currently, there are two similar but non-interoperable ITS communication standards, operating in the 5.9 GHz band, namely the IEEE Standard for Wireless Access in Vehicular Environments (WAVE) in the US and the ETSI Standard for Intelligent Transport Systems (ITS-G5) in Europe. At the physical and MAC layer, both use the IEEE 802.11p protocol to arbitrate access within each of the channels provided by the standards, namely control and service channels. This protocol relies on the well-known Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) distributed access arbitration method, with different enhancements on both cases. This arbitration method uses a stochastic exponential backoff and retry rule that may present a significant performance degradation in the presence of high network loads caused by dense traffic situations, leading to highly variable network delays and high message losses due to chained collisions [5, 6].

1.2 Problem statement

VANETs is a highly challenging research area in the field of Mobile Ad-hoc Networks. In the VANETs landscape, congestion in the communication channel has emerged as a serious problem that affects the performance of safety applications hindering their capacity to reduce road accidents. When a large number of vehicles exchange information, the bandwidth of the channel can be exhausted. Consequently, a significant number of transmission collisions occur. In the case of a safety application, such as platooning, if the channel is already congested then the safety critical messages are either lost or received with longer delay due to unsuccessful channel access or transmission collisions. Both loss and extended delay of information transmission have a significant impact on the safety of the road environment.

Therefore, we addressed the challenge of supporting safety-related applications on VANETs designing an efficient overlay MAC protocol that enhances timeliness and reliability of the communications, thus improving the QoS provided by the communication channel beyond what the current state-of-the-art allows.

1.3 Objectives

One of the challenges for VANETs is the design of an efficient MAC protocol that copes with the high speed of the nodes, the frequent changes in topology, the potential lack of an infrastructure, and still caters for various QoS requirements. With this motivation in mind, we realized that reducing message losses and network delay by avoiding collisions was still an open issue and we defined it as our main global objective.

The current IEEE 802.11p standard already has numerous features to cope with the requirements referred above. However, it has been advocated that further collisions reduction needs some kind of temporal coordination of transmissions such as with Time-Division Multiple Access (TDMA). This technique divides time into consecutive and cyclic non-overlapping slots and allocates each slot to one vehicle for exclusive channel access. There are multiple proposals for TDMA-based MAC protocols for VANETs in the literature. Some of these are deployed directly on the physical layer, generally requiring strict synchronization and complex management schemes to provide dynamic slot to vehicle assignment together with high scalability [7].

Alternatively, it is possible to deploy a TDMA layer on top of IEEE 802.11p, i.e., as an overlay protocol, combining the benefits of asynchronous access with CSMA/CA, which relaxes the requirements on synchronization, with collisions reduction with TDMA. We defined this combination as our specific objective, through the design of an overlay MAC protocol for using over IEEE 802.11p that improves the channel quality using mainly two metrics, collisions rate and busy time ratio, maintaining full compatibility with that standard. This way, such protocol can be readily deployed on existing IEEE 802.11p equipment.

1.4 Background

Our objectives were influenced by the work done in [8], where the Reconfigurable and Adaptive TDMA (RA-TDMA) protocol was proposed to support periodic state sharing within dynamic teams of cooperating mobile autonomous robots. This protocol was developed within the Cooperative Autonomous Mobile roBots with Advanced Distributed Architecture (CAMBADA) robotic soccer team for the RoboCup Middle-Size League (MSL). The protocol relies on a TDMA overlay on top of IEEE 802.11 (WiFi), which creates a frame with a fixed period and a number of slots equal to the number of active robots in the team at each moment. Each robot transmits its state within its slot, only. These slots are normally much larger than the communication requirements of each robot, thus leaving free gaps that are used to tolerate transmissions outside the team. Note that, in the MSL competitions, two different teams share a single wireless channel. Thus, the transmissions of one team are external (interfering) traffic to the other team. The idea of RA-TDMA is to use the underlying CSMA/CA layer to sort out the coexistence of a TDMA frame and uncoordinated external traffic. The TDMA frame is synchronized considering the eventual delays caused by the external traffic, without global clock synchronisation, creating a robust but loose synchronisation amongst the team members. If the two teams use RA-TDMA, then each will have its own TDMA frame and both frames will adjust their phases to minimize mutual interference, becoming implicitly entangled, but without explicitly knowing of each other. We believe this mechanism is interesting for platooning applications, potentially increasing the number of platoons that can coexist and in a highly scalable fashion since all coordination is carried out inside each platoon, only.

Moreover, we were also influenced by the work in [9], which proposes a TDMA overlay protocol on top of IEEE 802.11p for platoons, too. This protocol, named *PLEXE-slotted*, also sets a TDMA frame for the platoon, with each vehicle transmitting inside its own slot. The synchronization of the TDMA frame in each platoon is rigid, but its main feature is power control. In this case, the leader of each platoon, only, transmits its beacons at high power while the other platoon members use lower power beacons and forward information of each other in a multi-hop scheme. The result is a significant reduction of medium occupancy, favoring channel reuse along the road.

1.5 Thesis

Our thesis claims that:

An efficient MAC protocol for platooning applications, aiming at highway scenarios, can be developed merging the ideas behind RA-TDMA [8] and PLEXE-slotted [9]. We also claim that this combination leads to a reduction in collisions and channel occupation while offering full scalability. We call our protocol RA-TDMAp.

RA-TDMAp sets one TDMA frame on top of IEEE 802.11p for each platoon, independently. The TDMA round equals the IEEE 802.11p beacons period. A dynamic slots structure is set in place with as many slots as the vehicles in the platoon at each moment. Each vehicle, then, transmits its beacon inside a dedicated slot. These slots are significantly larger than the time needed to transmit the beacon. In this way, the TDMA frame is permeable. We claim that we can use this feature to support multiple independent TDMA frames that co-exist in time and space, corresponding to concurrent groups of interacting vehicles, in this case, concurrent platoons. Thus, we provide explicit per platoon slots coordination (slots in one TDMA frame), leading to implicit coordination of multiple platoons (multiple intertwined TDMA frames). The slots coordination mechanism achieves collisions reduction through synchronization of each platoon beacons (TDMA) and efficient bandwidth usage with asynchronous access among different platoons (CSMA/CA).

The slots coordination is, thus, the core mechanism of RA-TDMAp and it gathers ideas from [9], namely the beacons power management, and from [8], namely the slots adaptive synchronization. The leader of each platoon, only, transmits its beacons at high power, marking the beginning of a TDMA round. The other platoon members use lower power beacons and forward information of each other in a multi-hop scheme[1]. Each receiver, when receiving a beacon, can also assess the delay that affects its transmission caused by interference from other vehicles outside the platoon via the CSMA/CA arbitration. These delays are communicated to the leader that shifts correspondingly the following TDMA round. We claim that this phase adaptation allows the TDMA frame to escape the periodic interference that generated it, which can be caused by other TDMA frames of other platoons, leading to a bandwidth efficient intertwining of all such TDMA frames. Comparing to the original RA-TDMA protocol for teams of robots, RA-TDMAp takes advantage of the physical features of platoons, namely their line topology and longitudinal maneuvers. Thus, the mechanism to gather the packets delay information from the followers is novel, so as the reconfiguration mechanism to handle the dynamic platoon formation.

1.6 Contributions

Our main contribution, as stated in the section above, is the RA-TDMAp wireless communication protocol for platooning. Despite being inspired on previous works as discussed above, this is a novel protocol with specific features to support platooning, particularly the synchronization mechanism and the reconfiguration for dynamic platoons. RA-TDMAp is a TDMA overlay protocol on top of the native CSMA/CA MAC of IEEE 802.11p / DSRC, which is the standard established for

[1] Using this power control scheme, as proposed in [9], precludes the use of other power management mechanisms defined in other standards, e.g., the Distributed Congestion Control (DCC) in ITS-G5.

V2V communication. Thus, RA-TDMAp can be readily deployed on any IEEE 802.11p existing hardware.

We implemented RA-TDMAp on the PLEXE-Veins-SUMO framework that works on top of the OMNeT++ discrete event simulator. This led to another contribution, which is the associated simulation model. Using this model, we compared RA-TDMAp against other directly comparable approaches that are readily supported by IEEE 802.11p COTS equipment and which are available in the literature, namely PLEXE-slotted and plain CSMA/CA. As a result, we showed that RA-TDMAp is superior in reducing the rate of collisions and the busy time ratio, bringing a significant improvement in the quality of the channel under high traffic utilization.

Moreover, the simulation study revealed that those channel properties (collisions ratio and busy time ratio) could be expressed as a function of the number of neighbours that a car receives beacons from (we call these, the RF neighbors). Consequently, we generated another contribution, which are new empirical models that relate the current number of RF neighbours that a vehicle senses with those network performance metrics for the three referred protocols.

The dynamic reconfiguration and admission control mechanism of RA-TDMAp, to cope with platoons formation and maintenance, is another contribution worth of note. It is a novel mechanism that takes the relative localization of joining vehicles and platoon into account and that synchronizes the platoon reconfiguration at the control and communication layers.

Finally, this dissertation also describes a thorough experimental validation campaign, which constitutes another contribution that highlights the characteristic features of RA-TDMAp.

Most of these contributions have been published in the following references, shown in reverse chronological order:

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1.7 Organization of the Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 discusses relevant fundamental background knowledge for this dissertation and presents related work for communication in VANETs. Chapter 3 describes the proposed scalable communication protocol for vehicles platooning, i.e, RA-TDMAp. Chapter 4 describes the empirical performance models of RA-TDMAp, PLEXE-slotted and CSMA/CA protocols and their comparative study. Chapter 5 describes the reconfiguration mechanism of the protocol to cope with dynamic platoons. Chapter 6 shows the experimental validation of the protocol on a real testbed. Chapter 7 presents the main conclusions of this work, including the thesis validation and potential future research lines.

Chapter 2

MAC protocols for VANETs

In this chapter, we describe the fundamental concepts that are needed to understand the work in this thesis and we review the related work on the topic. We start by introducing VANETs (Section 2.1), then discuss medium access control techniques typical in VANETs (Section 2.2) and we survey the state of the art in MAC protocols for VANETs (Section 2.3). Finally, we conclude the chapter with an overview of design challenges at the MAC level in the VANETs domain (Section 2.4).

2.1 Vehicular Networks

VANETs appeared as a main research area over the last 10 to 20 years. The concept of VANETs developed from early experiments to provide communications among vehicles in highways as well as in rural and urban environments to support diverse collaborative applications with different QoS and safety requirements [16]. VANETs are a first step regarding the implementation of ITS. Presently, most of the car companies are producing vehicles with onboard wireless equipment and global position system (GPS) which are requirements to deploy VANETs, so vehicles can share information with the purpose of assisting the driver in making decisions, e.g., Advanced Driver Assistance Systems, or to improve the guidance of autonomous cars. VANETs can support communications among vehicles (V2V) and between vehicles and infrastructure (V2I) as shown in Figure 2.1 and allow vehicles to receive hazard warnings or information on the current traffic situation with low latency. The primary goals of these actions are to increase safety and transportation efficiency [17].

2.1.1 Wireless Medium Access Technologies, Standards, and Applications

Connected vehicles require an efficient communications system for adequate connectivity, throughput, latency and reliability. It can be achieved resorting to different wireless technologies, as referred in standard Communications Access for Land Mobiles (CALM) [18], which rely on a wide range of wireless access technologies including Universal Mobile Telecommunications System (UMTS) or 2G/3G/LTE, wireless broadband access (e.g., WiMAX), IEEE 802.11, etc, short-range wireless such as Bluetooth [19], ZigBee [20], Visible Light Communication (VLC) [21, 22] etc.

(**a**) Vehicle-to-Infrastructure communication, infrastructured architecture

(**b**) Vehicle-to-Vehicle communication, ad-hoc architecture

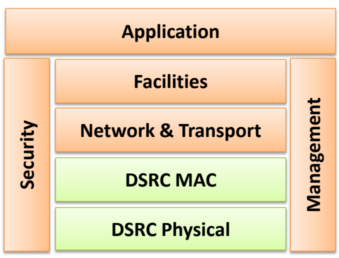
Figure 2.1: VANETs architectures

Each technology has different characteristics, advantages and drawbacks, and each one might be better suited for a particular application. For instance, the cellular network can easily support Traffic Information Systems (TIS), i.e., all those applications that are dedicated to the dissemination of traffic information, such as jammed roads due to accidents. Among all wireless medium access technologies, DSRC and UMTS are two widely used candidate schemes for V2V and V2I communication, respectively.

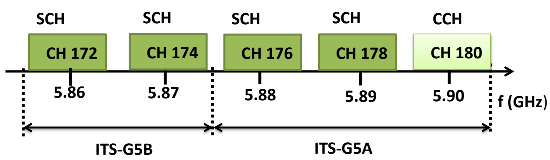
Cutting-edge wireless technologies also provide opportunities to support vehicle safety applications. In general, short-range communications are more suited for road safety applications because urgent safety-related information is more useful in the local vicinity of each vehicle. Numerous studies considered IEEE 802.11 (or WiFi) [23] as a communication technology for vehicular networks [24, 25, 26]. Some drawbacks of this technology, however, make it actually inadequate to real traffic environments. The most popular versions, namely IEEE 802.11b/g/n/ac standards, use the Industrial, Scientific and Medical (ISM) band that operates in the 2.4 GHz band [27]. The ISM band is used by cordless phones, Bluetooth, Near Field Communication (NFC), ZigBee, WiFi as well as other IEEE 802.11-based applications. Consequently working in the ISM band means competing for channel access with all these technologies, which is clearly undesirable, especially when considering safety-critical applications. The second problem arises from multi-path propagation in IEEE 802.11 technology. When a signal is sent by a radio device via its antenna, it reaches the receiver via multiple paths by bouncing on objects in the communication environment. The amount of time between the first (direct line of sight) and the last multi-path component arrived at the receiver is called the delay spread. In a jarring environment such as vehicular networks, the delay spread is larger than in indoor conditions. For this reason, the standard IEEE 802.11 protection against Inter Symbol Interference (ISI), called the Guard Interval (GI), is not enough. Third, the most common IEEE 802.11 deployment architecture follows a star topology, requiring a station to be associated to an access point for communicating, and all the traffic needs to go through the access point, forbidding the possibility of direct V2V communication, which is fundamental for safety applications.

DSRC [28] was initially originated in USA [29] by the Federal Communications Commission (FCC). DSRC is defined in the frequency band of 5.9 GHz with a total bandwidth of 75 MHz (from 5.850 GHz to 5.925 GHz). This band is organized in 7 different channels in the U.S and 5 in Europe [21]. Ultimately, the IEEE 802.11p [30] standard was proposed by the *p* Task Group in IEEE 802.11 standards, specifically to support VANETs and solve or attenuate the problems referred above. The idea was to avoid re-designing physical and medium access control layers while supporting rapidly changing environments and very fast and short-duration communications are required. IEEE 802.11p improves QoS by using the Enhanced Distributed Channel Access (EDCA) MAC derived from the IEEE802.11e standard [31], so it uses four access categories to prioritize traffic. The EDCA allows assigning safety messages to the highest priority category to provide a better chance of transmission than messages assigned to lower priority categories. Prioritization is achieved by varying the Contention Windows (CWs) and the Arbitration Inter-Frame Spaces (AIFS), which increase the probability of successful medium access for the messages in the higher priority categories. The multi-path propagation issue is mitigated by doubling the OFDM symbol time, and consequently the Guard Interval [30]. The bandwidth of each channel thus shrinks from the 20 MHz of 802.11a to 10 MHz, so the available data rates range from 3 Mbit/s to 27 Mbit/s. Finally, the association problem is addressed by defining a wildcard Basic Service Set (BSS), in practice it is a broadcast MAC address, allowing vehicles to send and receive frames without the need of being associated to BSS or IBSS [30].

In Europe, 30 MHz (i.e., 3 channels) are reserved for road safety in the ITS-G5A band and 20 MHz are assigned for general purpose ITS services in the ITS-G5B band. As a general rule, a control channel, namely CCH 178 in the USA and CCH 180 in Europe, is exclusively used for cooperative road safety and control information (Figure 2.2b). The remaining channels are designated as service channels (SCH). In the United States, concerns about the reduced capacity for road safety messages led to the decision to allocate SCH 172 specifically for applications regarding public safety of life and property [21](Figure 2.3b).



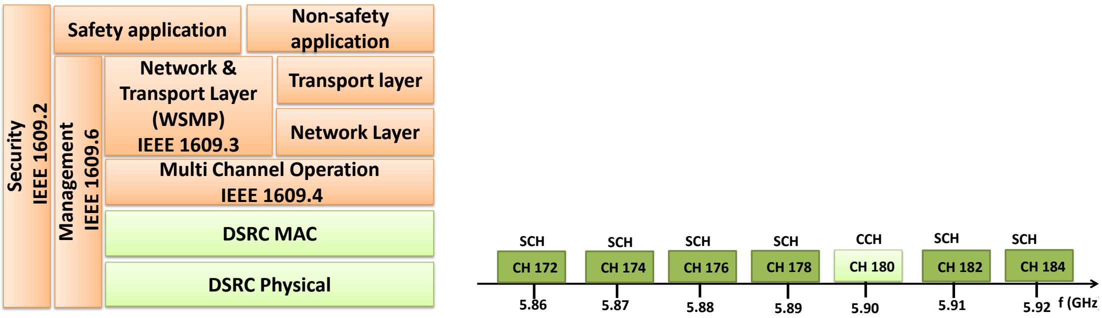
(**a**) Protocol stack in Europe



(**b**) Spectrum allocation in Europe

Figure 2.2: Protocol stack and spectrum allocation for vehicular communications in Europe

Layers above physical (PHY) and medium access control (MAC) are managed by a set of different standards. There are two protocol stacks for vehicular communications, one established by the Institute of Electrical and Electronics Engineers (IEEE) and the other one established by the European Telecommunications Standards Institute (ETSI). The protocol stack in the USA is entitled IEEE Wireless Access in Vehicular Environments (WAVE), while the one in Europe is entitled as ETSI ITS-G5. Both standards rely on IEEE 802.11p for the implementation of their PHY and MAC layers [21]. In the USA the IEEE developed the 1609 standard [32, 31], which is divided in different sub-standards, namely 1609.0, 1609.1, 1609.2, 1609.3, and 1609.4, 1609.11,



(**a**) Protocol stack in USA (**b**) Spectrum allocation in USA

Figure 2.3: Protocol stack and spectrum allocation for vehicular communications in USA

and 1609.12. The aim of IEEE 1609 is to defined higher layer packets format, security primitives, multi-channel operation, etc. as shown in Figure 2.3a. In Europe, instead, the ETSI developed the ITS-G5 stack [33, 5] as shown in Figure 2.2a. Similarly to IEEE 1609, ITS-G5 defines message formats, channel operations, traffic categories, etc. This standard defines two types of messages, Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs). CAMs are single-hop beacons that a vehicle periodically sends to inform neighbors about its presence. In the WAVE standard, the same kind of message is defined as Basic Safety Message (BSM). DENMs, instead, are event-triggered beacons used to inform vehicles about a specific event such as, for example, an emergency braking. To cope with wireless channel congestion, the ETSI adds Distributed Congestion Control (DCC) as an upper layer function on top of the PHY and MAC layers to dynamically measure the network load in real time and also to implement functionalities to keep the load below a threshold level by adapting MAC and other transmission parameters [34, 35]. Conversely, WAVE uses the existing CSMA/CA extended with EDCA mechanisms, only.

However, with or without DCC, the access methods of both protocols have been proved insufficient in dealing with what is regarded as one of the most challenging issues in providing real-time characteristics to vehicular communication systems: deterministic channel access under high load conditions [36, 37, 6]. The aim of both North American and European standards is to provide high level vehicular applications with some primitives used to share and obtain data from other vehicles, or from the infrastructure. Both standards are capable of assigning priorities to packets generated by different applications to give more importance, for example, to safety-related systems. Despite the existence of the two protocol stacks, in our work we will consider ETSI ITS-G5, only, unless stated otherwise.

ETSI together with the European Committee for Standardization (CEN) jointly delivered the first release of C-ITS standards, enabling deployment of applications in the vehicular domain. The main target applications supported by the release one of the standard is essentially the cooperative awareness applications and the road hazard applications. On the other side, since the beginning of the development of IEEE 802.11p, the National Highway Traffic Safety Administration (NHTSA) proposed several different applications. These applications are classified into two categories [38]:

- **Safety applications:** These applications provide information and assistance to drivers to avoid collisions with other vehicles. This can be accomplished by sharing information among vehicles and with road side units (RSU), which are then used to predict potential collisions. Such information can include vehicle position, paths intersection position, speed and distance heading. Moreover, information exchange among vehicles and with the RSU is used to locate hazardous situations on roads, such as slippery sections or road works. Examples of safety applications are: Intersection Movement Assist (IMA), lane ahange assistance, Emergency Electronic Brake Lights (EEBL), Forward Collision Warning (FCW), rear end collision warning, co-operative forward collision warning, pre-crash warning, wrong way driving warning, etc.

- **Non-safety applications:** These applications can be further classified in two sub-classes namely co-operative local services and Internet services. The co-operative local services applications target local infotainment services such as media downloading, electronic commerce, point of interest notification, etc. On the other hand, global Internet services focus on data that can be achieved from Internet such as communities services for insurance and financial services, fleet management, parking zone management, etc [39].

These applications focus on providing the driver with information (latter case) or warnings (former case) of a hazardous road situations using DENMs as well as of the kinematic state of other vehicles using CAMs. Both V2V and V2I communications are based on establishing a direct wireless ad-hoc network with low latency medium access. The CAMs in particular are one of the key basic features required for deployment of safety related applications [40]. This is a 1-10 Hz periodic heart-beat message, broadcast by each vehicle to its current communication neighbors. In the standard [41], CAM rate is dynamically updated between 1 Hz and 10 Hz according to vehicle speed, changes in acceleration and motion status. The CAM update rate is increased when there is an increase in the vehicle dynamic state to assure the vehicle dynamics are correctly reflected in the messages content [40].

Currently, European ITS standards organizations are preparing release two. This will address the development of Cooperative-ITS standards for connected automated driving applications and C-ITS-based advanced driver assistance applications. For instance, ETSI TC ITS has established three projects: Cooperative Adaptive Cruise Control (CACC), road user safety, and platooning. The main concern of these projects is to carry out a pre-standard study of these applications including their functional and operational requirements such as performance, data exchange and communication etc. The operational requirements analysis is important for evaluating the suitability of existing standards for these applications as well as new features needed, e.g., message condition, communication protocol conditions, congestion control conditions, etc.

Among the referred projects/applications, we are particularly interested in platooning, which is the target of our work.

- A **Platooning application** is a concept that aims to increase the current road capacity by allowing groups of communicating vehicles sharing a similar journey to circulate with a small safety gap between each other. Each such group forms a platoon and is managed by a platoon leader, which is the vehicle at the head of the platoon (Figure 2.4). With expanded levels of automation, the platoon leader may agree with platoon members for group maneuvers such as joining of new vehicles or leaving of current members or merge with another platoon, or moving to a different lane. The platoon leader may also make decisions for members in specific circumstances, like controlling their target speed. The platoon leader is also responsible for observing the driving road environment and informing for the platoon members. The platoon members typically restrict themselves to following the vehicle ahead, potentially using CACC in a velocity and proximity feedback control loop.

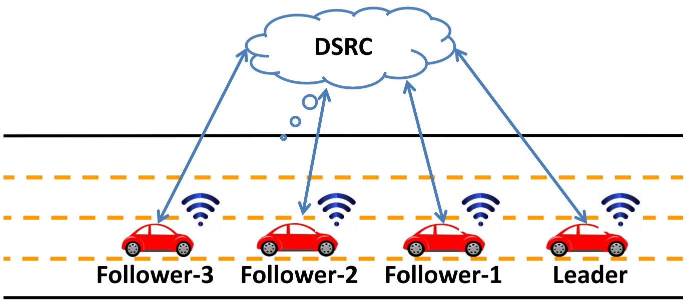


Figure 2.4: A group of cars making a platoon

In our work, we focused on the platooning application, only, and we aimed at providing specific MAC add-ons on top of IEEE 802.11p that enhance communications for this application. On the other hand, we do not address the feedback control part but the communication channel only. We believe platooning applications may benefit from a new communication protocol for better management of the wireless medium sharing among multiple platoons as well as for improved handling of platoon maneuvers such as joining, leaving and merging. To make the most out of the existing IEEE 802.11p standard, we aimed at the design of an overlay protocol that adapts IEEE 802.11p communications for different network conditions, particularly supporting higher loads caused by co-existence of other platoons, other collaborative applications and other background traffic that may create interference.

2.2 Medium Access Control (MAC)

VANETs are designed to provide various benefits in road safety. This aim essentially relies on supporting capable safety applications, which in turn require support for broadcasting messages to neighbouring vehicles, informing drivers about relevant situations. To assure their efficiency, safety applications require reliable periodic data dissemination with low latency. The MAC protocols in VANETs are responsible for improving access to the shared communication medium and thus play an important role in providing a reliable, fair and efficient communication channel. The MAC protocols are established in the data link layer, which is also responsible for providing multi-channel operation and error control mechanisms.

The vehicular MAC protocols can be broadly classified in two categories, **contention-based** and **contention-free** (also known as uncoordinated and coordinated, respectively) (Figure 2.5). The protocols in the former category have no predetermined communications schedule and vehicles are allowed to access the channel at arbitrary instants, whenever needed. Consequently, transmission collisions may occur, specially when the network load and the number of transmitters is high. The contention-based medium access protocols do not require synchronization among the vehicles, thus being simple to use, at the cost of inferior efficiency in the channel utilization under high network load due to collisions. One of such MAC protocols, CSMA/CA, is used by many technologies, including the current standard for V2V communication, IEEE 802.11p/DSRC, both in the WAVE [42] and ITS-G5 [5] protocol stacks. In CSMA/CA, a random backoff time drawn from an exponential distribution is enforced to mitigate collisions. However, due to the stochastic nature of the process, CSMA/CA fails to provide communication with bounded delays and may suffer from profound service degradation in dense traffic scenarios.

Conversely, contention-free MAC protocols require a predetermined channel access scheme that grants transmitters exclusive channel access, thus being generally collision-free. Several contention-free MAC protocols have been proposed in the literature for inter-vehicle communications using technique such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). These techniques allow each vehicle to access the channel using a predetermined time slot, frequency band or code sequence, respectively. The major advantage of these techniques is the absence of collisions among messages sent by vehicles in the same neighbourhood. The cost is a higher complexity of deployment since they require some kind of planning and, because of this planning, they are also less flexible for highly dynamic scenarios and they are also sensitive to misconduct by any transmitter, such as transmitting outside the allocated time or frequency slot.

Considering IEEE 802.11p, it is a contention-based MAC protocol as discussed at the beginning of Section 2.1.1, being thus highly flexible and easy to deploy. In WAVE, it is further enhanced with the priority-based access scheme of EDCA. Conversely, in ITS-G5 it is enhanced with DCC which acts on certain MAC parameters, e.g., transmission frequencies, data rate and power levels. However, both enhancements do not preclude access collisions and the quality of the channel can still be significantly degraded in the presence of intense localized traffic, particularly of the same priority class [31, 36, 6].

2.2.1 Adaptive Beaconing for Platooning

Platooning applications are typically built on periodic broadcast communications (beacons) for sharing the vehicles kinematic state. When using IEEE 802.11p, these communications are carried out with CAM messages. In the presence of multiple platoons, the network load can increase significantly to the point of degrading the performance of the IEEE 802.11p MAC. In these circumstances, there is a trade-off between the platoon control quality, which benefits from higher beacon rates, and the communication channel quality, which benefits from lower beacon rates.

Therefore, several research works were carried out to find adequate compromises for such trade-off, exploring dynamic adaptive techniques to avoid network congestion and their impact on the control performance. For example, the author in [43] investigated the DCC reactive control approaches based on message generation rate, transmission power and data rate, and focused on its impact on the stability of platooning control. An improved platoon control was proposed considering such impact.

In [44], the authors proposed Dynamic beaconing (DynB) according to which vehicles decrease or increase their beacon rates depending on whether the channel load is higher or lower than a desired level. In [45], the authors proposed a dynamic information dissemination protocol for platooning that exploits vehicle dynamics to adapt the transmission of beacons. The authors showed that the beaconing frequency can be less than 10 Hz when the control situation is stable. This allows reducing the channel load, hence improving the channel for transmitting safety messages.

In [46], the authors proposed a new MAC to facilitate reliable vehicle platooning. First, they proposed a consensus-based control mechanism and theoretically analyzed how the stability of the platoon could be affected by various parameters, including message loss due to imperfect inter-vehicle communication. Based on the control requirements, the authors proposed a communication protocol that considers both the periodic platoon control messages as well as event-triggered safety messages from individual cars.

2.3 Survey of TDMA-Based V2V Communications

Despite the mechanisms to control channel load and/or mitigate the impact of high network load and high collisions rate discussed in the previous section, handling these situations remains a challenge, particularly when contention-based MAC protocols are used.

In this thesis we focus on exploring the TDMA-based MAC protocols in the VANETs domain given their suitability to avoid, or at least significantly reduce, collisions [47, 37, 48]. For this reason, this section surveys this kind of protocols.

Generally, the benefits of TDMA-based techniques include a fair (equal) access to the channel for all vehicles, improved reliability of vehicles communications, more efficient channel utilization due to less collisions, and predictability of communication latency since messages arrive within a bounded delay or do not arrive at all, which is typically suitable for real-time applications.

TDMA protocols address the shortcomings of CSMA/CA by assigning concrete slots of time to each node, thus implementing a contention-free mechanism. TDMA protocols are well suited for use in platoon scenarios, given that platoons are well defined groups of vehicles that travel together for a significant time, thus making it easier to synchronize their communications. TDMA protocols can be broadly classified as distributed and centralized. Distributed TDMA can still be divided in direct implementations over the PHY and overlay protocols operating over some other MAC protocol. Centralized TDMA can be further divided in cluster-based and RSU-managed. We will not address RSU-managed TDMA since it departs from our V2V scenario. One example of such approach is V-FTT [21], which uses the RSU to execute centralized traffic scheduling, achieving superior traffic management capabilities and meeting strict real-time constraints. Conversely, other categories rely on a distributed approach in which vehicles coordinate among themselves without needing RSUs. Even if providing weaker real-time properties, this group does not pose any infrastructure requirements thus being easier to deploy. This is the approach we will follow.

Cluster-based TDMA MAC protocols map naturally onto the platooning application, where the leader can serve as the local network coordinator for each group while controlling the platoon. Overlay protocols offer exclusive communication time slots on top of an existing MAC protocol. As referred before, IEEE 802.11p is the standard MAC in VANETs, being available in many commercial off-the-shelf (COTS) equipment. Thus, implementing and testing overlay protocols is easy so as their deployment. Moreover, combining an overlay TDMA MAC with a CSMA/CA layer underneath also provides tolerance to bad transmissions timing, such as poorly synchronized nodes that may transmit outside their slots or asynchronous transmissions that do not have a slot assigned, such as event-based communications.

Figure 2.5 shows a comprehensive taxonomy overview of the various families of TDMA MAC protocols in VANETs. We highlight, with boldface font, the three protocols that we will use along this thesis, which we considered directly comparable, namely our proposal RA-TDMAp, PLEXE-slotted that is a protocol of the same class and which uses similar architecture, and the CSMA/CA mechanism of IEEE 802.11p to be used as reference. In the remainder of this section we review these families presenting representative examples of MAC protocols available in the literature. Finally, we also review existing models of network performance under specific MAC protocols. Most of the models are analytical and focus on the performance of CSMA/CA, as it is the MAC protocol implemented by IEEE 802.11p.

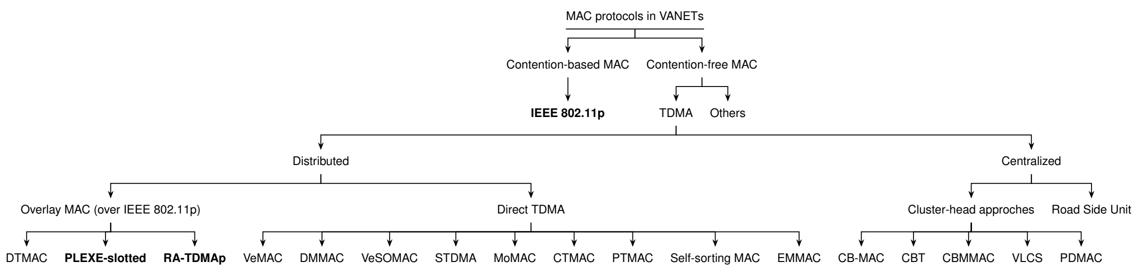


Figure 2.5: Classification of TDMA-based MAC protocols in VANETs.

2.3.1 Direct TDMA Protocols

This class of protocols implements TDMA directly over the physical layer with the TDMA layer controlling the exact transmission instants. Examples of this class include the following protocols.

Vehicular Ad Hoc Networks MAC (VeMAC) [49] is a contention-free multi-channel protocol for VANETs that supports efficient one-hop and multi-hop broadcast services on the control channel, which gives smaller rates of access and merging collisions caused by vehicle mobility. When a distributed mechanism is used to allocate a time slot, two types of collision may occur, access collision and merging collision [48]. Access collision occurs when more than two vehicles within the same two-hop neighborhood set attempt to access the same available time slot. This problem is likely to happen when a distributed mechanism is used. Merging collisions occur when two vehicles in different two-hop sets accessing the same time slot become members of the same two-hop set due to changes in their position. Generally, in vehicular networks, merging collisions are expected to happen in the following cases: when vehicles move at different speeds, vehicles move in opposite directions and RSUs installed along the road. In this protocol, merging collision rate is reduced by assigning disjoint sets of time slots to vehicles moving in opposite directions (Left and Right) and to the RSU. In VeMAC, each vehicle has two transceivers, the first one is always tuned to the CCH (control channel) while the other can be tuned to any SCH (service channel). The synchronization among vehicles is performed using the 1PPS signal provided by the GPS in each vehicle. Each frame transmitted on the CCH is divided into four essential fields: header, the announcement of services (AnS), acceptance of services (AcS) and high priority short applications. The VeMAC protocol can make use of the seven DSRC channels, it supports the same broadcast service on the CCH and on the SCHs, and decreases the rates of merging and access collisions. Although communications over the SCHs are overhead-free, the overhead of the VeMAC protocol on the CCH is reasonable due to the size of the control frame transmitted on the CCH. In addition, in VANETs, particularly in highway scenarios, the number of vehicles in each direction is not equal. Thus, the size of the slot sets should be adapted according to vehicle density on the highway. Anyway, the merging collision issue can arise when vehicle density is high. Indeed, if a moving vehicle detects that it cannot access a time slot from the set of slots reserved for vehicles moving in its direction, then it will attempt to access any available time slot reserved for vehicles moving in the opposite direction.

Dedicated multi-channel MAC protocol (DMMAC) [50] standing for Dedicated Multi-channel MAC protocol, is an alternative to the IEEE 802.11p standard. The aim of the protocol is to support an adaptive broadcasting mechanism designed to provide collision-free and delay-bounded transmissions for safety applications under different traffic conditions. The DMMAC structure is identical to IEEE 802.11p with the difference that the CCH interval is divided into an adaptive broadcast frame (ABF) and contention-based reservation period (CRP). The ABF further consists of time slots that are reserved by each vehicle as the basic channel for collision-free delivery of safety messages. The CRP uses CSMA/CA mechanism as its channel access scheme. During the CRP, vehicles negotiate and reserve the resources on service channels (SCHs) for non-safety applications. DMMAC implements a dynamic TDMA mechanism for basic channel (BCH) reservation based on the distributed access technique R-ALOHA. The length of the ABF frame is not uniform over the entire network. Each vehicle dynamically adjusts its ABF length according to its neighbors.

Vehicles Self-Organizing MAC protocol (VeSOMAC) [51] stands for vehicles Self-Organizing MAC protocol and uses an in-band signaling scheme that carries information about allocated slots and allows fast slot reconfiguration following topology changes such as when platoons merge. It aims at achieving fast TDMA slot reconfiguration without relying on roadside infrastructure or leader vehicles, which can enhance throughput for applications in highway scenarios. The VeSOMAC protocol operates in both synchronous and asynchronous manner. In the synchronous case, all the vehicles are assumed to be time-synchronized by using GPS where they share the same frame and slot boundaries. In the asynchronous case, each vehicle maintains its own frame boundaries.

Self-organized time-division multiple access (STDMA) [52], is a decentralized TDMA scheme that uses periodic frames further divided into time slots. When a vehicle joins the VANET, it first listens to the channel to get information from other vehicles positions and then performs four phases: initialization, network entry, first frame, and continuous operation. In the initialization phase, the vehicle listens for the channel activity within one frame called super frame to determine the frame structure. In network entry the joining vehicle introduces itself to the VANET by determining the first transmission slot; if all slots are occupied the vehicle will use the slot of the farthest away vehicle. In the first frame phase slot starts transmitting in the slot that it chose before and finally the vehicle enters the continuous phase transmitting periodically messages in that slot. Recently, the work in [53] compared STDMA with RA-TDMA [8] since both are ad-hoc, distributed and dynamic. STDMA works with a global frame divided in predefined slots that are reused by the vehicles within reach of each other. Under high traffic the mechanism to assign slots dynamically becomes less effective and collisions grow. Conversely, RA-TDMA is an overlay protocol (not part of this class) that allows using practically 100% of the bandwidth. It organizes nodes in individual groups, e.g., platoons, which they need to join or leave. It was the basis for the work in this thesis and will be explained later on.

Mobility-aware collision avoidance MAC (MoMAC) [54] assigns time slots according to the traffic road topology and lane distribution on roads. In this work, different lanes on the same road segment and different road segments at intersections are associated with disjoint slot sets, i.e., assigning vehicles that are bound to merge with disjoint time slot sets.

Cooperative TDMA (CTMAC) MAC based protocol merges CSMA and TDMA [55], in this work the idea is that CSMA works better in sparse vehicle density while TDMA is better for high density, thus they can complement each other. CTMAC rapidly switches the channel access method between CSMA and TDMA according to the vehicle density. When using CSMA it also determines the number of back-off time slots according to the vehicle density. Due to the use of fixed back-off to reserve channel, bounded delay is guaranteed, even in the case of large vehicle crowding. The most important thing to make smooth changes between the two methods is the vehicle density value.

Prediction-based TDMA MAC (PTMAC) [56] is designed to eliminate the so-called encounter collisions by prediction before the collisions happen, while maintaining high-slot utilization and with very small additional overheads. Most of the encounter collisions can be predicted and, potentially, eliminated before they really happen. The prediction is based on the vehicle kinematic information that is already provided to support safety-related applications. The protocol revealed suitable for the two-way traffic and four-way intersections in urban areas.

Self-sorting MAC protocol is proposed in [57], to improve VANETs performance in high-density scenarios. In this work vehicles form a transmission queue with others around them just like a “count off” process before sending data packets. Once the queue’s length reaches a set threshold, it has the right to control the channel and the members of the queue will send the data messages in the sequence recorded by the self-sorting process, which is described using a Markov chain. Different from the random access of all nodes, only the head of the queue which has completed the self-sorting process will compete to access the channel on behalf of all the nodes in the queue, which greatly alleviates the contention among the nodes competing for accessing the channel randomly. The control messages in the protocol are collision-tolerable, which are separated from data messages.

Efficient Multi-Channel MAC Protocol (EMMAC) in [58] is a multi-channel based protocol for VANETs. This work uses the modified announcement packet to reduce payload size of a packet transmitted in the TDMA period and thus improve efficiency. In this work, the author focuses on the multichannel hybrid media access control schemes, which are based on draft IEEE 802.11p and IEEE 1609.4 standards.

2.3.2 Cluster-Based TDMA Protocols

In this family of protocols, vehicles are clustered by physical proximity and relative position. A cluster head sets up the TDMA frame for that cluster and generally synchronizes the other vehicles in the group.

In Cluster Based Medium Access Control (CBMAC) [59], the medium is divided into multiple CCH and one data channel (DCH). Access to the CCH channels is based on CSMA/CA while the DCH channel uses TDMA to guarantee low transmission delay and collision-free transmissions within each cluster. To form clusters, all the vehicles tune to the CCH and elect one cluster head (CH). Each cluster member sends its position and speed to its CH periodically in its own TDMA time slot. To avoid inter-cluster interference, each CH selects a different orthogonal code from that of its neighbouring CHs.

Clustering-Based Multichannel MAC (CBMMAC) [60] has been developed to support both traffic safety applications and a wide range of non-safety applications. It combines contention-free and contention-based medium access control protocols. It redefines the functions of the seven DSRC channels, where CH178 and CH174 are respectively the Inter-Cluster Control (ICC) channel and the Inter-Cluster Data (ICD) channel. Ch172 is the Cluster Range Control (CRC) channel, and the remaining channels (Ch176, 180, 182,and 184) are the Cluster Range Data (CRD) channels. CBMMAC deploys three main protocols: cluster configuration, intra-cluster and inter-cluster coordination communication in order to avoid merging collisions and inter-cluster interference problems.

Cluster-Based TDMA system (CBT) protocol [61] aims at providing contention-free intra-cluster and inter-cluster communications while minimizing collisions when two or more clusters are approaching each other. The protocol uses a simple transmit-and-listen scheme to quickly elect a vehicular-network coordinator (VC). The CBT system assumes that each vehicle is equipped with a GPS positioning system and synchronization between the vehicles can be performed by using GPS timing information. The access time is divided into frames and each frame consists of n time slots.

Vehicle-to-Vehicle Local Clock Synchronization (VLCS) [62] initially starts with node clustering to improve the nodes managements. Nodes are classified in two types, Cluster Heads (CHs) and ordinary nodes. A CH manages a cluster by keeping record of all the nodes associated to its cluster, whereas any node other than a CH comes under the category of ordinary nodes. The clustering process is followed by clock synchronization, which is composed of two phases, namely, inter-cluster and intra-cluster clock synchronization. Here, the first phase involves all the CHs and updates their clocks to a commonly shared clock. In the second phase, each CH then synchronizes its member nodes, which completes the clock synchronization process. Similar intra-cluster clock synchronization techniques have also been presented in [63].

Priority-Based Direction-Aware Media Access Control (PDMAC) [64] is a TDMA-based protocol for Warning Message Dissemination in VANETs. In this work, the authors proposed a cluster-based vehicle-to-vehicle MAC protocol to prioritized warning messages delivery. The protocol introduces inter-cluster clock synchronization alongside intra-cluster synchronization, which minimizes communication overhead and improves channel utilization. Moreover, PDMAC uses a three-tier priority assignment to ensure reliable and in-time delivery of warning messages by taking into account some important parameters like the direction component of nodes, message type, and severity level on each tier.

2.3.3 Overlay TDMA Protocols

This group of protocols implements TDMA on top of the CSMA/CA layer of IEEE 802.11p. Thus, they can be readily implemented on COTS IEEE 802.11p interfaces and are tolerant to uncoordinated (non-complying timing) traffic. However, note that the transmission instants defined by the TDMA layer can be modified by the CSMA/CA layer below.

The fully distributed and infrastructure-free TDMA-based MAC protocol (DTMAC) [65] is based on the VeMAC protocol such that channel time is partitioned into frames and each frame is further partitioned into two slot sets, Left and Right as discussed before. In DTMAC protocol the road is dissected into small fixed areas across in which the time slots can be reused. Thus, any vehicles in different nearby areas accessing the channel at the same time will not interfere. DTMAC uses the vehicular location information to help the vehicles access the channel in an efficient way, in order to solve the collision problem caused by high mobility and to reduce the channel access delay. Thus, it contributes to alleviating the scalability limitations of VeMAC by allowing parallel transmission in different areas.

PLEXE-slotted [9] divides a TDMA round into equal intervals according to the number of vehicles in the platoon. Transmissions in the platoon take place in a cycle starting by the leader, which transmits with high power to synchronize all platoon members, followed by all the followers from first to last and transmitting with reduced power. The followers just reach the neighbouring followers and propagate information down the platoon in a multi-hop fashion. All platoon members transmit in consecutive intervals inside the TDMA round. A shortcoming of this protocol is the lack of support to handle extra-platoon periodic communications. For example, if nearby platoons or vehicles transmit with similar period and in phase, this can lead to frequent collisions until clock drifts separate their transmissions in time.

Re-configurable and Adaptive TDMA for platooning (RA-TDMAp) [13] is the protocol we propose in this thesis and which will be discussed in Chapter 3. It is similar to PLEXE-slotted, as it also divides the TDMA round period in equal intervals among the number of vehicles in the platoon. However, it addresses the limitation of the PLEXE-slotted method (of co-existence with extra-platoon periodic transmissions) by having each platoon shifting the phase of its TDMA frame (or round) thus moving away from the phase of other platoons or vehicles. In RA-TDMAp, the followers transmissions are in inverse order, starting from the last (farthest from leader) to the first. The phase-shifting mechanism is based on observing delays suffered by transmissions of the platoon members. By using an inverse round circulation, the leader acquires the delays information observed by all followers in just one round and can then adjust the start of the next round to adjust the phase as needed. This allows escaping, with high probability, the interference from other platoons or vehicles. When used over a set of neighbouring platoons, RA-TDMAp provides an implicit synchronization mechanism, by which platoons automatically adjust their cycle phase to avoid or reduce mutual interference.

2.3.4 Discussion

As we saw in the previous sections, there is a myriad of TDMA-based protocols proposed for VANETs, trying to exploit their capacity to avoid and/or reduce collisions, in an attempt to improve the channel quality and thus improve the performance of collaborative traffic applications, too. Generally, it is hard to find absolute improvements and each MAC protocol typically imposes specific trade-offs between features that make it more suited to some kind of applications than others.

Similarly, the classification of some protocols is not unique and other alternatives could be considered. For example, overlay protocols could be considered under contention-based MAC since they have the collision detection and arbitration mechanism of IEEE 802.11p in place. Another possible classification would be to consider PLEXE-slotted and RA-TDMAp under centralized cluster-head approaches, since they effectively set up one cluster per platoon in which the leader plays the role of cluster head synchronizing the other nodes in the cluster. The difference, however, is that these cases have on explicit inter-cluster synchronization, thus inter-cluster management is distributed. In PLEXE-slotted, there is no inter-cluster synchronization at all, which is a cause of performance degradation under high loads as we will see later on. RA-TDMAp has an implicit inter-cluster synchronization mechanism that is responsible for its good performance under high load, which we will explore in this thesis.

One of the typical requirements of VANETs is scalability since the number of vehicles in many traffic scenarios can be very large. This is challenging for MAC protocols using both centralized and distributed TDMA frame management relying on a global TDMA frame. Some distributed frame management protocols mitigate this problem by promoting slot reuse, e.g., DTMAC and STDMA. This, however, may lead to increased rates of collisions under high traffic density, limiting the efficiency that can be achieved. Two examples of centralized cluster-based protocols are CBT and CBMAC. Both perform well when node density is low, too. However, their performance degrades as density increases due to the high inter-cluster collision rates. In CBT, a high network load also implies a high access delay, further degrading network performance.

A particular aspect that seems to play a relevant role in cluster-based protocols is the overhead associated to the cluster management, namely election of cluster head and maintaining an updated list of cluster members. This can be a limiting factor for operation on a highly dynamic network topology.

Concerning direct TDMA approaches, they are all dependent on the quality of the synchronization to avoid collisions effectively. Poor synchronization immediately leads to high collisions and strong penalty in bandwidth efficiency. Moreover, due to the precise timing control needed to keep transmissions from overlapping, these protocols are incompatible with the IEEE 802.11p standard, which makes them harder to experiment with and also to deploy.

To give a broad general overview of the main features of representative protocols that we surveyed, we present a qualitative comparison in Table 2.1. We address the channel access scheme, namely TDMA or hybrid TDMA/CSMA, if clock synchronization is required or not, the resilience to external traffic, meaning whether asynchronous traffic is tolerated or not, the level of scalability, the effectiveness in reducing collisions, the support for real-time applications and finally whether the protocol was developed for safety-only applications, non-safety-only applications or both.

In terms of real-time support, we note that all direct TDMA protocols either deliver packets on time or not at all, which is a suitable behavior to support real-time applications. On the other hand, the overlay protocols, particularly without global control (PLEXE-slotted and RA-TDDMAp), may suffer unbounded delays caused by the CSMA/CA arbitration with external traffic. However, both protocols bound the maximum waiting time for a packet, thus presenting potentially longer but still bounded delays.

Beyond these properties, we note that all protocols were designed for highway scenarios. We also note that all protocols support communication between traffic traveling in both directions. However, some protocols (e.g., PLEXE-slotted and RA-TDMAp) were particularly designed to support platooning, which implies that vehicles are traveling in one direction, only. Nevertheless, those protocols support communications with nodes external to the platoon and these can be vehicles traveling in either direction.

Table 2.1: Qualitative comparison between distributed TDMA-based MAC protocols

Protocol	Medium access technique	Clock synchro-nization	Resilience to external traffic	Scalability	Reduction in collisions	Real-time support	Safety applications
VeMAC	TDMA	Yes	No	Low	High	High	safety+non-safety
DMMAC	TDMA	No	No	High	Medium	High	safety
VeSOMAC	TDMA	Yes	No	Low	Low	High	safety+non-safety
STDMA	TDMA	Yes	No	High	High	High	safety+non-safety
MoMAC	TDMA	No	No	Medium	High	High	safety
CTMAC	TDMA	No	No	Medium	Medium	High	safety
PTMAC	TDMA	No	No	Medium	High	High	safety
self-sorting MAC	TDMA	No	No	High	High	High	safety
EMMAC	TDMA/CSMA	No	No	Medium	Medium	Low	non-safety
DTMAC	TDMA	Yes	No	High	Medium	High	safety
PLEXE-slotted	TDMA/CSMA	Yes	Yes	High	Medium	Medium	safety
RA-TDMAp	TDMA/CSMA	Yes	Yes	High	High	Medium	safety

2.4 Towards a MAC for Platooning

Along this chapter we surveyed different MAC protocols for VANETs. From this survey, we saw that different protocols favor different applications. According to our objectives, we are looking for a MAC protocol that is particularly suitable for platooning. Moreover, we would like to address the scalability versus Quality-of-Service trade-off, which is one of the toughest challenges in VANETs. In other words, we seek a MAC protocol that has no predefined limit to the number of vehicles that can communicate in a given area beyond the capacity of the physical channel and causes the least degradation in Quality-of-Service under high spatial density of transmitters.

We saw that contention-based MAC protocols, from which CSMA/CA used by IEEE 802.11p is a notorious example, show a good fit in supporting scalability given the distributed operation and absence of any central or global management structure. However, the degradation observed under dense traffic is significant due to the potentially long delays caused by the arbitration process.

Conversely, we also saw that contention-free MAC protocols are dependent on tight synchronization, but have the potential to offer better QoS in dense scenarios. However, improving scalability implies some kind of dynamic slot allocation that brings overhead and potential collisions.

We also referred that overlay MAC protocols, which mix both paradigms, have the potential to offer the best of both worlds and this is the direction we will follow in this thesis towards a scalable and efficient MAC for platooning. Moreover, focusing on platooning allows to consider consistent topological units, the platoons, that remain stable for a long time. The high dynamics typically associated to VANETs topology is then limited to extra-platoon nodes, either from other platoons as well as from independent external vehicles. This allows looking at the network as just one platoon, which is stable, and include all communications from other nodes as external interference (in the platooning application).

This led us to propose the RA-TDMAp protocol, which is the central piece in this thesis and which exploits the concepts of permeable slot/frame and implicit frame synchronization to allow the coexistence of multiple platoons and independent vehicles up to the capacity of the physical channel with reduced QoS degradation.

Chapter 3

A Scalable Communication Protocol for Vehicle Platooning

This chapter describes the design and development of a communication protocol for platooning, namely RA-TDMAp, that addresses the challenge referred at the end of the previous chapter (Section 2.4), i.e., a MAC protocol that combines high scalability with good QoS under dense traffic.

RA-TDMAp has two distinct mechanisms, namely the reconfiguration of the TDMA frame slot structure and the adaptation of the frame phase, acting on the instantaneous round period. In this chapter, we discuss the adaptive feature of the protocol, only, and show its effectiveness. The reconfiguration is discussed in Chapter 5. Our protocol is able to keep all the vehicles in one platoon synchronized even in the presence of interfering traffic, e.g. from other vehicles, by adapting the phase of the TDMA frame to escape periodic interference. On the other hand, it reduces channel occupation by having the leader, only, transmitting with high power to reach all the platoon at once while the followers transmit with low power and may need to forward information of each other to make it reach the leader. The order of transmission in the round is such that the leader gathers information from the whole platoon in just one round.

We developed, tested and validated RA-TDMAp using the PLEXE simulation framework. In all tests we compared RA-TDMAp to two related protocols that are directly comparable, namely the overlay TDMA MAC PLEXE-slotted and the basic CSMA/CA of IEEE 802.11p, and we considered three metrics: channel busy ratio, collisions rate and safe time ratio.

The work in this chapter was essentially reported in the following publication:

- [13] A. Aslam, L. Almeida, and F. Santos, "A flexible TDMA overlay protocol for vehicles platooning," *in* Communication Technologies For Vehicles, 13th International Workshop, Net4Cars2018, pp. 169–180, Springer, 2018.

3.1 Reconfigurable and Adaptive TDMA Protocol for Platooning

3.1.1 TDMA Scheme

The aim of a MAC protocol for VANETs is to ensure that every vehicle is granted access to the channel in bounded time, mitigating access collisions and providing a channel quality that is adequate to the applications that run on top. TDMA is a time multiplexing scheme for periodic communications that consists of dividing the time into a periodic set of slots called frame, and assigning a slot in this frame to a different vehicle. Figure 3.1 shows a simplified diagram of TDMA frame with respective slot assignment structure in a VANET. If the allocation of vehicles to slots is exclusive and all vehicles transmit inside their slots, only, then channel access collisions are avoided. The advantages of TDMA MAC protocols are considerable since they provide equal access to the channel for all the vehicles, efficient channel utilization, lower number of collisions, high reliability for safety-related communications, deterministic access time even with a high traffic load and offered QoS adequate for real-time applications.

Generally, a TDMA mechanism requires strict global clock synchronization to allow vehicles determining the instants of all their slots into the future. In VANETs, clock synchronization is typically achieved from GPS. However, GPS signals are not always available, particularly inside cities and at vehicles start up, limiting synchronization and its precision. Moreover, the typical TDMA fixed slots-to-nodes allocation creates difficulties in the context of dynamic typologies typically found in VANETs.

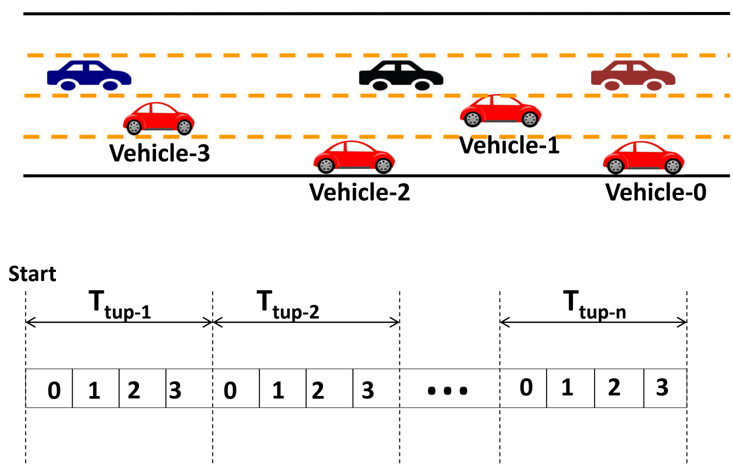


Figure 3.1: An example of a TDMA structure.

The synchronization of vehicles is a critical issue, too, in common TDMA approaches in VANETs. In fact, vehicles that are poorly synchronized with the TDMA frame, or completely asynchronous, will transmit concurrently with respect to the transmissions in the frame, creating collisions and leading to packet losses. One situation that seems particularly unfavorable, because it may create recurrent periodic interference, is when a non-synchronized vehicle transmits periodically in phase with the TDMA frame and with a period that is similar to the TDMA round period, or to a multiple or sub-multiple of it (coherent) as shown in Figure 3.2.

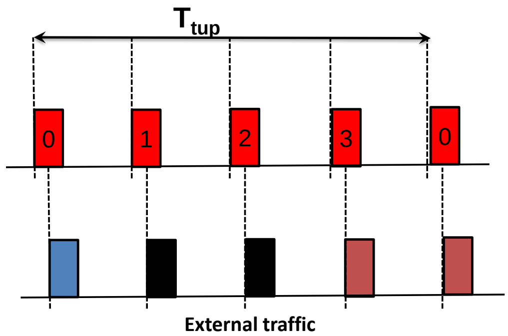


Figure 3.2: Recurrent interference between a TDMA frame (upper line) and external periodic traffic (lower line)

These limitations are also present in the Robotics domain, for teams of cooperating robots. In this case, previous work proposed the RA-TDMA [8] protocol, which is a modified TDMA approach to cope with the referred issues. In particular, RA-TDMA sets a frame per team, only, leaving any other transmitters out (these will generate *external traffic*, i.e., asynchronous traffic that may interfere with the team TDMA frame transmissions). Moreover, the synchronization inside the team does not rely on global clock synchronization. It uses, instead, the instant in which a message from the team is received to re-synchronize with the other team nodes. We believe that the same approach can be advantageously applied to VANETs over the IEEE 802.11p standard as we will see next.

3.1.2 RA-TDMAp for vehicle platoons

RA-TDMAp is an instantiation of RA-TDMA [8] to vehicle platoons that is modified with the use of transmission power control, synchronization state gathering and a specific reconfiguration mechanism. It is a thin layer inserted just above the IEEE 802.11p MAC protocol that controls the transmission instants, transparent for the applications that run on top (Fig. 3.3).

The power management approach is that of [9] (PLEXE-Slotted) in which the leader transmits with high power so that it reaches all platoon members at once and serves as a synchronization mark, setting the start of a round (Fig. 3.4). The follower vehicles transmit with low power equally spaced in the beacon interval (round period). Low power transmissions allow to significantly reduce the channel occupation and to increase the scalability of the protocol. However, RA-TDMAp differs from [9] in two main aspects, the leader adjusts its transmission instants according to the delays suffered by the platoon members in the previous round and the order of transmissions of the followers is inverted, starting from the last vehicle, which transmits after the leader, up to the first follower that transmits at the end of the cycle, before the next leader beacon (Fig. 3.4).

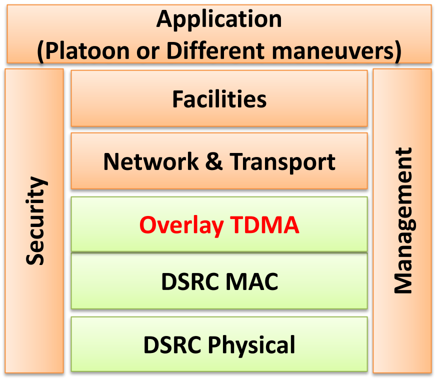


Figure 3.3: ITS-G5 architecture with an additional TDMA overlay layer

.

Figure 3.5 shows the sequence of TDMA frames and their structure in RA-TDMAp. Each frame is divided by the N vehicles in the platoon to create the frame slots. However, these slots are much larger than what is needed for the transmissions of each platoon member, typically just the beacon. the unused slot time is available for external traffic, managed with CSMA/CA. This is what makes these frames permeable and will be used to support the co-existence of multiple concurrent frames.

A distinctive feature of RA-TDMAp, which is inherited from the original RA-TDMA protocol, is the adaptive synchronization mechanism. This is based on measuring the delays suffered by the transmissions of the platoon beacons. These delays are typically caused by the CSMA/CA mechanism when mitigating collisions with external traffic both circumstantial and periodic (E in Figure 3.6). Note that, all nodes in the platoon know when a beacon is expected and thus can measure its delay upon reception. When a node measures a beacon delay it saves it in a *delayList* and shares this list piggybacked in its own beacon. At every hop, the *delayList* is consolidated and propagated *upstream*, reaching the leader at the end of the round. The leader then delays the start of the next round by an amount computed from the *delayList* reported by the followers, typically the maximum within predefined bounds (δ_2 in Figure 3.6). This corresponds to shifting the phase of the platoon round, causing all beacon transmissions in this platoon to be triggered later, potentially avoiding the collisions with external traffic that caused the delays in the previous round. The adaptation mechanism is independent per platoon and just considers the platoon members, implying low overhead and full scalability. The pseudo-code of the adaptive synchronization of RA-TDMAp is described in Algorithm 1.

Figure 3.6 also shows the assignment of logical IDs to vehicles according to their position in the platoon, starting with the leader that is node 0, followed by the last vehicle, 3 in this case, then 2 and then 1, the closest to the leader. This position-based rule can rely on GPS, on a topology tracking method or on both.

The beacon interval in RA-TDMAp, interchangeably called TDMA round period, is represented by T_{tup}. It is divided by N vehicles currently engaged in the platoon creating a target

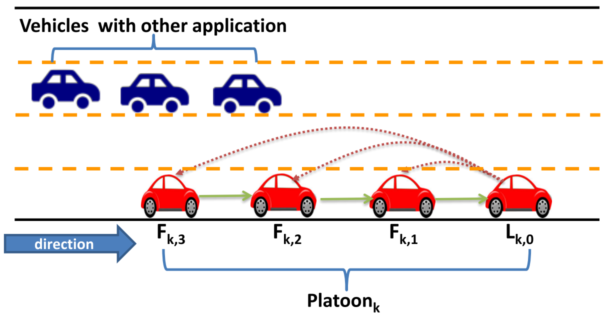


Figure 3.4: A platoon of four cars (red) and three external cars (blue), running separate applications, possibly another platoon.

separation between consecutive platoon beacons equal to $T_{xwin} = T_{tup}/N$. If in the n^{th} round the leader transmits at time $t_{n,0}$, the follower $i > 0$ in that round is expected to transmit at time $t_{n,i}$ (Eq. 3.1).

$$t_{n,i} = t_{n,0} + T_{xwin} \times (N - i) \tag{3.1}$$

Once vehicle 1 transmits, the leader becomes aware of all delays that may have affected the platoon beacons in that round (δ_i, i=1..N-1). The leader then uses the maximum observed delay value, truncated to a tolerable limit (Δ), and it delays its next beacon transmission by that value. Similarly to T_{tup}, Δ is predefined offline and bounds the maximum possible frame phase adaptation. Using Δ allows bounding the maximum delay that can affect the leader beacon transmission and it is normally set to a fraction ε of the slot width T_{xwin} (Eq. 3.2). A typical value is 0.5.

$$\Delta = \varepsilon \times T_{xwin}, \qquad 0 < \varepsilon < 1 \tag{3.2}$$

Larger values of ε can make the round too irregular because of too frequent adaptations consequently delay in the next transmission of platoon members which is not acceptable for safety critical application while shorter values smooth the round duration due to fewer adaptations.

This is formalized in Eq. 3.3. Note that δ_i is the delay between the effective and expected reception instants of the preceding vehicle(s).

$$t_{n+1,0} = t_{n,0} + T_{tup} + \min(\Delta, \max_{i=1..N-1}(\delta_i)) \tag{3.3}$$

In the presence of packet losses, if the leader does not receive information from the delays that affected the followers, it considers them as null and transmits one beacon interval after the previous transmission. Similarly, if a follower misses the leader beacon it transmits its own beacon one beacon interval after its previous transmission. This makes the protocol very robust to varying channel conditions.

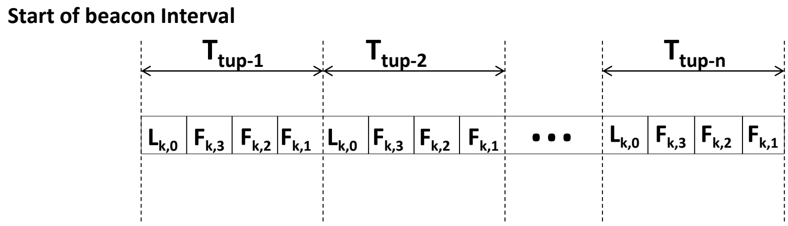


Figure 3.5: Platoon TDMA frame with inflated slots and their assignment.

Algorithm 1 RA-TDMAp protocol

```
procedure ADAPTIVE SYNCHRONIZATION IN RA-TDMAP
    initialize vector delayList[]:
    On startup protocol:
    if myRole = LeaderCar then
        scheduleAt(SendBeacon, beaconInterval);
    SendBeacon():
    if myRole = LeaderCar then
        sendBroadcast PlatooningMessage;
        scheduleAt(SendBeacon, beaconInterval+maximumDelay);
    else
        sendBroadcast PlatooningMessage;
        scheduleAt(SendBeacon, beaconInterval);
    OnBeacon(beacon):
    if myRole = LeaderCar then
        leader_now_time ← now_time;
    if myRole = getCarID then
        receive_instant ← now_time;
        expected_time ← leader_now_time + offset + transmission_time
        node_Delay ← receive_instant − expected_time;
        if node_Delay < 0 then
            node_Delay ← 0;
        push(delayList,(node_Delay));
        UpdatedelayList;
        if myRole = LeaderCar then
            maximumDelay ← *max_element(delayList.begin(), delayList());
    OnLeaderBeacon(beacon):
    unschedule(SendBeacon);
    scheduleAt(SendBeacon, myPosition · offset);
```

3.1.2.1 On the coexistence with platoons travelling in opposite directions

Finally, a quick note on the concrete situation of platoons that travel on opposite directions. This is a situation that is specifically addressed by some of the protocols referred in the Chapter 2. However, in our protocol there is no need to handle this situation separately. In fact, platoons traveling in opposite directions will hear each other for a few seconds, only, and during that time

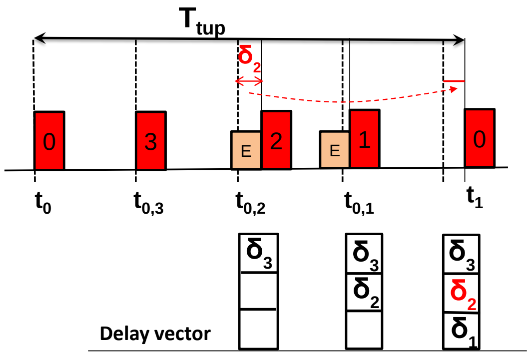


Figure 3.6: Adaptive synchronization in RA-TDMAp, with interference and delays measurement and propagation.

they will interference as any other platoons, triggering the frame phase adjustment mechanism. Since there is no specific slot allocation mechanism, as in the other mentioned protocols, there is no additional overhead caused by the short duration links between platoons traveling in opposite directions.

3.2 Simulation Framework

To analyse the RA-TDMAp protocol under different network and road traffic conditions we decided to use PLEXE [66], which is an Open Source extension to the well known and widely used Veins [67] simulation framework that builds on SUMO – Simulation of Urban MObility [68] for road traffic simulation and on the discrete event simulator OMNeT++ [69]. The Veins simulation framework provides a simulation environment able to test real-world scenarios, considering high mobility, high-level application protocols, together with communication and networking protocols with the full stack of IEEE 802.11p/ IEEE 1609.4 standards. In turn, OMNeT++ sets the environment to define the applications and protocols logic, allowing to collect operational data for performance analysis.

PLEXE is the current state-of-the art system level platooning simulator, incorporating mobility tightly-coupled with automatic control and communications. It allows defining highway scenarios, effective application, and protocols as well as analyzing network metrics such as collisions and packet delivery ratio etc. Figure 3.7 shows a snapshot of the PLEXE graphical front-end with a platoon (red cars) together with other external traffic (blue cars).

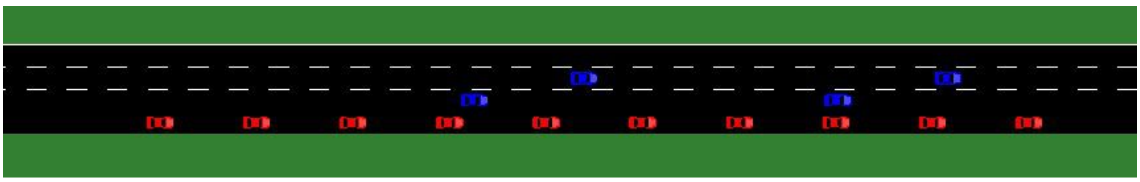


Figure 3.7: Screenshot of the PLEXE

3.3 Preliminary Evaluation of the Protocol

In this section, we analyze the performance of the RA-TDMAp protocol in demanding traffic conditions resorting to the PLEXE simulation framework (Section 3.2). We first show the simulation setup including the used models and scenarios, after we validate the adaptive feature of RA-TDMAp in platooning and then we compare RA-TDMAp with two other protocols, namely PLEXE-slotted and IEEE 802.11p (CSMA/CA) (Section 3.3.3). For the comparison we used two typical network metrics, similarly to [9], which are the *channel busy-time ratio* and the *collisions rate*, both metrics provided directly by the VEINS simulator. Moreover, we also included another comparison using the so-called *safe-time ratio*, which represents how well the protocols meet specified application timing requirements. These metrics will be explained further on.

3.3.1 Simulation Setup

We used the PHY and MAC models of IEEE 802.11p proposed in [70], using a bitrate of 6 Mbit/s, which is suited for demanding safety related applications [71]. We configured the transmission power of the leader to 100mW (high power) as it needs to reach all the cars in the platoon. For the followers we used three different power values (low power), namely 0.05mW, 0.5mW and 1mW, since they only need to communicate with the car in front. Furthermore, we only the CCH channel, only, without switching between Control Channel (CCH) and Service Channel (SCH). All beacons used the same Access Category (*AC*). Table 3.1 summarizes all communication related parameters.

Table 3.1: PHY and MAC parameters

Parameter	Values
PHY/MAC model	IEEE 802.11p/1609.4 (CCH only)
Channel	5.89 GHz
Bitrate	6 Mbit/s
MSDU size	200B
Leader's Tx power	100mW
Follwer's Tx power	0.05mW, 0.5mW and 1mW

To investigate the protocol performance, we carried out a set of simulations in a moderately dense traffic environment. We specifically simulated a realistic case with a stretch of a 4-lane highway filled with 160 cars organized in platoons of 10 vehicles, plus 10 external cars that create extra communication interference. Other relevant parameters are the distance between vehicles inside the platoon (gap), set to 5m, and the speed of all the platoons, set to 100 km/h. The summary of the simulation parameters is shown in Table 3.2.

3.3.2 Validating RA-TDMAp Adaptation to Interference Delays

The adaptive feature of RA-TDMAp is its capacity to shift the TDMA round to avoid transmissions that caused interference delays to the platoon beacons. If the interference is periodic and

Table 3.2: Scenario configurations

Parameter	Values
Number of cars	160
Platoon size	10 cars
External cars	10
Inter-vehicle gap	5m
Controller	CACC

with similar period, shifting the round removes the interference. If further delays subsist, the protocol continues shifting the round. Thus, given its relevance, we show here a validation of this adaptive feature of the protocol before moving to the comparisons. For the sake of simplicity of representation, we used a platoon with just 4 vehicles in the same simulation scenario and we logged the respective transmission instants.

Figure 3.8 shows the evolution of the offsets of the transmissions of the platoon members with respect to the leader transmission in each cycle. Each trace corresponds to the offset of one member (1 to 3 starting from below), except for the upper trace that represents the next leader transmission with respect to its previous one, thus it shows how much the leader has delayed the next TDMA round (or cycle). Without interference from external vehicles the offsets would be constant as given by Eq. 3.1. However, the figure shows there are in fact interferences, which are then accommodated by the leader in the following cycle (upper trace) according to Eq. 3.3. This behavior is clear in the figure with the upper trace containing the variations of the lower traces. However, it has more variations than these, since the leader transmissions also suffer direct interference. Finally, the tall spikes that sporadically affect the upper trace represent leader beacon losses, doubling the difference between consecutive leader beacons.

3.3.3 The Protocols under Comparison

We used the three protocols, namely RA-TDMAp, PLEXE-slotted and CSMA/CA for comparsion. The first MAC protocol we considered in this study was **CSMA/CA** (the MAC of IEEE 802.11p), which uses carrier sensing and random backoff intervals to mitigate potential collisions. In this case, all vehicles transmit a periodic beacon with period T_{tup} but without any control of their relative phases, i.e., all transmissions are independent periodic processes. Thus, it is possible to fall into pernicious scenarios (named *critical intervals* in [72]) in which several vehicles transmit practically in phase (or, in other words, with *high coherence* and a small phase difference), creating frequent collisions until their clocks drift away.

The second MAC protocol we considered is **PLEXE-slotted** [9], an overlay TDMA protocol for platoon communication that works directly on IEEE 802.11p and synchronizes the beacons of the vehicles in a platoon avoiding or further reducing potential collisions among them. The leader transmits its beacons with period T_{round}. This period is then divided in N equal slots of width $T_{\text{xwin}} = T_{\text{round}}/N$. The leader transmits at the beginning of the first slot and all follower vehicles synchronize upon the reception of the leader beacon and transmit their own beacons

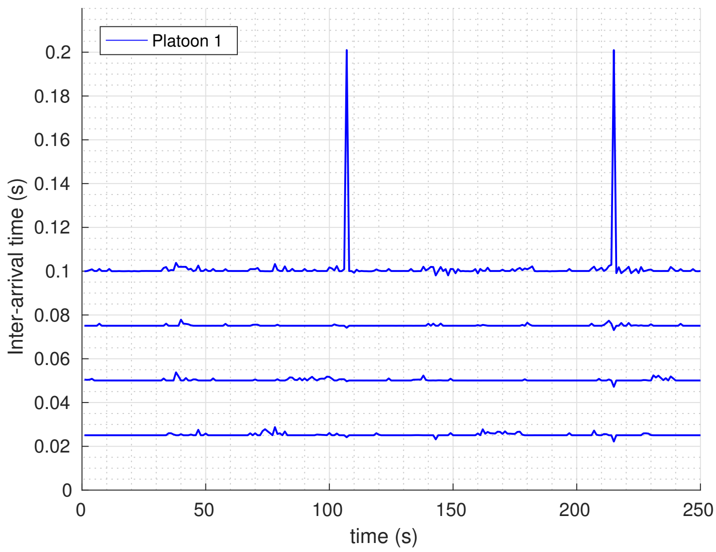


Figure 3.8: Adaptation mechanism of RA-TDMAp, offsets of the followers beacons (lower 3 traces) and of the next leader beacon (upper trace)

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at the beginning of their respective slots. Consequently, all transmissions in the platoon will be triggered with T_{xwin} separation. The sequence of transmissions starts with the leader and continues with the first follower and then throughout the platoon until the last follower. We refer to this sequence of platoon beacon transmissions as *downstream*. Nevertheless, this protocol is agnostic to the traffic external to the platoon. Thus, it is still possible to fall in critical intervals in which different platoons, or independent vehicles, transmit with a phase similar to that of the vehicles in the platoon, again leading to frequent collisions and degrading the quality of the communications until the clocks drift away. In the presence of sufficient number of platoons, the effect of the intra-platoon synchronization that PLEXE-slotted does is very slim and this protocol ends up behaving very similarly to CSMA/CA on which it operates.

RA-TDMAp is the third MAC protocol we consider, also an overlay protocol working over IEEE 802.11p that we proposed and discussed in Section 3.1.2. This is very similar to PLEXE-slotted in what concerns the transmissions inside each platoon but it includes a simple mechanism that enforces implicit global synchronization across all neighbouring platoons and independent vehicles. The fact that the mechanism is implicit makes it scalable to the capacity of the channel without needing explicit inter-platoon coordination.

3.3.4 Comparison Metrics

We ran the simulation for 30s of simulated time and gathered traces in the scenario referred in Table 3.2 using these three cases. All vehicles started transmitting at random instants, using the same seeds for the three protocols. For PLEXE-slotted and RA-TDMAp all followers synchronized with the respective leaders. RA-TDMAp further carried out the implicit synchronization among platoons with its phase adaptation mechanism.

3.3.4.1 Results of *Busy Time Ratio*

The first metric we use for comparison is the **channel busy time ratio** or **busy time ratio**. This is a physical layer metric that indicates the percentage of times each node tried to access the channel and the channel was busy. This metric is measured from the transmitter perspective and is described with more detail in [44].

Figure 3.9 shows the results for the three followers transmission power levels. We can see that while PLEXE-Slotted and CSMA/CA perform approximately similarly, RA-TDMAp shows a 4 to 5 times reduction for all the three cases. This is a direct consequence of the adaptation feature of the protocol that quickly moves the platoon transmissions away from the interference. Concerning the followers' transmission power, we can see that as it increases it causes the busy time ratio to increase approximately similarly for all approaches. This is expected as higher power reduces channel spatial reuse and increases interference.

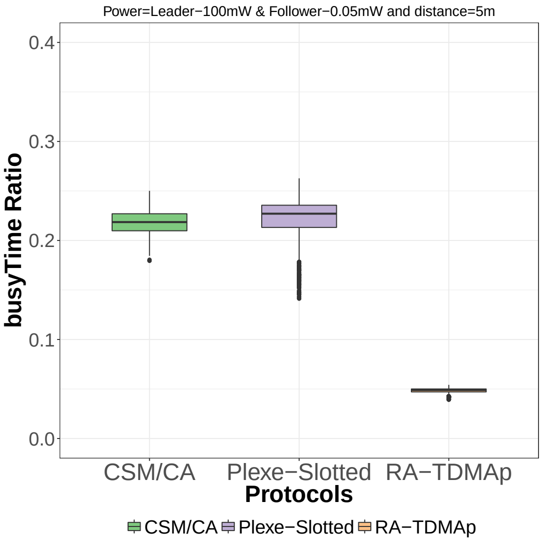
3.3.4.2 Results of *Collisions Rate*

The second metric is the **collisions rate**, i.e., the average number of collisions per second. The simulator determines collisions as the frames that were not correctly decoded due to interference between overlapping transmissions. Thus, it is a metric from the receiver perspective.

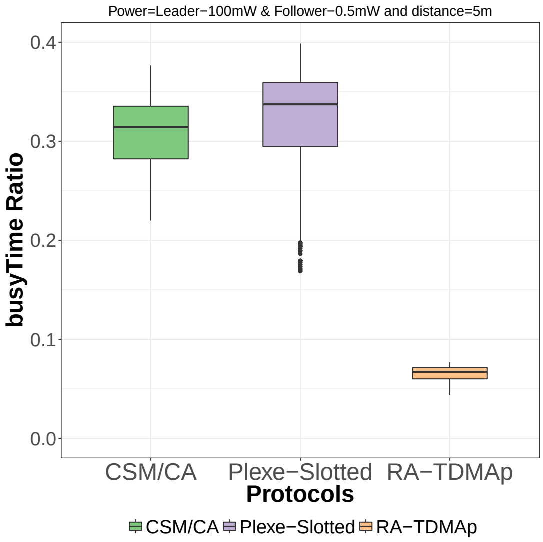
The results are shown in Fig. 3.10. PLEXE-slotted exhibits some benefits when compared to CSMA/CA because of synchronizing the beacons inside each platoon. However, the benefit is small. A much larger benefit is achieved by RA-TDMAp, from near one order of magnitude for very low power to around 7 times for intermediate and 5 times for higher followers transmission power. Again, this is due to the adaptive feature of the protocol that, upon interference, pulls the platoon away from it from one cycle to the next. Thus, periodic interference will not persist interfering as opposed to the other cases. Similarly to the previous metric, the relative performance of the three protocols is kept as the followers transmission power increases, since the corresponding larger range leads to increasing collisions.

3.3.4.3 Results of *Safe Time Ratio*

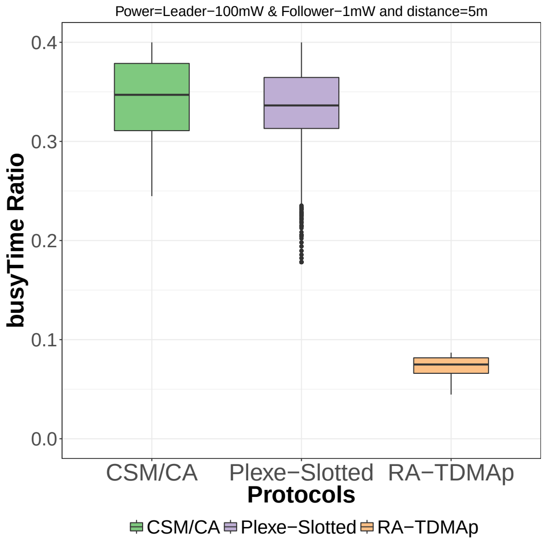
Beyond the properties of the communication channel, it is also relevant to asses how well the channel meets application requirements. Thus, we used the metric proposed in [9] called **safe time ratio** that aims at distributed feedback control in the context of vehicle platooning. This metric captures the ratio of the communications that meet a predefined delay requirement considered safe from the control perspective, during the simulation time. Longer delays are considered unsafe. The requirement is set following the controller design. The delays are measured by the receiver per each source, separately, and then averaged out. The metric considers a conservative approach



(**a**) TX power 0.05mW



(**b**) TX power 0.5mW

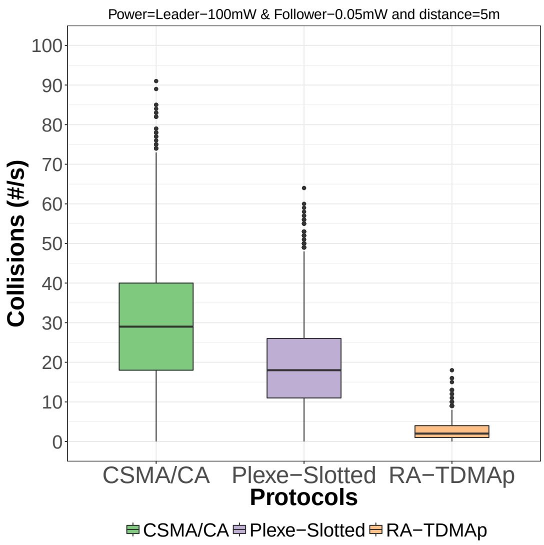


(**c**) TX power 1mW

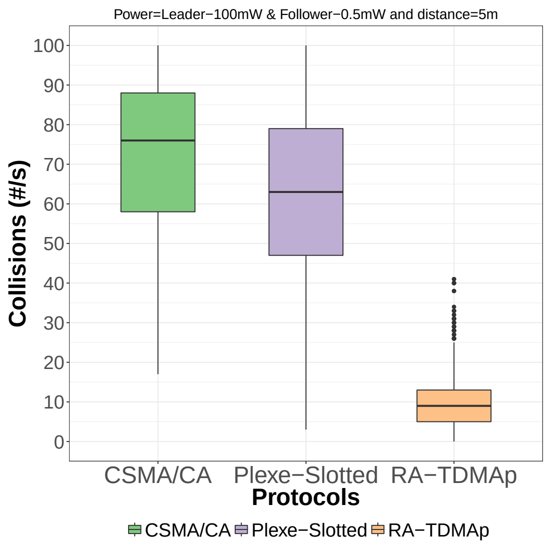
Figure 3.9: Busy time ratio in the given scenario with 5m gap and three follower transmit powers

in which the application is not synchronized with the TDMA frame and the delay is upper bounded by the inter-arrival time of packets per source.

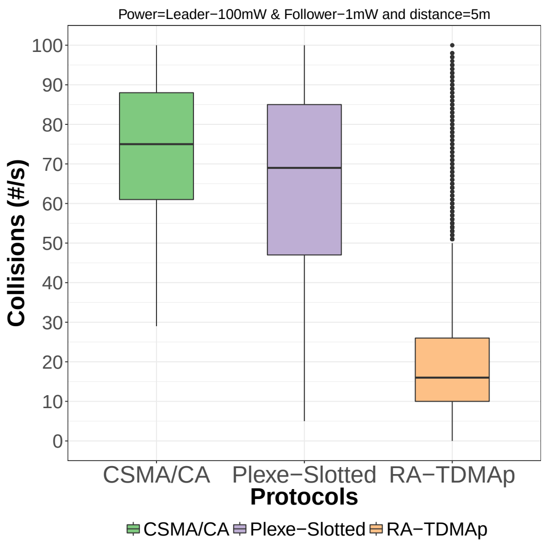
The results show, again, a superiority of RA-TDMAp, being the only protocol, among PLEXE-slotted and CSMA/CA, that keeps the platoons in safe state above 99% of the time for delay requirements down to 0.2s and for all tested power levels of the platoons followers. The advantage is specially noticeable for very low transmission power and tighter delay requirements, e.g., 99% for 0.2s with RA-TDMAp against 95% for PLEXE-Slotted and 90% for CSMA/CA.



(**a**) TX power 0.05mW



(**b**) TX power 0.5mW



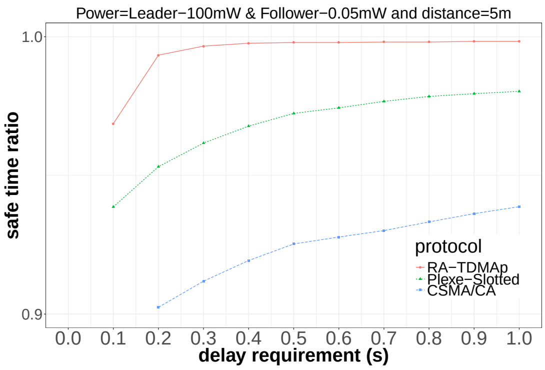
(**c**) TX power 1mW

Figure 3.10: Collisions rate for given scenario with 5m gap and three follower transmit powers

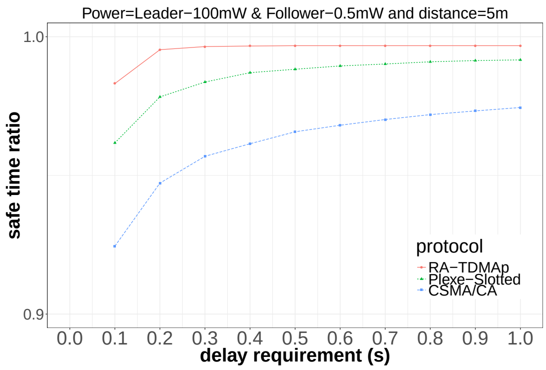
3.3.5 Insights into the transmission patterns

In order to observe the adaptation mechanism of RA-TDMAp, we looked into the traces obtained from the actual transmissions instants of the three protocols in two different scenarios, light load, i.e., just two platoons of 10 vehicles each, and intense load, i.e., the whole set of 16 platoons of 10 vehicles each. All simulation conditions are the same used in the previous experiments. The results are shown in Figure 3.12 and Figure 3.13, respectively.

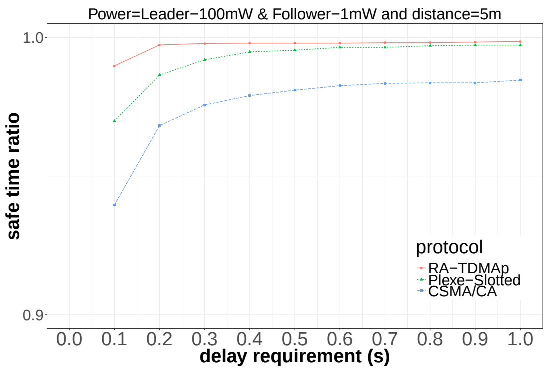
In the first scenario, the CSMA/CA trace shows the random transmission instants of the vehicles, which repeat periodically according to the round period T_{tup}. Conversely, both RA-TDMAp and PLEXE-slotted synchronize the vehicles is each platoon, but the relative phase between both platoons is random. However, since the load is low and the phases of the frames of the two platoons



(**a**) TX power 0.05mW



(**b**) TX power 0.5mW

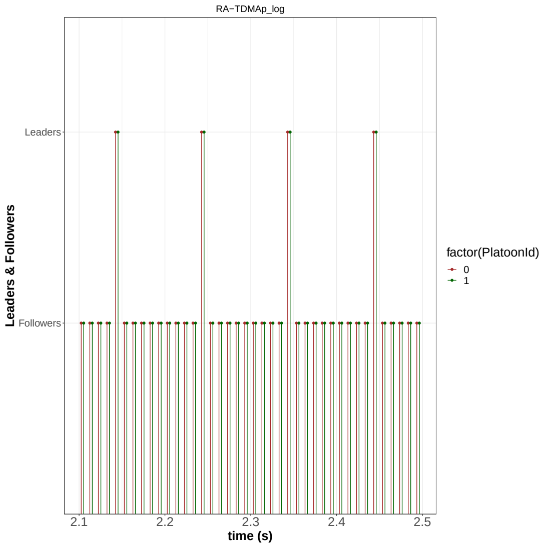


(**c**) TX power 1mW

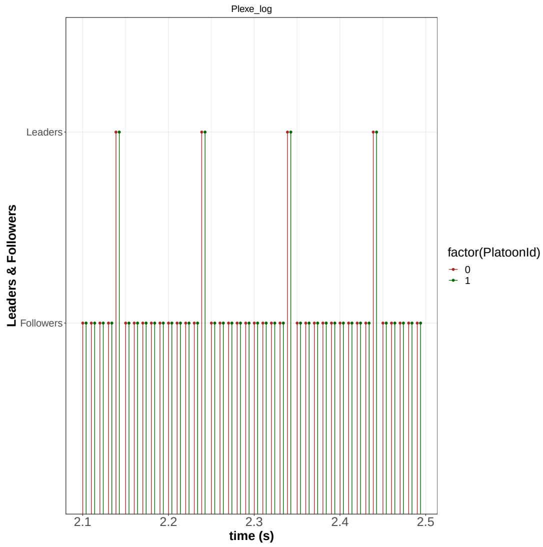
Figure 3.11: *Safe time ratio* for all approaches with three follower transmit powers

do not create mutual interference, we observe regular similar patterns in both cases.

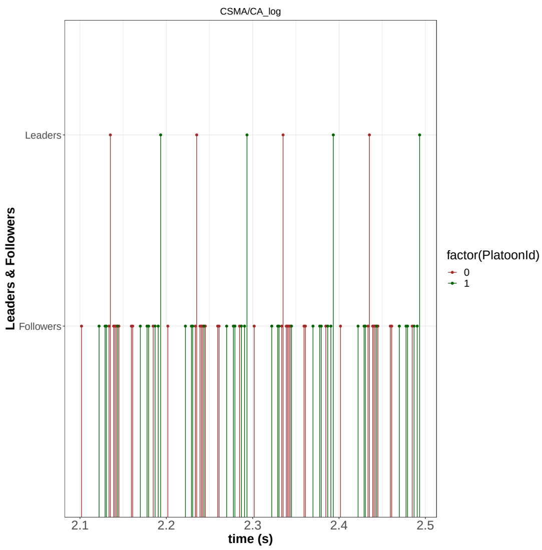
The second scenario is more interesting since the load is higher, leading to higher mutual interference, too. The first striking observation is the approximate regularity of the transmissions under PLEXE-slotted and CSMA/CA. Looking carefully at the colors representing the platoons, we see that the inter-followers intervals are irregular in CSMA/CA while in PLEXE-slotted they are around the expected $10ms$ (T_{tup}/N) interval. Conversely, RA-TDMAp shows a visibly more irregular pattern in the transmission instants, in some cases, with very small inter-transmission distances. We believe the reason for this difference between PLEXE-slotted and CSMA/CA on one side, and RA-TDMAp on the other, is that with the first two protocols, under high load as it is the case, there are periods like the one shown in which all medium access attempts find the medium busy. Thus the MAC forces the following transmission to wait for the inter-frame space plus the random interval in the contention window. Conversely, in RA-TDMAp, frequently, the TDMA frame phase adaptation layer leads the transmitter to access the medium when it is free, right after the inter-frame space. Thus, no contention window is needed, leading to occasional/frequent rather short intervals. This confirmsn the superior capacity of RA-TDMAp to pack the traffic of multiple platoons in a denser way than the other two protocols.



(**a**) Co-existence of 2 Platoons (Followers lower, Leaders higher) under RA-TDMAp



(**b**) Co-existence of 2 Platoons (Followers lower, Leaders higher) under Plexe-slotted

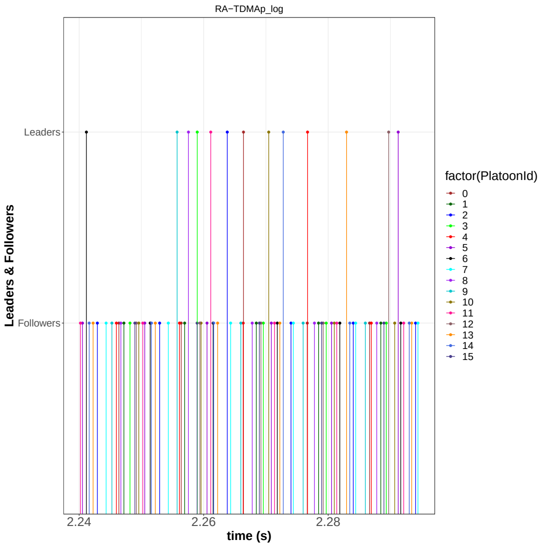


(**c**) Co-existence of 2 Platoons (Followers lower, Leaders higher) under CSMA/CA

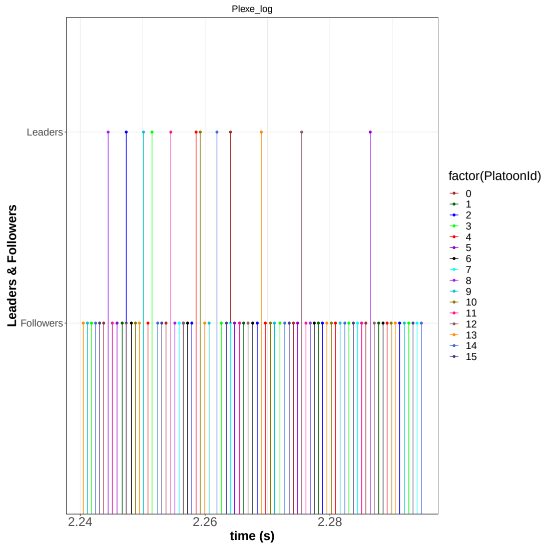
Figure 3.12: Co-existence of 2 platoons (Followers lower, Leaders higher)

3.4 Summary

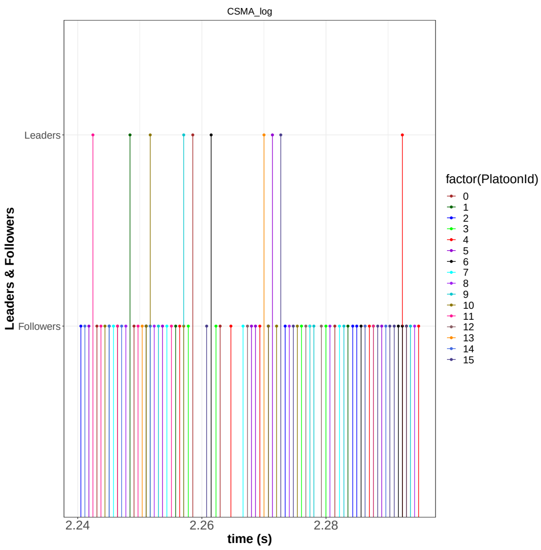
Vehicular networks are growingly important as the level of vehicles driving automation is increasing. In particular, collaborative applications such as platooning can improve vehicle and users safety as well as fuel efficiency. However, the effectiveness of these applications relies on the quality of the channel. In this chapter, we proposed the RA-TDMAp protocol that is deployed on top of IEEE 802.11p, which is the current standard for vehicular networks and which relies on CSMA/CA arbitration.



(**a**) Co-existence of 16 Platoons (Followers lower, Leaders higher) under RA-TDMAp



(**b**) Co-existence of 16 Platoons (Followers lower, Leaders higher) under Plexe-slotted



(**c**) Co-existence of 16 Platoons (Followers lower, Leaders higher) under CSMA/CA

Figure 3.13: Co-existence of 16 platoons (Followers lower, Leaders higher)

RA-TDMAp was designed combining the frame adaption mechanism of previously developed RA-TDMA protocols with the power control of PLEXE-slotted. According to the former, RA-TDMAp organizes the vehicle beacons in each platoon, independently, in a separate TDMA frame. At run-time, the protocol measures the arbitration delays affecting the respective beacons, i.e., interference from traffic external to that platoon. However, the power control feature assigned high power, thus high coverage, to the platoon leader, only, that synchronizes the respective platoon. The followers transmit with low power, thus with small spatial footprint. This feature required a novel mechanism to acquire the interference delays from the followers and bring them, in a multi-hop fashion and in a single TDMA round, to the platoon leader, who then adjust the phase of the next TDMA frame to escape from the interference that generated those delays. This mechanism implicitly synchronizes multiple platoons in a dense packing increasing the efficiency in using the channel capacity.

In this chapter we also carried out simulations in realistic highway scenarios using the PLEXE-Veins-SUMO-OMNeT++ framework, which also served as a preliminary validation of RA-TDMAp. We compared this protocol against two other alternatives that are directly comparable, namely CSMA/CA from native IEEE 802.11p and PLEXE-slotted, which was proposed within PLEXE and works similarly to RA-TDMAp but without the capacity to shift the TDMA round. The results showed a clear benefit of using RA-TDMAp, with nearly one order of magnitude reduction in collisions rate, a factor of 4 to 5 reduction in channel occupation and a significant improvement in safe time ratio, a communications-related control metric.

Chapter 4

Empirical Performance Models of MAC Protocols for Cooperative Platooning Applications

This chapter proposes empirical performance models for MAC protocols of different classes: the native CSMA/CA MAC of IEEE 802.11p and two overlay TDMA protocols (PLEXE-slotted [9] and RA-TDMAp [13]) that can be readily implemented on IEEE 802.11p as discussed in Chapter 3. The latter two protocols were designed for platoon-beaconing applications that explicitly synchronize beacons within each platoon. However, while PLEXE-slotted is agnostic to extra-platoon traffic, RA-TDMAp does an implicit synchronization among neighbouring platoons. We leveraged simulations to produce observations of relevant network performance metrics as we change selected parameters such as platoon size, number of occupied lanes and transmit power of the followers. We relate those observations to a contextual metric, namely the number of radio-frequency (RF) neighbours (defined further on). The observations are fitted with appropriate curves through regression: we showed that an exponential rule can be observed for the rate of collisions and busy time ratio.

The contributions of this chapter are summarized as follows:

- Motivation and verification that network performance follows consistent behaviours as meaningful wireless conditions change (e.g., the number of RF neighbours) for a variety of related MAC protocols;
- Empirical models of the relationship between network metrics and wireless conditions fitted to simulation observations of platooning scenarios;
- Verification that the models hold through a range of values of relevant parameters, namely average platoon sizes, number of occupied lanes and transmit power.

The remainder of this chapter is organized as follows. We first motivate the design of the models in Section 4.2. We extract the models parameters in Section 4.3. Section 4.4 shows concluding remarks.

The work in this chapter was essentially reported in the following publications:

- [11] A. Aslam, P. M. Santos, F. Santos, and L. Almeida, "Empirical performance models of macprotocols for cooperative platooning applications,"Electronics, vol. 8, no. 11, p. 1334, 2019.

- [12] A. Aslam, L. Almeida, and F. Santos, "Impact of platoon size on the performance of tdma-based mac protocols," in2018 IEEE Globecom Workshops (GC Wkshps), pp. 1–2, IEEE,2018

4.1 Overview of Analytical Models of Medium Usage

In this section we discuss a few analytical models of medium usage proposed in the related literature. The authors of [32] model analytically the probability of successful packet delivery ratio (PDR) in IEEE 802.11p scenarios as a function of the number of nodes and size of contention window. PDR is dependent on two phenomena: channel collisions and dropped packets (i.e., packets not transmitted during the CCH slot). As the number of nodes increases so do collisions, leading to a degradation of PDR. And while increasing the contention window should alleviate this problem, it is observed that it also leads to a drop in PDR since the nodes are not able to seize the CCH channel during its slot due to expiry time.

In [73], the authors propose analytical models of the CSMA/CA performance for periodic broadcasting in IEEE 802.11p scenarios. The authors also report PDR as a function of the number of nodes, for a scenario in which all nodes are in range of each other. The PDR decreases linearly until a tipping point, after which it degrades sharply. Collisions are the main responsible for packet losses up to the tipping point. For more nodes, the increasing probability of a packet being dropped (as nodes are unable to access the medium) is the main reason for the sharp decline in PDR.

The authors of [74] produce models of packet collision probability and average contention delay for a distributed coordination mechanism (CIDC) that uses deterministic backoff values, computed as a function of the contention intensity. Considerable reduction of collisions and delay are shown through the analytical framework and simulations.

While the works above develop analytical formulations of VANETs performance, we take the approach of exploring simulations to produce and fit models over empirical data. Most analytical formulations produce nominal performance bounds that are often not observed in practice, while empirical models can produce fitting models that are closer to reality. This is further stressed by our option to present the performance metrics as a function of the number of RF neighbours, a metric that we do not control directly, that is hard to model analytically, and that is practical, as it is a medium-state metric easily available to any IEEE 802.11p node.

4.2 Motivation and Methodology for Empirical Models of MAC Protocol Performance

We reported network performance in a highway platooning scenario (such as that of Figure 3.4) when only coordinated beaconing traffic exists, i.e., no other data or control flows exist apart from periodic beacons transmitted by platoons members. Periodic beaconing is a network functionality that is often explored to enable ITS applications, and it is provided by design by the two regional protocol stacks, with beacons being called cooperative awareness messages (CAM) in ETSI ITS-G5 [5] and basic safety messages (BSM) in WAVE [42]. Beacons are sent at fixed intervals in the range of $0.1s$ to $1s$ for cooperative applications. A number of works propose mechanisms to adapt the beaconing rate to the channel load, of which we highlight [44]; the authors of [47] and [45] apply the idea specifically to the platooning context, in which beacon transmissions of the platoons members can be coordinated.

We observed that relationships between network performance metrics and the number of vehicles in a platoon could be captured and described by empirical models. Such results motivated our interest in searching for a wider range of empirical relationships between network topology and performance metrics, to provide information to application designers. Our preliminary conclusions held for three MAC protocols: CSMA/CA (contention-based), and PLEXE-slotted and RA-TDMAp (overlay TDMA-based). Note that, among all protocols reviewed in Chapter 2, these are the only ones that are readily available or implementable on commercial off-the-shelf (COTS) IEEE 802.11p network interfaces, without need for any hardware or device modifications. We review briefly the conclusions reported in [12] that sustain our approach of producing empirical models.

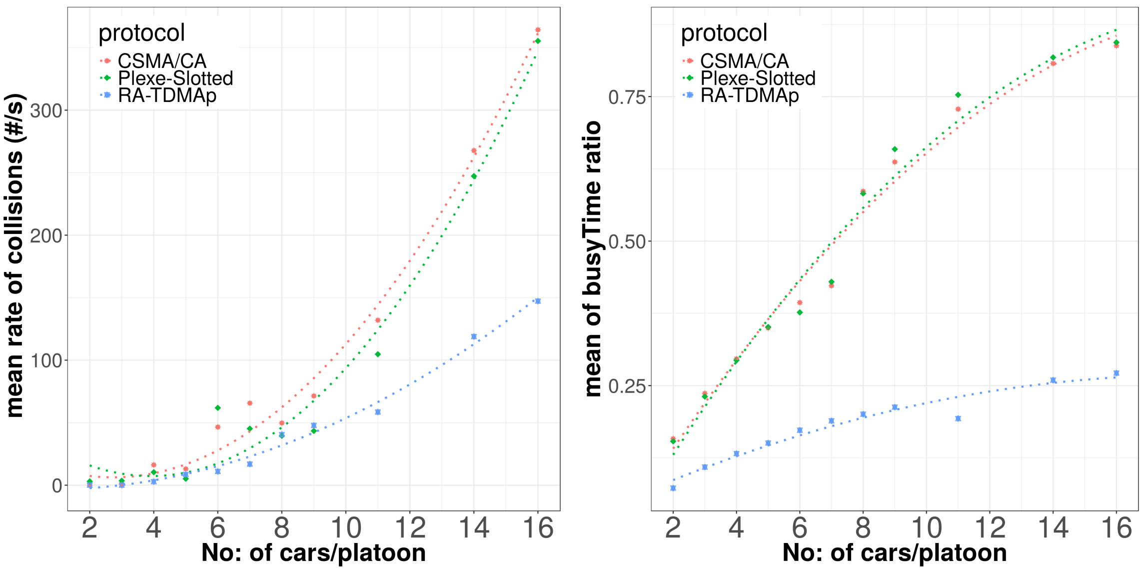
4.2.1 Network Metrics as a Function of a Scenario Parameter

In [12] we presented vehicular simulations to explore the behaviour of relevant network performance metrics, namely the rate of collisions and the ratio of medium accesses during which the medium was busy (after [66]), with the three aforementioned protocols, i.e., CSMA/CA, PLEXE-slotted and RA-TDMAp. The studied scenario encompassed 16 platoons travelling side-by-side in four parallel lanes at the same speed. This situation generates persistent interference among all vehicles, leading to a stationary process. The only parameter we varied was the platoon size, N, from 2 to 16 vehicles.

The respective results are shown in Figure 4.1, with 2nd order fitting curves superimposed over the measurement points. An initial observation is the effectiveness of RA-TDMAp to allow platoons to escape from the interference of each other adjusting the phase of their rounds. A second and more meaningful conclusion is that, despite the considerable differences in the operation of the three protocols, we observe a consistent relationship between the network performance metrics and a wireless network topological feature, namely the number of vehicles in the platoon.

This led us to hypothesize that relevant performance metrics (e.g., collisions rate and channel busy time ratio) may be related to a network topology parameter that represents a variety of physical and scenario parameters, such as the platoons sizes and physical layout, and the RF transmit power. Therefore, in this work we studied the number of RF neighbours in the vicinity of a particular vehicle as such network topology parameter. In fact, this number seems to depend directly on platoons size by means of the leader/follower ratio, but also on platoons physical arrangement either serialized in a single lane or side-by-side in multiple lanes, and also on the effective RF power received from each source, since higher power implies larger range. Moreover, the number of RF neighbours is easily measurable by each vehicle without need for specialized support from either network hardware or device–driver as it would be the case for measuring collisions rate or channel busy time ratio directly. The approach we propose opens the way to an online quantitative assessment of the channel quality in term of collisions rate and busy time ratio for the platooning application using COTS IEEE 802.11p network interfaces.

To evaluate this hypothesis, we proposed to model the performance metrics as a function of the number of RF neighbours in an empirical fashion (i.e., by carrying out extensive parameter-space exploration and extract fitting model parameters), and investigating if the relationship is kept as other parameters are varied.



(**a**) Collisions rate (**b**) Channel busy time ratio

Figure 4.1: Network metrics vs. platoon size.

4.2.2 Relevant Metrics and Parameters and Simulation Setup

In the process of building a more comprehensive set of empirical models relating selected network and topological metrics, we collected three metrics, classified into two categories: network topology and network performance. The number of RF neighbours is the only network topology metric and the one against which network performance metrics are characterized. The value is not under our direct control, thus being measured during the simulation. Our objective is to develop practical models that can be used by vehicles in real-world conditions:

- **Number of RF neighbours**: The number of different sources of the beacons correctly received by a vehicle per second.

The remaining metrics are related to network performance and are useful to characterize the network service to the application. They are directly provided by the used simulation framework (Veins [67]) and explored in Chapter 3:

- **Collisions rate**: The packets lost due to a collision between interfering transmissions per unit of time;

- **Busy time ratio**: The ratio of the times that the physical layer at each node observes the channel busy.

Both metrics are observed for each second j and by each vehicle i and referred to as m_{ji} standing for either collisions or busy time ratio. Then, they are averaged over the entire simulated time and among all vehicles according to the following equation, resulting in one value per simulation scenario. Note that *GlobalMetric* stands for collisions rate or channel busy time ratio depending on the semantics of m_{ij}.

$$GlobalMetric = \frac{1}{\#_{cars}} \sum_{i=1}^{\#cars} \left(\frac{1}{\#_{secs}} \sum_{j=1}^{\#secs} m_{ji} \right)$$

We vary several scenario and communication parameters over a range of values, in order to simulate realistic scenario modifications that can lead to a change in the number of RF neighbours.

- **Platoon Size:** increasing this parameter change has several effects: (i) It increases the frequency of messages transmitted during a round (round duration T_{tup} remains constant, while slots T_{xwin} decrease); (ii) it decreases the ratio of leaders to followers; and (iii) while the communication range is not filled with neighbours, it leads to an increase in the number of observable neighbours.

- **Platoon Size Homogeneity:** The size homogeneity concerns whether platoons have the same size (**homogeneous platoon sizes**), or variations between them around a known average (**heterogeneous platoon sizes**). In the first case, all platoons have the same integer number of nodes N. In the latter, we draw platoon sizes from a uniform distribution $\mathscr{U}(a,b)$, in which the mid-point is N; this strategy is expected to cause the average platoon size to be N, allowing for a fair comparison with the homogeneous-size counterpart scenario.

- **Number of Lanes with Traffic:** Increasing the number of lanes with traffic leads to an increase in the number of neighbours over a particular spatial layout. If a single lane is considered, increasing the platoon size may not lead to an increase in the number of neighbours (if neighbours exist up to the communication range); allowing traffic in adjacent lanes, however, immediately introduces a large number of neighbours to individual nodes.

- **Transmit Power of Followers**: Changing the transmit power of followers causes the communication range of individual nodes to increase. Note that leaders transmit with high power, already reaching all nodes in the simulated area.

The observations reported in the following section were obtained from simulations using the PLEXE-Veins-SUMO-OMNeT++ framework already referred in Section 3.2. As in our work [12], briefly described in Section 4.2.1, we simulated a stretch of a 10 km of a highway with five lanes where 16 platoons travel without any other traffic. The speed of all the platoons is set to 100 km/h and the length of each car is 4 m long. The 16 platoons are re-arranged spatially according to the number of lanes under analysis (e.g., single line if a single lane is used; three or four platoons/lane if all five lanes are considered). All protocols operate a beacon interval T_{tup} of 100 ms, an adequate value for a platooning application [75]. The MAC service data unit (MSDU) is always 200 bytes. We used the PHY and MAC models of IEEE 802.11p proposed in [70], using a bitrate of 6 Mbit/s that is suited for demanding safety related applications [71]. Furthermore, we used just the control channel (CCH), without the switching between this and the service channel (SCH), and all beacons use the same access category (AC_VI). We use a free-space path loss model with an α value of 2.0. We do not consider more complex path loss models, obstructions, or fading effects to avoid introducing artifacts caused by complex propagation phenomena in the network-level metrics (we expect to address this in future work).

Leaders transmit with power set to 100 mW (20 dBm). With the referred propagation model and equal omni-directional antennas, this power grants a communication range of approximately 1300 m. Each simulation experiment reproduces 30 s of real-world activity. Platoons start their periodic beaconing rounds with an independent and random delay between 10 ms and 1 s, drawn from a uniform distribution.

We varied the number of lanes between 1 and 5, using four lanes as default. The size of the platoons is varied from 2 to 10 cars in either heterogeneous or homogeneous way, with the default value of ten cars with heterogeneous platoon sizes. The followers transmit with power ranging from 0.1 mW (-10 dBm) to 5 mW (7 dBm) granting approximately 30 m to 254 m of communication range, respectively, under the referred propagation model and equal omni-directional antennas. The default transmit power value is 1 mW (0 dBm). Table 4.1 lists scenario parameters and Table 5.2 summarizes all communication-related parameters. In both tables, default values are underlined.

4.3 Empirical Models

This section presents and discusses the observations made from the simulation study and the respective fitted models.

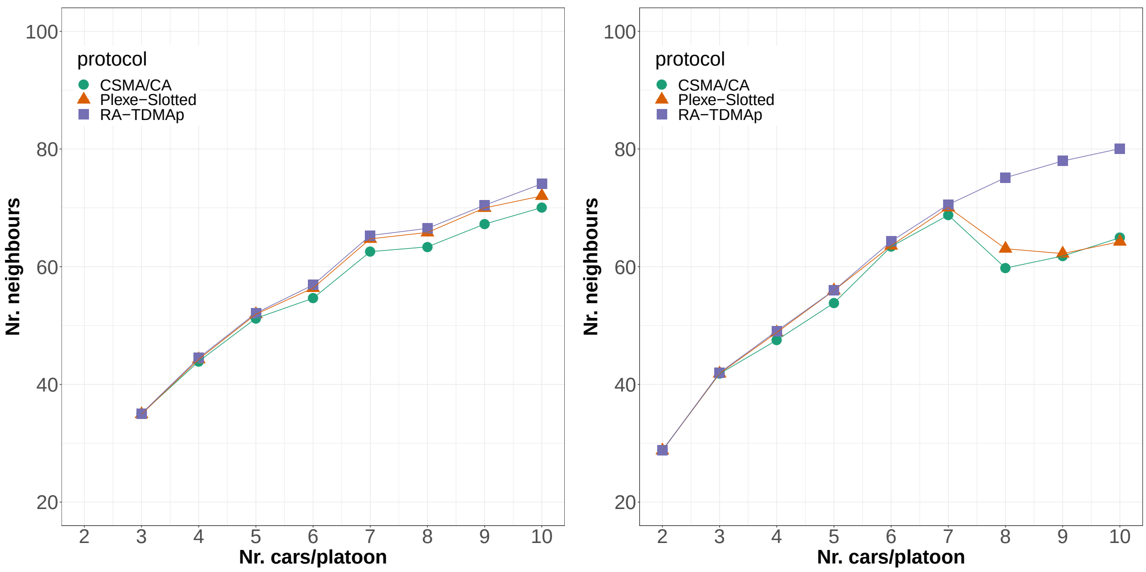
Table 4.1: Scenario configurations.

Parameter	Values
(Avg.) Platoon size	2 to 10 cars/platoon
Number of platoons	16
Number of lanes	1,2,3,4, 5
Inter-vehicle gap	5 m
Inter-platoon gap	≃28 m
Controller	CACC
Car length	4 m
Speed	100 km/h

4.3.1 Platoon Size and Homogeneity, and Coherence between Rounds of Platoons

We started by observing the relationship between the platoon size and homogeneity of platoon sizes on the number of RF neighbours (Figure 4.2). If platoon sizes are set to be heterogeneous (Figure 4.2a), we see a monotonically increasing relationship between the number of neighbours and platoon size.

For the homogeneous platoon size (Figure 4.2b), this relationship shows two different behaviours for the CSMA/CA and PLEXE-slotted: We register an increase in the number of neighbours as the platoon size increases until seven vehicles/platoon, while for larger platoons, the reported number of neighbours decreases.



(**a**) Heterogeneous platoon size (**b**) Homogeneous platoon size

Figure 4.2: Number of radio-frequency (RF) neighbours vs. platoon size (default Tx power and used lanes).

We attribute this effect to the relationship between the slot duration T_{xwin} between nearby

Table 4.2: PHY and MAC parameters.

Parameter	**Values**
PHY/MAC model	IEEE 802.11p/1609.4 (CCH only)
Path loss model	Free space (α = 2.0)
Channel	5.89 GHz
Bitrate	6 Mbit/s
MSDU size	200 B
Access category	*AC_VI*
Leader's Tx power	20 dBm
Follower's Tx power	[−10, −6.9, −3, $\underline{0}$, 3, 4.7, 6, 7] dBm

platoons. In a scenario where all platoons have the same size, thus slot duration is equal (so as the frequency of transmission by platoon elements), despite the random transmission delays assigned to each vehicle at the start of the simulations, some overlap of transmissions of different platoons may occur. As CSMA/CA and PLEXE-slotted are not able to adjust the phases of TDMA rounds, this overlap persists and is not resolved except partially by the CSMA/CA backoff mechanism. Thus we fall into a *critical instant*, or a period during which there is a susceptibility for many platoon pairs to experience small or null phase differences among their rounds simultaneously. We refer to this state of generalized coherence (small or even null phase differences) as *high coherence* conditions. Critical instants (and high coherence) are typically transient and eventually wear out with differences in the clocks of the platoons/vehicles; however, in this particular case, they become persistent.

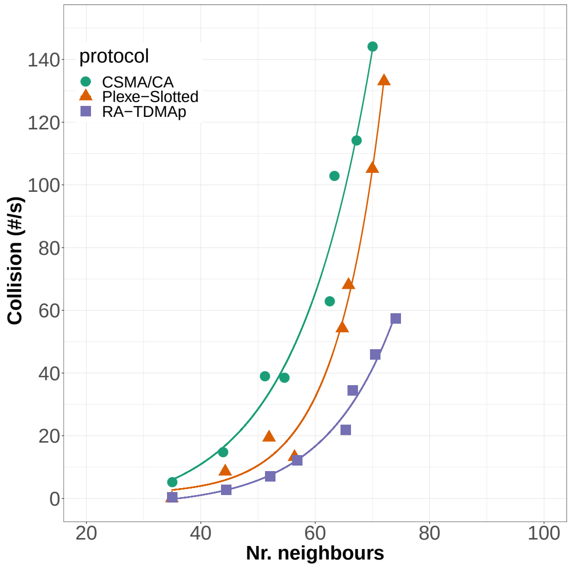
Accordingly, we identify the existence of two system conditions in Figure 4.2b with respect to the platoon size: one of **high coherence** (platoon sizes larger than 7) and a second one without high coherence (platoon sizes up to 7). If the neighbouring platoons have different sizes, as in the case of heterogeneous platoon sizes (Figure 4.2a), slot duration is also different, thus high coherence will not occur and the likelihood of overlapping periodic transmissions decreases. RA-TDMAp, in turn, is capable of handling both scenarios equally well, not exhibiting the effects of high round coherence, given its capacity to slide the relative phases of the platoons transmissions to avoid/reduce mutual interference. In this case, the homogeneous scenario is even more favourable (i.e., reaches more neighbours for the same number of vehicles/platoon), since the phase adjustment is more effective when all slot have similar width.

These results show that the number of RF neighbours, in the absence of high coherence conditions, also reveals the impact of both platoon size and its homogeneity.

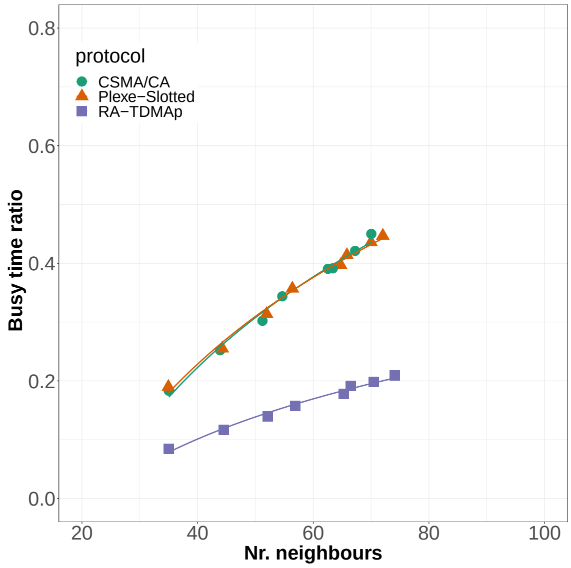
4.3.2 Network Metrics In and Out of High Coherence

In a scenario of heterogeneous platoon sizes, the network metrics follow the behaviour discussed earlier: despite more nodes being present in the system, platoon communications are not experiencing high coherence and the number of collisions and busy time ratio increase monotonically, as a result of more RF neighbours. The rate of collisions is shown in Figure 4.3a and busy time ratio in Figure 4.3b.

To model the rate of collisions, we propose an exponential model of the form $y = \alpha \cdot e^{\beta\, x}$, where we force the y-intersect value to be 0. For busy time ratio, we found that a log-linear model $y = \beta_0 + \beta_1 \ln(x)$ provides an appropriate fit. The corresponding parameter values are shown in Table 4.3, for all models. The mean square error (MSE) is used as the fitting quality evaluation metric. In most cases, alternative fitting curves were tested; we selected the ones providing inferior MSE.



(**a**) Collisions rate

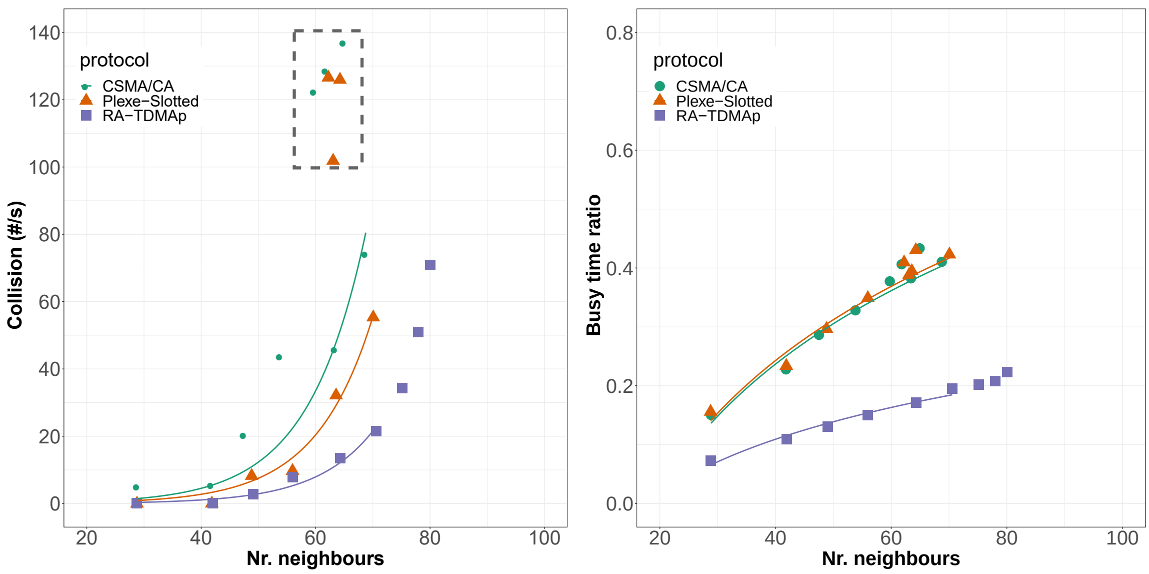


(**b**) Busy time ratio

Figure 4.3: Network metrics for RF neighbours varying heterogeneous platoon size.

The homogeneous platoon size case is more complex since both CSMA/CA and PLEXE-slotted exhibit high coherence in their rounds, as discussed previously. For larger platoons, the reported number of neighbours decreases but the number of collisions increases substantially. This is shown in Figure 4.4a; e.g., refer to the CSMA/CA points in the range $x = [59, 65]$ and $y = [100, 140]$ (highlighted in the square in the plot), that correspond to platoon sizes 8 to 10. In the busy time ratio (Figure 4.4b), similar results are observable although at a relatively inferior scale. The pre-existing effects of increasing platoon size (higher frequency of hidden nodes, higher frequency of simultaneous transmissions) are aggravated by the high coherence between platoon rounds and degrade the channel performance, causing collisions to increase drastically while the number of neighbours decreases.

This conclusion has an important consequence. In real-world conditions, the number of RF neighbours is easier to learn than the size of the platoons in our vicinity. However, as we observe that the number of neighbours above 60 is not monotonically increasing with respect to the platoon size, we cannot learn in that case whether the medium is in high coherence among rounds or not. RA-TDMAp is able to avoid the high coherence region by actually **promoting** decoherence (through its adaptive adjustment of round duration) for short periods until a steady state of coherent co-existence is achieved.



(**a**) Collisions rate (**b**) Busy time ratio

Figure 4.4: Network metrics for RF neighbours varying homogeneous platoon size.

4.3.3 Number of Lanes and Transmit Power of Followers

We observed that increasing the number of lanes used by the platoons side-by-side and the transmit power of followers increases monotonically the number of neighbours, as shown in Figures 4.5a and b, respectively. In the case of the increasing number of lanes, the different spatial arrangement of the platoons as more lanes are introduced leads to more nodes effectively entering the range of each individual node.

A similar effect, even more pronounced, happens when increasing the transmit power of the followers. Higher transmit power means larger communication range and thus more neighbours are observed. Consequently, there are less hidden nodes and the CSMA/CA becomes more effective in avoiding collisions. This occurs among all kinds of nodes, both followers and leaders. Therefore, the number of neighbours is also representative of the platoons layout in lanes as well as the power the followers use to transmit.

The results for the number of collisions as a function of the number of neighbours, when varying the number of lanes, are shown in Figure 4.6a. Figure 4.7a shows the same relationship but when varying the followers transmit power. We consider the observed points to follow a bell shaped curve that we chose to describe analytically using the Gaussian function as follows.

$$y = \alpha \cdot e^{\left(\frac{x-\beta}{2\gamma^2}\right)}$$

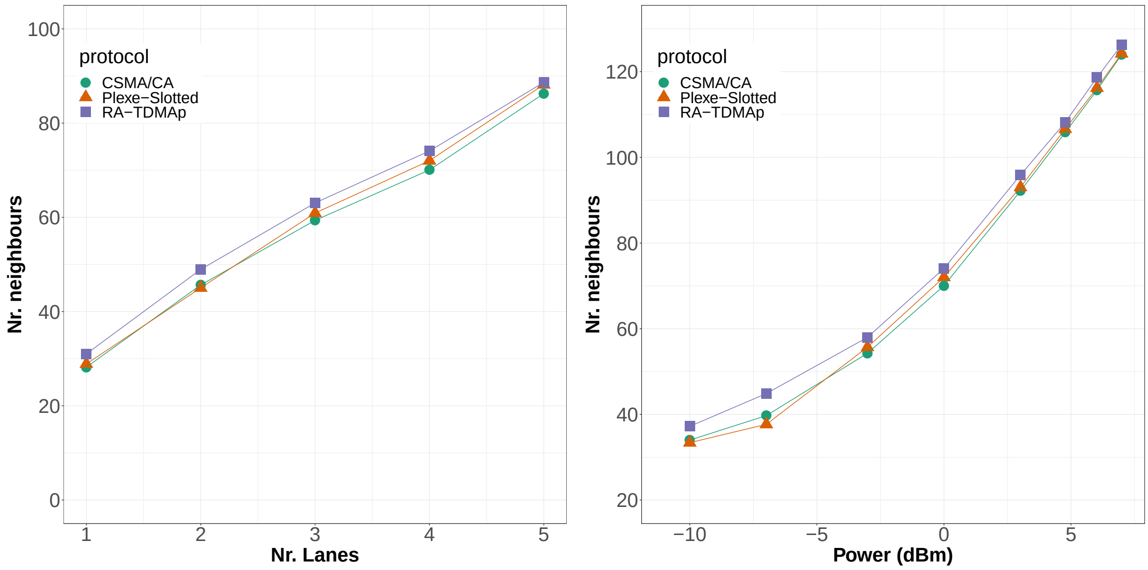


Figure 4.5: Number of RF neighbours vs. number of used lanes and Tx power. (**a**) Number of RF neighbours vs. number of lanes (default Tx power and platoon size); (**b**) number of RF neighbours vs. Tx power (default number of lanes and platoon size).

We observed that below the maximum value the communication range is small, so as the number of observed neighbours and thus collisions. Above that value, nodes start progressively listening to more nodes, making the underlying carrier sense MAC mechanism more effective, particularly reducing the occurrence of hidden nodes. Thus, collisions also decrease as, in this case, they result mainly from the occurrence of two (or more nodes) trying to access the medium simultaneously (i.e., their backoff counter hits zero).

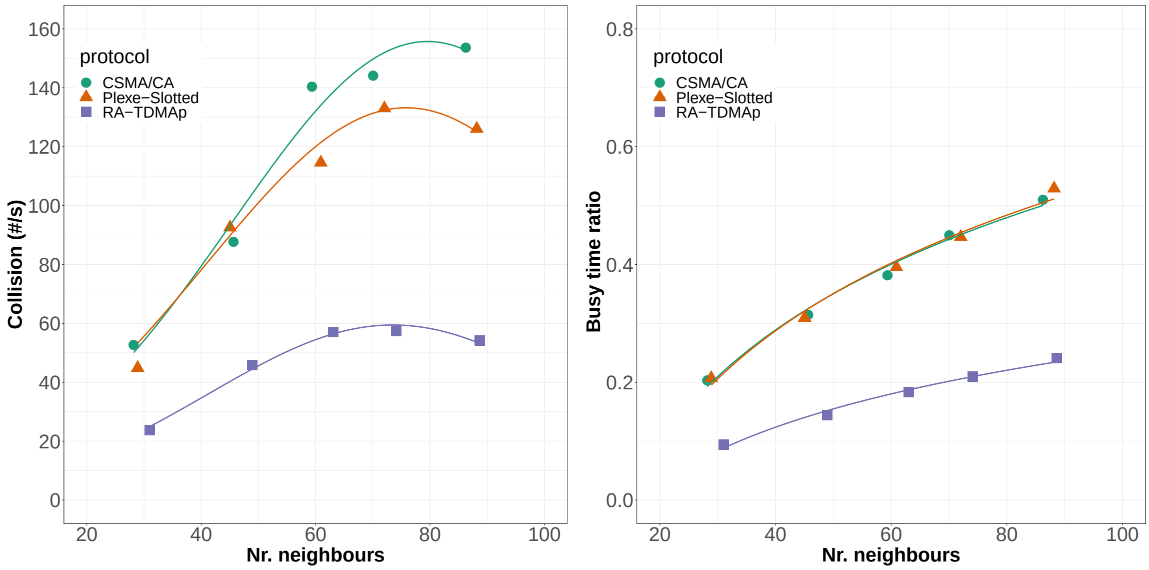
The busy time ratio still presents a log-linear relationship with the number of RF neighbors for both cases, as depicted in Figures 4.6b and 4.7b.

4.3.4 Discussion

The results shown in the previous sections show that, as the selected parameters are changed, different but consistent behaviours of the target metrics may occur. The main takeaways are:

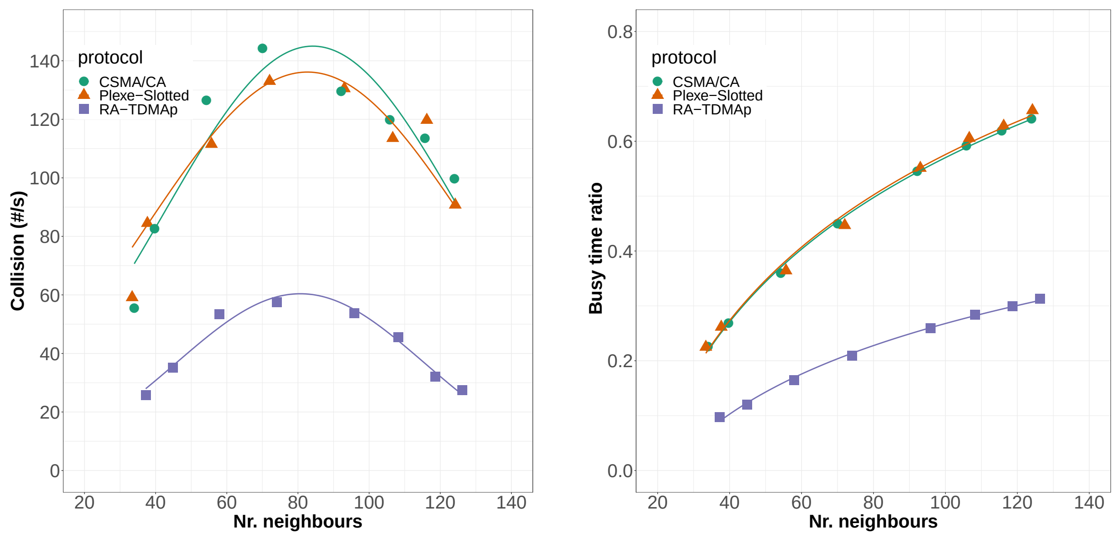
- **Homogeneous platoon sizes can lead to degradation:** Situations of similar slot duration and small phase differences between rounds of disparate platoons for protocols without round adaptation can lead to a high collision rate and decrease of the known neighbourhood.

- **Sets of large platoons experience more collisions:** Increasing the platoon size in a convoy of platoons increases the number of messages in each round, and thus leads to more collisions and higher busy time ratio.



(**a**) Collisions rate (**b**) Busy time ratio

Figure 4.6: Network metrics for RF neighbours varying number of lanes.



(**a**) Collisions rate (**b**) Busy time ratio

Figure 4.7: Network metrics for RF neighbours varying the transmission power of followers.

- **High power can contribute to collision reduction:** Increasing the transmit power of followers increases spatial coverage, thus causing more neighbours to become known and more collisions up to a tipping point, after which we observed a reduction in the rate of collisions due to the inferior occurrences of uncoordinated medium accesses. This effect was also verified with the leader messages when varying the followers transmit power.

Table 4.3: Description of fitted models.

Parameter	Protocol	Collisions Metric				Busy Time Ratio Metric		
Hetero-geneous Platoon size		Exponential Model				Log Linear Model		
		α	β		MSE	β_0	β_1	MSE
	RA-TDMAp	0.138	0.082		7.043	-0.520	0.168	2.106×10^{-5}
	PLEXE-slotted	0.023	0.120		17.792	-1.112	0.363	5.223×10^{-5}
	CSMA/CA	0.816	0.074		84.502	-1.179	0.379	7.765×10^{-5}
Lanes		Gaussian Function Model				Log Linear Model		
		α	β	γ	MSE	β_0	β_1	MSE
	RA-TDMAp	4.806×10^{3}	73.502	32.26	1.688	-0.391	0.139	2.916×10^{-5}
	PLEXE-slotted	1.126×10^{4}	76.66	33.74	17.195	-0.758	0.283	1.540×10^{-4}
	CSMA/CA	1.331×10^{4}	79.57	34.11	37.398	-0.726	0.275	1.196×10^{-4}
Tx Power		Gaussian Function Model				Log Linear Model		
		α	β	γ	MSE	β_0	β_1	MSE
	RA-TDMAp	5.300×10^{3}	80.66	35.0	4.421	-0.562	0.180	1.580×10^{-5}
	PLEXE-slotted	1.530×10^{4}	85.51	44.85	51.175	-0.945	0.330	1.385×10^{-4}
	CSMA/CA	1.523×10^{4}	84.17	41.84	96.195	-0.934	0.326	2.714×10^{-5}

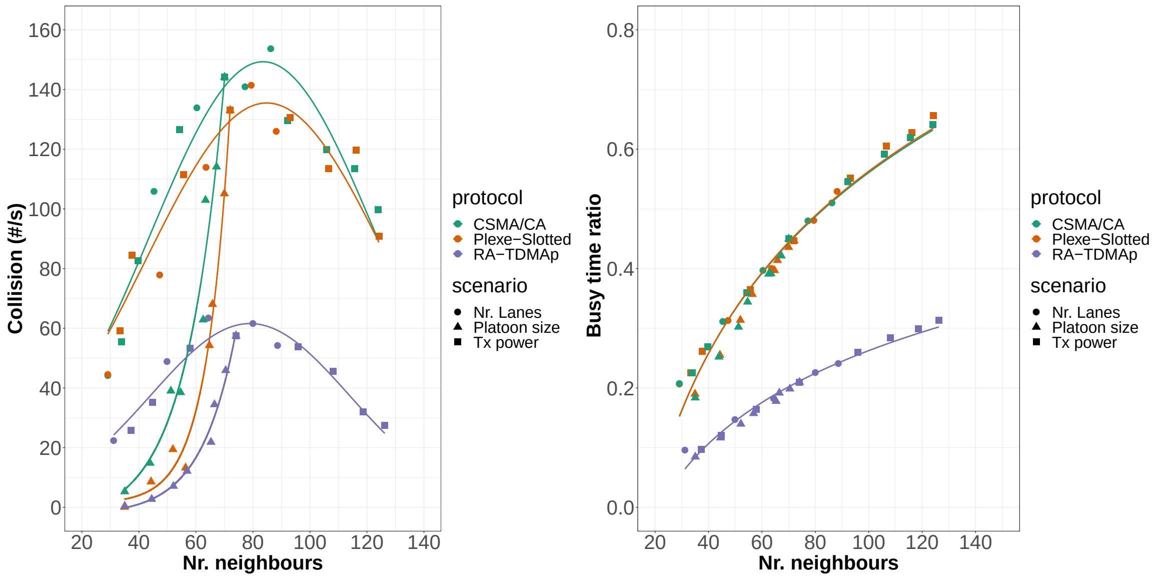
- **More lanes introduce new neighbours only up to a point:** Rearranging the platoons over more parallel lanes brings an immediate increase in the number of neighbours by spatially deploying new platoons side-by-side to existing ones. Our results reveal that this effect wears out as the number of lanes increases.

- **Protocol performance:** In all the experimented scenarios, RA-TDMAp consistently showed a smoother behaviour and no susceptibility to conditions of high coherence, leading to better fitting, with significantly lower MSE than the other protocols. Between CSMA/CA and PLEXE-slotted, the latter had, generally, lower MSE thus better fittings. The exception is the variation of the transmit power, in which case, the fitting for CSMA/CA was better (Table 4.3).

In order to explore the existence of a universal model of the rate of collisions and busy time ratio with respect to the number of RF neighbours, we consolidated the data from all scenarios in Figures 4.8a and b, respectively. In the first case, we observe that the data points relating to varying number of lanes and varying transmit power do present an alignment along a bell-shaped curve. This alignment indicates that both factors influence the number of RF neighbours and the rate of collisions in the same way, and may indicate a universal relationship between the average rate of collisions and the number of RF neighbours. For this reason, we aggregated the data sets relating to a varying number of lanes and transmit power, and fitted a single curve to produce a common and generic model (bell-shaped curves in Figure 4.8a).

The platoon size presents a different effect than that of the number of lanes and transmit power: The rate at which the number of RF neighbours increases is inferior, and yet collisions also grow as there are considerably more packets in the air (due to the smaller slot duration). Being different phenomena, the collisions rate curve due to increasing platoon sizes does not fit the trend that occurs when increasing number of lanes and transmit power.

The busy time ratio shows a very clear logarithmic and almost linear relationship with the number of RF neighbours. Again, the points concerning the platoon size scenario deviate from those of the number of lanes and transmit power scenarios, as different phenomena are involved. However, the deviation is, in this case, small, supporting a universal model to estimate the busy time ratio as a function of the number of RF neighbours, only.



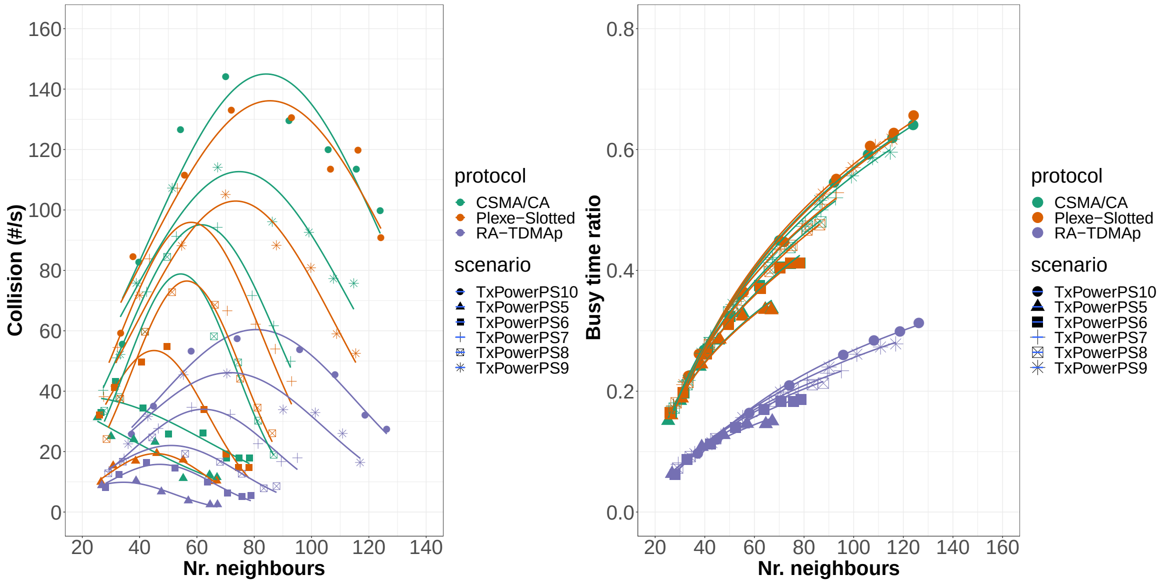
(**a**) Collisions rate (**b**) Busy time ratio

Figure 4.8: Consolidating the metrics of all scenarios.

Therefore, in an attempt to put together the effects of both the number of lanes / transmit power with the platoon size, we tried whether we could parameterize the bell-shaped curves of the former with the platoon size as an offset (e.g., $\mathrm{C}(N) = C + g(N)$). For this purpose, we carried out an extensive simulation campaign to cover the space of varying both the followers transmission power and the platoon size, doing all combinations of the following ranges (the number of lanes was kept equal to four):

- **Platoon Size**: We considered heterogeneous platoon sizes, drawing the specific size of each platoon from a uniform distribution $\mathscr{U}(a,b)$ in which the mid-point is N. We simulated the scenarios varying the mid-point (N) value from 10 to 5.
- **Followers Transmission Power**: We considered varying the transmission power of followers from 0.1mW to 5mW as in the previous experiments.

The results are shown in Figure 4.9a and Figure 4.9b for rate of collisions and busy time ratio, respectively, both as a function of the number of RF neighbors. Figure 4.9a shows sets of bell-shaped curves for the three protocols for each value of N, as expected. These curves are consistent



(**a**) Collisions rate (**b**) Busy time ratio

Figure 4.9: Network metrics for RF neighbours varying the power followers transmit under different platoon size

with the exponential curves achieved when varying the platoon size (heterogeneous platoon size) for fixed number of lanes and followers transmission power (Figures 4.3a and 4.8a). Thus, we observed that the average rate of collisions can be modeled with a family of Gaussian curves parameterized with platoon size.

Figure 4.9b shows the corresponding curves for busy time ratio as a function of the number of RF neighbours. All curves show a similar logarithmic and almost linear behavior even when varying the platoon size. Some differences become noticeable for a number of RF neighbors larger than 60. Thus, below that number the channel busy time ratio can be represented by a unique model for the three protocols and the conditions tested. For larger number of neighbors the model needs to be parameterized with the platoon size, too.

4.4 Summary

In this chapter, we presented empirical models that relate the number of RF neighbours that a platoon member observes, in a highway platoon-only scenario, with relevant network performance metrics.

We show that, as we change scenario and communication parameters, there are underlying and recurrent relationships between the number of RF neighbours and both the average rate of collisions and the busy time ratio, across the studied three MAC protocols. Concerning the rate of collisions, the relationship with the number of RF neighbors takes the form of an exponential curve if we increase platoon size, and a bell-shaped curve if we change the number of occupied lanes and followers transmission power. Concerning the busy time ratio, we observed a logarithmic-linear relationship with the number of RF neighbors in all cases. The referred network metrics models, namely for rate of collisions and busy time ratio, as a function of the number of RF neighbours can be used to support the design and operation of applications in highway platoon-only scenarios.

We also found that the models are generally applicable to RA-TDMAp in all cases. However, we realized that CSMA/CA and PLEXE-slotted deviate from the behavior in the models when operating in conditions of high coherency, i.e., when neighboring platoons have a similar TDMA frame structure (e.g., same size) and with small or null phase difference. In these cases, their performance profoundly degrades in both metrics. Moreover, we also confirmed in all simulated configurations that RA-TDMAp performs better in all metrics than either CSMA/CA and PLEXE-slotted, which perform similar to each other.

Chapter 5

Dynamic reconfiguration in RA-TDMAp

The most widely studied platoon configuration in transportation is the column, also known as *road train* [76]. This configuration considers longitudinal operations of the platoon, only, with vehicles following exactly the dynamics of the platoon leader generally using some kind of cruise control, either adaptive (ACC) or cooperative and adaptive (CACC) [77][78]. Specifically, the latter relies on inter-vehicle communications and must consider inherent communication delays and losses [47]. The platoon control may also benefit from specific structuring of the communications [79] that improves the channel quality. Further channel improvements can be achieved enforcing a TDMA scheme to reduce collisions in the access to the communication medium [51][13], as we saw in the previous chapters.

Beyond the essential function of car-following, there are a number of practical aspects related to the management of platoons that must be handled adequately, such as vehicles joining and leaving, as well as platoons splitting and merging, or even change of platoon leader. These maneuvers have been addressed at the control application level [76]. However, when using structured communications, such as platoon-oriented TDMA frameworks, the reconfiguration of both platoon control and TDMA frame must be synchronized. Curiously, few works, only, have addressed this problem in the past, e.g. [51].

In this chapter, we propose a dynamic TDMA frame reconfiguration mechanism for RA-TDMAp that tracks the current platoon configuration. RA-TDMAp is a distributed TDMA overlay protocol on top of IEEE 802.11p. It combines the benefits of both TDMA and CSMA/CA paradigms, namely collision reductions with efficient bandwidth use. This efficiency results from the adaptive feature of the protocol, explained in Chapter 3, that allows the co-existence of TDMA frames of neighboring platoons with minimum separation. We discuss the dynamic reconfiguration feature of RA-TDMAp in the context of platoon formation and splitting maneuvers and we show its state machine together with validating simulations on the PLEXE-Veins-SUMO-OMNeT++ framework.

This chapter is organized as follows. In Section 5.1 we present related work focused on platoon formation techniques. Section 5.2 presents the proposed TDMA reconfiguration approach while Section 5.3 presents the validation of the proposed approach through simulations in different highway scenarios. Finally, Section 5.4 summarises the chapter.

The work in this chapter was essentially reported in the following publication:

- [10] A. Aslam, F. Santos, and L. Almeida, "Reconfiguring TDMA Communications for Dynamic Formation of Vehicle Platoons," IEEE Int. Conf. on Emerging Technologies for Factory Automation, Vienna, Austria, September 2020.

5.1 Communications and Platoon Formation

Platoon formation, i.e., building up the physical platoon configuration, has been extensively addressed in the literature, but mostly from the control application perspective. Here we briefly revisit some representative works that consider the platoon communications jointly with the platoon control during platoon formation.

In this topic, the work in [66] deserves a particular reference since it proposed an integrated simulator, PLEXE, for studying joint control and communication strategies for longitudinal platoon operations, which had a significant impact in the research community. It also proposed the PLEXE-slotted protocol that was extensively studied and used for comparison against RA-TDMAp (and CSMA/CA) in the previous two chapters. Moreover, concerning platoon formation, the work addressed the join maneuver, only, and from a control application perspective, not clarifying the dynamic reconfiguration of the communications in PLEXE-slotted.

In [80], the authors proposed a high-level platoon management protocol that supported three basic maneuvers, namely platoon merge, split and lane change. This protocol uses CACC as control strategy and defines several specific IEEE 802.11p messages to negotiate the platoon reconfiguration. However, no specific reconfiguration of the communications used in CACC operation is done. Similarly, the work in [81] proposed a protocol specifically for platoon merging in highways, when two platoons that run side by side have to merge due to road works on one of the lanes. The authors introduced new messages to support the merging negotiation and maneuvering scenarios, but without reconfiguring the messages used for platoon control.

The work in [51] proposes a TDMA-based communication protocol, VeSOMAC, that supports platooning and self-reconfigures the TDMA frame to track dynamically the current platoon topology. This protocol was already described in Chapter 2, being based on in-band signaling using the vehicles beacons to carry information about allocated slots. Thus, it allows fast slot reconfiguration upon topology changes such as when a vehicle joins the platoon. Despite considering control applications as a motivation for the reconfigurable TDMA approach, the work does not clearly synchronize the platoon controller activity with the communication protocol states and focuses on the communications aspect.

5.2 Dynamic Reconfiguration of RA-TDMAp

RA-TDMAp was proposed in Chapter 3, but omitting the frame reconfiguration mechanism, which we address now. Previous RA-TDMA protocols [8][82] addressed cases of teams of autonomous robots and had their own dynamic reconfiguration mechanisms to cope with run time joining and leaving of robots. However, the specific power control used in RA-TDMAp and the position constraints imposed by the platoon maneuvers and operation make the reconfiguration mechanism of the previous protocols non-applicable to the current case.

Therefore, in this section we propose a specific reconfiguration mechanism for RA-TDMAp that is suitable for operation in realistic highway scenarios and to support the platoon maneuvers that are expected therein. As referred before, our proposal enforces the synchronization between the platoon control and the platoon TDMA frame so that topological changes in the platoon are reflected in both domains, simultaneously. This is achieved with a single state machine that runs in all vehicles, without global information across platoons.

5.2.1 System Model for Reconfiguration

In this work we consider a set of vehicles that move in a highway scenario and which are engaged in a platooning application, exploiting opportunities to build up platoons. Each vehicle has a unique vehicle identifier and each platoon is composed by a leader and $n-1$ followers, where n is the current number of platoon members. Note that $1 \leq n \leq N$, where N is a limit to the platoon size that is specific to each platoon and may be determined by multiple criteria such as control algorithm, communication range and weather or road conditions. Platoons have a unique platoon identifier, too, which can be derived from the respective leader vehicle identifier. When a vehicle activates the platooning application, it immediately starts as leader without followers ($n = 1$).

Since the leader gathers information from the whole platoon every TDMA round, it is in a privileged position to enforce consistency in the platoon. For this purpose, the leader announces in its beacon the current TDMA frame structure, namely the current number of slots, which equals the number of platoon members, and a vector with the current platoon formation. This is used by all followers to determine their slot and compute the respective offset.

Finally, the proper operation of RA-TDMAp, as common in ITS protocols, requires the vehicles to know their positions. Thus, we assume that all vehicles are equipped with a Global Navigation Satellite System (GNSS) such as GPS.

The structure of RA-TDMAp regular beacons (Type-0) of both leader and followers is shown in Table 5.1.

Table 5.1: RA-TDMAp Beacon Types and Formats

Regular	Type-0	Platoon	Source	Speed	Position	LaneID	Numberofslots	PlatoonFormation[]	DelayList[]
Request	Type-1	PlatoonID	SourceID	Position	LaneID	Speed	TargatedPlatoonID		
	Type-2	PlatoonID	SourceID	LeaveInform					
Response	Type-3	PlatoonID	SourceID	Distance	Lane	Capacity			
	Type-4	PlatoonID	SourceID	Ack					

5.2.2 RA-TDMAp Reconfiguration Mechanism

As a specific goal for our work we consider the following concrete platoon maneuvers that we wish to support:

1. **Joining**: Independent vehicles traveling in a highway find one or more platoons ahead of them, select one and request joining;

2. **Merging**: A platoon finds another platoon ahead of it, in the same lane, and issues a merging request;

3. **Follower leaving**: A follower vehicle in the platoon announces it wishes to leave;

4. **Leader leaving**: The platoon leader announces its intention to leave;

The first two maneuvers involve different entities, either independent vehicles or platoons, that will merge in a single platoon. The last two maneuvers start from a single platoon in which one of its vehicles wishes to leave. We consider that multiple vehicles can leave a platoon, but one at a time, only. Direct splitting of one platoon into several with more than one vehicle is not currently supported. For simplicity of terminology, we refer to leaving announcements as requests.

Each maneuver is coordinated by a structured exchange of specific IEEE 802.11p CAM messages (beacons), piggybacked with necessary information. The regular RA-TDMAp beacons are used for certain implicit confirmation actions, too. The additional beacons are transmitted periodically, with the same T_{tup} period, but during a short interval of time, until proper acknowledgement is received. These beacons are transmitted asynchronously with respect to the RA-TDMAp frame and handled by the CSMA/CA medium access mechanism of IEEE 802.11p. They are classified in two groups, namely request and response. All the beacons implied in the RA-TDMAp dynamic reconfiguration are displayed in Table 5.1. We use request/response beacons for convenience of implementation and not to tamper the RA-TDMAp regular beacons. Alternatively, we could use just the RA-TDMAp beacons with changing types, but this would require frequent changes of the beacon semantics and structure, which we opted to avoid.

During steady operation, all vehicles engaged in platooning are in one of two states, *Leader* or *Follower*. During reconfiguration, some of the involved vehicles have to temporarily move to transient maneuvering states. In order to support the maneuvers specified before, we use three extra states, two related to the process of joining or merging, and the third one related to the process of leader leaving, which requires designating a new leader. All the states are listed here:

- **Leader**: Platoon head, or single vehicle looking for platooning opportunities (high power beacons);

- **Follower**: All the trailing vehicles in a platoon after the platoon head (low power beacons);

- **Decide platoon**: A leader (single vehicle or platoon) that detects one of more platoons ahead of it that it can join, deciding which to join and moving to a *joining position* (high power beacons);

- **Waiting for response**: A joining leader that issued a join request to a specific platoon, and is in the joining position waiting for the respective response (high power beacons);
- **Leader election**: First follower of a leader that issued a leave request (low power beacons).

While in the *Leader* state, a vehicle has to carry out three main functions. It has to execute the TDMA frame phase adjustment, announce the current platoon presence and composition, and handle any joining requests that may appear. However, when a leader enters a joining process and moves to the maneuvering states, it still does the phase adjustment and platoon announcement, but blocks joining requests. This avoids potentially inconsistent states of a leader simultaneously asking to join a platoon while receiving joining vehicles itself. From the maneuvering states, a leader will eventually become a follower or return to its original *Leader* state.

On the other hand, the *Leader election* state is a transient state in which the first follower acknowledges that it is ready to take over, so that the leaving leader can exit the platoon.

While in the *Follower* state, the vehicles execute an adequate vehicle-following controller such as CACC. Note that followers do not seek other platoons. They remain in the same platoon until explicitly signaling intention to leave or disengaging the platooning application.

The state machine that governs the reconfiguration process using the states referred above is shown in Figure 5.1. This state machine is the same for all vehicles engaged in a platooning application with RA-TDMAp. Note that, initially, when the platooning application is turned on in any vehicle, it immediately starts as a leader. By detecting neighboring leaders in adequate relative positions, the vehicles use the joining maneuver and start building up platoons. In the remainder of this section we go through each maneuver scenario to observe how the state machine operates.

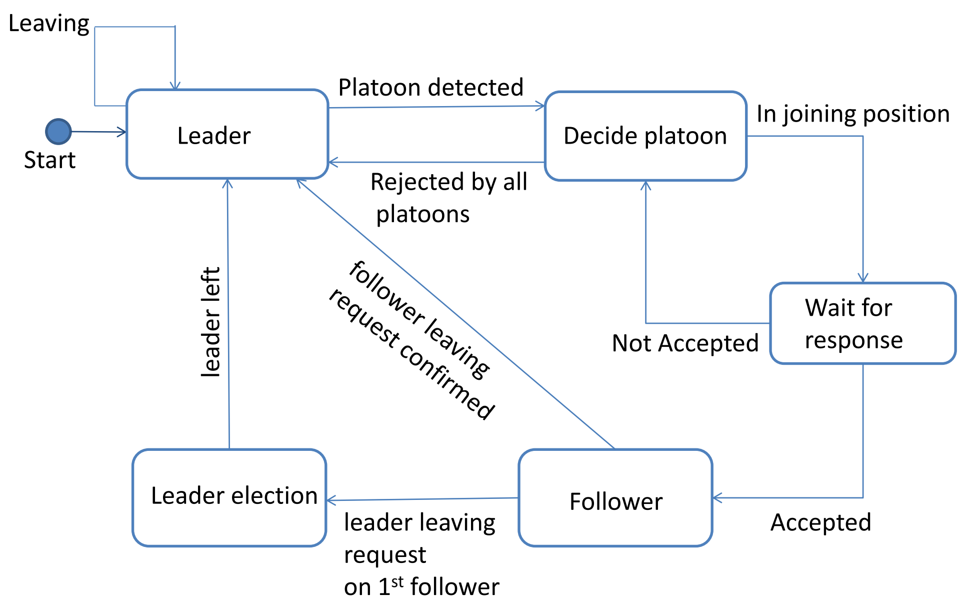


Figure 5.1: RA-TDMAp reconfiguration state machine

The pseudo-code of RA-TDMAp, which was initially shown in Algorithm 1, has now to be updated to include the reconfiguration mechanism, particularly when receiving a join request beacon.

The needed updates are represented in Algorithm 2. Lines 1-4 correspond to the reception of any beacons. When it is the leader receiving the beacon, depending on the outcome of the admission control, it will update the platoon formation vector and the number of slots in the current frame. Then, lines 5-11 correspond to the reception of regular beacons from the leader by the followers. In this case, the followers that receive the beacon update their view of the platoon formation prior to recomputing their offset for that round.

Algorithm 2 Updated RA-TDMAp pseudo-code to include reconfiguration (updates Algorithm 1)

1: **OnBeacon(beacon)**:
2: **if** $NodeId == Leader$ **then**
3:     PlatoonFormation($[platoonmembers]$);
4:     $NumberOfSlots \leftarrow platoonSize$
5: **OnLeaderBeacon(beacon)**:
6: unschedule(SendBeacon);
7: getPlatoonFormation;
8: getNumberOfSlots;
9: $platoonSize \leftarrow NumberOfSlots$;
10: $offset \leftarrow BeaconInterval \div platoonSize$;
11: scheduleAt(SendBeacon, myPosition $\cdot$ offset);

5.2.2.1 Joining

The joining maneuver is illustrated in Figure 5.2. In this scenario we have a platoon travelling in the highway and, for now, let us assume there is one independent vehicle approaching the platoon from the tail. Both independent vehicle and platoon leader are in the *Leader* state and transmitting *Type-0* beacons with high power, asynchronously to each other. When the vehicle starts receiving the platoon beacons, it checks whether the platoon is in a compatible position, e.g., sufficiently ahead and traveling in the same direction, and in that case moves to the *Decide platoon* state. In this state the vehicle checks whether there are other potential platoons it can join in different lanes, decides for one based on convenient criteria, e.g., direction, lane, distance, speed, and moves to a joining position, which is at a certain distance d behind the chosen platoon tail in the same lane.

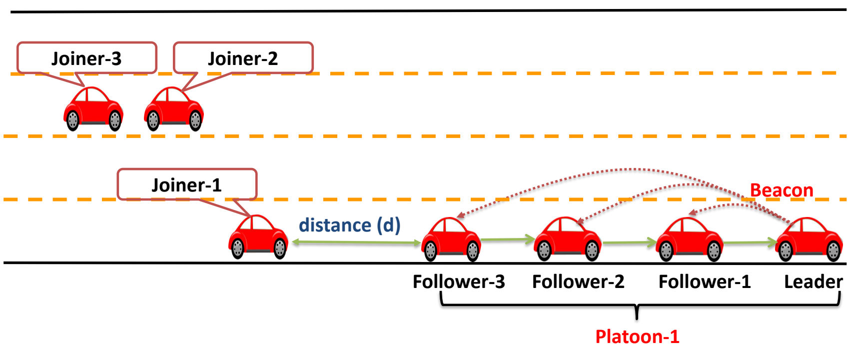


Figure 5.2: Joining scenario with multiple independent vehicles reaching up to a platoon and requesting to join

Once the joining vehicle gets to that position, it moves to the *Wait for response* state and starts emitting *Type-1* join request beacons indicating the ID of the platoon to join. These beacons are transmitted with high power to guarantee reaching the leader. The chosen platoon leader receives these beacons and triggers an admission control checking three parameters: (i) if the joiner is in the same lane of the platoon; (ii) if the current number of platoon members n plus the joiner does not override its limit N; and (iii) if the joiner is within a certain range around distance d from the platoon tail. If these conditions are met, the platoon leader integrates the joiner incrementing n and adding its ID to the platoon formation vector, and starts sending *Type-3* response beacons. Upon receiving these beacons, the joiner moves to *Follower* state and engages the platoon vehicle-following controller. Once the leader verifies that the joiner is integrated among its followers, it stops the response beacons and concludes the admission process.

If multiple independent vehicles that do not engage in joining among themselves detect the same platoon they may all start concurrent joining processes. However, they remain in the *Wait for response* state (or in the *Decide platoon* state until reaching the joining position) while the platoon handles the join requests in sequence, one at a time. If the independent joiners engage in a joining process among themselves, then they will first conclude the creation of a new platoon before attempting a merge with the other platoon. Remember that a leader is either handling joining processes or issuing joining requests, but not both at the same time. The behaviour of the joining maneuver is described in the sequence diagram in Figure 5.3.

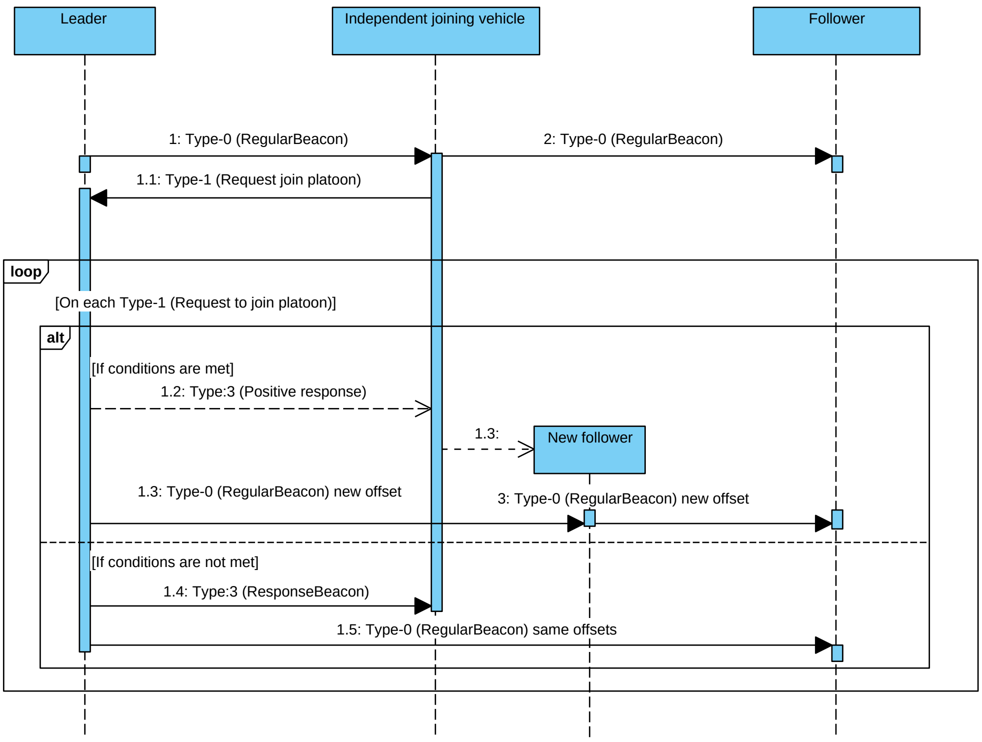


Figure 5.3: Sequence diagram of joining scenario with independent vehicles reaching up to a platoon and requesting to join

5.2.2.2 Merging

In this scenario, currently limited to *concatenation*, one platoon with $n > 1$ (the rear platoon) is traveling in the highway and joins another platoon ahead of it (the front platoon). The leader of the rear platoon follows through the maneuvering states. In the *Decide platoon* state it decides whether to try joining the front platoon. Due to control complexity, currently we do not consider merging of platoons in different lanes. In that case, the rear leader returns to the *Leader* state marking the front platoon as non-suitable for joining for a certain time, after which it may try again. If the front platoon is traveling in opposite direction it is obviously marked as non-suitable, too. If the front platoon is in the same lane, necessarily traveling in the same direction, the rear platoon leader may request merging. In this case, it moves, dragging its followers, to a joining position at distance d behind the tail of the front platoon. Once there, it moves to the *Wait for response* state and starts emitting the *Type-1* request beacon, which triggers a request for joining in the leader of the front platoon.

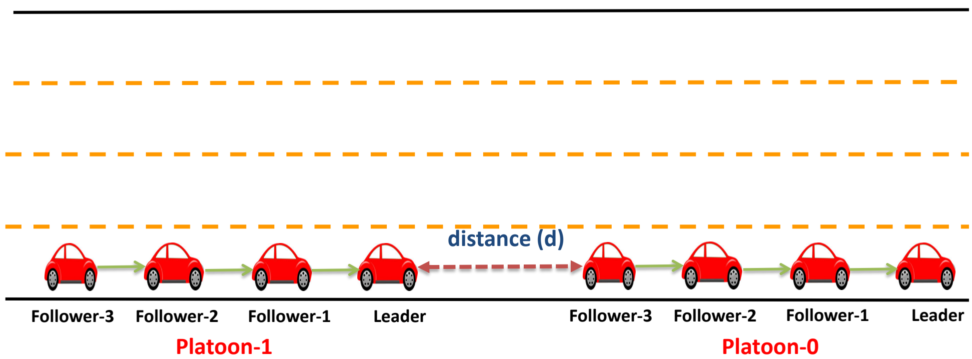


Figure 5.4: Merging of two platoons

Comparing to the previous case, the request beacon now indicates that the joining vehicle is a platoon leader with $n_{rear} - 1$ followers. The request also triggers the admission control in the front leader, which now considers all the n_{rear} vehicles of the rear platoon. If all can be accommodated in the front platoon, the front leader starts emitting *Type-3* response beacons with a positive response and changes its *Type-0* regular beacon with the updated information of the merged platoon (number of vehicles $n_{front} + n_{rear}$ and platoon formation). When the *Type-3* response beacons are received by the rear platoon vehicles they all move to the TDMA frame of the enlarged front platoon. The rear leader, stops emitting the request beacon, changes its state to *Follower* and switches on the platoon vehicle-following controller that will close the gap to the front platoon.

If the admission control in the front leader fails, the *Type-3* response beacons will indicate this condition. The rear leader also stops emitting *Type-1* requests and returns to the *Leader* state (through the *Decide platoon* state). Its TDMA frame will remain unchanged and its followers will remain with it. The behaviour of the merging maneuver is described in the sequence diagram in Figure 5.5.

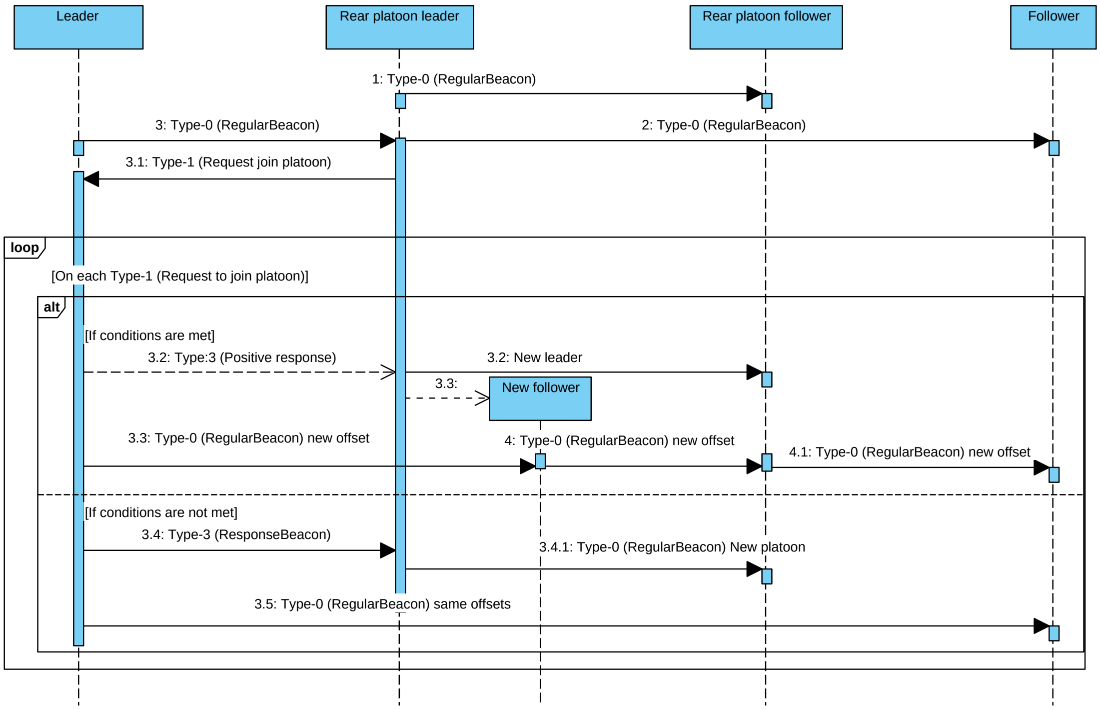


Figure 5.5: Sequence diagram of merging of two platoons

5.2.2.3 Follower leaving

Followers remain in this state until they disengage the platooning application or issue an explicit request to leave. In the former case, by disengaging platooning a vehicle will no longer participate in any platoon and stops executing the RA-TDMAp state machine and sending the respective beacons. The leader will detect the omissions of that follower and after a pre-defined number of consecutive TDMA rounds with omissions, the leader reconfigures the platoon and the TDMA frame, excluding the vehicle.

Alternatively, a follower willing to leave may start emitting *Type-2* requests that cause the leader to reconfigure the platoon and TDMA frame to remove the requesting follower. When this follower detects it is no longer in the platoon formation announced by the leader in its regular *Type-0* beacons, it considers itself out of the platoon, stops emitting request beacons and moves to the *Leader* state.

In both cases, the leaving vehicle may stay amidst the platoon for some time, until it physically leaves, e.g., by taking an out ramp (Figure 5.6). This does not compromise the platoon operation. While in the middle of the platoon, the platooning controllers, e.g., CACC, will keep a safe distance to that vehicle. As soon as the vehicle leaves its position, the platooning controller in the following followers will make them close the gap to the previous followers in the platoon. The behaviour of the follower leaving is described by mean of general sequence diagram in Figure 5.7.

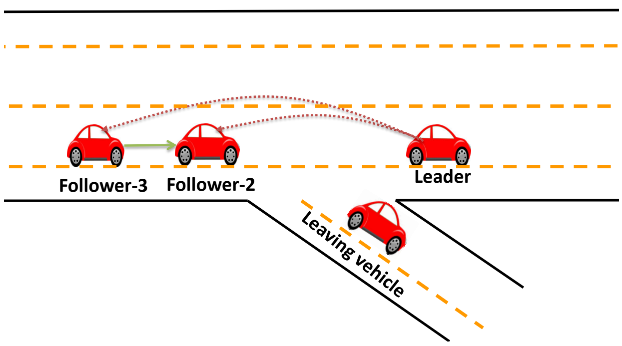


Figure 5.6: Follower leaving a platoon

5.2.2.4 Leader leaving

In this case, the first follower is promoted to leader, taking over the role of synchronizing the platoon, rearranging the TDMA frame and platoon formation accordingly. If the leader simply disengages the platooning application, its absence will be detected by omission after some time (pre-defined number of consecutive omissions). This will be a period without synchronization and TDMA frame adaptation. During this time the first follower keeps its speed constant to avoid following an absent or unreliable leader. The leader may also request leaving by emitting *Type-2* requests. These will be detected by the first follower that moves to the *Leader election* state. Once in this state, it emits *Type-4* response beacons until the leader leaves. This is signalled by the leaving leader stopping emitting the request beacons and changing its platoon ID to a different value and its formation to itself alone. In the original platoon, the first follower then moves to the Leader state, reconfigures the TDMA frame and platoon formation and resumes regular platoon operation. The new platoon with the leaving leader does not accept join requests until it is sufficiently away from the original one. The behaviour of the leader leaving is described in the sequence diagram in Figure 5.9.

5.3 Validation

In this section we show a validation of the proposed RA-TDMAp dynamic reconfiguration mechanism in the maneuvering scenarios that were referred before. We will use simulation for our validation purposes, relying on the Plexe/Veins/OMNeT++ framework [66][67]. We first present the simulation setup and then simulation results that confirm the proper operation of the proposed mechanism.

5.3.1 Simulation Setup

Plexe is the current state-of-the-art system level platooning simulator, incorporating mobility tightly-coupled with automatic control and communications. It allows defining platooning applications on highway scenarios, including the full stack of IEEE 802.11p/ IEEE 1609.4 network standards and analyzing network metrics such as collisions and packet delivery ratio. We use these

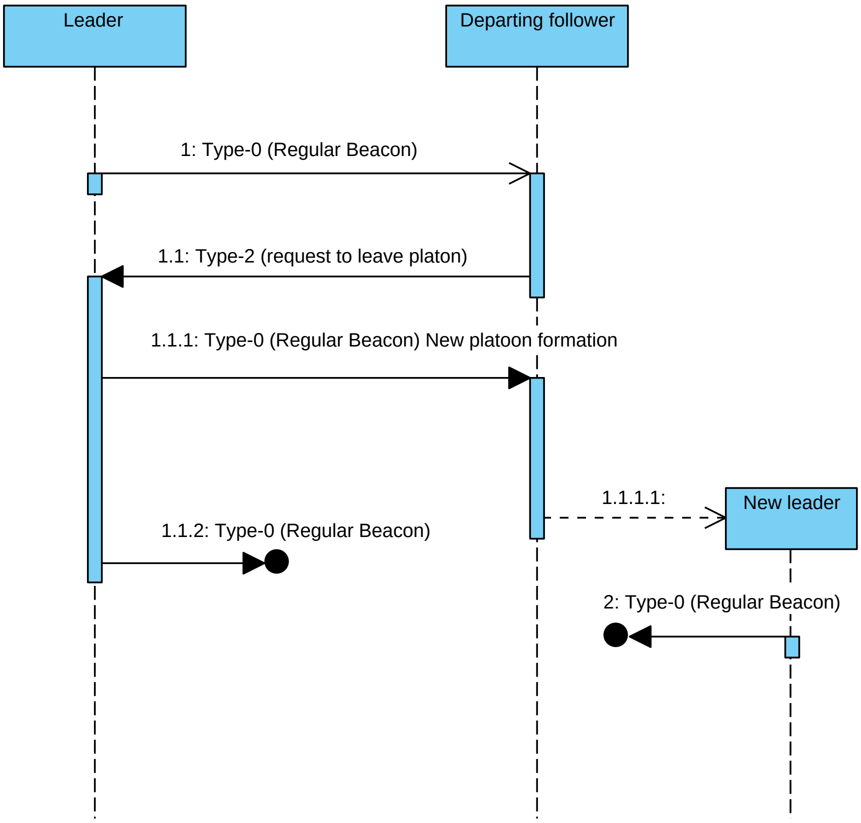


Figure 5.7: Sequence diagram of follower leaving a platoon

features to validate the proposed reconfigurable mechanism of RA-TDMAp in a straight four-lanes highway scenario.

5.3.1.1 Communication model

We use the PHY and MAC models of IEEE 802.11p proposed in [70], with a bitrate of 6 Mbit/s, which is suited for demanding safety related applications [71]. The leader transmission power is set to 100 mW (high power) and the followers to 1 mW (low power). We employed the common free-space propagation model with $\alpha = 2.0$. Furthermore, we used the Control Channel (CCH), only, without the Service Channel (SCH), and all beacons used the same Access Category (AC_VI). Table 5.2 summarizes all communication related parameters.

5.3.2 Validating the reconfiguration mechanism

To validate the reconfiguration mechanism we carried out simulations recreating the previous maneuvering scenarios. Each simulation trace is 100s long and we logged all the transmissions in that interval. Target speeds are set to 100km/h and RA-TDMAp round periods are set to 100ms with a small random variation. The platooning application uses CACC with a target distance between vehicles of 5m and the joining position d is 17m behind the platoon tail.

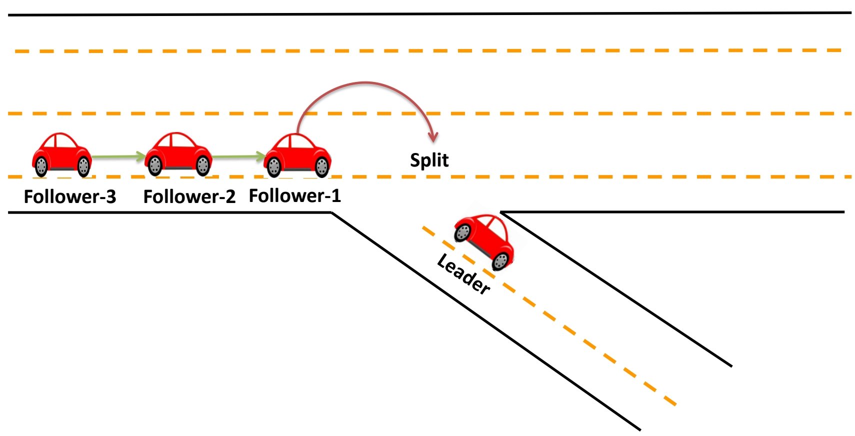


Figure 5.8: Leading vehicle leaving the platoon

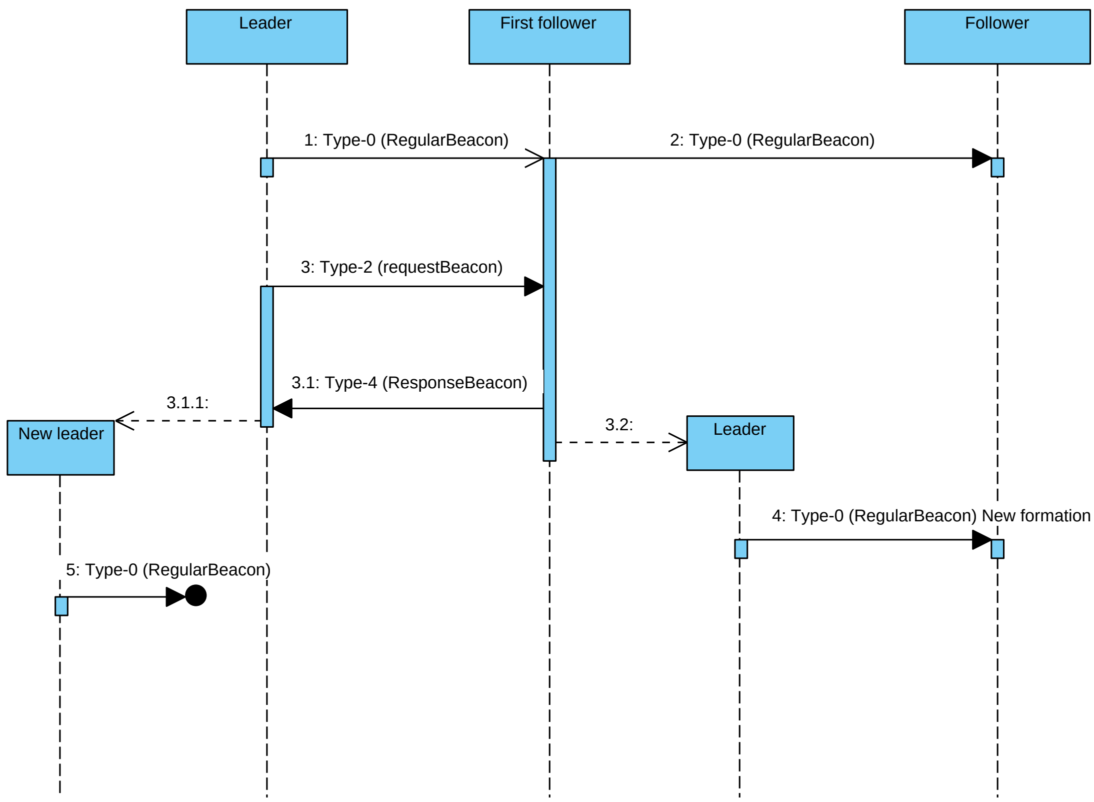


Figure 5.9: Sequence diagram of leader leaving a platoon

5.3.2.1 Joining

To validate the joining maneuver we consider one independent vehicle (ID=4) and one platoon with four vehicles (ID=0 -leader; IDs=1,2,3 -followers). Figure 5.10 shows the TDMA frame reconfiguration process in time for $0 \leq t \leq 70$s (the remaining part of the trace has no relevant information). The top plot shows the offsets of the vehicles transmissions relative to the transmission of the leader (offset 0) in each TDMA round. A vertical cut would show the actual offsets in a particular TDMA frame. The top line is the offset of the next leader transmission relative

Table 5.2: PHY and MAC parameters

Parameter	Values
PHY/MAC model	IEEE 802.11p/1609.4, CCH only
Path loss model	Free space ($\alpha = 2.0$)
Channel	5.89 GHz
Bitrate	6 Mbit/s
MSDU size	200B
Access category	AC_VI
Leader Tx power	100mW
Followers Tx power	1mW

to the previous one, i.e., the actual TDMA round period. Thus, from top to bottom we have the offsets of vehicles 0 through 3. These offsets are constant due to the synchronization enforced by RA-TDMAp and the absence of interference. The lower plot in the figure shows the inter-vehicle distances. The upper line is the distance between the joining vehicle and the platoon tail and the lower line is the distance between the other vehicles (overlapped), which is constant at 5m as enforced by the CACC.

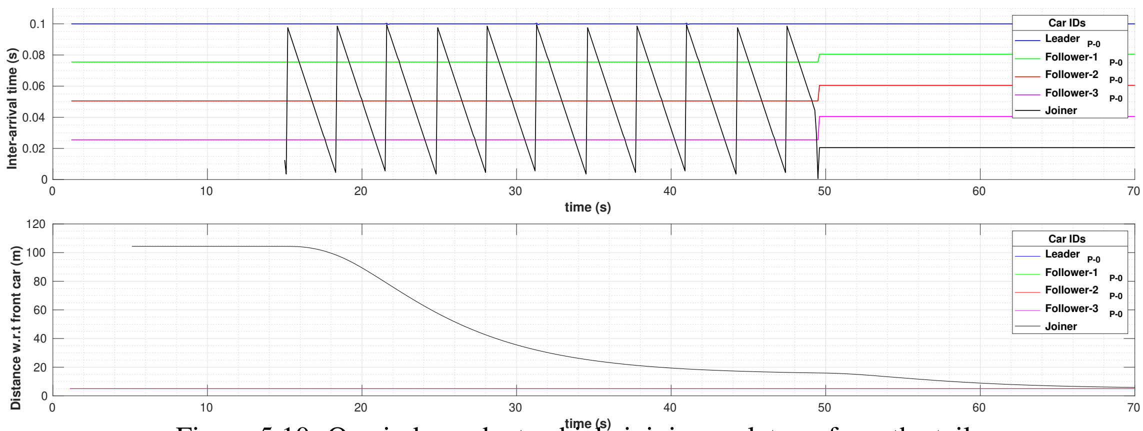


Figure 5.10: One independent vehicle joining a platoon from the tail

The joining vehicle was inserted in the simulation at $t = 5$s at a distance of 100m to the platoon tail and traveling at the same speed, with the platooning application switched off. At $t = 15$s it engages the platooning application and enter the *Leader* state, becoming an independent leader, and starts transmitting its own beacon (black line). Since they are not synchronized and its effective T_{tup} is slightly shorter than that of the platoon, its offsets (phases) relative to the platoon leader keep changing linearly, thus the diagonal traces.

Soon after starting the platooning application it detects the beacons of the platoon leader and moves to *Decide platoon* state. Since this is the only platoon in range and it is sufficiently ahead of it (more than distance d), it chooses to try joining this platoon and moves to the joining position (17m behind the tail). It reaches this position at $t = 49s$, moving to the *Wait for response* state and sending the join request beacon (Type-1). The platoon leader receives the request, runs the admission control and sends the joiner a response beacon (Type-3) informing acceptance. In this case, just one beacon of each type was sent. If one of them is not received, the protocol waits for the next beacon, since they are transmitted periodically until successfully received.

At this point the leader reconfigures the TDMA frame updating the number of platoon vehicles to $n = 5$ and the formation vector to include vehicle ID=4. All followers start using the offsets of the new frame. The joiner changes to the *Follower* state, starts transmitting in the right offset in the platoon frame and switches on the CACC. The CACC then controls the speed of the joiner to bring it to a distance of 5m to the next follower, which it achieves at $t = 70$s.

5.3.2.2 Merging

This scenario is illustrated in Figure 5.11, where the two plots have similar semantics as in the previous case. We have two platoons with $n = 4$, entering the simulation at the same speed. Platoon 0 (in blue) enters first and contains vehicles 0 (leader), 1, 2 and 3. Platoon 1 (in red) comes after and contains vehicles 4 (leader), 5, 6 and 7. The upper plot shows the offsets of the transmissions of both platoons with respect to the leader of platoon 0 (blue). Again, while the platoons are separated, their transmissions are synchronized internally but not between platoons. Thus, the offsets of platoon 1 (red) appear in diagonal when referred to the transmissions of platoon 0 (blue), but showing parallel lines, i.e., they are internally synchronized.

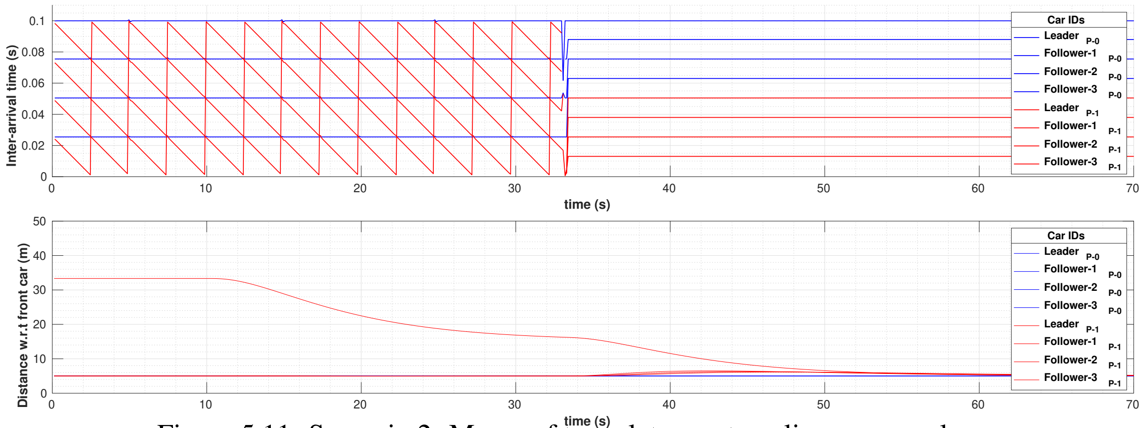


Figure 5.11: Scenario 2: Merge of two platoons, traveling on same lane

The lower plot in Figure 5.11 shows the inter vehicle distances. Initially, all distances inside each platoon are at 5m and we insert platoon 1 at 33m behind the tail of platoon 0. We give some initial time for platoon 1 to be fully inserted in the simulation before allowing its state machine to evolve. For this reason, only at $t = 10$s platoon 1 reacts to the detection of platoon 0 in a compatible position and its leader (ID=4) transitions to the *Decide platoon* state. In that state it decides to merge with platoon 0 and thus brings its platoon to the joining position (17m). The leader gets there at $t = 34$s. At that point, it transitions to *Wait for response* state and starts emitting joining/merging request beacons (Type-1) informing the leader of platoon 0 that it wishes to merge with its 4 vehicles altogether.

The platoon 0 leader runs the admission control and, given the positive outcome, it reconfigures the TDMA frame accordingly, i.e., increases its n to 8 and adds vehicles ID 4 through 7 to its formation vector. Then, it starts emitting response beacons (Type-3) allowing the merging. At that point the vehicles of platoon 1 start engaging the platoon 0 with their corresponding offsets. The leader of platoon 1 moves to the *Follower* state, starts transmitting with low power in the right offset of the TDMA frame of platoon 0 and activates the CACC. As soon as the leader detects that all vehicles of the joining platoon are merged, it stops emitting the response beacons. The activation of the CACC in the follower that was the previous leader closes the gap between both platoons, and all inter-vehicle distances converge to 5m at $t = 70$s.

5.3.2.3 Follower leaving

Figure 5.12 shows the reconfiguration process when a follower leaves the platoon. We consider platoon 0 traveling in a highway with 4 vehicles (IDs 0-leader, 1, 2 and 3). In the upper plot (offsets) we can see that, at $t = 21$s, the first follower announces it is leaving the platoon. For that purpose, still in the *Follower* state it starts emitting the a request leaving beacon. The platoon leader receives this beacon and reconfigures the platoon and the TDMA frame, removing the vehicle from the formation vector and decrementing n. When the leaving follower receives a regular beacon from the platoon leader showing it is no longer in the platoon, it changes to *Leader* state. This is clearly visible in the offsets plot. The leaving vehicle is now transmitting asynchronously with respect to the platoon.

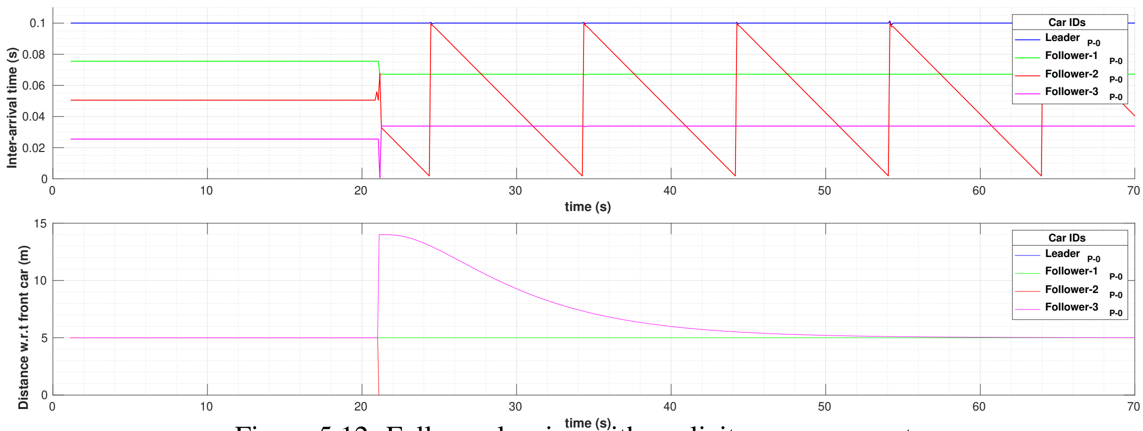


Figure 5.12: Follower leaving with explicit announcement

In this experiment, we make the leader move away from the platoon, driving to a different lane. This is visible in the lower plot, where we can see the sudden increase in the distance between the previous second follower, now promoted to first follower, and the platoon leader. As the leaving car moves to another lane, the CACC of the followers brings them to the target 5m inter-vehicle distance, converging at $t = 40$s.

5.3.2.4 Leader leaving

Figure 5.13 shows the RA-TDMAp reconfiguration in the case a leader explicitly leaves a platoon. In this case, the inter-vehicle distances are not relevant and are thus omitted. We use the same scenario as in the previous case, with one platoon of four vehicles. However, in this case it is the leader that announces its willingness to abandon the platoon at $t = 20$s. It starts emitting the leave request beacon (Type-2), which is captured by the first follower causing it to transition to the *Leader election* state. In this state, the first follower starts emitting the response beacon (Type-4) acknowledging that it is ready to take over the leader role. Upon receiving this beacon, the current leader creates a new platoon just with itself and leaves the previous platoon. The first follower waits for one omission of the regular beacon (Type-0) of the previous leader and changes to *Leader* state, effectively taking over the platoon. This occurs at the time it would do its regular beacon transmission. The figure shows the offsets referred to the old leader (blue). The reconfigured platoon, with one vehicle less, maintains its internal synchronization, despite being asynchronous to the old leader.

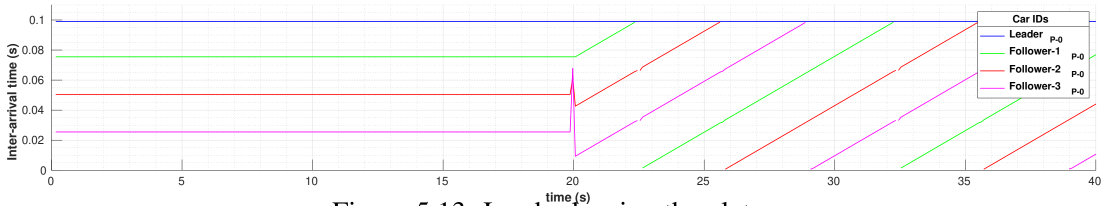


Figure 5.13: Leader leaving the platoon

5.3.3 Global Comments

The results in this section validate the correct behavior of the reconfiguration mechanism and its capacity to keep the platoon controller synchronized with the corresponding state of the communication protocol. The transition between configurations was swift, even under distributed operation, reducing the interval during which synchronization ambiguities can occur. Our simulations, under low traffic, revealed reconfiguration times below 2.5 TDMA rounds. Losses of signalling beacons extend this interval an integer number of TDMA rounds. The impact of high traffic is left for future work.

5.4 Summary

Practical platooning requires handling reconfiguration scenarios, to allow vehicles joining or leaving. These scenarios have been addressed mostly from the control point of view, disregarding the communications reconfiguration. However, this is mandatory when using TDMA-based protocols. In this chapter we proposed a novel reconfiguration mechanism for RA-TDMAp. We presented the state machine of the reconfiguration mechanism, which is the same for all vehicles, and validated it with simulation using the PLEXE-Veins-SUMO-OMNeT++ framework and realistic joining, merging and leaving scenarios in highways. Future work will consider more reconfiguration scenarios, including with high traffic density and non-longitudinal platoon operation (e.g, zipper merging [83]).

Chapter 6

Experimental Validation

This chapter addresses the experimental validation of the RA-TDMAp protocol in practice, first using regular WiFi in ad-hoc mode and then COTS IEEE 802.11p hardware. This is important as a proof-of-concept. Most of the results shown in this thesis are simulation-based. Simulation is important for quick validation and verification, and it is the only way when we need to search through extensive configuration spaces or when we need to check scalability.

Although we believe the PLEXE-Veins-SUMO-OMNeT++ simulation framework we used is sufficiently accurate to support the development and analysis of our proposed protocol, we still think that experiments on real hardware are an important piece to verify whether the basic properties of our protocol hold in practice.

The first experiments we show concern a preliminary implementation on WiFi (ordinary IEEE 802.11 standard), essentially aiming at verifying the capacity of the original RA-TDMA synchronization mechanism to support the coexistence of multiple concurrent applications, each with its own TDMA frame and each one considering the other as external traffic. We used IEEE 802.11b in ad-hoc mode with broadcast frames, whose MAC is relatively similar to that of IEEE 802.11p. This experiment shows that the phase adaptation and synchronization mechanism embedded in the base RA-TDMA protocol automatically sets out of phase multiple frames when multiple teams of autonomous cooperating agents co-exist in space. Each team simply senses the delays in its own traffic, caused by the interference of the other team(s) together with other external traffic, and adapts its frame phase. This sets both frames out of phase without being explicitly aware of each other. This capacity to support multiple co-existing TDMA frames was not a requirement for the original RA-TDMA protocol, but it is fundamental for RA-TDMAp.

Finally, we implemented the RA-TDMAp protocol, as proposed in this thesis, on real IEEE 802.11p hardware for experimentation and final validation of the synchronization and reconfiguration mechanisms. The results show the desired effect of the adaptive mechanism to escape coherent periodic interference, i.e., that with a similar period, as well as the reconfiguration of the TDMA round following physical reconfiguration of the platoon composition.

While the validation on IEEE 802.11p equipment was not published in any other venue than this thesis, yet, the preliminary experimental validation on WiFi was reported in:

- [14] A. Aslam, L. Almeida, and F. Santos, "Using RA-TDMA to Support Concurrent Collaborative Applications in VANETs", in Smart Technologies, IEEE EUROCON 2017-17th International Conference on, pp. 896–901, IEEE, 2017

6.1 Preliminary Experiments with RA-TDMA

To verify the capacity of the original RA-TDMA synchronization mechanism to handle multiple frames co-exiting in space, we organized an experimental setup in the laboratory with two teams, A and B. Team A comprised three laptops and team B comprised four laptops, all configured in ad-hoc mode, i.e., without using an access point. We also used one more laptop for monitoring purposes that time-stamped and logged frame receptions, without performing any transmission (Figure 6.1). We configured the wireless card of this laptop in monitor mode so that it could capture all types of packets from all the networks operating on the selected channel. All laptops were running the Linux operating system and using their internal WiFi interfaces.

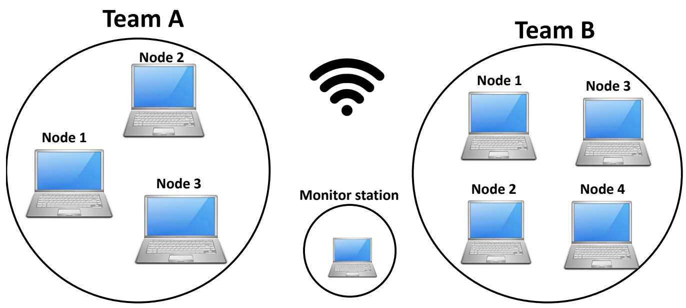


Figure 6.1: Laboratory setup with two teams, A and B

We started by setting the round length T_{tup} with approximately coherent periods in both teams. Note that T_{tup} is an application dependent parameter typically configured offline. The round length for team A was set to T_{tup_A} = 100ms corresponding to a slot duration $T_{xwin_A} \approx$ 33ms. Similarly, the round length for team B was set to T_{tup_B} = 101ms corresponding to a slot duration $T_{xwinB} \approx$ 25ms. The small variation in round periods aims at creating a slowly sliding relative phase among both teams.

All members of both teams are active and run the RA-TDMA protocol. Note that the protocol allows each member to synchronize internally in each team, independently of each other. Finally, we ran the set up for 280 seconds with the two teams coexisting in close proximity, to observe the impact of using RA-TDMA.

The results shown in Figure 6.2 reveal the coexistence of both teams as expected and the adaptations and synchronization enforced by RA-TDMA. Both team A and team B sense the delays in their own TDMA frames caused by the interference of the other team. In this plot, each vertical line represents a reception in the timeline. Different colors represent different team members and the two different heights represent the two teams. Note that some lines are very close together since the messages transmission time is relatively short. However, recurrent collisions were not observed. Moreover, there were other delays caused by other interfering traffic in the channel.

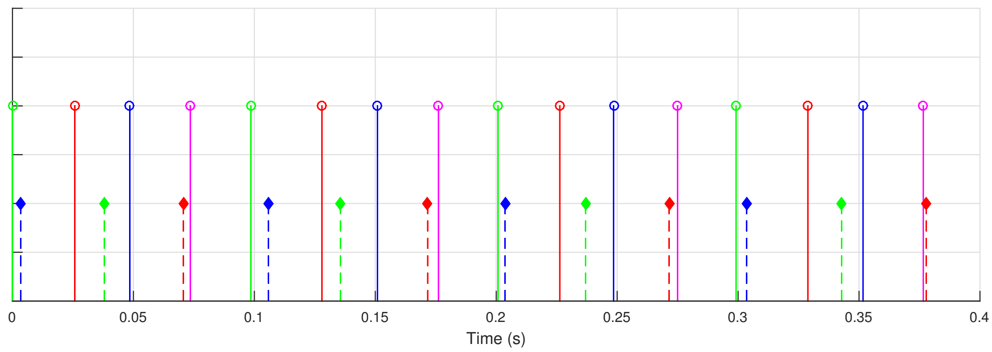


Figure 6.2: Co-existence of two teams (team A lower, team B higher)

The operation of RA-TDMA is better illustrated by the time offsets of the receptions of each team member transmissions with respect to its team reference node. These offsets should be constant and equal to the slot interval T_{xwin} but suffer deviations caused by interfering traffic and packet losses. Figure 6.3a shows the time offsets for Team B where the horizontal full lines represent the receptions from nodes 1, 2 and 3 after the reception of the respective reference (node 4) represented by the x-axis. Negative spikes in these curves indicate lost packets while positive spikes indicate delays caused by interference.

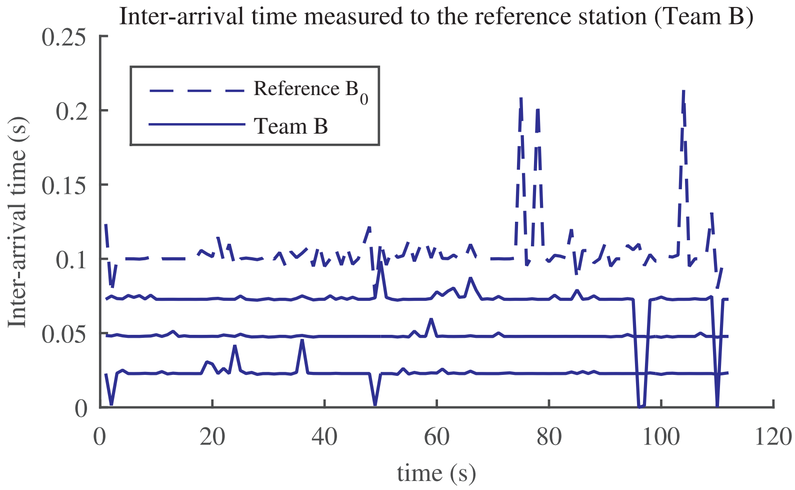
The upper dotted line represents the time offset of the reception of the next reference transmission, representing, thus, the actual round period including its continuous adaptation. The strong positive spikes around seconds 80 and 100 represent lost packets from the reference node.

The same information is represented in Figure 6.3b in the form of histograms, showing the precision of the slots structure in the round, with nodes 1, 2 and 3 transmitting at 25, 50 and 75ms after the reference, respectively. Figure 6.4 shows the same information for Team A, which has just two nodes beyond the reference.

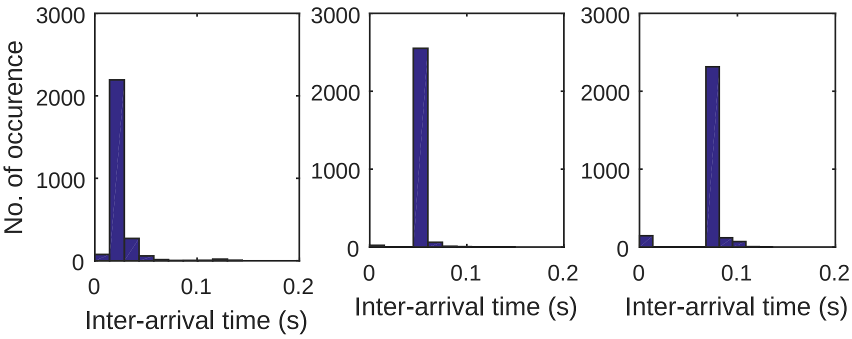
Finally, Figure 6.5 shows the same data but with both teams superimposed, using the reference of Team B for both. Naturally, the data of Team B matches that in Figure 6.3a. Conversely, Team A is now clearly not-synchronized, exhibiting the expected sliding phase with respect to Team B. This figure shows that both teams synchronize internally but co-exist in a mutually agnostic way, imposing occasional interference to each other.

6.2 Experimental Validation of RA-TDMAp on IEEE 802.11p

To validate experimentally the RA-TDMAp protocol that is the core of our thesis, we performed measurements with real IEEE 802.11p devices in scenarios similar to those that were used in simulation (Chapters 3 and 5). The devices are all APU.3C4 System board, with 4GB of RAM from PC Engines, running the Arch Linux operating system. The wireless network cards are



(**a**) Each line represents the offset of one Team B member



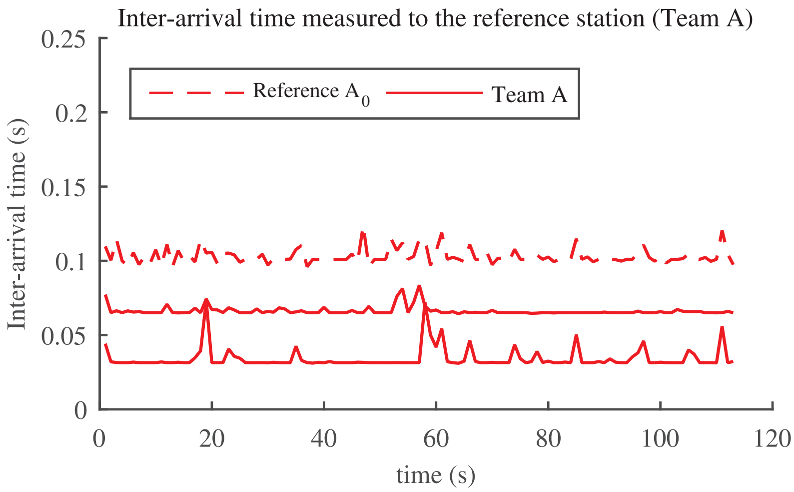
(**b**) Histogram of Team B offsets (except reference node)

Figure 6.3: Time offsets of the receptions from team B with respect to its reference node

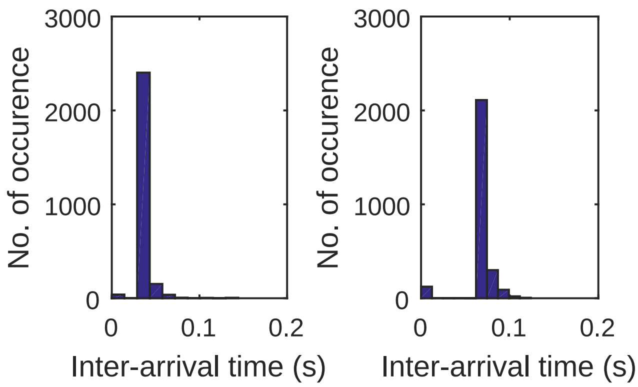
WLE200NX, with a modified firmware to implement the IEEE 802.11p MAC in the 5.9GHz band.

We implemented RA-TDMAp as a layer sitting on top of the original IEEE 802.11p MAC layer and used an experimental setup in a laboratory incorporating six of those IEEE 802.11p devices. Among them, one device is used as a monitoring station, only, that time-stamped and logged frame receptions in monitor mode. The monitoring station did not transmit and was not included in the RA-TDMAp protocol. We also used one device dedicated to generate more external interfering traffic, the traffic generator, again not included in the RA-TDMAp protocol. With the remaining four devices we generated different platooning scenarios.

We configured the RA-TDMAp protocol and the IEEE 802.11p radios using the parameters in Table 6.1. Note that, as opposed to the experiments with WiFi in which the channel had substantial background traffic, in this case, the channel was essentially clean, just with the traffic explicitly generated in the experiment. Therefore, to make the phase adaptation visible, we created some level of external interference using the traffic generator device injecting packets of 1216 Bytes with a transmission period of 11ms. This period creates a sliding interference with the traffic from the platoons that uses a beacon interval (T_{tup}) equal or close to 100ms. This interference is present



(**a**) Each line represents the offsets of Team A memebrs



(**b**) Histogram of Team A offsets (except reference node)

Figure 6.4: Time offsets of receptions from team A with respect to its reference node

in all experiments.

Table 6.1: Parameters employed in the experimental validations of RA-TDMAp

Parameter	Values
PHY/MAC model	IEEE 802.11p/1609.4
Channel frequency	5860 MHz
Channel number	172
Bit rate	6 Mbit/s
Protocol beacon size	36 B
Beacon interval (T_{tup})	100 ms and 101 ms
Interfering packet size	1216 B
Period of interfering packet	11 ms

Moreover, when using either two platoons or one platoon and an independent vehicle, we use two approximately coherent beacon intervals, namely $T_{tup} = 100$ or 101 ms. This slight difference

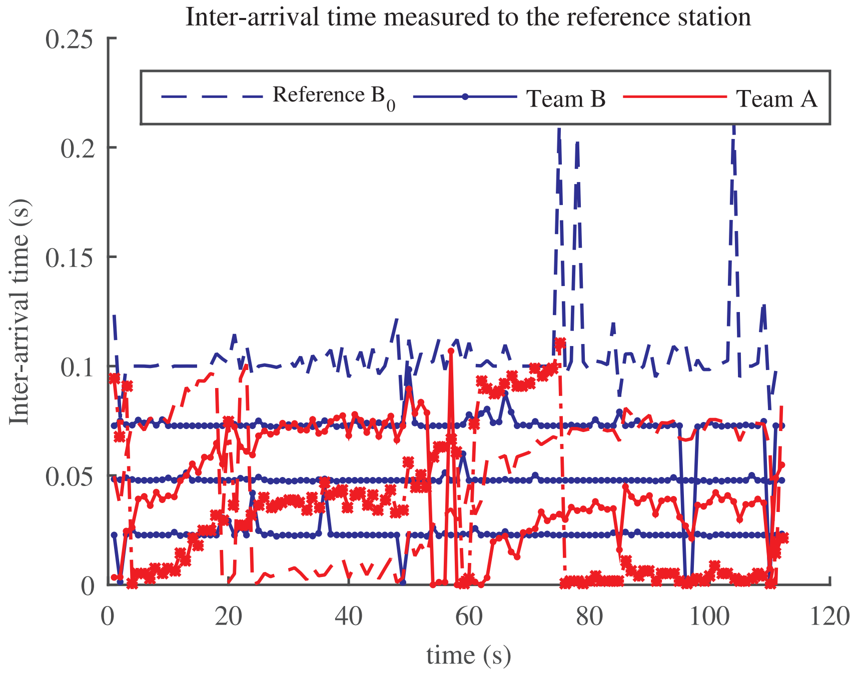


Figure 6.5: Time offsets of the receptions from both teams, A and B, with respect to Team B reference node

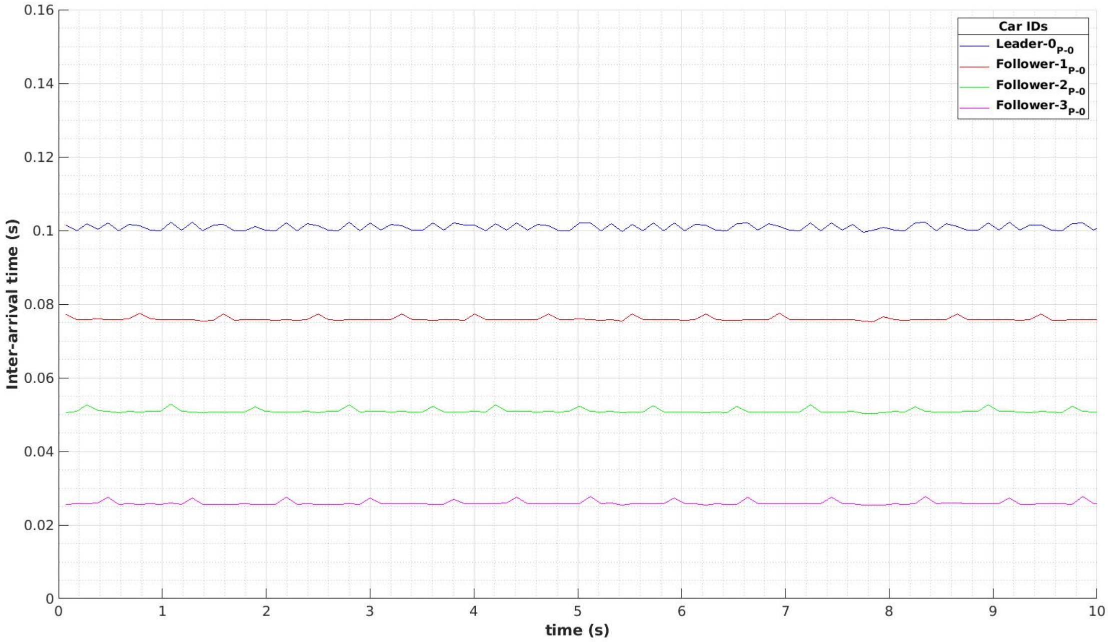
causes a sliding relative phase of both platoons, to create clear but slow phase drifts thus provoking recurrent critical periods of interference. Finally, except stated otherwise, we ran all experiments for 160 seconds and logged all message reception instants with the monitor device.

6.2.1 Validating RA-TDMAp Phase Adaptation Mechanism

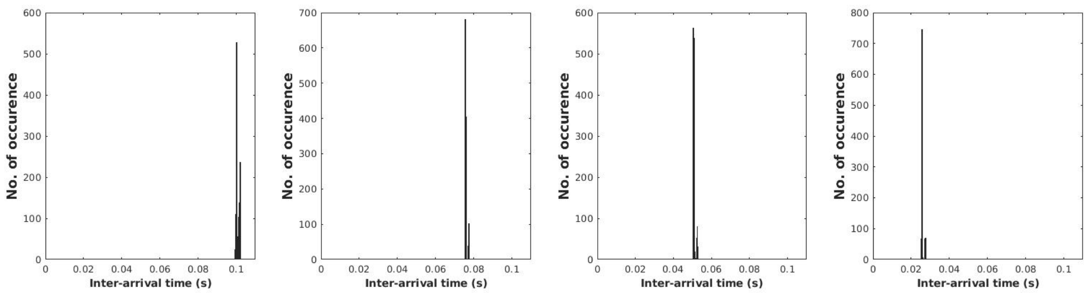
In this section, we aim at validating the synchronization mechanism of RA-TDMAp protocol, based on phase adaptation, similarly to what we did with simulation in Section 3.3.2 and with the RA-TDMA experiments on WiFi shown in the previous section.

We define one single platoon, *Platoon 0*, with four vehicles, thus $n = 4$. We use a beacon interval of $T_{tup0} = 100$ms. Figure 6.6a shows the evolution of the offsets of the transmissions of Platoon 0 members with respect to its leader ($Leader_{P-0}$) using RA-TDMAp. The upper line (blue) shows the offset of the next leader transmission with respect to the current round, i.e., to the previous leader transmission. Thus, this is the interval between the successive transmissions of $Leader_{P-0}$. Consequently, this trace shows the effective beacon interval in each TDMA round. The following trace (red) shows the offset of the $Follower\text{-}1_{P-0}$ with respect to the previous leader transmission that initiated that round, and so consecutively for $Follower\text{-}2_{P-0}$ (green) and $Follower\text{-}3_{P-0}$ (cyan).

All platoon transmissions, from leader and followers, can suffer delay due to the transmissions of the traffic generator. In each round, the delay that affects the followers is measured by the RA-TDMAp mechanism and passed on, in a multi-hop fashion, to $Leader_{P-0}$, which uses that information to adjust the time of its next transmission. We can see these adjustments in Figure 6.6a, thus empirically validating the RA-TDMAp synchronization mechanism based on the frame phase adaptation. Note that the interference affecting the $Leader_{P-0}$ transmissions are not compensated, thus the upper trace shows offset variations beyond those inherited from the followers.



(**a**) Evolution of the offsets of *Platoon 0* members



(**b**) Histogram of the offsets of *Platoon 0* members

Figure 6.6: Time offsets of the receptions of *Platoon 0* measured by its $Leader_{P-0}$

Figure 6.6b shows the histograms of the offsets measured during the whole experiment, showing the small adaptations around the precise slots start instants, for both the $Leader_{P-0}$ (left, 100 ms) and $Follower\text{-}1_{P-0}$ through $Follower\text{-}3_{P-0}$ (second to forth, from right to left, 75, 50 and 25 ms, respectively).

6.2.2 Validating the Coexistence of Multiple Platoons

Here we use two platoons, *Platoon 0* and *Platoon 1*, each with two vehicles ($n = 2$) and close beacon intervals ($T_{tup0} = 101$ms and $T_{tup1} = 100$ms). We show that RA-TDMAp allows the platoons to coexist in space, each internally synchronized, only, being agnostic to each other except for suffering the respective mutual interference. Figure 6.7 shows the offsets of two platoons with respect to the transmissions of $Leader_{P-0}$ as reference. The upper plot (Figure 6.7a) shows a segment of the offsets evolution in time. The horizontal traces (red) are from *Platoon 0*, while the diagonal traces are from *Platoon 1* (blue). As expected, *Platoon 1* is not synchronized with *Platoon 0*, thus the small difference between T_{tup0} and T_{tup1} is enough to create a drifting phase that generates the visible linearly varying offsets of *Platoon 1* with respect to *Platoon 0*.

Figure 6.7b shows the corresponding histograms of the offsets. The offsets of *Platoon 0* are centered around the corresponding slot starts at 101ms and 50.5ms, respectively. On the other hand, the offsets of *Platoon 1* with respect to *Platoon 0* show a uniform distribution as expected due to their approximately constant period difference.

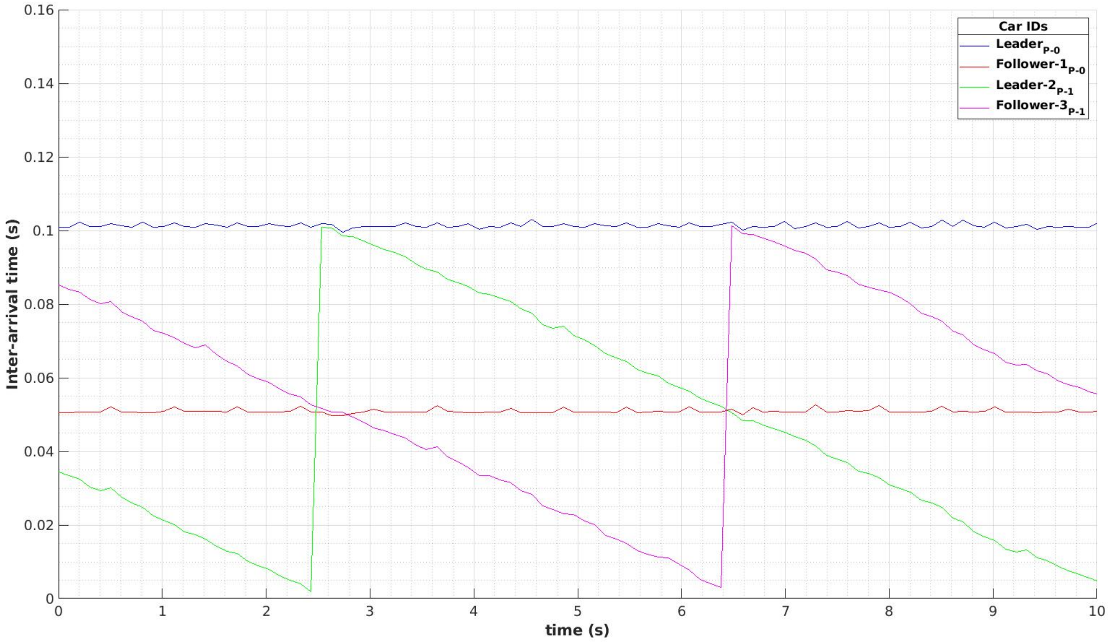
Figure 6.8 shows the actual reception instants from both platoons during a short time interval. Each vertical line represents the reception of a message in the timeline and its color represents the respective platoon, namely red for *Platoon 0* and blue for *Platoon 1*. Two heights are used to discriminate the leaders (higher lines) and the followers (shorter lines). We can again observe the drifting phase of one platoon with respect to the other one, but even when they are close together, the phase adaptation mechanism separates them in the following round. This validates the RA-TDMAp capacity to support platoon co-existence in space as necessary for scalability.

6.2.3 Validating the Dynamic Reconfiguration of RA-TDMAp

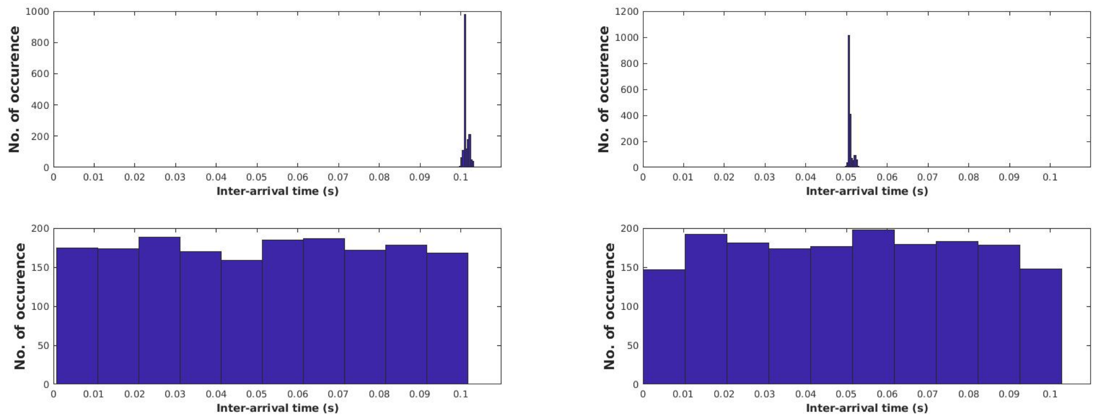
In this section, we validate the dynamic reconfiguration of RA-TDMAp that we elaborated in Chapter 5. We implemented the state machine of the reconfiguration mechanism and considered the same highway maneuvers (joining, merging and leaving) that we simulated in PLEXE. In this section, the experimental results confirm that RA-TDMAp effectively tracks the platoon configuration while running the phase adaptation mechanism to maintain the synchronization in the platoon. These experiment traces are 200s long and we logged all the transmissions in that interval. Since all the nodes are relatively close to each other and it is not practical, in this setup, to move them around, and that we lack GPS receivers in the nodes, too, we decided to trigger the reconfiguration requests by time. Moreover, due to the lack of GPS we do not use position information in the admission control, but maximum capacity of the platoon, only.

6.2.3.1 Joining

The first experiment represents the joining maneuver. We organized the experimental setup by considering one device as a joiner and the other three devices as a platoon. Figure 6.9 shows the offsets of all the transmissions relative to the transmissions of the $Leader_{P-0}$ (blue trace) in



(**a**) Evolution of the time offsets in both platoons referred to $Leader_{P-0}$



(**b**) Histogram of the offsets in both platoons

Figure 6.7: Time offsets of the receptions from both platoons (0 and 1) with respect to $Leader_{P-0}$

each TDMA round. The platoon suffers interference from both the traffic generator and the asynchronous joiner that behaves as an independent leader (it is in the *Leader* state, thus representing a single vehicle platoon). The offsets of the joiner (black trace) are naturally drifting linearly with respect to the platoon given the approximately constant difference in period.

At approximately second 97.5, we enable the reconfiguration process in the joiner. At that moment, it detects the other platoon through the reception of its beacon. Since we are not controlling actual position, the joiner transitions through the *Decide platoon* state directly to the *Wait for response* state in which it starts transmitting the request beacon. When the targeted leader ($Leader_{P-0}$) receives the request and concludes the admission control process, it reconfigures the

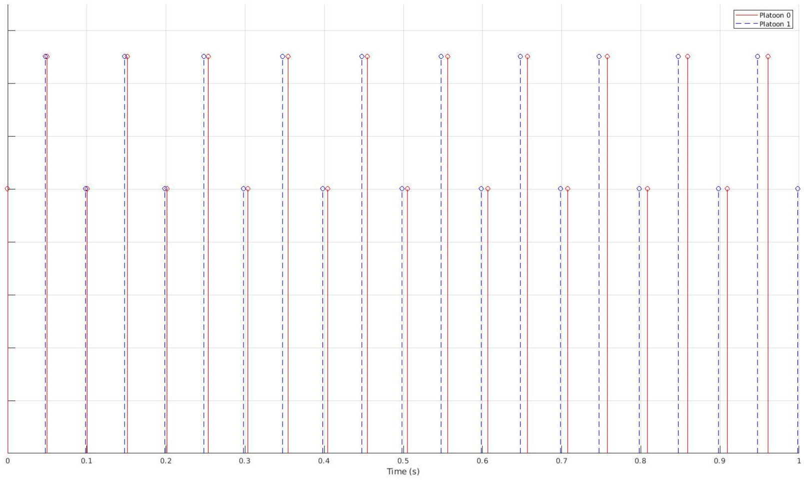


Figure 6.8: Timeline of the transmissions of two platoons co-existing in space

frame structure at approximately second 97.6. All offsets in the platoon were adjusted accordingly. This is visible in the offsets of the followers. After receiving the positive response from the targeted leader ($Leader_{P-0}$) the joiner moves to the *Follower* state and joins the platoon by using the offset corresponding to the first slot after the leader transmission (corresponding to the last Follower, i.e., platoon tail), which it does at approximately second 97.8. During the whole process, the leader continues adjusting the frame phase to maintain the synchronization in the platoon.

Note that *Platoon 0* is using $T_{tup0} = 101$ms while the joiner is using $T_{tup1} = 100$ms. However, after joining (in the *Follower* state), the transmissions of the joiner are controlled by the corresponding offset after the leader reception, assuring a synchronization with the platoon and independently of its internal $T_{tup1} = 100$ms (see Equation 3.1 in Section 3.1.2). This value will be used again in case of losses of leader messages or when leaving the platoon, only.

6.2.3.2 Merging

The merging maneuver is rather similar to the joining case, differing in the fact that the joining leader has followers attached, instead of being a lone leader. The scenario we use here is the same as to show the coexistence of platoons in Fig. 6.7. We have two platoons with $n = 2$, *Platoon 0* and *Platoon 1*, and the offsets of their transmissions with respect to the leader of *Platoon 0* are shown in Figure 6.10. The offsets of *Platoon 0*, for $Leader_{P-0}$ and $Follower\text{-}1_{P-0}$, and of *Platoon 1*, for $Leader\text{-}2_{P-1}$ and $Follower\text{-}3_{P-1}$, are shown in the blue and red traces, and in the green and cyan traces, respectively.

Until approximately second 95.5, the two platoons coexist asynchronously, though each one synchronized internally by RA-TDMAp. At that moment we enable the reconfiguration state machine and the leader of Platoon 1 moves through the *Decide platoon* state directly to the *Wait for response* state as explained in the joining scenario. In this state, it starts transmitting the

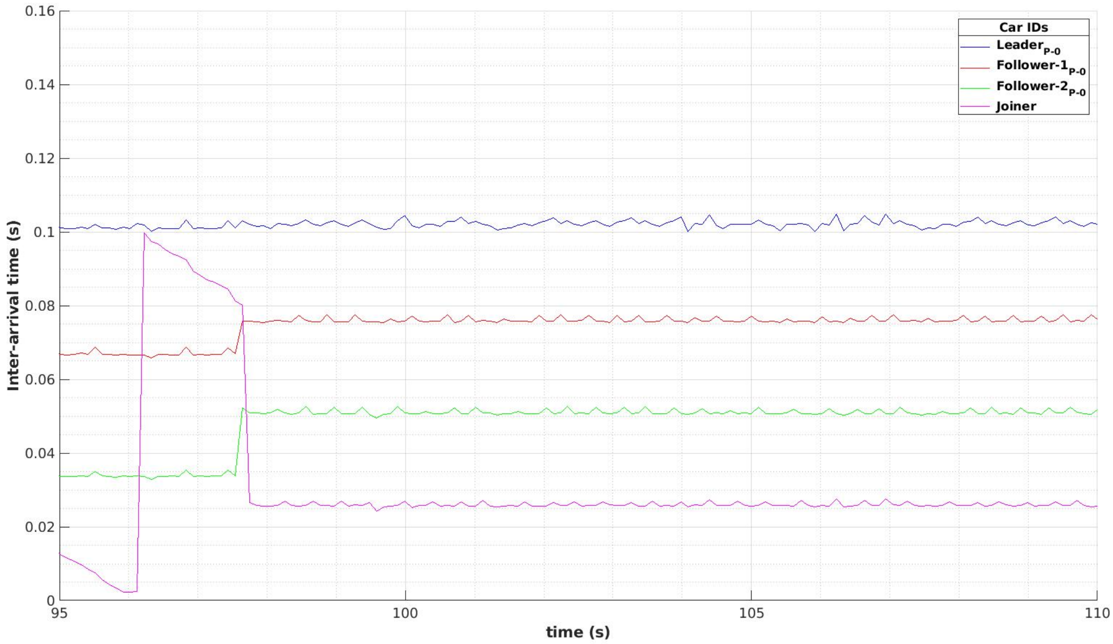


Figure 6.9: One independent vehicle joining a platoon from the tail

request beacon that triggers an admission control in the targeted leader (*Leader*$_{P-0}$). Upon a positive outcome from the admission control process, it reconfigures the frame structure adjusting the offsets and adding slots for all the members of *Platoon 1* at its tail. This is visible in the offset of the initial follower at time 95.6s.

After receiving the positive response from the targeted leader (*Leader*$_{P-0}$) the merging platoon leader moves to the *Follower* state and joins the platoon by using the assigned offset. Its follower remains in the *Follower* state but changes its leader, thus its reference, to *Leader*$_{P-0}$, too, occupying the first slot after the new leader transmission (corresponding to the last Follower, i.e., platoon tail), which it does approximately at time 95.7s. During the whole process, the leader continues adjusting the frame phase according to the delays it perceives directly (from *Follower*-1$_{P-0}$) or receives from its new followers (*Leader*-2$_{P-1}$ and *Follower*-3$_{P-1}$)), thus maintaining the synchronization in the platoon.

Again, the two platoons synchronize with $T_{tup0} = 101$ms from *Leader*$_{P-0}$, independently from the fact that the merged platoon (*Leader*-2$_{P-1}$) was using $T_{tup1} = 100$ms.

6.2.3.3 Follower leaving

Here we validate the scenario in which one follower leaves a platoon. We use a platoon of four vehicles ($n = 4$), *Leader*$_{P-0}$, *Follower*-1$_{P-0}$, *Follower*-2$_{P-0}$ and *Follower*-3$_{P-0}$. Figure 6.11 shows the offsets of the vehicles transmissions with respect to the leader of the original platoon (*Leader*$_{P-0}$), during the reconfiguration process.

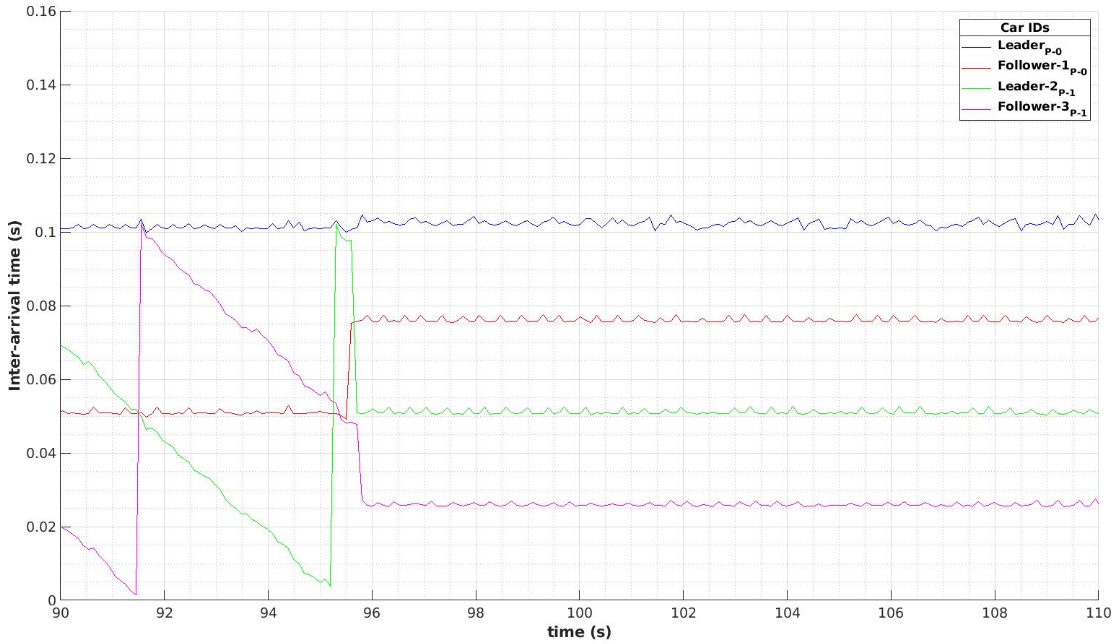


Figure 6.10: *Platoon 1* merges *Platoon 0*

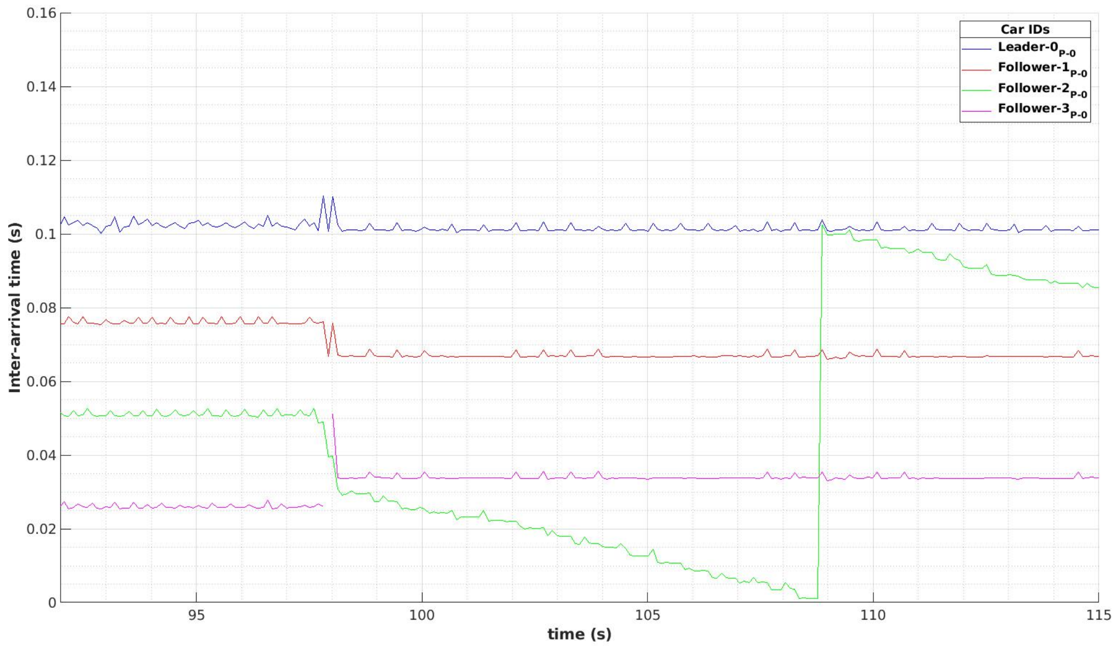


Figure 6.11: Follower leaving a platoon

At time 97.8s $Follower\text{-}2_{P-0}$ announces to $Leader_{P-0}$ its willingness to leave the platoon, sending the corresponding request beacon. The platoon leader ($Leader_{P-0}$) receives this beacon and reconfigures the platoon formation and the TDMA round, approximately at time 97.9s, removing the vehicle from the formation vector and decrementing n. When the leaving follower ($Follower\text{-}2_{P-0}$) receives a regular beacon from $Leader_{P-0}$ showing it is no longer in the platoon, it changes to *Leader* state (becoming a lone leader), with a different platoon ID, and using its own $T_{tup1} = 100$ms. The remaining followers, that remain in the original platoon with $Leader_{P-0}$, move to their adjusted slots approximately at time 98s.

We can see the synchronization of the initial platoon as well as the adjustment in n from 4 to 3 and consequently the new offsets of the remaining followers. After the reconfiguration, the leaving vehicle is now transmitting asynchronously with respect to the platoon with its shorter slightly shorter T_{tup}.

6.2.3.4 Leader leaving

The last scenario we are validating in this section is the reconfiguration that occurs when it is the leader that leaves the platoon. This is somewhat similar to the previous case, except that it implies electing a new leader among the remaining followers. We use the same platoon with four vehicles ($n = 4$). The offsets of the vehicles transmissions during the process are shown in Figure 6.12.

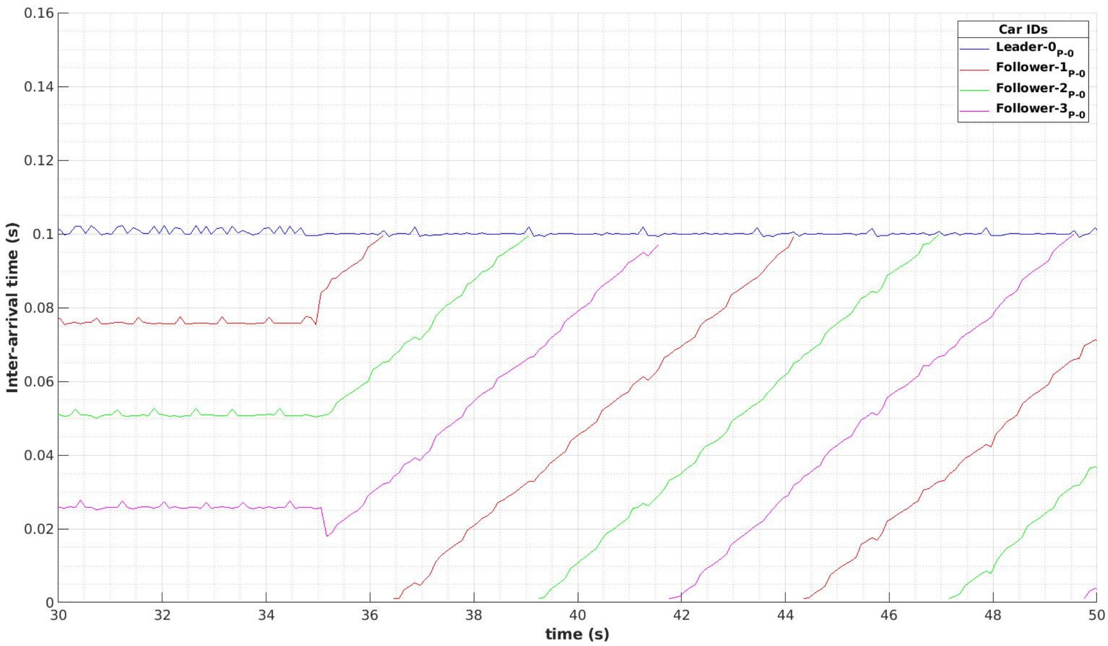


Figure 6.12: Leader leaving a platoon

Approximately at time 35s, $Leader_{P-0}$ announces its willingness to leave the platoon emitting the leave request beacon. This is captured by the followers and, particularly, the first one, $Follower\text{-}1_{P-0}$, that transitions to the *Leader election* state. In this state, $Follower\text{-}1_{P-0}$ starts transmitting the response beacon acknowledging that it is ready to take over the leader role. When $Leader_{P-0}$ receives this beacon, it changes its platoon ID, effectively becoming a new platoon (with a lone leader) with $T_{tup1} = 100$ms.

$Follower\text{-}1_{P-0}$) waits for one omission of the regular beacon from $Leader\text{-}0_{P-0}$ and changes to *Leader* state, effectively taking over the platoon. This occurs at the time it would do its regular beacon transmission, approximately time 35.1s. The remaining followers continue in Follower state but adjust their leader to the previous $Follower\text{-}1_{P-0}$ and start transmitting with the updated offsets at approximately time 35.2s.

Note that the internal T_{tup} of $Follower\text{-}1_{P-0}$ is 101ms. This causes its phase with respect to $Leader\text{-}0_{P-0}$ to increase approximately linearly in time, dragging the remaining followers with it. After the reconfiguration, the old leader $Leader\text{-}0_{P-0}$ (blue trace) just shows the delays caused by the direct interference of the traffic generator (periodic spikes in the trace) and the new platoon with the followers.

6.3 Summary

In this chapter we showed several experiments aimed at providing an empirical validation of the main mechanisms of the RA-TDMAp protocol, namely the synchronization, the phase adaptation, the coexistence with other platoons without any explicit control, and the dynamic reconfiguration to support the joining and leaving maneuvers of vehicles and the merging between platoons.

The chapter started with an experimental verification of the synchronization and phase adaptation mechanisms to support the coexistence of platoons using the base RA-TDMA protocol on WiFi ad-hoc technology. Then IEEE 802.11p technology was used to validate the proposed RA-TDMAp protocol in all referred scenarios. The results agreed with the expected behaviors, thus the desired empirical validation was achieved.

Chapter 7

Conclusion

VANETs are a core component in ITS enabling communication among vehicles and thus opening the path for a myriad of collaborative applications. One example of such an application is platooning. This application coordinates a group of vehicles that travel together, doing automatic control of inter-distances and speeds. Vehicle platooning is expected to have a significant impact on the future ITS framework by reducing traffic congestion, environmental contamination, road accidents, fuel consumption, reducing travel time, and improving safety.

Despite all scientific and technological advances of the last two decades, platooning is still a very challenging application with several open problems. It is a critical application, too, since design errors or unexpected run-time situations may lead to disasters with potential loss of human lives. Nevertheless, the challenges of platooning have been consistently addressed by the research community towards the deployment of platoons on real roads, which is expected to start happening soon, with several successful experiments already carried out.

In this work, we focused on the communication part of platooning. Inter-vehicle communication is critical for the correct operation of platooning, highlighting the importance of improving the quality of the communication channel. Our approach focused on the design of an efficient MAC protocol specifically for platooning, given the impact this layer has on the quality of the channel and potentially on the performance of the platooning application, too. We set as our goal to design a MAC protocol that would build on transmissions control, timing and power, with simplified synchronization, to offer greater scalability with significant reduction in medium occupancy and collisions.

7.1 Revisiting the Thesis and Contributions

Following the observations referred above, we set the following as our thesis (reproduced from Chapter 1):

An efficient MAC protocol for platooning applications, aiming at highway scenarios, can be developed merging the ideas behind RA-TDMA [8] and PLEXE-slotted [9]. We also claim that *this combination leads to a reduction in collisions and channel occupation while offering full scalability. We call our protocol RA-TDMAp.*

In the course of establishing the correctness of this thesis, we made three main contributions to the state-of-the-art in communication (MAC) protocols for platooning:

- The RA-TDMAp protocol, which combines the TDMA frame phase adaption of RA-TDMA [8] with the power control proposed in PLEXE-slotted [9] to achieve low medium occupancy and reduced collisions, supporting high scalability.
- Empirical models of relevant network performance metrics for RA-TDMAp, PLEXE-slotted and CSMA/CA that express the rate of collisions and busy time ratio as a function of the RF neighbors that a vehicle senses.
- A dynamic reconfiguration mechanism with admission control for platoon formation and maintenance in RA-TDMAp that keeps the platoon physical configuration synchronized at the TDMA frame and platoon control levels.

7.2 Thesis Validation

Following the contributions referred in the previous section, we aim, here, at showing that our thesis holds and that, in fact, RA-TDMAp offers the properties that were claimed. For this we make the following observations:

- Firstly, we observed that the traffic patterns generated by cooperative platooning applications, namely periodic broadcasts for state sharing, are amenable to the simplified synchronization carried out in the RA-TDMA protocols. This does not need clock synchronization and allows reducing collisions by organizing the transmissions of the platoon members as a TDMA frame and shifting the phase of the frame to escape from delays caused by interference of traffic outside the platoon. Then, we realized the power control scheme of PLEXE-slotted is very adequate to reduce the medium occupancy, having the platoon leader, only, transmitting with high power while all followers transmit with low power. Combining these two techniques required a multi-hop propagation of the delays affecting the platoon beacons as detected by the platoon members so the delays could reach the leader in just one TDMA round. The result was the RA-TDMAp, which is the central proposal in this thesis and which offers reduced collisions and low medium occupancy, resulting in high scalability (Chapter 3). Preliminary experiments with WiFi technology in ad-hoc mode and later with IEEE 802.11p-enabled equipment (Chapter 6) confirmed the correct operation of the protocol and its capacity to support multiple concurrent platoons in a way that each platoon is agnostic to all other. The properties of the protocol were also verified in simulation, confirming the reduction in collisions and busy time ratio, as well as a high level of scalability (Chapter 3).

- Secondly, the simulation set up was used to study in detail the performance of RA-TDMAp in comparison with alternatives that operate directly on IEEE 802.11p COTS equipment, namely PLEXE-slotted and the standard CSMA/CA (Chapter 4). We could understand fundamental properties of the protocols when supporting concurrent platoons on a highway and again verify that RA-TDMAp outperformed the other protocols in all considered scenarios, covering a vast space of configurations. This allowed us to develop empirical models for the rate of collisions and busy time ratio for the three protocols as a function of the number of RF neighbors that each vehicle senses. These models allow any vehicle to estimate such important network metrics just by tracking the number of different sources of the received packets.

- Thirdly, the RA-TDMAp protocol was complemented with a state machine that controls the platoon formation and maintenance while keeping the TDMA frame and the platoon control synchronized (Chapter 5). This is a fundamental piece to make RA-TDMAp a working solution for real platooning. This dynamic reconfiguration includes an admission control that decides whether joining requests can be accepted or not. It also determines when the platoon controller, e.g., CACC, should be engaged or disengaged and how many platoon members it should consider as well as the delays of the corresponding messages. This dynamic reconfiguration was validated in simulation (Chapter 5) and with practical experiments (Chapter 6) with the most common operational scenarios, namely joining, leaving and merging.

- Finally, an experimental campaign with IEEE 802.11p equipment allowed validating in actual operation the main features of RA-TDMAp (Chapter 6). The experiments allowed observing the intra-platoon synchronization, the frame phase adaptation, the power scheme and the reconfiguration state-machine.

7.3 Future Work

Beyond the results presented in this thesis, the work conducted disclosed various interesting research ideas that we believe are worth further exploration. Some are more fundamental, other are problems that we found but which we could not address in this work.

- In our simulations we considered a free-space path loss model with an value of 2.0. It would, therefore, be relevant to see how the protocol properties, and essentially its benefits, hold in more complex path loss models, possibly with obstructions or fading effects.

- The reconfiguration scenarios that we considered in this work are the most common ones. However, the validation we did was relatively limited, with simple traffic situations. Thus, it would be interesting to validate the reconfiguration state-machine with high traffic density, too. On a more elaborated line, it would be interesting to see whether this reconfiguration protocol supports more complex operations, particularly non-longitudinal platoon operation (e.g, zipper merging [83]).

- One specific work that we originally planned to carry out was the verification of the reconfiguration protocol with a model checker, specifically Uppaal, as a proof of correctness. Unfortunately, there was not time enough and this is still an open issue.

- Due to delays that affected the experimental validation, it was not possible to complete it with comparisons against the competing protocols that were used in simulation, all along the thesis. This is an open issue that would be desirable to complete in the short term.

- This thesis focused on the communications for platooning, only. However, as referred in several parts, the control of the platoon is obviously fundamental. Thus, developing a control approach that is tuned for RA-TDMAp in a communication-control co-design approach seems an interesting line of work.

- In this thesis, we considered the platooning application, only. However, the question remains on whether the RA-TDMAp protocol can extend to other ITS applications namely intersection management, lane change assistance and others. Moreover, making the protocol work in urban areas also seems quite challenging.

- Finally, it also seems interesting to explore how the techniques of RA-TDMAp could be applied to a broader concept of vehicles, for example bicycles, to allow multimedia communication among groups of users in an urban mobility concept.

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