Efficient Communication for Platooning and Overtaking in Intelligent Transport Systems

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Masaki Suzuki

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Masaki Suzuki

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School of Science for Open and Environmental Systems
Graduate School of Science and Technology
Keio University

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Chapter 1

Introduction

1.1 Background

Recently, the studies on Intelligent Transport Systems (ITS) are very active to realize a future sophisticated transportation. The purpose of ITS is to design to integrate people, roads and vehicles in harmony to resolve road traffic problems such as traffic congestion, traffic accidents and environmental degradation as well as to give comfort to drivers and passengers. These researches started at the developed countries in Europe, Asia and America, in 1970s. When we take a look at the ITS progress in Japan, we can easily find several examples of its development; Traffic control center for Metropolitan Expressway (1973), trial operation of Highway Advisory Information Radio System (1980), service-in of Vehicle Information and Communication System (VICS) [6] (1996), a world first test of the cruise control system on the public road (1996), introduction on Electronic Toll Collection (ETC) system [7] (1997), start of new service named ITS Spot [8] which provides three basic services of dynamic route guidance, support for driving safety and extensive use of ETC.

Following the steady improvements of vehicle equipments and traffic systems such as navigation system, dynamic adjustment of traffic signaling system corresponding to the actual traffic flow, and several human engineering improvements to drivers and distinct progresses are identified. For examples, the usage rate of ETC on toll roads in Japan reach 90% [9], and more than 40 million automobiles installed ETC equipments nowadays. As a result, it eliminates almost all toll-gate congestion on expressways which corresponds to the 30% of all the expressway congestion [10]. This also corresponds to reduce CO_2 emissions by approximately 210,000 tons each year. In another example, VICS provides road traffic information on car navigation screens equipped around 35 million cars in Japan which estimated to reduce annual CO_2 emissions by 2.4 million tons in 2009 [11].

Together with the ITS developments, people in the world are so much interested in the ecological aspects of the social life and living. Considering the severe adverse effects of the global warming caused by CO_2 emission in developed countries, United Nations decided the international agreement, called Kyoto protocol, linked to the Framework Convention on climate change, which committed its parties by setting internationally binding emission reduction targets. This protocol was agreed in Kyoto, Japan, on 11 December 1997 [12]. After the several meetings to implement the protocol, its first commitment period started in 2008 and ended in 2012. Despite of the good philosophy and worldwide wishes, the actual realization of their emission reduction target seems to be not easy. Different view and ideas by developed and under-developing countries bring the very complicated problems to this issue. Since the effects of Kyoto Protocol is very much expected, the industries are trying to reduce CO_2 emission as possible as they can. The rapid adoption of hybrid engine to the automobile and introduction of Electronic Vehicle (EV) at the automobile industries are the resulted typical effects of these attempts.

Also, if we take a look closely at the technological aspects of the ITS, significant amounts of researches and developments have been performed in last ten years. IEEE Transactions on Intelligent Transportation Systems published many special issues covering the wide ranges of ITS. "Artificial transportation systems and simulation", "Wireless communication technologies in vehicular transportation network", "Machine learning for traffic sign recognition", "Grand cooperative driving challenge", and "Emergent cooperative technologies in ITS" are the typical examples of special issues. The publications of special issue in the flagship technical journal themselves show the recent rapid progress of ITS research and development self-explanatory.

There are three research motivations: drive the automobile to the destination comfortably and safely, drive without stuck in a traffic jam, and drive without giving adverse effects to the environment. ETC, VICS, EV, etc. are examples of ITS products encour-

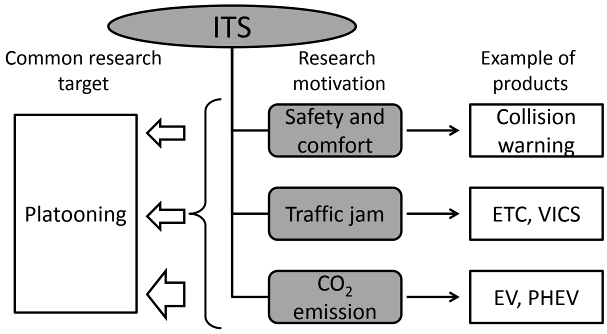


Figure 1.1: Development in ITS

aged by those motivations. In order to step out to the future ITS society smoothly, the several researchers are focusing on their research and development on common research target on platooning as shown in Fig. 1.1.

The platoon is a collection of vehicles that travel together at a high speed with quite small inter-vehicular distance and the platooning is set of the operational procedures to establish, maintain and release the platoon.

The platooning has the following advantages; reduction of air resistance at all platoon member vehicles due to the very short inter-vehicular distance, avoidance of unnecessary acceleration and deceleration of the vehicles due to the synchronization driving of platoon members, and increase of road capacity and decrease of congestion. These advantages reduce the total energy consumption and CO_2 emissions [13]. The main technology of platooning is the Cooperative Adaptive Cruise Control (CACC) [14]. CACC system makes use of the communication technology to exchange their location, speed and acceleration information every pre-determined short period, and enables safe and smooth driving.

The research on platooning is usually attacked by two approaches. One is the experimental approach to realize a group driving using real vehicles. The other is the computer simulation to analyze the mechanism of platoon and examine the introduction of new ideas to the platooning. A typical example of experimental platooning in the United States of America is the project by Partners for Advanced Transportation Technology (PATH) [15]. In Europe, Safe Road Trains for the Environment (SARTRE) [16], KONVOI [17] and Grand Cooperative Driving Challenge (GCDC) [18] put great efforts in realizing distinctive ways of platooning. Also in Japan, Energy ITS project [13] has successfully achieved platooning by four trucks at the velocity of 80 km/h with the 4 m distance between a truck and the one in front.

While many of research efforts try to platooning into practical use, platooning using real vehicles was examined in the case where a single platoon is driving at the test tracks or at the specially prepared duration on the highway without the effects of other vehicles. Furthermore, the current discussion of platoon is limited to run in one lane and not to include the effects of the parallel lanes and also excludes the case where plural platoons and non-platoons drive on the same road. Even if we limit to discuss on a single platoon, the necessary methodology for the vehicle to join and leave the platoon is undecided. Therefore, if we extend to discuss platoon behavior in more realistic situation, such like to extend to mix platoon, non-platoon and individual vehicles on the plural lanes road with both direction, much more efforts will be required on the communication methodologies among vehicles.

Besides the communication issue, platoon has several issues to be clarified. One important issue is how to examine the platooning under the mixed condition where platoons and non-platoon vehicles are driving on the same road. Currently, though platoons are supposed to drive in a dedicated lane or a designated lane, all the discussion is started after it is established and studied only on the driving period of a single platoon [19]. However, in the future, it will be realistic that the situation where the non-platoon vehicles drive on the same load. In these situations, a platoon will be running in more flexible way such that it will overtake preceding slow vehicle by changing its lane and fast vehicle will overtake a platoon. At present, research on platooning is its beginning, and there will still need a lot of effort to realize platooning.

1.2 Position of This Dissertation

Among the several ITS studies, cooperative driving is a very attractive research topic from several reasons such that it can significantly increase traffic throughput, limit CO_2 emission, etc. Spirit of cooperation is to help each other before, on spot, and after they face the difficult situations. In order to develop the cooperative driving, the reliable and high

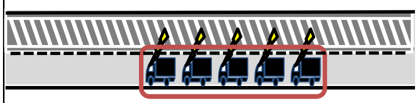
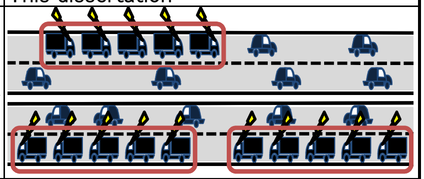
	Existing researches		This dissertation
Communication image		→	
Approach	Experiment with real vehicles (Trucks) in test track or limited district in a highway (PATH, SARTRE, Energy ITS, GCDC, SCANIA, KONVOI)		Not considered (High cost/ Time consuming)
	Simulation (PATH, SARTRE, Energy ITS, KONVOI)	→	Simulation
Communication	CSMA/CA(intra-platoon) (PATH, SARTRE, Energy ITS, GCDC, KONVOI)	→	Time slotted communication protocol for platooning
	Time slotted communication (RR-ALOHA, MS-ALOHA)	→	
Platooning	- Single lane - Single platoon (PATH, SARTRE, Energy ITS, GCDC, KONVOI)	→	- Plural lanes (including single lane) - Plural Platoons (including single platoon)
Overtaking	No overtaking(PATH, SARTRE, Energy ITS, GCDC, SCANIA, KONVOI)	→	Overtaking

Figure 1.2: Position of this dissertation

speed communication between vehicles to vehicles, and vehicles to road infrastructures is indispensable.

In the cooperative driving, platooning is a key technology to establish, maintain and release a platoon. It is for the several vehicles to make a unit, and move to the destination synchronously with keeping the same distance between a car and the one in front. Platooning has important merits. In the case that a platoon goes to a destination, the aerodynamic drag on platoon members is reduced significantly. Since the car in front and the following keeps the same distance in synchronization, the following cars can suppress over-accelerate and over-decelerate. This brings the great merit to reduce the use of gasoline and, in consequence, good for the environment. Moreover, drivers will receive less pressure on driving affairs and comfortable feelings. Also platooning is the promising technology for the future non-driver autonomous driving.

Up to now, the researches on platooning have been organized either by experiments using real vehicles on road or by computer simulations. The experiments using real vehicles on the road need a lot of cost and time consuming preparation, and testing items can be limited. On the contrary, computer simulation is rather easy to conduct in the case that the driving model and road condition are well incorporated. It is also true that simulation will exhibit a chance to overcome a problem step by step and can extend its scope of study gradually.

There need to consider two aspects on the study of platooning. One aspect is the communication protocol itself. The other is the service that use communication. These two aspects are closely related and in some cases application program are developed based on the communication characteristics. In the vehicle-to-vehicle communications, IEEE 802.11p or an experimental guideline for vehicle to vehicle communication, ITS FORUM RC-005 [20] is used, and both of them are based on Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA). Therefore, all the experiments on platoon using real vehicles are examined by CSMA/CA. So far they are limited to examine the driving behaviors of a single platoon without the effect of other vehicles, CSMA/CA protocol can work without interference among platoons. The platooning experiments by PATH in U.S.A, and SARTRE, KONVOI and GCDC in Europe, as well as Energy ITS, Japan, use this protocol. However, if we extend the communication with other platoons and non-platoon vehicles, we can easily assume the adverse effects of the hidden terminal problems [21], as well as the biased use for the specific vehicle's communication on the CSMA/CA channel. In order to cope with these problems, time slotted communication protocol has been studied [5, 22–24]. Time slotted communication protocol introduces the idea of time slot from Time Division Multiple Access (TDMA) protocol. The Reliable Rservation-ALOHA (RR-ALOHA) [22] is one of the time slotted communication protocol designed to resolve the hidden terminal problem. However, these studies of time slotted communication protocols do not work as it expected in the case where time slot synchronization becomes inaccurate. Therefore this dissertation proposes to add time slotted communication mechanism to the CSMA/CA to overcome above difficulties by applying both merits of stable performance under congested network conditions of CSMA/CA and periodical fair usage of time slotted communication protocol.

Another problem on platooning discussed in this dissertation is the overtaking problem. Current platooning experiments using real vehicles and computer simulations do not take into consideration of the mutual effect between non-platoon vehicles and platoon such as overtaking, since they examine the performance and member vehicle's behavior of a single platoon. However, in the realistic environment, it can be assumed that platoons and non-platoon vehicles are running on the same road. In the case of Energy ITS, Japan, platoons are supposed to never change lanes except for the emergency case and to follow the preceding vehicle even if the vehicle drives slowly [25]. Therefore, it is better to tackle this overtaking problem as a step towards the future realistic simulation. This dissertation clarifies the overtaking control by using the model of two lane highway for one direction where inner lane is used for the platoon and passing lane for overtaking. The applicability of the distributed mutual exclusion algorithm at the overtaking zone is examined precisely to avoid the unnecessary vehicles block at the passing lane.

As for the summary of this section, Fig. 1.2 shows the position of this dissertation. While the existing researches focused on the model where a single platoon drives, this dissertation extends it to the model where plural platoons drive in a designated lane and non-platoon vehicles drive in plural lanes as shown in the row of "Communication image".

1.3 Contributions

Platooning is the key technology for the future ITS, especially for the reduction of energy consumption and CO_2 emission caused by vehicles, and once a vehicle joins a platoon, the driver can obtain less pressure for driving due to the synchronized driving with other member vehicles. The former studies on platooning is performed in the limited environment where a single platoon is running without considering the effects of other vehicles running in the same or opposite directions. This dissertation extends the platooning environment to mixed conditions where a platoon is running together with other platoons.

The communication to maintain the platoon needs high speed and reliable information exchange. Currently, IEEE 802.11p or Experimental guide line for vehicle to vehicle communication RC-005 is used for platooning, and both of them are based on CSMA/CA. Since all platoon members are necessary to exchange the information periodically at very short intervals, we will have to face the congestion and the hidden terminal problems when we extend the simulation to the the mixed conditions of plural platoons in plural lanes. There were some attempts to overcome the effect of hidden terminal problems in the past. The RR-ALOHA and Mobile Slotted ALOHA protocols were the examples. However, in the case where the road becomes crowded and the communication slots on channel were occupied by the information of the specific vehicles unevenly, these protocols could not realize a uniform and unbiased information exchange within platoon member vehicles. Therefore, this dissertation proposes the time slotted communication protocol. It also introduces the cyclic retransmission mechanism which is named repetitive transmission and the slot assignment by the leader vehicle in platoon. In this protocol, the successful data transmission increases the reliability of the information exchange among platoon members by solving wireless channel congestion at CSMA/CA channel and hidden terminal problem. This dissertation clearly exhibits that proposed protocol keeps the higher data arrival ratio than the RR-ALOHA protocol, and realizes to weaken the adverse communication effects by the congestion and hidden terminal problems. It is also exhibited that giving the slot assignment priority to the leader vehicle can avoid the collision of slot reservation among the member vehicles in platoon and improve the platoon maintenance.

This dissertation also clarifies the platoon overtaking action by efficient communication support. One platoon consists of several vehicles, and the distance from the top front vehicle to the last vehicle is long. Currently, the rule for the vehicle to join and leave in the middle of platoon is not decided as well as the rule to suspend the platooning. As a result, if some vehicle tries to overtake a platoon, this vehicle will need a long journey to overtake a platoon. When the actual overtaking starts, the adjacent lane to the platoon becomes the critical section. In the case that two vehicles enter the critical section at the same time, and the speed of former vehicle is slower, the following vehicle will be difficult to overtake until the former vehicle finishes overtaking the platoon. This dissertation proposes an overtaking control method based on the distributed mutual exclusion algorithm. In this method, the leader vehicle of the platoon allow surrounding vehicles to enter the critical section one by one according to the First Come, First Served (FCFS) policy. It is also clarified the case that a non-platoon vehicle overtakes plural platoons driving in tandem. This dissertation exhibits the proposed method reduces unnecessary acceleration/deceleration and CO_2 emissions.

Table 1.1: Summary of contributions

	Models and features	Contributions
Communication	- Time slotted communication protocol for platooning	- Solve wireless channel congestion - Solve hidden terminal problem
Platooning	- Plural lanes (including single lane) - Plural Platoons (including single platoon)	- Improve information exchange within platoon members - Improve platoon maintenance
Overtaking	- Overtaking where platoon drives in a designated lane (using Token-based method at critical section)	- Reduce unnecessary acceleration/deceleration and CO_2 emissions

As for the summary of this section, Table 1.1 shows the contribution of this dissertation. The contributions of this dissertation is described in terms of communication, platooning and overtaking. In each aspect, contributions are introduced from the models and features.

1.4 Organization of This Dissertation

The purpose of this dissertation is to identify the importance of platooning in ITS and clarify the communication needed for platoon by two aspects. One is the communication protocol itself to realize to establish, maintain and release a platoon. The other is the efficient realization of overtaking of platoon using the communication facilities. Therefore, the rest of this dissertation describes the following the flow as depicted in Fig. 1.3.

Chapter 2 first describes the concept of ITS and worldwide attempts to its promotion to future comfortable and ecological society. Then this chapter covers the researches and developments on cooperative driving and its one of the core technology of platooning. Since the former researches are limited to study on the very simple platooning where only a single platoon is driving alone. However, this chapter expresses the necessity to extend the driving situation where platoon is running together with other platoon and non-platoon vehicles. Finally this chapter suggests the two needs to study. One is the study on communication protocol necessary to cope with the mixed driving situation of platoon and non-platoon situations. The other is the study on the overtaking of platoon at the case where slow vehicle is running in front, and where the faster vehicles come after

Table 1.2: Overview of Chapters 3 and 4

Chap. 3	Purpose	- To keep exchanging information for maintaining platoon under crowded traffic conditions
	Problem	- Wireless channel congestion and hidden terminal problem occur when plural platoons drive
	Proposed scheme	- Time slotted communication protocol for platooning ·CSMA/CA channel with pseudo TDMA frame ·repetitive transmission rate control ·mechanism of representative slot reservation
	Contribution	- To solve wireless channel congestion and improve information exchange within platoon members - To solve hidden terminal problem and improve platoon maintenance
Chap. 4	Purpose	- To develop overtaking platoons driving in a designated lane
	Problem	- It is difficult for a faster vehicle to overtake a slower vehicle when a platoon drives between them
	Proposed scheme	- Communication for overtaking using token-based distributed mutual exclusion algorithm
	Contribution	- To develop the platoon overtaking model based on Energy ITS assumption - To reduce unnecessary acceleration/deceleration and CO_2 emission

the platoon.

Chapters 3 and 4 are the main body of this dissertation. The overview of these chapters are sown in Table 1.2. Chapter 3 proposes and describes the time slotted communication protocol in detail. In the case where plural platoons in the same road, it is easy to assume the occurrences of wireless channel congestion in the CSMA/CA channel and hidden terminal problems. Therefore, this dissertation proposes the time slotted communication protocol introducing CSMA/CA channel with pseudo TDMA frame, congestion avoidance using repetitive transmission rate control, and mechanism of repetitive slot reservation. The simulation results clarify that the proposed protocol solves wireless channel congestion and improves information exchange within the platoon members. Also they clarify that the proposed method solves hidden terminal problem and improves platoon maintenance.

Chapter 4 shows the communication for overtaking in detail. Currently in Energy ITS, Japan, there is an assumption that the platoon is driving in the designated lane on the highway. Therefore, the overtaking is possible to occur when a platoon catches up with the slower vehicle driving ahead, the slower vehicle has to change its lane to the passing lane and gives its way to the platoon. Also the faster vehicle can overtake a platoon from its behind. Trouble will happen when slower and faster vehicles enter the passing lane at the same time. The faster vehicle can not overtake the slower vehicle. In order to solve this problem, this dissertation proposes to use a token-based distributed mutual exclusion mechanism to assure only a single vehicle can enter the critical section. This chapter conducts series of platoon overtaking simulations. The amount of acceleration/deceleration and CO_2 emission are suppressed by the token-based method.

Finally in Chapter 5, this dissertation gives the concluding remarks.

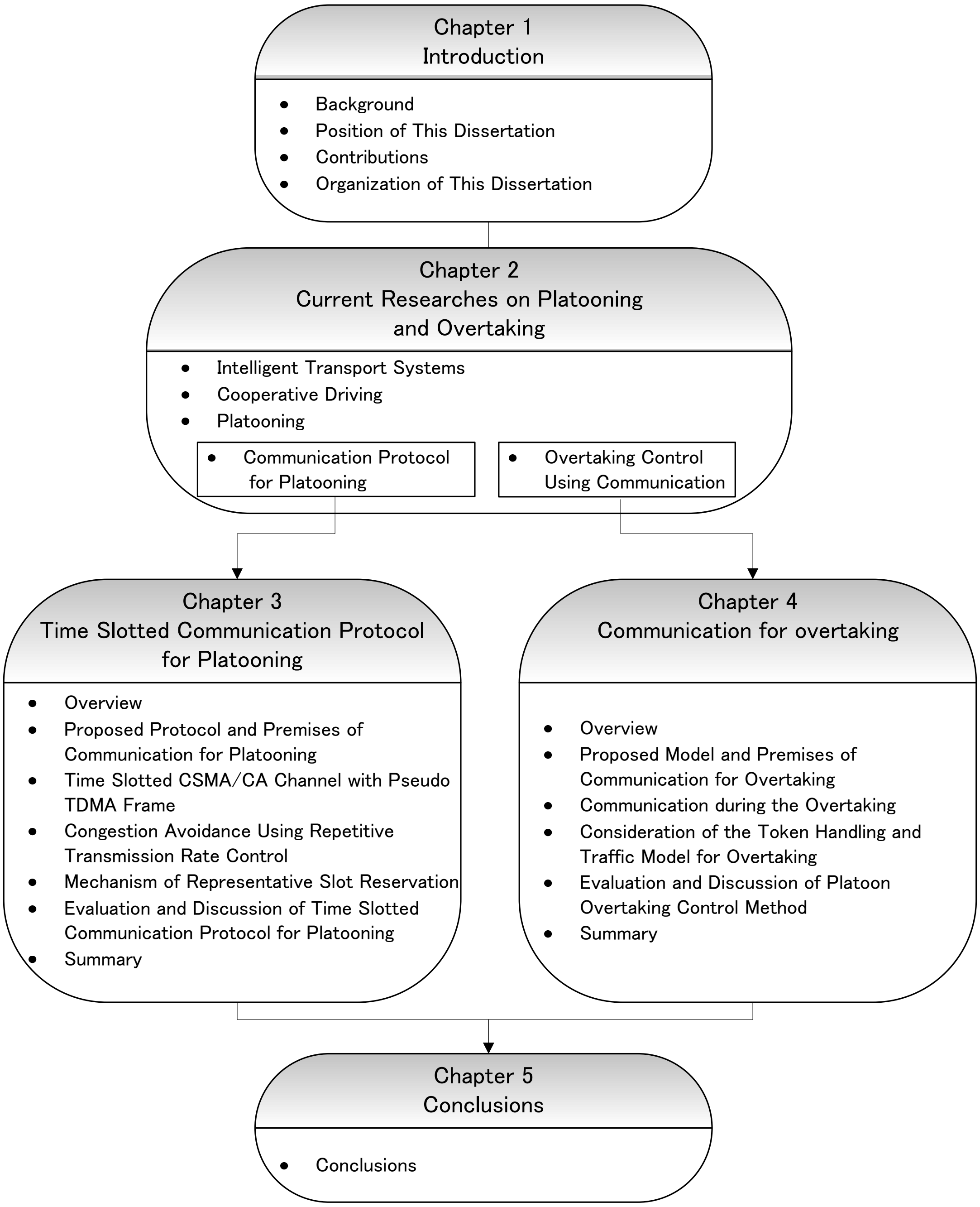


Figure 1.3: Organization of this dissertation

Chapter 2

Current Researches on Platooning and Overtaking

2.1 Intelligent Transport Systems

ITS aims to integrate people, roads and vehicles using Information, Telecommunication and Computing (ITC) technology to reduce traffic jam, accident and energy consumption and improve ecological environment. Figure 2.1 shows the concept of ITS. Since the necessary technologies for ITS are very wide, their individual developments enable to change our whole society and create new markets and industries.

Studies on ITS started in early 1970s. Government, automobile industries and academia in Europe, the U.S.A. and Japan are very active to make research and development on it. They have been encouraging to study ITS, and organizing the World ITS Congress annually to ensure their accomplishments and future research directions. In the case of Japan, the developments of ITS can be classified by three stages [1]. The first stage started in 1995 when Road bureau of Ministry of Land, Infrastructure, Transport and Tourism in Japan advocates "the promotion for practical use of ITS" [4, 26]. They defined 9 comprehensive plans and 21 required user services as the guideline for development as shown in Table 2.1. The second stage started from 2004. They claimed on the "Encourage the use of ITS services and return their profits to society". Also in 2010, they advocated the "next-generation ITS" and appealed the necessity to cope with the social problems.

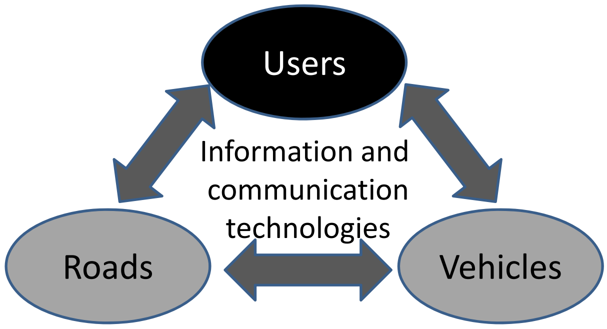


Figure 2.1: Concept of ITS [1, 2]

Much progress can be seen in the history of ITS development in Japan. The examples are the followings. Traffic control center was established on Metropolitan Expressway in 1973. Trial operation of the highway advisory information radio system started in 1980. The introduction of the navigation equipments to the individual cars was getting popular during this period. VICS Service began in 1996. This service provides road traffic information on the car navigation screens, and driver can detour to avoid the congested route with the help of VICS's information dynamically. VICS is installed over 35 million automobiles nowadays, and reduced annual CO_2 emission significantly.

In order to promote the safety and ecological driving, the world first test of cruise control system on the public road was demonstrated in 1996. 25 companies participated in this final test and 11 vehicles were successfully operated continuously for 11 km. Much attention was paid to the popularity of the ETC. ETC service began in 1997, and around 87 % of toll gates already introduced in 2009 [9]. Around 39 million automobiles have ETC equipments as well. The Effects of ETC is very large, and successfully eliminates almost all toll-gate congestion on expressway which causes the 30 % of all expressway congestion before the introduction of the ETC service [10]. More advanced navigation service named "ITS Spot" started in 2011 [8]. This service includes three basic services, dynamic route guidance, safety driving support and extensive use of ETC. More than 1,600 ITS Spots are installed mainly on expressway and collecting the road and traffic information. If the automobiles equip the ITS spot compatible navigation system and access this service, ITS dynamically presents the optimum route guidance to the destination with the time data. This service also provides the congestion warning, obstructions warning on the road, weather conditions at the next coming route cities etc., till the destinations. This service also includes the extensive usage of ETC for the parking charge and for shopping as same as the credit card.

Beside the service issues of the ITS, much of the works are concentrated in the improvements of the mechanism for automobile itself and adoption of new technologies. Japanese government and industries have strong wishes to resolve the air polution and global warning problem. In Japan, 19 % of CO_2 emission is derived from transportation and 90 % of it is from vehicles [2]. Therefore, reduction of CO_2 emission from vehicles becomes the most urgent issue. Automobile companies are trying to introduce EV and Plug-in Hybrid Electric Vehicle (PHEV). They equip with lithium rechargeable batteries or another type of new energy devices. Since they drive with electric power instead of gasoline, the energy efficiency is superior to the traditional gasoline automobile, and brings strong effect to the reduction of CO_2 emission. The other is the development of technology to prevent the collision and to enhance comfortable safety driving. For example, following the declaration by ITS Strategy Headquarter in Japan, ITS-SAFTY 2010 project has started in 2009 aiming at "the safest transportation system society in the world". This project concentrated the work to prevent the collision with forward obstacles and support for keeping same lane, which is called Lane Keeping Assist System (LKAS). This project also focuses on the prevention method for intersection collision and rear-end collision which occurs at the curve with poor visibilities. In order to avoid these accidents, driver should be better to receive road and traffic condition beforehand he/she reaches the critical area. In this context, the close communication among drivers, automobiles, and road infrastructure is indispensable. This dissertation calls them "vehicle to vehicle cooperation" and "vehicle to infrastructure cooperation", respectively. Among the several research issues on ITS, researches on safe and comfortable driving are also very important. Since very long period ago, people were dreaming the autonomous driving. It may be a great dream to the human beings, however again the realization for the communication with other vehicles and infrastructure will be essential.

Table 2.1: Comprehensive plans and user services in ITS [1,4]

Comprehensive plan	User services
1. Advances in navigation systems	(1) Provision of route guidance/ traffic information (2) Provision of destination-related information
2. Electronic toll collection systems	(3) Electronic toll collection
3. Assistance for safe driving	(4) Provision of driving and road conditions information (5) Danger warning (6) Assistance for driving (7) Automated highway systems
4. Optimization of traffic management	(8) Optimization of traffic flow (9) Provision of traffic restriction information on incident management
5. Increasing efficiency in road management	(10) Improvement of maintenance operations (11) Management of special permitted commercial vehicles (12) Provision of roadway hazard information
6. Support for public transport	(13) Provision of public transport information (14) Assistance for public transport operations and operations management
7. Increasing efficiency of commercial vehicle operations	(15) Assistance for commercial vehicle operations management (16) Automated platooning of commercial vehicles
8. Support for pedestrians	(17) Pedestrian route guidance (18) Vehicle-pedestrian accident avoidance
9. Support for emergency vehicle operations	(19) Automatic emergency notification (20) Route guidance for emergency vehicles and support for relief activities (21) Utilization of advanced information enabled in the advanced information and telecommunications society

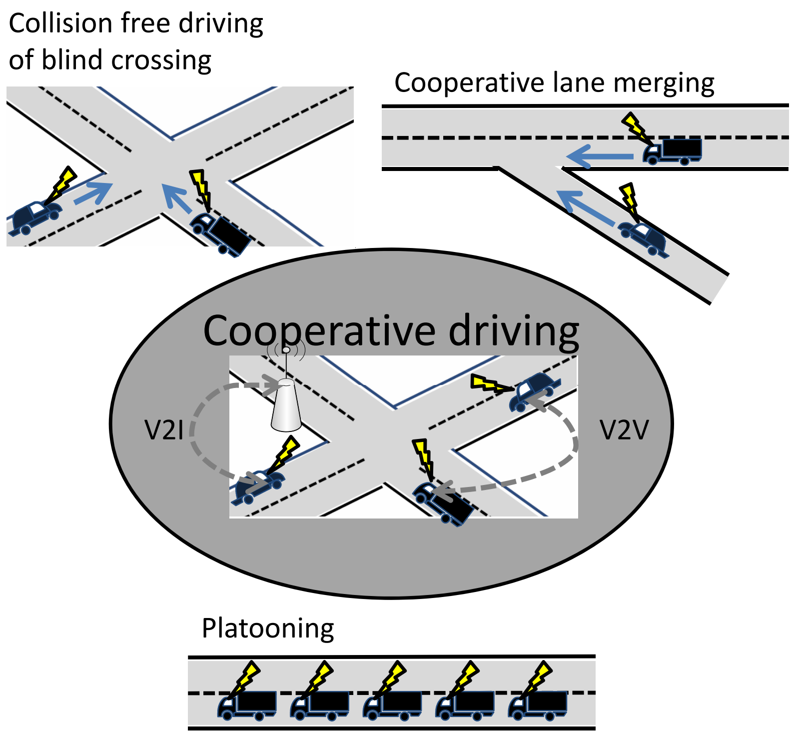


Figure 2.2: ITS applications using cooperative driving

2.2 Cooperative Driving

Cooperative driving is defined in various way, however the following definition is given by Ellen van Nunen et al. [27] has the general consensus. Cooperative driving is a promising technology that can significantly increase traffic throughput, limit CO_2 emissions, improve traffic safety, and increase driving comfort. Cooperative driving covers several comprehensive plans; 3, 4, 6 shown in Table 2.1. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) connectivity allow cooperative systems to offer drivers, road authorities, roadside infrastructure more information about vehicle's state, their intensions, and road conditions. This enables efficient and safe traffic, as well as early warning for upcoming possible traffic situations, e.g. incidents and hazards.

Figure 2.2 shows the several applications of ITS using cooperative driving. Cooperative lane merging, collision-free driving at blind crossing and platooning are the typical

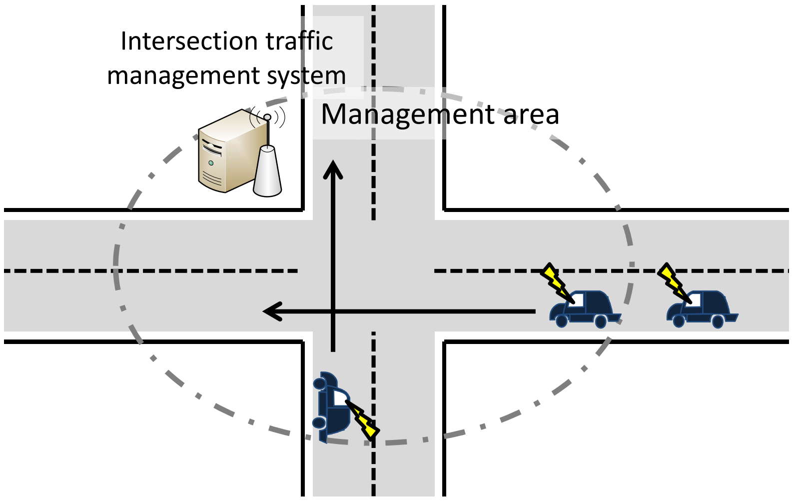


Figure 2.3: Cooperative driving for passing through the intersection [3]

examples which make use of cooperative driving. In cooperative lane merging, the blind spot monitoring system prevents the side-swipe accidents during lane-change and merging scenarios [28]. Once a vehicle decides to change the lane, the vehicle communicates with surrounding vehicles to exchange the information on their location, lane and velocity. If the vehicle has the potential to collide with another vehicle, the blind spot monitoring system alert the driver to suspend and wait changing lanes. So that the vehicle is able to notice whether it crashes into other vehicles even if other vehicles are in the blind side. In consequence, vehicles are able to avoid side-swiped accidents.

The concept of collision-free driving [3] is a control method for vehicles to pass through an intersection by cooperation with each other through the contact with intersection traffic management system. Vehicles periodically announces the observed information of location and velocity. The centralized system collects such information within the management area and estimates each vehicle's trajectory. Then, it checks whether trajectories of vehicles are overlapped at the intersection or not. If the overlap exists, those vehicles have potential to collide with each other. In this case, first, the centralized system synchronize the clock on those vehicles. Then, it calculates the schedule which vehicles enter the intersection without overlaps of their trajectories based on the First Come, First Served (FCFS) policy. According to the calculated schedule, it indicates the proper acceleration

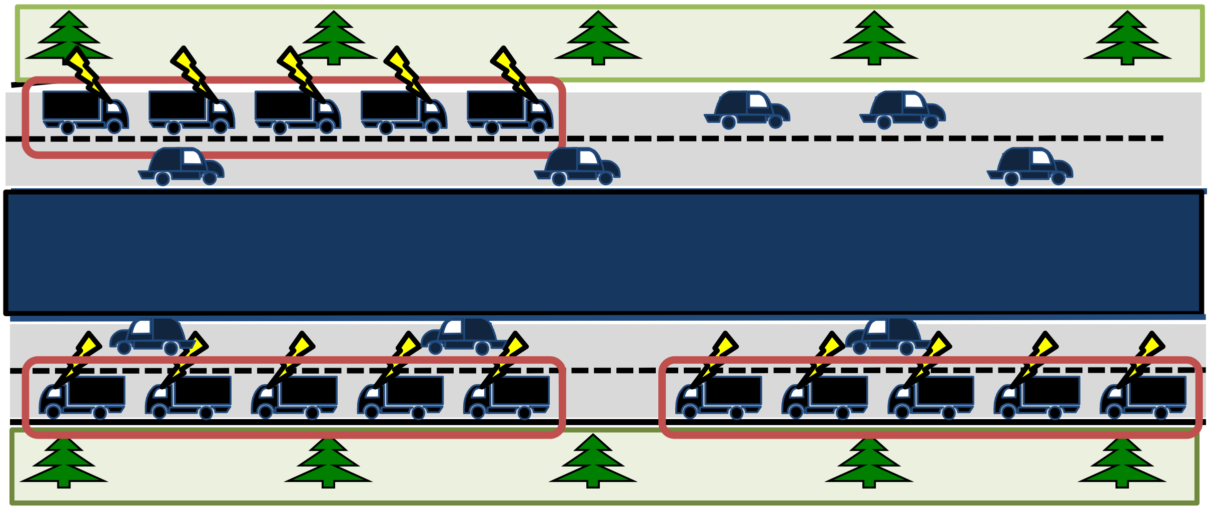


Figure 2.4: Concept of platooning

Table 2.2: Measurement items for lateral and longitudinal control

Lateral	**Longitudinal**
Distance from a front wheel to line markings	Distance to preceding vehicle or obstacles in front
Distance from a rear wheel to line markings	Brake pressure
Current position	Acceleration
Yaw rate (angular acceleration)	Velocity
Velocity	

for vehicles. It controls entire vehicle movement there to cross the intersection without stop and collision as shown in Fig. 2.3.

Platooning is also used in the cooperative driving as one of the key technologies. The details are described in Section 2.3.

2.3 Platooning

The platoon is defined as a group of synchronized driving vehicles under the same policy, and platooning is the generic procedures to establish, maintain, and release the platoon.

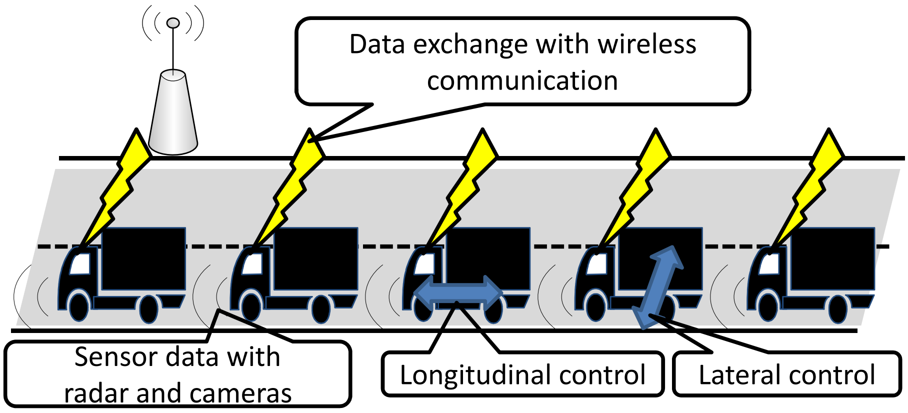
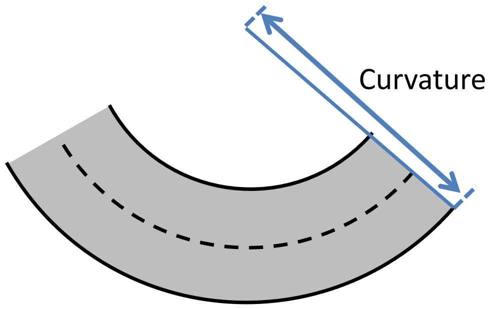


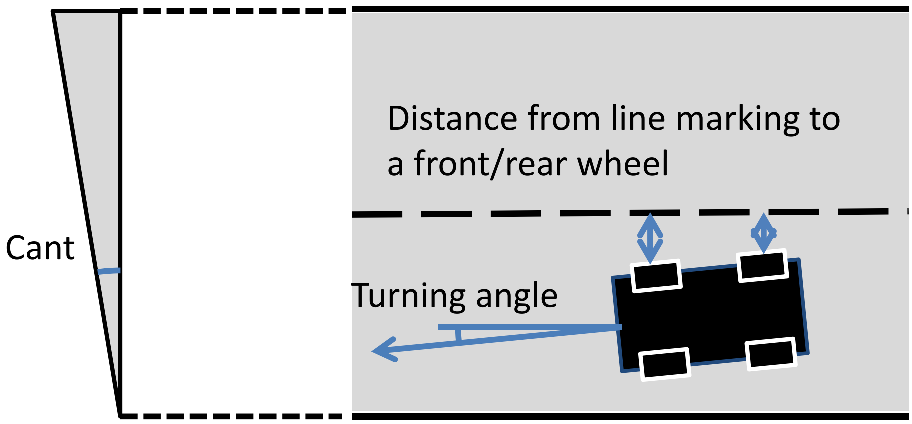
Figure 2.5: Key elements of platooning

Grouping several vehicles into a platoon is an efficient method to increase the road capacity. Platoon can decrease the distance between all vehicles in the platoon and drive smoothly with the synchronized acceleration and deceleration, and move as a single unit. The expected potential merits of platooning are greater fuel economy due to reduced air resistance, reduced traffic congestion, almost automated driving on longer highway trip in the following mode, and fewer traffic congestion. Figure 2.4 shows the concept of platooning. In the figure, bidirectional road of two lanes in each direction and vehicles drive on the left. 5 trucks organizes a platoon with short inter vehicular distance only in the inner lane. As the typical values of platoon, the total length of platoon member is about 12 m and the inter vehicular distance is 4 m. It means that the length of platoon becomes about 76 m. At the same time, non-platoon vehicles drive on the same road, non-platoon vehicles drive in the both of inner and passing lane.

In order to safely keep short inter vehicular distance, the autonomous driving is required instead of the manual driving. The autonomous driving consists of two key technologies; lateral control and longitudinal control as shown in Fig. 2.5. In other words, they are steering and acceleration control, respectively. Platoon members are equipped with wireless communication devices and various sensors; speed meter, micro-wave radars, laser radars, GPS, cameras, etc.. Sensors measure conditions inside and outside of the vehicle. Table 2.2 shows the measurement items by sensors for the lateral and longitudinal control



(a)



(b)

Figure 2.6: Lateral control (a) Curvature (b) Cant and turning angle

in Energy ITS project as the example. Then, vehicles exchange those data periodically through wireless communication. Finally, vehicles adjust acceleration and steering angle according to the lateral and longitudinal control algorithm.

In the lateral control, the vehicles measure the distance to line markings, calculate the current angle and refer the cant and curvature as shown in Fig. 2.6. The vehicle measures the distance from a front wheel and a rear wheel to the line markings, then the vehicle calculates the current turning angle. The vehicle measures the current position with GPS and knows the cant and the road curvature according to the corresponding road map information which the vehicle knows in advance. Moreover, combining with the current yaw rate and velocity, the lateral control system calculates the optimized steering angle for keeping the lateral position in the lane, based on the lane keeping algorithm. Then, the lateral control system controls the hydraulic power steering system according to the optimized steering angle.

In the longitudinal control, the vehicle measures the distance to preceding vehicle or obstacles in front, the brake pressure, the acceleration and the velocity. At the same time, the vehicles share such information among platoon members at 20 msec cycle through the wireless communication [29]. The leader vehicle drives at an expected velocity decided in advance unless the obstacles are detected. Once the leader vehicle detects the obstacles, the leader vehicle decelerates to avoid the collision. Right after the detection, the leader vehicle informs the deceleration to the following vehicles. The following vehicles adjust their velocity to the preceding vehicle in order to keep a certain constant inter vehicular distance based on the Cooperative Adaptive Cruise Control (CACC) system. In this example, the longitudinal control system corrects the error in the inter vehicular distance according to the measured inter vehicular distance by sensors.

There exist various projects for platooning in Europe, the U.S.A. and Japan. Table 2.3 shows the typical researches on platooning with their features on communication and traffic action. In Europe, SARTRE [16], GCDC [18, 30], KONVOI [17] are the major projects on platooning. Safe Road Trains for the Environment (SARTRE) [16, 31] is funded by the European Commission under the Framework 7 programme (FP7 project). SARTRE aims to develop strategies and technologies to realize platooning on normal public highways in order to get environmental benefit, safety and comfort driving. In SARTRE, platoons drive on public highway without modification to the infrastructure such as dedicated lanes, and platoons are led by a manually driven heavy vehicle which is controlled by a trained professional driver. Moreover, platoons follow the leading vehicle automatically, and a vehicle may join or leave the platoon dynamically as it wishes. Its communication [32] is based on ITS-G5 which is originally based on IEEE 802.11p and standardized by European Telecommunications Standards Institute ITS (ETSI ITS). As a backup for the communication, 2.4 GHz WLAN device is also equipped on the vehicles. V2V communication allows vehicles to share data such as speed and sensor data and to autonomously follow leading vehicle both laterally and longitudinally.

Table 2.3: Typical researches on platooning with their features on communication and traffic action

Year	project on promoting organization	Research Groups	Features on communication	Features on traffic action	Other remarks
1986- (1994- for platoon)	Platooning by PATH [15]	Carifornia PATH, (in the U.S.A.)	- 802.11b(CSMA/CA)	- lateral and longitudinal control - assume no non-platoon vehicle - using the magnetic guides on the road	- focusing on traffic throughput per lane and energy saving
1996	R-ALOHA [33]	Bolt Beranek and Newman Inc.(in U.S.A.)	- Time slotted communication protocol in distributed fashion - solving data collision due to hidden terminal		
2000	Cooperative Driving System in DEMO 2000 [34]	Ministry of International Trade and Industry (in Japan)	- 5.8 GHz band communication for demonstration (DOLPHIN)	- support non-platoon vehicle to lane changing at lane merging	- demonstration of platooning with autonomous driving
2002, 2004	RR-ALOHA [22]	Politecnico di Milano (in Italy)	- reliable R-ALOHA for Vehicular Ad-hoc NETwork (time slotted communication protocol)		
2005-2009	KONVOI [17]	RWTH Aachen University (in Germany)	- based on 2.4 GHz broadband communication(CSMA/CA) and 3G communication	- lateral and longitudinal control - assume no non-platoon vehicle	
2008-2012	Energy ITS [13]	NEDO (in Japan)	- Repetitive transmission - RC-005(CSMA/CA)	- lateral and longitudinal control - platoons follow the preceding slow vehicle - platoons avoid obstacles changing lane	- focusing on tenergy saving and mitigating lack of skilled drivers
2009-2012	SARTRE [31]	European Commission under the Framework 7 programme	- based on ITS-G5(802.11p (CSMA/CA)) - 2.4 GHz WLAN for backup	- lateral and logitudinal control - vehicles dynamically join and leave platoon	- focusing on comfort, safety, congestion and energy
2010-2011	(a part of) the Strategic Platform for Intelligent Traffic System (SPITS) [35]	ITS sector (in the Netherlands)		- reduction in shockwave - drastic reduction in chain collision accident - improvement in traffic throughput	
2011	Grand Cooperative Driving Challenge (GCDC) [18]	High Tech Automotive Systems (empowered by Dutch Ministry of Economic Affairs)	- based on 802.11p(CSMA/CA) - communication requirement is not severe because of no lateral control (RTT between vehicles = 16 ms in one team)	- longitudinal control	- International teams competing to deliver the most effective cooperative vehicle-infrastructure system (platoon) in terms of the platoon length and the string stability (equals shockwave reduction performance)

Application	Application
	GCDC Interaction Protocol
Networking service	CALM-FAST
MAC	IEEE 802.11p
Physical	(5.9 GHz)

Figure 2.7: GCDC communication stack

The Grand Cooperative Driving Challenge (GCDC) [18, 30] in the Netherlands is an international teams competition providing the possibility for teams to develop and compare their cooperative driving solutions. GCDC aims to accelerate the implementation of platooning and contribute significantly to alleviate traffic problems worldwide [27, 36–41]. Nine international teams challenged each other to handle both an urban and a highway scenario. The specific systems vary depending on the team. For instance, a team from Karlsruhe, Germany, adopted the stereo vision sensors for longitudinal control. A team from Halmstad, Sweden, adopted Real Time Kinematic Global Positioning System (RTK-GPS) in order to measure precise vehicle's location. However, several parts of the system are defined by the organizer of the competition. The vehicle assumed to be controlled only in longitudinal way and not to be controlled in lateral way. Therefore, the communication requirement is not severe compared with other projects. According to the result of the team from Chalmers University of Technology in Sweden, round trip time between vehicles is 16 msec. It is short enough for only longitudinal control to work appropriately. Figure 2.7 shows the GCDC communication stack. MAC and PHY layers are IEEE 802.11p and, above that, Communication Access for Land Mobiles (CALM-FAST) protocol is employed. On top of the CALM-FAST protocol, the specific GCDC protocol [42] is employed. The application on the GCDC is developed by each team. As a unique point, the competition focuses on the compatibility between vendors struggling to achieve safe interaction between competing teams.

KONVOI [17] was a German national project which focused on platoons consisting of only heavy duty trucks and these trucks were electronically controlled. After the virtual test drives by the truck driving simulator, they had conducted the real test drives on the public highway. The trucks were required to communicate with other member trucks through 2.4 GHz broad band and with Central KONVOI-Server through 3G communications such as Universal Mobile Telecommunications System (UMTS), General packet radio service (GPRS) or Global System for Mobile Communications (GSM). The trucks are also equipped with sensors and cameras in order to keep lane and to control short inter vehicular distance. Platoon is assumed to drive alone in the dedicated lane and there exists no other platoon and non-platoon vehicles around the platoon. KONVOI finally achieved platoon consisting of 4 trucks with 10 m inter vehicular distance.

In the U.S.A., PATH [15] is a California traffic automation program studying platooning. Since in the U.S.A., especially in California state, the traffic jam is a social problem, originally the project aims to produce a significant increase in the capacity of a highway lane. Four electronically grouped platoon automobiles were demonstrated in 1994. In addition, heavy duty truck was also a social problem, so that large zone of the truck lane has been constructed and platooning for commercial logistics truck becomes a possible target. Therefore, recently in this project, the platoon is assumed to consist of only heavy duty truck and drive in the dedicated lane. The platoon traces magnetic markers which are placed at regular intervals in the dedicated lane. Therefore, the platoon is laterally controlled. The longitudinal control is based on the Cooperative Adaptive Cruise Control (CACC) as same as the other project. The CACC requires vehicle to vehicle (V2V) communication for longitudinal control. The standard for V2V communication is called the Dedicated Short-Range Communications (DSRC)/Wireless Access in Vehicular Environments (WAVE) based on IEEE 802.11p. The wireless communication is also used for the lateral control exchanging the vehicle information of inter-vehicle distance, velocity and acceleration along with the platoon coordination information of fault status and operating mode. The communication requirement is strict (same as Energy ITS, Japan), the transmission of the state information for all vehicles within the platoon at 20 msec intervals. Therefore, in the demonstration in 2004, Real Time Token Ring protocol was employed on IEEE 802.11b [43].

Energy ITS is initiated by Japanese Ministry of Economy, Trade and Industry in 2008 [13,44] and later empowered by New Energy and Industrial Technology Development

Organization (NEDO). The project aims at two goals; an automated truck platooning and establishing evaluation method of effectiveness for energy saving. As partially described above, the platoon in Energy ITS consists of only heavy duty truck for commercial logistics. The platoon is both laterally and longitudinally controlled without any centralized system except line markings. The platoon drives under mixed condition with non-platoon vehicles, though in the final goal, platoon is supposed to drive in a designated lane. The wireless communication is used for the longitudinal control in V2V communication and based on DSRC/ITS FORUM RC-005 [20]. The vehicles exchange the information of the operating mode which decides the inter vehicular distance and emergency stop, the order in the platoon, the measured velocity, the measured acceleration, the measured location, the expected velocity, the expected acceleration, the steering angle, the turning angle and the yaw rate. The transmission is required to be success at every 20 msec, among all platoon members [29]. Since the data arrival ratio is required to be more than 99.96 %, the packet is replicated and transmitted repetitively. Energy ITS finally achieved platooning of 4 m gap at 80 km/h in the test circuit.

The Summary of communication requirements and achievements for platooning in typical projects is shown in Table 2.4. Some projects include lateral control while the other projects do not include it. The former projects required shorter communication cycle and achieved shorter inter vehicular distance than the latter projects. It is clear that the requirements and achievements depend on the usage of lateral control. The current technology of the lateral control realizes very short inter vehicular gap of 4 m, instead, it requires severe communication cycle requirement of 20 msec.

Table 2.5 shows the list of challenges for platoon and their relation to intra/inter-platoon. Intra-platoon means cooperation and affect among platoon members in a single platoon. The challenge issues relating to the intra-platoon are the collection of communication performance. For instance, it is important to keep the high string stability and the shockwave reduction performance at the time of communication loss. Therefore, these challenges should be resolved. Also, inter-platoon in the table means cooperation and affect between platoons as well as between platoons and non-platoon vehicles. The challenges relating to the inter-platoon are the collection of interference between platoons and non-platoon vehicles. For example, the communication within the platoon is greatly

Table 2.4: Summary of communication requirements and achievements for platooning in typical projects

Project	Communication requirements				Achievements	
	Control	Additional facilities on infrastructure	V2V communication	Required communication cycle	Inter vehicular gap	Achieved number of platoon members
SARTRE	lateral and longitudinal	none	- based on ITS-G5 (802.11p(CSMA)) - 2.4 GHz WLAN for backup	25 ms	6 m	4
PATH	lateral and longitudinal	magnetic marker	2.4 GHz WLAN (802.11b)	20 ms	4 m	2
GCDC	longitudinal	augmented GPS	based on 802.11p	100 ms	-	-
Energy ITS	lateral and longitudinal	(RTK-GPS) lane markings	RC-005	20 ms	4 m	4
SCANIA	longitudinal	none	no V2V communication	-	20 - 25 m	4
KONVOI	lateral and longitudinal	central server, GPS	2.4 GHz WLAN (802.11b)	-	10 m	4

affected by wireless channel congestion caused by other platoons. Legal issues are also important. For instance, currently, the entire autonomous driving is not permitted except for Nevada state in the U.S.A. Further researches and experiments should be required for the practical realization.

Table 2.5: List of challenges for platoon and their relation to intra/inter-platoon

Issues	Contents	Relation to platoon	
		Intra-platoon	Inter-platoon
Improving string stability [38]	Communication loss reduces string stability or shockwave reduction performance. Repetitive transmission is done by [13]	√	
Stretching platoon length	Maintaining long platoons is difficult due to the communication delay for emergency information	√	
Improving vehicle tracking	While longitudinal control is accurate, lateral control techniques are not matured	√	
Cooperative control [39]	Vehicles still needs information from the infrastructure or road markers	√	
Compatibility among different vendors	Each research is implemented on individual system	√	
Erroneous information	Erroneous location information could make the performance be worse than pure ACC	√	
Network congestion	One platoon requires large amount of wireless communication resources		√
Overtaking	Platoon is too long for surrounding vehicles to overtake easily		√
Lane merging	Platoon could prevent surrounding vehicles's smooth lane changing		√
Flexible joining, leaving, splitting and merging platoon	Procedures are undecided limited scenario is done by [16]	√	√
Crossing intersections	It is difficult to decide stopping, going, splitting and so		√
Noncommunicating vehicles [39]	There exists enough inter vehicle distance for nonequipped vehicles enter between platoon members		√
Legal issues	Entire autonomous vehicle with passengers is hardly permitted yet	√	
	very short inter vehicle distance is illegal	√	√

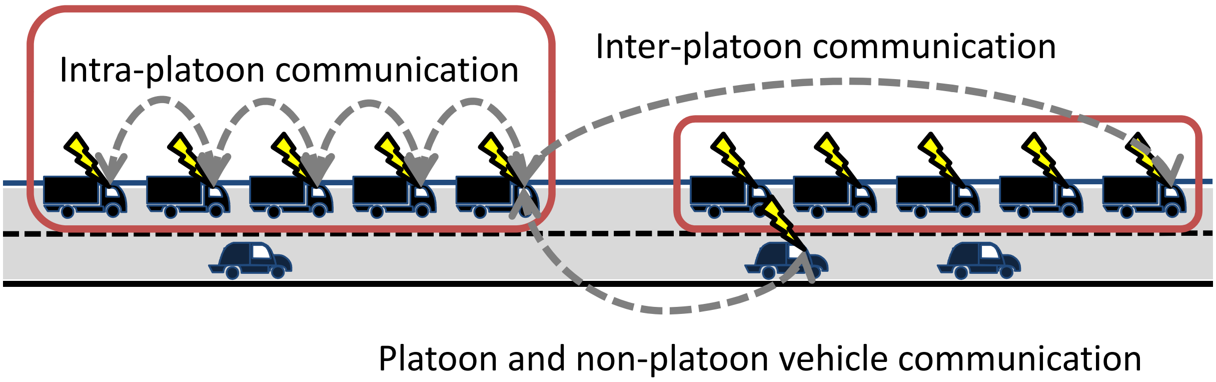


Figure 2.8: Intra-platoon, inter-platoon, and platoon and non-platoon vehicle communications

2.4 Communication Protocol for Platooning

Communication is the key technology for platooning and is categorized into intra-platoon, inter-platoon, and platoon and non-platoon vehicle communications. The intra-platoon communication is for organizing and maintaining platoon. The inter-platoon, and the platoon and non-platoon vehicle communications are for cooperation between platoons and non-platoon vehicles such as shockwave reduction, overtaking action control and lane merging assistance. Figure 2.8 shows the relation among intra platoon, inter platoon, and platoon and non-platoon vehicle communications.

The inter-platoon, and platoon and non-platoon vehicle communications have not been discussed well yet. The applications using those communications work on Vehicular Ad-hoc NETwork (VANET) [45] and their requirement depends on the application. Therefore, the communication protocol for platooning is likely to be based on the 802.11p CSMA/CA standards which are designed for VANET.

In the intra-platoon communication, platoon members have to share the information of the order in the platoon, the current velocity, the current acceleration, the current location, the expected velocity, the steering angle, the turning angle, and others. In Energy ITS, above information is contained into 50 bytes payload and all platoon members have to share at every 20 msec. Furthermore, for example, in the case of the emergency stop during platooning, the leader vehicle informs its intention for the stop sequentially from the leader vehicle to the tail. In order to avoid the rear-end collision within the platoon, the tail vehicle decelerates first, then the tail vehicle returns information for the start of its deceleration in reverse. Its latency is called kickback delay and it is required to finish within 100 msec from the start. These communication requirements for platooning are the same as safety application which avoids the collision between vehicles. Even though the safety application has to fulfill its severe communication requirement only when the collision is about to occur, the platooning has to keep its severe requirement all the time during its maintenance of platooning. Therefore, it can be said that the communication requirement for platooning is the severest one and need much more effective communication protocol than existing protocols.

2.4.1 CSMA/CA Communication Protocol

The communication protocol for platooning described in Section 2.3 are based on IEEE 802.11. It has several versions such as 802.11b and 802.11p corresponding to the time of their experiments. IEEE 802.11p is especially designed for ITS. Europe adopts ETSI ITS-G5 and the U.S.A. adopts Dedicated Short Range Communications (DSRC)/Wireless Access in a Vehicular Environment (WAVE) based on IEEE 802.11p, respectively. On the other hand, Energy ITS, Japan, adopted ITS FORUM RC-005 as an experimental standard which is slightly different from 802.11p. Both protocol use similar frequency band, 5.8 GHz or 5.9GHz. While IEEE 802.11p covers broadcast without acknowledgement, multicast and unicast with acknowledgement, RC-005 covers only broadcast without acknowledgement. All the standards are based on the CSMA/CA. Since vehicles have mobility and the network topology dynamically changes in the Vehicular Ad-hoc NETwork (VANET), it is better for the vehicles to share the wireless channel in a distributed manner than to share in the centralized control manner.

To fulfill the severe requirement of information exchange at every 20 msec and emergency kickback delay in less than 100 msec, a redundant wireless communication system architecture for fail safe is adopted in Energy ITS in Japan and SARTRE in Europe. It consists of primary and secondary systems and it is also called a built-in back up system. If the primary system goes down, the secondary system can take over to continue communicating. In addition, Toyota ITC proposed group communication for cooperative vehicle platooning [46]. They intended to reduce the volume of acknowledgement in the bidirectional communication among platoon members. The reason is as follows. Assuming that a platoon consists of N vehicles, when one vehicle sends a request, it needs $N-1$ acknowledgements. Processing time for these acknowledgements could be large to prevent smooth platoon management such as changing inter vehicle distance. They proposed an efficient bi-directional communication for platoon members using multicast. In this method, vehicles autonomously organize a communication group using vehicle's short IDs. The method also allows vehicles to join and leave platoon dynamically using blackboard. Note that, the blackboard is simple knowledge base and it is the list of vehicle's short IDs. One vehicle in a platoon keeps this blackboard and each vehicle updates the blackboard when it joins and leaves the platoon in order to know exact members of the platoon.

In Energy ITS, in order to achieve the high data arrival ratio of 99.96 % [29], a repetitive transmission method is adopted. Here, the repetitive transmission method copies the information in the MAC layer and sends the replicated packet repetitively. Note that, the term "packet" is used for layer 2 packet unless otherwise stated. In the case where at least one of them arrived at the other members, platoon members are able to maintain the platoon. However, according to the requirement of information exchange at every 20 msec, since the amount of the packet is quite large, the wireless channel congestion and the hidden terminal problem likely occur in the case plural platoons drive closely in the same direction or opposite direction on the road.

In order to avoid the effects of the hidden terminal, IEEE 802.11p includes Request To Send/ Clear To Send (RTS/CTS) mechanism [47, 48] as shown in Fig. 2.9. In the figure, the upper part shows the geological relation of three vehicles. Vehicles A and B, and B and C communicate with each other. Vehicles A and C are hidden from each other. Middle part of the figure shows the CSMA/CA communication without RTS/CTS mechanism. In this situation, vehicles A and C do not know the timing for packet transmission of each other. The packets from vehicles A and C could collide at vehicle B. This figure shows the occurrence of collision in the red dotted circle. In the lower part of the figure, the CSMA/CA with RTS/CTS mechanism is demonstrated in the certain period of time to avoid the collision of packet transmission. In the beginning of transmission, vehicle A sends a RTS which indicates the duration to use the wireless channel for transmission.

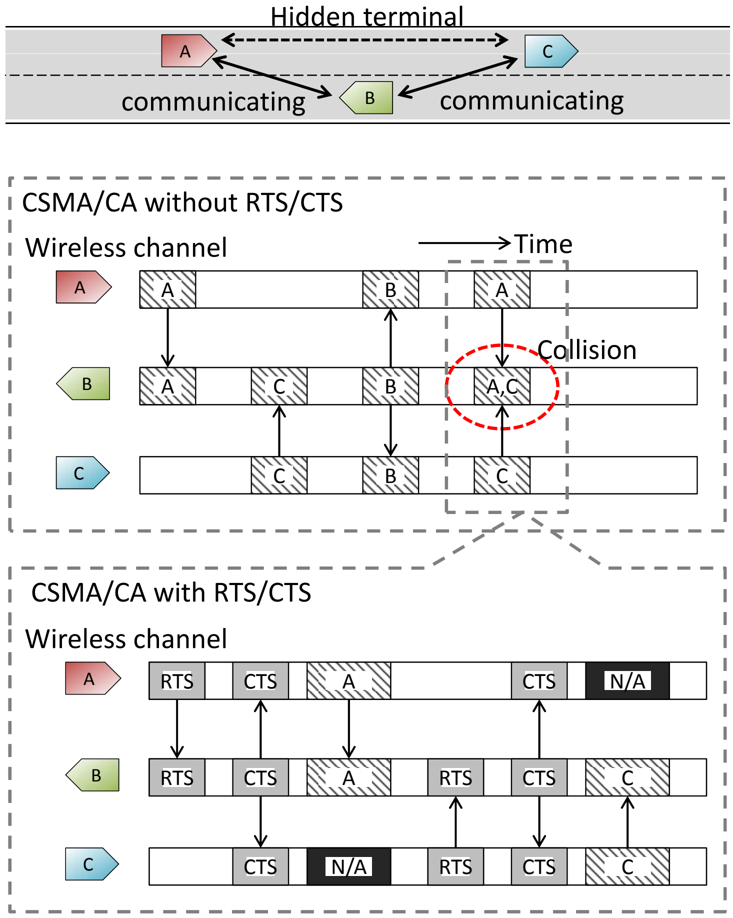


Figure 2.9: Mechanism of RTS/CTS

Vehicle B replies with CTS which is echoing expected duration of the data transmission. Vehicle C hears the CTS and knows it should refrain from transmitting for a certain amount of time. After the certain amount of time, vehicle C starts transmission in the same procedures as vehicle A. Through these procedures, RTS/CTS avoids the collision. However, RTS/CTS limits the goodput. Therefore, RTS/CTS should not be used in the case where the data size is small [48]. Therefore, we have to find an alternative solution.

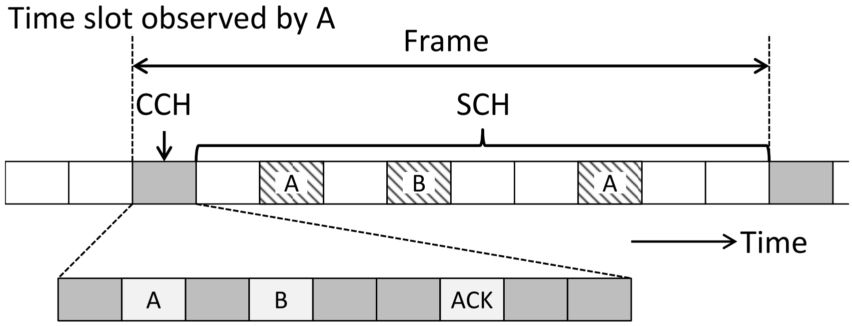


Figure 2.10: Mechanism of R-ALOHA

2.4.2 Time Slotted Communication Protocol

Time slotted communication protocol is an efficient solution for the hidden terminal problem. It introduces time slot as same as TDMA protocol. Reservation-ALOHA (R-ALOHA) [33, 49] is a well known example for the time slotted communication protocol. R-ALOHA aims to provide prompt access, reliable channels and support for quality of service in ad-hoc network [49]. Vehicles send packets with time slots with reservation and its mechanism is shown in Fig. 2.10. The wireless channel is divided into frames with fixed duration. Note that, the term "frame" is used for grouped fixed number of time slots. Each frame is divided into two parts. One slot is assigned to Control CHannel (CCH) for reservation and the other slots to Service CHannel (SCH) for packet transmission. CCH is divided into smaller time slots, vehicles send a request for slot usage in SCH based on the contention mechanism. A centralized system replies slot usage to requesters, vehicles use time slots according to the slot usage. Note that, the centralized system is required to be on a specific vehicle or infrastructure. In this protocol, the centralized system assigns time slots making sure that they do not overlap with others. Therefore, the packets can avoid collision regardless of whether vehicles are hidden from each other or not. In Vehicular Ad-hoc NETwork (VANET), a specific vehicle is need to be decided in an autonomous distributed manner, however, it is difficult since vehicles have mobility. Also it is difficult for infrastructure to cover all vehicles request on roads. Therefore, R-ALOHA is not suitable for VANET.

An approach for a time slots to use in VANET is Universal mobile telecommunications

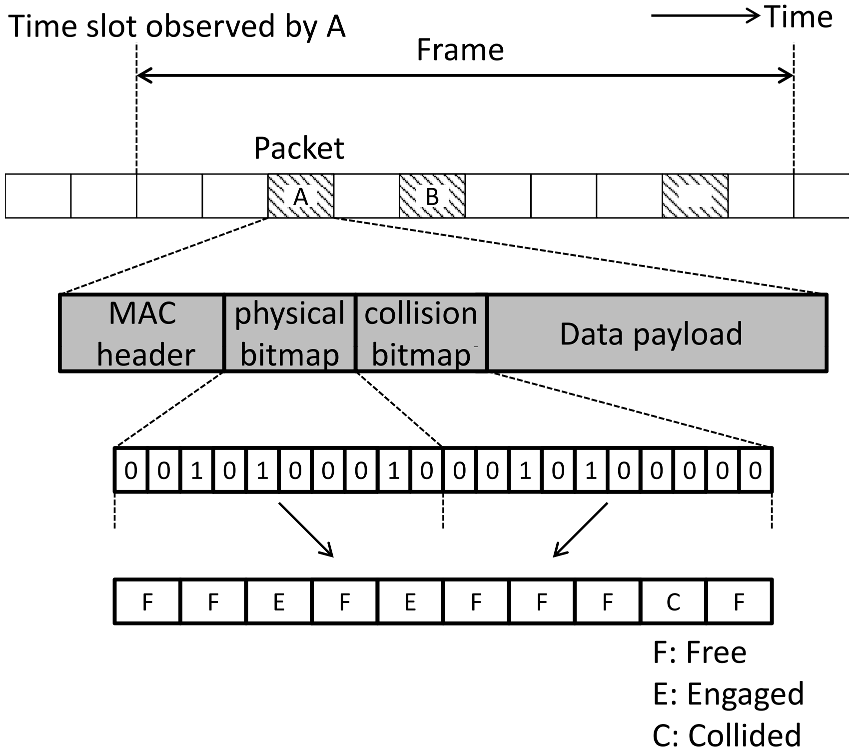


Figure 2.11: Mechanism of UTRA-TDD

system Terrestrial Radio Access-Time Division Duplexing (UTRA-TDD) protocol [5, 24] introducing "bitmap". UTRA-TDD achieve time slotted communication in a distributed manner. In UTRA-TDD, each time slot transports the following information fields in its header; MAC source and destination addresses, physical layer bitmap and collision bit map as shown in Fig. 2.11. The physical layer bitmap indicates state for physical signal of time slots. If the received power of antenna is greater than the threshold, the bit is set "busy", otherwise the slot is set "free". The collision bit map indicates collision state of time slots. If the time slot is declared busy and the MAC layer receives successfully a data block, the slot is set "engaged". If the time slot is declared busy and the MAC layer does not decode correctly a data block, the slot is set "collided" The combination of these bitmaps classifies time slots into three states; free, engaged and collided. Since these bitmaps are included in the packet, each vehicle can collect them from other vehicles

Table 2.6: Slot state in UTRA-TDD [5]

Slot state observed by itself	Slot state informed by other vehicles	Final slot state
Time slot i is free	At least one node classifies time slot i as collided	Collided
Time slot i is free	All received bitmaps classify time slot i as not collided, but at least one bitmap classifies time slot i as engaged	Hidden (Not Available)
Time slot i is free	All received bitmaps classify time slot i as free	Available
Time slot i is engaged	At least one bitmap classifies time slot i as collided	Collided
Time slot i is engaged	All received bitmaps classify time slot i as not collided	Engaged
Time slot i is collided	Any	Collided

during entire frame. According to Table 2.6 [5], vehicles judge the final slot state and detect the collision by hidden terminals. Vehicles use only time slots which are available in final slot state. Vehicles can recover from the collision in both cases where they can communicate directly and they are hidden from each other. Different from the R-ALOHA, UTRA-TDD can recover from the collision immediately after it actually occurs. However, in the case where the wireless channel is congested, when the collision occurs, the vehicles likely to choose the same time slot to send since there are few available slots. In this situation, the throughput goes down. Therefore, the UTRA-TDD is not suitable for communication for platooning which requires quite high data arrival ratio. We have to find an alternative protocol that can avoid the collision.

Compared with both two protocols of R-ALOHA and UTRA-TDD, Reliable Reservation-ALOHA (RR-ALOHA) [22, 50] is a promising protocol for VANET. RR-ALOHA is extended from the R-ALOHA method [33] for VANET. RR-ALOHA introduces frame information instead of using CCH in order to work in autonomous distributed manner instead of centralized manner. Figure 2.12 shows the frame information. Each packet consists of

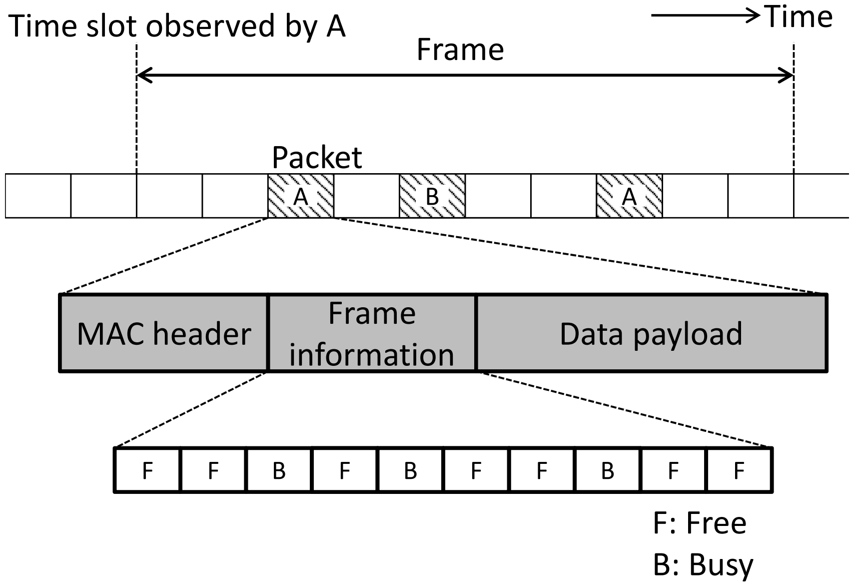


Figure 2.12: Frame information in RR-ALOHA

three components; MAC header, frame information and data payload. The frame information is quite similar to the bitmap. However, the frame information indicates list of slot usage observed by the vehicle as well as reservation. If the received packet is successfully decoded together with the identity of the transmitting vehicle, the slot is set "busy". Otherwise, the slot is set "free". The same as the bitmaps, since the frame information is included in the packet, each vehicle can collect them from other vehicles. When at least one vehicle reports "busy", vehicles judge the slot is busy. Therefore, vehicles can avoid the packet collision regardless whether it is direct collision or due to the hidden terminals. Figure 2.13 shows the reservation in RR-ALOHA. In the startup for communication, vehicles collect the slot usage observed by itself and by other vehicles with frame information. Vehicles randomly choose a time slot which is commonly free in all received frame information and send data without reservation as indicated 1. When vehicles use another time slot, vehicles reserves a time slot using frame information. Vehicle B chooses a slot from free time slots as indicated 2. Then vehicle B modifies its frame information, the slot which corresponds to the chosen time slot is set "reserved" as indicated 3. Vehicle B sends the frame information with a time slot which vehicle B already used as indicated

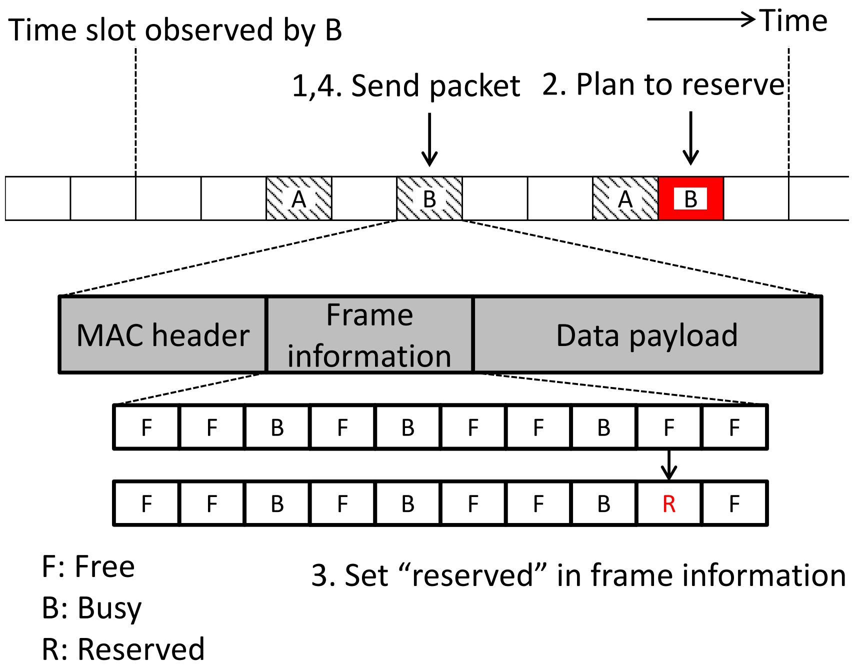


Figure 2.13: Reservation in RR-ALOHA

4, before it uses the chosen time slot. Other vehicles can know vehicle B plans to use the slot which is set "reserved". Vehicle B judges the reservation is succeeded if it receive a frame information in which the chosen time slot is set "busy" until the time to use the chosen slot. Through these procedures, vehicles can communicate with each other without collisions as shown in Fig. 2.14. The geological relation of three vehicles is as same as Fig. 2.9. While a collision occurs in the case of CSMA/CA without RTS/CTS, RR-ALOHA avoid the collision.

RR-ALOHA includes two problems. One is the problem that the vehicles do not distinguish the difference between the transmission error and the packet collision by busy information. Therefore, vehicles have to change the time slot frequently to send packets under the unstable wireless conditions. This problem is already resolved and described as follows. Scopigno et al. proposed Mobile Slotted ALOHA system (MS-ALOHA) [23] which is extended from RR-ALOHA. MS-ALOHA uses CLS flag information added to busy flag information in order to clearly inform the slot conflicts due the hidden termi-

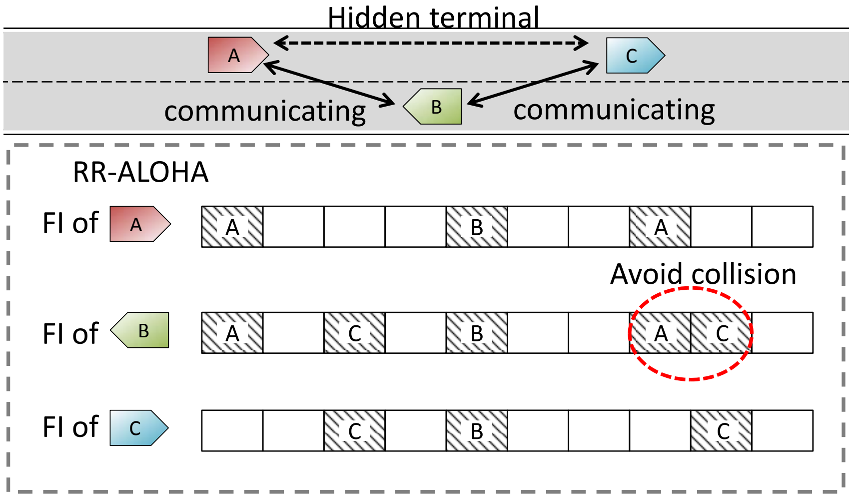


Figure 2.14: RR-ALOHA mechanism

nal. Hence, MS-ALOHA reduces the false positive rate for the busy slots and efficiently uses the available slots. In addition, in MS-ALOHA, vehicles refresh the slot occupancy information quicker than the RR-ALOHA protocol. Thus, vehicles are able to use the time slots as soon as they become available. The MS-ALOHA method is efficient under the congested and highly dynamic mobility conditions. As another example of extended RR-ALOHA protocol, autonomous-decentralized TDMA protocol is studied by Makido et al [51, 52]. This method distinguishes the packet collision and the transmission error, so that vehicles avoid unnecessary reservation and can work stable even in the case the transmission error occurs frequently.

The other problem is that the communication loads are biased by vehicles which are hidden from each other. As described in Fig. 2.14, the communication load observed by vehicle B is heavier than vehicles A and C. Therefore, the wireless channel congestion at vehicle B likely occurs compared with vehicles A and C. This dissertation focuses on wireless channel congestion and biased communication load due to the hidden terminals and it will solve them in Chapter 3. In time slotted methods which are described above, vehicles avoid the collision with another vehicle which is hidden from each other. Therefore, those two vehicles occupy the time slots at the vehicle which is between them and the communication load on the vehicle likely to become heavy unequally with the other

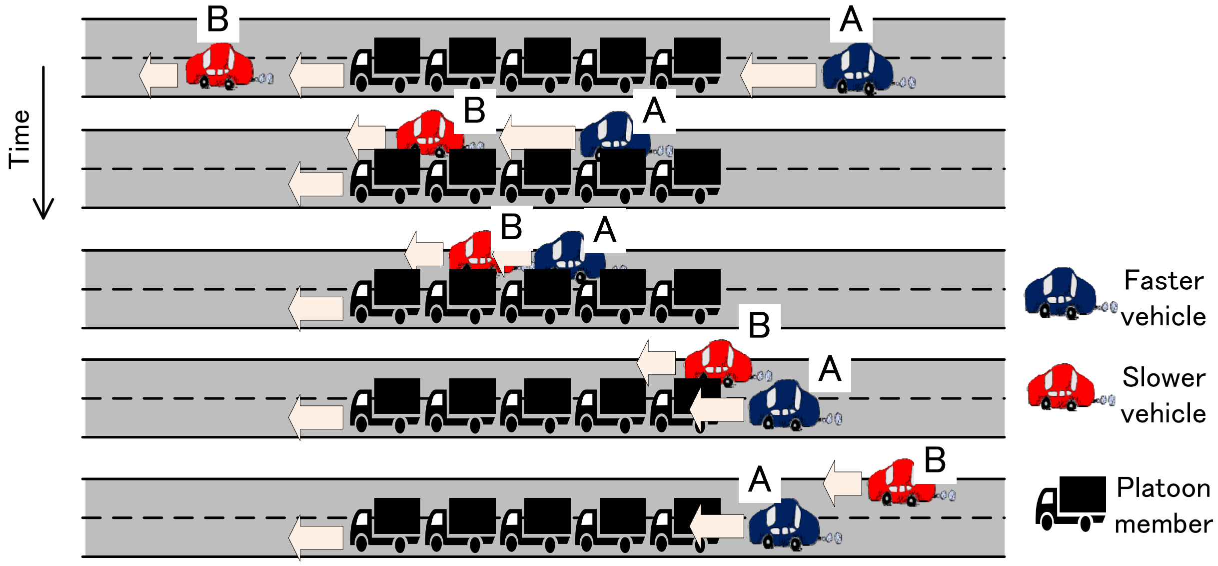


Figure 2.15: Faster vehicle's deceleration due to overtaking conflict

two vehicles. Here, since vehicles are not able to reduce the communication load, the packet arrival ratio could get worse seriously in the case where there exists no available slot. In the case where the communication load is biased, the packet arrival ratio could get worse unequally at the specific vehicle. Furthermore, the time slotted methods include the possibility of the reservation conflict among the platoon members even they are in the same platoon.

From the above discussions, both of the existing CSMA/CA and the time slotted protocols are not enough for the platoon communication. However, the merit of the CSMA/CA protocol is relatively high packet arrival ratio under the congested conditions and the merit of time slotted communication protocol is periodic information exchange without centralized system. The communication method having the both merits is expected to be efficient for the platoon communication. In order to respond to this expectation, this dissertation proposes a time slotted communication protocol for platooning in Chapter 3.

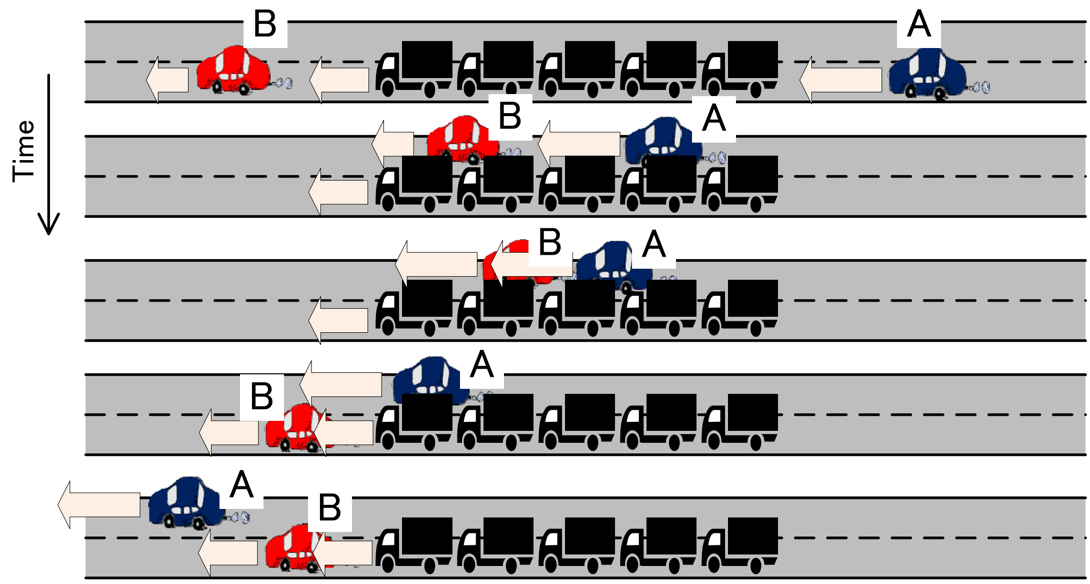


Figure 2.16: Slower vehicle's acceleration due to overtaking conflict

2.5 Overtaking Control Using Communication

In order to put the platooning into practical use in the express highway, we will have to solve many technical issues beforehand. As shown in Table 2.5, the list of challenges for platoon is given for the further development of the platooning. Overtaking is included as one of the important research issues. The issue of overtaking is to clarify the control method where the platoon is overtaken by non-platoon vehicles and where a platoon itself overtakes the other non-platoon vehicles and/or obstacles. To the best of our knowledge, any detailed mechanisms or methods for overtaking have not been publicly reported.

Energy ITS, Japan organized the experiments under the condition that platoon is running on the designated lane of the express highway, and studied the basic platoon running itself, however it did not cover the study on overtaking [25]. The use of designated lane for platooning is rather a political decision, however, it also shows the difficulties of its actual operation. Considering these backgrounds, this dissertation also adopts the policy for the use of designated lane, and studies the overtaking for the future platooning.

The problem in overtaking is the followings. As shown in Figs. 2.15 and 2.16, five vehicles are driving as a platoon, and non-platoon vehicles A and B are running in front of and behind a platoon respectively on the two lanes highway. Overtaking of around 70 to 80 meters long platoon needs rather long time. The simple overtaking model is named the distance-based overtaking. Overtaking is triggered when the platoon catches up to the slower vehicle B driving in front within the certain threshold of inter vehicular distance. Vehicle B has to change its lane to the passing lane in order to gives its way to the platoon. Also the faster vehicle A catches up to the platoon from behind and it changes its lane to passing lane in order to overtake the platoon. The trouble will happen when vehicles A and B enter the passing lane at the same time. High speed vehicle A will find a low speed B in its front, and will have to decelerate in order to avoid a rear-end collision. There are two solutions for the problem. One solution is that vehicle A will decelerate and go back to the original lane and wait vehicle B goes behind as shown in Fig. 2.15. The other solution is that vehicle B accelerates by higher speed than a platoon and will drive back to the original lane, and allow vehicle A to overtake as shown in Fig. 2.16. The both solutions are not the perfect solutions, if the platoon catches another slow vehicle in front, the same trouble will happen. In this case, since acceleration and deceleration bring the severe energy consumption, the conflict should be solved and unnecessary acceleration and deceleration should be reduced.

Main reason for these overtaking conflicts is simply due to the results by the lack of conversation between two vehicles, A and B, in advance. Therefore, the application of the distributed mutual exclusion algorithm is effective to avoid the conflict in case that the appropriate communication method is established among these vehicles. In this context, a part of passing lane adjacent to the platoon becomes the critical section. In general, the distributed mutual exclusion algorithms are classified into two categories. One is permission-based algorithm and the other is token-based algorithm [53].

Permission-based algorithm is initially studied by Ricart and et al. [54]. In the algorithm, if the process A likes to use the critical section, process A has to request to all the potential processes of the critical section beforehand, and received the acknowledgement from all of them. Only the case where A has received permissions from all processes, A can enter the critical section. When process B received the request from the process A, if the process B has not issued the request yet, it sends the permission message to A, and if

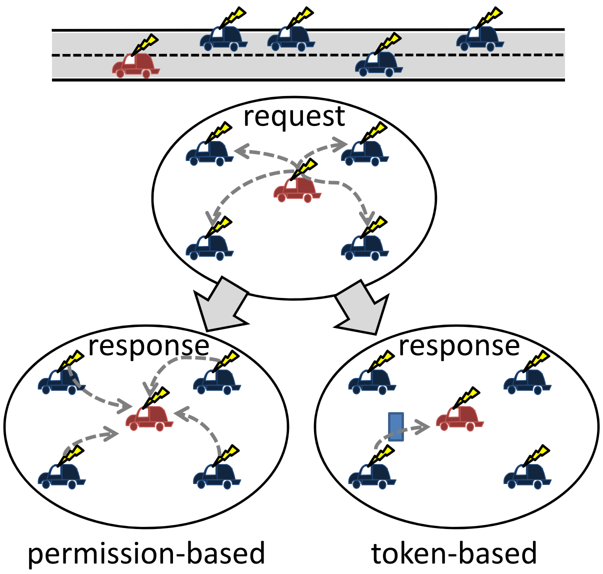


Figure 2.17: Qualitative comparison between permission-based and token-based

B has already issued a request, it compares the time stamps on the request and takes the precedence by FIFO order. In some case, selection to use critical section is decided among the voting by all the potential processes, which is named as quorum-base algorithm.

Token-based algorithm exchanges a token within the member processes, and only the process that has the token can enter the critical section. This algorithm also ensures the avoidance of the deadlock and starving problem by the addition of simple procedure. The deadlock is a situation in which two or more vehicles are waiting for the other to finish, and the starving problem is a situation in which a specific vehicle waits for a very long time and never enters the critical section. In the token-based algorithm, processes logically construct ring or tree structures. When process B likes to enter the critical section and requests the token while process A has the token, sometimes in the case of tree structure, it will take much time to receive the token depending on the topological structure of processes. For example, if the logical structure of the processes are given by perfect binary tree with depth m, in the worst case, it will need $4m$ hops communication from the token request to the token acquirement. Therefore it is recommended to apply the shallow tree structures for the tree topology. There are two weaknesses in the token-

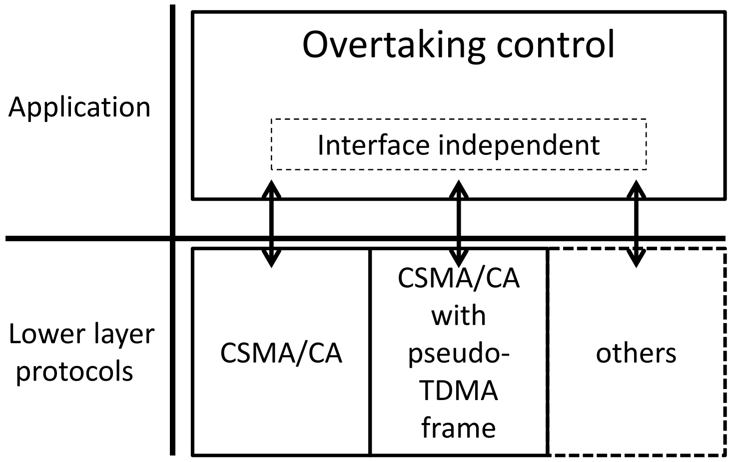


Figure 2.18: Overtaking control and lower layer protocols

based algorithm [55]. One is the assurance of fair scheduling among the processes without an excessive amount of communication. The other is the re-issuing problem of the token if the original token is lost by some reasons. There will need much complicated procedure to re-issue tokens [56].

Both algorithms can be applicable to solve the overtaking for platoon. Figure 2.17 shows the qualitative comparison. In the case when the leader of platoon likes to ask the surrounding vehicles to their wish to overtake, it will broadcast a request packet to all of them. In the case of token-based algorithm, the poll will be finished by the emergence of first affirmative response. On the contrary, the permission-based algorithm needs the responses from all surrounding vehicles. Therefore, it seems that the token-based algorithm can easily reach the consensus than permission-based algorithm from the volume for message exchange's point of view. In the following Chapter 4, this dissertation will compare both algorithms precisely with focusing on the unnecessary acceleration/deceleration of overtaking vehicles which increase the CO_2 emission.

Role of communication for overtaking control is very important. All the procedure to decide which vehicles will enter the critical section using mutual exclusion algorithm is executed over the communication media. However, in this dissertation, the overtaking control problems are solved as the application layer protocol over the communication protocols as shown in Fig. 2.18.

Chapter 3

Time Slotted Communication Protocol for Platooning

3.1 Overview

As discussed in Section 2.4, in order to maintain a platoon, each platoon member has to exchange the lateral and longitudinal control information in very short interval such as 20 msec [29]. It is also pointed out that the frequent data exchange of a large volume of packet will bring the wireless channel congestion in the current technology of CSMA/CA communication. Also, in the single channel communication by CSMA/CA, the hidden terminal problem is the important issue to resolve. Currently, all discussions on platooning are limited to single platoon and not extended to plural platoons or to mutual effects between platoons. If we consider the future platooning, it is easy to figure the plural platoons are running both directions on the highway. In such a situation, avoidance of congestion and the hidden terminal problem will be the mandatory conditions to realize the safe and reliable platooning. In addition, time slotted protocols [5, 22, 33] are well known solutions for the hidden terminal problem. These protocols can avoid collisions due to the hidden terminal problem, however, they can not avoid the biased communication load due to the hidden terminal.

Therefore, this chapter proposes a time slotted communication protocol for platooning in order to overcome the wireless channel congestion and the hidden terminal problem and describes three key functions; a time slotted CSMA/CA channel with pseudo TDMA frame, a repetitive transmission rate control, and a representative slot reservation by leader vehicle.

This chapter also evaluates the time slotted communication protocol for platooning comparing with the simple repetitive transmission protocol and RR-ALOHA protocol through computer simulations. The comparison is exhibited in terms of the data arrival ratio and platoon maintenance and shows the effectiveness of the proposed protocol.

3.2 Proposed Protocol and Premises of Communication for Platooning

This chapter proposes a time slotted communication protocol for platooning in order to overcome the wireless channel congestion and hidden terminal problem. The proposed protocol consists of three key functions described as follows.

- Time slotted CSMA/CA channel with a pseudo TDMA frame for efficient and periodical information exchange with high data arrival ratio.
- Repetitive transmission rate control to avoid the wireless channel congestion.
- Representative slot reservation by the leader vehicle to avoid the reservation conflict among platoon members.

In the proposed protocol, the model of platooning is extended that plural platoons drive in a designated lane of each direction. Platoon consists of a certain number of vehicles and its members are predetermined. Each member knows the exact members and their order in the platoon. One of the members is a leader vehicle in the platoon and it takes an initiative for platooning. The member vehicles exchange information for maintenance of the platoon among all members. The information exchange is done by a time slotted communication protocol for platooning. The protocol is based on IEEE 802.11p, which adopts a CSMA/CA protocol. It introduces time slot and frame that is named pseudo TDMA frame over CSMA/CA single channel. The duration of frame is the same as the cycle for information exchange. Therefore vehicles know the duration of time slot and frame in advance. By reference to the repetitive transmission in Energy ITS, Japan [29], when vehicles send packets, they replicate the packets and transmit them repetitively. The transmission of the replicated packets uses different time slots in the same frame. Each packet includes MAC header and frame information in its header as same as the RR-ALOHA protocol [22]. Vehicles share time slots with other vehicles without overlap using reservation procedures. Different from RR-ALOHA, the leader vehicle represents of the other members in the platoon, and it reserves and assigns time slots for them. The details of the time slotted communication protocol for platooning are as follows.

3.3 Time Slotted CSMA/CA Channel with Pseudo TDMA Frame

The communication for platoon requires periodical exchange of information with high packet arrival ratio. In the existing protocol for platooning, CSMA/CA is widely adopted because it enables vehicles to share the wireless channel with high packet arrival ratio in distributed manner. In addition to it, introducing a time slot mechanism of Time Division Multiple Access (TDMA) is efficient for the periodical information exchange. From this idea, this dissertation proposes a time slotted CSMA/CA channel and pseudo TDMA frame with the time slot reservation mechanism. In this protocol, vehicles share a single channel which is subdivided into a fixed size of time slots. The vehicles use each slots avoiding conflicts since every vehicle exchanges the frame information with surrounding vehicles as same as the RR-ALOHA protocol. In the case of accurate slot time synchronization, vehicles communicate with each other through the time slot reservation mechanism. On the other hand, if slot time synchronization is inaccurate, vehicles communicate through the contention mechanism, which is adopted in the CSMA/CA protocol. Therefore, this dissertation assumes that every vehicle has GPS clock to share precisely synchronized time slots. This mechanism is named time slotted CSMA/CA channel with pseudo TDMA frame. Figure 3.1 shows the synchronization of slot and frame. A pseudo TDMA frame consists of a certain number of consecutive time slots and the leader of the platoon which is named leader vehicle uses the first slot of the frame. The other platoon

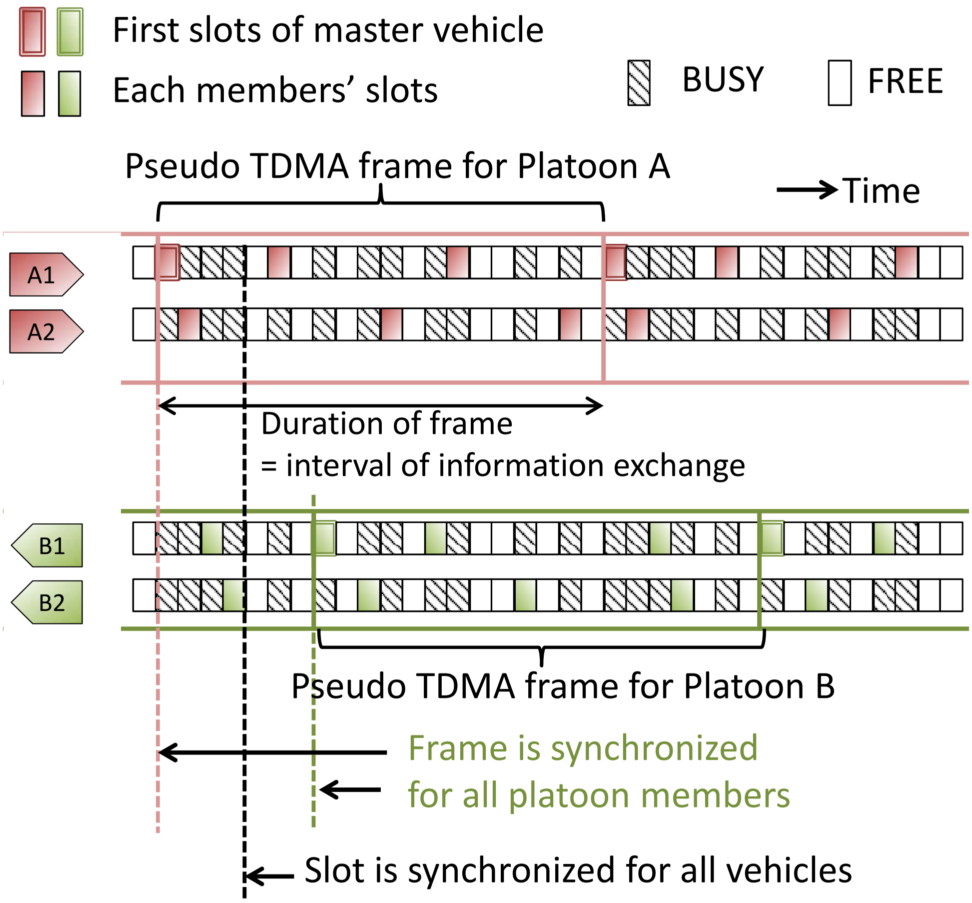


Figure 3.1: Synchronization of slot and frame in CSMA/CA channel

member vehicles recognize the first slot when it receives the packet from the leader vehicle. Through the process mentioned above, the member vehicles share precisely synchronized frames. Note that it is not necessary for all platoons to share synchronized frame. Figure 3.1 depicts slot and frame synchronization in CSMA/CA channel. The time length of a pseudo TDMA frame equals the information refresh interval of the platoon communication, therefore each vehicle selects as many slots as the number of the repetitive transmission and sends copies of one packet with the selected slots. In this process, the slots for the repetitive transmission are not necessary to be sequential as long as they are in the same frame. Each vehicle exchanges information including not only platoon control

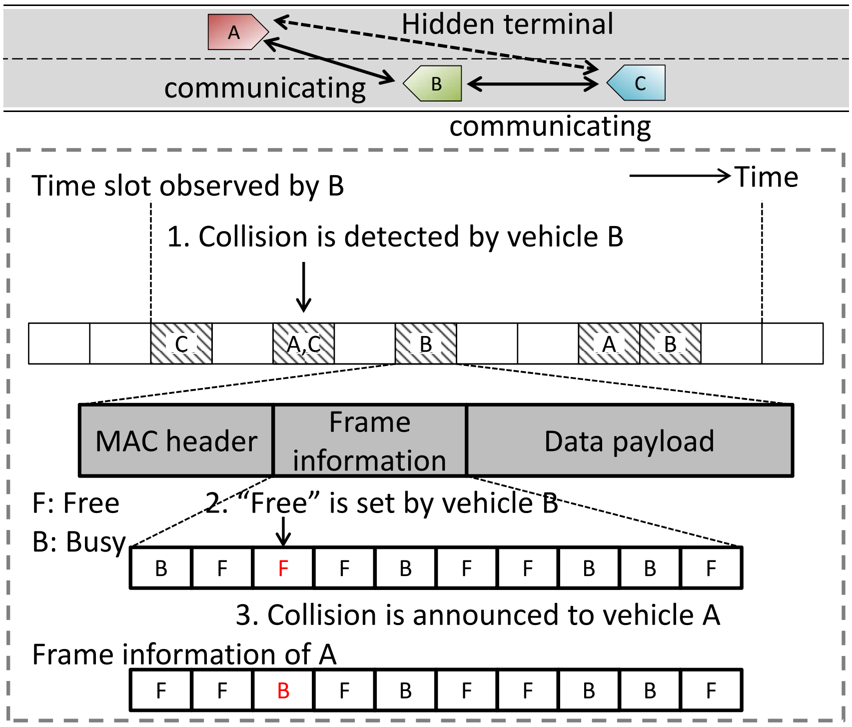


Figure 3.2: Example of collision detection

information such as location, speed, etc., but also slot occupancy information of the last frame it received. The slot occupancy information is named frame information and the number of repetitive transmission.

Each vehicle receives packets from vehicles within the communication range which are named neighboring vehicles. After each vehicle examines the frame information of the sender vehicle, checks whether the collision occurs or not. The mechanism of collision detection is based on the RR-ALOHA protocol and its example is depicted in Fig. 3.2. The upper part of the figure depicts the geological relation of vehicles A, B and C, and the bottom part of the figure depicts the demonstration of collision detection. Vehicles A and C are hidden from each other and drive in different direction. Packets from A and C collide at vehicle B. Each packet consists of three components; MAC header, frame information and data payload. When vehicle B can not correctly decode the packet, it judges that the collision occurs and it sets the corresponding slot "free". Vehicle B

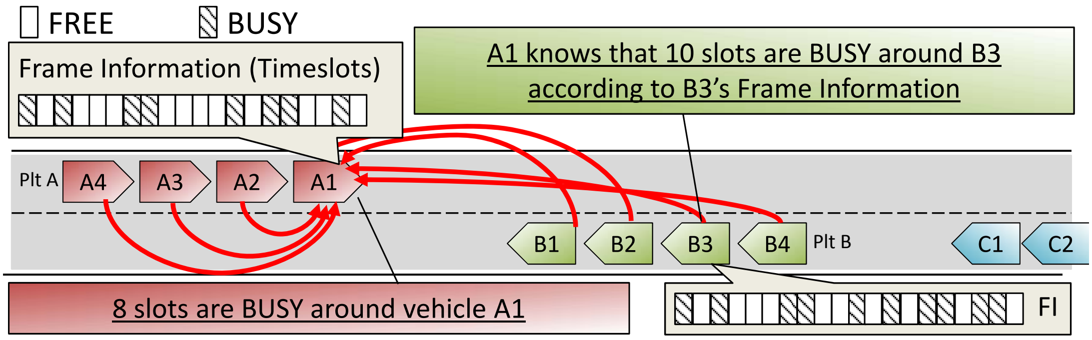


Figure 3.3: Example of time slot occupancy information

announces this information with frame information in its packet. Vehicle A knows the slot is set "free" when it receives packet from vehicle B though it expected that the slot was "busy". In this case, vehicle A judges the collision occurred.

Also, the vehicle judges whether the wireless communication band of any neighboring vehicle is congested or not. Then, each vehicle increases or decreases the number of repetitive transmission according to the slot occupancy in order to keep high communication success ratio. Figure 3.3 depicts an example of the time slot occupancy information. Each group of vehicles A1 – A4, B1 – B4 and C1 – C2 organize a platoon. The frame information of A1 indicates that A1 is easy to distinguish that A2 – A4 and B1 – B4 are within the communication range of A1. Also the frame information of B3 indicates that B3 is able to know A1 – A4, B1, B2, B3 and C1 – C2 are within the communication range of B3. When A1 receives a packet from B3, A1 gets the frame information of B3, and A1 notices B3 is communicate with C1 and C2 which are out of communication range of A1. The relation between A1 and C2 is known as the hidden terminal. This procedure enables each vehicle to know whether neighboring vehicles' wireless channel are congested or not and control the amount of transmission information according to the slot occupancy in the frame information. This mechanism enables the vehicles to know the congestion of the neighboring vehicles. It is recommended to include in the proposed protocol that the vehicles avoid the wireless channel congestion of neighboring vehicles, and the leader vehicle reserves and assigns the time slots representing other member vehicles.

3.4 Congestion Avoidance Using Repetitive Transmission Rate Control

In order to judge whether the time slot is congested or not, each vehicle compares the slot occupancy ratio in the frame information with the threshold for congested or sparse. The slot occupancy ratio is the proportion of the number of busy slots in a frame against the total number of slot in a frame. The increment/decrement repetitive transmission is decided according to its own frame information and neighboring vehicles' frame information. Since each vehicle compares them every time it receives a packet, vehicles autonomously avoid the wireless channel congestion. The algorithm for deciding the number of repetitive transmission is shown in Algorithm 1. Where, I is a set of vehicles whose packets reach vehicle k, O_i is an occupancy ratio of vehicle V_i's slots ($i \in I$), N'_k is the number of repetitive transmission for vehicle k in previous frame, N_{max} is the maximum number of repetitive transmission, N_{min} is the minimum number of repetitive transmission, Th_1 is the threshold for congestion avoidance, Th_2 is the threshold for emptiness and n is the number of increment/decrement, N_k is the number of repetitive transmission for vehicle k, and d_k is a status identifier distinguishing increment/decrement slot number.

In the Algorithm 1, each vehicle examines O_i at first. If any of O_i is superior to Th_1, the vehicle decreases the number of repetitive transmission unless the number of transmission becomes smaller than N_{min} to avoid the wireless channel congestion. If all of O_i is inferior to Th_2, the vehicle increases the number of repetitive transmission unless the number of transmission becomes larger than N_{max}.

Algorithm 1 Algorithm for deciding number of repetitive transmission

INPUT:

I : Set of vehicles whose packets reach vehicle k

O_i : Occupancy of $V_{i\in I}$'s slots $(= \frac{\text{Number of Busy of V}_\text{i}}{\text{Number of Slots of V}_\text{i}})$

$N'_k : \begin{cases} \text{Initial vlaue} & \text{(start platooning)} \\ \text{Number of transmission for vehicle k in previous} & \text{(otherwise)} \end{cases}$

N_{max} : Maximum number of repetitive transmission

N_{min} : Minimum number of repetitive transmission

Th_1 : Threshold for congestion avoidance

Th_2 : Threshold for emptiness

n : Number of change

OUTPUT:

N_k : Number of transmission for vehicle k

VARIABLE:

$d_k : \begin{cases} -1 & \text{(increment of slot number)} \\ 0 & \text{(same slot number as previous, initial value)} \\ 1 & \text{(decrement of slot number)} \end{cases}$

```
d_k ⇐ 0
for all i such that i ∈ I do
    if O_i > Th_1 then
        d_k ⇐ 1
        break
    else if O_i < Th_2 then
        d_k ⇐ −1
    end if
end for
if d_k = 1 ∧ N_k − n ≤ N_min then
    N_k ⇐ N'_k − n
else if d_k = −1 ∧ N_k + n ≥ N_max then
    N_k ⇐ N'_k + n
end if
```

3.5 Mechanism of Representative Slot Reservation

When we assume the situation that platoons pass by each other or platoons take over another one, a vehicle's packet in a time slot could conflict with a packet of another vehicle (which is called time slot conflict in this dissertation), and the remaining number of reserved time slots becomes less than it is expected. In the proposed protocol, each vehicle has the mechanism for reservation to recover the deficiency. In this situation, since the platoon members likely drive together in their communication range, the representing leader vehicle reserves and assigns time slots for entire platoon members. In other words, the proposed protocol has a partially centralized slot assignment mechanism because the leader vehicle controls time slots of platoon members instead that each vehicle reserves time slot by itself. This mechanism avoids the slot conflicts and unbalanced number of platoon members' time slots. In the procedures, the leader vehicle, firstly, collects frame information, knows the expected number of repetitive transmission of platoon members, and calculates the total number of transmission to be reserved. Then, the leader vehicle finds the available time slots by checking the occupied slot list in the frame informations as well as the reserved slot list which is created when the leader vehicle reserves time slots. After that, the leader vehicle selects the time slots to be reserved and send reservation packets with these slots. The platoon members overhear the reservation packets from the leader vehicle and autonomously understand which time slot is assigned to themselves using the vehicle's order in the platoon.

3.5.1 Calculation for Number of Repetitive Transmission

Time slot conflict can be detected either one or both of the leader vehicle and the platoon members. When the leader or the platoon members find a conflict, they have to inform other members of the occurrence of the conflict, the leader and platoon members exchange the frame information of each. The execution flow for deciding reservation slot by leader vehicle at the time of receiving packet is shown in Fig. 3.4. When the leader vehicle receives a packet, it determines whether the packet is received correctly or not. If correct, it checks the frame information in the received packet whether the conflict is reported at the slots assigned to the platoon members. If errors are detected, the leader vehicle checks whether the incorrect packet conflicts with the time slot for platoon members. In both cases, if no conflict occurs at time slots for platoon members, the leader vehicle ignores the error. If any conflict is detected at time slots for platoon members, the leader vehicle checks whether alternative slots are already reserved or not. This process avoids the duplicate reservation due to the conflict detection by plural vehicles. After the leader vehicle confirms all conflicts have alternative reserved slots, it does not increase the number of time slot to be reserved. If the leader vehicle finds that the conflict does not have any alternative reserved slot, it increases the number of time slot to be reserved for unhandled conflicts. After that, the leader vehicle examines whether the number of assigned time slot is less than the required number of time slots for platoon members. In the case that the assigned time slots is not enough, the leader vehicle increases the necessary number of time slot to be reserved for deficiency. Through above procedures, the leader vehicle decides the number of repetitive transmission.

3.5.2 Slot Selection for Reservation

After the leader vehicle decides the number of time slots to be reserved, it sends a reservation packet using the selected time slots. When the leader has to reserve more than two slots at the same time, it selects different time slots for each of them. For this purpose, the leader vehicle keeps the list of reserved time slots in hand. Then, in order to know the list of time slots which are available for all platoon members, the leader executes OR operation with the list of reserved time slots and the frame information of platoon members. The leader vehicle knows the list of commonly available time slots for all platoon members according to the above execution result. After that, the leader vehicle randomly selects required number of time slots from the available time slots. Then, the leader vehicle sends a reservation packet using the selected time slot and adds the used time slot to the list of reserved time slots. Note that, in the case that the reservation packet conflicts with another platoon leader's reservation packet, it is recognized as the conflict or deficiency. In this case, the leader vehicle executes this selection procedures recursively and reserves the necessary number of time slots in consequence.

3.5.3 Slot Assignment for Platoon Members

Each platoon member overhears the leader vehicle's reservation packets and creates the list of the reserved slots. It is assumed each member knows its own order in the platoon in advance, and autonomously knows assigned slots which are corresponding to the order in the platoon. The member vehicle can distinguish reserved time slots ID which fulfills Equation 3.1 as the assigned time slot.

$$i \bmod N = j, \tag{3.1}$$

where, i is the reserved order of time slot, N is the number of platoon members, j is the order of the member vehicle in the platoon. An example of time slot reservation by leader vehicle in the case of 40 time slots per frame is shown in Fig. 3.5. It depicts the relation between the vehicle IDs of A1 – A5 and the reserved slot IDs. Vehicle A1 is the leader vehicle of platoon and vehicles A2 – A5 are the member. In the case that the number of repetitive transmission is three, vehicle A1 reserve fifteen slots for members. Vehicles A2 – A5 hear the reservation by A1, and distinguish slot IDs for themselves.

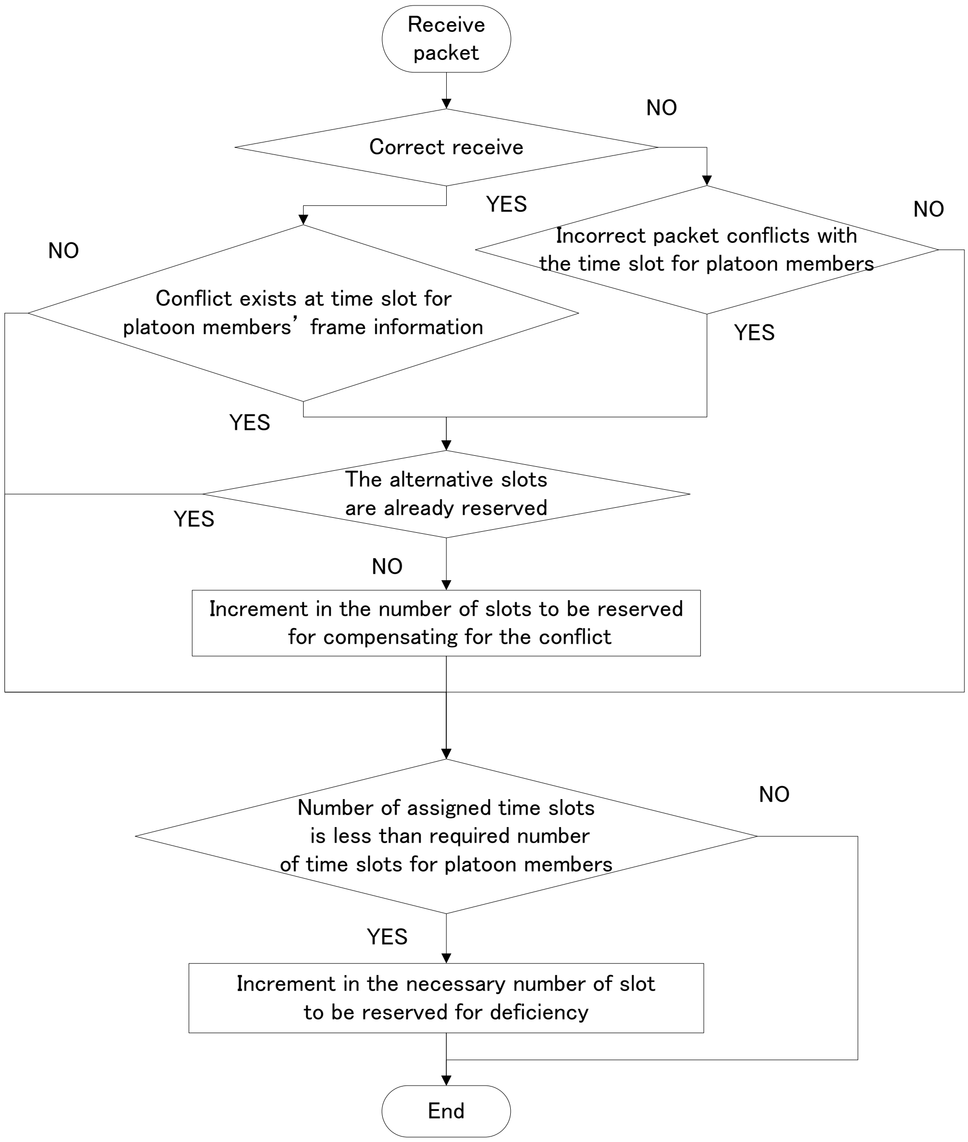


Figure 3.4: Calculation flow for number of repetitive transmission

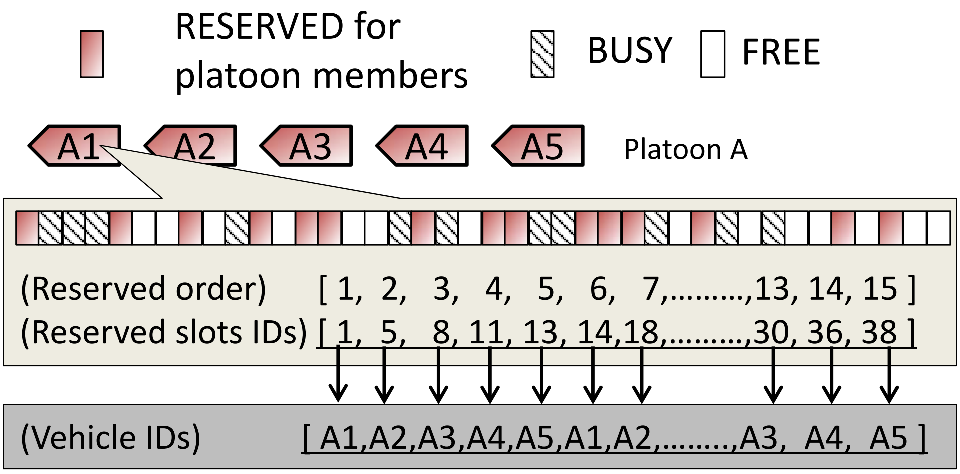


Figure 3.5: Example of time slot assignment by leader vehicle

3.6 Evaluation and Discussion of Time Slotted Communication Protocol for Platooning

3.6.1 Simulation Setups

In order to show the efficiency of the proposed protocol for platooning, the computer simulation compares the proposed protocol and typical existing communication protocols such as the repetitive transmission protocol without transmission rate control, namely the simple repetitive transmission for further discussion, and RR-ALOHA. The simulation environment consists of the network simulator and the traffic simulator. We adopt Scenargie 1.4 [57] as the network simulator. Scenargie is specially designed for the performance evaluation of ITS communication. We adopt ADVENTURE Mates Version 0.11 beta [58] as the traffic simulator, Mates has well compatibility with Scenargie and is designed for microscopic traffic simulations. Both simulators execute alternately. The traffic simulator calculates vehicles inflow and movement based on "the following driver model [58]" and the network simulator calculates the wireless communication using the result of the traffic simulator. After that, traffic simulator calculates vehicles movement in the next time step referring to the network simulator's calculation results.

Table 3.1 shows the simulation parameters. The parameters for communication are adopted by the report of utilization proposition committee for ITS simulator, Japan Automobile Research Institute [59], which provides the reference typical communication parameters and their values for ITS simulations. These parameters and values are based on DSRC/WAVE which is the most leading standard for ITS communication. The simulation parameters for road model is referring to the Government Order on Road Design Standards [60]. This simulation assumes that platoon members exchange 50 byte information at every 20 msec referring to [29]. Moreover, the number of repetitive transmission of the simple repetitive transmission protocol and RR-ALOHA protocol is 5 which is adopted in Energy ITS, Japan [29], and the maximum number of repetitive transmission of the proposed protocol is also 5. The duration of frame and the number of slot in a frame are equal in the simple repetitive transmission protocol and RR-ALOHA protocol and the proposed protocol. The frame length and the number of slot per frame of RR-ALOHA

Table 3.1: Simulation parameters

Communication	
Simulation parameters	Value or reference
Simulator	Scenargie 1.4
Payload Size	50 Bytes
Transmission Cycle	20 msec
Number of repetitive transmission	5 times
Frame size	20 msec
Number of slot	40 slot/frame
Modulation Scheme	OFDM (QPSK 1/2)
Transmission Power	20 dBm
Band Frequency	5.9 GHz
Bandwidth	10 MHz
Bit Rate	6.0 Mbps
Propagation Model	ITU-R_P.1411
Modulation Scheme	OFDM(QPSK1/2)
Traffic	
Simulation parameters	Value or reference
Simulator	ADVENTURE Mates Version 0.11 beta
Intervals between Trucks	4 m
Road Length	10.00 km
Road Width	3.5 m
Size of Trucks(W, L, H)	2.5 m, 12 m, 3.8 m
Number of Platoon members	5 vehicles

protocol and the proposed protocol equals the simple repetitive transmission protocol in terms of the maximum transmission speed. Bit Error Rate (BER) model is also referring to the report by Utilization Proposition Communication for ITS simulations, Japan Automobile Research Institute [59]. In the case that the transmission power is 20 dBm, the communication range is about 500 m without obstacles. "The following driver model" is used to calculate vehicle's velocity and acceleration according to the relative distance and velocity to the preceding vehicle. This simulation also assumes that the time slot synchronization is accurate enough among all vehicles.

In order to evaluate the time slotted communication protocols for platooning, this dissertation simulates two cases; without and with platoon mobility. The former is the static case where the platoons are not moving. It is better to analyze the fundamental characteristics of the platoon communication. The latter is the dynamic case where the platoon are driving in a designated lane to analyze the dynamic characteristics of the platoon communication in more realistic conditions.

3.6.2 Simulation without Platoon Mobility

Simulations are conducted at two conditions where three or five platoons are in tandem. In both simulations, each platoon consists of 5 vehicles. All headway distance which is the distance from the head of the platoon to the head of the next platoon is equal for all platoons and varies from 100 to 700 m. Vehicles in each platoon exchange information with the other platoon members.

(a) Packet Arrival Ratio versus Headway Distance by Simple Repetitive Transmission Protocol

This simulation evaluates the simple repetitive transmission protocol in terms of the packet arrival ratio. In this simulation, three platoons are allocated in tandem. Equation 3.2 shows the packet arrival ratio of MAC layer D_k for platoon k.

$$D_k = \frac{\sum_{i=1}^{N_v} \frac{p_i}{S_i}}{N_v}, \tag{3.2}$$

where, N_v is the number of platoon members, p_i is the number of received packets from platoon member i, S_i is the number of packets which are sent by platoon member i.

Figure 3.6 shows the packet arrival ratio versus the headway distance between three platoons. In the case that the headway distance is more than 600 m, since there exists no radio interference between platoons, the packet arrival ratios are equally high. On the contrary, in the case that the headway distance is from 100 to 200 m, since all platoons equally have high communication load, the packet arrival ratios of them are equally low value of 0.53. Figure 3.7(a) shows the relation between position of platoon, communication range and communication load in the case of entirely same communication range and, in this figure, L is the headway distance between platoons. More than two vehicles are more likely to send a packet at the same time when the headway distance is quite small and many vehicles are in the same communication range. In this situation, either of them has

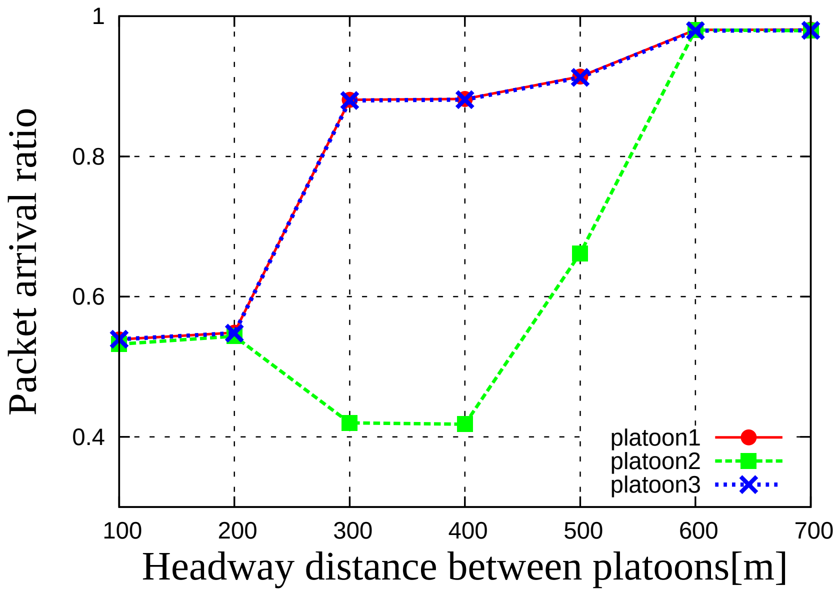
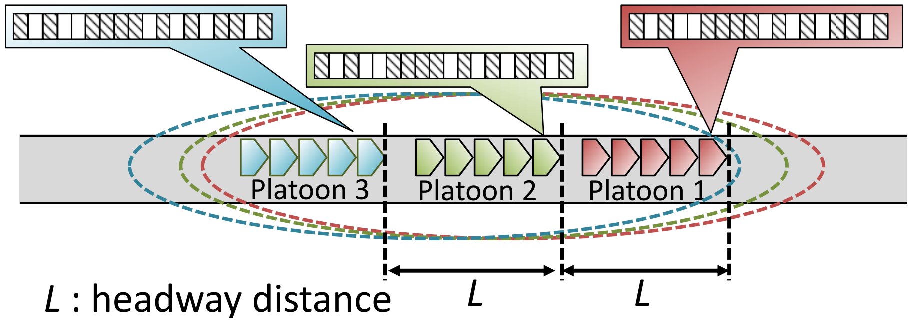


Figure 3.6: Packet arrival ratio versus headway distance between 3 platoons

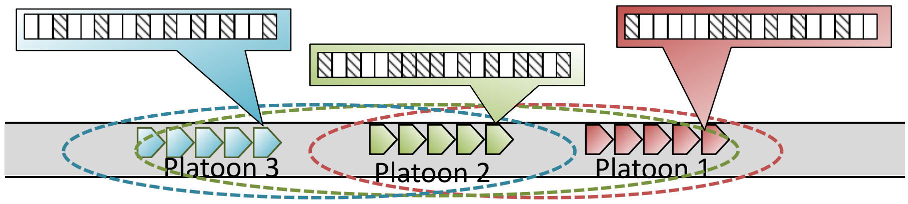
to wait until the wireless channel becomes available. Consequently, these vehicles cause heavier communication load than the wireless channel capacity and cause the wireless channel congestion. Thus, the packet arrival ratio of all platoons becomes low.

By contrast, in the case that the headway distance is from 300 to 500 m, since the biased communication load is triggered by the hidden terminal, the packet arrival ratio of platoon 2 is lower than platoons 1 and 3. For instance, when the headway distance is 300 m, the packet arrival ratios of platoons 1 and 3 are equally 0.88 but the ratio of platoon 2 is 0.43. Figure 3.7(b) shows the case of partially same communication range in the relation between position of platoon, communication range and communication load. While communication range of platoon 1 and 3 cover two platoons, communication range of platoon 2 covers three platoons. It means the communication loads on each platoon's slots are biased. Since the communication load of platoon 2 is very high compared with the platoon 1 and 3, the packet arrival ratio of platoon 2 decreases much lower than the other.

Regarding to these results, since the simple repetitive transmission requires large amount of transmission and possibly exceeds the wireless channel capacity, the wire-



(a)



(b)

Figure 3.7: Relation between platoon position, communication range and communication load (a) The case of entirely same communication range (b) The case of partially same communication range

less channel congestion and the bias on the communication load occur depending on the headway distance. Therefore, the communication protocol solving these problems is necessary for platoon members to keep exchanging information frequently, even under the congested situation.

(b) Data Arrival Ratio versus Headway Distance between 5 Platoons

In the platoon communication, replicated packets are transmitted repetitively and the transmission is considered as success if at least one of them reaches to the other platoon members within the required time limit, its success ratio is named the data arrival ratio. The relation between the packet arrival ratio and the data arrival ratio in the case where the number of repetitive transmission is 5, is given in Table 3.2. Even in the packet arrival ratio is 0.5, if it is possible to send five times repetitively, the data arrival ratio will increase to 0.969. Equation 3.3 shows the data arrival ratio R_k for platoon k.

Table 3.2: Packet arrival ratio versus data arrival ratio

Packet arrival ratio	Data arrival ratio
0.1	0.410
0.2	0.672
0.3	0.832
0.4	0.922
0.5	0.969
0.6	0.990
0.7	0.998
0.8	1.000
0.9	1.000
1.0	1.000

$$R_k = \frac{\sum_{i=1}^{N_v} \frac{r_i}{T_i}}{N_v}, \tag{3.3}$$

where, N_v is the number of platoon members, r_i is the number of received data from platoon member i, T_i is the number of data which is the number of packet before it is replicated and is sent by platoon member i. Figures 3.8 to 3.10 evaluate the data arrival ratio versus the headway distance between platoons in the case of simple repetitive transmission protocol, RR-ALOHA protocol and proposed protocol, respectively.

In Fig. 3.8, when the headway distance is more than 300 m, the data arrival ratio is high for all platoons. However, in the case that the headway distance is 100 m, the wireless channel congestion occurs in all platoons, so that the data arrival ratio indicates more than 0.8 up to 0.95. In the case that the headway distance is from 150 to 300 m, the biased communication load occurs. Consequently, the data arrival ratio of platoon 3 is the lowest among the platoons, and the ratios of platoons 1 and 5 are high and the ratios of platoons 2 and 4 are in between.

Figure 3.9 shows the case of RR-ALOHA protocol and obtained a very similar results to the case of simple repetitive transmission protocol. RR-ALOHA protocol, however, does not use the back-off and contention control mechanism, so that RR-ALOHA protocol requires less idle time and efficiently shares the wireless channel among vehicles. In consequence, when the headway distance is from 150 to 250 m, RR-ALOHA improves the

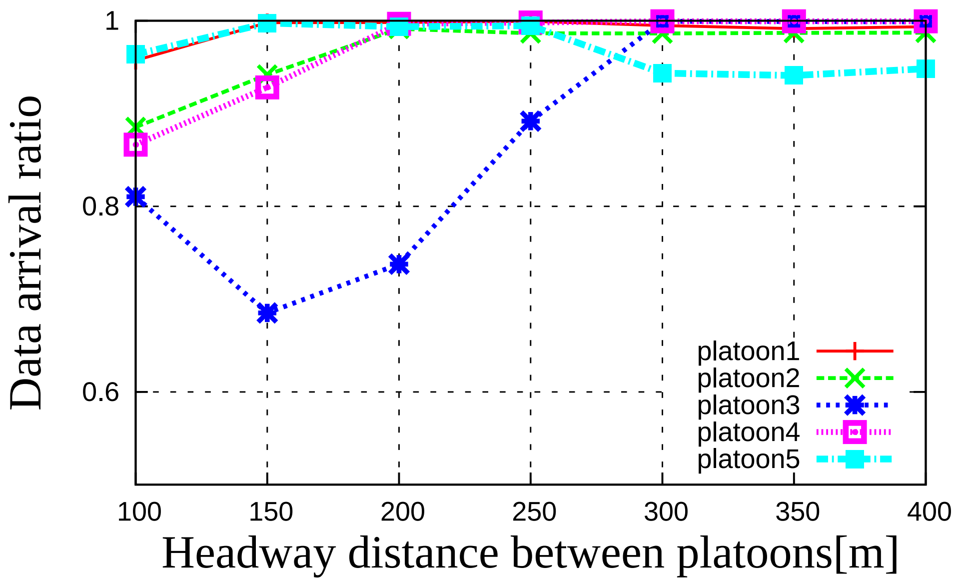


Figure 3.8: Data arrival ratio by simple repetitive transmission protocol

data arrival ratio of platoon 3 compared with the simple repetitive transmission protocol.

Figure 3.10 shows the data arrival ratio and the average number of repetitive transmission versus the headway distance by the proposed protocol. In this figure, the data arrival ratio is quite high for any platoon at any case. Though the repetitive transmission originally aims to enhance the data arrival ratio, it works negatively under the congested situation. The way of thinking is that how effective to increase or continue the repetitive transmission even in the congested situation. Therefore, the proposed protocol reduces the number of repetitive transmission in the case of wireless channel congestion. As a result, the proposed protocol keeps high data arrival ratio at small headway distance. Furthermore, since each platoon controls the number of repetitive transmission according to surrounding platoon's wireless channel condition, the proposed protocol can get rid of the biased communication load as well.

When comparing the data arrival ratio among Figs. 3.8, 3.9 and 3.10 as a whole, in the case that the headway distance is 100 m, the wireless channel congestion appears in the simple repetitive transmission and the RR-ALOHA protocols. The closer to the center the platoon is, the less the data arrival ratio is. On the contrary, there exists little congestion

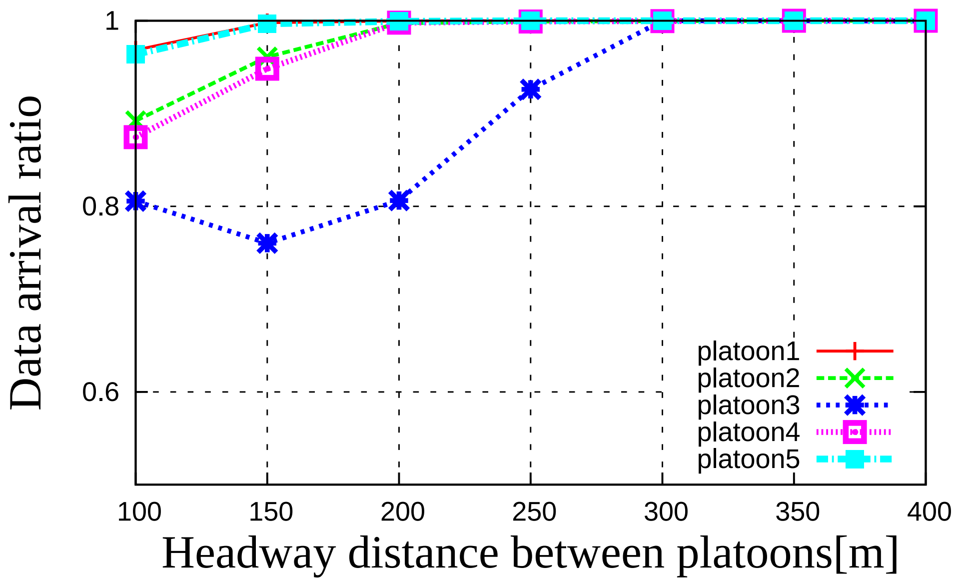


Figure 3.9: Data arrival ratio by RR-ALOHA protocol

and indicates high data arrival ratio in the case that the headway distance is large. In the case of 150 to 200 m, vehicles often face to the expiration of the required time limit to exchange the information in the simple repetitive transmission protocol. The closer to the center the platoon is, the more frequently vehicles expire the time limit of 20 msec. Therefore, the platoon which is close to the center indicates low data arrival ratio. RR-ALOHA protocol is similar to the simple repetitive transmission protocol. RR-ALOHA protocol can slightly improves the data arrival ratio, however, the congestion and biased communication load are not reduced. Hence, RR-ALOHA protocol is insufficient for platoon communication. By contrast, proposed protocol almost eliminates the congestion and biased communication load. This is because each vehicle in the platoon is able to detect the congestion at any surrounding vehicles in other platoons in the communication range and temporally decrease the number of repetitive transmission by the proposed protocol.

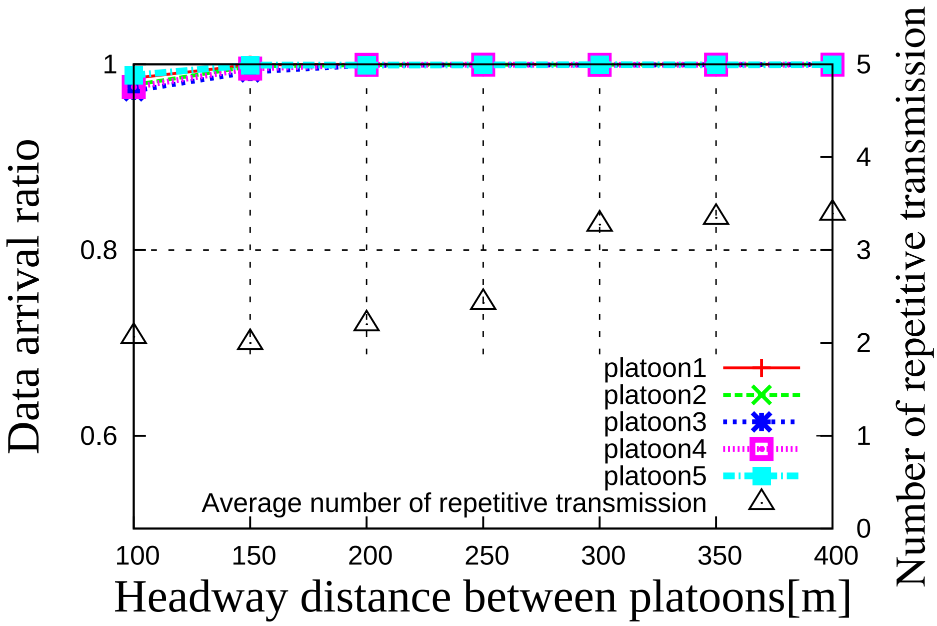


Figure 3.10: Data arrival ratio and average number of repetitive transmission by proposed protocol

3.6.3 Simulation with Platoon Mobility

In order to evaluate each protocol in more realistic scenario, platoons have mobility and drive on the straight road representing an express highway. Platoons inflow from the either edge of the road, drive to the other side of the edge and outflow through there. The road consists of one lane each way, and platoons pass by each other. All platoon members are heavy duty trucks and there is no other vehicle in the simulation. The expected speed of every platoon is 80 km/h, and platoons do not overtake another platoon.

During the following simulations, in order to measure the data arrival ratio and the platoon maintenance ratio under the stable condition, the simulation starts the measurement after 1000 seconds from the start of the execution. In the following figures, the time depicted 0 seconds means the start of the measurement.

(a) Data Arrival Ratio versus Platoon Inflows

This simulation assumes a realistic traffic condition and measures the data arrival ratio when varying the platoon inflows. The high data arrival ratio means the reliable

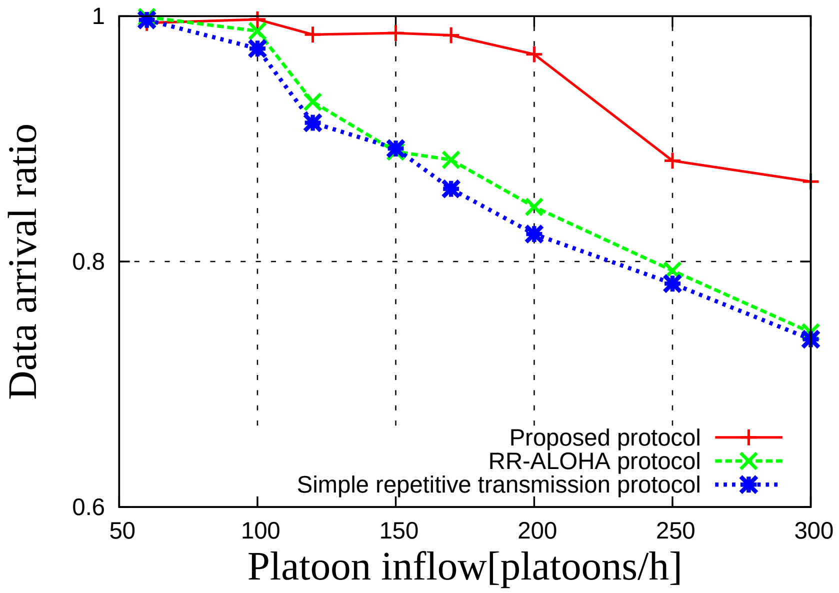


Figure 3.11: Relation between data arrival ratio and platoon inflow

exchange of information. Equation 3.4 shows the average data arrival ratio per platoon $R_{average}$.

$$R_{average} = \frac{\sum_{k=1}^{P} R_k}{P} = \frac{\sum_{k=1}^{P} \sum_{i=1}^{N_v} \frac{r_{ki}}{T_{ki} N_{kv}}}{P}, \tag{3.4}$$

where R_k is the data arrival ratio for platoon k which is given by Equation 3.3, P is the number of platoon on the road, N_{kv} is the number of platoon member in platoon k, r_{ki} is the number of received data from member i in platoon k, and T_{ki} is the number of data which is sent by member i in platoon k.

Figure 3.11 shows the relation between data arrival ratio and platoon inflow. In the case of low platoon inflow such as 50 to 100 platoons/h, all protocols indicate that the data arrival ratio is around 1. In the simple repetitive transmission and RR-ALOHA protocols, the data arrival ratio is decreasing as the platoon inflow increases, especially in the case of over 120 platoons/h, which corresponds to the average headway distance of 667 m. On the other hand, in the proposed protocol, the data arrival ratio is higher than the other protocols and it indicates 0.96 at 200 platoons/h, which corresponds the average headway distance of 400 m. Though the data arrival ratio goes down at 300 platoons/h, the proposed protocol still indicates higher data arrival ratio than RR-ALOHA protocol by 11 %.

From the results, it can be said that there exists almost no difference between protocols in the case of small platoon inflow. However, in the case that the platoon inflow is over 120 platoons/h, the proposed protocol is more efficient than the simple repetitive transmission and RR-ALOHA protocols.

(b) Platoon Maintenance Ratio versus Platoon Inflows

This simulation introduces the platoon maintenance ratio (P_d) and the platoon maintenance time ratio (P_t) as shown in Equations 3.5 and 3.6. The platoon maintenance ratio is defined as the number of platoon which succeeds the information exchange in the total number of platoon. The platoon maintenance time ratio is defined as the time which all platoon members succeed the information exchange in the entire measurement time.

$$P_d = \frac{P_m}{P}, \tag{3.5}$$

$$P_t = \frac{T_{\text{platoon}}}{T}, \tag{3.6}$$

where, P is the total number of platoon on the road, P_m is the number of platoon in which all platoon members exchange data, $T_{platoon}$ is sum of time which all platoon members exchange data, T is the measurement time.

Figures 3.12, 3.13, 3.14 show the time alteration of platoon maintenance ratio in the case of 120, 170, 250 platoons/h respectively. These figures compare the proposed and RR-ALOHA protocols. The proposed and RR-ALOHA protocols show the almost same performance in Figs. 3.12 and 3.13. In Fig. 3.14, while RR-ALOHA protocol indicates low platoon maintenance ratio, the proposed protocol keeps high platoon maintenance ratio. Regarding to the average platoon maintenance ratio, 0.62 of the proposed protocol is 14 % higher than 0.54 of RR-ALOHA protocol in the case of 250 platoons/h. In this case, the amount of received data by the proposed protocol is 48 Kbps and the one by RR-ALOHA is 43 Kbps. Since the minimum amount of received data for maintaining platoon is 80 Kbps, the achievement rate of the proposed protocol is 60 % and RR-ALOHA is 54 %. The

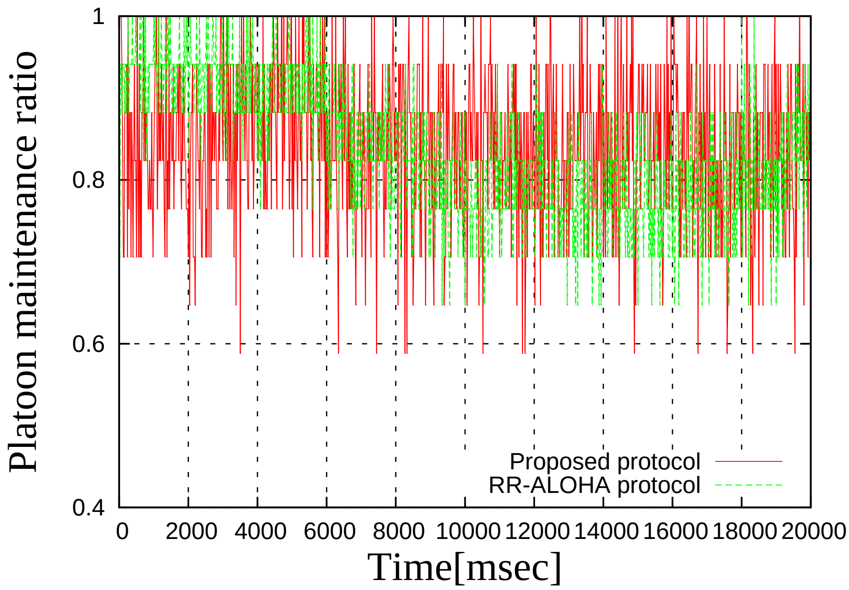


Figure 3.12: Time alteration of platoon maintenance ratio (120 platoons/h)

platoon maintenance ratio against the amount of received data by each protocol is facing their limits since there already appears the tendency of congestion as shown in Fig. 3.11. Therefore, a method for controlling platoon density or for loosening the communication requirement is needed for more improvement, however the study on this method is out of this dissertation. Cumulative frequency distribution of platoon maintenance time ratio in the case of 250 platoons/h is shown in Fig. 3.15. While more than 90 % of platoons are included over 0.15 of the platoon maintenance time ratio by RR-ALOHA protocol, more than 90 % of platoons are included over 0.4 of the platoon maintenance time ratio by the proposed protocol. Moreover, the dispersion of RR-ALOHA protocol is 0.35 and the dispersion of the proposed protocol is 0.22. The proposed protocol shows smaller dispersion than RR-ALOHA protocol. Regarding to the results, the proposed protocol reduces the bias on the communication load compared with RR-ALOHA protocol.

The fluctuation is shown in Figs. 3.12, 3.13 and 3.14. In VANET, since the network topology dynamically changes, the conflict of time slot often occurs. In this case, the proposed protocol enables vehicles to reserve the available slots in the next frame, then recover the data arrival ratio which temporally goes down. Hence, in the case that pla-

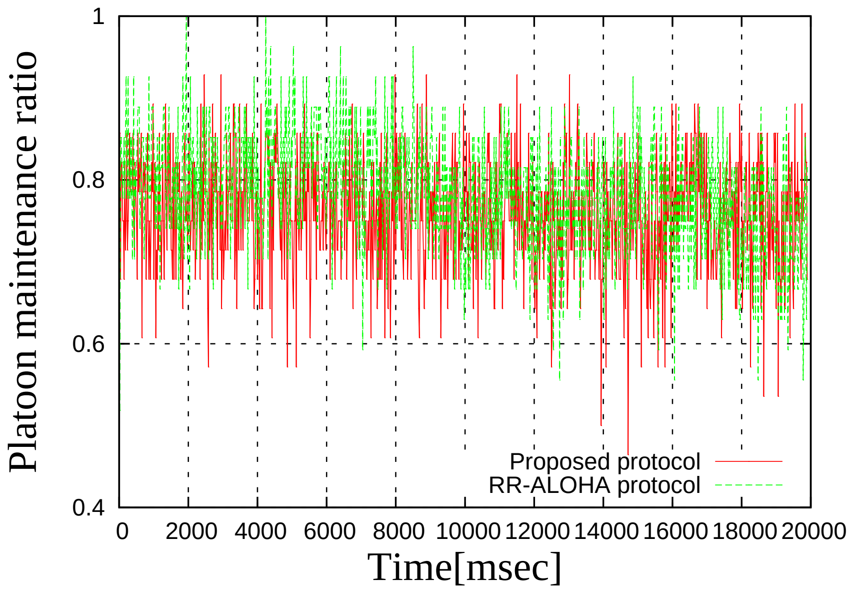


Figure 3.13: Time alteration of platoon maintenance ratio (170 platoons/h)

toons pass by each other frequently, the conflicts also occur frequently. In consequence, such a large fluctuation appears. Especially in the case that plural slot conflicts occur in a platoon at the same time, since the leader vehicle representatively reserves slots for recovery in the proposed protocol, vehicles are able to use time slots without unnecessary conflicts. Therefore, proposed protocol keeps high platoon maintenance ratio.

According to these results, while the proposed protocol shows same performance as RR-ALOHA at the small platoon inflow, it is more efficient at the large platoon inflow in terms of the platoon maintenance ratio. Moreover, while RR-ALOHA protocol causes the biased communication load, the proposed protocol reduces it. This is because the proposed protocol reduces the communication load when they detect the wireless channel congestion at surrounding platoons.

We assume that the slot time synchronization is accurate with GPS clock. Since the accuracy of GPS clock depends on the radio propagation, it becomes worse in some cases such as vehicles drive in a tunnel. Therefore, it is better to study the case where the slot time synchronization becomes inaccurate. In this case, the proposed protocol is designed for vehicles to communicate with each other through the contention mechanism which is

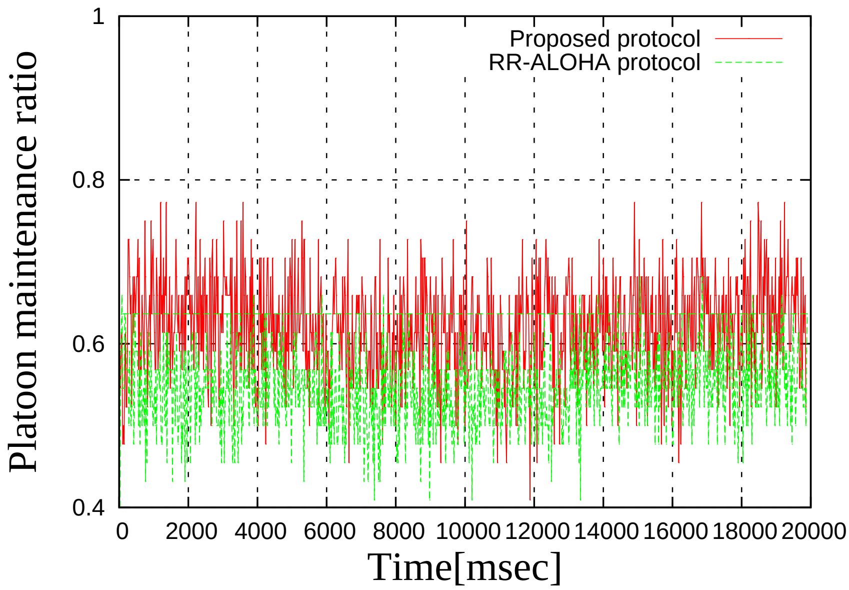


Figure 3.14: Time alteration of platoon maintenance ratio (250 platoons/h)

adopted in CSMA/CA. Vehicles are able to re-transmit a packet within a random short time autonomously and they can keep communicating even without slot time synchronization. It should be better to be evaluated through the simulation with/without vehicle mobility.

Also, we assume the road model of one lane in each direction. This assumption is based on the model where platoons drive in a designated lane. However, as a future model, platoons might drive in all lanes and dynamically change their lanes. In the case of two lanes in each direction, the density of platoons is able to become double compared with the case of one lane in each direction. There is no difference between overtaking and passing by each other in terms of wireless communication interference between platoons. Thus, the proposed protocol is expected to work more effective than the simple repetitive transmission and RR-ALOHA protocols, however the data arrival ratio and the platoon maintenance ratio possibly become worse than the case of one lane in each direction. As described in this subsection, since the proposed protocol reaches full throughput of the wireless channel, it is necessary for the density of platoons should be controlled not to exceed a certain level of density.

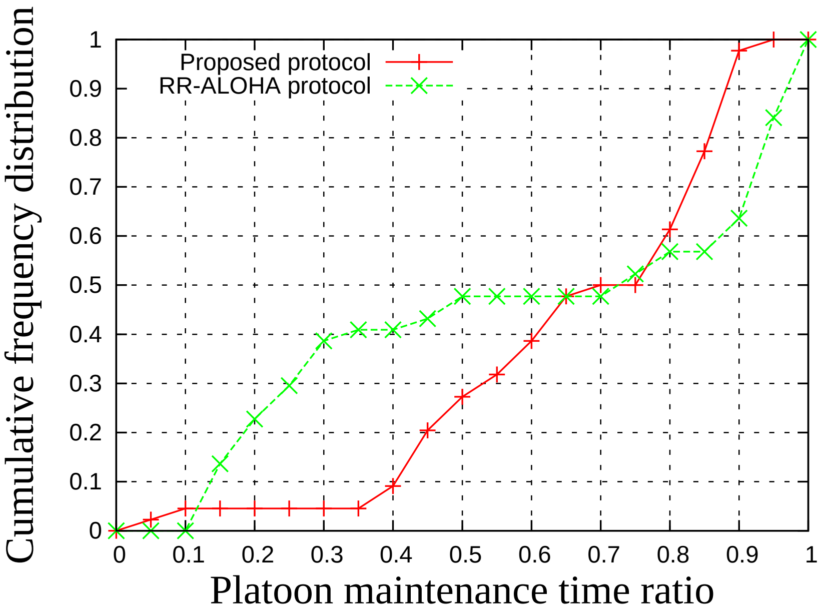


Figure 3.15: Cumulative frequency distribution of platoon maintenance time ratio (250 platoons/h)

3.7 Summary

This chapter proposes a time slotted communication protocol for platooning in order to overcome the wireless channel congestion and biased communication load due to the hidden terminal. The proposed protocol consists of three key functions as follows; time slotted CSMA/CA channel with pseudo TDMA frame, repetitive transmission rate control and representative slot reservation by the leader vehicle.

This chapter reveals the following results.

(1) This dissertation clarifies the existence of wireless channel congestion and biased communication load due to the hidden terminal problem over the CSMA/CA channel in the vehicle to vehicle communication for platooning. The simulation was done in the situation that plural platoons are located in tandem with keeping the equal headway distance and without mobility. This dissertation evaluates the packet arrival ratio versus headway distance between platoons by simple repetitive transmission and RR-ALOHA protocols. In both experiments, the result shows a large degradation of the packet arrival ratio in the center platoon among several platoons. Since the communication coverage size of each platoon is assumed to be the same, communication load is heavy to the center platoon and light to the edge platoon. The effect of hidden terminal problem is clearly shown.

(2) When the plural platoons are driving on the same road, frequent data exchange is needed to maintain a platoon. For this purpose, the repetitive transmission rate control is introduced at the pseudo TDMA frame over the time slotted CSMA/CA channel. Vehicles increases/decreases the number of repetitive transmission when the slot occupancy information (Frame Information) is lower/higher than the threshold. In this context, vehicles can autonomously avoid the congestion and increase the data arrival ratio. It is also obtained the improvement of the data arrival ratio in the case that plural platoons are in the same communication range. At the same time, since vehicles exchange their Frame Information among neighboring vehicles, they are able to know the communication load on neighboring vehicles. They can avoid biased communication load on any other neighboring vehicle. It is shown by

improvement of the data arrival ratio of the central platoon in the case the both edge platoons are hidden from each other.

(3) The leader vehicle represents the other platoon members and reserves time slots for them. Therefore, it can avoids the reservation conflicts among platoon members. Moreover, since the leader vehicle assigns those time slots equally to the other members, platoon members can exchange information in a balanced manner. Results of the simulation shows the high data arrival ratio and platoon maintenance ratio in the case where plural platoons drive on the road in both directions.

(4) We assume that the slot time synchronization is accurate with GPS clock. Since the accuracy of GPS clock depends on the radio propagation, it becomes worse in some cases such as vehicles drive in a tunnel. It is better to consider the case where the slot time synchronization becomes inaccurate. In this case, the proposed protocol is designed for vehicles to communicate with each other through the contention mechanism which is adopted in CSMA/CA. Vehicles are able to re-transmit a packet within a random short time autonomously and they can keep communicating even without slot time synchronization. It should be better to evaluate the proposed protocol through the simulation.

Chapter 4

Communication for Overtaking

4.1 Overview

As described in Section 2.5, in Energy ITS, Japan, the platoon drives in the designated lane and never changes its lanes except the case of emergency. In the case that the slower vehicle drives in the lane, the platoon decelerates and follows the slower vehicle [25]. Making progress on platooning toward more practical use, it is better to consider the overtaking of platoons and non-platoon vehicles, under the assumption that the platoon is driving in the designated lane. In the simple overtaking model, vehicles decide overtaking based on the distance and relative velocity between vehicles and one in front. This type of overtaking is named distance-based method. In order to abide by the rule, if a vehicle is driving ahead and speed of it is slower than the platoon, it has to move to the passing lane and will give its way to the platoon. At the same instance, if the faster vehicle overtakes the platoon, the faster vehicle is not able to overtake the platoon because the slower vehicle is in the passing lane. It is called overtaking conflict and the cause of overtaking conflict is that more than two vehicles enter the passing lane at the same time.

In order to solve this conflict, this chapter proposes the communication method for overtaking and it applies the distributed mutual exclusion algorithm into the overtaking at the critical section which is a part of lane next to the platoon. The distributed mutual exclusion algorithm is categorized into permission-based algorithm and token-based algorithm. Considering the number of message exchange and required processing time to

Table 4.1: Features of overtaking methods

Overtaking method	Timing for start overtaking
Token-based method	Vehicle get token from the leader of the platoon
Permission-based method	Vehicle collect permission from the other vehicle in the communication range
Distance-based method	Inter-vehicular distance becomes less than a certain threshold and velocity is faster than the one in front

decide the one specific vehicle, it seems that the token-based algorithm is more suitable for the overtaking from the qualitative point of view. Therefore, this dissertation first selects the token-based algorithm as a first candidate, and compare with the permission algorithm and distance-based method through the simulation. In the token-based method, vehicles get the token according to the FCFS policy in order to avoid the starving problem. The starving problem is the situation where a specific vehicle waits for a very long time and never enters the critical section. Platoon controls the inter platoon distance to avoid the deadlock and the leader vehicle in the platoon reissues the token when the token is lost.

We evaluate the overtaking control methods through computer simulations. In the simulation, this chapter compares the token-based method, the permission-based method, and the distance-based method. The features of these three methods are shown in Table 4.1. It is shown that the token-based method and the permission-based method are more efficient for overtaking control than the distance-based method in terms of the average speed, the amount of the acceleration and the amount of CO_2 emissions. Also It is shown that the token-based method is more efficient than the permission-based method in terms of the waiting time of a vehicle from its request to overtaking until its actual start of overtaking. Finally, this dissertation shows the token-based method is effective for overtaking control under mixed road condition with platoons and non-platoon vehicles.

4.2 Proposed Model and Premises of Communication for Overtaking

In this chapter, the model of platooning is extended that plural platoons drive in a designated lane of one direction under mixed condition with non-platoon vehicles. Members of platoon are predetermined. Non-platoon vehicles do not join and leave the platoon and platoons do not join another platoon dynamically. Also platoons are not split or dismissed during driving. Each member knows exact member and their order in the platoon. Platoons drive with non-platoon vehicles. Non-platoon vehicles drive in any lane on the road which consists of two lanes. The fail-safe and fail-tolerant policies are based on Energy ITS, Japan and they are out of scope of this dissertation. Vehicles are supposed to be installed a redundant communication system and this chapter assumes that communication devices are never broken. In emergency cases, platoons are supposed to safely decelerate and suspend platooning and this chapter assumes that traffic accidents never occur.

4.3 Communication during the Overtaking

Supposing that the several vehicles and platoon are running to the same direction in the inner lane of the two lanes express highway. Since the platoon should drive in the designated lane which is assigned to the inner lane, this dissertation assumes that platoon always remains in the same lane. Therefore, the overtaking the platoon will be accomplished in two cases. One is the case that a platoon catches up the slower vehicle just running in front and asks the vehicle to change the lane. Then the slower vehicle changes its lane to the passing lane, and platoon will overtake using inner lane. The other is the case that the faster vehicle catches up with the platoon from the tail, and overtakes the platoon using passing lane of the highway.

In order to realize overtaking smoothly, this dissertation discusses the communication between platoon and vehicles, and the logic itself to overtake. The mechanism to realize through the communication is briefly the followings. Every vehicle has communication devices and they are able to communicate with each other. In general, vehicle to vehi-

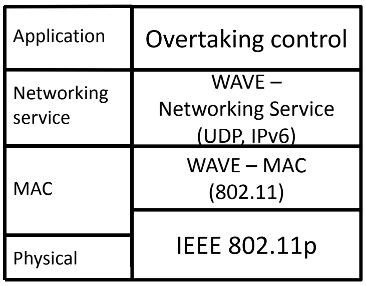


Figure 4.1: Protocol stack for overtaking control

cle (V2V) communication adopts IEEE 802.11p/WAVE. Its protocol stack is shown in Fig. 4.1. Vehicles periodically announces its own position and velocity information using the payload in its packet as shown in Fig. 4.2. In addition, vehicles know the sender ID according to the packet header. Vehicles can detect that they are about to overtake neighboring vehicles and neighboring vehicles about to overtake them.

Within the platoon, one vehicle becomes the leader of platoon, and it manages a logic of overtaking which decides the scenario of overtaking. When a vehicle overtakes a platoon or the platoon overtakes a vehicle, a zone of passing lane next to the platoon becomes the critical section. In order to realize a overtaking control, it is possible to introduce the distributed mutual exclusion algorithm to put only a single vehicle into the critical section. There are two algorithms, one is permission-based, and the other is token-based. Permission based is a voting system by all participants, and token-based is the priority system in which only a token holder has the privilege. The token-based selection requires less volume of message exchange and shorter waiting time from request for token until actual start than permission-based selection. From the qualitative point of view, the token-based method seems appropriate.

The mechanism of overtaking can be summarized in four phases. Its phase shifts will be done cyclically.

(1) Stable phase:

Vehicles and platoons are running at their original speed in the inner lane.

(2) Accessing phase:

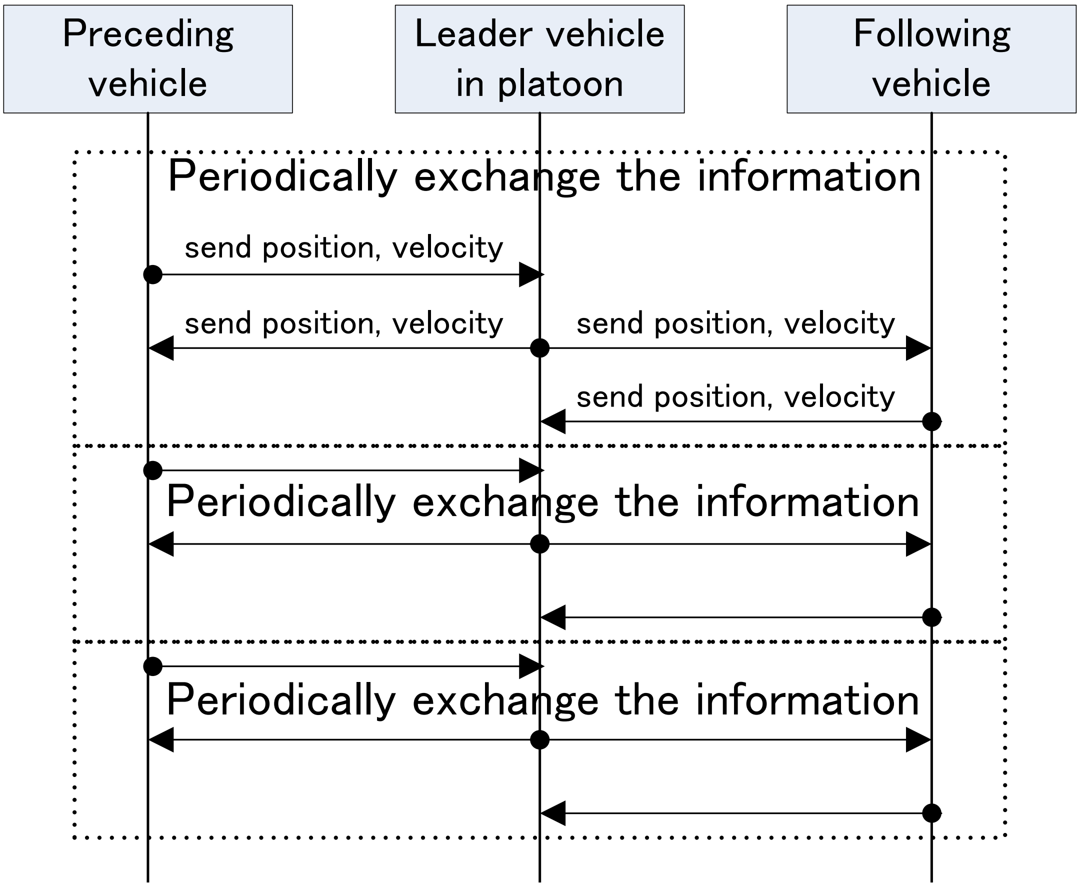


Figure 4.2: Periodical exchange of vehicle's position and velocity

There are two cases. One is the case that a platoon catches up the slower vehicle just running in front and asks the vehicle to change the lane. The other is the faster vehicle catches up the platoon and expresses the overtaking wish to the platoon. Which vehicles has the right to enter the passing lane is decided by the leader vehicle using mutual exclusion algorithm.

(3) Overtaking phase:

There are two cases. One is the case that slower vehicle in front changes the lane to the passing lane and gives a platoon the inner line. The other is the case that platoon gives an accept response to the following faster vehicle and gives it a permission to

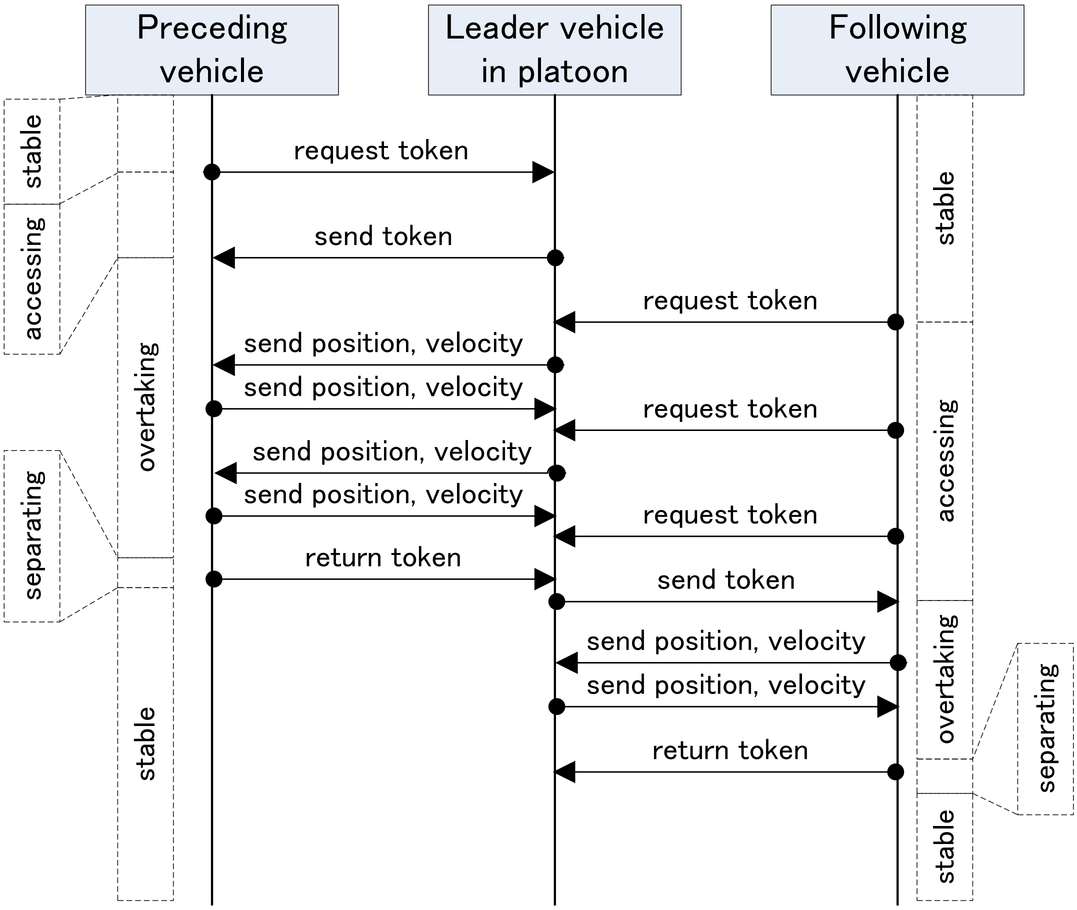


Figure 4.3: Overtaking procedure using token-based algorithm

enter the passing lane and allows its overtaking.

(4) Separating phase:

Overtaking vehicle or overtaken vehicle goes back to the inner lane and drives to the forward and goes back to the stable phase.

Overtaking procedure using token-based algorithm is given in Fig. 4.3 as an example. There are three vehicles; preceding vehicle, leader vehicle in platoon and following vehicle. There are two cases for start of the procedure. One is the case that the non-platoon vehicle notices that the inter-vehicular distance becomes less than the threshold. The non-platoon vehicle sends a request token for the leader vehicle of platoon. The other is that the leader vehicle of platoon notices the inter-vehicular distance becomes less than the threshold. The leader vehicle ask the non-platoon vehicle to change its lane to passing lane. In the figure, the preceding vehicle sends a request for token to the leader vehicle and waits for the token. The leader vehicle sends back a token. The preceding vehicle starts to be overtaken after receiving token, and shifts to the passing lane. During overtaking, the preceding vehicle and the leader vehicle exchange their own position and velocity in order to check whether the overtaking is finished or not. As soon as the preceding vehicle finishes overtaking, it returns the token to the leader vehicle and leaves from the management of the leader vehicle. Here, the following vehicle sends a request for token to the leader vehicle during the preceding vehicle's overtaking. In this case, the leader vehicle has already sent the token to the preceding vehicle and it does not have the token. The leader vehicle adds the following vehicle to the last of queue for token waiting list. The following vehicle sends requests periodically until it gets the token. As soon as the leader vehicle gets the token back from the preceding vehicle, it will send the token to the following vehicle according to the queue for token waiting list. The following vehicle starts overtaking, and the operations hereafter are same as the preceding vehicle.

4.4 Consideration of the Token Handling and Traffic Model for Overtaking

There are several important considerations to the token handling and traffic model for overtaking the platoon.

4.4.1 Token and Priority

Vehicles decide the overtaking order depending on the time-stamped token based on FCFS. Figure 4.4 shows the overtaking where vehicle B is running in front of platoon, A_1 and A_2 are running behind the platoon. After the certain token request procedures, if the token priority is given to the order of A_1, B, A_2, vehicle A_1 starts its overtaking procedure. A_1 changes its lane to the passing lane and overtakes the platoon. In this case, vehicles

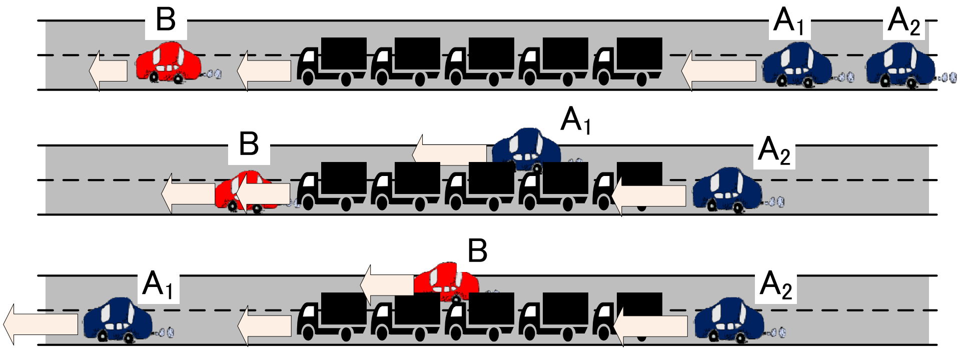
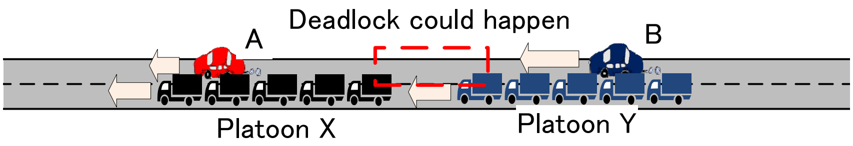


Figure 4.4: Example of overtaking based on token priority

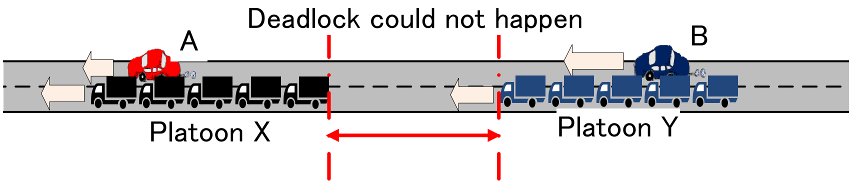
Figure 4.5: Example case where long queue of vehicles are overtaking

B and A_2 keep their order as they are and A_1 is running in front of platoon and A_2 is waiting right behind the platoon. After A_1 overtakes the platoon, B receives the token and starts its overtaking procedure. B changes its lane to the passing lane and gives its way to the platoon. The platoon overtakes B using inner lane, and B will return the token to the leader vehicle of platoon and go back to the inner lane. Finally, A_2 will overtake the platoon. This is the current rule of overtaking.

When one vehicle is overtaking a platoon, if we do not introduce the appropriate token handling procedure, it may also possible for another faster vehicle to catch up with to platoon and start overtaking. This case is very similar to the starving problem as shown in Fig. 4.5. If many faster vehicles start overtaking the platoon successively without token, vehicle B will not have a chance to move to the passing lane for a long time. Therefore, the proposed method defines the strict token and priority rule that only the token holding vehicle can enter the critical section to solve the starving problem.



(a)



(b)

Figure 4.6: Distance margin between platoons (a) Short distance between platoons (b) Long distance between platoons

4.4.2 Distance Control between Tandem Platoons

Up to here, overtaking is discussed only the case where the vehicle overtake a single platoon, however, if we discussed the case where plural platoons are driving in tandem on inner lane of highway, overtaking will be rather complicated. Generally, the number of platoon members is limited to about five vehicles by communication requirement. It is difficult for a platoon to join another platoon. We assume that platoons do not join another platoon dynamically. There are two important points for consideration. One is to keep the appropriate distance between two platoons. The other is to manage different token for each platoon, respectively. The following gives explanation and solution of this problem. Figure 4.6 shows the effects of distance between two platoons in tandem. (a) shows the case where the distance between platoons are short. In this case slower vehicle A is in the passing lane and platoon X is now overtaking it, and vehicle B is also overtaking platoon Y at the same time. Of course, A has a token for X and B has a token for Y. Trouble will be happen in the next step, if the distance between platoon X and Y is short. A reaches the tail edge of critical section of platoon X but no room to enter the inner line, and it can not return token X to platoon. Also, same trouble will happen at the platoon Y. Vehicle B reaches the front edge of critical section of platoon Y, but can not find a room in inner lane and can not return token to the platoon Y. In this situation, if A/B likes to enter the critical section of platoon Y/X, it must have token Y/X, respectively. Since vehicle A/B can not return token X/Y to their leaders of platoon, it will face to the deadlock. Therefore, certain distance should be kept between two platoons as shown in Fig. 4.6(b).

4.4.3 Token Reissuing

In the token-based method, the leader vehicle sends its token to the vehicle which requests the token. The leader vehicle records the ID number of vehicle when it receives a token request from a vehicle and is able to monitor the location of token holder by periodical information exchange of location and velocity. Thus, the leader vehicle can detect the token loss by detecting the communication loss with the token holder. Note that, the loss of the token might happen when the vehicle carries the token out of the communication range of the leader vehicle or when the radio communication device on the token holder does not work. After the leader vehicle checks whether any vehicle drives in the critical section by using sonar, radar, lidar or driver's visual judgment, it reissues the token. The leader manages the queue for the token, it sends the token to the request vehicle according to the FIFO based queue.

4.5 Evaluation and Discussion of Platoon Overtaking Control Method

4.5.1 Simulation Setups

The proposed token-based method is evaluated by comparing with the permission-based method and the distance-based method. In the distance-based method, the overtaking is triggered when the fast vehicle catches up to the slow vehicle driving in front within the certain threshold of inter vehicular distance as described in Section 2.5. In this simulation, the distance adopts 70 m and 150 m. In order to show the efficiency of the distributed mutual exclusion algorithms for overtaking, the simulation compares those methods in terms of the average velocity of vehicles, the amount of CO_2 emission, and the amount of CO_2 emission derived from the acceleration. Especially, the CO_2 emission is a typical metric for measuring traffic efficiency and environmental effect. In addition, platooning originally aims to reduce the energy consumption, the reduction in CO_2 emission is important. The amount of CO_2 emission E and the amount CO_2 emission derived from the acceleration E_A are presented by Ohguchi [61] as shown in Equations 4.1 and 4.2.

$$E = 0.3K_C T + 0.028K_C D + E_A, \tag{4.1}$$

where, K_C is the conversion factor from the fuel consumption to the amount of CO_2 emissions, T is the travel time from inflow until outflow, D is the travel distance from inflow until outflow, E_A is the acceleration shown in Equation 4.2.

$$E_A = 0.056K_C \sum_{k=1}^{K} \delta_k (v_k^2 - v_{k-1}^2), \tag{4.2}$$

where, K is the number of vehicles to be measured, δ_k is a dummy parameter which equals 1 if it accelerates, equals 0 if else, and v is the velocity of the vehicle. The simulation also compares the proposed token-based method and the permission-based method in terms of the waiting time from request for token until actual start for overtaking. The waiting time affects on the driver's comfort and safety.

The simulation environment consists of the network simulator, Scenargie [57] and the traffic simulator, MATES [58]. They are executed alternately exchanging those execution results same way as in Chapter 3. The simulation parameters are shown in Table 4.2. The parameters and values correspond to the report by Utilization proposition committee for ITS simulator, Japan Automobile Research Institute [59], which supposes to represent the communication parameters for typical ITS communication simulations. In the simulation, Platoons and non-platoon vehicles drive on the straight express highway. The highway consists of two lanes in one way. 1000 seconds of simulation is executed 3 times with varied random seeds for inflows of platoon and non-platoon vehicle. Platoon consists of heavy duty truck and non-platoon vehicle is a normal sedan type of vehicle. They inflow from one edge of the highway and outflow from the other edge. Their velocity is simplified into three different values. Platoons drives at 80 km/h. Non-platoon vehicles drives at 60 or 100 km/h and they inflow with the same amount. All vehicles drive according to "the following model [58]" and obey the leader vehicle giving a token to a certain vehicle to start overtaking. In this model, vehicles never crash into each other. The platoon inflow is fixed and non-platoon vehicle inflow is varied from 0 (corresponding to sparse situation) to 1500 (corresponding to almost jammed situation). The network protocol model is based on IEEE 802.11p/WAVE. All vehicles and platoons can communicate with each other and periodically exchange information of their position and velocity. Bit Error Rate (BER) model adopts the typical model for V2V communication [59]. BER depends on Signal to Noise Ratio (SNR). The higher the SNR is, the lower the BER is. In the case where the SNR equals 0 dB, the BER equals 0.5. In the case that the transmission power is 20 dBm, the communication range is about 500 m without obstacles.

Table 4.2: Simulation parameters

Model	Parameter name	Value
Road model	Road length	10.0 km
	Number of lanes	2 (One way)
	Designated lane for platoon	1 (Inner lane)
	Lane width	3.5 m
Platoon model	Number of platoon members	3 trucks
	Distance between platoon members	4.0 m
	Member length	12 m
	Member width	2.5 m
	Member height	3.8 m
	Expected velocity	80 km/h
	Volume of platoon inflow	60 platoons/lane/hour
Non-platoon vehicle model	Volume of inflow	variable (0–1500)
	Vehicle's expected velocity	60 or 100 km/h
	Length	4.7 m
	Width	2.5 m
	Height	3.8 m
Communication protocol model	Frequency	5.9 GHz
	Modulation	OFDM (QPSK1/2)
	Transmission speed	6 Mbps
	Bandwidth	10 MHz
	Transmission Power	20 dBm
	MAC	CSMA/CA
	Propagation model	ITU-R P.1411
Application configuration	Request range	100 m
	Permission range	Communication range

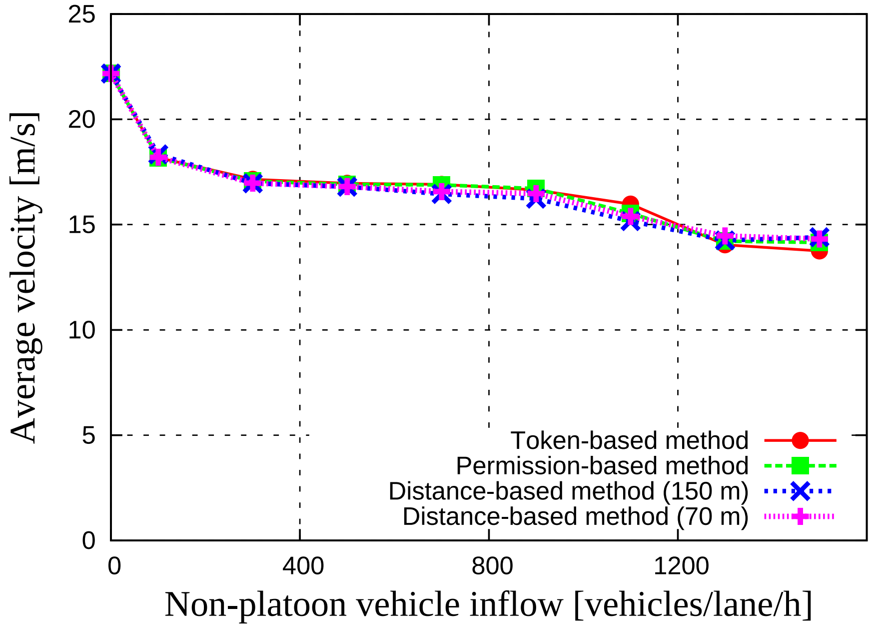


Figure 4.7: Average velocity versus vehicle inflow

4.5.2 Simulation Results and Discussions

The average velocity versus the vehicle inflow is shown in Fig. 4.7. In common to the token-based, the permission-based method and distance-based methods (70 m and 150 m), as the vehicle inflow increases, the average velocity decreases and there exists no significant difference among those methods. Since overtaking becomes less smooth when the vehicle inflow increases, it takes longer for vehicles to overtake platoons regardless of the method. In the case where only the platoon inflows, the average velocity is 22.2 m/s, corresponding to 80 km/h, which is the platoon's expected velocity. On the other hand, in the case the non-platoon vehicle inflow is 1,500 vehicles/lane/h, the average velocity is 14.2 m/s corresponding to 50.9 km/h. This vehicle inflow means the traffic is quite congested and traffic jam is about to occur, however the average speed is still over 50 km/h. It means that it is difficult for the driver model in this simulation to reproduce the traffic jam. In this figure, there is no significant difference between methods. Thinking about the case where two vehicles request to enter the critical section at the same time from

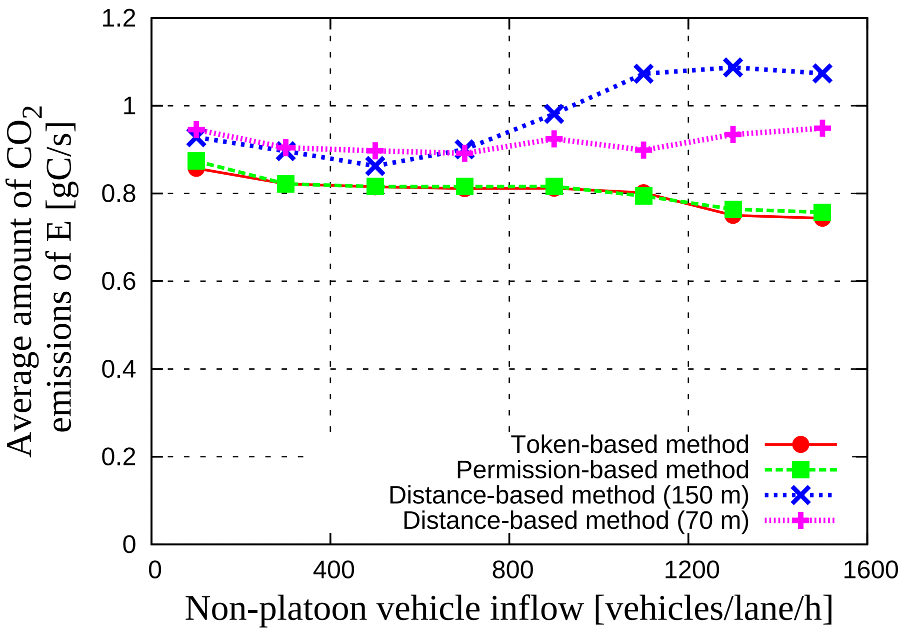


Figure 4.8: Average amount of CO_2 emissions per travel time versus vehicle inflow

both direction to the platoon, since the distribute mutual exclusion has little influence the time from the first vehicle enters the critical section until the second vehicle separates from the platoon, there is no significant difference between methods.

The average amount of CO_2 emissions from non-platoon vehicles versus vehicle inflow is shown in Figs. 4.8 and 4.9 when the non-platoon vehicle inflow changes. Figure 4.8 is the average amount of CO_2 emissions per travel time and Fig. 4.9 is the average amount of CO_2 emissions per travel distance respectively. When the traffic is not congested, the overtaking conflict is unlikely to happen and there is just a small difference between methods. In the case where the traffic is congested, the overtaking conflict tends to take place and the difference between methods becomes large. In terms of the emissions per travel time, when the vehicle inflow is 900 vehicles/lane/h, the amount of CO_2 emissions by the token-based method is 19 % less than by the distance-based method (150 m), and is 12 % less than by the distance-based method (70 m). In these cases, there exists no significant difference between the token-based method and the permission-based method. In terms of the emission per travel distance, when the vehicle inflow is 900 vehicles/lane/h,

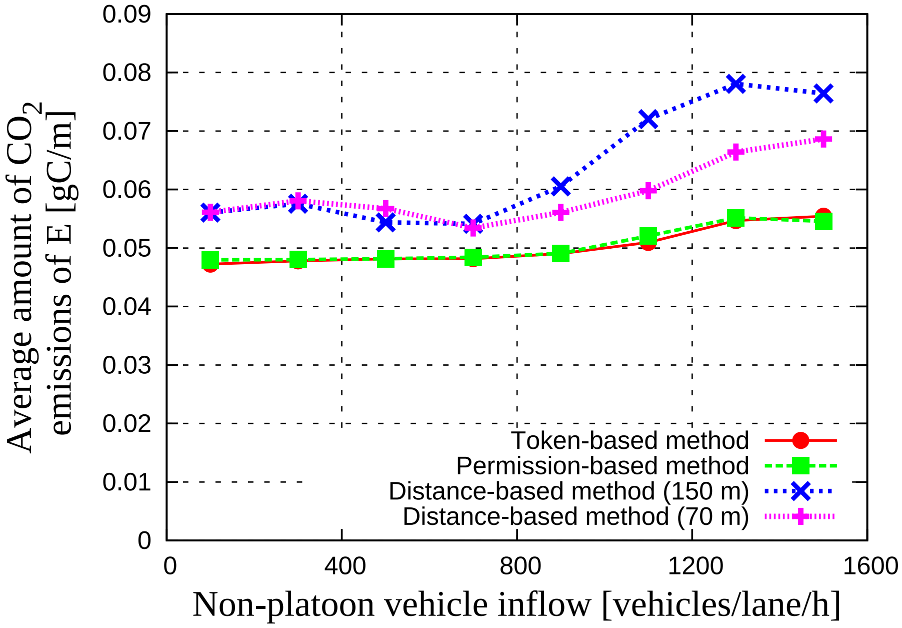


Figure 4.9: Average amount of CO_2 emissions per travel distance versus vehicle inflow

the amount of CO_2 emissions by the token-based method is 17 % less than by the distance-based method (150 m). Also in this case, there exists no significant difference between the token-based method and the permission-based method. Both figures show that the overtaking control method is efficient in terms of the CO_2 emissions. If the driver model is able to simulate the traffic jam, the difference at the large vehicle inflow might become smaller than it is shown in Figs. 4.8 and 4.9.

The average amount of acceleration E_A per travel time versus non-platoon vehicle inflow is shown in Fig. 4.10, comparison among four methods is shown in Fig. 4.10(a), comparison between the token-based and the permission-based method is magnified in Fig. 4.10(b). Also the average amount of acceleration E_A per travel distance versus non-platoon vehicle inflow is shown in Fig. 4.11, comparison among four methods is shown in Fig. 4.11(a), comparison between the token-based and the permission-based method is magnified in Fig. 4.11(b). In the case that the vehicle inflow is large, there exists the difference between the token-based method and the permission-based method according to the Figs. 4.10(b) and 4.11(b). In these cases, the token-based method indicates smaller amount of acceleration than the permission-based method. Specifically in the case of 1300 vehicles/lane/h, the token-based method is 8 % smaller in terms of the average amount of acceleration per travel distance, 10 % smaller in terms of the average amount of acceleration per travel time than the permission-based method. Same as in E, when the traffic is not congested, since the overtaking conflict is unlikely to happen and there is just a small difference of E_A between methods. In the case where the traffic is congested, the overtaking conflict tends to take place and the difference of E_A between methods becomes large. According to Figs. 4.9 and 4.11(a), since the difference between methods in terms of E_A is almost same as the difference of E and there is no difference of average velocity, it can be said that the difference of E is derived from the acceleration. The same thing is derived from Figs. 4.8 and 4.10(a). Therefore, the token-based method and the permission-based method reduces the amount of CO_2 emissions because both methods reduce the unnecessary acceleration.

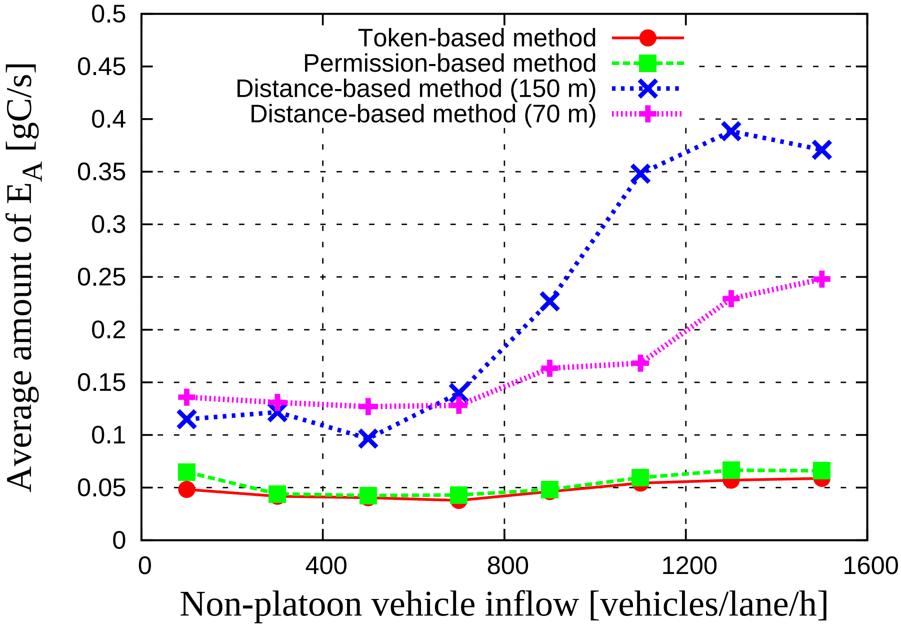
The waiting time from the request until actual start for overtaking versus the vehicle inflow is given in Fig. 4.12. In the case the vehicle inflow is small, the difference between the token-based method and the permission-based method is also small. As the vehicle inflow increases, the average waiting time of the permission-based method becomes larger than the token-based method. In the case of 500 vehicles/lane/h, the token-based method shortens 47.6 % of the waiting time compared with the permission-based method and in the case of 1300 vehicles/lane/h, the token-based method shortens 43.0 % of the waiting time. The permission-based method requires responses from all vehicles within the communication range of the leader vehicle, and the number of overtaking vehicles increases as the vehicle inflow increases. On the contrary, the token-based method requires less volume of message exchange. The difference between two methods increases as the vehicle inflow increases. As the token-based method shortens the waiting time, two effects can be expected. One is to shorten the distance between platoon and non-platoon, and increase the road capacity for vehicles due to the quick response to overtaking request assignments by token-based algorithm. The other is to reduce the drivers stress. According to Fig. 4.12, in the case of 1300 vehicles/lane/h, the time difference between two methods is 1.2 seconds. It is corresponding to about 30 m of the vehicle's travel distance. Therefore, the vehicles are able to start overtaking a platoon 30 m before by the token-based method. Thus, the amount of acceleration by the proposed method is smaller than the permission-based method as shown in Figs. 4.10(b) and 4.11(b). Moreover, intuitively, the difference of distance brings the drivers comfort because the difference is the margin for the drivers action; acceleration, deceleration and changing lane. Especially in the congested condition, the drivers choice for the next action is limited, the effective margin in terms of the time and distance is very important.

Referring to the results, the overtaking control methods based on the distributed mutual exclusion algorithm effectively reduces the CO_2 emissions, especially under the congested road conditions. The proposed token-based method is more effective than the permission-based method in terms of the amount of the acceleration and the waiting time. The proposed token-based method is efficient for overtaking control.

We adopted strict FCFS policy for distributed mutual exclusion in order to avoid the starving problem, there is a possible alternative option to loosen the FCFS policy and adopt the scheduling algorithm. For instance, in the case that plural vehicles overtake a platoon from the same direction at the same time, it is better to overtake together than one by one in terms of the efficiency for entire traffic.

This chapter assumed that all vehicles obediently wait and change lanes as the platoon indicates. It might be better to consider that the vehicle can enter the critical section without having the token. To deal with this situation, two options are possible. One is to give priority to the vehicle for overtaking. The other is to include the overtaking by platoon itself. Platoon changes its lane to a passing lane and overtake a slower vehicle. In addition, the platoon model should be better to include its organization and dismissal procedures. In current model, the platoon drives strictly in a designated lane and the preceding vehicle gives its way to the platoon when it drives slowly. However, it is possible to consider that the platoon temporarily dismissed, each member vehicle individually overtakes the slower vehicle and the member vehicles re-organize the platoon after overtaking. Those procedures for dynamical organizing and dismissing platoon are undecided and under discussion [25]. If the procedures are established, they should be compared with the proposed procedures in terms of the efficiency and feasibility. The procedures enable vehicles to join the platoon temporarily and will save the CO_2 emission while it waits for token as well.

Since the overtaking in one direction is independent from the overtaking in another direction, the simulations of this chapter assumed that the road model of two lanes in one way. Therefore, in the case of the two lanes in two directions, the overtaking control method is expected to be effective as same as the case of one direction. In the case of three lanes in one direction, since the faster vehicle can overtake the slower vehicle easily, the overtaking conflict never occur except the case of traffic jam. Thus, there is no need to use overtaking control method. However, there is large amount of two lanes road on highway especially in Japan. It is necessary to consider the road model of two lanes. Additionally, it is better to consider operations at abnormal and emergency conditions where the platoon and vehicles encounter the obstacle during overtaking.



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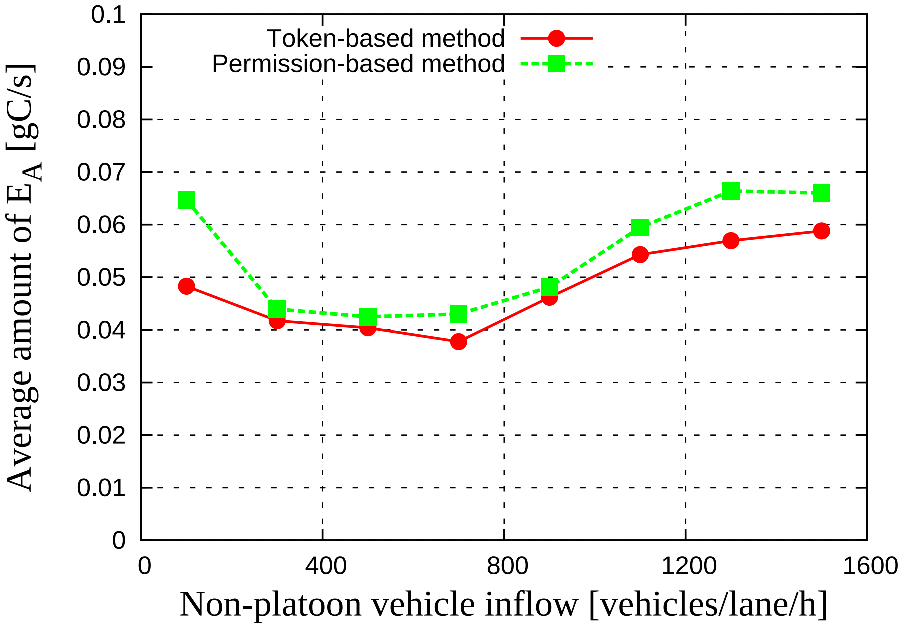
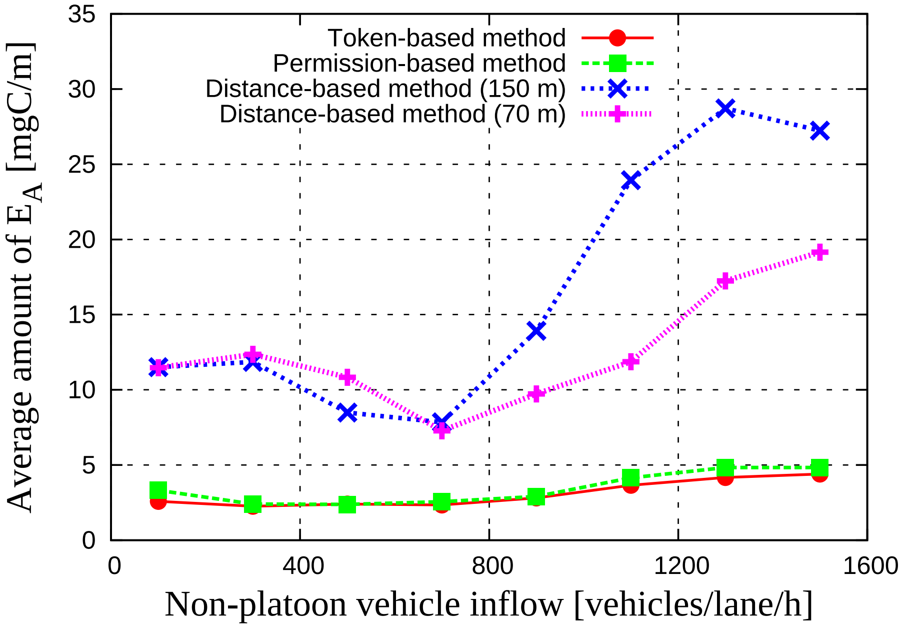


(b)

Figure 4.10: Average amount of E_A per travel time versus vehicle inflow (a) comparison among four methods (b) comparison between token-based and permission-based methods



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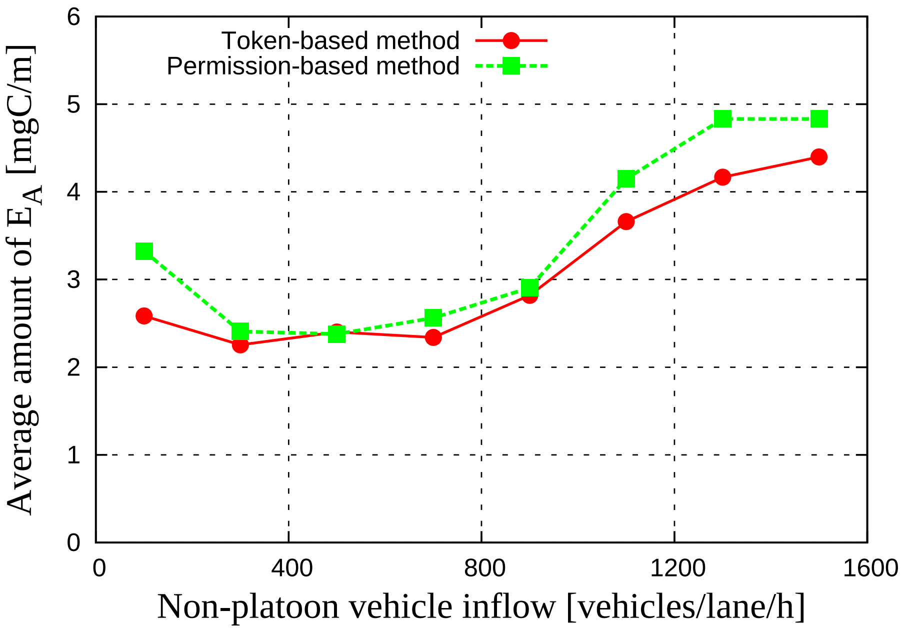

(b)

Figure 4.11: Average amount of E_A per travel distance versus vehicle inflow (a) comparison among four methods (b) comparison between token-based and permission-based methods

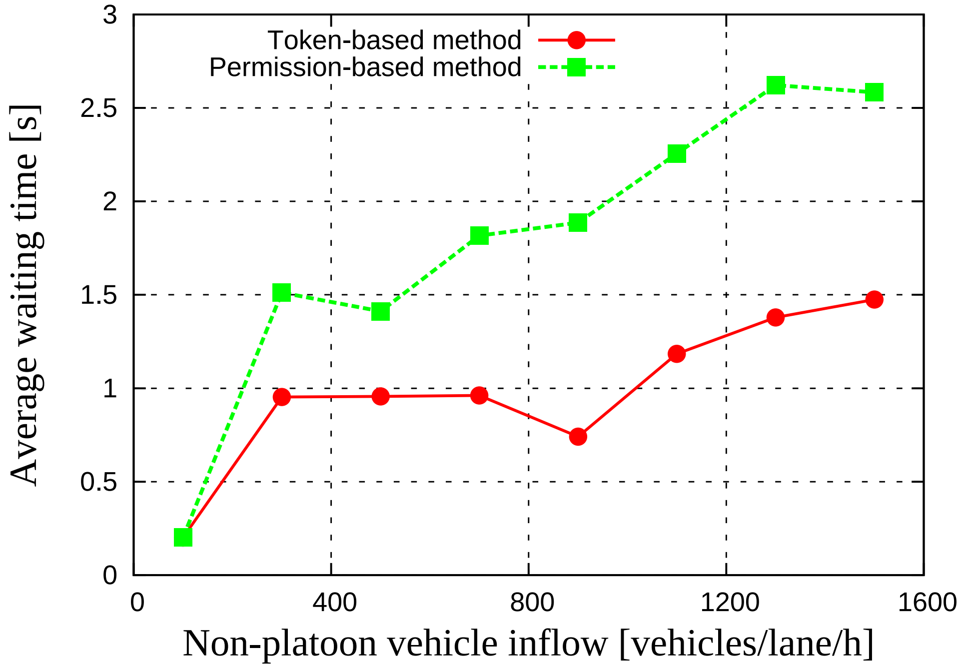

Figure 4.12: Average waiting time for overtaking versus vehicle inflow

4.6 Summary

In Energy ITS, Japan, the platoon drives in the designated lane and never change lanes except the case of emergency. When slower vehicle drives in the lane, the platoon has to decelerate and follow it. Making progress on platooning toward the practical use, it is better to consider the overtaking where platoon and non-platoon vehicle overtake each other in the mixed vehicle traffic condition.

This chapter reveals the following results.

(1) To analyze the problems on platoon overtaking model, this chapter first develops the overtaking method based on Energy ITS platooning. Platoon is driving at designated lane of two lanes highway and keep designated lane except the case of emergency. If platoon catches up with a slower driving vehicle in front, the slower vehicle changes its lane to passing lane, and gives its way to platoon. If a faster vehicle catches up with a platoon, the faster vehicle overtakes a platoon using passing lane. In order to realize overtaking smoothly, this dissertation makes a critical section next to the platoon in the passing lane and controls the usage of critical section.

(2) This chapter conducts series of platoon overtaking simulations and evaluates average amount of CO_2 emission, average amount of acceleration, and average waiting time versus vehicle inflow by applying three different methods of token-based method, permission-based method and distance-based method to control critical section. The results clearly shows that the CO_2 emission is much suppressed by the case of the token ring method than others. Another interesting results is that the amount of CO_2 emission is so much related to the amount of acceleration during the overtaking. Moreover, the experiments show the shortest average waiting time is realized at the case of token-based method. Since it means the time between request token to the actual overtaking is short, driver can start overtaking a platoon a little bit earlier as well as not too much close to the platoon. This gives a comfort driving to driver.

(3) This chapter is based on the assumption that the strictly one vehicle can enter the critical section. This rule can be extended more flexible way such that consecutive

token waiting vehicles overtake platoon in succession. Those extensions are expected for further progress on platooning.

(4) The current overtaking model assumes that the platoon drives in the designated lane. However, as a future work, the model should considers that the platoon itself overtakes a slower vehicle which drives in the designated lane. In this case, the platoon may be required to dismiss and re-organize itself dynamically. Also, the model should take into account that platoon allows the vehicle to cut in between the platoon members when another following much faster vehicle overtakes the same platoon during the overtaking.

Chapter 5

Conclusions

This dissertation describes the communication for platooning and overtaking.

Platooning is the key technology for the cooperative driving in ITS from the safe and comfortable driving, the traffic efficiency and the environment point of view. Therefore, platooning need to be studied and used more effectively. Currently, platooning is studied without the effect of other platoons and non-platoon vehicles. This dissertation proposes a new communication protocol which is efficient to realize platooning under the mixed traffic condition and shows its effectiveness. This dissertation also studies on the platoon overtaking problem where the platoon is driving in the designated lane. The model of overtaking exhibits the efficient overtaking.

This dissertation draws the following conclusion;

(1) This dissertation clarifies the existence of wireless channel congestion and biased communication load due to the hidden terminal problem over the CSMA/CA channel in the vehicle to vehicle communication for platooning. The simulation was done in the situation that plural platoons are located in tandem with keeping the equal headway distance and without mobility. This dissertation evaluates the packet arrival ratio versus headway distance between platoons by simple repetitive transmission protocol and RR-ALOHA protocol. In both experiments, the result shows a large degradation of the packet arrival ratio in the center platoon among several platoons. Since the communication coverage size of each platoon is assumed to be the same, communication load is heavy to the center platoon and light to the edge

platoon. The effect of hidden terminal problem is clearly shown.

(2) When the plural platoons are driving on the same road, frequent data exchange is needed to maintain a platoon. For this purpose, the repetitive transmission rate control is introduced at the pseudo TDMA frame over the time slotted CSMA/CA channel. Vehicles increases/decreases the number of repetitive transmission when the slot occupancy information (Frame Information) is lower/higher than the threshold. In this context, vehicles can autonomously avoid the congestion and increase the data arrival ratio. It is also obtained the improvement of the data arrival ratio in the case that plural platoons are in the same communication range. At the same time, since vehicles exchange their Frame Information among neighboring vehicles, they are able to know the communication load on neighboring vehicles. They can avoid biased communication load on any other neighboring vehicle. It is shown by improvement of the data arrival ratio of the central platoon in the case the both edge platoons are hidden from each other.

(3) The leader vehicle represents the other platoon members and reserves time slots for them. Therefore, it can avoid the reservation conflicts among platoon members. Moreover, since the leader vehicle assigns those time slots equally to the other members, platoon members can exchange information in a balanced manner. Results of the simulation shows the high data arrival ratio and platoon maintenance ratio in the case where plural platoons drive on the road in both directions.

(4) To analyze the problems on platoon overtaking model, this dissertation first develops the overtaking method based on Energy ITS platooning. Platoon is driving at designated lane of two lanes highway and keep designated lane except the case of emergency. If platoon catches up with a slower driving vehicle in front, the slower vehicle changes its lane to passing lane, and gives its way to platoon. If a faster vehicle catches up with a platoon, the faster vehicle overtakes a platoon using passing lane. In order to realize overtaking smoothly, this dissertation makes a critical section next to the platoon in the passing lane and controls the usage of critical section.

(5) This dissertation conducts series of platoon overtaking simulations and evaluates average amount of CO_2 emission, average amount of acceleration, and average waiting time versus vehicle inflow by applying three different methods of token-based method, permission-based method and distance-based method to control critical section. The results clearly shows that the CO_2 emission is much suppressed by the case of the token ring method than others. Another interesting results is that the amount of CO_2 emission is so much related to the amount of acceleration during the overtaking. Moreover, the experiments show the shortest average waiting time is realized at the case of token-based method. Since it means the time between request token to the actual overtaking is short, driver can start overtaking a platoon a little bit earlier as well as not too much close to the platoon. This gives a comfort driving to driver.

From above conclusions, this dissertation shows the efficient communication for platooning and overtaking, it extends the model of platooning from a single platoon to mixed traffic condition with plural platoons and non-platoon vehicles. Since platooning is the key technology for the future ITS, the simulation techniques and communication protocol in this dissertation will be the baseline for further practical extension of platooning.

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Achievement Lists

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(2) Masaki Suzuki, Ryo Harada, Shohei Kanda, and Hiroshi Shigeno, Paper Award, IPSJ Multimedia, Distributed, Cooperative and Mobile Symposium (DICOMO2011), “A Passing Priority Control Method Considering Influence of Platoon on Surrounding Vehicles,” 26 Aug. 2011.

(3) Masaki Suzuki, Best Conversant Award, IPSJ Multimedia, Distributed, Cooperative and Mobile Symposium (DICOMO2011), 8 July 2011.

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