

A STUDY ON PLATOON FORMATIONS AND RELIABLE
COMMUNICATION IN VEHICLE PLATOONS

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Abstract

Vehicle platooning is a promising concept in dealing with traffic jams. Several simulations and field trials have shown how platooning can improve lane capacity and lower trip times. Despite extensive research in the area of vehicle platooning, the first vehicles were only recently equipped with adaptive cruise control, a basic platooning system without cooperation between vehicles.

An important topic of research concerning platooning has been longitudinal control and achieving string stability. For advanced platoon concepts, other topics like lateral and maneuver control are important as well. In this research we investigate such topic of platooning: the process of forming platoons.

In this thesis we develop a new strategy for the formation of platoons. This so-called *transient formation strategy* is evaluated and compared against already existing strategies in a traffic simulator. The results show that our formation strategy is capable of increasing the average platoon length and hence the lane capacity and lower average trip times.

In order to support the *transient formation strategy*, a general multicast protocol has been developed to improve the reliable communication between vehicles in a platoon. This protocol is evaluated in a network simulator and the results indicate significant improvements of the success rate and delay for high traffic densities and large vehicle platoons.

Preface

This master thesis presents and concludes the research that I have performed during a ten-month internship at Toyota InfoTechnology Center Co., Ltd., in Tokyo, Japan. The research was conducted in affiliation with the chair Design and Analysis of Communication System (DACS) of the Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, The Netherlands.

The ten months that I was living and working in Tokyo was a great adventure and has left many good memories. I would like to express my gratitude to everybody who has supported me.

First of all I would like to thank my supervisor at Toyota InfoTechnology Center Dr. Onur Altintas. I am very grateful for his encouragement and guidance during my internship as well as supporting me during my stay in Tokyo. It is for Onur that I am now doing what I like to do. Furthermore, I would like to thank all my other colleagues at Toyota InfoTechnology Center and in particular Ryokichi Onishi-san and Mitsuhiro 'bori' Nishibori-san for their great support and guidance around Tokyo.

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Chapter 1

Introduction

We take our motorbike for a spin, drive to work in the morning and even fly to our holiday destination. Mobility has become a common practice in our lives. In fact, the Dutch people traveled more than 30 kilometers per person per day in 2008 [8]. For most of these trips they used the car. To be precise, 47.7% of the trips and 76% of the traveled kilometers were done by car [8]. The car has become our main mode of transportation.

Unfortunately, we are also familiar with the problems caused by the massive use of vehicles, in terms of traffic jams and air pollution. Given the increasing number of vehicles on the road [19] and economical damage inflicted by traffic jams –this damage was estimated at 87.2 billion dollar in 2007 for the United States of America (USA) [6]–, these problems have become a hot topic in today’s politics.

Over the last decades, several solutions have been proposed and implemented. The solutions range from increasing road capacity by creating more roads to the encouragement of car sharing and the use of public transport. Another idea proposed is the concept of road pricing in which a driver is no longer charged for owning a vehicle, but instead charged for using it. This idea does not solve immediately any traffic jams but it provides a mechanism to apply financial incentives. For example, a driver can be motivated to drive outside the rush hours by charging a lower fee when commuting outside rush hours.

Most of these solutions have shown positive affects but have not been able to solve congestion problems. In fact, traffic jams have become more severe because of the growing number of vehicles [19]. Hence, more drastic and innovative solutions are needed. One of the innovations is the concept of in-vehicle systems, which assist drivers on the road. These so-called Driver Support Systems (DSS) aim to improve efficiency, safety and comfort with the use of advanced information and communication technologies [4].

TomTom introduced in 2007 a well-known example of a DSS system: the TomTom High Definition Traffic™ service, which augments their satel-

lite navigation products with accurate up-to-date traffic information. This information is obtained by combining traditional information sources (e.g. induction loops in the road and camera surveillance) with anonymized location data of mobile phone and TomTom users. With the up-to-date information, a driver is able to reroute around traffic jams and hence improve the efficiency of the road.

Adaptive Cruise Control (ACC) is a system with the same goals but uses a different approach. Implemented by the main car companies, this system assists the driver in keeping a desired time-gap to the preceding vehicle. So, a benefit of ACC is its ability to smooth traffic flow [13].

A follow-up of ACC is Cooperative Adaptive Cruise Control (CACC). This concept augments a traditional ACC concept with wireless communication capabilities and enables close cooperation between vehicles. This can improve the traffic flow even more. However, both ACC and CACC systems are limited by the human driver, which is able to overrule the system.

The ultimate system would be one, which automates all human tasks. By replacing human tasks with a high performance, electronic counterpart, vehicles can be highly cooperative. This allows them to react quicker to traffic situations, which can result ultimately in vehicles driving with smaller headways. The concept in which vehicles are driving as highly cooperative groups, using information and communication technology, is called vehicle platooning.

Vehicle platooning has the potential to significantly increase the highway capacity and decrease fuel consumption. These results were found in simulations [15] and in field experiments [20, 14] like the recent Connect & Drive project [24].

Considering the benefits of a vehicle platoon, it is no wonder that it has been a topic of research for decades. A strong focus existed especially on longitudinal control. That is the cooperative acceleration and braking of vehicles. Within the research mentioned here above, vehicles were preformed in platoons. Until now, the actual platoon formation process itself has been underexposed.

1.1 Objectives

This research will focus on the formation of vehicle platoons and the communication involved. Taking this into consideration, we have defined the following objectives for this research:

Objective 1 - Gain insight in the field of Intelligent Transportation Systems (ITS) and *Vehicle Platooning*;

Objective 2 - Develop and evaluate a strategy for the formation of vehicle platoons;

Objective 3 - Design a communication solution for the support of the developed formation strategy;

Objective 4 - Evaluate the performance of the formation strategy and communication solution.

1.2 Research Questions

This research will address the following research questions:

1. **How to develop a platoon formation strategy that increases the benefits of platooning?**
2. **What is the performance of the developed platoon formation strategy?**
3. **What are the information requirements for this strategy?**
4. **How to design a communication solution to support the formation strategy?**
5. **What is the performance of the designed communication solution?**

1.3 Approach

In order to answer the research questions as stipulated in the research paragraph, this research uses the following approaches:

- Study the existing platoon formation strategies proposed in literature;
- Design a new platoon formation strategy;
- Evaluate and compare the designed platoon formation strategy against existing platoon formation strategies;
- Analyze the communication requirements of the designed platoon formation strategy;
- Design a communication solution in order to support the designed platoon formation strategy;
- Evaluate the performance of the designed communication solution.

1.4 Outline

The remainder of this report is structured as follows:

- Chapter 2 provides background information with respect to Intelligent Transportation Systems (ITS), vehicle platooning and technologies for enabling wireless communication in vehicular environments. The information in this chapter gives a basic understanding of the topics covered in the following chapters;
- In Chapter 3 we first present a survey of platoon formation strategies based on literature study. This study enables us to identify the properties of a formation strategy in order to improve its benefits. These properties are secondly used to design a new platoon formation strategy, which is evaluated and compared against the strategies from the survey;
- Chapter 4 starts with an analysis of the information requirements of the developed platoon formation strategy. The analysis is subsequently used to develop a communication solution to support the designed formation strategy;
- In Chapter 5 we evaluate the performance of the communication solution using network simulation;
- Chapter 6 contains the conclusions of this research, a recapitulation of answers to our research questions and recommendations for future research.

Chapter 2

Background

This chapter provides the background information, which helps in the understanding of our research. First we provide a general overview of Intelligent Transportation Systems (ITS) and its variety of topics. The focus is put on one of these topics: *vehicle platooning*. Second, the WAVE-standard is introduced. This standard aims to bring wireless access in vehicular environments. IEEE802.11p is part of the WAVE-standard. This protocol is described in more detail, as it is part of our communication solution in the next chapters.

This chapter starts in Section 2.1 with an introduction to ITS, followed by the concept of vehicle platooning in Section 2.2. Finally, we present the Wireless Access in Vehicular Environments (WAVE) standard in Section 2.3 as well as a description of the IEEE 802.11p protocol.

2.1 Intelligent Transportation Systems

Information and Communication Technology (ICT) has changed our Western society into an information society. Computers are generally accepted and Internet is available on our laptop, smart phone and mp3-player. For that reason, we have access to huge sources of information, available on the Internet; whenever we like, wherever we like. The value of this ubiquitous source of information manifests itself in providing us with the ability to make better decisions. For example, the weather forecast on the Internet can show whether it will be raining in the next five minutes and we can better decide whether to take the bike or car.

ICT has also changed our business in the same way as it changed our daily lives. Better information allows us to automate and optimize our operations. A good example is a stock exchange, which is now fully dependent on information technology. The latest stock prices are available all around the world and trading stocks is nowadays just a mouse-click away.

ICT is now about to change our transportation systems as well. While

building more roads or fixing old infrastructure is often considered the best option to enhance our transportation system; the future lies increasingly in the use of ICT. That is, the information contained in our transportation system is of great value for its optimization. For example, a traffic light is able to optimize the outgoing traffic flow if it knows the amount of incoming traffic. Hence, ICT can make this information available to traffic lights or other elements of the transportation system.

In general, it is envisioned that ICT is able to increase the efficiency of the current transportation system significantly. However, this will require a significant investment because embedding transportation systems with sensors, wireless communication technologies and other electronics will be required to make them more intelligent. Hence the name Intelligent Transportation Systems (ITS).

According to *Ezell*, ITS applications can bring the following benefits [30]:

Increasing Driver and Pedestrian Safety: ITS can bring significant safety improvements to drivers and pedestrians. These improvements are very much needed; the traffic statistics of the United States of America (USA) from 2008 show 5,811,000 estimated police-reported traffic accidents, which means a traffic accident every 5.5 seconds on average. The total costs of these motor vehicle crashes were estimated to be 230.6 billion dollars for the year 2000. Even more important are the number of fatalities and injuries: 37,261 people died and 2,346,000 were injured. Fortunately, these numbers have reduced over the years possible because of passive safety systems like the seat belt –a seat belt reduces the probability of being ejected in a crash when restrained from 30 to 1 percent– and the airbag [21]. ITS is able to further reduce these numbers with applications like cooperative intersection collision avoidance and lane departure warning systems. These applications use an active approach and aim to prevent accidents instead of protecting passengers after an accident has happened.

Performance Improvement of the Transportation Network: Some ITS applications are also able to improve the performance of the transportation network. For instance, highly cooperating vehicles, using Vehicle-to-Vehicle (V2V) communication, can optimize the overall traffic flow at highway intersections. These intersections, where vehicles are merging and leaving the highway, are often a bottleneck.

Enhanced convenience: Another benefit of ITS application can be the increased convenience for drivers and passengers. A well-recognized application, appearing in some upscale vehicles, is Adaptive Cruise Control (ACC). With ACC, the system attempts to keep the vehicle at a preferred time-gap from the preceding vehicle [7]. Especially in

stop and drive situations like traffic jams such system could improve convenience.

Delivering environmental benefits: Transportation is considered to be a main contributor to CO_2 emission. Certain ITS applications can bring benefits in terms of a better traffic flow, more efficient use of the current transportation capacity or support people in driving more efficient. These efficiency improvements can lower fuel consumption and hence bring environmental benefits.

Boosting productivity, economic, and employment growth:

Improvements to the efficiency of the transportation system can also boost productivity, economic and employment growth; products can arrive quicker and more efficient at their destination, which can lower the transportation costs.

The development of ITS applications is driven by its potential benefits of which a few have been described here above. ITS enables a wide range of ITS applications. According to Ezell [30], most of these applications can be organized in the following five categories. Note that this list is not exhaustive, as ITS might enable applications that we cannot even envision now.

Advanced Traveler Information Systems (ATIS): Applications in this category provide travelers with valuable information to help them make travel decisions in order to reach their destination timely and safely. Such information used to be consulted before traveling; a web-site offering a service to plan your itinerary is such example. But nowadays, with the emerging wireless communication technologies, travelers can receive itinerary updates in real-time such as road and traffic conditions as well as user-targeted information such as the weather forecast, tourist information or information about sport events. Basically, these types of applications are most effective if they provide information that is relevant to the traveler's journey and its current location.

This category of ITS is most likely the best recognized because numerous applications are nowadays available to us; route planners, satellite guided navigation systems and parking guidance systems are just a few examples.

Advanced Transportation Management Systems (ATMS): This category contains the applications that focus on the traffic control elements of our transportation system such as ramp metering, traffic lights and traffic operations centers. By aggregating information coming from cameras, road sensors, probing vehicles or other technologies,

a view of transportation systems can be generated. Hence, this view can be used to optimize traffic flows by means of adaptive traffic lights and dynamic road signs.

ITS-Enabled Transportation Pricing Systems: The applications involved with payment of the transportation system are classified in this category. Probably, the most recognized application is electronic toll collection, which aims to simplify toll collection and eliminate toll-booth delays. Another type of pricing applications is considered in Germany and The Netherlands; this system records the movement of the vehicles and charges drivers based on the distance traveled.

Advanced Public Transportation Systems (APTS): All applications in the APTS category are related to public transport; including applications to locate busses, trains or subways and make them visible for central train operators. The same application can make the public transport more attractable to the public by announcing expected arrival and departure times.

Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) integration:

The applications in the final category are the ones that try to create a "comprehensively integrated intelligent transportation system" [7]. These applications can bring a wide range of benefits if a large number of elements of the transportation system are equipped with communication technology. For instance, the communication between vehicles and infrastructure (V2I) and the mutual communication between vehicles (V2V) can support a wide range of vehicle safety and operation applications.

In order to support the diverse array of applications, a wide range of technologies are combined by ITS. Some of the main technologies are listed below:

Global Positioning System (GPS): is a satellite-based navigation system that provides reliable time and location information. Initially, developed in the early 1970's by the department of defense of the United States of America for military purposes. Since 1983 the GPS system is also available for the public. The GPS system consists of the following three segments [10]:

Space Segment: This segment includes a constellation of 24 satellites that circle around the earth in 6 orbits at a distance of around 20,200 km from the earth's surface. The purpose of these satellites is to transmit a GPS signal so users can determine their location and synchronize their time. The transmitted GPS signal

therefore contains among others the satellite's orbital information and time of transmission. The time of the satellite is controlled by a highly accurate atomic clock.

Control Segment: This segment contains the *Master Control Station* and 10 additional monitoring stations, located around the world. The primary task of the monitoring stations is to track the navigation signals and send these signals back to the *Master Control Station*. This information is subsequently processed 24 hours a day in real-time, to detect malfunctions as quickly as possible. The *Master Control Station* then feeds the satellites a number of times a day new instructions to improve the accuracy of the system.

User Segment: The user segment is the most visible segment, as it includes all military and civilian users. These users are able to determine their location and synchronize their time, based on the signals of a minimum of 4 GPS satellites, using relatively cheap hardware. The GPS service provides two types of location services: the Precise Position Service (PPS) and the Standard Position Service (SPS). PPS is a worldwide service available on continuous basis but is only available to authorized users of the United States. This service provides a location accuracy of 16 meter horizontally and 23 meter vertically. The SPS is a similar service, which is freely available. Initially, the location accuracy of SPS was in the order of magnitude of approximately 100 meters. However, the location accuracy has improved, comparable to the accuracy of the PPS after a decision by the United States (US) government.

GPS technology or similar location services play a central role in ITS applications [9]. These services enable the locating of a vehicle which can then be used in the optimization of the traffic flow.

Cellular Technology is the general term used for wireless technologies that divide their service area into *cells*. These cells are relatively small areas, each served by at least one base station. Cellular and wireless network technologies, envisioned to be used in ITS are 3rd Generation Universal Mobile Telecommunications System (UMTS) and pre-4G technologies like Worldwide Interoperability for Microwave Access (WiMAX) and 3GPP Long Term Evolution (LTE). The main value of these technologies in ITS lies in their large bandwidth. So, entertainment applications like video streaming or Internet browsing are likely to use cellular or wireless technologies for their connectivity. Unfortunately, these technologies are too slow to support delay-critical applications like safety applications.

Another application of cellular technology enables us to detect traffic jams. Traffic jams were traditionally detected using induction loops and camera surveillance. Cellular technology enables us to collect anonymized location and speed data, obtained through signal triangulation and intra-cell handover rates. In combination with smart algorithms, it is possible to detect traffic jams, even at local roads where traditional traffic jam sensors are too expensive to install.

Dedicated Short-Range Communications (DSRC) is a short- to medium-range wireless communication spectrum, specifically allocated for V2I and V2V communication. This spectrum should complement cellular technology by providing high transfer rates and low communication delays in situations where communication is limited to small zones [35].

The Federal Communications Commission (FCC) has allocated a spectrum of 75 Mega Hertz (MHz) in the 5.9 Giga Hertz (GHz) band to DSRC. A similar spectrum of 30MHz in the 5.8GHz band has been allocated in Europe and Japan for the same purpose. Unfortunately, the DSRC systems from the USA, Europe and Japan are not compatible, yet.

Camera Recognition Cameras alongside the road can be used for traffic flow measurements and automatic accident detection. Another camera recognition application is automatic license plate recognition, a technique based on *Optical Character Recognition*, which makes it possible to recognize license plates. This information can be used to charge drivers for the use of the road. Such a system is already in use on the roads around London.

2.2 Vehicle Platooning

The previous section provided an introduction to ITS and briefly described a number of ITS applications and technologies. This section continues to describe one more ITS concepts in detail: *vehicle platooning*.

Vehicle platooning is a concept that aims to increase the current road capacity. The key in achieving this goal is the organization of vehicles in tightly controlled groups, also called platoons that operate close together. As a result, a highway can accommodate more vehicles compared to the manual driving conditions.

Several implementation of the vehicle platooning concept have been proposed. Before describing the benefits of vehicle platooning in Section 2.2.1 and its basic control functions in Section 2.2.2, a number of potential implementations of vehicle platooning are described below:

Adaptive Cruise Control (ACC): systems that implement the concept of ACC are currently available in many of the upscale vehicles and are expected to be available for other vehicles in the near future as well. Car manufacturers place ACC systems in the market as the next generation cruise control system. In fact, ACC and the conventional cruise control are similar in situations where a vehicle not directly following another vehicle. The ACC system maintains under these conditions a pre-set speed. However, when a preceding vehicle is detected, the ACC system adjusts the vehicle's speed in order to maintain a fixed time-gap to the preceding vehicle. This all happens without the intervention of the driver.

Vehicles with ACC are equipped with front radar or camera systems. These systems can detect a preceding vehicle and are able to measure its distance and speed. This information enables ACC to react to speed changes and control the vehicle's time-gap to the preceding vehicle. Although this driver task is automated, the driver stays responsible for the speed and steering and can overrule the system when needed.

A vehicle platoon arises when a vehicle, equipped with ACC, starts following another vehicle. Figure 2.1 illustrates a three-vehicle platoon under ACC. Since vehicles with ACC can operate autonomous, the preceding vehicle does not have to be equipped with ACC. However, with higher market penetrations, more vehicles can engage in a vehicle platoon.

Cooperative Adaptive Cruise Control (CACC): Unfortunately, the front-radar of an ACC system is only able to detect vehicles in line of sight. In practice, this means that an ACC system is not able to measure the distance and speed of vehicles driving a) in front of the



Figure 2.1: Vehicle Platoon using ACC

immediate preceding vehicle, b) behind the vehicle, or c) driving in a different lane. This is illustrated in Figure 2.2. As a result, speed information flows down the platoon with increasing delays: if the first vehicle brakes, the second vehicle detects and reacts to this behavior after a short delay. The third cannot detect the speed change of the first vehicle so it reacts only to the behavior of the second vehicle after another delay.

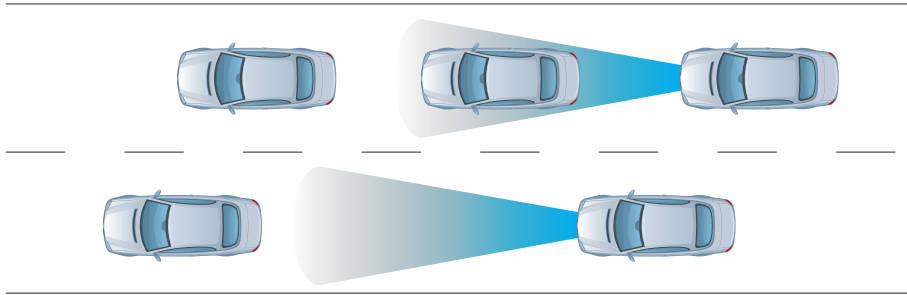


Figure 2.2: A typical view of a front-radar used in ACC

To overcome this shortcoming and to further stabilize the traffic flow, the concept of CACC has been proposed. CACC augments ACC with wireless communication, new control logic and GPS as illustrated in Figure 2.3. Wireless communication allows vehicles to extend their view beyond the line of sight of the radar. With CACC, the third vehicle in the illustration of Figure 2.3 is notified via wireless communication of the behavior of the leading vehicle. The third vehicle can almost instantly react to speed changes of the first vehicle and as a result a CACC system enables to drive with closer headways.



Figure 2.3: Vehicle Platoon using CACC

Automated Highway System (AHS): With both ACC and CACC, the driver is (partly) responsible for the operation of the vehicle. The

driver is for example still responsible for steering the vehicle. A next step in vehicle platooning is a system in which vehicles are fully automated. Such a system, called AHS, has been under research by the Program for Advanced Technology for the Highway (PATH). According to Ioannou [22], AHS aims "to produce a highway system where fully automated vehicles are guided to their destination and the flow of traffic is controlled and optimized for maximum efficiency and safety".

AHS platoons are similar to CACC platoon as illustrated in Figure 2.3. However, AHS platoons are highly dependent on wireless communication to create automated and high cooperative vehicles.

2.2.1 Benefits of Vehicle Platooning

Vehicle platooning has a number of benefits. These benefits range from an increased road capacity and improved safety to a reduction of the environmental impacts and improved driving comfort. Understanding these benefits and the impact of vehicle platooning is very important; they serve as the justification of the development of vehicle platoon systems. The next four sections cover these benefits in more detail.

Increase of Road Capacity

The main aim of vehicle platooning is to increase road capacity. In order to achieve this, it is key to operate vehicles closer together than is possible with manual driving. Unfortunately, a vehicle platoon system has never been deployed on a large scale. Most of the capacity studies are hence based on simulations.

One of these studies, conducted by VanderWerf, et al., focused on the capacity impacts of an increasing market penetration of ACC and CACC vehicles, relative to manual driving [17]. They performed a microscopic simulation of a 16-kilometer one-lane highway with on- and off-ramps every 1.6-kilometer. Initially, an analysis of simulation scenarios was conducted with vehicle type compositions of 100% manual driving, 100% ACC vehicles (time gap of 1.4 seconds) and 100% CACC vehicles (time gap of 0.5 seconds). These simulations resulted in a nominal capacity of respectively 2100, 2150 and 4250 vehicles per lane per hour.

Later, they analyzed a scenario with a more realistic mix of vehicles. As it turns out, both ACC and CACC improve the highway capacity in all cases. However, the impact of ACC is relatively small: a capacity increase of at most 7% was achieved compared to manual driving. It is argued that ACC achieves this benefit by smoothing the traffic flow instead of closing the operating gaps. In fact, the 1.4 seconds time gap turned out to be modest compared to an average time gap of 1.1 seconds under manual control.

The analysis shows besides that CACC has the potential to significantly increase the capacity, especially for high market penetrations. This effect is explained by the need of a CACC system to have a preceding vehicle, which is also equipped with a CACC system. After all, a preceding vehicle needs to transmit information for following vehicles to operate. If a preceding vehicle is not equipped, the system behaves like ACC and acts solely on radar information.

Similar results in terms of road capacity increase have been shown in AHS studies. One of them is a numerical analysis by Michael, et al., [15]. Their main conclusion is that AHS can increase the road capacity but the increase is dependent, among others, on a) the degree of inter-vehicle cooperation, b) average platoon length and c) the intra-platoon spacing.

Unfortunately, most studies about the impacts of platooning systems on the road capacity are based on simulation or analytical analysis. Better would be to measure the impacts of a particular platooning system in a large-scale test bed. However, this is very costly and requires a good motivation in order to do so.

Reduction of Environmental Impacts

The transportation system is a large contributor to the emission of greenhouse gasses. Indeed, transportation can be accounted for approximately 30% of the total CO_2 emission in the USA over 2008 [33]. Since environmental issues are a hot topic, the transportation industry is also looking for solutions to reduce fuel consumption and hence reduce environmental impacts.

Vehicle platooning can be one of these solutions. Closely operating vehicles in a platoon reduce the average air resistance and hence the fuel consumption. This result was obtained in wind tunnel tests and field experiments [36, 20]. The results of the field experiments show that fuel savings vehicle platoons are strongly correlated to the position of the vehicle in the platoon and operating distance. A vehicle operating with a vehicle in front and back can save fuel up to 10% (operating distance of 3 to 6 meters). The last and the leading vehicle of a platoon experience savings of respectively 7% and 3-4%. Hence, all vehicles in a platoon benefit.

Improved Safety

The majority of traffic accidents are caused by human errors. In fact, the driver can partly or fully be blamed in well over 90% of the traffic accidents [22]. Speeding, distractions, fatigue and even drunk driving are just some of the reasons, which can cause these human errors.

Vehicle platooning is one of the concepts, which can improve the traffic safety. A system, which implements vehicle platooning by means of a com-

combination of technologies may not only react quicker to dangerous situations. Technologies like wireless transmission may also extend the traffic view beyond the driver's line of sight. This enables early detection of dangerous situations and hence may improve safety.

Improved Driver Comfort

A final benefit of a vehicle platoon is its ability to improve the driver comfort. Depending on the amount of automated functionalities, the driver may delegate certain driver tasks. Especially for long trips on the highway, this can relieve stress and allows the driver to shift its focus. The comfort is further improved due to the smoothing property on traffic flow by vehicle platooning. Speed changes tend to be less jerky compared to vehicles under human control.

Vehicle platooning can, on the other hand, also have a negative impact on the comfort. Small headways in combination with a lack of control are experienced as uncomfortable [3].

2.2.2 Vehicle Platooning Control Functions

The benefits of vehicle platooning mentioned in the previous paragraph, can only be achieved by automating certain human driving task by a better performing functionality. The following sections describe the most basic functionality for automated vehicles in vehicle platoons, being respectively longitudinal control, lateral control and maneuver control. The sections mainly cite Shladover [27].

Longitudinal Control

Longitudinal control of a vehicle is the functionality that controls the speed and distance to the preceding vehicle using the powertrain and brakes. Longitudinal control has two areas of concern. On the one hand, it should provide a comfortable ride for passengers to increase the acceptance and comfort. On the other hand, it should have a high accuracy so that safety can be guaranteed.

In order to meet these requirements, implementations of longitudinal control are highly dependent on measurements of headway and the speed of the preceding vehicle. For these measurements, typically a front-radar is used as well as image-processing sensors. Longitudinal controllers that control the speed of a vehicle, purely based on the vehicle's own sensors are classified as autonomous. Autonomous controllers are used in ACC (see Section 2.2). Research has indicated that these type of controllers are capable of maintaining string stability i.e. headway errors do not flow down the platoon, under constant time gaps between vehicles.

Another type of longitudinal control is cooperative control. These controllers typically complement radar and image-processing sensors with wireless communication in order to collect state information (position, speed, acceleration and maneuver information) of close operating vehicles. These types of controllers are not only able to maintain string stability under a constant time gap, like autonomous controllers, but also under constant distance gaps. As these constant distance gaps are independent of the operating speed of the vehicles, the cooperative controllers are capable of keeping the headway small, even at high speeds. This is one of the reasons why cooperative controllers, as used in CACC systems, can achieve a much higher road capacity (see Section 2.2).

Lateral Control

Lateral control by means of steering a vehicle is a task for which a human driver is still responsible in certain vehicle platooning concepts like ACC and CACC. However, for vehicle platooning concepts where driver-less vehicles are envisioned, such as AHS, also lateral control is automated. The primary functionality of lateral control is keeping the vehicle in the center of the lane. Lateral control is in addition concerned with lane changing. Both functions are discussed in more detail in the next paragraphs.

Lane Tracking Lane tracking is the functionality that keeps a vehicle centered in a lane. Designing such functionality involves a trade-off between the ride quality and the accuracy of the system, just like for longitudinal control.

A good ride quality is important for passengers to accept automated vehicles. A high accuracy of such a system is essential for the safety. However, a higher accuracy may lead in itself to a jerkier driving experience.

For steering a vehicle towards the center of a lane, it is important to know the current lateral position of the vehicle. Several technologies have been considered to measure this position, such as permanent-magnet tracking, computer-vision and Differential Global Positioning System (DGPS), an enhancement of GPS that provides a higher accurate location service.

Magnet tracking turns out to be a very robust option, even at high speeds, as direction information, specific to a location, can be encoded into the polarization of magnets. From experimental data, it was shown that a magnet tracking system could provide tracking errors that are 3 to 4 times smaller compared to manual driving. A major downside of this approach is the need to equip the roads with these magnets.

The need for special magnets is not present when computer vision is used to detect lanes in order to determine the vehicle's lateral position. The difficulty with computer-vision lies in the ability to handle the varying road

conditions. For instance, road stripes can be temporarily unavailable, moved in case of road construction or invisible because of light conditions.

Lane Changing Lane changing is the functionality to steer a vehicle from the current lane to an adjacent lane. This aspect of lateral control is considered to be the most challenging as it involves more vehicle dynamics, a change of front-radar target and coordination between vehicles.

In order to support this task, a magnet tracking system can be used. Such a magnet trail can guide a vehicle to an adjacent lane, similar to railroad switch that guides a train to an adjacent track. Despite the high accuracy of such a system, it lacks flexibility in the sense that vehicles can only change lanes where guiding magnets have been installed. Another approach could be based on dead reckoning in which a vehicle is steered without guidance and the lateral position is estimated based on a previous known position and direction of the vehicle.

Maneuver Coordination

Vehicle platooning involves, apart from longitudinal and lateral control, the coordination of vehicle maneuvers. These maneuvers are typically the formation and splitting of platoons, the merging of traffic streams and coordination of changing lanes.

This research is mainly concerned with the formation and splitting of platoons. In the following sections we limit our description to these maneuvers.

Platoon Formation Platoon formation –also called *Joining*– is the term used for a situation where two platoons (or a combination of a platoon and a vehicle or two vehicles) are combined into one platoon. An example of such a situation is illustrated in Figure 2.4 where vehicle number 4 accelerates in order to join the platoon (i.e. vehicles 1 to 3).

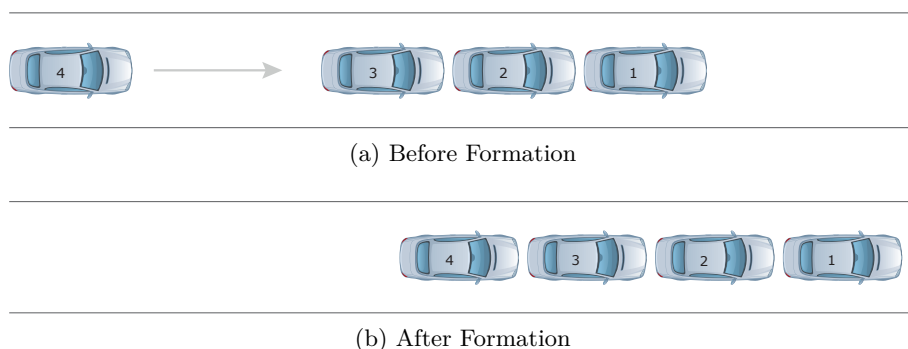


Figure 2.4: Platoon Formation

The above example illustrates a situation in which a vehicle joins at the back of a platoon. This is however not the only way of joining a platoon: a vehicle might also join the platoon in the middle or in front of a platoon.

Platoon Split A platoon split is the situation where a vehicle or a number of vehicles leave the platoon. An example of this situation is illustrated in Figure 2.5 where the last vehicle (i.e. vehicle number 4) leaves the platoon.

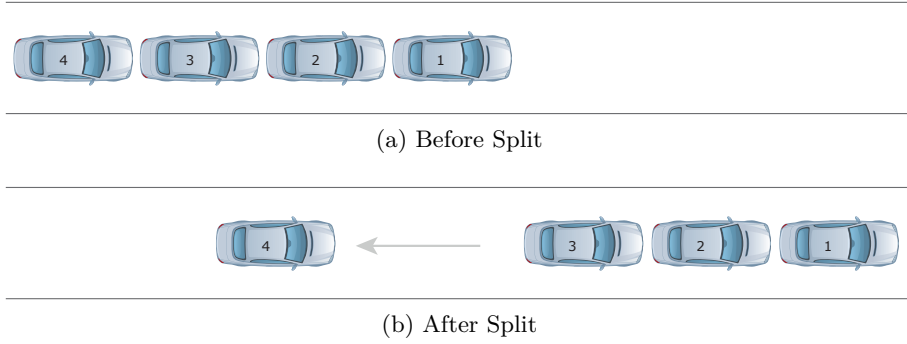


Figure 2.5: Platoon Split

In ACC and CACC, the maneuvering is human controlled. Basically, a human driver accelerates and steers to the end of a platoon after which the ACC or CACC is enabled. Similar with splitting a platoon, a human driver would decelerate and optionally steer to an adjacent lane. In case the splitting vehicle is followed (i.e. the splitting vehicle is not the last vehicle in the platoon), the following vehicles should decelerate as well. This results in the split of a platoon. For obvious reasons, it would be more efficient if a leaving vehicle does not result in a split of the platoon.

By coordinating the maneuvers among the involved vehicles, an improvement of the efficiency could be enabled. Such automatic coordination is envisioned in AHS and depends heavily on wireless communication. An introduction to wireless communication in vehicular environments is provided in the next section.

2.3 Wireless Access in Vehicular Environments

This section provides an introduction to the WAVE standard by mainly citing Uzcátegui and Acosta-Marum in [34].

Since the early start of ITS, wireless communication has been considered by the National Intelligent Transportation Systems Architecture (NITSA) as one of the cornerstone technologies in the support of ITS. In fact, the first commercial ITS application was electronic toll collection. This application used wireless communication in the spectrum of 902 MHz and 928 MHz. Soon, it turned out that these bands were too small and too polluted to accommodate a large growth of ITS applications. Consequently, the Federal Communications Commission (FCC) reserved a bandwidth of 75 MHz in the 5.9 GHz band, dedicated to the short-range communication of ITS applications. This band is called the DSRC band.

Figure 2.6 shows the DSRC spectrum band and its channels as allocated by the FCC. This allocation consists of 7 channels with a bandwidth of 10 MHz each. Some of these channels are restricted to be used for the transmission of a particular type of information. For instance, channel 178 is the control channel and can only be used for the transmission of safety related data. The outer channels number 172 and 184 are reserved for special purpose communication and the remaining four channels can be used for both safety and non-safety related communication.

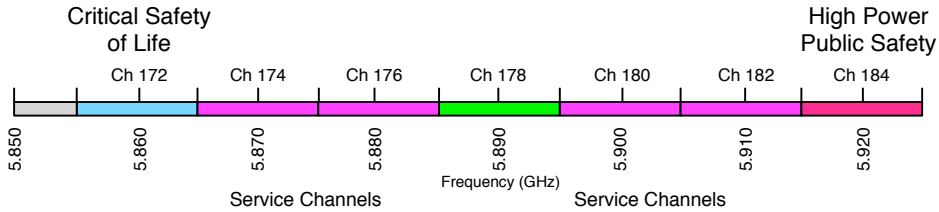


Figure 2.6: DSRC spectrum band and channels in the US

The DSRC bandwidth reservation did not provide the needed set of rules controlling the technologies to be used in this band. After a lobby by the Intelligent Transportation Society of America (ITSA), the FCC officially adopted a recommendation by the ITSA to use a technology based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 protocol family. Initially the American Society for Testing and Materials (ASTM) started the development of the lower protocol layer standards for the DSRC band. This work was continued in 2004 by a workgroup of the IEEE. The result of this IEEE workgroup is a document known as IEEE 802.11p. At the same time, the IEEE 1609 working group started the development of

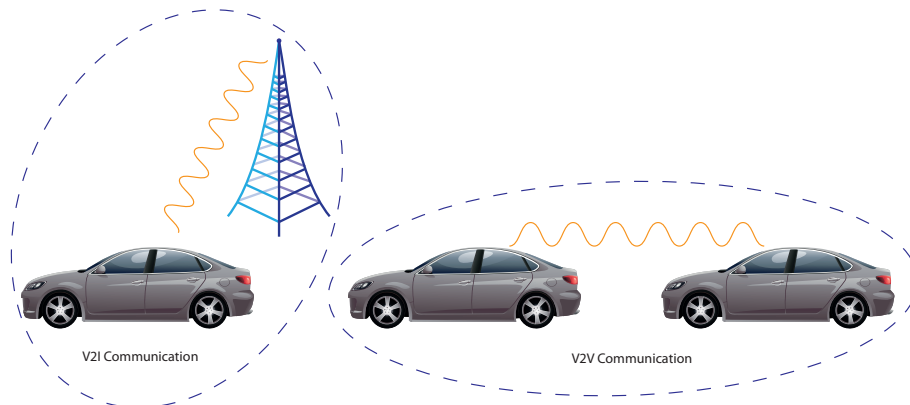


Figure 2.7: Communicating Units in a WAVE System

additional protocol layers to complement the IEEE 802.11p protocol. This has resulted in four documents: IEEE 1609.1, IEEE 1609.2, IEEE 1609.3 and IEEE 1609.4. Together with the IEEE 802.11p protocol, this protocol suite is called the WAVE standard.

The WAVE standard describes two types of communication nodes. The first is the Road-Side Unit (RSU), which is mounted to road infrastructure like road signs or traffic lights. Although these RSUs are not restricted to a single location, they are considered to be static or slowly moving as for example moving road works. Secondly, the WAVE standard defines a unit that is highly mobile. These so-called On-Board Units (OBUs) are mounted inside vehicles. Figure 2.7 illustrates the communication between OBUs and RSUs.

The communication in RSUs and OBUs are supported by means of two protocols stacks, as shown in Figure 2.8. In Open System Interconnection (OSI) terminology, these stacks use the same layer 1 (physical layer) and layer 2 (Medium Access Control (MAC) layer) protocols. However, these stacks differ in the used layer 3 (network layer) and layer 4 (transport layer) protocols. Unlike the OSI-stack, the WAVE does not specify any layer 5 (session layer), layer 6 (presentation layer) and layer 7 (application layer).

The main motivation for the specification of two protocol stacks is the ability to support different communication requirements. For example, a web browsing application can profit from a large bandwidth but is not delay sensitive, whereas a safety application is delay sensitive but does not require a large bandwidth. The two protocol stacks have been designed to support these different requirements.

The following section describes the WAVE architecture in more detail. As our communication solution is built onto the MAC-layer, we limit the overview in Section 2.3.1 to the lower layers i.e. the MAC- and Physical

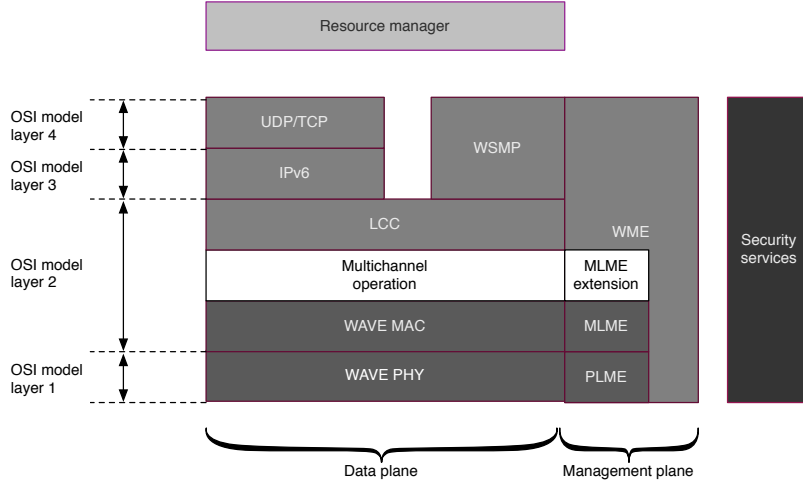


Figure 2.8: Communication Architecture in a WAVE System

Layer (PHY)-layer of WAVE architecture.

2.3.1 The IEEE 802.11 Protocol Family

The description in this section cites mainly Gast [12] and Schiller [28].

IEEE802.11 is a member of the IEEE802 family, as the standard number indicates. The IEEE802 is a series of specifications for Local Area Network (LAN) and includes a specification of the lower layer Open System Interconnection (OSI) components i.e. the Medium Access Control (MAC) and PHY layer. The main task of the former one is providing medium access such that multiple nodes can communicate by means of a single medium. The latter one is concerned with the medium specific transmission and reception of data.

The IEEE802.11 is another protocol family concerned with LAN in wireless environments (WLAN). This means that similar MAC and PHY layer components are adapted to the special requirements of wireless environments. A few examples of these components are the well-known IEEE 802.11a/b/g/n standards, meant for generic wireless area networks, and IEEE802.11p for wireless communication in vehicular environments.

The main difference between these versions lies in their physical layer and the modulation technique used. The initial version of IEEE802.11 specifies two physical layers for microwave transmission using respectively Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) modulation techniques. Later, Orthogonal Frequency-Division Multiplexing (OFDM) was ratified as a third modulation technique.

Unlike the PHY-layer, the functionality of the MAC-layer is fairly sim-

ilar for all versions of the IEEE802.11 standard. The remainder of this overview focuses on the generic MAC-layer functionality and amendments of IEEE802.11p.

System Architecture Two types of architecture have been standardized for the wireless communication IEEE802.11: the infrastructure-based and the ad-hoc architecture. With the former architecture, nodes (also called stations) connect to an Access Point (AP). An AP and all its connected stations make up a Basic Service Set (BSS). When multiple BSS's are connected via a distribution system, these BSS's form a single network, called an Extended Service Set (ESS). When the infrastructure of an AP is unavailable, stations can use the ad-hoc architecture to setup an ad-hoc network between stations in the transmission range. All stations connected to the same ad-hoc network make up an Independent Basic Service Set (IBSS).

For the MAC component, two types of medium access mechanisms have been standardized: the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). The DCF is a contention-based access mechanism providing an asynchronous service. As the DCF is a distributed mechanism based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), it can be used with the infrastructure-based and the ad-hoc architecture. The PCF is a central controlled mechanism, offering asynchronous and time-bounded service. This mechanism needs an AP that controls the medium access. This mechanism can hence only be used in combination with the infrastructure-based architecture.

Since the communication solution, presented in this research, is based on ad-hoc communication, we are limited to the ad-hoc architecture and hence the DCF access mechanism. The following overview is limited to an overview of CSMA/CA, the mandatory access method of DCF.

Carrier Sense Multiple Access with Collision Avoidance CSMA/CA is a random access scheme using carrier sense and collision avoidance. This scheme works as follows: if a node wants to transmit a packet, it first senses the medium. If the medium is busy, the node should defer its transmission until a later moment. If the medium is idle for a specific period, the node is allowed to start its transmission. In this sense, the scheme is similar to Carrier Sense Multiple Access with Collision Detection (CSMA/CD), used in IEEE802.3. The difference between the schemes lies in how collisions are handled.

A collision occurs when a node receives several simultaneous signals. In such a case, the node cannot distinguish the signals and the transmission gets corrupted. With collision detection, as used in IEEE802.3, the sending node keeps listening to the medium in order to detect the simultaneous

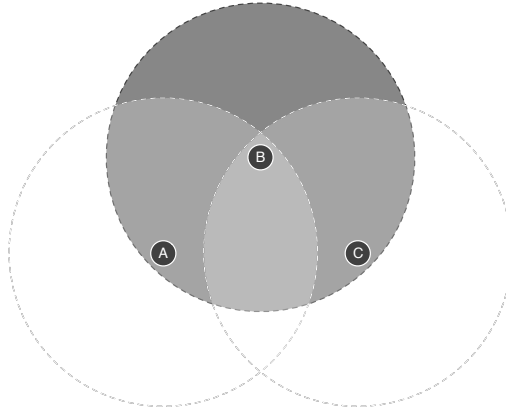


Figure 2.9: Hidden Terminal Problem

transmission of other nodes. If this situation occurs, the transmission is interrupted and a jam signal is transmitted instead.

Collision detection cannot be used for wireless communication. Nodes are just not able to transmit and listen for signals simultaneously, simply because the transmitted signal drowns out the received signal or a node can be out-of-reach. Take for example the three-node network as illustrated in Figure 2.9. A problematic situation can be observed where node A wants to transmit to node B while node C is already transmitting to node B. As node C is out-of-reach of node A, node A senses the medium idle and starts transmitting. As a result, the transmission of node A and node C collide at node B. This problem is called the hidden-terminal problem.

Instead of collision detection, the CSMA/CA uses acknowledgements to detect collisions. After a successful transmission, the receiving node confirms the sender by sending an acknowledgement. Only a receiving node knows after all whether a transmission was successful or not. If a sending node does not receive this acknowledgment, it assumes a collision and schedules the frame for retransmission.

Figure 2.10 illustrates the basic access method of CSMA/CA. A sending node first senses the status of the medium. If the medium is busy, the access to the medium is deferred until the medium is sensed idle for at least a period of DCF Inter-Frame Space (DIFS). The receiver node confirms the frame immediately after a successful transmission and waiting for an idle period of Short Inter-Frame Space (SIFS). This spacing is shorter than DIFS and therefore has priority over a normal transmission.

Upon the correct reception of the acknowledgement, the sending node schedules the next frame for transmission. Again, this requires the sender to sense the medium idle for a period of at least the DIFS. After this idle period, the sender enters the contending phase, as the medium has been

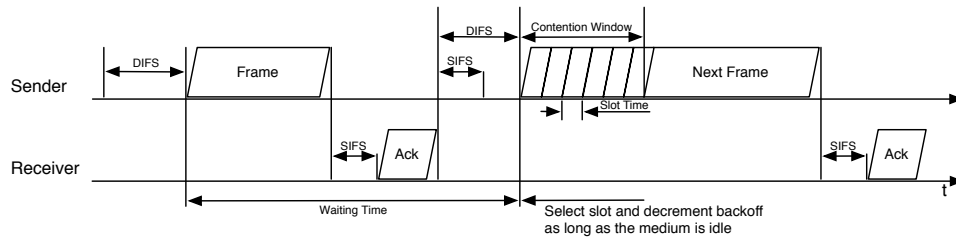


Figure 2.10: IEEE 802.11's Basic Access Method based on Figure 9-11 of [2]

busy after the first transmission by another node. This was in fact because of the transmission of the acknowledgement. In the contending phase, the node picks a random slot time within the contention window and delays the transmission up to that period. If the medium becomes busy in the meanwhile –this is because the backoff timer of another contending node expired– the timer is interrupted. When the medium is sensed idle for at least a period of DIFS, the timer starts again. Eventually, the timer expires and the node starts to transmit. This mechanism aims to provide fairness in medium access, as the probability to start a transmission increases with the time in contention.

A common starting size for the contention windows is 7 slot times. Under a light load, this is not a problem and results in low access delays. However, with many contending nodes, it is very likely that two nodes pick the same slot, which results ultimately in a collision. In order to handle high loads, the size of the contention window is doubled at each occurrence of a collision. The larger the windows size, the lower the probability of two nodes picking the same time slot but it results in a higher average medium access time. This algorithm is called *exponential backoff* and is similar to the algorithm used in IEEE802.3.

CSMA/CA with RTS/CTS extension Despite the exponential back-off algorithm, collisions still occur. After all, the hidden terminal problem still exists. IEEE802.3 handles collisions efficiently by suspending the transmission as soon as a collision is detected. Since IEEE802.11 cannot detect such a collision during transmission, it wastes scarce resources.

An extended mechanism has been standardized in IEEE802.11 to handle this problem. This mechanism introduces two control packets, called Request to Send (RTS) and Clear to Send (CTS). Instead of transmitting the frame, a sender first sends an RTS to the receiver. When the receiver responds with a CTS and the sender receives this control packet, it may start transmitting the data as usual. Failing to receive a CTS packet is considered to be a collision and is handled accordingly.

Both control packets contain the duration of the entire transmission. Every node receiving either an RTS or CTS now assumes the medium to be busy for the duration as indicated in the packet. A hidden node cannot hear the RTS by definition but can hear the CTS so even a hidden node defers its transmission.

With this mechanism, control packets can still collide. In fact, the hidden terminal problem shifted to the control packets. For that reason, the size of the control packets are kept small and a collision of the control packets have a relative small impact compared to the collision of data frames.

Unfortunately, the acknowledgement and RTS/CTS mechanisms cannot be used in packet broadcasting as the MAC-layer does not know the number of receivers.

IEEE 802.11p

IEEE802.11p is an amendment to the IEEE802.11 standard for vehicular networks. Modifications to the original standard were needed as the MAC- and PHY-layers were never designed for mobile environments.

Modifications to the MAC-layer The description in this paragraph, of the amendments to the MAC-layer in IEEE802.11p, cites Jiang et al. [16].

WAVE mode Nodes are able to transmit and receive frames in the WAVE mode without the need to join the same BSS. As long as they operate in the same channel and use the wildcard Basic Service Set Identifier (BSSID), these nodes can communicate immediately on encounter without any additional overhead. This is essential for time-critical safety communication.

WAVE BSS A new type of BSS has been introduced. This so-called Wave Basic Service Set (WBSS) allows a station to connect without the overhead of a traditional BSS. The advertisement of a WBSS contains all the information for higher level-layers to join the WBSS.

Expanding wildcard BSSID usage Considering the importance of safety, the amendment allows nodes to be connected to a WBSS and still use the wildcard BSSID for safety related communication. Similar, a node connected to a WBSS can still receive frames with the wildcard BSSID.

Modifications to the PHY-layer Amendments to the PHY-layer for efficient communication between fast moving nodes are kept to a minimum. Changing existing radio hardware is a challenging task whereas a MAC-layer is usually implemented in software. Keeping the amendments to a minimum is feasible as IEEE802.11p is essentially based on IEEE802.11a, which already operates at 5GHz.

The following changes were made to the PHY-layer of IEEE802.11p:

10MHz channels The channels in IEEE802.11p have a width of 10MHz instead of the usual 20MHz. The reason behind this decision is the guard interval which is not long enough to prevent inter-symbol interference within the radio's own transmission in vehicular environments.

Improved receiver performance requirements Channel interference is a well-known property of wireless communication. Especially in vehicular environments, where the vehicles are close distributed, channel interference is of high concern. Hence, IEEE802.11p introduces improved receiver performance requirements in filtering adjacent channels.

Chapter 3

Platoon Formation Strategies

The previous chapter provided an overview of the concept of Intelligent Transportation Systems (ITS) and introduced *vehicle platooning*, an ITS concept in which vehicles drive in close cooperative formations. Vehicle platooning has the potential to *a)* increase the lane capacity, *b)* increase safety, *c)* lower the fuel consumption and *d)* improve the level of driver comfort. In order to achieve these benefits, an implementation of vehicle platooning should automate at least longitudinal control and possibly lateral and maneuver coordination.

Maneuver coordination is the function that coordinates the maneuvers between the involved vehicles. These maneuvers include the formation and splitting of vehicle platoons, the merging of traffic flows and the coordination of changing lanes. In this thesis, we investigate a sub-function of maneuver coordination: the process of organizing vehicles into platoons. The goal of this so-called *formation strategy* is to increase platoon benefits as described here above.

In order to maximize the benefits, it is desirable for a formation strategy to [25]:

Form platoons of a reasonable length: With large platoons, the vehicles drive closer together on average and hence consumes less lane capacity. Vehicles that drive closer together consume in addition less fuel (see Section 2.2.1).

Form platoons that stay intact for a reasonable length: A high rate of vehicles joining and leaving a platoon may cause vehicles to drive further apart. In addition, it can decrease the safety. A stable platoon, which stays intact for a reasonable length, is hence a desirable property of a formation strategy.

This chapter presents a literature survey of platoon formation strategies followed by a categorization of these strategies. Based on the categorization, we propose a new formation strategy. The performance of this new strategy

is finally evaluated and compared against the formation strategies of the survey.

This chapter is organized as follows: section 3.1 starts with a brief overview of platoon formation strategies that are described in literature. These strategies are classified according to 2 classes and their advantages and disadvantages are presented. As a result of this survey, a new platoon formation strategy is developed and described in Section 3.2. In Section 3.3, the performance of the proposed formation strategy is evaluated and compared against the performance of the strategies from the survey. Finally, in Section 3.4, the results are discussed and recommendations for future research are described.

3.1 Related Research

This section presents a survey of strategies for the formation of vehicle platoons. Unfortunately, just a few papers have addressed this topic. Based on the survey, a classification of platoon formation strategies is presented in this section.

3.1.1 Survey of Platoon Formation Strategies

The most basic strategy for a vehicle to form a platoon is to adopt the speed of the immediate preceding vehicle on encounter [29]. This ad-hoc approach is used in most of the current vehicle platooning systems, like Adaptive Cruise Control (ACC). Unfortunately, this approach has some major drawbacks like the slowest driving vehicle dictates the speed of the platoon. So, a vehicle slowing down in order to leave the platoon may lead to a split of the platoon.

The cooperation between vehicles in order to form a platoon may lead to more efficient platoons. Randolph Hall and Chinan Chin [25] have developed and analyzed a number of these cooperative strategies. Their strategies have been developed with the focus on maximizing the distance that a platoon stays intact. This entails basically the grouping of vehicles according to their destination, which can be performed in several ways. Three strategies, based on this concept, have been developed and described in their work.

A common property of these formation strategies is their restriction to form platoons only at the entrance ramp. As a result, the vehicles are unable to regroup on the highway. Arriving vehicles on the entrance ramp are assigned to a specific lane and all the vehicles in a lane form a platoon. An inevitable consequence of this property is the introduction of a waiting time. Vehicles have to wait after all for other vehicles to be assigned to the same lane.

The following 4 strategies have been described in [25]:

Destination Group (DG): Under the DG assignment strategy, the lanes of the entrance ramp are statically assigned to a range of destinations i.e. a destination group. The destinations in this destination group are a set of adjacent exit ramps. In fact, all exit ramps are uniquely assigned to a specific destination group. Upon the arrival of a vehicle at the entrance ramp, it is assigned to the appropriate lane, based on the vehicle's destination.

Figure 3.1 illustrates a situation in which the DG strategy is used. In this example, the total number of 6 exit ramps have been statically distributed over the three entrance lanes; the first two destinations to the left lane, destinations 3 and 4 to the middle lane and finally the last two destinations 5 and 6 to the right lane. The example shows, in addition, 4 vehicles that have arrived in the following order:

1. Vehicle with destination 5
2. Vehicle with destination 6
3. Vehicle with destination 2
4. Vehicle with destination 3

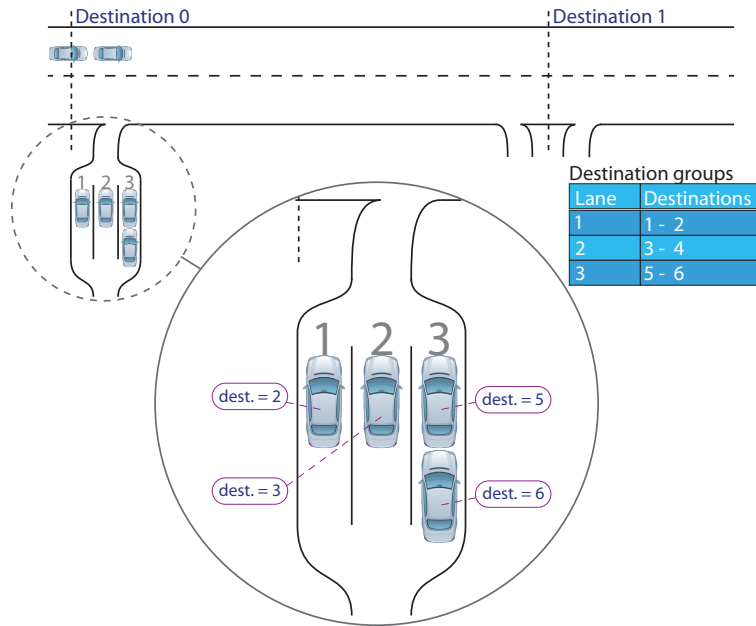


Figure 3.1: Example of the DG Strategy

Vehicles form after lane-assignment a platoon with other vehicles in the same lane. Each arrival causes the lanes to queue up and once a lane contains a certain number of vehicles or a fixed amount of time has elapsed, the lane is released. During release, all the vehicles in a

lane enter the highway as a single platoon. The platoon stays intact until just before the first exit of the destination group is reached. At this moment, the complete platoon splits and the vehicles continue driving individually to their destination.

Using multiple lanes at the entrance for the formation of platoons, like is used for the DG strategy, may lead to smaller platoons on average or longer waiting times. The total arrival rate is after all divided over the lanes. However, the arriving vehicles are not necessarily divided equally over all lanes, which result in variations in the average platoon size and waiting times. Another downside of multiple entrance lanes for platoon formation is the need for space to accommodate multiple lanes.

Dynamic Grouping (DYG): With dynamic grouping, the destinations groups are no longer statically assigned to a particular lane of the entrance ramp. Instead, the range of vehicle destinations in a platoon is constrained to a maximum called the destination range. That is, the difference in index of the nearest and most distant destination over all vehicles in a platoon should be smaller or equal than a defined constant r .

Figure 3.2 illustrates this situation in which the DYG strategy was applied with a destination range(r) or 2. Except for the strategy, this situation is similar to Figure 3.1 as used to explain the DG strategy. This includes the order of vehicle arrival i.e. vehicle 5 - vehicle 6 - vehicle 2 - vehicle 3.

Now, at the arrival of vehicle 5, all the entrance lanes were empty. Vehicle 5 was therefore assigned to the empty left lane. Vehicle 6 arrives next and is assigned to the left lane as well, as the DYG constraint holds i.e. the difference between 6 and 5 is smaller than the destination range of 2. This constraint does not hold for vehicle 2 however, so it was assigned to the middle lane. Finally, for vehicle 3, the destination range constraint does not hold for the left lane but does hold for the middle lane. Hence, vehicle 3 joins vehicle 2 in the middle entrance lane.

The result of the DYG strategy is the formation of two platoons of two vehicles. Compared to the DG strategy, this is an improvement of the average platoon size.

With the DYG strategy, it is even possible that a vehicle can be assigned to multiple platoons. In which case the vehicle is assigned to the platoon, which hosts vehicles with the most similar destination. If no feasible platoon exists and no free lanes are available, the longest waiting platoon is released. The arriving vehicle subsequently uses the freed lane to start a new platoon.

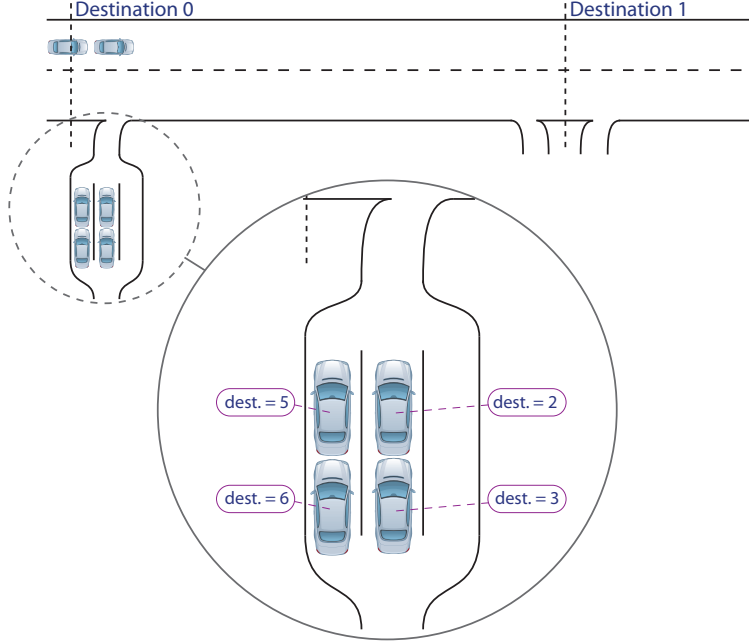


Figure 3.2: Example of the DYG Strategy (destination range = 2)

With the introduction of the maximum destination range, the DYG strategy enables the creation of platoons, which contain vehicles with similar destinations. A smaller destination range creates platoons of vehicles with more similar destinations and allows the platoon to drive farther without splitting. On the other hand, a small destination range makes it difficult to cover all destinations if the number of lanes is limited. As a consequence, a platoon might be released quicker, leading to smaller platoons on average.

Dynamic Grouping and Platoon Splitting (DGPS): For both the DG and DYG strategies, the platoon splits up just before the first exit of their destination group. After the split, the vehicles drive individually to their destination. The DGPS differs from DYG and DG in the sense that it permits a platoon to continue driving after vehicles have left the platoon. This is achieved by sorting the vehicles in a platoon, according to their destination with the leading vehicle having the farthest destination.

This formation strategy is illustrated by the situation in Figure 3.3. This situation is equal to the situations used to illustrate respectively the DG and DYG strategies in Figure 3.1 and 3.2.

Let us assume the same order in vehicle arrival as previously used – that is, vehicle 5 - vehicle 6 - vehicle 2 - vehicle 3. When vehicle 5

arrived, all the lanes were empty so it was assigned to the left lane. This is not different from the DYG strategy. The difference becomes clear when vehicle 6 arrives. With the DGPS, it is not allowed to join vehicle 5 as it will result in a disordered platoon: vehicle 6 follows then a vehicle with a closer destination. So, vehicle 6 is assigned to the middle lane. Now, when vehicle 2 arrives, there is the option to join the first or second entrance lane. As the difference in destination between vehicle 2 and 5 is smaller than between vehicle 2 and 6, it is assigned to the left lane. For arriving vehicle 3, only the final left option is to join vehicle 6 in the middle lane.

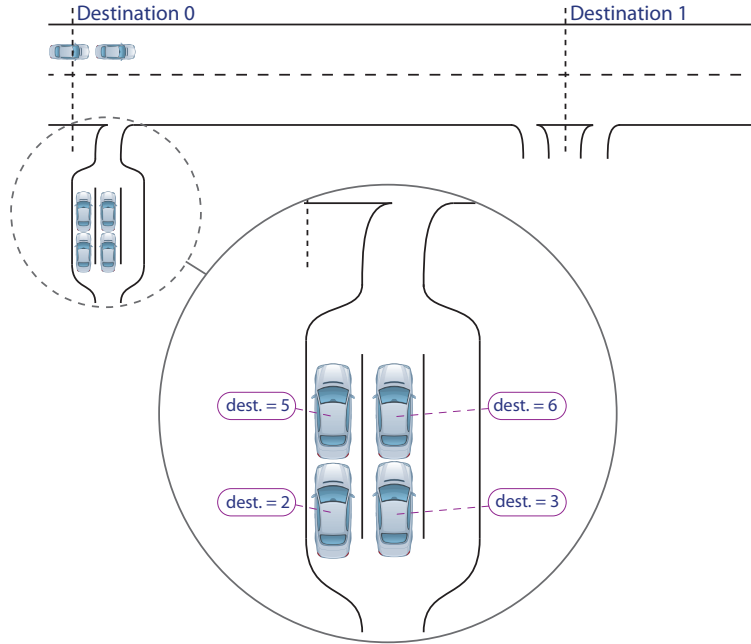


Figure 3.3: Example of the DGPS Strategy

In order to sort a platoon, an arriving vehicle can only be assigned to a lane if the last vehicle in the lane has a farther destination. If no lane can satisfy this constraint, one of the platoons is released and the freed lane is used to start a new platoon. A platoon is anyhow released after a pre-defined time interval or when the platoon has reached the maximum length.

For the DGPS strategy, the last vehicle is by definition the first vehicle to leave the platoon. If the last vehicle has reached its destination, it can leave the platoon without splitting the platoon. All other vehicles in the platoon are not disturbed and can continue to drive as a single platoon.

Random Assignment (RA): The random assignment formation strategy

is the most basic formation strategy in which vehicles, on arrival are randomly assigned to a lane. This strategy is similar to the ad-hoc formation strategy and is used by Hall and Chin [25] for comparison reasons.

Another platoon formation strategy has been proposed by Dao in [31]. Dao's approach is aimed towards enhancing the road capacity by finding an optimal assignment of merging vehicles at the entrance ramp into platoons. The main difference with the previously described formation strategies is the location at which the formation takes place. The strategies as described by Hall and Chin [25] form platoons at the entrance ramp. The formation strategy by Dao performs a logical assignment of arriving vehicles to platoons at the merging point – the point at which the entrance ramp merges into the highway– and the physical formation happens eventually at the highway itself.

Figure 3.4 illustrates Dao's approach towards platoon formation. The assignment of vehicles to platoons according to this strategy is executed by each unassigned vehicle –a vehicle that is not yet assigned to a platoon– on the entrance ramp as soon as it arrives at the merging point. This vehicle starts communicating with all the other vehicles on the entrance ramp and the upstream platoons within its transmission range. With the information communicated, the executing vehicle subsequently assigns the vehicles on the entrance ramp, including itself, to the platoons. As soon as the vehicles are assigned to the platoons, they maneuver to the platoon and no longer execute the formation strategy by themselves.

Other than for the previously described formation strategies of Hall and Chin [25], platoons are formed between the current merging and on the highway driving vehicles. So, there is no need to wait for future vehicles to enter the highway. As a result, Dao's strategy lacks a waiting time.

An optimal assignment of vehicles to platoon is achieved, according to Dao, when the total distance that vehicles stay intact is maximized. The following criteria are used in the assignment of vehicles to platoons in order to maximize this distance:

1. Vehicles are assigned to a platoon and stay with the platoon until they reach their destination;
2. The platoon length is limited in the number of vehicles;
3. Platoons are constrained to a maximum range of destinations;
4. The vehicles in a platoon are sorted according to their destination with the leading vehicle having the most distant destination;
5. If a vehicle cannot be assigned to a feasible platoon, it starts its own platoon.

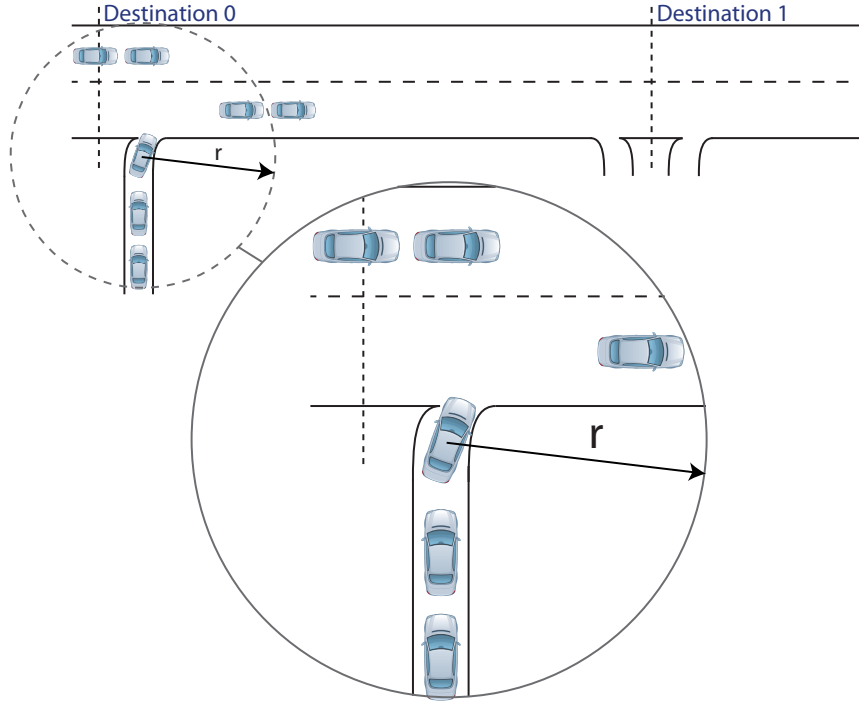


Figure 3.4: Intelligent Platoon Formation's Strategy [31]

The simulation results of this formation strategy show an increase of the lane capacity and average platoon size for increasing input flows and increasing destination ranges. Especially for a used destination range of 5 intersections, the lane capacity ranges between 2300 veh/hr and 4880 veh/hr , depending on the input flow. However, these larger destination ranges come at the cost of platoon instability compared to smaller destination ranges. Indeed, the smaller the destination range, the smaller the variation in destinations between vehicles of a platoon. This leads to a platoon that can stay intact for a longer distance.

Despite the positive simulation results, Dao's formation strategy has unfortunately not yet been compared against other formation strategies.

3.1.2 Classification of Platoon Formation Strategies

The final step of this survey is the classification of the identified formation strategies. This classification provides us a clear view of approaches which have been taken in order to solve the problem of platoon formation. In addition, it allows us to identify which approaches have not been taken yet. This will serve as our motivation for the development of a new formation strategy in Section 3.2. In this section we classify the formation strategies according to 2 classifications.

The first classification of formation is based on the location of the formation. As previously described, the strategies by Hall and Chin [25] form platoons at the entrance of a highway. On the other extreme is the traditional strategy of an ACC system, which forms platoons on the highway. In between these two extremes is the strategy by Dao, which performs the logical formation at the entrance and the physical formation on the highway.

Given these strategies, we divide the strategies in 3 classes:

- **Entrance Ramp Formation Location:** for this class, the formation strategy is coordinated and executed on the entrance ramp;
- **Highway Formation Location:** the coordination and the execution is performed on the highway for this class of formation strategies;
- **Hybrid Formation Location:** a combination of the previous 2 classes where the formation strategy is coordinated on the entrance ramp and subsequently executed on the highway.

The second classification is based on the type of organization policy. As it turns out, the identified formation strategies in this section show similarities. For example, the RA strategy and the strategy by ACC are uncoordinated and vehicles form platoons on random. The DGPS strategy and partly also the strategy by Dao incorporate the policy of sorting platoons. Finally, the strategy by Dao and the DG and DYG limit the destination range of vehicles in a platoon whereby DG limits this range statically and DYG dynamically. The similarities between strategies led to the identification of the following policy classes:

- **Ad-Hoc Formation Policy:** vehicles are grouped on encounter;
- **Platoon Sorting Formation Policy:** a formation policy in which the vehicles are sorted according to their destination in order to allow a vehicle to split the platoon once the destination is reached without the need to split the entire platoon;
- **Destination Ranging Formation Policy:** vehicles with close destinations are grouped.

The identified classifications and their appropriate formation strategies are visualized in Table 3.1. Most notable about this table are the lacking formation strategies. As far to our knowledge, no hybrid, ad-hoc formation strategy has been developed, nor a highway formation strategy using sorting or destination ranging.

3.2 Transient Platoon Formation Strategy

In this section, a new conceptual formation strategy is proposed with the aim to increase the average platoon size. The strategy tries to achieve this

	Entrance Ramp	Highway	Hybrid
Ad-Hoc	RA	ACC	
Platoon Sorting	DGPS		Dao
Destination Grouping	DG & DYG		

Table 3.1: Classification of Formation Strategies

goal by forming platoons on the highway, using the concept of destination ranging. The previous section motivates the development of this formation strategy. According to that survey, such a formation strategy has not been proposed yet for on-highway formation.

According to Dao, the policy of destination ranging enables a tradeoff between the stability of the platoon and the average platoon length. In fact, destination ranging is a limiting factor in terms of platoon size. For example, the policy may prohibit a vehicle from joining the only available platoon as the vehicle’s destination falls outside the platoon’s destination range. Instead, the vehicle is forced to start its own platoon while in terms of capacity it would be more efficient to create one large platoon instead of two. This limiting factor is confirmed by the simulation results of Dao: limiting the range results in smaller average platoons under similar simulation conditions.

Our proposed strategy incorporates the concept of destination ranging but extends it by allowing vehicles to temporary join a non-feasible platoon (i.e. a platoon for which the vehicle’s destination falls outside the range) in search of a better platoon. We call this strategy the *transient formation strategy*. The strategy works as follows:

As soon as a vehicle enters the highway, it drives as an individual vehicle. At the same time, it starts searching for a feasible platoon to join. If such a platoon is found, the vehicle joins the particular platoon. When no feasible platoons are found, the vehicle joins the closest non-feasible platoon while it continues searching for a feasible platoon. If such a platoon is eventually found, the vehicle switches to that particular platoon. This behavior is illustrated in Figure 3.5. Once a vehicle has found a feasible platoon, it stays with the platoon up to its destination. Only in the case when no feasible platoon has been found, the vehicle keeps searching until one is found or another vehicle joins the searching vehicle.

In order to determine the feasibility of a platoon, the searching vehicle communicates with all downstream platoon leaders within its transmission range. The destinations of the leaders are communicated as the formation strategy aims to find a platoon leader, which the vehicle can follow up to its destination. In fact, this policy is a variation of Destination Grouping Formation Policy where the range is dynamically based on the destination

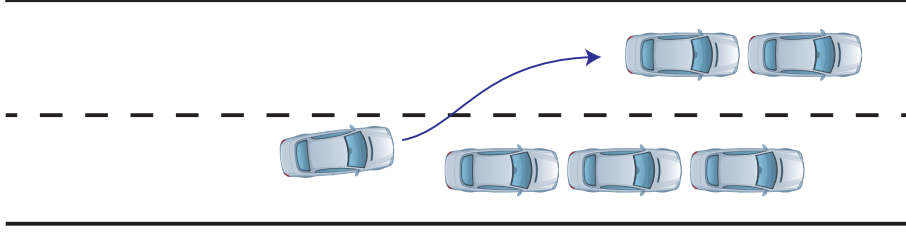


Figure 3.5: Switching behavior of the Transient Formation Strategy

of the platoon leader. For example, if the platoon leader has destination i , the range of the platoon is between the *current position* and destination i . In other words, a vehicle aims to join a platoon for which the leading vehicle has a farther destination.

The functioning of the formation strategy for a single vehicle is illustrated in Figure 3.6 by means of a state diagram. Assumptions made in this diagram and during later simulations are:

1. Destinations are fixed once the vehicle has entered the highway;
2. The formation strategy is executed once the vehicle enters the highway and stops when the destination is reached.

The state diagram of Figure 3.6 consists of the following states:

Idle State The *Idle State* is a result of the 2nd assumption. From this *Idle State*, the formation strategy is executed once the vehicle enters the highway, which results in a transition to the *Searching State*.

Searching State In the *Searching State*, the vehicle starts searching for a feasible downstream platoon in its communication range according to the previously described destination range policies. From this *Searching State*, there are 5 options:

1. A feasible platoon is found which results in the vehicle joining the platoon and a transition to the *Following State*;
2. No feasible platoons are found but at least one (non-feasible) platoon is found. This results in the vehicle, temporary joining the closest platoon; hence a transition to the *Temporary Following State*;
3. Another vehicle requests to join the current vehicle, which results in a transition to the *Leading State*;
4. The destination is reached resulting in a change to the *Leaving Highway State*;
5. The vehicle keeps searching if none of the previous events happened.

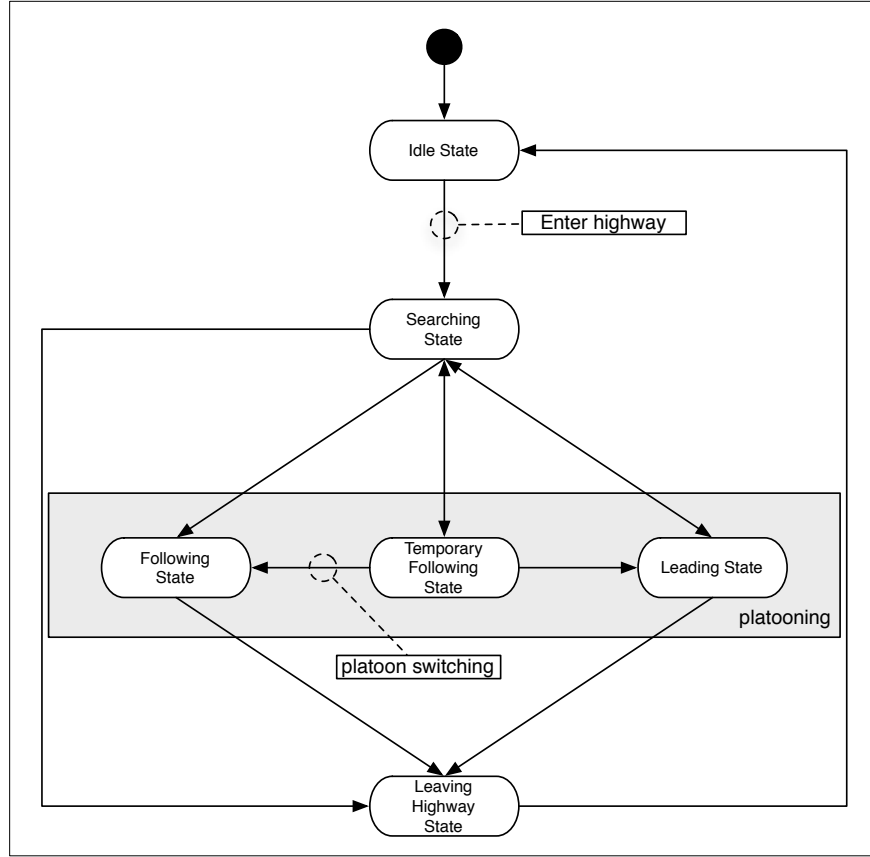


Figure 3.6: State diagram of Transient Formation Strategy

The *Following*, *Temporary Following* and *Leading State* are the states in which the vehicle drives in a platoon.

Following State In the *Following State*, the vehicle is following by definition a platoon with a leader having a farther or equal destination. As a consequence, the vehicle stays in the platoon up to its destination and only changes to the *Leaving Highway State* when the destination is reached.

Temporary Following State In the *Temporary Following State*, the vehicle is, by definition, following a platoon with a leader having a closer destination. The following events can happen:

1. The vehicle finds a feasible platoon. This results in the vehicle changing platoons and a transition to the *Following State*;
2. All preceding vehicles have left the platoon but other vehicles are still following the current vehicle. This results in a state change

to the *Leading State*;

3. The leading vehicle leaves the platoon, leading to a change of leader. If the new leader has a farther destination, the current vehicle becomes a follower resulting in a state-change to the *Following State*;
4. All other vehicles have left the platoon, which leaves the current vehicle without platoon. This results in a state change to the *Searching State*.

In the *Temporary Following State*, it is impossible for a vehicle to reach its destination. Proof of this statement is given in Appendix A.

Leading State A leading vehicle is never searching for a feasible platoon. The leader stays the leader by policy up to its destination. As a result, the *Leading State* has a transition to:

1. The *Leaving Highway State* which happens when the destination is reached;
2. The *Searching State* when all following vehicles have left the platoon.

Leaving Highway State Finally, the *Leaving Highway State* represents a vehicle leaving the highway. Once the vehicle left the highway, the state changes to the *Idle State*, waiting for moment the vehicle enters the highway again.

For the *transient formation strategy* to take advantage of the searching policy, a small difference in the preferred speed is introduced between lanes. When all vehicles have nearly the same speed, the vehicle's relative positions are nearly static from a vehicle's point of view. Hence the need for a multi-lane road with speed differences between lanes. In the next section we evaluate the performance of the *transient formation strategy* for such a 2-lane highway scenario.

3.3 Evaluation of Formation Strategies

In the previous section, we have designed a new platoon formation strategy. This strategy extends the concept of destination ranging for the on-highway formation of vehicle platoons with the aim to create large platoons. In this section we describe the performance evaluation of this strategy and compare it with the formation strategies identified in Section 3.1.1, by means of simulations.

This section starts with a description of the simulation setup after which the simulation metrics and finally the results are presented.

3.3.1 Simulation Setup

Simulation Scenario

For the evaluation of the formation strategies, we have simulated a 2-lane straight highway with a total length of 34 kilometer as illustrated in Figure 3.7. This length is equal in length to the highway used in the simulation scenario by Hall and Chin [29]. The total length of the highway is divided into 17 sections, which results in 16 intersections with 2 kilometer inter-spacing. An equal intersection spacing was used by Dao [31].

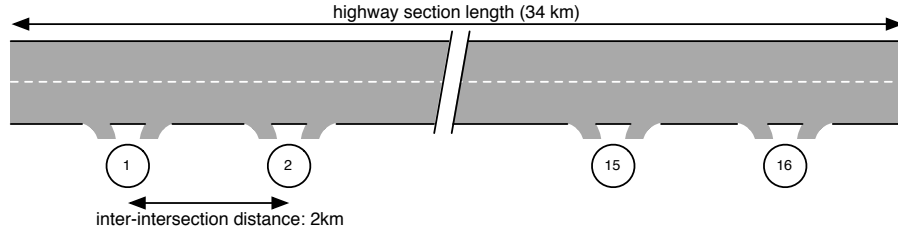


Figure 3.7: Roady Layout used for the Simulation of Formation Strategies

Vehicles in our simulation are generated at the start of the highway and each intersection according a Poisson process. This results in exponential distributed inter-vehicle arrival times.

The vehicle input flow at the start of our highway is changed for each simulated scenario. The vehicle input flow at each intersection is statistically equal to the vehicle output flow for the particular intersection such that the vehicle flow in between intersections remains statistically constant.

In order to determine the intersection input flow, we need to calculate the expected output flow. This rate is dependent on the expected vehicle destination, which is either a downstream intersection or end of the highway.

For the destinations, we use the geometric distribution –the discrete analogue of the exponential distribution as used by Hall and Chin [29]– with an average trip length of 16 km –the rounded average trip length in the United States of America (USA) of 2009 [11]. Using a geometric distribution implies that a vehicle decides at each intersection whether to leave or continue driving the highway with respective probabilities p and $1 - p$. The probability p of this Bernoulli trial is equal to $\frac{\text{inter-intersection distance}}{\text{average trip length}}$; in our case $p = \frac{2 \text{ km}}{16 \text{ km}} = \frac{1}{8}$.

For an assumed float rate of F vehicles/hour, the output flow is binomial distributed with a mean of Fp or $\frac{F}{8}$ in our case. The intersection input flow becomes hence $\frac{F}{8}$ as well.

Modeling of Traffic

For our simulation, it is important that nodes behave like vehicles. Our focus is on longitudinal behavior of a vehicle as well as lateral behavior. We simulate after all a two-lane highway where vehicles are allowed to change lanes. In what follows, we describe the driver models used in our simulation.

Car-Following Model Traffic flow models aim to describe the driver behavior and the following interactions between vehicles. These models can be classified in two categories: macroscopic and microscopic models. Macroscopic models relate accumulative traffic properties like traffic flow, densities and speeds while microscopic models describe the behavior of individual vehicles. As our formation platoon strategies are described as state machines for individual vehicles, we use a microscopic approach to perform our simulations.

In this research we use two types of car-following models for longitudinal control. For free flow vehicles we adopt Intelligent Driver Model (IDM) [32]. Treiber, Hennecke and Helbing developed this model in 2000 to provide a more realistic car-following model than for example Gibb's model [23].

The acceleration (\dot{v}_a) of a vehicle under IDM is described with Equation 3.1:

$$\dot{v} = a \left[1 - \left(\frac{v_\alpha}{v_0} \right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha} \right)^2 \right] \quad (3.1)$$

The first term of this equation describes the acceleration on a free road: $1 - \left(\frac{v_\alpha}{v_0} \right)^\delta$. The desired acceleration (v_α), desired velocity (v_0) and factor δ describe how the acceleration behaves when a vehicle approaches the desired velocity.

The second term $\left(-a \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha} \right) \right)$ is a function of the gap (s_α) and speed difference (Δv_α) with a preceding vehicle and describes the deceleration when it approaches that vehicle. s^* is the desired gap as function of the velocity, acceleration and desired headway in seconds (T):

$$s^*(v_\alpha, \Delta v_\alpha) = s_0 + T v_\alpha + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}} \quad (3.2)$$

The actual IDM parameter values we used in our simulation are presented in Table 3.2. These values show to be robust and quite realistic [32].

As IDM is a free-flow model in which vehicles attain their desired speed while being influence by a preceding vehicle, this model is only applicable to platoon leaders and individual driving vehicles. The objectives of a following vehicle in a platoon are to keep a fixed headway instead of the desired speed. So, we need a different driver model for following vehicles in platoons.

parameter	value
Minimum spacing at stand-still (s_0)	2
Safe time headway (T)	1.8 s
Maximum acceleration (a)	0.73 m/s^2
Desired deceleration (b)	1.67 m/s^2
Acceleration component (δ)	4.0
Vehicle length (l)	5.0 m
Desired velocity	30 m/s

Table 3.2: Intelligent Driver Model parameters [32]

A second car-follow model we use in our simulation is a perfect model in which a vehicle adjusts its acceleration in order to keep headway of 10 meter. It is common to have headway that is dependent on speed, for example, the 2 second rule between manually driven vehicles. Some longitudinal controllers for platoons are however able to keep a fixed distance headway [5] and hence we use a model which keeps the headway at a fixed distance, independent of the speed.

In our ideal model, the speed of the platoon leader –which behaves according to the IDM model– results in an instant speed change of all other vehicles in the platoon. This model describes an ideal but not realistic behavior. It requires after all perfect communication of location, speed and acceleration of the platoon leader without any delay. We assume that such a model is good enough to compare our strategies under test.

Lane-Change model With our two-lane simulation scenario we also introduced the need for a lane-change model. We use a simple model in which vehicles are allowed to change lanes when this is physically feasible i.e. there should be enough space to host the vehicle on the next lane and a lane-change does not result in a crash. Once a vehicle is eventually allowed to change, the maneuver takes no time to be performed.

In reality, lane changing takes time and vehicle drivers usually take into account the speed of upcoming vehicles on the next lane. Despite that our model abstracts from these aspects, we expect that our lane-changing model resembles reality good enough to compare our formation strategies.

Modeling the Communication Channel

The *transient formation strategy* developed in Section 3.2 is dependent on inter-vehicle communication for the exchange of destination information and position of the last vehicle in a platoon. In this Section we focus on the performance evaluation on traffic so for the sake of simplicity we assume in

our simulation a perfect communication channel between all vehicles.

Traffic Simulator Implementation

The formation strategies under test have been evaluated in an own-implemented traffic simulator. Our traffic simulator has been written in the Java programming language and implemented the scenario and driver models described above.

Although we used continuous-time driver models to model the behavior of vehicles, our simulator was implemented as a discrete-time microscopic simulator for the sake of simplicity. This means that traffic state is simulated at small time intervals; in our implementation each 50 milliseconds. The assumption behind this decision is that driver behavior does not drastically change within this small time interval and so the impact on our results is limited.

The implementation of our traffic simulator has been verified for correctness by first analyzing the behavior of the traffic models in debug mode. For each model, the behavior was compared manually with the expected behavior as described in Section 3.3.1. Secondly, some of the simulation metrics were compared with statistical averages. For example, Section 3.3.2 shows average trip times, which are similar to the statistical average trip time.

Performance Metrics

In this section we present the simulation metrics and explain how we measure their values in simulation. These metrics aim to give insight in the operation of the formation strategies under test and allow us to draw conclusions regarding their performance.

Platoon Length The platoon length is measured as the number of vehicles in a platoon. The platoon length directly impacts the lane capacity: an increase of the platoon length leads to an increase of the lane capacity. The formation of large platoons is hence a desired property of a formation strategy and a measurement of the average platoon length provides a good indication of the performance.

In order to calculate the average platoon length, we measure for every second of a simulation run the total number of vehicles and platoons. Individually driving vehicles are counted as a platoon as well. The average platoon length for a simulation run r is then calculated as the sum of counted vehicles over the sum of counted platoons:

$$AvgPLLgth_r = \frac{\sum_{t \in T} \#vehicles_{r,t}}{\sum_{t \in T} \#platoons_{r,t}} \quad (3.3)$$

The number of vehicles in simulation run r at moment t is expressed as $\#vehicles_{r,t}$. Likewise, $\# platoons_{r,t}$ is the number of platoons in simulation run r at moment t and T is the set of all sample times.

The results show the calculated mean and 95% confidence interval over the 25 simulation runs.

Maximum Lane Capacity With this metric we aim to measure the effects of each formation strategy on the maximum lane capacity. This metric relates the average platoon length $AvgPlLgth$ and average vehicle speed ν in km/h to the maximum lane capacity C in $veh/ln/hr$ using the following equation [31]:

$$C = \frac{3600\nu AvgPlLgth}{3.6[(AvgPlLgth - 1)h + AvgPlLgth \cdot l] + T\nu} \quad (3.4)$$

Fixed parameters in this equation are the intra-platoon distance headway (h), vehicle length (l) in meters and the minimum distance between platoons (T) in seconds. The values in Table 3.2 for l and T are used in our simulation. Appendix C provides an elaborated explanation this equation.

The maximum lane capacity is calculated for each simulation run by taking its average platoon length and vehicle speed. The vehicle speed of a simulation run is derived from the experiments by measuring each second the speed. The sum of the vehicles speeds are divided by number of vehicles in order to get the vehicle speed at time t of simulation run r . The average speed of the simulation run is calculated with the following formula:

$$\nu_r = \frac{\sum_{t \in T} speed_{r,t}}{|T|} \quad (3.5)$$

The speed at time t for simulation run r is expressed by $speed_{r,t}$ and T is the set of sample times. The mean values and mean platoon length is used to calculate the maximum lane capacity. The results show the calculated average maximum lane capacity and 95% confidence interval for 25 the simulation runs.

The maximum lane capacity of Equation 3.4 should not be confused with the actual throughput. The throughput is the actual flow of vehicles and is dependent on the vehicle arriving rate and driver behavior whereas the lane capacity is the maximum capacity taking into account the average platoon length and speed.

Trip Time The trip time is the average time a vehicle takes to reach its destination from the start position. This implies for our simulation the average time between vehicle generation and the moment it reaches its destination. The metric hence consists of two factors: a) the on-ramp waiting time, which is the time it takes for a vehicle to merge with vehicles on the highway and b) the driving time, the total driving time.

The average trip time indicates how the stream of vehicles is flowing. In free flow, the average trip time is mainly influenced by the preferred vehicle speed. When the traffic flow is denser, the flow will be more disturbed by traffic jams and vehicles will drive slower. As a consequence, the average trip time is likely to increase.

In order to measure the average trip time, each vehicle v remembers its generation time. When the vehicle reaches its destination, the time difference is used to calculate the trip time. At the end of each simulation run, the average trip time for simulation run r is calculated over all vehicles with measured trip times in set V , using the following equation:

$$AvgTrpTime_r = \frac{\sum_{v \in V} TrpTime_{r,v}}{|V|} \quad (3.6)$$

$TrpTime_{r,v}$ expresses the trip time of vehicle v and simulation run r . The results show the calculate mean trip time and 95% confidence interval of the 25 simulation runs.

Platoon Ratio The platoon ratio is the ratio of the average time spent in a multi-vehicle platoon over the average trip time. This metric gives an insight into the effectiveness of the formation strategies under the simulated scenarios. Indeed, the higher the platoon ratio, the larger the part is that a vehicle spends driving in a platoon.

The platoon ratio provides insights, which do not become apparent with the average platoon length. For instance, a situation of two platoons with each two vehicles is similar in terms of the average platoon size to a situation with a three-vehicle platoon and an individual driving vehicle. However, the former situation is to be preferred in terms of fuel economy as the individual driving vehicle has no platoon benefits at all. The platoon ratio makes the difference between these situations apparent by comparing the platooning time to the trip time.

The platoon ratio is measured by keeping track for each vehicle the time it drives in a platoon. A platoon-timer is started as soon as a vehicle joins a platoon and stopped when it leaves a platoon. Note that a vehicle may join multiple platoons so the timer can be started and stopped multiple times. The platoon ratio is then calculated as the ratio of platoon-time and trip

time:

$$AvgPlatoonRatio_r = \frac{\sum_{v \in V} PlatoonTime_{r,v}}{\sum_{v \in V} TripTime_{r,v}} \quad (3.7)$$

Here, the $PlatoonTime_{r,v}$ and $TripTime_{r,v}$ are respectively the platoon-time and trip time of vehicle v for simulation run r . The results show the mean platoon ratio and 95% confidence interval of the 25 simulation runs.

Platoon Stability The final metric aims to measure the impact of formation strategies under test on the stability of a platoon. This instability is caused by composition changes of the platoon (see Section 2.2.2). So in order to evaluate the stability of a platoon we measure the number of vehicle maneuvers. For this reason, each simulated vehicle holds a counter $\#Disturbances$. For each vehicle maneuver, this counter is incremented for the particular vehicle.

The number of disturbances is obviously dependent on the number of vehicles on the road; the more vehicles, the higher the total number of disturbances. To be independent of the number of vehicles, we normalize the disturbances ($\#Disturbances$) for the number of vehicles. The average number of maneuvers per vehicle for simulation run r is calculated as follows:

$$AvgManeuversPerVehicle_r = \frac{\sum_{v \in V} \#Disturbances_{r,v}}{|V|} \quad (3.8)$$

The number of disturbances for vehicle v in simulation run r is expressed by $Disturbances_{r,v}$. The results show the calculated mean and 95% confidence interval of the 25 simulation runs.

3.3.2 Simulation Results

Using the simulation setup from the previous section, we are now able to simulate and compare the various platoon formation strategies. In this section we present the simulation results of the *transient formation strategy*, as developed in Section 3.2 and the identified strategies in the survey of Section 3.1.1.

The implementation of the transient formation strategy is based on the description of Section 3.2. Similar descriptions of the simulated Ad-Hoc, Sorted and Ranged formation strategies are given in Appendix B.

Apart from these formation strategies, we change the vehicle arrival rate in order to evaluate our strategies for changing traffic loads. The vehicle arrival rate is increased with steps of 100 vehicles per lane per hour

(veh/ln/hr), starting from 500 to 2500 veh/ln/hr. For each combination of strategy and arrival rate, 25 simulation runs were performed which last for 3600 seconds, excluding a startup time of 1250 seconds. The startup time assures that the first generated vehicle leaves the highway before we start the evaluation.

During each simulation run, the necessary statistics were collected in order to calculate the metrics of Section 3.3.1. The results are described for each metric in the following sections.

Platoon Length

The results of the average platoon length and its 95% confidence interval are illustrated in Figure 3.8. The confidence interval is in some cases hardly visible as the range is too small. For all performed experiments, the 95% confidence interval of the average platoon length is less than 1.2% of the mean values.

The most important observation from these results is that our transient formation strategy forms the largest platoons among all simulation formation strategies and arrival rates in this scenario. In fact, the transient formation strategy improves the average platoon length from 1.85 to 2.95 for an arrival rate of 500 veh/ln/hr. For the arrival rate of 2500 veh/ln/hr, the increase is from 5.3 for the ad-hoc strategy to 6.3 vehicles. The largest increase of 1.48 vehicles is achieved for an arrival rate of 1200 veh/ln/hr. This is an improvement of 49.4%.

These results show as well that the sorted and ranged formation strategy form average smaller platoons compared to the ad-hoc formation strategy. This result is explained by the fact that these implementations are equal to the ad-hoc strategy with restricting conditions on the formation. The ability to join a platoon in another lane does not seem to overcome these restrictions.

Maximum Lane Capacity

The maximum lane capacity results in Figure 3.9 show the best capacity results for the transient formation strategy. As the transient formation strategy forms larger platoons, this result was expected.

The capacity curve of the ad-hoc formation strategy shows an interesting result. The curve starts for the lowest simulated arrival rates at a capacity of 2777.6 veh/ln/hr which is closer to the capacity of the ranged formation strategy (2807.4 veh/ln/hr) than to the transient formation strategy (3581.3 veh/ln/hr). When the arrival rate increases, the capacity starts to approach the capacity of the transient formation strategy, even though the difference in platoon length is still significant for these arrival rates.

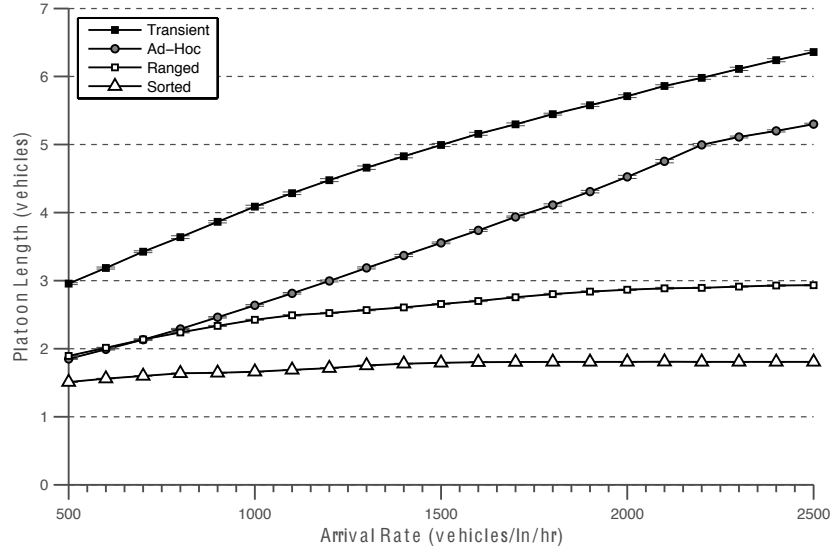


Figure 3.8: Influence of Arrival Rate on the Platoon Length

The maximum lane capacity of the sorted and ranged formation strategies cannot even nearly match the maximum lane capacity of the transient formation strategy. Especially when the capacity increases, the maximum lane capacity drops for the sorted and ranged strategies due to dropping average speeds.

The reason for this behavior lies in the asymptotic nature of the capacity. Take for instance a fixed vehicle population of X vehicles and an average platoon length of c vehicles/platoon. The number of platoons becomes, on average, X/c . The multiplicative inverse $\frac{1}{c}$ in this equation is the cause of the asymptote. An increase of the average platoon size from 1 to 2 has a much bigger reduction of platoons and hence an increase of capacity than, for instance, an increase from 5 to 6.

Trip Time

Our simulation results for the average trip time are illustrated in Figure 3.10. These results show a general behavior: the trip times stays relatively flat around a trip time of 375 seconds.¹ When the arrival rate increases, there is an arrival rate at which the trip time starts to increase.

¹The minimum trip time of approximately 375 does not stroke with an average trip length of 16km and preferred speed of 30 m/s. The geometric distribution we use for the destination results indeed in an expected trip length of 16 km. However, this holds for a highway with an infinite length. This is not the case in our simulations, which limits our average trip length to 11.250 meter. This explains the minimum trip time of 375 seconds at the preferred speed.

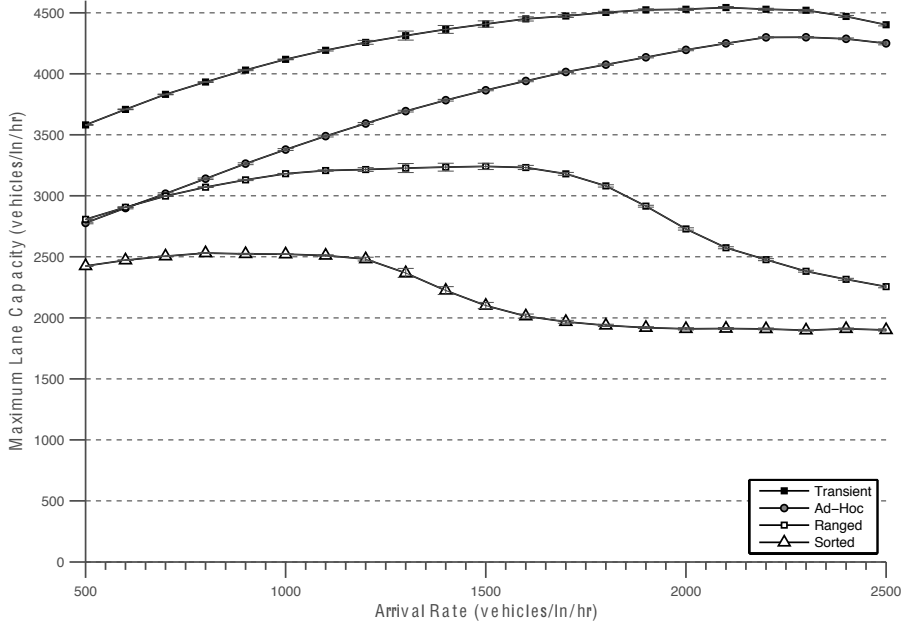


Figure 3.9: Influence of Arrival Rate on the Lane Capacity

The arrival rate at which the trip time starts to increase is significantly lower for the sorted and ranged formation strategies; respectively at 900 and 1100 veh/ln/hr. This arrival rate for the ad-hoc and transient formation strategy is less clear. Approximately for an arrival rate of around 2100 and 2300 veh/ln/hr the trip time starts to increase. Even though, it is clear that the transient formation strategy results in to the lowest trip time for high arrival rates.

Platoon Ratio

Affiliated to the trip time is the platoon ratio, which relates the platooning time to the average trip time. Higher ratios are obviously more beneficial as it indicates that vehicles drive for a larger part of their trip in a platoon.

The average platoon ratios for the simulated formation strategies and their corresponding 95% confidence interval of are illustrated in Figure 3.11. The calculated 95% confidence interval was for all experiments smaller than 5.7% of the calculated mean values. We observe a general trend of increasing average ratios for all formation strategies. Higher arrival rates correspond to higher vehicle densities, which make it easier and quicker to form platoons.

The platoon ratios increase up to a certain arrival rate value after which the ratio drops. The arrival rate, at which the ratio drops, largely corresponds to the increase in trip time. The trip time is hence most likely the main cause of the drop.

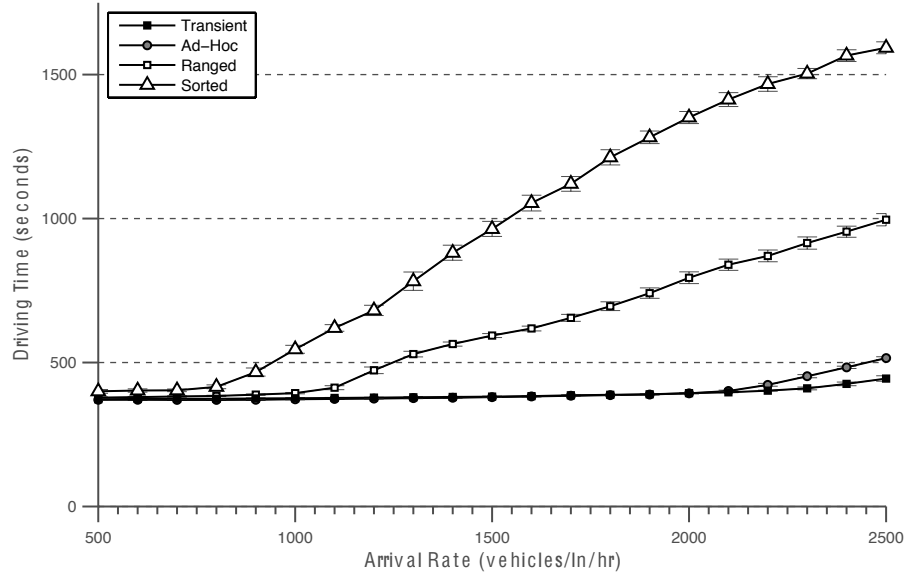


Figure 3.10: Influence of Arrival Rate on the Trip Time

In Figure 3.11 we see that the highest platoon ratio is overall achieved by the transient formation strategy. Especially for the lower arrival rates, the increase is significant. For example, the transient formation strategy achieves for an arrival rate of 500 veh/ln/hr a ratio of 92.6%; an improvement of 15.1% compared to second best strategy.

The second best performing strategy is the ad-hoc approach. For increasing arrival rates, the ratio of the ad-hoc strategy starts to approach the transient formation strategy. The difference is minimized to 1.7% for the arrival rate of 2000 veh/ln/hr.

For even higher arrival rates, the platoon ratio of the ad-hoc formation strategy drops before the transient formation strategy does. This is likely caused by smaller trip times for the highest simulated arrival rates.

Platoon Stability

The stability of a platoon, measured by the average number of maneuvers per vehicle trip, is illustrated in Figure 3.12. The results show that the transient formation strategy increases the number of maneuvers during a trip, compared to the other simulated formation strategies.

For the lowest, simulated arrival rate, the difference with the second-worse strategy – the ranged formation strategy – is 0.1 maneuvers. At the same time, the ad-hoc formation strategy performs best with 1.6336 maneuvers; 0.2 maneuvers on average less than the transient formations strategy.

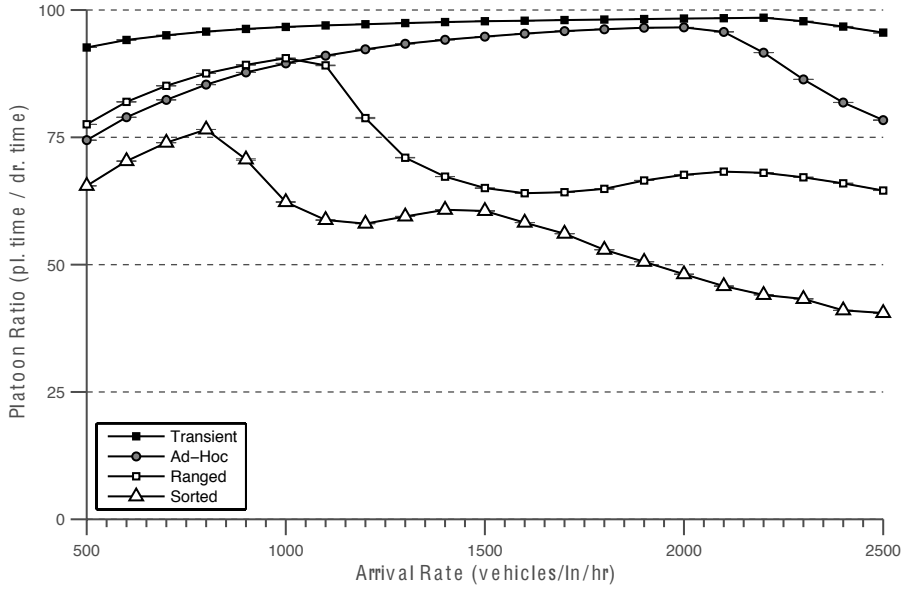


Figure 3.11: Influence of Arrival Rate on the Platoon Ratio

As soon as the arrival rate increases, we see an increase in the number of maneuvers for all simulated strategies. The curve of the transient formation strategy stays relatively flat –1.83 maneuvers against 1.90 maneuvers for arrival rates of respectively 500 and 2500 veh/ln/hr– whereas the curve of the ranged and ad-hoc formation strategies approaches the transient formation strategy curve. The stability impact by the transient formation strategy is hence comparable to the ad-hoc and ranged formation strategy for higher, simulated arrival rates. Only the sorted formation strategy has a notable lower impact on the platoon stability.

Although an increase of 0.2 maneuvers, as mentioned before, seems relatively small, one has to remind that this increase accounts to every vehicle. The increase in the total number of maneuvers is more significant and impacts safety.

3.4 Conclusions

We conclude that the transient formation strategy improves the platooning benefits over existing formation strategies in our simulated scenario. The average length of a platoon is increased by the transient formation strategy, which results in an increase of the highway capacity.

The transient formation strategy especially improves the highway capacity for the lowest arrival rates. This is confirmed by a higher platoon ratio, which indicates that vehicles can more easily form platoons at those rates.

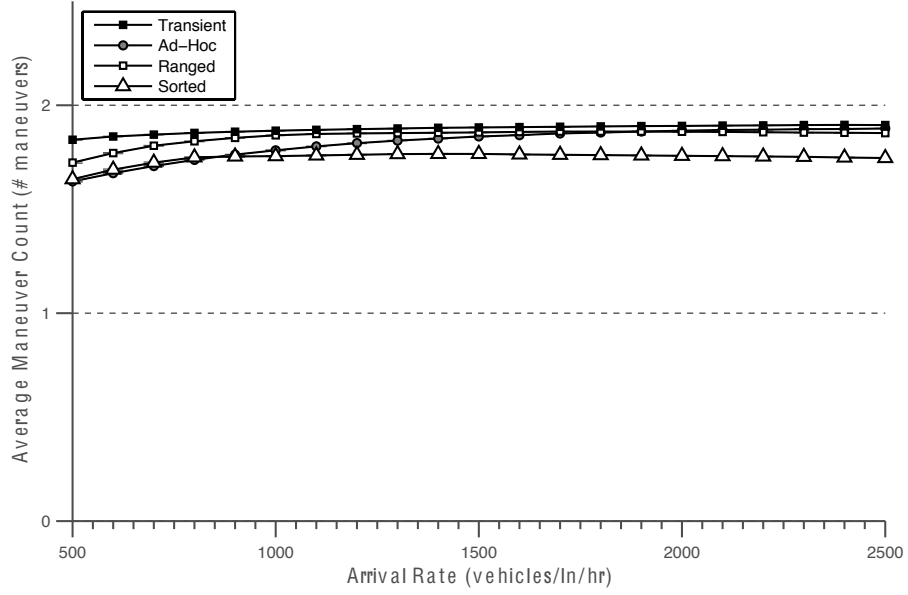


Figure 3.12: Influence of Arrival Rate on Platoon Disturbances

However, the transient formation strategy turns out to be advantageous at higher arrival rates as well. This strategy results in the lowest average trip time under congested situations. This result is achieved for a slight increase in the number of maneuvers to be performed by each vehicle.

We simulated the formation strategies on a 2-lane highway scenario. The strategies are however not limited to this scenario and can work on roads with more lanes. The impact of a highway with more lanes on our simulation metrics cannot be derived from our results. More lanes means more potential to form platoons but traffic might be more disturbed if vehicles are crossing multiple lanes. A challenge in deploying the transient formation strategy lies in the negotiation between vehicles to keep disturbances of lane change to a minimum; especially in scenarios with multiple lanes.

In our simulations, we made the assumption of a perfect communication channel between vehicles. This channel is used by the platoon formation strategy to keep a perfect headway as well for the coordination between vehicles of maneuvers.

This assumption of a perfect communication channel is obviously unrealistic. The reliability and latency of communication between cooperating vehicles is influencing the performance of the transient formation strategy. So in the next chapter we develop a method to improve the reliable communication between cooperating vehicles.

Chapter 4

Reliable Multicast Communication for Vehicle Platoons

In this chapter we develop a method to improve the reliability of inter-vehicle communication for the *transient formation strategy* as developed in Section 3.2. This method aims to lower the impact of the imperfect communication channel on the performance of our formation strategy.

Section 4.1 starts with an analysis of the transient formation strategy for its information requirements. This identifies the need to exchange information between vehicles in a platoon. For this reason we introduce in Section 4.2 wireless communication for platooning and describe how some information requirements are already fulfilled by existing solutions. Section 4.3 describes the development of a protocol to improve the reliability of inter-vehicle communication in platoons. Two enhancements of the protocol are finally described in Section 4.4.

4.1 Information Requirements Analysis

This section analyses the information requirements of the transient formation strategy. This analysis is based on the state diagram in Figure 3.6 and corresponding description in Section 3.2.

Accordingly, the following information needs were identified:

Position and Destination of the Ego-Vehicle: The position and destination of the ego-vehicle are used to determine whether the destination is reached. This information can be provided by respectively a Global Positioning System (GPS) and navigation device. A driver can register its destination in the navigation device while GPS measures the

ego-vehicle's position. Both devices are so common nowadays that we assume their availability;

Role of Ego-Vehicle: The role of the ego-vehicle (i.e. platoon leader or follower) affects its state. So up-to-date information about the vehicle role is essential for the operation of the *transient formation strategy*. A preceding vehicle can be detected by combining front-radar and wireless received information. The same approach can be used to detect a succeeding vehicle if a rear-radar available and the range of rear-radars is sufficient;

Destination of Other Platoons in Neighborhood: The destination of a platoon is equal to the destination of the leader for the transient formation strategy. The destinations of all surrounding platoons are used while searching for a platoon;

Position of last Vehicle in a Platoon: The position of the last vehicle determines the location where a vehicle joins a platoon;

Destination of the Platoon Leader: This affects all following vehicles in the particular platoon whether they are temporarily or permanently following the platoon. Each vehicle joining a platoon first of all needs such information. Second of all, a change of platoon leader and corresponding destination may happen. When such event happens, the updated platoon destination needs to be communicated to all following vehicles in the platoon.

Apart from the position and destination of the ego-vehicle, all other information should be shared among the vehicles in order to execute the transient formation strategy. The need for wireless communication is apparent. However, the communication in platoons is likely not limited to communication for the transient formation strategy alone. In the next section we describe how wireless communication can support basic control functions of platooning and how it can fulfill some of our information requirements.

4.2 Wireless Communication in Vehicle Platoons

In Section 2.2.2, we identified the basic control functions of vehicles in platoons as being longitudinal, latitudinal and maneuver control. Especially automated longitudinal controllers can increase the highway capacity considerably [17, 15]. Current and near future platooning systems like Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) only automate longitudinal. Full-automated vehicles as in Automated Highway System (AHS) are expected in the long term. So in this section we focus

the overview of wireless communication for longitudinal control.

Considerable effort has been carried out in the design of strategies for longitudinal platoon control. These strategies control basically the speed and acceleration of each individual vehicle. Important for these strategies is to address the problem of string stability: the problem where a disturbance of the head vehicle leads to the propagation or amplification of a heading error, down the platoon [5].

The need for wireless communication in a platoon has become apparent by a study of Swaroop and Hedrick [5]. They analyzed the ability of some vehicle following strategies to keep string stability under constant spacing. A subset of the analyzed strategies is illustrated in Figure 4.1. As it turns out, only when the position, speed and acceleration of the leading vehicle is used as reference information, one can achieve strong string stability. But having just this information about the leading vehicle is not safe. One also needs the position, speed and acceleration of the immediate preceding vehicle.

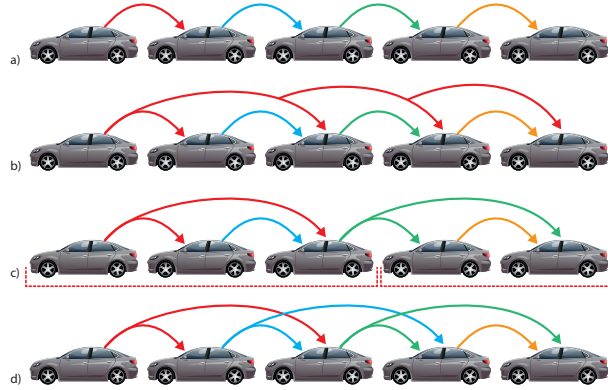


Figure 4.1: Platooning Strategies a) control with preceding vehicle information b) control with leading and preceding vehicle information c) Mini-Platoon Control d) Control with Information of $R (=2)$ preceding vehicles

In traditional control strategies, the information exchange is uni-directional i.e. a following vehicle is only influenced by one or more preceding vehicles. A complete view of the platoon composition is hence not needed.

A more recent development, proposes a strategy in which the platoon is modeled as *one* dynamic system. In this case, the control algorithm in a particular vehicle takes into account the position, speed and acceleration of all other vehicles in the platoon. So also its followers influence the lead vehicle. This strategy results in a more stable platoon [18].

Under the assumption that a platoon is limited in size and each vehicles in a platoon falls within the transmission range of all other vehicles, a method of communication would be to broadcast a vehicle's position, speed and acceleration periodically. Bi-direction communication in a platoon could

however increase the flexibility and cooperation within a platoon [26].

A protocol for bi-directional communication for cooperative vehicle platooning has been proposed Onishi et al. in [26]. The protocol is characterized by the grouping of acknowledgements to improve efficiency. The protocol firstly acts like a normal uni-directional protocol: it requires all vehicles in a platoon to broadcast their position, speed and acceleration. The received information during each cycle is used by the platoon leader to determine the composition of the platoon. This view is then piggybacked onto its transmission such that all vehicles in the platoon can update their view as well.

The platoon composition is subsequently used at each vehicle to record (negative) acknowledgements: if a vehicle has received the transmission of other vehicles in the platoon, the acknowledgement is stored instead of being sent immediately. The platoon composition view plus (negative) acknowledgements of the previous cycle are piggybacked onto the transmission of each vehicle.

As opposed to the basic way of acknowledging –sending an acknowledgements for each received transmission–, this protocol is more efficient. The downside is the increased packet size, especially when large vehicle identifiers are used. Take for example a platoon of 5 vehicles using 16 bit identifiers. This adds to the transmission at least 80bit for the platoon composition and 5 bit for Acknowledgements (ACKs). To address this problem, a method has been described in [26] to shrink the identifiers to 4 bits and to resolve conflicts.

The protocol by Onishi et al. in [26] can fulfill some of the information requirements of the transient formation strategy like position of each vehicle and platoon composition. The need to disseminate the destination of a platoon still has to be addressed though. In the next section, we will develop a method to disseminate the destination of the platoon leader to all following vehicles in a platoon.

4.3 The Cooperative Acknowledgements-Protocol

The analysis in 4.1 and survey in 4.2 have identified the need for multicast-communication to support the transient formation strategy. In this section, we develop such a protocol.

Our protocol is based on the following two assumptions:

1. All vehicles in a platoon are within each other's transmission range. In Section 3.3.1 we have seen that the length of a platoon is roughly limited between 2 and 7 vehicles. With an average inter-vehicle headway of 10 meter and an average vehicle length of 5 meter, the length of the platoon is well within the assumed transmission range of 250 meter;
2. Platoons drive in fixed formation for a longer period of time. Although *relative* speeds in a Vehicle Ad-Hoc Network (VANET) are usually high, platoons are a special case with relatively low mobility.

The idea is to improve the reliability of multicasting in vehicle platoons, based on the cooperative delivery of acknowledgements. Vehicles can transmit their own acknowledgement plus received acknowledgements from all other vehicles in the platoon. When an ACK was not received, for example because of a packet-collision, another vehicle can forward and deliver the acknowledgement anyway.

Figure 4.2 illustrates our idea with a simple example: vehicle A transmits a payload to destination-vehicles B and C. Vehicle C replies but its acknowledgement is only received by vehicle B. Vehicle B also replies with its acknowledgement plus the one received from vehicle C. So in the end both acknowledgements are received by vehicle A.

Without the forwarded acknowledgement, vehicle A should have performed a retransmission. This shows how our Cooperative Acknowledgements (COACK)-protocol can improve the reliability and delay of communication.

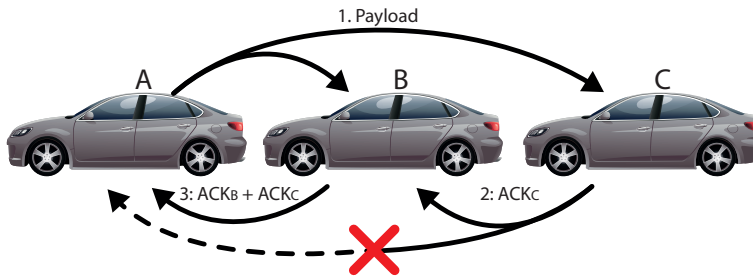


Figure 4.2: Forwarded Acknowledgement to Improve Delivery

Our idea differs from Onishi et al. [26] as we aim to piggyback overheard acknowledgements redundantly in order to improve the reliable delivery of

acknowledgements. Acknowledgements in our idea are hence transmitted from multiple destinations to one source. In the example above, vehicles B and C aimed to acknowledge to vehicle A.

Onishi et al. do not aim to improve reliability but more for grouping of acknowledgments in order to limit the number of transmissions and hence overhead. Their acknowledgements are used for feedback about the communication link and enables the lead vehicle to update to set of vehicles in a platoon.

Cooperative Acknowledgements Roles

We identify three roles from the example in Figure 4.2:

Source-Role: The vehicle starting the multicast, or *notification*, has the source role. In our example, the lead vehicle is the source but basically any vehicle can start to transmit a notification.

Forwarder-Role: All other vehicles in the platoon are forwarders for the particular notification. Their goal is to forward all received acknowledgements.

Destination-Role: The destination of a transmitted notification. A destination acts as a forwarder too but not all forwarders are by definition a destination. The difference is that a destination *creates* an acknowledgement when payload is received.

Please note that the role of a vehicle is different per notification. A vehicle may be the source of a notification while being a destination for another one.

Cooperative Acknowledgements Protocol Data Unit

A source wants to address multiple destinations and a forwarder wants to transmit an ACK for each destination. A regular IEEE802.11 frame-header has no such facility. So instead we have defined our own Protocol Data Unit (PDU) structure as illustrated in Figure 4.3 which is meant to be encapsulated inside a Institute of Electrical and Electronics Engineers (IEEE)802.11 Medium Access Control (MAC) frame. The IEEE802.11 frame requires no changes as the COACK-PDU is considered to be a payload of the MAC frame.

The COACK-PDU is used by all vehicles (i.e. source, forwarder and destination) vehicles and consists of a 32-bit platoon identifier and 8-bit vehicle identifiers. We use these small pseudonyms instead of a larger identifier like the 48-bit MAC address, to limit the PDU size. The size increases in the end with the number of destinations and identifier size.

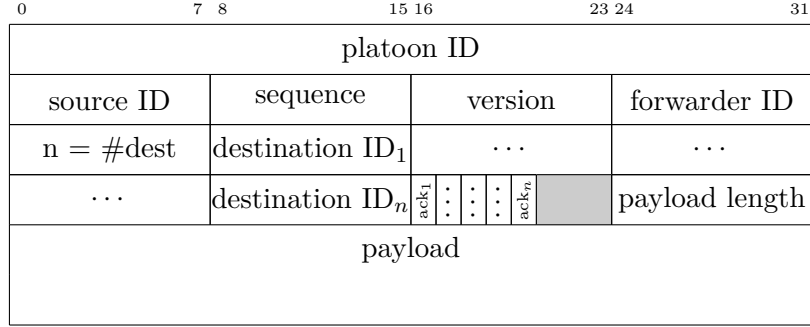


Figure 4.3: Cooperative Acknowledgement PDU

A prerequisite for this decision is the existence of a mechanism to assign and resolve conflicts between platoon and vehicle identifiers. A feasible mechanism for 4-bit vehicle identifiers has been described by Onishi et al. in [26]. So we consider this topic out-of-scope and assume a more conservative size of 8-bit vehicle identifiers.

The PDU contains in addition an array of ACK-fields; one bit per destination. The value 1 indicates an ACK while 0 means an unknown or no ACK.

The COACK service is provided on top of the MAC-layer but unlike the *Network Layer* of the Open System Interconnection (OSI) model, the COACK service provides no connectivity between multiple networks. Instead we consider the COACK service as an extension of the MAC-layer as illustrated in Figure 4.4.

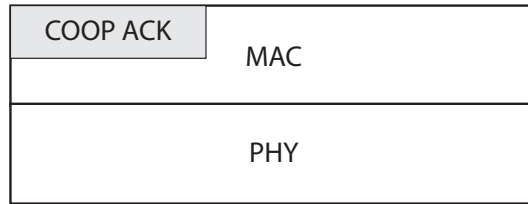


Figure 4.4: Cooperative Acknowledgements Protocol Architecture

COACK protocol description

Transmission of Notification by a Source

The transmission of a notification starts at the source-vehicle after a request by the upper layer. This request consists of the destination list and payload to be transmitted. As illustrated in Figure 4.5, the sender spawns a thread to handle the request and generates a notification-PDU.

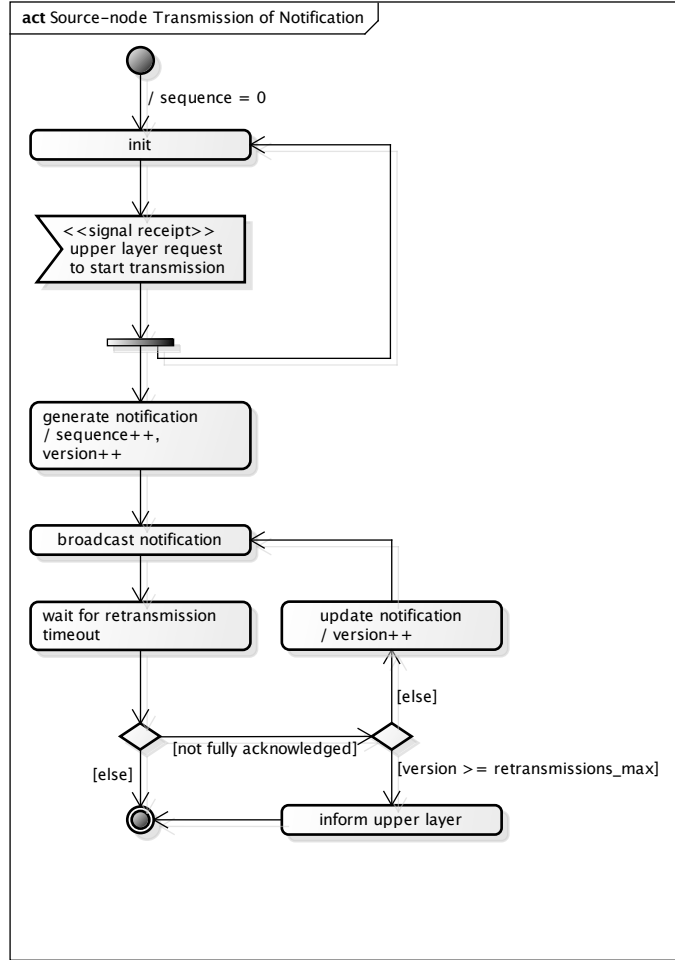


Figure 4.5: Transmission of COACK-notification by Source-Vehicle

The source, forward and platoon identifiers of the source-vehicle are set in the appropriate fields of the notification-PDU. The *version* and *sequence*-fields are set furthermore to respectively 0 and the next sequence number. Finally the *destination* and *payload*-related fields are set according to the upper layer request.

The generated notification-PDU is then broadcasted and a thread waits for a retransmission-timeout. This sequence continues until all destinations have acknowledged or the maximum number re-retransmission has been reached. Figure 4.6 illustrates the internal state of a source-vehicle for a particular notification just before retransmission. In this example, no acknowledgment was received from vehicles D to F so the source-vehicle will retransmit the notification with an increased version number and updated destination list. There is after all no need to include destinations B and C and related acknowledgement-fields.

	source: A sequence: 1 version: 1				
Nodes	B	C	D	E	F
Destinations	✓	✓	✓	✓	✓
Acknowledgements	Ack	Ack			

Figure 4.6: Retransmission State of Source-Vehicle

The upper layer is in the end informed of a failed multicast when the maximum number of retransmissions has been reached and some destination did not acknowledge.

Reception of a Notification

A received notification is first checked for its relevancy. A vehicle is basically just interested in notifications from the same platoon. So only notifications with a *platoon identifier* equal to the receiving vehicle's platoon identifier are processed. The complete processing of a received notification is shown in the activity diagram of Figure 4.7.

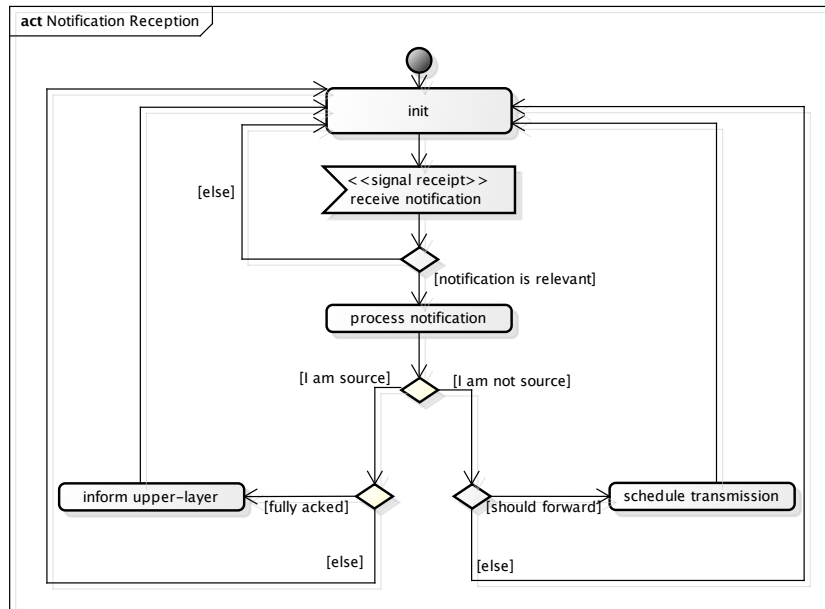


Figure 4.7: Reception of a COACK-notification

For each relevant notification, identified by the tuple $\langle \text{Platoon ID}, \text{Source ID}, \text{sequence} \rangle$, the following information is stored:

Destinations: Set of destinations for a particular notification.

Version: The latest version number of the destination set. It is use to detect a received update of the destination set.

Acknowledgements: Received acknowledgements and related destinations.

This information is updated in the *process notification*-state in the following order:

1. The destination set and version are updated when the notification is received for the first time or contains a larger *version* than stored;
2. Received acknowledgements and corresponding destinations are stored in the list of *Acknowledgements*;
3. An acknowledgement is stored for itself if the receiving vehicle is a destination and payload is received for the first time.

To understand better how a notification is processed, we consider the internal state of vehicle E in the *before*-state of Figure 4.8. It has apparently received notifications before, including acknowledgements of vehicles C and D.

	<div>source: A</div> <div>sequence: 1 version: 1</div>				
Nodes	B	C	D	E	F
Destinations	✓	✓	✓	✓	✓
Acknowledgements		Ack	Ack		

----- before -----

after

	<div>source: A</div> <div>sequence: 1 version: 2</div>				
Nodes	B	C	D	E	F
Destinations			✓	✓	✓
Acknowledgements		Ack	Ack	Ack	

Figure 4.8: State changes after reception of a COACK-notification

Imagine now that vehicle E receives a retransmitted notification from source-vehicle A. This notification contains an updated destination set –we assume vehicles D, E and F–, an increased version and the payload. As the version is increased, vehicle E first updates its destination set: vehicle B and

C are removed. Next, the notification is checked for new acknowledgements but none are found – a retransmission contains by definition no ACKs. Then finally, an ACK is stored for destination-vehicle E as payload was received for the first time. All these state changes are reflected in the *after*-state of Figure 4.8.

The next step after processing a notification is role dependent. A source-vehicle checks whether acknowledgements for all destinations were received. If so, the transmission was successful and upper layer is informed. A forwarder-vehicle will decide whether to rebroadcast a notification with all relevant ACKs. The transmission is scheduled when the following criteria apply:

1. The received notification was new or an update;
2. An ACK is stored for at least one destination:
 $\exists d \in Destinations : Acknowledgements[d] = Ack;$
3. No other transmission is scheduled.

The first rule limits the number of transmissions per forwarder; at most one transmission per received update. The second rule limits to forward only when ACKs are known for destinations. This can either be its own ACK or an ACK from another destination. It could happen after all that a notification is received from the source but receiving node is not a destination. This node would not have any stored ACKs and it would be useless to schedule a transmission. The third rule allows scheduling only one transmission at the same time.

For vehicle E in our example, at least the first two criteria apply: the version number is increased which indicates an update and an ACK is stored for vehicle E. If also no other transmission was schedule then all criteria apply and a transmission is scheduled.

Transmission Timer A notification is however not sent immediately when these criteria apply. The transmission is delayed by means of a transmission timer.

Such a timer affects directly the delay at which the overall multicast is a success or a failure. One can expect a higher overall delay, compared to an approach of immediate transmission. We believe however that a transmission timer can improve the reliability of the COACK-protocol for two reasons:

1. Varied timeouts can break synchronized transmissions. Vehicles that reply instantly will transmit at almost the same time. This can lead to higher contention or more collisions;

2. Varied timeouts can lead to more forwarded ACKs. A vehicle can receive and forward ACKs that were received while waiting for timeout.

The overall delay is not only impacted by delayed transmission but also by the reliability. The higher the reliability, the less retransmissions are needed for a successful multicast. This makes the overall delay of COACK-protocol an interesting metric to evaluate.

Now the question arises how to use the transmission timer; what timeout each vehicle should use? We use a method that takes into account the distance between forwarder and source-vehicle. This idea is based on the assumption that a transmission between closer vehicles is more likely to succeed. So a vehicle closer to the source-vehicle is better in forwarding ACKs and should wait for a longer period in order to forward more ACKs.

Our method takes also into account the added value of a transmission. Let's assume a source waiting for 5 ACKs and a far vehicle that can forward all 5 ACKs. The transmission of this vehicle has more added value than a closer vehicle with only one ACK. We give the far vehicle a smaller transmission timer.

We propose the following equation to calculate the transmission backoff time:

$$T = \frac{T_{max}}{2} \left(1 - \left| \frac{ACK_s}{D} - \frac{d}{d_{max}} \right| \right) + \frac{T_{max}}{2} \left(1 - \frac{d}{d_{max}} \right) \cdot \left(1 - \frac{ACK_s}{D} \right) \quad (4.1)$$

T	Calculated backoff time
T_{max}	Maximum backoff time
ACK_s	Number of stored ACKs for destinations
D	Number of destinations
d	Distance to source-vehicle
d_{max}	Maximum distance between any forwarder and source-vehicle

To comprehend the backoff times using this equation, we have visualized them in Figure 4.9 for a maximum backoff time T_{max} of 100 ms. The z-axis represents this backoff time while the other two axis represent the distance ratio to source (d/d_{max}) and relevance ratio (ACK_s/D).

For the lower relevance ratio, the backoff time is inversely proportional to the distance ratio. In other words, in situations in which vehicles have a low number of ACKs to transmit, the farthest vehicle transmits earlier. At the other extreme with a high relevance ratio, the backoff becomes proportional to the distance ratio. So a vehicle with many ACKs transmits earlier when it is closer to the source-vehicle compared to a farther vehicle.

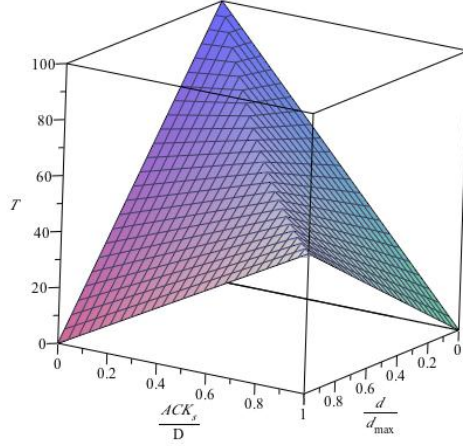


Figure 4.9: Backoff-Times for COACK-protocol ($T_{max} = 100ms$)

Transmission of Notification by a Forwarder-Vehicle

When the transmission timer ends, a forwarder-vehicle forwards the notification. This behavior is illustrated in Figure 4.10.

When the notification-PDU is constructed, the *platoon ID*, *source ID*, *sequence* and *version*-fields are set equal to the last received notification. Also the stored destinations and their acknowledgements are used to construct the notification. Each stored destination and corresponding ACK (or empty value when no ACK is received) is added to the PDU. No payload is added.

In the case of our example, a notification is constructed by vehicle E with vehicles D, E and F as destination and corresponding acknowledgements (assuming no other notifications were received).

After construction, the notification-PDU is broadcasted.

4.4 Improving the Cooperative Acknowledgments-Protocol

In the previous section, we have introduced a simple protocol called COACK. This protocol aims to improve the reliability of multi-casting inside vehicle platoons. The idea of the protocol is to improve reliability by letting vehicles forward acknowledgements of other vehicles in the platoon.

The reliability of a transmission is not only influenced by the reliable

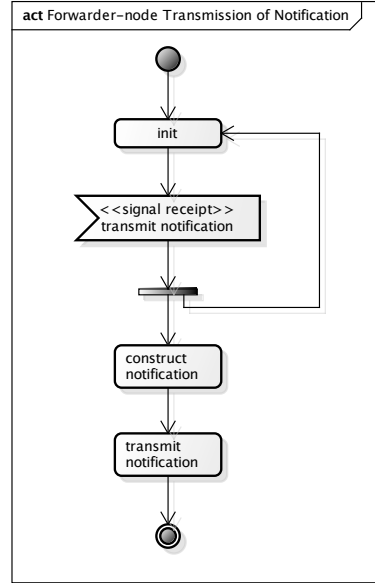


Figure 4.10: Transmission of COACK-Notification by Forwarder-Vehicle

delivery of ACKs. The payload should also be delivered to all destinations. With our COACK-protocol, the source-vehicle is the only vehicle sending data. If a destination fails to receive this transmission, no ACK is created and no cooperative forwarding of ACKs can improve the reliability.

In the next two sections, we propose two methods to improve the basic COACK-protocol. The first method tries to improve the reliability of data delivery. The second enables the quick retransmission of ACKs when the source fails to receive the ACKs.

4.4.1 Data Forwarding

In order to improve the delivery of data in the COACK-protocol, we apply the same principle as we used to improve the delivery of ACKs. All vehicles in the platoon may help to forward the payload to destinations. We call this approach COACK with *data forwarding*.

To illustrate the principle, we take the platoon in Figure 4.11 as example. Imagine that vehicle A transmits a notification, which is destined for vehicles C and D, but only vehicle C receives it. With the COACK-protocol, vehicle C will retransmit the notification with its ACK but without payload. Vehicle D will not receive the payload until vehicle A retransmits the original notification. With *data forwarding*, vehicle C forwards the payload as part of the transmitted notification. If this notification is received by vehicle D, it receives the payload before the retransmission of vehicle A.

Vehicle C can forward the payload until all destinations are reached but

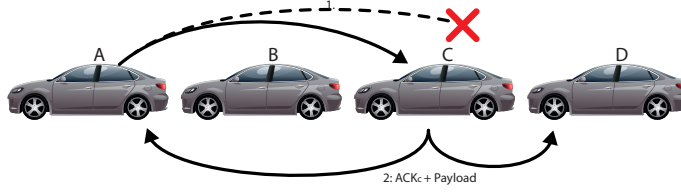


Figure 4.11: Forwarding of Payload to Improve Delivery

this can get expensive when many vehicles are forwarding. Especially because payload is in general larger in size than an ACKs. So it is important to limit the number of forwards in a smart way.

Our approach is to exploit the structure of a platoon –a string of vehicles in a certain order– to assume a correlation between a received transmission and the same reception by all vehicles in between the source and receiving-vehicle. For example, when vehicle C in Figure 4.11 receives the transmission of vehicle A, it may assume that vehicle B also received it but not vehicle D.

With *data forwarding*, a notification is received via one or more forwarders. Each of these forwarders can also apply our correlation. If we combine all these assumptions, it turns out that we can assume that all vehicles in between the notification-source and receiving vehicle have received the notification. If vehicle D in Figure 4.11 receives a notification with payload, it can assume the reception of payload by vehicles A to D. It turns out this statement holds for an independent number of forwarders and their position in the platoon (see Appendix E).

Unfortunately, our correlation does not always hold. The success of a transmission depends on the received signal at each receiver. A signal may collide at vehicle C with the transmission of vehicle A but that signal may be too weak to collide at vehicle D. A source-vehicle can therefore not use our correlation. It should judge the success of a transmission purely on received ACKs. Instead, we use our correlation just to limit the number of payload-forwards.

We can take our correlation even one step further. If a vehicle knows which other vehicles in the platoon have received the payload, it can apply the correlation also for all these vehicles.

In order to detect which other vehicles have received the payload, we have two indications:

Received ACKs: A received ACK indicates that a destination-vehicle has received the data.

Received Notification with Payload: Non-destination vehicles do not send ACKs so the only indication is a direct received notification with

payload.

The COACK-protocol already stores received ACKs. The only extra effort is to record from which vehicles a notification with payload was received. In order to do so, we reuse the internal storage of the COACK-protocol (see Figure 4.6).

In Figure 4.12 this is illustrated for a vehicle that received a notification with payload and an ACK from respectively vehicle B and F. Based on this information, this vehicle assumes that vehicles B to F have received the notification with data (illustrated by the grey-colored boxes).

<div>source: D</div> <div>sequence: 1 version: 1</div>							
Nodes	A	B	C	D	E	F	G
Destinations	✓	✓	✓		✓	✓	✓
		Pld		Src		Ack	

Figure 4.12: Stored Information for the COACK-protocol with Data Forwarding

The implication of our assumption is that the range of grey boxes, expands from the source-vehicle to both ends of the platoon. A received ACK from vehicle E does not expand the range in our example while an ACK of vehicle G does.

In order to limit the number of data-forwards, only vehicles at either end of the range are allowed to forward the payload. These vehicles are after all closest to the destinations that have (presumably) not yet received the payload. Only when the following rule applies, a vehicle will transmit the payload:

There exists a destination that (the ego-vehicle assumes) has not received the payload and the distance ¹ between the ego-vehicle and the destination is smallest among all other vehicles that (the ego-vehicle assumes) have received the payload.

Our assumed correlation does not always hold, as explained in this section. As a result, a forwarder may wrongly assume the reception of payload by other vehicles and may neglect to forward the payload. The forwarding of payload is in such situation less effective than possible.

4.4.2 Quick Retransmission of Acknowledgements

The COACK-protocol in Section 4.3 already aims to improve the delivery of ACKs. This is achieved by having multiple vehicles forwarding ACKs.

¹The distance is the difference in position in the platoon (e.g. the distance between vehicle 2 and 4 in Figure 4.12 is 2)

Whether the ACK is really received by the source-vehicle is however not guaranteed. Only after a certain delay, when the source retransmits the notification without the ACK's vehicle as destination, it can be concluded that the ACK was received.

In this section we describe a method to predict whether a transmitted ACK was *not* received by the source-vehicle. In order to do so, we reuse of the correlation of Section 4.4.1. Take for example the platoon in Figure 4.11 and assume that vehicle D transmits an ACK. If source-vehicle A receives this ACK then vehicle C should have received it as well, according to our correlation. If vehicle D however receives a notification without its ACK from vehicle C, this indicates that the ACK was never received by vehicle A either.

In order to detect this situation, a forwarder vehicle checks a received notification for the following criteria:

- The transmitted vehicle is located in between the ego-vehicle and source-vehicle;
- The received notification contains a destination without an ACK while the ego-vehicle has stored an ACK for that particular destination.

Only when another transmission was not already scheduled and all criteria apply, a new transmission is scheduled according to the rules of the COACK-protocol. This functionality is highlighted in Figure 4.13 as extended handling of a received notification (see Figure 4.7).

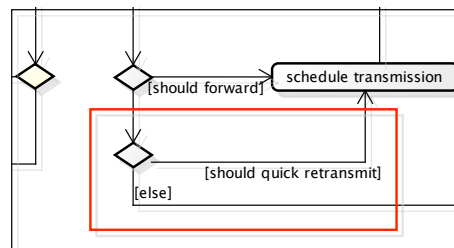


Figure 4.13: Quick Retransmission of ACKs after Reception of Notification

Our assumed correlation does not always hold, as explained in Section 4.4.1. An ACK can be considered not to be received by the source-vehicle while in fact it was. The result is unnecessary retransmissions of notifications.

Chapter 5

Evaluation of the Protocols

In the previous section, the design of the Cooperative Acknowledgements (COACK)-protocol and two enhancements –*data forwarding* and *quick retransmission of acknowledgements*– were described. Based on these descriptions, the protocols were implemented in a network simulator.

The simulated scenario and implementation in a network simulator are described in respectively Sections 5.1 and 5.2. The goal of this simulation is to evaluate the performance of our methods by means of the performance metrics of Section 5.3. The results in Sections 5.4, 5.5 and 5.6 describe respectively the influence of the vehicle traffic density, platoon length and payload size on the performance metrics of the protocols under test. In Section 5.7 the simulation is evaluated and finally conclusions are drawn in Section 5.8.

5.1 Simulation Scenarios

In our simulation study we compare the COACK-protocol of Section 4.3 and the COACK-protocol with *data forwarding(df)* and *quick retransmission of acknowledgements (gra)* of Section 4.4 against a basic approach. The basic approach is an implementation of a stop-and-wait Automatic Repeat-Request (ARQ) in the source-vehicle broadcasts a packet and waits for acknowledgements. Please note that these acknowledgements are part of the stop-and-wait ARQ and not layer-2 Acknowledgements (ACKs). If the acknowledgements are not received in time from all destinations, the notification is retransmitted. Despite the fact that a Stop-and-wait ARQ is a basic protocol, it can assure that packets are received.

Our test setup is a 1 km long stretch of highway with six lanes. Vehicles in the first three lanes are formed in platoons. Vehicles on the other three lanes are positioned with equal headways. The actual headway depends on the traffic density. In order to evaluate the performance of the protocols under test, we change first this traffic density; second the platoon length

and finally the payload size.

For each simulated scenario we run the simulation 50 times. During each run, the head of a platoon initiates 10 notifications. The average results of the simulations are plotted along with the 95% confidence interval of the result.

All vehicles in our simulation are non-mobile i.e. their position is fixed for a particular simulation run. This corresponds to low relative speeds in platoon. High mobility is expected to have limited impact on the results. After all, the protocols under test are used for inter-platoon communication.

5.2 Protocol Implementations in NS-3

The protocols under study have been implemented in ns-3 [1]. NS-3 is a discrete event network simulator that is open source and provides simulation modules for Internet protocols, ad-hoc and wireless networks. The simulator has been implemented in C++ and Python and provides a framework to build and analyze communication protocols.

The basic computing device used in ns-3 is called a node. Just like a normal computer, one can add peripheral devices and protocols stacks to a node. For our evaluation, we used nodes to represent vehicles. Each node was installed with a peripheral device operating the Institute of Electrical and Electronics Engineers (IEEE)802.11p protocol at 5.0Giga Hertz (GHz)) and corresponding IEEE802.11p Medium Access Control (MAC)-layer protocol. See Appendix G for a complete list of network parameters.

NS-3 adopts in addition the concept of applications, which can be installed on each node. Applications typically use network stacks and peripheral cards to accomplish a certain task. In our case, we have implemented in the simulator our COACK protocol plus enhancements, the Stop-and-Wait ARQ (see Appendix F) and code that initiates the transmission as individual applications. An application was implemented in addition to broadcast a frame with a payload of 50 bytes at 10Hz. This frame is used to resemble the communication of awareness or basic control information in a vehicle platoon. We assumed that the 50 bytes include the network header and information among others like position, altitude, speed and acceleration.

The nodes in our simulation were positioned according the scenario described in Section 5.1. All nodes were installed with the application to broadcast awareness or basic control information. In addition, one platoon most in the middle of our scenario was selected to run either the COACK or Stop-and-Wait ARQ application.

As we simulated non-mobile vehicles, we assumed no change in the platoon composition –no vehicle was leaving or joining the platoon– during a simulation run. Platoons were hence formed and given a unique identifier during the initialization phase and each vehicle in a platoon was made aware

of all other vehicles in the same platoon. This is a prerequisite to execute the COACK and Stop-and-Wait ARQ protocols. We assumed this platoon composition could be derived from the broadcasted 50 bytes awareness or basic control information.

5.3 Performance Metrics

This section describes the performance metrics that are used in the evaluation of our protocols. These metrics are output of the simulation and gain insight in the performance of the protocols.

5.3.1 Reliability

The main objective of the COACK-protocol is to improve the reliability of multicasting between vehicles in a platoon. A metric for the reliability is hence our main tool to analyze and compare the performance of our protocols.

In order to express the reliability, we use the success-ratio of a protocol i.e. the number of successful transmissions over the total number of transmissions. In fact, we are interested in the average success-ratio as well as the 95% confidence interval.

We determine the success-ratio of a protocol by counting at the source-vehicle the number of successful transmissions (*success*). This counter is increased as soon as the source vehicle has received all acknowledgements for a notification. The success-ratio of simulation run r is then calculated with the following equation:

$$success\ ratio_r = \frac{success_r}{n_r} \quad (5.1)$$

The success counter is expressed as $success_r$ and n_r is the number of initiated notifications for simulation run r . The results show the average success ratio over 50 simulation runs and its 95% confidence interval. We assumed a normal distribution of the success ratio for the calculation of the 95% confidence interval.

5.3.2 Delay

The delay of a transmission is directly influenced by its reliability. The more reliable a payload is delivered to its destinations, the less retransmissions are needed to succeed. The delay also impacts the highway capacity when the behavior of vehicles is dependent on the communication like in our *transient formation strategy*. This makes the delay of our protocols an interesting metric.

The delay we measure in our simulation is the average delay between a request and its result that is indicated back to upper layer (i.e. either a success or failure) and the 95% confidence interval. The influence of reliability is clear: for less reliable transmissions, a larger part of the average delay is caused by the maximum timeout. This metric measures what a source-vehicle can actually expect as delay.

In order to measure the delay, we store the time of each request made by upper layer. Whenever the result is indicated back to upper layer, the difference in time is calculated and becomes a *delay* measurand.

The delay of a simulation run r is calculated with Equation 5.2:

$$delay_r = \frac{\sum_{i=1}^{n_r} delay_i}{n_r} \quad (5.2)$$

The delay measurand is expressed as $delay_i$ and the number of initiated notifications in simulation run r as n_r . The results show the mean values and 95% confidence interval calculated over 50 simulation runs. We assume a normal distribution of the delay for the calculation of the 95% confidence interval.

5.3.3 Overhead

The overhead is measured by the number of Protocol Data Unit (PDU)-bytes per notification. This metric gives insight in the efficiency of the protocols under test. In order to calculate the overhead, each vehicle counts the total number of own transmitted PDU bytes ($txBytes$). The overhead of a simulation run r is then calculated with the following equation:

$$overhead_r = \frac{\sum_{i=1}^{v_r} txBytes_{r,v}}{n_r} \quad (5.3)$$

The $txBytes_{r,v}$ expresses the total number of transmitted PDU bytes by vehicle v in simulation run r . The mean values and 95% confidence intervals calculated over 50 simulation runs are shown in the results. A normal distribution of the overhead is assumed for the calculation of the 95% confidence interval.

5.4 Influence of Traffic Density on the Protocols

In this section we compare the protocols under test for their impact on changing traffic densities. The protocols are executed by a platoon of 5 vehicles, a payload of 50 bytes, a maximum of 4 retransmissions and a backoff time (T_{max}) of 100 ms. The traffic density of three lanes with non-platooning vehicles is increased from 0 to 200 vehicles per kilometer per lane ($veh/km/ln$) with steps of 25 $veh/km/ln$.

5.4.1 Reliability

The success-rate results for the tested protocols are plotted in Figure 5.1.

The results show a maximum success-rate at low traffic densities for all protocols. When the density increases beyond 75 $veh/km/ln$, the Stop-and-Wait ARQ protocol is the first to drop in success-rate. The COACK and COACK+df+gra manage to keep a near maximum result up to 125 $veh/km/ln$. For even higher densities the ratio drops for all protocols under test. This can be accounted to higher network-traffic.

Overall, the COACK+df+gra achieves the best success-rates under all traffic densities in the tested scenario, followed by the COACK-protocol. The worst rates are achieved by the Stop-and-wait ARQ protocol. In fact, largest increase is achieved at a traffic density of 175 $veh/km/ln$: the ratios of COACK and COACK+df+gra are respectively 32% and 49% better than the Stop-and-Wait ARQ.

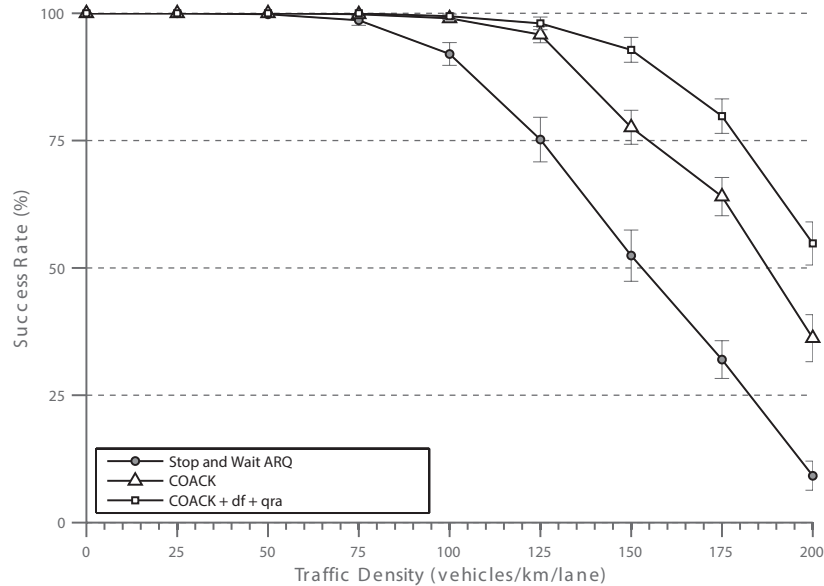


Figure 5.1: Influence of Traffic Density on Success-Rate

5.4.2 Delay

The impact of the traffic density on the delay of our protocols under test is illustrated in Figure 5.2. The results show increasing delays for increasing traffic densities for all protocols. This is mainly caused by the need for retransmissions because of increased network-traffic.

The lowest delay is achieved by the Stop-and-Wait ARQ protocol for traffic densities up to 80 *veh/km/ln*. This result can be accounted to backoff timer of the COACK-protocol. Stop-and-Wait ARQ transmits immediately an ACKs in response to received payload while the transmission is delayed by the backoff timer for the COACK-protocol.

For traffic densities beyond 80 *veh/km/ln*, the average delay of the Stop-and-Wait ARQ protocol is larger than the average delay of COACK + *df* + *gra*. The negative effect of the backoff timer on the delay is compensated by the increased reliability.

The basic COACK-protocol never achieves the lowest delay among the tested protocols. This is an expected result as the COACK-protocol does have the negative impacts of the backoff timer, but never achieves the highest reliability (see Section 5.4.1).

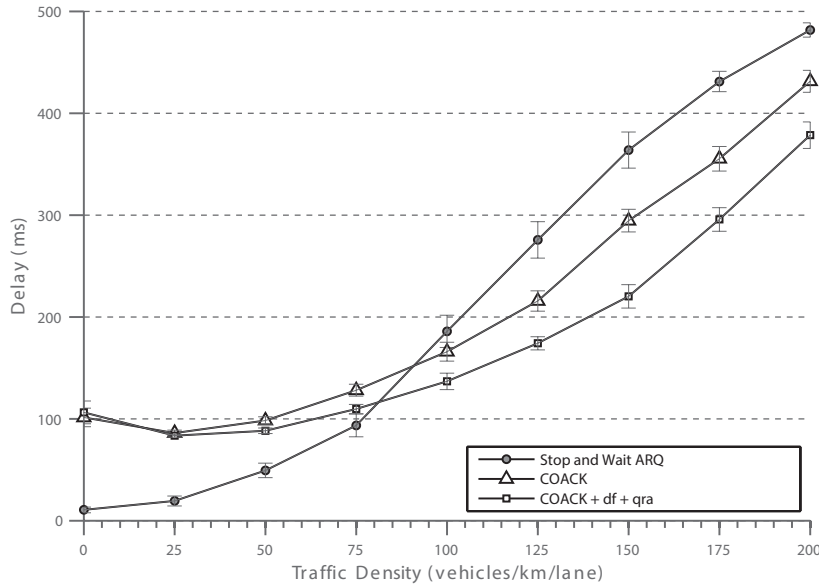


Figure 5.2: Influence of Traffic Density on Delay

5.4.3 Overhead

The results of the total number of PDU-bytes per notification are presented in Figure 5.3. These results show for low traffic densities that the COACK transmits more bytes than Stop-and-Wait ARQ. This increase can be accounted to forwarded (N)ACKs and their vehicle identifiers. For higher traffic densities, the difference in bytes becomes smaller. In fact, from a traffic density of around 80 *veh/km/ln*, the COACK-protocols transmit less bytes while increasing the success-rate. Only when the curve of Stop-and-Wait ARQ drops at high traffic densities, the COACK + *df+qra* consumes more.

Remarkable about these results is also the difference between COACK and COACK + *df+qra*. The average total number of bytes is almost equal up to 150 *veh/km/ln*, despite the use of *data forwarding* and *quick retransmit of ACKs* by the latter protocol. Only for traffic densities between 150 and 200 *veh/km/ln*, the COACK + *df+qra* consumes more bytes.

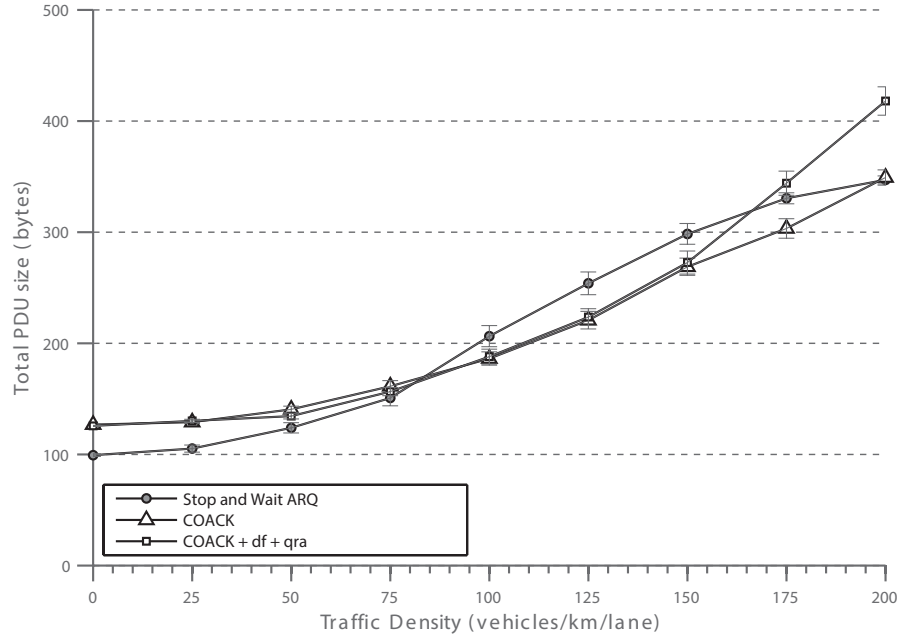


Figure 5.3: Influence of Traffic Density on PDU-bytes per Notification

5.5 Influence of Platoon Length on the Protocols

In this section we compare the impact on the protocols under test for changing platoon lengths. For this setup, we used a traffic density of 150 *veh/km/ln*, 50 bytes payload, a maximum of 4 retransmissions and a back-off time (T_{max}) of 100 ms. The platoon length is changed between 2 and 7 vehicles and all vehicles in the platoon except the source-vehicle are set as destination.

5.5.1 Reliability

The results of the success-rate for increasing platoon lengths (and increasing number of destinations) are illustrated in Figure 5.4.

COACK+df+qra achieves the best success-rates for all tested platoon lengths, except for a 2-vehicle platoon. Indeed, for a platoon of 7 vehicles, it achieves a success-rate of 84.6% compared to 64% and 15.2% for respectively COACK and the Stop-and-Wait ARQ. So also the COACK-protocol improve the success-rate significantly compared to the Stop-and-Wait ARQ protocol.

The success-rate for a 2-vehicle platoon is nearly 100% for all protocols. Although a better success-rate cannot be achieved, the forwarding-mechanisms in COACK are not effective in such a platoon. There is no other vehicle in the platoon that can forward information.

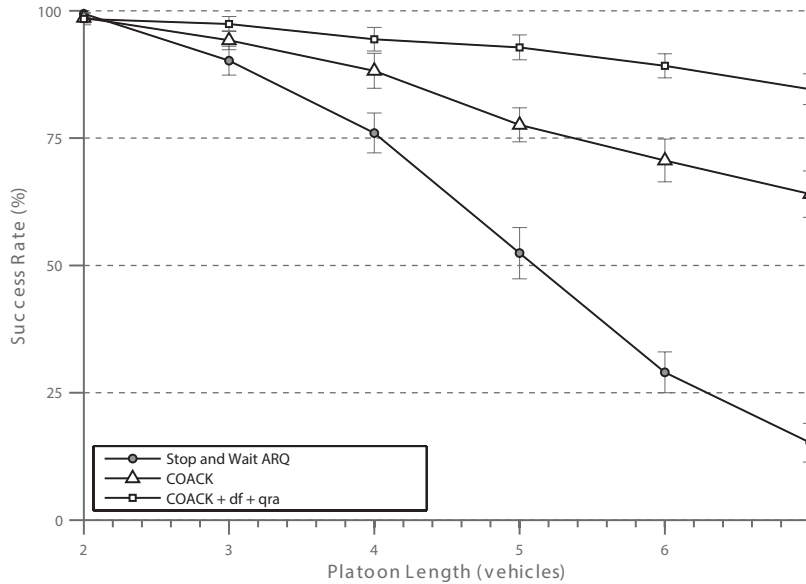


Figure 5.4: Influence of Platoon Length on Success-Rate

5.5.2 Delay

Increasing the platoon length and number of destinations has the general effect of increasing the delay as the results in Figure 5.5 show. This effect is explained by decreasing success-rates and the need for retransmissions.

COACK+df+qra achieves the lowest average delay for platoons of 3 to 7 vehicles. Only Stop-and-Wait ARQ achieves a lower delay for a 2-vehicle platoon. This is the result of the backoff timer of both COACK-protocols. The lowest delay of COACK+df+qra are achieved because of the improved success-rate and the need for less retransmissions. So COACK but especially COACK+df+qra benefits the most from increased platoon lengths.

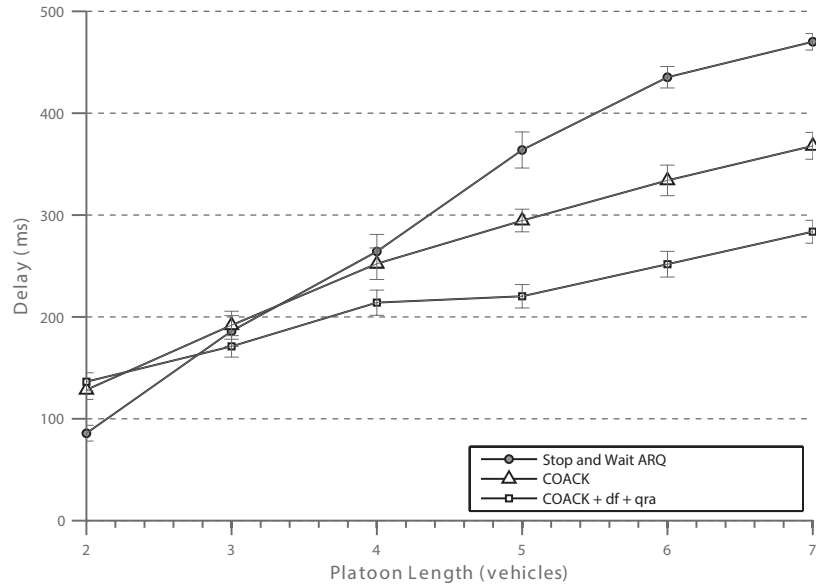


Figure 5.5: Influence of Platoon Length on Delay

5.5.3 Overhead

The average number of consumed PDU-bytes per notification grows with the length of the platoon in our test for all protocols. This result is presented in Figure 5.6 and can be explained by more vehicles transmitting PDUs. In fact, the growth seems to be linear with the length of the platoon for all tested protocols.

The differences in consumed bytes between the protocols are relatively small. Our protocols use respectively 216.0, 229.0 and 233.8 bytes per notification for a platoon length of 4 vehicles.

If we study the results in more details, we notice that both COACK-protocols consume less bytes than Stop-and-Wait ARQ for a platoon length of 3 to 6 vehicles. Also COACK+df+qra consumes more bytes than COACK

for all platoon lengths. For a platoon of 4 vehicles, the difference is 13 bytes but increases in our test to 43.8 bytes for a 7-vehicle platoon.

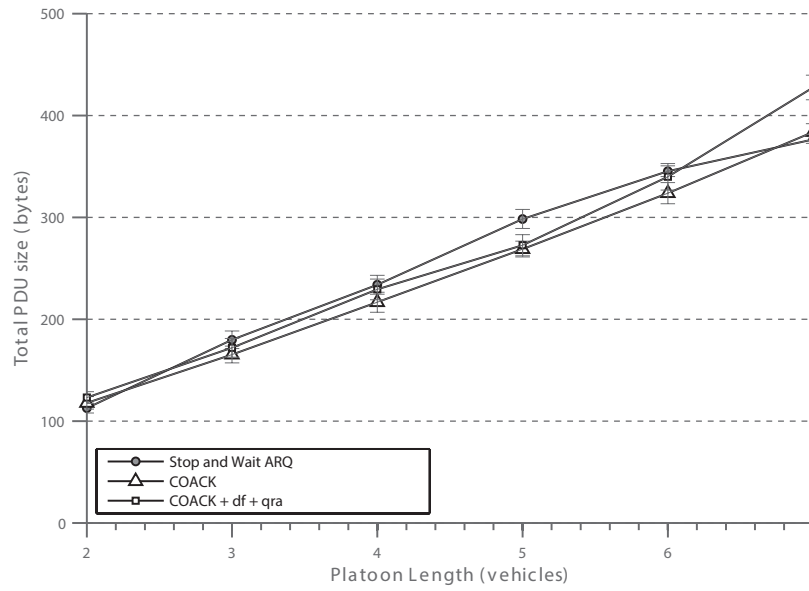


Figure 5.6: Influence of Platoon Length on PDU-bytes per Notification

5.6 Influence of Payload Size on the Protocols

In this section we compare finally the influence of the payload size on the performance of the protocols under test. For this setup, we simulate again a traffic density of 150 veh/km/ln , a 5-vehicle platoon, a maximum of 4 retransmissions and a backoff time (T_{max}) of 100 ms. The payload size is increased with 10 bytes from 10 to 100 bytes.

5.6.1 Reliability

The success-rate results for the protocols under test for changing payload size are presented in Figure 5.7.

The results show for all protocols a fluctuating success-rate for increasing payload sizes. No clear influence of the payload size on the success ratio can be noticed for these results. Especially because the many overlapping confidence intervals for the different payload sizes of all protocol.

We are however cautious to conclude that the payload has no impact on the success-rate. These fluctuating values and their confidence interval indicate that more simulations are needed.

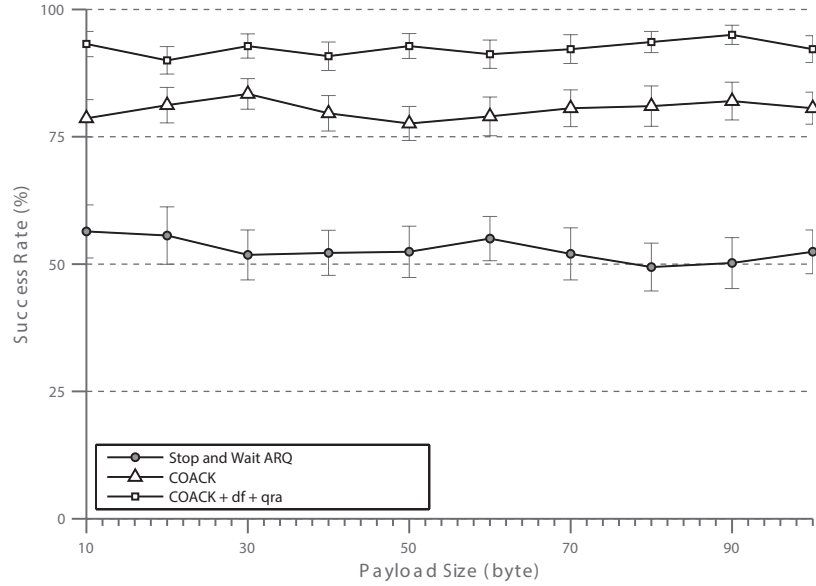


Figure 5.7: Influence of Payload Size on Success-Rate

5.6.2 Delay

The impact of the payload size on the delay has similar results as for the success-rate. The results in Figure 5.8 shows no clear influence of increasing payload size on the delay. In fact, the difference between minimum and maximum average delay over all payload sizes falls within 18.5, 19.7 and 19.2 milliseconds for respectively the Stop-and-Wait ARQ, COACK and COACK+ $df+qra$. This is respectively 5.1%, 6.8% and 8.5% of their average value.

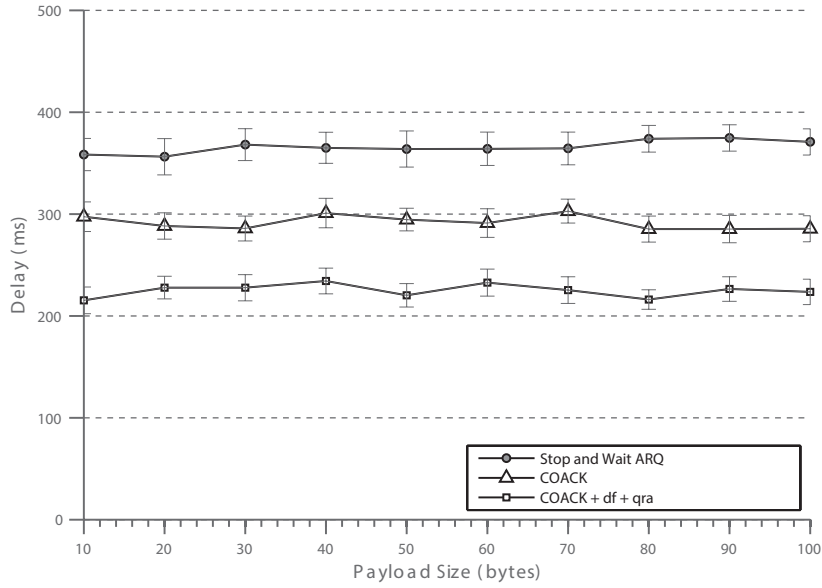


Figure 5.8: Influence of Payload Size on Delay

5.6.3 Overhead

The results of the payload size on the total number of PDU-bytes per notification are presented in 5.9.

The results show a logic increase of the total PDU-size for an increasing payload size for all protocols under test. Actually, the increase seems to be linear, which can be explained by nearly stable success-rates for increasing payload size. If the success-rate is hardly affected by payload size, the number of transmissions will stay nearly the same and the increase of total PDU-size is only affected by increase of payload size.

The COACK and COACK+ $df+qra$ consume less bytes than Stop-and-Wait ARQ for the higher payload sizes. The higher number of retransmissions probably causes the high consumption by Stop-and-Wait ARQ.

The COACK+ $df+qra$ consumes, despite the higher success-rate, slightly more bytes than the COACK-protocol for the larger simulated payloads.

The *data forwarding* features is likely the main cause of this result.

Interesting is also the total PDU-bytes for a lower payload size. Surprisingly, both COACK-protocols consume more bytes. This effect is caused by the extra information included in a COACK-PDU. For small payloads, the overhead becomes relatively large and is not compensated by a higher success-ratio and less retransmissions.

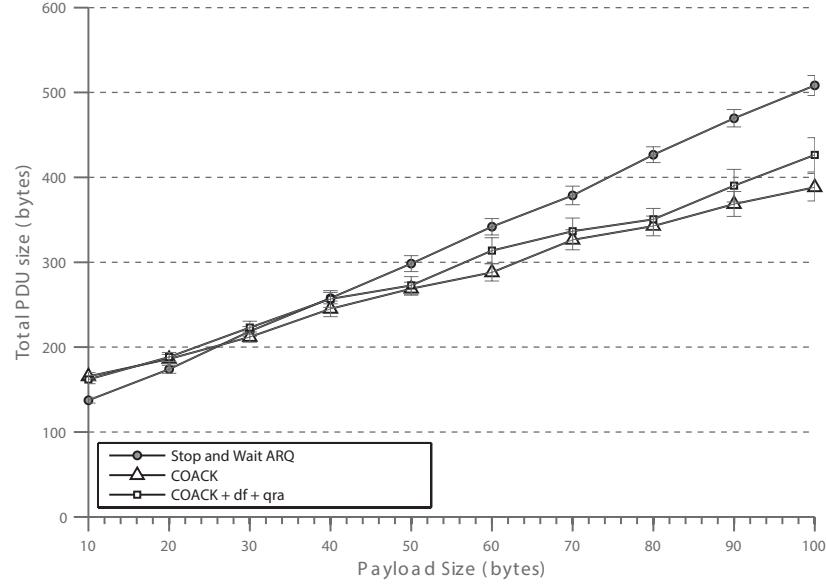


Figure 5.9: Influence of Payload Size on PDU-bytes per Notification

5.7 Discussion of the Evaluation

Before we conclude the results in the next section we need to reflect our evaluation first. The first remark is that our simulation has been performed with a scenario of only stationary vehicles. The relative speed between vehicles in a platoon is indeed low but the mobility of other vehicles can indeed change the condition of the communication channel. These effects on the protocols have not been explored in our study.

In our simulation we have assumed that all vehicles in the platoon are destinations, except for the source-vehicle. Also the source-vehicle was in all scenarios the head of the platoon. Our used scenarios are just a few of many possible scenarios in which our protocol can be applied. Take for example a vehicle leaving the platoon in the middle. It may want to announce this maneuver to the lead and immediately following vehicle in order to limit the disturbances.

Another remark is about the conditions of simulation. We used a fre-

quency of 5.0 GHz to transmit the packets but this does not correspond to the allocated part of the band for inter-vehicle communication. In Europe, United States of America and Japan, the allocated part of the band is around 5.9 GHz. Also not taken into account in our simulation is the effect of multi-path propagation. In a real situations, the signal is reflected by surround buildings, infrastructure and even by cars themselves. This can result in signal distortion, loss of data or multi-path fading.

In the end, we should treat the results of our evaluation as an indication of the performance.

5.8 Conclusion

In this chapter, we have evaluated the performance of the COACK-protocol and two enhancements i.e. *data forwarding* and *quick transmission of ACKs* that were described in Chapter 4. The protocol and enhancements were implemented in ns-3 [1] together with a basic Stop-and-Wait ARQ so we could compare our methods against a basic protocol.

A highway scenario was used to evaluate the protocol in our simulation. In the first three lanes, vehicles were grouped in platoons. Vehicles on the other three lanes were spread equally over the road. All vehicles were broadcasting a payload of 50 bytes in order to simulate the inter-vehicle communication for cooperative control functions in platooning.

Vehicles in the most middle platoon were used to evaluate the protocols for their impact on the success-rate, delay and overhead for changing traffic densities, platoon lengths and payload size.

Our results show that at high traffic densities, the COACK-protocol improves the success-rate and lowers the delay. In fact, the best success-rates and delays are achieved when *data forwarding* and *quick retransmissions of ACKs* are enabled. This at the expensive of a small increase of packet size for only the highest simulated traffic densities. The basic Stop-and-Wait ARQ shows only to be beneficial at low traffic densities.

COACK is most effective in large platoons. The success-rate and delays are improved the most by COACK with *data forwarding* and *quick retransmissions of ACKs* for the largest simulated platoon length. Less effect on the success-rate and delay is noticeable when the payload size is changed.

The *transient formation strategy* of Section 3.2 can benefit from the results of the COACK protocol with *data forwarding* and *quick retransmission of ACKs* in the reliable dissemination of the platoon leader's destination to all platoon vehicles in dense traffic situations. The gained improvements depend however on the rate at which this information needs to be disseminated. A change of platoon leader or change of its destination will not happen too often and hence the overall gain might be low.

As a result of the *transient formation strategy*, a platoon is often split

because of leaving vehicles. The COACK protocol with *data forwarding* and *quick retransmission of ACKs* can improve the reliable dissemination of this split command to all other platoon vehicles in heavy traffic situations. The real traffic effects depend however on the application that performs the platoon split.

Chapter 6

Conclusions

In this final chapter we conclude our research with an overview in Section 6.1. Next, in Section 6.2 the research questions of Section 1.2 are answered and finally some future research topics are discussed in Section 6.3.

6.1 Overview of Results

This thesis started with a survey of strategies to form vehicle platoons. The formation strategies that were found in literature were described and classified according to the location of formation and how vehicles in a platoon are organized. This classification led to the development of a new formation strategy: the *transient formation strategy*.

Our strategy combines the benefits of forming a platoon on the highway – no waiting time at entrance ramp – with the stability of grouping vehicles with similar destinations. The leading vehicle determines the range of the group. All other vehicles should have a closer destination so they can follow the platoon leader up to their destination.

The concept of destination grouping is however limiting the average length of a platoon. In order to overcome this issue, vehicles are allowed to join any platoon while searching for a better platoon. If such a platoon is found, the vehicle switches to the new platoon.

The performance of the *transient formation strategy* was compared against the formation strategies of the survey in a self-implemented traffic simulator. The strategies were analyzed for changing vehicle arrival rates and their impact on the platoon length, lane capacity, trip time, platoon ratio and stability. It was found that the *transient formation strategy* forms larger platoons than any other simulated strategy. This directly translates into an increase of the maximum lane capacity.

In order to implement the *transient formation strategy*, it was analyzed for its information requirements. One of the identified requirements was the need to disseminate the leader’s destination to all vehicles in the pla-

toon. In the traffic simulation, we assumed however a perfect communication channel which is unrealistic in real situations. To limit the impact of the communication channel on the performance of our strategy, the Cooperative Acknowledgements (COACK)-protocol was developed.

The COACK-protocol aims to improve the reliability and delay of multicasting in platoons by cooperative forwarding of acknowledgements by vehicles in a platoon. In addition, two enhancements were developed: *data forwarding* and *quick retransmission of Acknowledgements (ACKs)*. *Data forwarding* improves the delivery of payload by having vehicles in the platoon forwarding the payload. *Quick retransmissions of ACKs* is a method to predict whether a vehicle has received an ACK without receiving their ACK. Both enhancements make use of an assumed correlation for platoons: when a vehicle receives a transmission we assume that other vehicles in the platoon, in between the source and receiving vehicle, have received it as well.

The COACK-protocol and two enhancements were implemented in the network simulator ns-3 [1] together with a basic Stop-and-Wait Automatic Repeat-Request (ARQ). The protocols were analyzed for their impact on the success-rate, delay and overhead for changing traffic densities, platoon lengths and payload size.

The simulation results showed that COACK-protocol improves the success ratio, improves the success ratio lowers the delay in high traffic situations and large platoons. The best success ratios are achieved for COACK when *data forwarding* and *quick retransmission of ACKs* are enabled. These results were achieved with only a small increase of the packet size for the highest simulated traffic densities. Only at low traffic densities, a basic Stop-and-Wait ARQ is beneficial to be used, as the increased packet overhead is not compensated by increased reliability.

6.2 Answers to Research Questions

The research questions of Section 1.2 were answered throughout this study. In this section we will briefly recapitulate these answers.

How to develop a platoon formation strategy that increases the benefits of platooning?

The benefits of vehicle platoons have been identified in Section 2.2.1 as fourfold. The first and most predominant benefit is the increase of the road-capacity. Vehicles in platoons operate at smaller headways and hence more vehicles can be accommodated on a highway. The second benefit is a reduction of environmental impacts as a result of close operating vehicles. Wind tunnel tests and field experiments have shown that close operating vehicles reduce the drag on vehicles and hence lower the fuel consumption. The third benefit is improved safety. The majority of traffic accidents is caused by or can be blamed on human drivers. Some vehicle platooning concepts apply technologies like wireless communication to support the driver in its task and enable to early detection of dangerous situations. The final benefit of vehicle platooning is improved driver comfort. Vehicle platoons have a smoothing effect on traffic flow. Speed changes tend to be less jerky which improves comfort.

It was found that two properties of a platoon formation strategy are important in order to increase the benefits of platooning:

- Form platoons of reasonable length;
- Form platoons that stay intact for a reasonable time.

With these properties in mind, a platoon formation strategy has been developed: the *transient formation strategy*. This strategy groups vehicles together that can follow the leader for their entire trip in order to keep a platoon intact for a longer period of time. This tends to limit however the length of a vehicle platoons; vehicle can be denied to join a platoon while they are physically capable to do so. In order to overcome this issue, we allow a vehicle to join any platoon temporarily (and gain all benefits) while searching for a better platoon to join.

What is the performance of the developed platoon formation strategy?

In order to analyze the performance of the *transient formation strategy*, we have introduced 5 performance metrics. These metrics cover first of all the two properties that are important to increase the benefits. The following metrics were used:

- **Platoon length:** the average number of vehicles in a platoon;
- **Maximum Lane capacity:** measurement of the maximum possible vehicle flow at the average speed;
- **Maneuver count per vehicle:** the average number of maneuvers per trip.
- **Trip time:** average time it takes for a vehicle to drive from start to destination;
- **Platoon ratio:** the percentage of the trip time for which a vehicle is driving in a platoon;

It turns out that the *transient formation strategy* improves the average platoon length, maximum lane capacity, trip time and platoon ratio at the cost of a small increase of the number of maneuvers per vehicle in all of our simulation scenarios. The minimum and maximum observed increase of platoon length by the *transient formation strategy* is respectively 1 and 1.48 vehicle. This results in an increase of lane capacity of at least 300 *veh/ln/km* for the highest arrival rates.

Based on these preliminary results, we carefully conclude that it is always beneficial to apply our formation strategy in favor of an ad-hoc, sorted or ranged formation strategy.

What are the information requirements for this strategy?

The information requirements for the *transient formation strategy* were identified based on its design of Section 4.1. The following information requirements were identified:

- **Position and destination of the ego-vehicle:** The position and destination of the ego-vehicle are used to determine whether a vehicle has reached its destination;
- **Role of ego-vehicle:** The role of the ego-vehicle (i.e. platoon leader or follower);
- **Destination of other platoons in close vicinity:** The destinations of platoons are used by vehicles searching for an appropriate platoon to join;
- **Position of last Vehicle in a platoon:** The position of the last vehicle is the location to join the particular platoon;
- **Destination of platoon leader:** this affects the state of following-vehicles in a platoon
- **Platoon composition:** The set of vehicles and their position in the platoon.

How to design a communication solution to support the formation strategy

In order to implement the *transient formation strategy*, its information requirements should be fulfilled. Some of the information requirements of the *transient formation strategy* do not need the communication between vehicles; for example the position and destination of the ego-vehicle. For other information requirements like the platoon composition, solutions have been described [26]. In this thesis, we focussed on a reliable protocol for multicasting in platoons in order to support the dissemination of the platoon leader's destination among all vehicles in the platoon.

In our protocol for reliable multicasting in vehicle platoons, all vehicles in the platoon help to deliver acknowledgements. Especially platoons are suitable for such a solution as they tend to stay in a fixed formation for a longer period of time. We exploited the structure of a platoon additionally to predict the reception of a particular transmission and further improve the reliable delivery of acknowledgements and payload.

What is the performance of the designed communication solution?

The performance of the COACK-protocol (with and without *data forwarding* and *quick retransmission of ACKs* enabled) was tested with the following three metrics for changing traffic densities, changing platoon lengths and changing payload size:

- **Reliability:** measured as the success-rate of sent notification;
- **Delay:** the time between an initiated notification by the platooning application and the indicated result of the transmission;
- **Overhead:** the accumulated Protocol Data Unit (PDU)-bytes used for the dissemination of a single notification by all vehicles in a platoon.

The results of the performance evaluation indicate that COACK significantly improves the success-rate and delay for medium to high traffic densities as well as for medium to large-size platoons. In addition, enabling the *data forwarding* and *quick retransmission of ACKs*-features show an even greater improvement of the success-rate and delay. The assumed correlation on which these enhancements are based show useful in improving reliability in vehicle platoons. Only for low traffic densities, the overhead of the COACK-protocol becomes too large and a simple Stop-and-Wait ARQ-based approach achieves a lower delay and overhead with equal reliability.

6.3 Future Work

In this thesis we have accomplished the design of a formation strategy and supporting communication protocol to improve the benefits of platooning. Both this formation strategy and communication protocol has been validated for limited number of scenarios. Future work related to this formation strategy and communication protocol should focus for this reason on further evaluation of our solutions.

A first topic of research is the evaluation of our formation strategy in a more advanced traffic simulator. This would allow first to compare our results and second to analyze the impact of more realistic platoon-follow-models and lane-change-models on the benefits of the *transient formation strategy*.

A second topic of research could be impact analysis of a multi-lane highway on the performance of our formation strategies. As we argued in Section 3.4, multi-lane highways may have a negative or positive impact on the performance.

A third topic of research could be the simulation of the *transient formation strategy* and COACK-protocol in an integrated network and traffic simulator. This would allow investigating the impact of the protocol on the formation strategy.

Finally, we should evaluate the accuracy of ns-3 [1] as network simulator for Vehicle-to-Infrastructure or Vehicle-to-Vehicle (V2X) communication. Ns-3 is still a very young simulator. In fact, the first release was in June 2008 and despite the fact that it is based on ns-2, a widely used network simulation, and actively being developed, the accuracy of ns-3 as network simulator for V2X communication is still a question. The simulator should be compared against a test bed.

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Acronyms

3GPP 3rd Generation Partnership Project

ACC Adaptive Cruise Control

ACK Acknowledgement

AHS Automated Highway System

AP Access Point

APTS Advanced Public Transportation Systems

ARQ Automatic Repeat-Request

ASTM American Society for Testing and Materials

ATIS Advanced Traveler Information Systems

ATMS Advanced Transportation Management Systems

BSS Basic Service Set

BSSID Basic Service Set Identifier

CACC Cooperative Adaptive Cruise Control

COACK Cooperative Acknowledgements

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CSMA/CD Carrier Sense Multiple Access with Collision Detection

CTS Clear to Send

DCF Distributed Coordination Function

DG Destination Group

DGPS Differential Global Positioning System

DIFS DCF Inter-Frame Space

DSRC Dedicated Short-Range Communications

DSS Driver Support Systems

DSSS Direct Sequence Spread Spectrum

DYG Dynamic Grouping

ESS Extended Service Set

FCC Federal Communications Commission

FHSS Frequency Hopping Spread Spectrum

GHz Giga Hertz

GPS Global Positioning System

GSM Global System for Mobile Communications

IBSS Independent Basic Service Set

IEEE Institute of Electrical and Electronics Engineers

IDM Intelligent Driver Model

ICT Information and Communication Technology

ITS Intelligent Transportation Systems

ITSA Intelligent Transportation Society of America

LAN Local Area Network

LTE 3GPP Long Term Evolution

MAC Medium Access Control

MANET Mobile Ad-Hoc Network

MHz Mega Hertz

(N)ACK (Negative) Acknowledgement

NITSA National Intelligent Transportation Systems Architecture

OBU On-Board Unit

OFDM Orthogonal Frequency-Division Multiplexing

OSI Open System Interconnection

PATH Program for Advanced Technology for the Highway

PCF Point Coordination Function

PDU Protocol Data Unit

PDR Packet Delivery Ratio

PHY Physical Layer

PLR Packet Loss Ratio

PPS Precise Position Service

RA Random Assignment

REQ Request

RTS Request to Send

RSU Road-Side Unit

SIFS Short Inter-Frame Space

SPS Standard Position Service

UMTS Universal Mobile Telecommunications System

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

V2X Vehicle-to-Infrastructure or Vehicle-to-Vehicle

US United States

USA United States of America

VANET Vehicle Ad-Hoc Network

WAVE Wireless Access in Vehicular Environments

WBSS Wave Basic Service Set

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

Appendix A

Proof of inability to reach destination in the Temporary Following State

Section 3.2 has introduced a new platoon formation concept called the transient formation strategy. The formation strategy incorporates the destination ranging concept but extends this by allowing vehicles to temporary join a non-feasible platoon in search for a feasible platoon. This state of the formation strategy is called the *Temporary Following State*.

In the same section, it was claimed that a vehicle cannot be in the *Temporary Following State* while reaching its destination. This chapter provides the proof for this claim.

First, consider the platoon as illustrated in Figure A.1. This platoons consists of n vehicles, each having a unique number, counted from the leading vehicle. For each of these vehicles we define D_i and L_i as the destination and current location, respectively for the i^{th} vehicle ($1 \leq i \leq n$).



Figure A.1: Example of Vehicle Platoon Formation

The state diagram of the transient formation strategy for each vehicle in this platoon was presented in Figure 3.6. A part of this state diagram is again illustrated in Figure A.2, augmented with state variants and transition conditions. In order to proof our claim, we need to proof that the transition condition $L_v = D_v$ never holds in the *Temporary Following State*—illustrated with the dashed line— for vehicle v ($2 \leq v \leq n$).

Therefore, we first define D_v^{max} as $\max(D_1, \dots, D_{v-1})$ i.e. the maximum

destination of all preceding vehicles of vehicle v . Now, for D_v^{max} we have the following two options:

1. $D_v > D_v^{max}$ All preceding vehicles 1 to $v - 1$ leave the platoon before vehicle v . At location $L_v = D_v^{max}$, the condition $v = 1$ holds and vehicle v becomes leader before the condition $D_v = L_v$ holds;
2. $D_v \leq D_v^{max}$ At location D_1 , the leader leaves the platoon which results in a new leader with a farther destination. This may result in the condition $D_v \leq D_0$ to hold or vehicle stays in the *Temporary Following State*. In the latter case, vehicle 1 leaves before vehicle v . This continues until condition $D_v \leq D_0$ holds which happens before vehicle v reaches its destination as $D_v \leq D_v^{max}$.

In either case the conditions $D_v \leq D_0$ and $v = 0$ hold before condition $L_v = D_v$ which results in a state change to the *Following State* or *Leading State*, respectively. Hence, a vehicle will never reach its destination in the *Temporary Following State*.

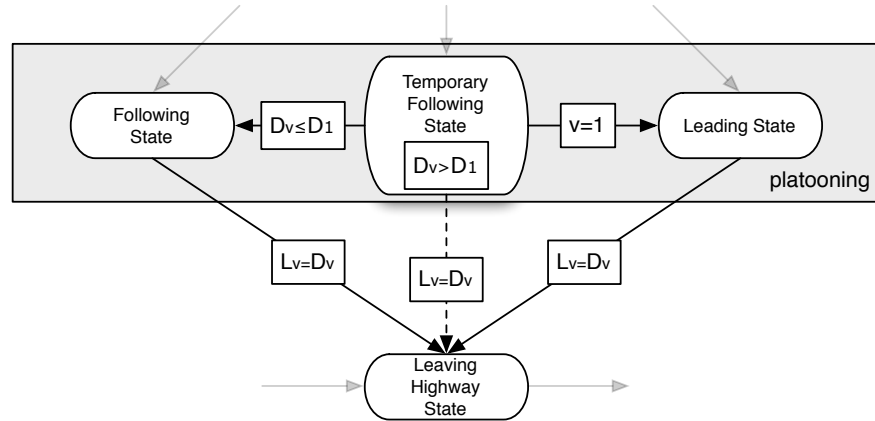


Figure A.2: State variants and transition conditions of the Transient Formation Strategy

Appendix B

Platoon Formation Strategies

In Section 3.2 we have developed a new strategy –the transient formation strategy– for the formation of vehicle platoons. The performance of this strategy was compared in Section 3.3 against the *Ad-Hoc*, *Platoon Sorting* and *Destination Ranging* platoon formation strategies, which were identified during a literature survey.

The description in Section 3.2 of the transient formation strategy includes a state transition diagram and a detailed description. A similar description of the state diagram for the *Ad-Hoc*, *Platoon Sorting* and *Destination Ranging* platoon formation strategies is lacking. So, this chapter provides these descriptions.

B.1 Ad-Hoc Platoon Formation Strategy

Before we start describing the state diagram of the Ad-Hoc formation strategy, let us recapitulate this formation strategy. The Ad-Hoc formation strategy is basically a strategy in which vehicles form platoons on encounter. No complicated interaction is required and as a consequence, a vehicle typically joins a slower driving vehicle on the same lane in order to form a platoon.

The state diagram of the Ad-Hoc formation strategy, as used for evaluation in Section 3.3, is illustrated in Figure B.1.

This state diagram consists of the following states:

Idle State The idle state is basically the state in which the vehicle is not driving on a highway. In this state, the only transition that can occur is a transition to the *Searching State*. This transition happens upon entering a highway.

Searching State In the searching state, a vehicle is waiting for an encounter with another vehicle in order to form a platoon. In our model, an encounter can only occur between vehicles in the same lane as

lane changing requires cooperating vehicle. For the Ad-Hoc formation strategy we assume after all the lack of complicated interaction.

In the Searching State we have three possible transitions:

- A transition to the *Following State*, which occurs when the current vehicle encounters a slower driving leading vehicle;
- When another vehicle starts following the current vehicle, it becomes the leader of a platoon and a transition happens to the *Leading State*;
- A final possible transition happens when the current vehicle reaches its destination. The state transits to the *Leaving Highway State*;

Following State The Following State is the state in which a vehicle follows another vehicle in the same platoon. In this state we have the following possible transitions:

- A transition to the *Searching State* when all preceding and following vehicles of the current vehicle left the platoon. In this case, the state transits to the Searching State in order to find a new platoon to join;
- In a similar situation when all preceding vehicles have left but not all following vehicles, the current vehicle becomes the leader of the platoon and the state transits to the *Leading State*;
- Again, the final possible transition happens when the vehicle reaches its destination. In such a situation, the state changes to the *Leaving Highway State*.

Leading State In the *Leading State*, the current vehicle is the leader of a platoon. The following transitions can occur in this state:

- If a vehicle is no longer followed by another vehicle in the same platoon, the current vehicle is no longer the leader of a platoon. In this case, the vehicle starts looking for another platoon to join and the state changes to the *Searching State*;
- In the other situation in which the leader reaches its destination, the state changes to the *Leaving Highway State*.

Leaving Highway State The final state of the state transition diagram is the *Leaving Highway State*. This state is merely a symbolic state to indicate that the vehicle left the highway. The state changes after all immediately to the *Idle State*.

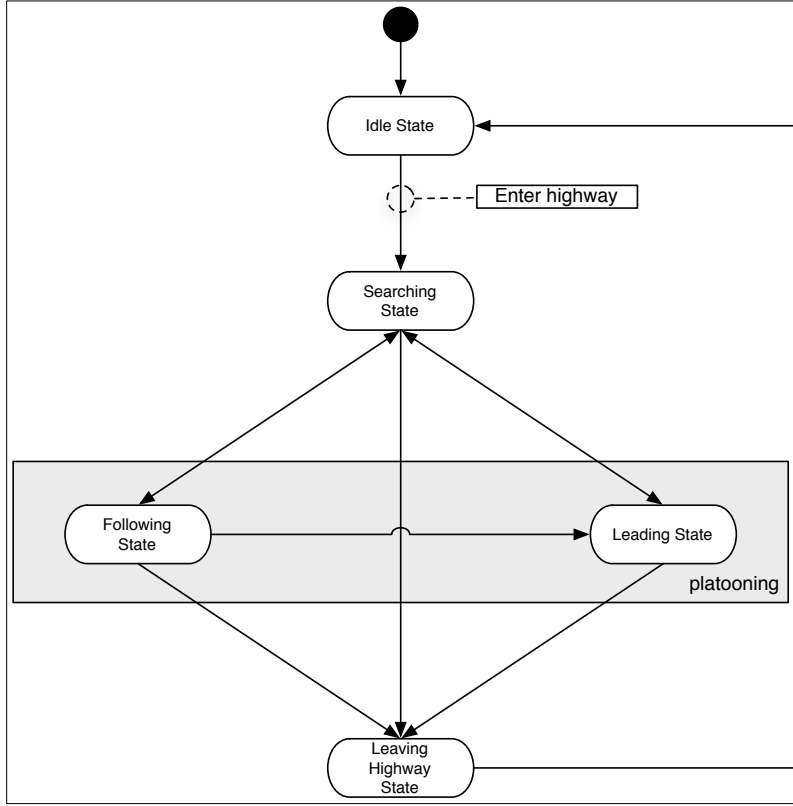


Figure B.1: State diagram of the Ad-Hoc platoon formation strategy

B.2 Sorting Platoon Formation Strategy

The sorting platoon formation strategy is a strategy in which the vehicles are sorted according their destination with the leading vehicle having the farthest destination.

A possible implementation of this strategy is an implementation where vehicles join at a certain position in a platoon such that the platoon stays ordered according to the destinations. This requires however a tight and complex cooperation between vehicles as this position may be in the middle of the platoon. We don't follow this approach in our implementation. Instead, we restrict a vehicle to join only at the back of a platoon. In order to guarantee an ordered platoon we restrict vehicles to join the platoon if the last vehicle has a farther or equal destination than the joining vehicle. The advantage of this approach is that it requires less cooperation, which makes the strategy easier. On the other hand, some vehicles may be restricted to join the platoon in our implementation whereas this is not the case in the other implementation.

The state diagram of the sorting platoon formation strategy is illustrated in Figure B.2. This state diagram is almost equal to the ad-hoc platoon formation strategy of Figure B.1. In the following we will cover the differences between the two.

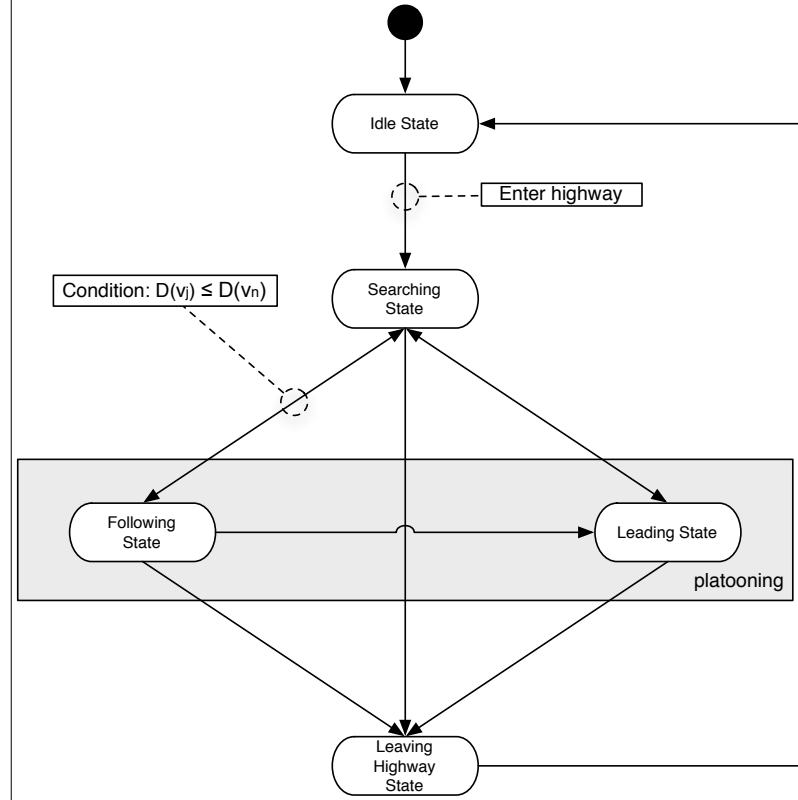


Figure B.2: State diagram of the Platoon Sorting formation strategy

The differences between the two state transition diagrams lies in the transition between the *Searching State* and *Following State*. The first difference is the condition as mentioned before. This condition is illustrated in the state diagram by the formula $D(v_j) \leq D(v_n)$, which restricts the destination (D) of the joining vehicle (v_j) to be less or equal than the destination of the last vehicle of the platoon (D_n). This obviously requires the communication of destinations between involved vehicles.

The second difference is the ability of a vehicle to join a platoon in another lane. Even though this requires more communication and cooperation in order to perform lane changes, we already assume the communication between vehicles in order to perform the formation.

B.3 Destination Ranging Platoon Formation Strategy

The destination ranging platoon formation strategy is a strategy in which the destination differences between vehicles in a single platoon are limited to a maximum range.

The state diagram of our implementation of this formation strategy is illustrated in Figure B.3. This state diagram is equal to the state diagram of the sorting formation strategy of Figure B.2. The only difference is the joining condition between the *Searching State* and *Following State*.

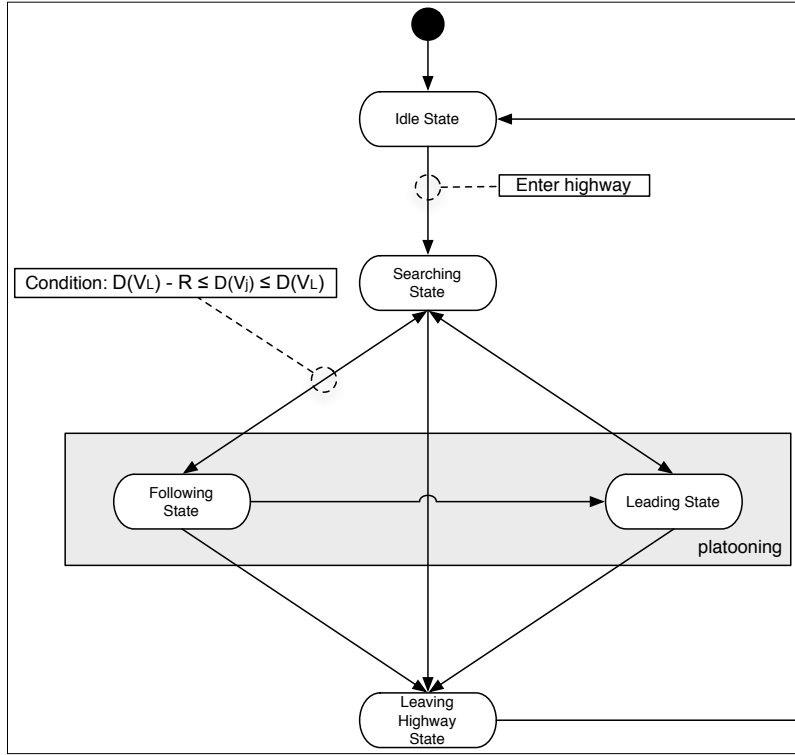


Figure B.3: State diagram of the destination ranging platoon formation strategy

The difference is illustrated with the formula $D(v_L) - R \leq D(v_j) \leq D(v_L)$. This formula restricts a joining vehicle to have a destination, which deviates no more than the range (R) with respect to the destination of the leading vehicle (v_L).

Appendix C

Deriving the Maximum Lane Capacity

A metric used in our simulation of formation strategies is the maximum lane capacity. This metric calculates the maximum lane capacity based on the average platoon length using Equation 3.4 in Section 3.3.1. In this appendix we explain how the formula is derived.

In order to calculate the maximum lane capacity, let us first calculate the space that an average platoon occupies. We assumed the following variables:

$AvgPLgth$	average platoon length in number of vehicle
h	headway between vehicles in a platoon in meters
l	Length of a vehicle in meters
T	Safe time headway in seconds
ν	steady state platoon speed in km/h

Table C.1: Maximum Lane Capacity Parameters

The space that a platoon occupies on average is:

$$(AvgPLgth - 1)h + AvgPLgth \cdot l + \frac{T\nu}{3.6} \quad (C.1)$$

If we divide this space by the average platoon length, we can calculate the average occupied space for one vehicle:

$$\frac{(AvgPLgth - 1)h + AvgPLgth \cdot l + \frac{T\nu}{3.6}}{AvgPLgth} \quad (C.2)$$

The time it takes in hours for the average occupied space per vehicle to pass a certain point, assuming a speed of ν is:

$$\frac{3.6[(AvgPlLgth - 1)h + AvgPlLgth \cdot l] + T\nu}{3600\nu AvgPlLgth} \quad (C.3)$$

The maximum lane capacity is then calculated as the inverse of the formula above:

$$C = \frac{3600\nu AvgPlLgth}{3.6[(AvgPlLgth - 1)h + AvgPlLgth \cdot l] + T\nu} \quad (C.4)$$

Appendix D

Simulation Parameters for Platoon Formation Strategies

The parameters in this appendix used in the simulation of platoon formation strategies in Section 3.3.

Parameter	Value
Road length	32 km.
Number of lanes	2
Inter-intersection distance	2 km.
Number of intersection	17
Vehicle inter-arrival distribution	Exponential
Vehicle destination distribution	Geometric
Average trip length	16 km.
Vehicle length	5 m.
Intra-platoon headway	10 m.
Maximum platoon length	10 vehicles
Maximum vehicle speed	40 m./s.
Transmission range	200 m.
Simulation Run Time	4600 sec.
Simulation Initialization Time	100 sec.
Simulation Runs per Scenario	25
Evaluated Formation Strategies	Adhoc Formation Strategy Sorting Formation Strategy Destination Ranging Formation Strategy Transient Formation Strategy
Main Average Arrival Rates	500 - 2500 veh./hr./ln.

Table D.1: Parameters of Simulation of Platoon Formation Strategies

Appendix E

Proof of Accumulated Correlation for Notifications in Vehicle Platoons

In sections 4.4.1 and 4.4.2 we have improved the functionality of the COACK-protocol by introducing a correlation. The correlation basically assumes that when a vehicle receives a transmission of another vehicle in the same platoon, all vehicles in between these two vehicles have received the transmission as well.

When the COACK-protocol with *data forwarding* of section 4.4.1 is applied, a notification can reach a receiver via multiple hops. Each forwarding-vehicle can apply the above correlation. In section 4.4.1 it was stated that if we accumulate the assumptions of all forwarding and receiving vehicle then at least all vehicles in between the source and receiving vehicle are assumed to have received the notification. This assumption is independent of the number of forwarding vehicles and their position in the platoon. In this section we proof this statement.

Let us first assume that a sent notification is forwarded by $n - 1$ vehicles until it is received by a vehicle n . An abstraction of this situation is illustrated in figure E.1. The vehicles are illustrated in order of transmission and not in order of location in the platoon.

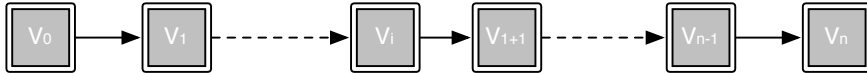


Figure E.1: Multi-Hop forwarding of Notification

For the location of a vehicle in the platoon, we introduce function $L(V_i)$ i.e. $L(V_0)$ is the index of vehicle V_0 in the platoon. Our assumption now

states that if a vehicle i receives a transmission from vehicle $i - 1$, it can assume that all vehicles in between $L(V_i)$ and $L(V_{i-1})$ have received it as well. If we accumulate all these assumptions for an $n - 1$ -times-forwarded notification we get:

$$\begin{aligned}
\sum_{i=1}^n (L(V_i) - L(V_{i-1})) &= \sum_{i=1}^n L(V_i) - \sum_{i=1}^n L(V_{i-1}) \\
&= \sum_{i=1}^n L(V_i) - \sum_{i=0}^{n-1} L(V_i) \\
&= \sum_{i=1}^n L(V_i) - L(V_0) - \sum_{i=1}^{n-1} L(V_i) \\
&= \sum_{i=1}^{n-1} L(V_i) + L(V_n) - L(V_0) - \sum_{i=1}^{n-1} L(V_i) \\
&= L(V_n) - L(V_0)
\end{aligned}$$

The result of the accumulation is the difference between receiving vehicle V_n and sending vehicle V_0 and is independent of the number of forwarders and their location in the platoon. Hence, all vehicles between the receiving vehicle and the source of the notification are assumed to have received the notification.

Appendix F

Implementation of Stop-and-Wait ARQ

The Stop-and-Wait ARQ protocol has been implemented in ns-3 [1] in order to compare its performance against the COACK protocol in Section 4.3 using the metrics of Section 5.3. This appendix describes how the Stop-and-Wait ARQ protocol has been implemented and the parameters being used during simulation.

For the Stop-and-Wait ARQ protocol we can identify two types of roles: the source and destination. The source is the node that initiates a transmission by sending a PDU with payload to the destinations. The destinations are the nodes that are destined to receive the transmitted PDU. Note that these roles are defined per transmission so a node may be the source of one transmission while being the destination of another.

According to these roles, we have split the implementation of the Stop-and-Wait ARQ protocol in two functional blocks: the source protocol operations and destination protocol operations. In the next two paragraphs we will describe respectively both functions.

Source Protocol Operations The source protocol operations are initiated on the transmission request of an upper layer. Figure F.1 illustrates these operations for one transmission request in an activity diagram. The upper layer request contains the set of destination identifiers as well as the payload. Upon this request, the source will store the destinations and set the retransmission counter to 0. Next a Request (REQ) PDU is constructed and broadcasted in a Medium Access Control (MAC) frame after which a retransmission timer is started. Figure F.3 illustrates the content and structure of the REQ PDU.

The source will then wait for the reception of an ACK PDU or timeout of the retransmission timer. When an ACK PDU is received, the corresponding destination is removed from the stored set of destinations. If this set is not

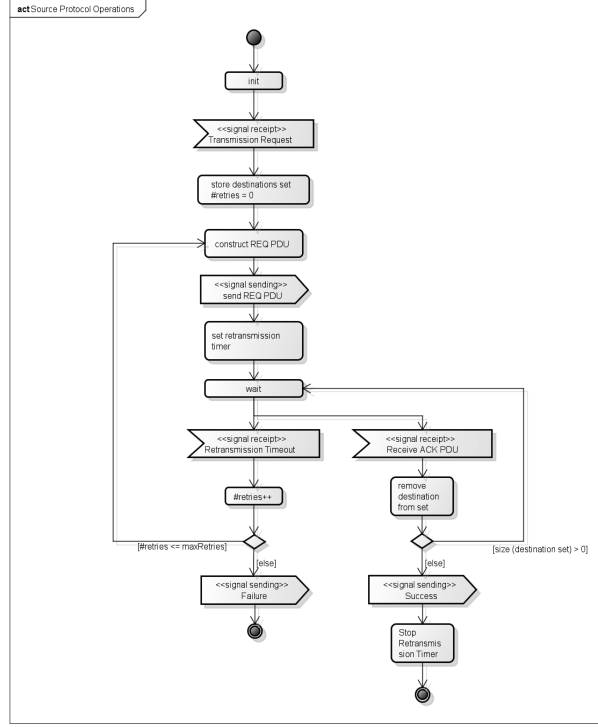


Figure F.1: Stop-and-Wait ARQ Source Protocol Operations

empty i.e. not all expected ACKs have been received, the source continues waiting for the next received ACK PDU or retransmission timeout. If the destination set is empty this means that all ACK PDUs have been received so the retransmission timer is stopped and the upper layer is informed of the success.

Upon the timeout of the retransmission timer, a new REQ PDU is constructed and broadcasted with the latest stored destination set. The transmission fails when the REQ PDU has been retransmitted for the maximum number of times. The upper layer is in that case informed of the failed transmission and the protocol operation is stopped.

The parameters used in our simulation for the retransmission time and maximum number of retransmissions are listed in Table G.1 and are respectively 100 ms. and 4 times. The same values are used for the evaluation of the COACK protocol in Section 5.

Destination Protocol Operations The destination protocol operations are illustrated in the activity diagram of Figure F.2. This diagram shows that a destination reacts on the reception of a REQ PDU. The destination node will reply with an ACK PDU when the received REQ PDU is destined to the destination node. That is when the platoon identifier of the PDU

equals the platoon identifier of the destination node and destination node is part of the destination set. In addition, the payload of the REQ PDU is indicated to upper layer.

The content and structure of the ACK PDU is illustrated in Figure F.4.

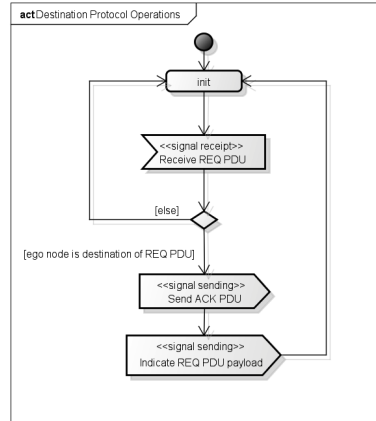


Figure F.2: Stop-and-Wait ARQ Destination Protocol Operations

0	7 8	15 16	23 24	31
platoon ID				
source ID	sequence	type = 0	n = #dst	
destination ID ₁	destination ID _n	
payload length	payload			

Figure F.3: Stop-and-Wait ARQ PDU

0	7 8	15 16	23 24	31
platoon ID				
source ID	sequence	type = 1	destination ID	

Figure F.4: Stop-and-Wait ARQ Acknowledgement PDU

Appendix G

Network Simulation Parameters

The parameters in this appendix are used in the network simulation of Chapter 5.

Parameter	Value
Link Layer	IEEE802.11p
Channel Bandwidth	10 Mhz! (Mhz!).
Channel Number	176
Channel Frequency	5.0 Giga Hertz (GHz).
Modulation Method	OFDM
Transmission Rate	6 Mbps.
Propagation Loss Model	Log-Distance Propagation Model
Log-Distance Reference Distance	10.0
Log-Distance Path Loss at Reference Distance	63.3
Log-Distance Loss exponent	1.77
Road length	1 km.
Vehicle Length	5 m.
Intra-platoon headway	10m
Simulation Runs per Scenario	50
Platoon Length	3, 5 or 7 vehicles per platoon
Maximum Number of Retransmissions	4
Retransmission Timeout	100 ms.
Traffic Densities	0, 50, 100, 150, 200 vehicles/km/lane

Table G.1: Network Simulation Parameters

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