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著者(和文)	林哲弘
Author(English)	Che-Hung Lin
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チェ-ホン　リン

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Interdisciplinary Graduate School of Science and Engineering
大学院総合理工学研究科
Department of Computational Intelligence and Systems Science
知能システム科学専攻

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Abstract

The VANET (Vehicular Ad-hoc Network) optimization based on fuzzy network stability, including routing protocol and roadside units deployment is proposed, and is applied to ITS (Intelligent Transportation System) to improve the network performance.

In chapter 2, the fuzzy network stability expresses the real-time vehicle to vehicle network stability of each road segment that cannot be easily expressed directly by a mathematical model, and the optimization routing protocol decreases the end-to-end delay and the overall network control overhead. The computation time of the proposed protocol is analyzed and shown as $O(I \lg I + R + V)$, where *I*, *R*, and *V* represent the number of intersections on a map, the number of road segments on a map, and the number of vehicles within communication range of the vehicle that wants to transfer a data packet, respectively. The simulation results show that the proposed method decreases end-to-end delay and decreases the control overhead by 20% compared with other routing protocols, e.g. GyTAR and RTRP.

In chapter 3, the extended fuzzy network stability integrates two different wireless network characteristics that is not easy to be expressed as a single mathematical model, and it optimizes the deployment of road side units to decrease the number of deployed road side units; furthermore, it increases the network performance, even though the number of road side units is decreased. The experiment results show that the proposed roadside units deployment scheme decreases the number of the deployed road side units more than 50% and improves the packet delivery ratio 30%.

In chapter 4, the common driving notification protocol (CDNP) defines standardized formats and definitions based on the classified driving behavior for autonomous vehicles. The CDNP make the autonomous vehicles have a common language to achieve cooperated drive with other vehicles, increases the reaction preparing time before other vehicles perform any driving decision. The simulation results present that the CDNP can increase the reaction preparing time with maximum value 250 seconds, and it also decrease the driving decision identification time average travel time.

The optimization improves the performance of data packet routing and decreases the deployment cost of basic infrastructure of VANET. The CDNP protocol realizes more detail driving information exchange between vehicles. Prospectively, more ITS systems, e.g., roadside unit deployment system, infrastructure-less real-time cooperative traffic-monitoring system, safety cooperative autonomous driving system, centralized urban traffic management system, can be developed to improve the future transportation environment and provide drivers good driving experience and more safety and comfortable driving environment. The optimizations and CDNP are planned to be implemented as the ITS component using embedded system in Taiwan.

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Chapter 1

Introduction

According to the 2012 urban mobility report [1], the traffic congestion wastes a massive amount of time, fuel, and money, and the cost caused by congestion is still increasing year by year. Furthermore, traffic accidents also produce substantial congestion [2], and more seriously, it causes a lot of deaths and injuries every year. Actually, 60 percent of accidents could be avoided if the driver were provided with a warning half a second before the moment of collision according to [3]. The Intelligent Transportation System (ITS) [4, 5] is the key to solving these problems. The Intelligent Transportation System (ITS) could provide a variety of applications, e.g., co-operative traffic monitoring, control of traffic flows of each road segment, prevention of collisions, nearby real-time information services, and real-time detour routes computation. Hence, it plays an important role to decrease the growing traffic accidents and congestions.

1.1 VANET in Intelligent Transportation System

The ITS is a system that applies information technologies in the field of transportation systems to make them more intelligent. Those technologies include wireless communications technologies, sensing technologies, and computational intelligence technologies, etc. To provide each vehicle a variety of ITS applications, the data packets transmission via wireless communications is one of the basic requirements. Therefore, the 75 MHz spectrum band around 5.9 GHz is allocated by the United States

Federal Communications Commission (FCC) for Dedicated Short-Range Communications (DSRC) [6]. IEEE also defined the IEEE 802.11p [7] and IEEE 1609 family standards [8, 9, 10, 11] for wireless access in vehicular environments (WAVE). The vehicular ad-hoc networks (VANET) [12] are expected to implement these wireless technologies to realize the wireless communication between vehicles and realize various ITS applications. The VANET became possible with the development of wireless communication, and it plays an important networking technology for ITS [13]. The applications [14, 15, 16, 17, 18, 19, 20] provided by VANET can be classified into safety applications and non-safety applications. It can be viewed as a part of the ITS. Each vehicle, equipped with a wireless communication device, on the road turns into a wireless router (or called node), and they can communicate with each other to transmit and receive packets for various mobile distributed applications. The information sent to (or receive from) other vehicle (or remote server) is useful and desirable for drivers. Normally, there are two kinds of nodes in VANET. One is vehicle, and the other one is roadside unit (RSU). The roadside unit is always installed at the fixed locations, e.g. intersections or along the road segments, i.e., between two intersections, to provide continuing coverage or connectivity for vehicles. Therefore, the communication in VANET includes vehicle-to-vehicle (V2V) communication and vehicle to infrastructure/RSU (V2I) communication. The wireless communication link can only be established when the distance between two vehicles is shorter than their communication ranges. Normally, the communication range of VANET is approximately 250 meters. The VANET routing protocol will affect the performance of V2V communication, and the deployment positions of RSUs will affect the performance of V2I communication.

1.2 Background Problem of Routing Protocol in VANET

To transmit and receive the information, a suitable and high efficient routing protocol is necessary. The primary objective of vehicular ad-hoc network is to provide a stable communication environment for the data packet transmission from a source to the specified/unspecified destinations without any preconfigured information. Actually, the VANET can be considered as a special type of mobile ad-hoc networks (MANET) [3] with some unique features, including rapid topology changing, high node mobility, high probability of network partitions, etc. The most different characteristic is the high node mobility. The node mobility in VANET is faster than the mobility in MANET because one of the main nodes in VANET is vehicle. Hence, the network stability of VANET environment is unstable than MANET.

Traditional ad-hoc routing protocol of MANET, e.g., Ad-hoc On-Demand Distance Vector Routing (AODV) protocol [21], Dynamic Source Routing (DSR) protocol [22], Privacy-friendly Routing in Suspicious MANETs (PRISM) protocol [23], are not suitable for VANET because the maintenance overhead of routing path is large [24, 25]. According to [26], it is known that the design of routing protocol will profoundly affect network performance of VANET. According to [27, 28, 29, 30], various routing protocols for VANETs are constantly proposed to address routing protocol issues. The geographic source routing (GSR) [31] uses geographic information to address the issues of traditional ad-hoc routing protocols. The GSR uses the digital map and the position information of each vehicle to construct the routing path and forward the data packets along the streets. The routing path is composed by a sequence of intersections and stored in the packet header. Then, the data packets are transmitted according to the routing path stored in the data packet header. The transmission, however, will fail if the traffic density is low. In this situation, it will be difficult to not find any next-hop node that is close to the destination node to forward the data packets. The Greedy Perimeter Coordinator Routing (GPCR) [32] is proposed to deal with this kind of problem. It consists of two parts: a restricted greedy forwarding procedure and a repair strategy. The GPCR prefers to chosen the node near to the intersection even if its geographical position is not closest to the destination node. This strategy can avoid the local optimum problem, i.e., no available next-hop exists which is closer to the destination node. The movement-based routing algorithm (MORA) [33] is a protocol based on not only the position, but also the moving direction of vehicles. In [34], the analytical model for determining the network connectivity of a one-dimensional VANET is proposed. The exact relation between vehicle speed statistics and VANET network connectivity is shown. Furthermore, it also shows that the network connectivity is improved if the standard deviation of vehicle speed increases. However, the assumption that the speed of vehicles follows a normal distribution is necessary. The VANET connectivity is analyzed thorough a theoretical analysis using bond percolation model and Bolloba´s model in different scenarios in [35]. The quantitative relationship among network connectivity, vehicle density, and transmission range is shown. Hence, the minimum transmission range can be calculated from the vehicle density for achieving good network connectivity. The Greedy Traffic Aware Routing (GyTAR) protocol [36] is an intersection-based geographical routing protocol, and it detects the traffic density using the cell density packet (CDP). The real-time road vehicle traffic variations and remaining distance to the destination are considered to efficiently choose the intersections and relay data packets. The road-aware and traffic-aware routing protocol (RTRP) [37] calculates the best path, composed by intersection sequent numbers, based on distance and density factors. It uses a greedy data-forwarding algorithm to forward packets based on a Reaching Intersection Time (RIT) and a Turning Direction Probability (TDP).

However, to conquer the frequent network fragmentation, which is caused by high node mobility and traffic signal changes, the continuously change the routing path and data packet forwarding strategies for accommodating the unstable network environment is necessary. From previous studies, i.e., [34, 35], it can be known that the real-time distribution and speed of vehicles is the key factor to determining network connectivity of each road segment. However, the real-time mobility characteristics and speeds of vehicles are uncertain. The speeds of vehicles do not have a normal distribution. Therefore, it is not easy to define an explicit and simple mathematical model to describe the real-time network connectivity of each road segments for real environment.

1.3 Background Problem of Roadside Units Deployment in VANET

The RSUs is another factor that affects the wireless network performance of VANET, especially the ITS applications that depends on the access of Internet or quickly message exchanges between vehicles. The data transmission to the RSUs is necessary for the ITS applications that depends on the Internet access. This is because the RSUs are the gateways for vehicles to connect to the Internet. Those applications cannot work well if the vehicle cannot transmit the data packets to any RSU immediately. If all of the data packets, however, are transferred to the same RSU, the bandwidth loading of the RSU will be very large. To balance the bandwidth loading of each RSU, an efficient routing protocol is necessary. The Location-aware and Load-balanced Data Delivery [38] is a RSU selection mechanism and routing data thereto to achieve the load balancing of RSUs. The RSU with lower loading will be selected as the gateway to access the Internet. The GwDisc and GwDiscE2E are two gateway discovery algorithms [39] for delay-tolerant applications and delay-constrained applications, respectively. The appropriate gateway, i.e. the RSU, is selected according to advertisement messages issued by the gateways for the corresponding traffic types. Therefore, the suitable gateway can be found according to the time requirements.

Not only the routing protocol for V2I communication, however, but also the deployment of RSUs will also affect the network connectivity of VANET. How to maximize the vehicular network connectivity through an effective placement of roadside units is a challenge [40]. To cover all of the road segments so that vehicles can always directly connect to Internet through at least one near RSU, a large number of deployed RSUs is necessary. This will cause huge costs. To address this issue, a suitable approach is necessary to find the optimized deployment strategy in a specified area to achieve maximum network performance using a minimum of roadside units. The roadside units deployment problem is transformed into a vertex selection problem in a graph in [41], and the heuristic algorithm, called RoadGate, is proposed to find greedily the optimal deployment locations by exploiting the time-stable mobility pattern. It is proved that the roadside units deployment problem is a NP-hard problem in [42], and two scalable roadside unit placement algorithms are proposed to search the deployment positions of RSUs for a large city scenario. The intersection-priority based RSU placement methods [43] finds the optimal number and positions of RSUs for the full distribution providing with a maximal connectivity between RSUs. It includes three optimal algorithm, i.e., greedy, dynamic, and hybrid algorithms. In the D-RSU deployment polity [44], RSUs are placed using an inverse proportion to the expected density to provide the lowest possible cost to alert emergency services. It means that more RSUs are deployed in the areas with low density of vehicles, and less RSUs are deployed in the areas with a large number of vehicles. The roadside units placement scheme in [45] increases the possibility for a vehicle accesses the RSUs based on the given number of RSUs, the transmission range, and the overlap ratio. Actually, some countries, e.g., Japan and Taiwan, have already started to deploy the RSUs along the road to provide various ITS applications. The “Ministry of Land, Infrastructure, Transport and Tourism” of the Japanese government has already started to deploy RSUs in many major roads from 2011 [46] to provide real time safety warning support service, real time traffic information service, etc. The Industrial Technology Research Institute (ITRI) in Taiwan developed ITRI WAVE/DSRC. Communication Unit (IWCU) 4.0 system [47], including on-board unit (OBU) and roadside unit (RSU), for telematics system in 2012 and deployed the RSUs for real world experiment.

The Cellular-VANET is a kind of heterogeneous wireless network that is one of the important architectures of wireless network. The advantage of heterogeneous wireless network architecture is that it provides mobile device with varying communication coverage by integrating different wireless network [48, 49, 50]. The cellular networks, such as 4G-LTE, 3G, HSPA, and HSPA+, provide a wide network coverage and reliable data dissemination via base station [51]. The VANET provides Internet via RSUs. Therefore, each vehicle can access the Internet via two types of infrastructure, i.e., roadside units and base stations, in Cellular-VANET heterogeneous wireless network environment. The Cellular-VANET heterogeneous wireless network provides each vehicle with high reliability and wide-range communication environment to access various ITS applications depended on the Internet [52]. The functions of RSUs cannot be completely replaced by cellular network, even though the cellular network has already widely used in our daily life to provide wide range communication capability. For example, when the wireless connection between the source node and destination node is temporarily disconnected, the RSUs can be used as data buffer for temporary data caching of VANET communication. It can also be used to spread the warning message if the distance between two vehicles is larger than their transmission range, especially near the intersection. Furthermore, because the resources, such as connection number and radio resource, of the cellular network base station are limited [53, 54], the performance of the applications that rely on Internet access will be affected if the resource of per cell of the base station is not enough. There are so many end-users who use mobile devices to connect to the Internet via cellular network today, especially in the urban area. The cellular network base stations could not afford the increasing of the connections if all vehicles also connect to the Internet via cellular network. In this situation, the RSUs can balance the loading of cellular network to increase the network performance and provide some services for drivers. The communication prices of RSUs, i.e., Wi-Fi based technology, are also normally cheaper than the communication prices of cellular network for the end-users. Hence, the deployment of RSUs in Cellular-VANET Heterogeneous Wireless Network is important.

Actually, both roadside unit and base station are the gateways for vehicles to access the Internet. The roadside units deployment problem for the cellular-VANET heterogeneous wireless network environment, however, is not considered in previous studies, e.g., [41, 42, 43, 44, 45]. To make the network more stable and further decrease the number of deployed RSUs, the network stability of cellular network should also be considered to develop the roadside units deployment strategy. Hence, in this thesis, it also aims to optimize the deployment of RSUs in the cellular-VANET heterogeneous wireless network environment that is not considered in previous studies using 2-level approach.

1.4 Objective of Fuzzy Network Stability based VANET Optimization and its Application to ITS

The objective of this thesis includes routing protocol optimization, roadside units deployment optimization, and standard protocol for future autonomous vehicles using VANET technology.

In chapter 2, it focuses on the routing protocol optimization for VANET. To determine network connectivity is a challenge and a suitable model is necessary to adapt the unstable real-time network connectivity. Therefore, in chapter 2, the idea of fuzzy network stability, called fuzzy inference based vehicle to vehicle network connectivity model, is proposed. It describes the real-time network connectivity of vehicles on the road segments using fuzzy inference. The vehicle density, the average safety distance, and the opposite direction ratio of vehicles are the three input parameters of the fuzzy inference based vehicle to vehicle network connectivity model. The fuzzy output, called the fuzzy network connectivity ratio, is taken as the network connectivity of each road segment. Then, the fuzzy network connectivity ratio is used to support an optimization routing protocol to construct the transmission path from the source node to the destination node using network connectivity as the weight of each road segment. Furthermore, the optimization routing protocol optimizes the data packet forwarding strategy and decreases the packet loss caused by incorrect packet-forwarding decisions.

The optimization routing protocol calculates the best transmission path with high network connectivity. If the fuzzy network connectivity ratio is higher, then the network connectivity of road segment is better. The optimization routing protocol dynamically adapts the packet-forwarding strategy to optimize the performance according to network connectivity. When the traffic signal changes and the distribution of vehicles on the road segment is not scattered enough, a suitable adaptive strategy will be selected to adapt the packet forwarding strategy or re-construct a new transmission path that has high network connectivity. Therefore, the optimization routing protocol decreases the probability of unsuitable next-hop selection of packet forwarding; furthermore, because it uses the fuzzy inference based vehicle to vehicle network connectivity model to determine the network stability of each road segment, it does not need to send any packets to detect the network situation. Thus, the optimization routing protocol also decreases the control overhead necessary to maintain the network topology and routing information, improves the delivery ratio with different packet forwarding strategies, and keeps the end-to-end delay within a range. Furthermore, the computation time of the optimization routing protocol is $O(I \lg I + R + V)$, where I is the number of intersections on a map, R is the number of road segments on a map, and V is the number of vehicles within communication range of the vehicle that wants to transfer a data packet, respectively.

The open source network simulation tool NS2 [55] is used to assess the control overhead and the delivery ratio of proposed routing protocol. In addition, to more accurately match simulations and real life, a realistic vehicle traffic simulator is required that can also perform realistic wireless network simulations. The TraNS [56] is used to quickly generate a realistic vehicle traffic trace file for NS2. The simulation results are used to evaluate the influence of traffic signals changes on the routing protocol and analyze overall performance.

The chapter 3 focuses on the optimization of roadside units deployment. It is clearly known that the characteristics of network stabilities of cellular networks and VANET are different. The network stability of cellular network depends on the signal strength, and it will not be the same in all locations. On the other hand, the network stability of VANET depends on the distribution and movement of vehicles. The network stability of VANET is also more unstable, so the information for packet routing is imperfect. Hence, how to integrate the different characteristics of the two network stabilities and how to find an optimized deployment strategy are challenges in cellular-VANET heterogeneous wireless network environment. To address it, a GA with Fuzzy Network Stability based

2-level Road Side Units Deployment Scheme is proposed for cellular-VANET heterogeneous wireless network. Furthermore, to integrate the different characteristics of network stabilities, the Fuzzy Network Stability (FNS) is proposed using fuzzy inference. It is an extension of the fuzzy network proposed in chapter 2. Then, the two different fitness functions are designed for 2-level Road Side Units Deployment scheme to meet the requirements, that are maximizing the network connectivity and minimum the number of deployed road side units. The VANET network connectivity and the FNS of each deployment point of RSU, defined as candidate deployment point (CDP), are calculated. The genetic algorithm (GA) with two different fitness functions is used to optimize the deployment of RSUs. The level 1 of 2-level Road Side Units Deployment scheme is intersection deployment optimization, and level 2 is road segment deployment optimization. The level 1 is performed first, and then the level 2 is performed.

The proposed scheme aims to optimize the deployment strategy of RSUs, maximize the network coverage, maximize the network stability, decrease the network loading of base stations, and decrease the number of deployed RSUs in Cellular-VANET heterogeneous wireless network environment. The idea of FNS integrates different kind of wireless network characteristics, and it calculates the network stability that is not easy to be expressed as mathematical model directly. The deployment scheme looks for the optimized deployment combination of RSUs based on the GA and fuzzy network stability. The network stability is increased by deploying the RSUs at the necessary CDPs. Hence, each vehicle can access the Internet steadily via VANET or cellular network using one of the two communication interfaces. From the vehicles owners' view point: if the vehicles just install one of the VANET and cellular network wireless interfaces, they still can access the Internet using its own wireless interface. For the vehicles only install VANET interface, they can access the Internet though RSUs. If there is no RSU around, they can also transfer the data packets to other vehicles which install cellular network wireless interface or near to any RSU using V2V communication. For the vehicles that install both wireless interfaces, if the network connectivity of VANET is stable enough, then the data packet can be transferred directly to the RSUs; therefore, the network loading of the base station is decreased. On the other hand, from the service providers' view point: for the increasing mobile devices, the loading of the based station will be increased, and the network performance will be decreased if all of the users access the cellular network. In this situation, it is necessary to deploy more base stations to provide stable network access. However, the deployment of base station is very expansive. If the vehicles that already installed a VANET wireless interface onboard unit can access the Internet via RSUs, the requirement of base station will not be increased so much.

In the simulation, the open source network simulation tool NS2 is used to simulate both of VANET and Cellular communication. The network delivery ratio, the loading of base stations, and the number of the deployed RSUs are assessed. To make a more accurate matching between simulation and real vehicle movement, a realistic vehicle traffic simulator is required to generate realistic vehicle mobility traces used to perform realistic wireless network simulations. The TraNS is used to simulate the realistic vehicle movement with different traffic density and different speed of vehicles. It generates traffic trace file of vehicles for the network simulation.

In chapter 4, a common driving notification protocol (CDNP) is proposed for autonomous vehicles based on the various classified driving behaviors. It is an important future application of ITS system. It a protocol designed below the application layer. It focuses on not only the safety warning message dissemination, more importantly, but also normal driving information dissemination. The disseminations of normal driving information can realize the "talking" between vehicles using VANET technology. The CDNP is a common language between vehicles. It defines a standard with the common message format with a series of message types and codes, so each vehicle is able to understand what the driving decision other vehicle wants to do. It can be used to instead of the function of car light signal or horn. The human driver normally determines the driving actions of other vehicles by identifying the car light signal of other vehicles. For autonomous vehicle, however, the time of image processing [57, 58] is necessary to identify the driving actions of other vehicles. The CDNP enabled vehicles is termed cooperation intelligent autonomous vehicle in this thesis.

The CDNP provides more detail driving decision information of autonomous vehicles. With the CDNP, each vehicle can understand the driving situations or intentions of other vehicles without image or audio processing algorithm. With the CDNP, the autonomous vehicle can get not only the information from its sensors, but more importantly, the information about the position, speed, and driving decisions or intentions from other autonomous vehicles. The autonomous vehicles can make a more suitable driving decision according to the common messages stored in the CDNP packet header. The CDNP changes the passive detection of the driving decision of other vehicles into proactive notification to other vehicles about its driving decision. It also makes the identification of the driving decisions of other vehicles before the decisions performed possible. Therefore, the identification time (IT) is decreased. The identification time is defined as the necessary time for one vehicle identify the driving decisions of the other vehicles. Furthermore, the reaction preparing time (RPT) is increased. The reaction preparing time means the buffer time period of one vehicle to prepare a suitable reaction to react to the other vehicle's driving decision before the driving decision is performed. Furthermore, the average traveling time to the destination can also be decreased when in a hurry. The CDNP protocol can also be extended for more complex driving behaviors to make the cooperation intelligent autonomous vehicle more intelligent.

Finally, the summarization of this thesis is described in chapter 5.

The roadmap shown in Figure 1.1 summarizes the relations of each chapter and the organization of this thesis.

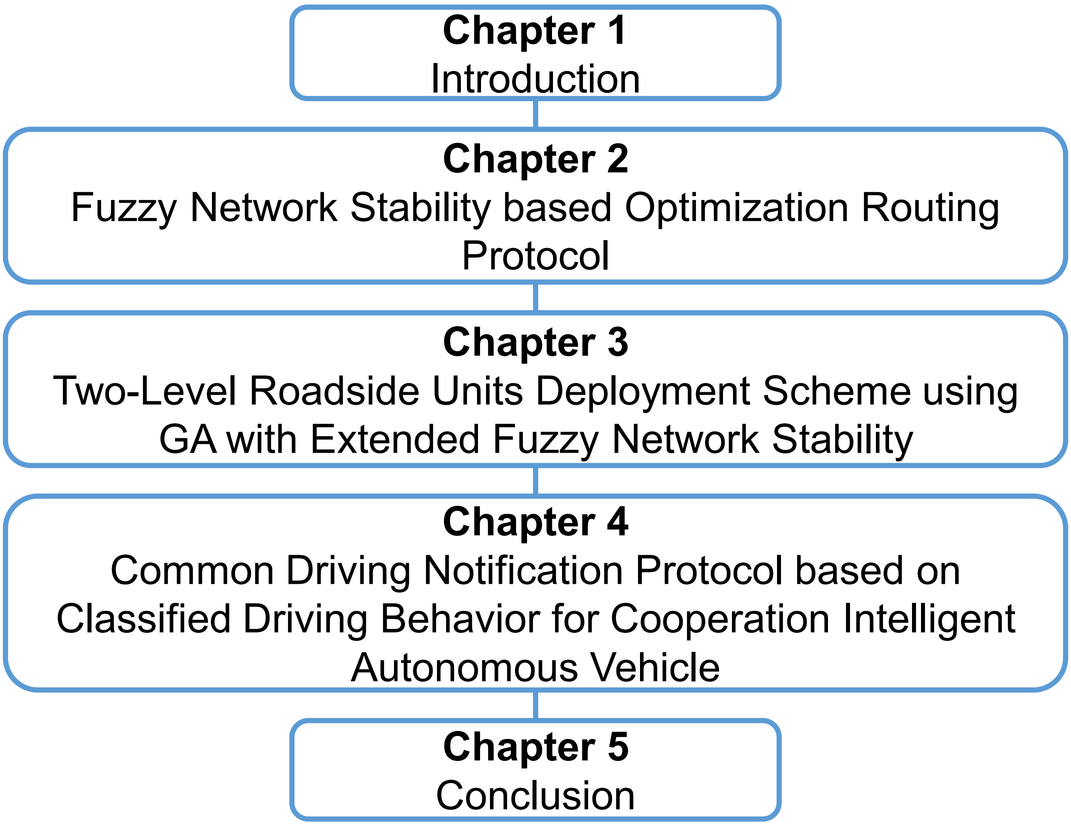

Figure 1.1. Thesis roadmap.

Chapter 2

Fuzzy Network Stability based Optimization Routing Protocol

2.1 Fuzzy Network Stability for Vehicular Ad-hoc Network

The real-time distribution of vehicles on a road segment is the key factor to determining network stability. The **Figure 2.1** shows vehicle distribution examples on the road segment. The L denotes the length of road segment. The maximum wireless transmission range of both the RSU and vehicle are the same, denoted by $T_{R\max}$ meters. As in the situation shown in **Figure 2.1 (a)**, the number of vehicles and average distances are large enough and the communication range can cover the entire road segment, so network of the road segment is fully connected. Basically, to cover the entire road segment at least $n = \lfloor L/T_{R\max} \rfloor - 1$ vehicles are necessary if there are no RUS deployed. The vehicles, however, are not evenly distributed on the road segment in most situations, as shown in **Figure 2.1 (b)**. In that case, the distance between vehicles will be larger than the transmission range. The network will be only partially connected and the data cannot be forwarded to the next-hop directly. It is known that the distribution and velocity of vehicles on the road segment are not always the same, and it will be affected by traffic signal, road surface condition, geometry, etc. Therefore, the distribution of vehicles on the road segment is the key factor that affects the network stability of VANET.

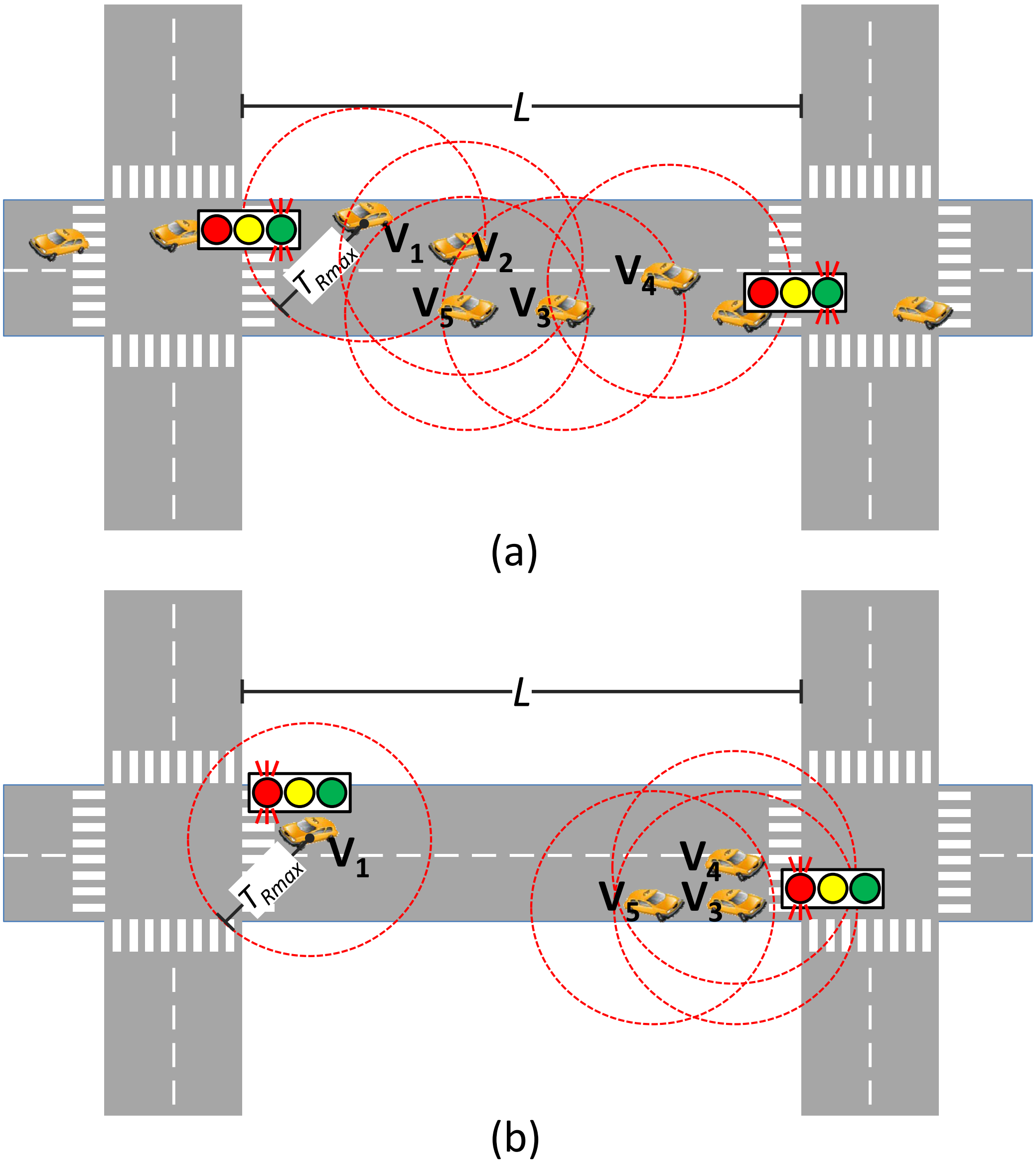

Figure 2.1. Vehicle distribution examples for (a) fully connected network and (b) fragmented network.

To define a mathematical model to express the real-time distribution of vehicles on a road segment is not easy. The fuzzy network stability, called fuzzy inference based vehicle to vehicle network connectivity model, is proposed to meet the requirements that the maximum vehicle density of road segments and the maximum average distance between vehicles under the conditions that the movement of vehicles is unstable and the information for routing is imperfect. Fuzzy inference is applied to define the uncertainty parameters via membership functions and rules-based fuzzy inference, which are described in the following subsections. The fuzzy input variables are vehicle density (VD_i), average distance (AD_i), and opposite ratio (OR_i), and the output variable is a fuzzy network connectivity ratio (CR_i). The i denotes the unique road segment ID. The boundary values of the membership function and inferences rules are determined by analyzing the simulation results. Some techniques can be used to optimize the membership function, such as using a genetic algorithm (GA).

2.1.1. Membership Functions of Fuzzy Network Stability

There are three input parameters for the fuzzy inference based vehicle to vehicle network connectivity model, including the vehicle density of road segment ($VD_{i,t}$), the average safety distance between vehicles ($AD_{i,t}$), and the opposite ratio of vehicles ($OR_{i,t}$). The parameters are described using three linguistic variables (Low, Medium, and High), t represents the time stamp, and i denotes the road segment ID. First, the average vehicle density on the road segment is defined by determining whether the number of vehicles is large enough and the packet can be transferred hop by hop through the road segment:

$$VD_{i,t} = \frac{T_{R\max} \times N_{i,t}}{L_i}, \qquad (2.1)$$

where T_{Rmax} denotes the maximum of transmission range (m), $N_{i,t}$ represents the number of vehicles on the road segment i at time t (s), and L_i is the length of road segment i (m).

Higher vehicle density means that there are enough vehicles to forward packets hop by hop. In the VANET environment, the value of T_{Rmax} is normally set to 250 meters. The three linguistic states, Low (L), Medium (M), and High (H), represent members' degrees, and the membership function is shown in **Figure 2.2**. The Very Low (VL) and Very High (VH) states are also considered. However, when VL and VH are added into the membership functions considered, the simulation results obtained do not differ significantly. Therefore, to simplify the design of the inference rules, we only use L, M, and H.

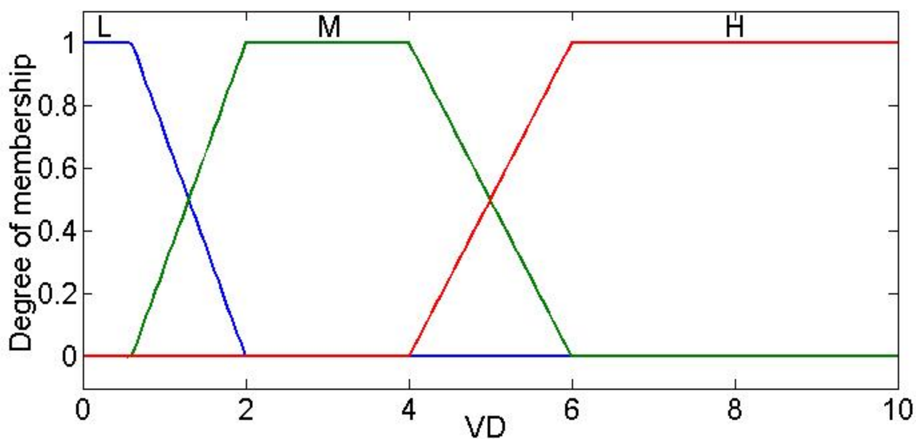

Figure 2.2. Membership function of VD.

Second, it is assumed that the vehicle is driven according to the safe distance rule [59]. Thus, the average distance between vehicles is calculated as

$$AD_{i,t} = v_0 t_d + v_0^2 / 2a_m + d \qquad (2.2)$$

The average distance between vehicles is defined to represent the possible distance between each vehicle for the reason that the safety distance between vehicles is increased in the wake of an increase in average velocity.

The v_0 is a vehicle's velocity before braking, t_d is the braking delay time and its value is 1.2 ~ 2.0s [59], d is the safety distance from the leading car after the following car stops and the general value is 2 ~ 5m [59], and a_m is the leading car maximum reduction and the general value is 6 ~ 8 m/s^2 [59]. A larger safe distance means that the vehicles are farther separated from each other and the network coverage ratio is larger. The membership functions are shown as **Figure 2.3**.

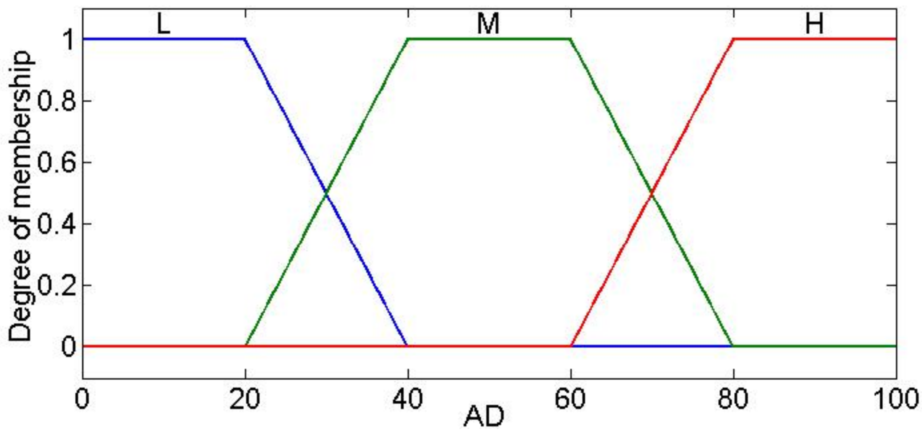

Figure 2.3. Membership function of AD.

Third, the equation of the opposite direction ratio of vehicles on the road segment i is defined as

$$OR_{i,t} = \begin{cases} \min\left(N_{i,D_1}, N_{i,D_2}\right) / \max\left(N_{i,D_1}, N_{i,D_2}\right) & , \quad \max\left(N_{i,D_1}, N_{i,D_2}\right) \neq 0 \\ 1 & , \quad \max\left(N_{i,D_1}, N_{i,D_2}\right) = 0 \end{cases} \quad ..(2.3)$$

The value of N_{i,D_1} and N_{i,D_2} is the number of vehicles on both directions of the road segment i. A smaller OR_i means that the probability of vehicle running in the same direction on the road segment is larger and the network connectivity is more stable because the relative speed difference between vehicles is smaller. The membership functions are shown as **Figure 2.4**.

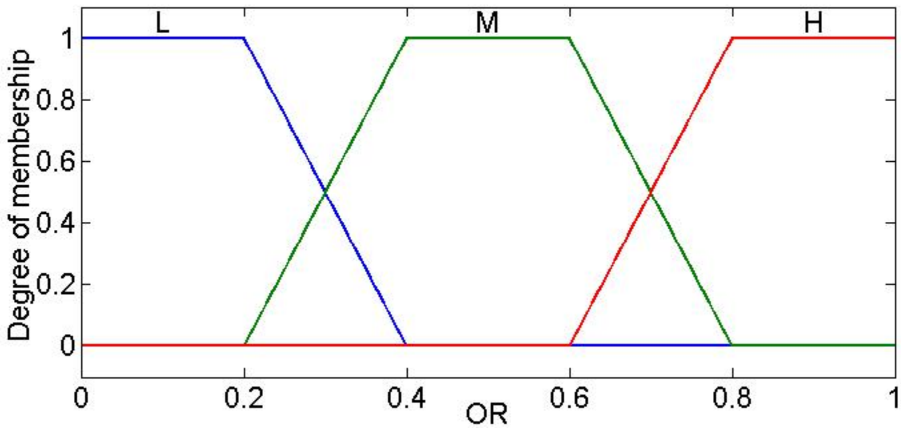

Figure 2.4. Membership function of OR.

The output, the fuzzy network connectivity ratio (CR_i), for each road segment is generally a single number. Therefore, the aggregate of the fuzzy set, encompassing a range of output values, must be defuzzified. The centroid method is the most commonly used technique with good performance in e.g., [60, 61]. After investigating other defuzzification methods, the centroid method is ultimately accepted as the defuzzification method. Using the centroid method of defuzzification, the fuzzy network connectivity ratio is calculated as

$$CR_i = \frac{\sum_{x=1}^{n} y \times \mu_x(y)}{\sum_{x=1}^{n} \mu_x(y)} \quad , \qquad (2.4)$$

where y is the center point of each membership function and $\mu_x(y)$ is the strength of the membership function.

The CR_i is represented by a triangular membership function, and the expressions of membership functions are shown as **Figure 2.5**.

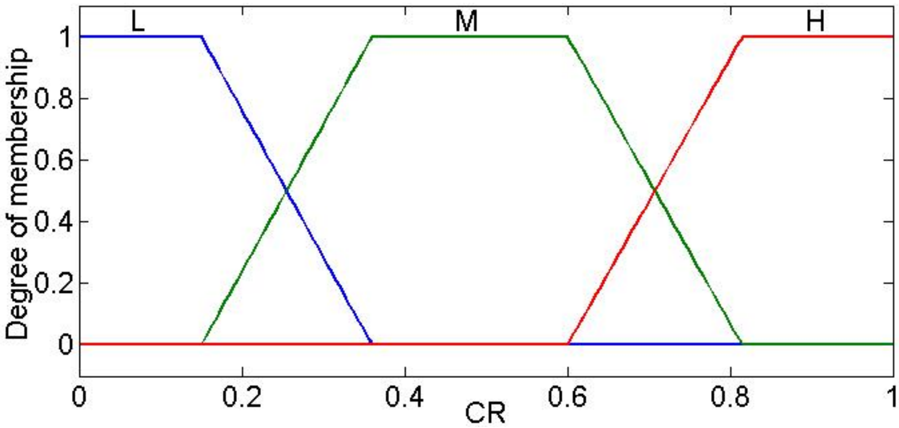

Figure 2.5. Membership function of CR.

2.1.2. Rule-based Fuzzy Inference of Fuzzy Network Stability

The rules-based fuzzy inferences, or fuzzy if-then rules, are defined to determine the relationship between the inputs and output, as shown in **Table 2.1**. To establish a set of rules, first a set of basic rules is defined and the simulation is performed to get the result. After the simulation, the rules are changed and the simulation is performed again. After each simulation, the performance of each simulation is compared and a new set of rules is adopted if the new performance is better.

Table 2.1. Rules-based fuzzy inference table.

Rule	Vehicle Density	Average Distance	Opposite Direction Ratio	Fuzzy Network Connectivity Ratio
1	L	L	L	L
2	L	L	M	L
3	L	L	H	L
4	L	M	L	L
5	L	M	M	L
6	L	M	H	L
7	L	H	L	M
8	L	H	M	M
9	L	H	H	L
10	M	L	L	L
11	M	L	M	L
12	M	L	H	L
13	M	M	L	M
14	M	M	M	M
15	M	M	H	L
16	M	H	L	H
17	M	H	M	H
18	M	H	H	M
19	H	L	L	L
20	H	L	M	L
21	H	L	H	L
22	H	M	L	M
23	H	M	M	M
24	H	M	H	L
25	H	H	L	H
26	H	H	M	H
27	H	H	H	M

2.2 Fuzzy Network Stability based Optimization Routing Protocol

It is assumed that each node has an installed wireless device to enable wireless communication in the VANET. The wireless link can only be established if the distance between two nodes is less than their transmission range. Each node participating in the network should be able to forward packets for other nodes in the network. Each node also has an installed navigation system with a GPS receiver and preloaded digital maps. Using the GPS receiver, each node can determine its accurate geographical location and map its GPS locations on the road. The optimization routing protocol also assumes that the preloaded digital map provides a street-level map. Finally, it assumes that each node periodically sends out beacon (hello) messages to its neighbors. Because periodic beaconing is a necessary mechanism for many safety applications in VANETs, it is a necessary approach that is clearly not bandwidth efficient. The road-based traffic data can be gathered via ITS applications such as the traffic-monitoring system proposed in [62] and a VANET-based ITS may be used where infrastructure-based traffic monitoring systems are not deployable for various reasons.

As each node periodically sends out beacon messages, some information, including geographical location, velocity, and navigation path, is added to the beacon messages. The format of beacon messages is shown in **Table 2.2**.

Table 2.2. Format of beacon messages.

Position X	**Position Y**	**Velocity X**	**Velocity Y**	**Navigation Path**
100.3	200	30	40	$<I_1, I_5, I_6, I_7>$

That information is used for next-hop selection. To control the packet size of beacon messages, the navigation path column consists of four intersection IDs that the current vehicle may travel. For example, as shown in **Figure 2.6**, node V_1 will travel from current road segment $<I_0, I_1>$ to road segment $<I_{11}, I_{12}>$. The sequence of intersection IDs can be expressed as $< I_1, I_5, I_6, I_7, I_{11}, I_{12}>$, and accordingly, the node V_1 stores intersection IDs $<I_1, I_5, I_6, I_7>$ into the navigation path column of beacon messages.

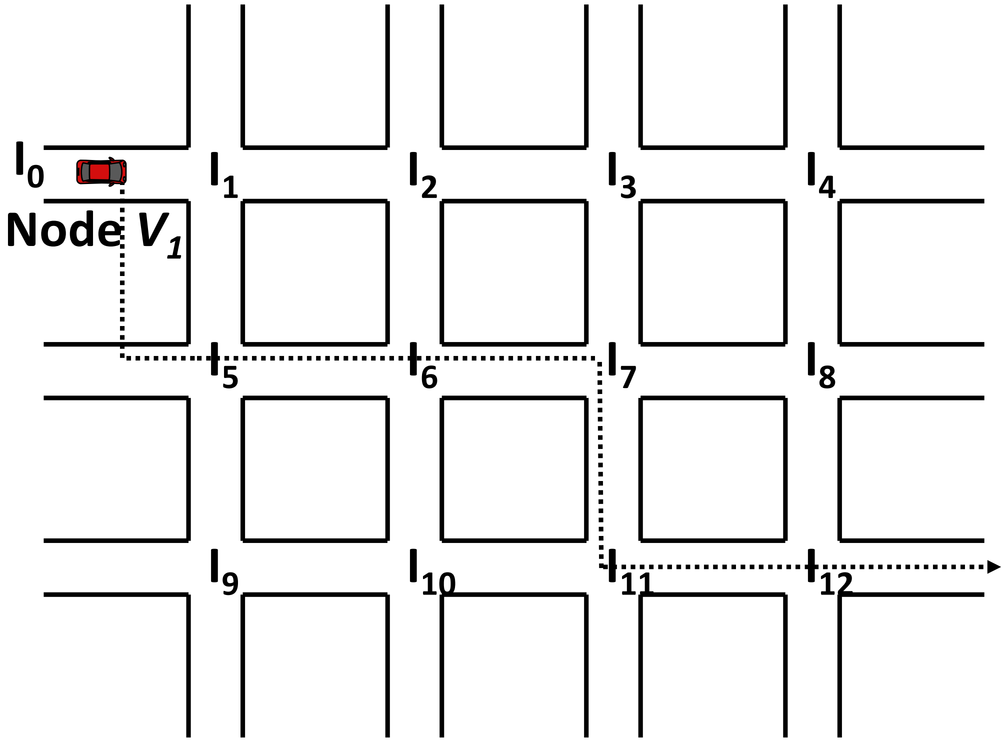

Figure 2.6. Example navigation path for node V_1.

2.2.1. Design of Information Table

Each node maintains an information table that records the information of its neighbors. When one node receives a beacon message from another node, it first checks whether any information entry is already recorded in its information table. If not, it stores the geographical location, velocity, and time stamp received in the beacon message, and the navigation path of its neighbors in its information table; otherwise, it updates the information entries of its neighbors. The information stored in the information table will be used to make the next-hop selection. An example information table is shown in **Table 2.3**.

Table 2.3. Format of information table.

Node ID	Geographical Location	Velocity	Time Stamp (sec.)	Navigation Path
V_1	(100.3, 200)	(30, 40)	20	$\langle I_1, I_5, I_6, I_7 \rangle$
V_2	(140.6, 20)	(50, 0)	27	Null

2.2.2. Design of Transmission Path Table

To reduce the size of the packet header and avoid frequently re-writing the packet header, the transmission path of each data packet does not need to be stored in the packet header. The information stored in the packet header simply contains the geographic location of the source and destination nodes. The transmission path is temporarily stored in the transmission path table of each node. The format of the transmission table is shown in **Table 2.4**.

Table 2.4. Format of transmission path table.

Source	Source Location	Destination	Destination Location	Transmission Path	Time Stamp (sec.)
V_1	(100.3, 200)	V_{10}	(1000.3, 600)	$\langle I_1, I_2, I_4, I_9, I_{14}, I_{23} \rangle$	50
V_4	(140.6, 20)	V_{20}	(2500.3, 1400)	$\langle I_{13}, I_{15}, I_{26}, I_{27} \rangle$	50

When the network connectivity changed, the transmission path needs to be reconstructed. Therefore, when the current node receives a data packet, it first checks whether a transmission path update is necessary. If it is, the transmission path is updated using the newer fuzzy network connectivity ratio. This is because that the fuzzy network connectivity is recalculated after a fixed time interval. After the transmission path is checked, the current node forwards the data packet to the next road segment according to the transmission path.

2.2.3. Packet-Forwarding Strategy

The movements of vehicles are unstable and random because they are driven by human beings. Therefore, the vehicle distribution changes continually. The network connectivity is also changed. When the network connectivity is high enough to forward data packets hop by hop to the next road segment, the farthest node is the best choice. However, if the network is partially connected, a carry-and-forward mechanism may be used, so the node that has the farthest moving distance is the best choice. If there are not any suitable nodes that can be selected as the next-hop node, it is necessary to reconstruct the transmission path. Therefore, the packet-forwarding strategy must be changed to meet to the network connectivity of each road segment. When the current node wants to forward data packets, according to the output of the fuzzy inference based vehicle to vehicle network connectivity model, i.e., fuzzy network connectivity ratio, a suitable strategy will be selected to forward packets to the next-hop node. Three adaptive forwarding strategies—high, medium, and low connectivity—are proposed in this paper.

- High Connectivity Strategy

When the fuzzy network connectivity ratio is larger than 0.5, the current node N_{cur}

selects a suitable node that satisfies

$$\forall n \in IT(N_{cur}), \quad (2.5)$$

$$n \in N_{set}(P_t), \quad (2.6)$$

$$\left\| \overrightarrow{Vec_{(t)}(N_{cur}, n)} \right\| \le T_{R\max}, \quad (2.7)$$

$$Max\left(\left\| \overrightarrow{Vec_{(t)}(N_{cur}, n)} \right\| \right) \quad (2.8)$$

The $IT(N_{cur})$ denotes the node set in the information table of the current node, and the $Vec_{(t)}(N_{cur}, n)$ represents a vector going from N_{cur} to node n at time *t*. The current node selects the forwarding node based on the node that is on the transmission path, and as the next-hop node, it is the farthest node within the transmission range.

- Medium Connectivity Strategy

When the fuzzy network connectivity ratio is larger than 0.3 and smaller than 0.5, the current node N_{cur} selects a suitable node as the next-hop node that satisfies

$$\forall n \in IT(N_{cur}), \quad (2.9)$$

$$n \in N_{set}(P_t), \quad (2.10)$$

$$\left\| \overrightarrow{Vec_{(t)}(N_{cur}, n)} \right\| \le T_{R\max}, \quad (2.11)$$

$$Vec_{(t+\Delta t)}(N_{cur}, n) \cdot V_{(t)}(n) > 0, \quad (2.12)$$

$$Max\left(M(P_n, P_t) \times \left(\left\| \overrightarrow{Vec_{t+\Delta t}(N_{cur}, n)} \right\| - \left\| \overrightarrow{Vec_t(N_{cur}, n)} \right\| \right) \right). \quad (2.13)$$

The $Vec_{(t+\Delta t)}(N_{cur}, n) \cdot V_{(t)}(n)$ denotes the dot product of two vectors $Vec_{(t+\Delta t)}(N_{cur}, n)$ and $V_{(t)}(n)$, $M(P_n, P_t)$ means the matching degree between P_n and P_t. That is, if P_n ={1,2,3,4} and P_t={1,2,5,7}, then $M(P_n, P_t) = 2$. Therefore, the current node selects the forwarding node based on the node that is traveling on the road segment that matches the transmission path and is moving toward the destination node that has the farthest moving distance after a time span within the transmission range.

- Low Connectivity Strategy

When the fuzzy network connectivity ratio is smaller than 0.3, it is not suitable to select the current road segment as a part of a transmission path. Therefore, the current node re-establishes a new transmission path by using the Dijkstra algorithm [63] and then forwards the packet through the new transmission path.

2.2.4. System Flow of the Optimization Routing Protocol

The flowchart of the optimization routing protocol is shown in **Figure 2.7**. First, when the source node wants to send packets, it queries the geographical location of the destination node from the location service, such as [64, 65, 66].

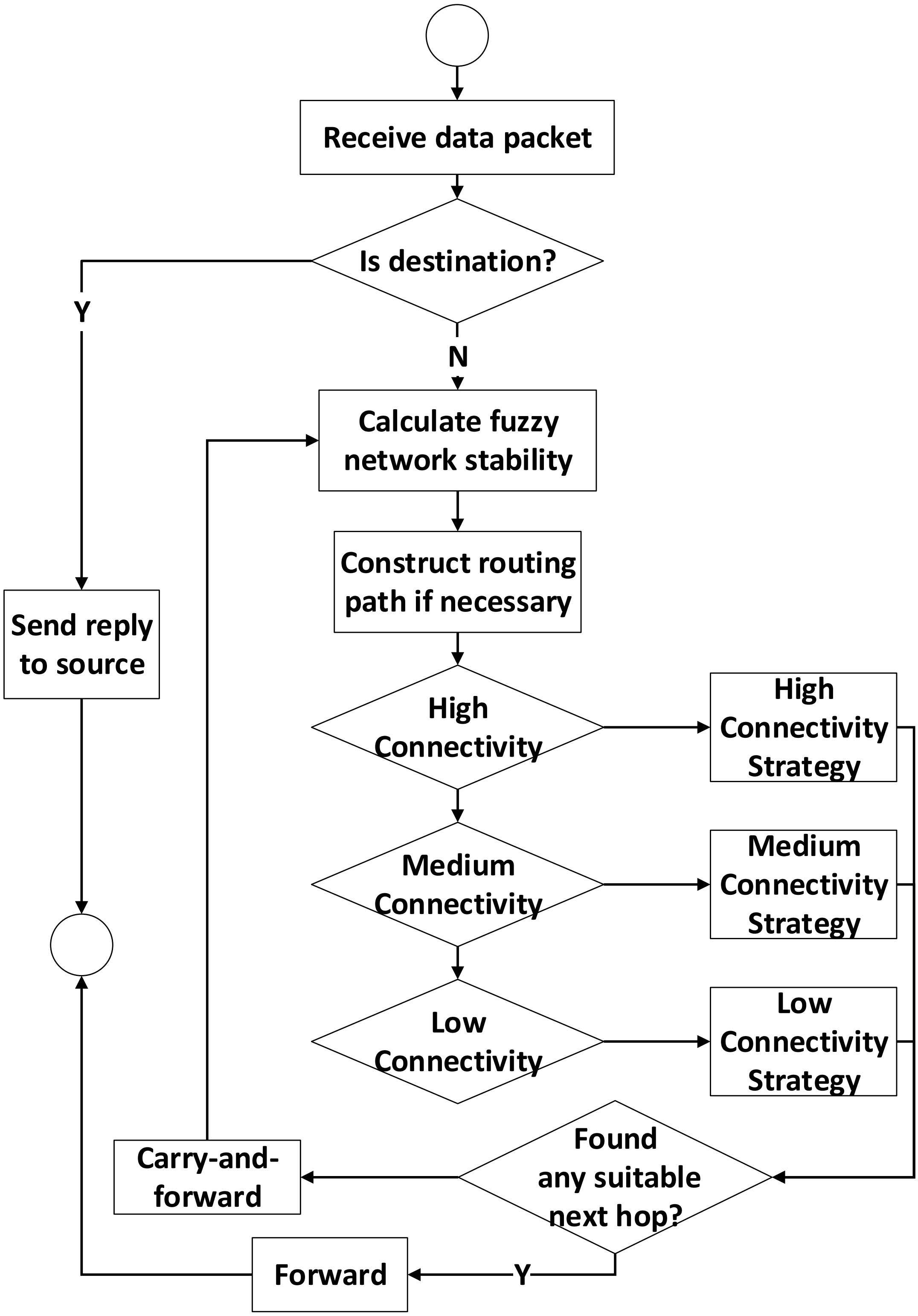

Figure 2.7. Flowchart of the optimization routing protocol.

The road network can be considered an undirected graph, and the Dijkstra algorithm is used to establish a transmission path to the destination node. Hence, the route discovery process is not necessary and the control overhead caused by a flood of route discovery packets is avoided. The weight of each road segment ($weight_i$) is calculated using the fuzzy inference based vehicle to vehicle network connectivity model, and $weight_i = \frac{1}{CR_i}$, where i is the unique road segment ID, and CR_i is the fuzzy network connectivity ratio. The transmission path is formed by a sequence of intersection IDs, and data packets are forwarded toward the next intersection contained in the transmission path by intermediate nodes. When the intermediate node receives a packet, it first checks whether it is itself the destination node. The intermediate node sends a reply packet to the source node if it is the destination node; otherwise, it checks the transmission path that is temporarily stored in transmission table and routes the data packets using the optimization routing protocol. According to the value of the fuzzy network connectivity ratio, one of forwarding strategies will be selected and used to forward the data packets to the next-hop node. If the intermediate node cannot find any suitable node as the next-hop node, the carry-and-forward mechanism will be used. The packets will be stored in the intermediate node's buffered memory until it encounters a new neighbor.

The carry-and-forward mechanism is useful in sparse areas, but it will increase the total end-to-end delay because the data packet is not forwarded immediately to the next-hop node. Finally, if the destination node leaves its current road segment, it will send a location reply packet to the source node. Therefore, it is not necessary for the source node to re-query the location service to get a new geographical location of the destination node each time it wants to send data packets.

2.3 Analysis of Computation Time

Theorem: Let R, I, and V be the number of road segments on a map, number of intersections on a map, and number of vehicles within communication range of the vehicle that wants to transfer a data packet, respectively. Then, the computation time of optimization routing protocol is

$$f(R,I,V)=O(I\lg I+R+V) \quad (2.14)$$

Proof: The optimization routing protocol can be divided into three main steps. The first step is fuzzy network connectivity ratio calculation, the second step is the construction of transmission path and the last step is next-hop node selection.

Table 2.5. Fuzzy network connectivity ratio calculation procedure.

Fuzzy network connectivity ratio calculation	*Cost*	*Times*
1 for i =1 to *R.length*	C_1	R
2 //sequences of if-then-else instruction of fuzzy inference	*0*	R
3 if ($VD_{i,t} < 0.6$) then	C_2	R
4 $\mu_L(VD_{i,t})=1$	C_3	R
5 else if ($0.6 \le VD_{i,t} < 3.25$) then	C_4	R
6 ……	$C_5 \sim C_n$	R

The fuzzy network connectivity ratio calculation procedure with the time "cost" of each statement is shown in **Table 2.5**. Each statement of the fuzzy inference consists of a sequence of if-then-else instructions, so the computation time of fuzzy network connectivity ratio calculation of each road segment is clearly a constant. The computation time of the fuzzy network connectivity ratio calculation is the sum of the computation times for each statement executed. Therefore, the computation time is

$$f(R) = C_1R + C_2R + C_3R + ... + C_nR = (C_1 + C_2 + C_3 + ... + C_n)R = \sum_{i=1}^{n} C_iR \quad (2.15)$$

It is not difficult to find a positive real number M and a real number R_0 such that $\left|\sum_{i=1}^{n} C_iR\right| \le M|R|$ for all $R > R_0$. Hence, to calculate the fuzzy network connectivity ratio of each road segment, the total computation time will be $O(R)$. This is not unreasonable if the fuzzy network connectivity ratio is updated every 5 seconds.

In the second step, when one vehicle receives a data packet, it checks whether it is necessary to construct a new transmission path using an updated fuzzy network connectivity ratio for each road segment. To construct the transmission path, the Dijkstra algorithm is used find the shortest path from the current vehicle to the destination vehicle using the fuzzy network connectivity ratio as the weight of each road segment. According to [67], the computation time of finding the shortest path using Dijkstra algorithm is $O(I\lg I + R)$ by implementing the min-priority queue with a Fibonacci heap.

After constructing the transmission path, one of the neighbor nodes is selected as the next-hop node to forward the data packet. The procedure is shown in **Table 2.6**.

Table 2.6. Next-hop selection procedure.

Next-hop selection		*cost*	*times*
1	for *i* =1 to *V.length*	C_1	*V*
2	Calculate the priority of vehicle *i*	C_2	*V*
3	If the priority of vehicle *i* larger than maximum priority, selected as next-hop	C_3	*V*

The current vehicle that wants to transfer the data packet checks whether the V vehicles within communication range meet the requirements of selection rules and finds the most suitable one as the next-hop node. Therefore, the computation time is

$$\mathrm{f}(V) = C_1 V + C_2 V + C_3 V = (C_1 + C_2 + C_3) V \quad (2.16)$$

A positive real number M and a real number V_0 exist such that $|(C_1 + C_2 + C_3)V| \leq M|V|$ for all $V > V_0$. Hence, the computation time of the next-hop selection is $O(V)$.

Therefore, according to the three steps described previous, the total computation time $f(R, I, V)$ will be $O(I \lg I + R + V)$ in the worst case, when a reconstruction of the routing path is necessary.

2.4 Experiment and Analysis of Fuzzy Network Stability based Optimization Routing Protocol

In this section, the experiment on computation time and the simulations of wireless data transmission performance analysis, including end-to-end delay, delivery ratios, and control overhead, is discussed to verify the efficiency of the proposed routing protocol. A traffic-monitoring system is also implemented to provide real-time road traffic information. The open source tool NS2 (Network Simulator 2) [55] is used to simulate the wireless data transmission. The proposed routing protocol is implemented as a routing component of NS2, using C++. The experiments of proposed routing protocol are conducted using a MacBook Pro with a Quad core processer (Intel Core i7 2.4 GHz) and 8 GB of memory.

2.4.1. Computation Time Experiment

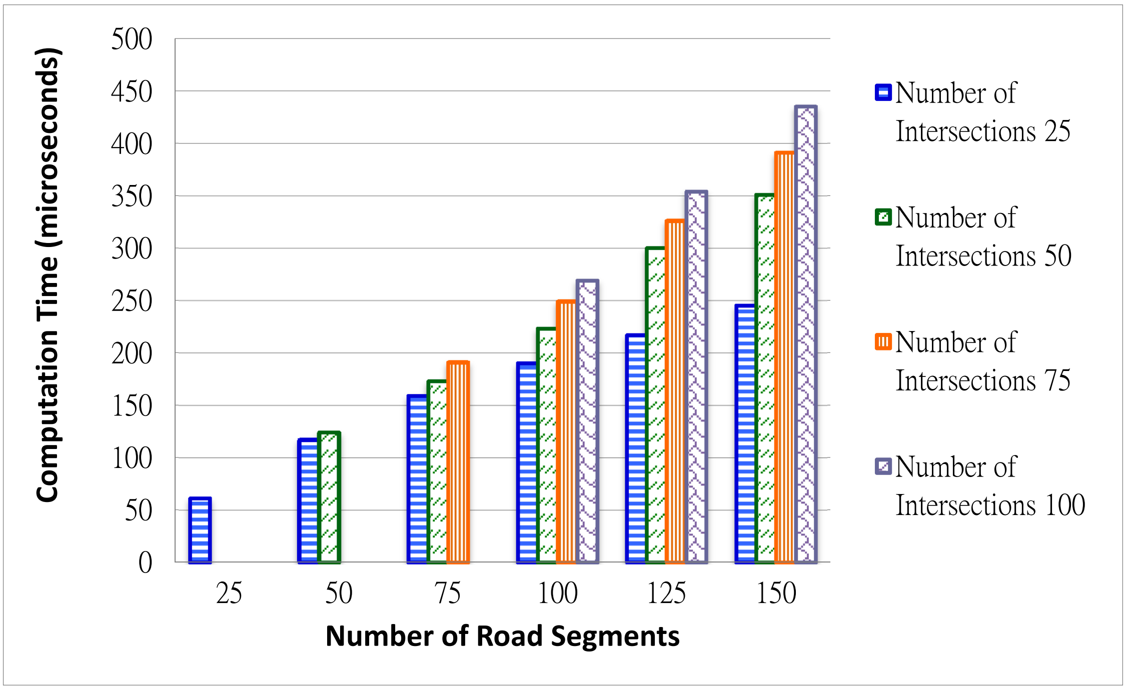

Figure 2.8. Running time between different numbers of road segments and intersections.

To verify the relation between the three parameters and computation time, different parameters are compared and the number of intersections is between 25 and 100, the number of road segments is between 25 and 150, and the number of vehicles is between 50 and 400.

As shown in **Figure 2.8**, when doubling the number of road segments, the computation time will increase almost the same value indicating linear growth, and when the number of intersections doubles, triples, and increases four-fold, the running time interval also increases. Because the NS2 is a single thread simulator, so the experiment is done in single thread. In this situation, the computation time is small enough (microseconds) to be applied to real-time applications.

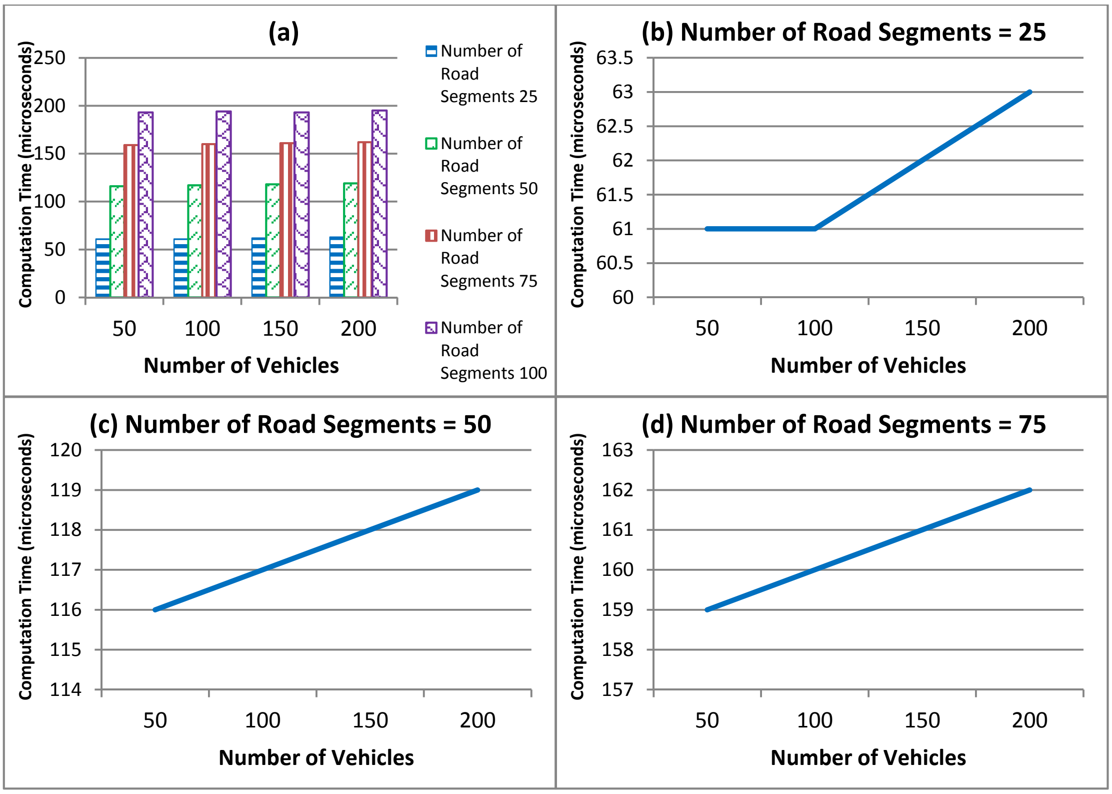

Figure 2.9. Running time between different numbers of road segments and vehicles.

In **Figure 2.9**, the comparison between different vehicles is shown. As shown in **Figure 2.9 (a)**, the increasing computation time between different numbers of road segments is almost the same. In addition, from **Figure 2.9 (b)** to **Figure 2.9 (d)**, it is shown that the computation time indicates linear growth when the number of vehicles increases. Furthermore, even though the number of vehicles increases from 50 to 100, 100 to 150, and 150 to 200, the computation time increases by just 1 microsecond. Therefore, the effect on computation time caused by an increased number of vehicles is small.

2.4.2. Wireless Data Transmission Performance Analysis

- Environment Setup and Parameter

In the Media Access Control (MAC) layer, the IEEE 802.11b protocol with DCF standard is used, and each node is equipped with an IEEE 802.11b DCF wireless device with a transmission range of 250 m to transfer and receive data packets. The TraNS (Traffic and Network Simulation Environment) [56] is a GUI tool that integrates traffic and network simulators (SUMO [68, 69] and ns2) to generate realistic VANET simulations.

The SUMO (Simulation of Urban Mobility) is an open source project, mainly developed by employees of the Institute of Transportation Systems at the German Aerospace Center, which and it can generate realistic mobility with a car-following model, lane-changing model, traffic lights model, etc. Therefore, to achieve more realistic mobility generation, a combination of TraNS and the Manhattan street map obtained from the Open Street Map, shown in **Figure 2.10**, is used in the simulation together with a random routes generation module.

The original TraNS source code is modified to make it compatible with the latest version of the SUMO (version 0.16.0) and record more information for each vehicle in the simulation, such as the navigation path of each vehicle. The number of vehicular nodes considered in this simulation varying between 200 and 450 in a 3000 m × 3000 m area. Nodes are travelling at an average velocity between 0 and 80 km/h. The movement of the vehicles and the traffic light control is generated randomly by SUMO using TraNS. The important parameters of simulation are summarized in **Table 2.7**.

Figure 2.10. Manhattan street map used for simulation.

Table 2.7. Simulation parameters.

Simulation Time	200 sec.
Topology Size	3,000 m x 3,000 m
Number of Vehicles	200 ~ 450
Source / Destination Selection	Randomly selected
Media Access Control	802.11b DCF
Transmission Range	250m
Data Packet Type	Constant Bit Rate (CBR)
Data Packet Size	512 bytes
Packet Rate	8 packets/second
Hello Message Interval	2 sec.
Information Table Threshold	20 sec.
Vehicles Movement	Randomly generated by SUMO
Traffic Light Interval	Randomly generated by SUMO

- Experiment Results of end-to-end delay, delivery ratios, and control overhead

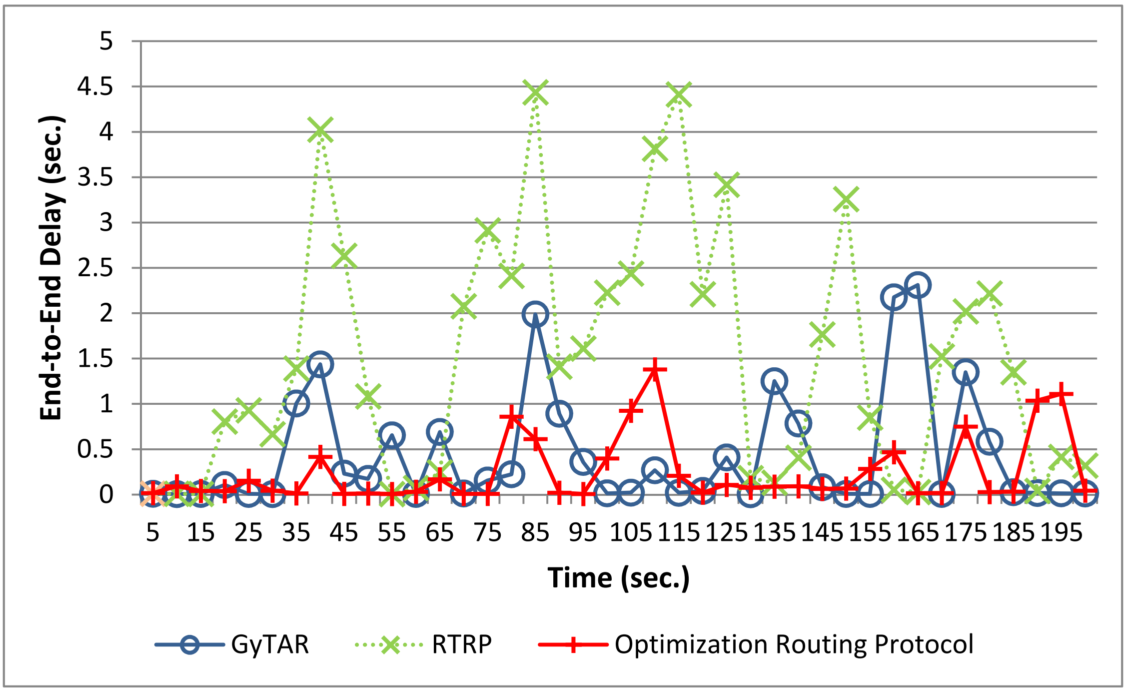

Figure 2.11. Comparison of end-to-end delay.

The influence of unstable mobility of vehicles on end-to-end delay is shown in **Figure 2.11**. Because the RTRP uses a route discovery procedure to construct a transmission path from the source node to the destination node, the transmission path will break when the distribution of vehicles on the road segment changes as a result of traffic signal changes. Therefore, the result of the end-to-end delay in RTRP is unstable. The GyTAR sends a CDP to estimate the traffic density. However, when the network on a road segment is not connected, the CDP cannot reach other intersections. Because the cell density information cannot be gathered, the determination of the next intersection selection will be incorrect.

Therefore, the end-to-end delay is higher when the traffic signals change. The optimization routing protocol constructs the transmission path according to the fuzzy network stability calculated by using the fuzzy inference based vehicle to vehicle network connectivity model. It decreases the probability of an incorrect path selection and selects the suitable forwarding strategy to forward the data packet. When the network connectivity becomes unstable, the data packets will be redirected to another road segment to avoid the network fragments. Therefore, the proposed protocol keeps the end-to-end delay within a range.

Because the end-to-end delay is unstable, as shown in **Figure 2.11**, the delivery ratio of GyTAR and the RTRP is affected. A comparison of the overall delivery ratio is shown in **Figure 2.12**.

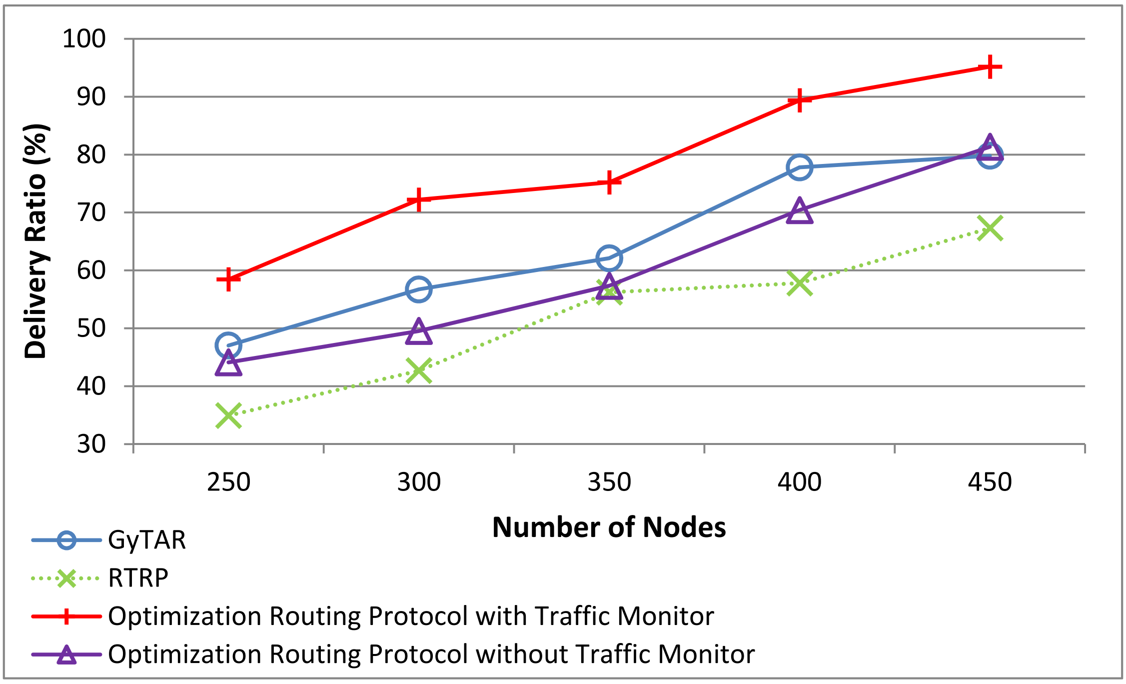

Figure 2.12. Delivery ratio for the GyTAR, RTRP, and optimization routing protocol.

In this comparison, the delivery ratio of the optimization routing protocol without a traffic-monitoring system is also compared, wherein the optimization routing protocol calculates the fuzzy network connectivity using just the statistical data. The result shows that the total delivery ratio of the optimization routing protocol with the traffic-monitoring system is higher than the GyTAR and RTRP. When the traffic signals change, the packet-forwarding strategy of the optimization routing protocol is adapted according to the fuzzy network connectivity Therefore, the optimization routing protocol avoids making incorrect packet-forwarding decisions when the network becomes unstable. The GyTAR and RTRP, however, cannot adapt their transmission strategy in that situation, causing some packets to be dropped. Therefore, the delivery ratio of GyTAR and RTRP are lower than the optimization routing protocol. Furthermore, the transmission path of RTRP is broken and needs to be reconstructed in this situation, so the delivery ratio of RTRP is lower than that of GyTAR. However, the result of the optimization routing protocol without a traffic-monitoring system is lower than that of GyTAR, because the statistical data does not reflect the real condition of that road segment and the fuzzy network connectivity may be in error.

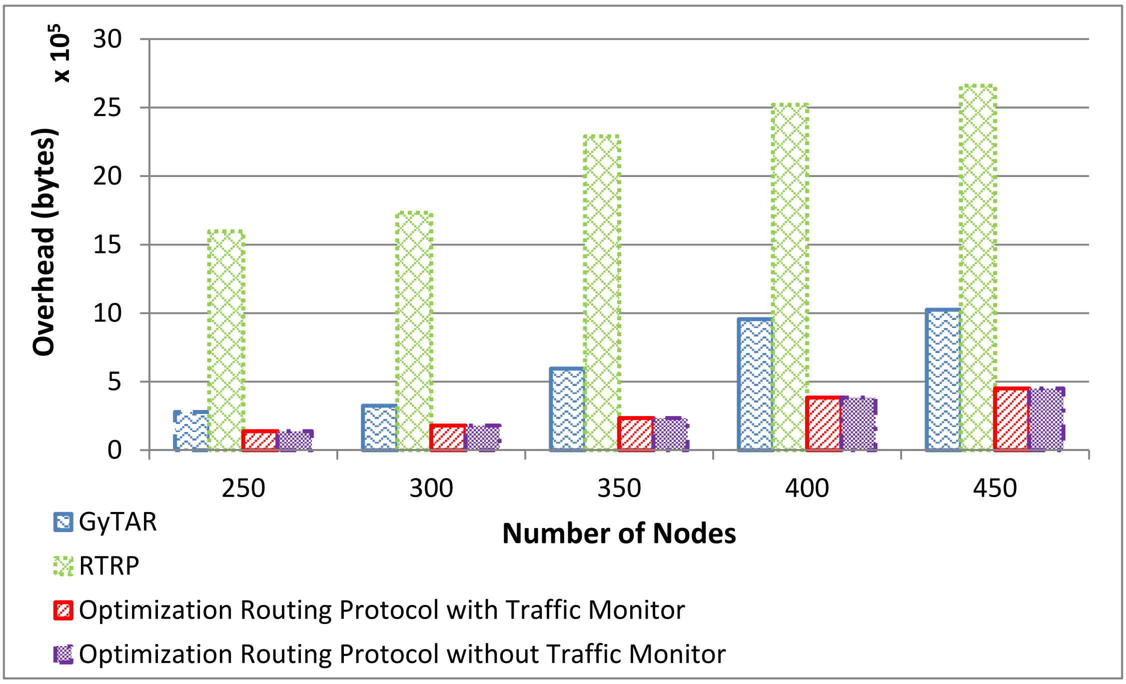

Figure 2.13. Comparison of the overhead in the GyTAR, RTRP, and optimization routing protocol with and without a traffic-monitoring system.

The comparison of the overall overhead is shown in **Figure 2.13**. The overhead of the optimization routing protocol is the beacon messages used to inform its neighbors of its information, the request packet used to query the location service about the geographic location of the destination node and the packets used to spread the traffic information in each road segment. The results show that the optimization routing protocol has lower control overhead and the traffic-monitoring system only produces a minimal control overhead. When the transmission path is broken, the RTRP needs to find a new one; therefore, the control overhead increases when the vehicle distribution changes. The GyTAR sends a CDP to calculate the traffic density and propagates the traffic density information to vehicles around the intersection, increasing overhead.

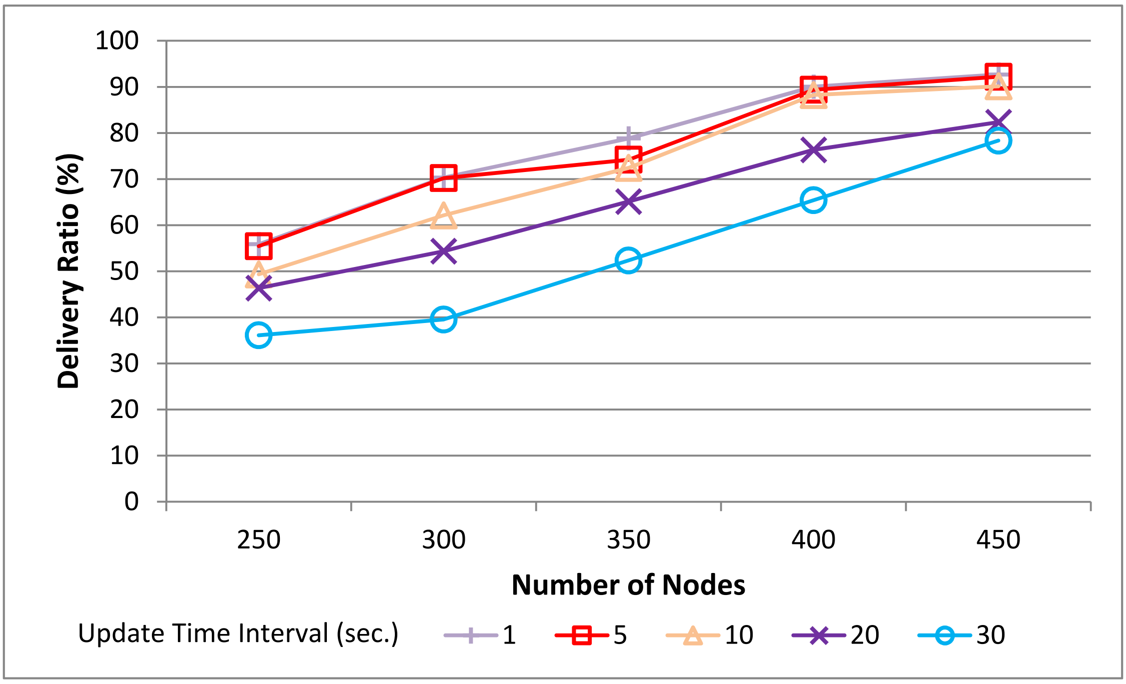

Figure 2.14. Delivery ratio of the optimization routing protocol between the different update time intervals in the traffic-monitoring system.

In **Figure 2.14**, the delivery ratio of the optimization routing protocol between the different update time intervals in the traffic-monitoring system is compared. The results show that if the update time interval is shorter, the delivery ratio is higher.

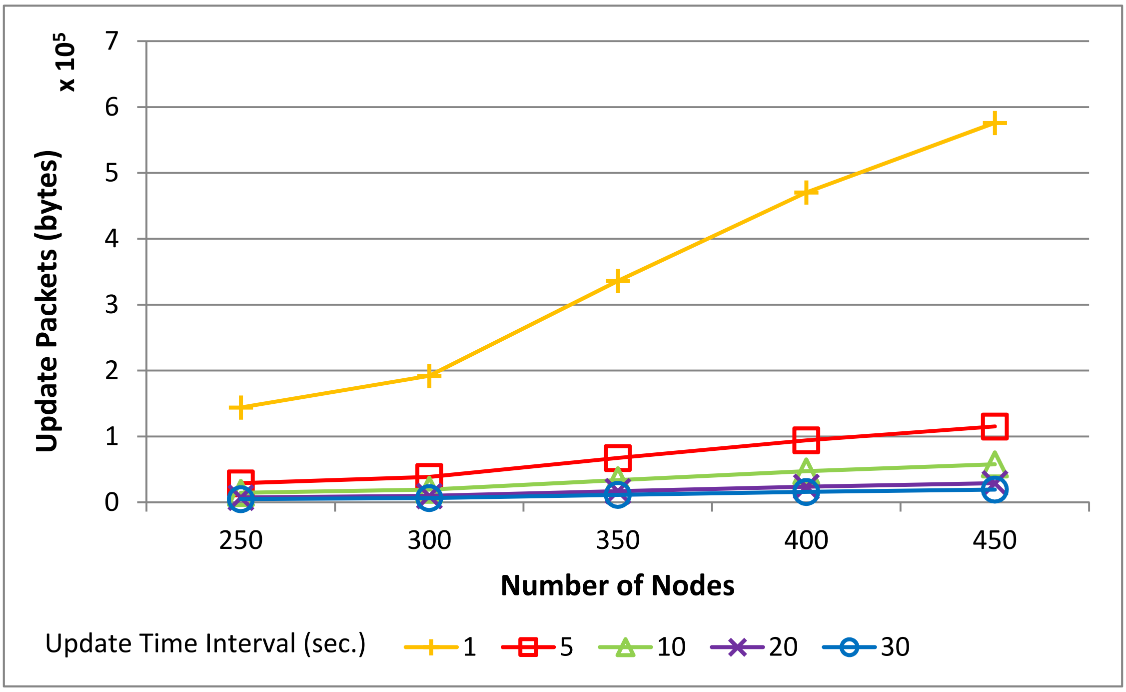

Figure 2.15. Update packet for different update time intervals in the traffic-monitoring system.

However, the delivery ratio of the update time intervals of 1 second and 5 seconds are almost the same. Therefore, the time interval of 5 seconds is a better choice than 1 second because it produces less control overhead, as shown in **Figure 2.15**. The results show that the number of control packets in an update time interval of 1 second is five times larger than that of the update time interval of 5 seconds. This is because each node sends control packets each second when the update interval is 1 second, but the control packets are only sent once every 5 seconds if the update time interval is 5 seconds.

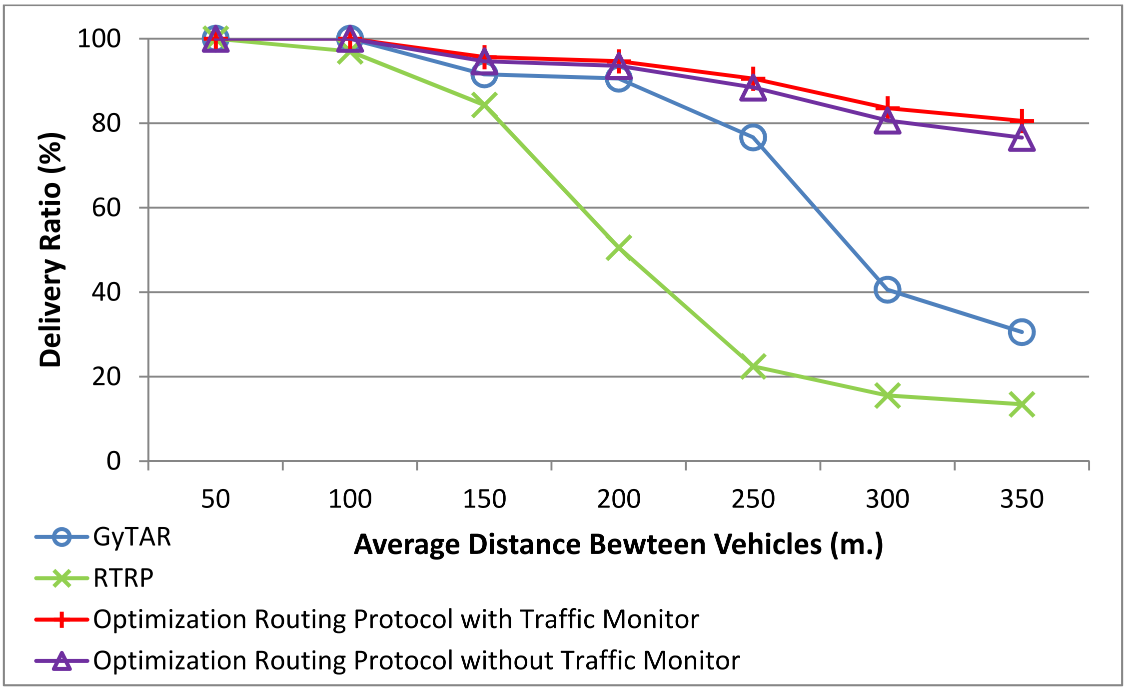

Figure 2.16. Packet delivery ratio of different average distance between vehicles.

Figure 2.16 shows the compassion of different average distance between vehicles. That means different vehicle density. It is shown that the packet delivery ratio of RTRP is decreased when the average distance between vehicles is increased. This is because the RTRP constructs the routing path before start to transmit the data packets. If the average distance between vehicles is larger than the transmission range, the RTRP cannot find a stable routing path from the source node to the destination node. The packet delivery ratio is poor in that situation. The GyTAR detects the network situation to decide the next road segment to forward the data packets. The transmission of data packets cannot be forwarded to any next-hop node if the network stability of next road segments is not good. That means the averaged distance between vehicles in the next road segment is larger than the transmission range. The optimization routing protocol finds a stable routing path from global multiple rouging path, so it avoids the road segments whose network stability is not good. Even though the current vehicle cannot forward the data packet to the next-hop immediately, it can carry the data packet to the suitable next road segment with high network stability.

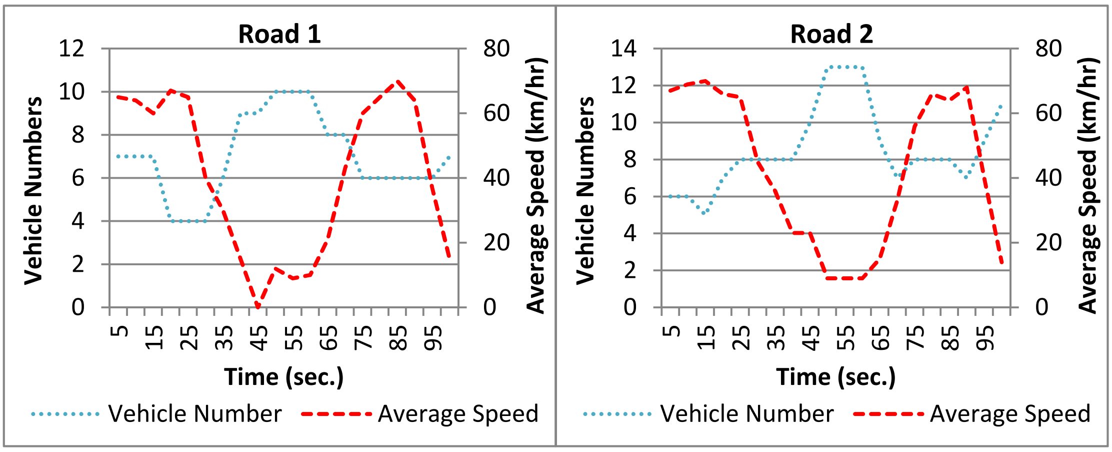

Figure 2.17. Vehicle numbers and average speed of the selected road segment 1 and road segment 2.

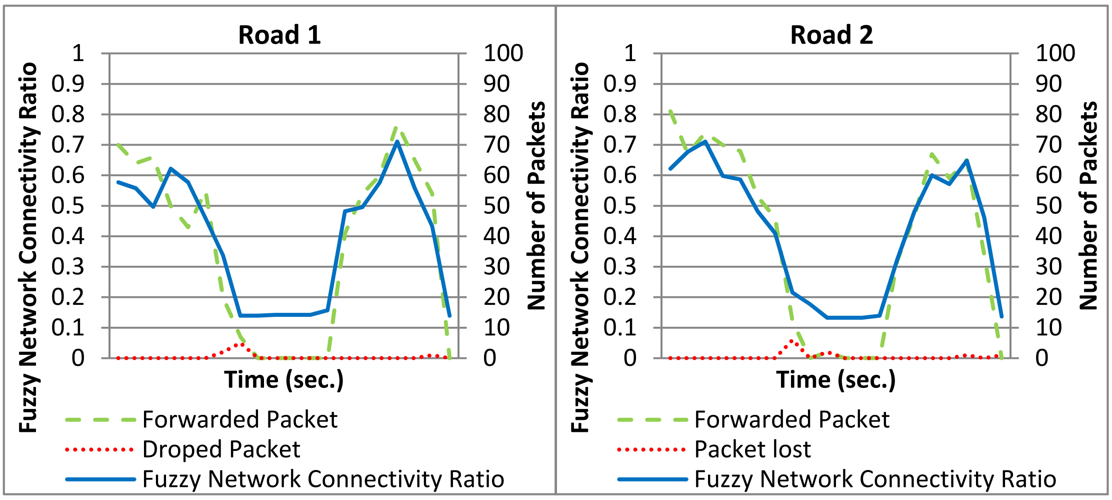

Figure 2.18. Number of forwarded and dropped packets for the selected road segment 1 and road segment 2.

For further analysis, four connected road segment of the Manhattan street map are selected to compare the relation between the change in the vehicle numbers, average speed, fuzzy distribution ratio, number of forwarded packets, and number of dropped packets, as shown in **Figure 2.17**, **Figure 2.18**, **Figure 2.19**, and **Figure 2.20**. The four road segments intersect at an intersection, and the mobility of vehicles is generated by SUMO using TraNS.

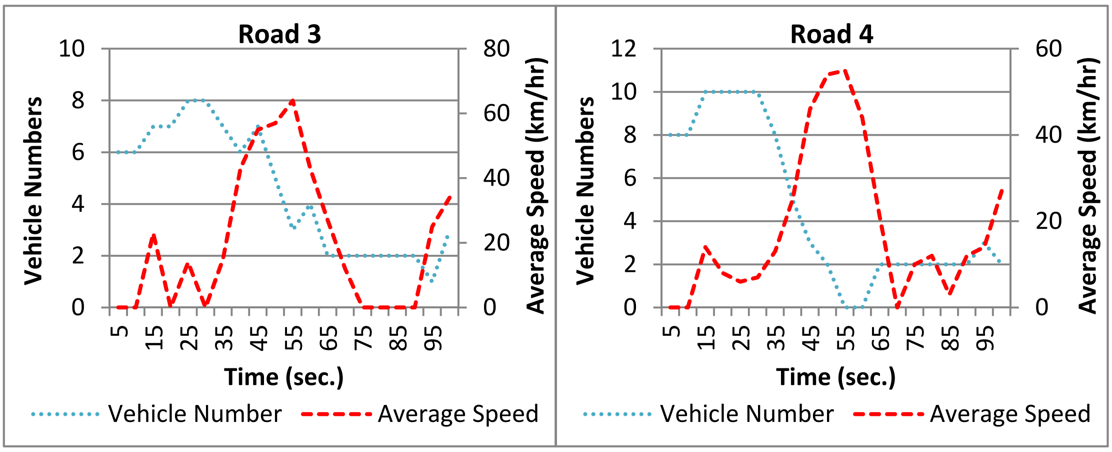

Figure 2.19. Vehicle numbers and average speed for the selected road segment 3 and road segment 4.

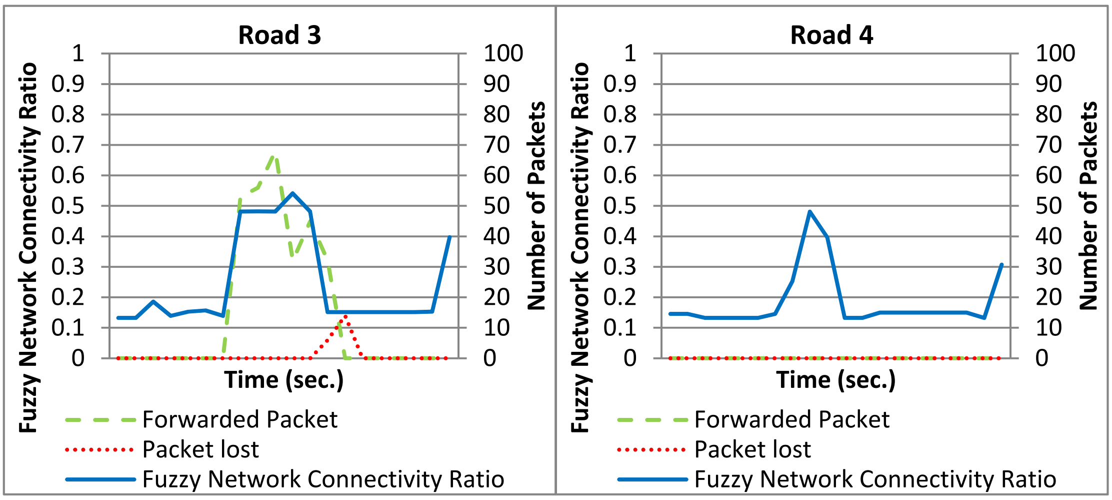

Figure 2.20. Number of forwarded and dropped packets for the selected road segment 3 and road segment 4.

As shown in **Figure 2.17**, the vehicles in road segment 1 and 2 are stopped in about

30 to 60 seconds and 90 to 100 seconds, and the fuzzy network connectivity ratio is reduced during 30 to 60 seconds and 90 to 100 seconds, as shown in **Figure 2.18**. As shown in **Figure 2.19**, the number of vehicles on road segments 3 and 4 is decreased and the average speed is also decreased after 30 seconds. Hence, the fuzzy network connectivity ratio is very low, as shown in **Figure 2.20**.

As shown in **Figure 2.18** and **Figure 2.20**, the results indicate that the average number of forwarded packet is increased when the fuzzy network connectivity ratio is higher and decreased when the fuzzy network connectivity ratio is lower. The average number of dropped packet is low because the packet-forwarding strategy dynamically changes according to the value of the fuzzy network connectivity ratio and the data packets can be forwarded to another road segments with high fuzzy network connectivity ratio. In road segment 4, the fuzzy network connectivity ratio is low and no packets are forwarded, so there no packets are dropped.

Chapter 3

Two-Level Roadside Units Deployment Scheme using GA with Extended Fuzzy Network Stability

3.1 Extended Fuzzy Network Stability for Cellular-VANET Heterogeneous Wireless Network

To decide whether the roadside units (RSU) should be deployed at a specific position, the network stability plays an important factor. If the network stability is always good, it is not necessary to deploy any RSU at specific position. In the Cellular-VANET heterogeneous wireless network, there are two types of communications, i.e., cellular network wireless communication and the other one is VANET wireless communication. Therefore, the factors that affect the network stabilities of cellular networks and VANET are different.

3.1.1. Extended Fuzzy Network Stability

The network stability of VANET depends on the moving characteristic and distribution of vehicles on the road segments, as described in chapter 2. It is also known that the distribution and velocity of vehicles on the road segment are always changing, and it is affected by many factors, e.g., traffic signal, road surface condition, geometry, etc. Hence, the distribution and mobility of vehicles on the road segment is the key factor to decide the network stability of VANET.

On the other hand, the network stability of cellular networks can be determined using received signal strength indicator (RSSI). In cellular networks, the RSSI is a measurement of the signal power when the signal is received by the client. According to [70], the RSSI is affected by various factors in cellular networks, including the distance from cellular network base station to client, environment topography, and obstacle by the building or something, etc. Hence, it is known that the network stabilities of cellular network are different in different geographic positions [71, 72]. Normally, the higher the RSSI value the better communication quality and speed through the base stations.

Hence, to determine the network stability of a certain CDP in Cellular-VANET heterogeneous wireless network environment, the integration of two different network stability characteristics and the classification of them are necessary. It actually is not easy, however, to directly integrate this two different network stability characteristics using an explicit mathematical model. According to [73], the computational intelligence techniques, e.g., fuzzy logic, perform well in classification. Hence, the extended fuzzy network stability is proposed in this section. It is an extension of the fuzzy network stability proposed in chapter 2. Here, it is assumed that the historical data, i.e., average number and velocity of vehicles of each road segment, is available. It is also assumed that the RSSIs at each CDP from the base stations are also available. There are two input variables, i.e., VANET network connectivity (NC) and signal strength (SS) from the base station. The two input variables affecting the network stability are fuzzified, and the output is the fuzzy network stability ratio (FNS). The fuzzy inference is utilized to classify the network stabilities.

3.1.2. Input Variables, Output Variable, and Membership Functions of Extended Fuzzy Network Stability

The VANET network stability depends on the distribution and mobility of vehicles traveling along the road segments. In chapter 2, the fuzzy network stability is proposed, called fuzzy inference based vehicle to vehicle network connectivity model. It calculates the network connectivity of each road segment based on the mobility and distribution of vehicles**.** The output of the fuzzy inference based vehicle to vehicle network connectivity model is taken as the network connectivity (NC) of VANET in this chapter. The wireless communication of VANET is more stable if the value of NC is higher. The vehicles can transmit/receive the data packet through the VANET wireless interface hop-by-hop. There are three linguistic states, including Low, Medium, and High. The linguistic states are defined to represent as members' degrees. The **Figure 3.1** expresses the membership functions of NC.

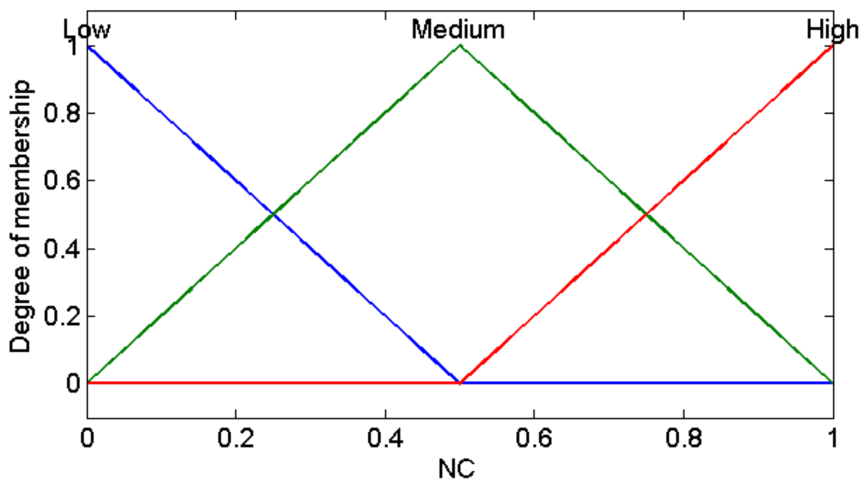

Figure 3.1. Membership function of network connectivity.

The received signal strength indicator (RSSI) from the base station at a certain candidate deployment point is the second input parameter (*SS*). The RSSI is different in different geographic positions. Normally, the typical values of RSSI are -100dBm for a week signal level to -60dBm for a very strong signal level [74]. The definition of dBm is that an abbreviation for the power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW). There are five linguistic states, including Very Weak, Weak, Medium, Strong, and Very Strong. The linguistic states are used to represent as members' degrees. The **Figure 3.2** represents the membership function of *SS*.

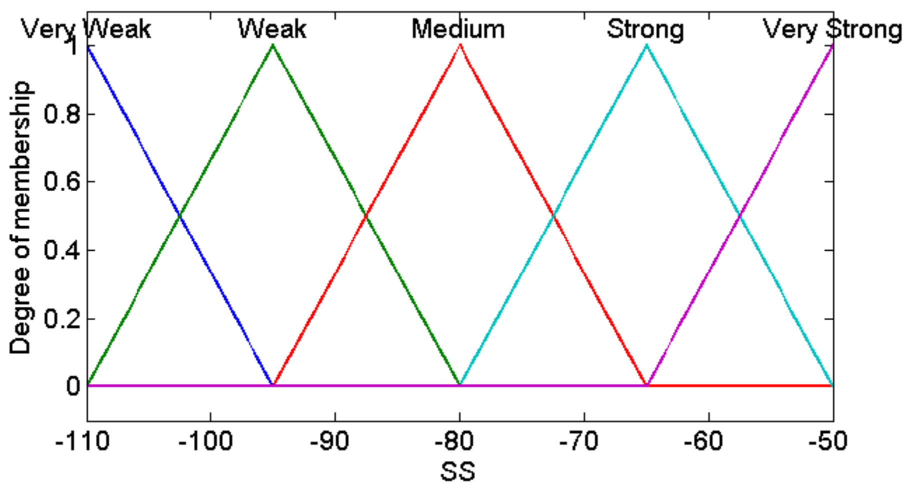

Figure 3.2. Membership function of signal strength.

The output, fuzzy network stability (FNS), must be defuzzified into an explicit single number. After surveying other methods of defuzzification, the centroid method is most suitable and accepted as the method of defuzzification. This is because the centroid method is the most commonly used technique with good performance in e.g., [60, 61]. The centroid method of defuzzification is used, and the fuzzy network stability is calculated as

$$FNS = \frac{\sum_{x=1}^{n} y \times \mu_x(y)}{\sum_{x=1}^{n} \mu_x(y)}, \quad (3.1)$$

where y is the center point of each membership function, and $\mu_x(y)$ is the strength of membership functions. The membership functions, including Very Low, Low, Medium, High, and Very High, of fuzzy network stability are defined and shown as **Figure 3.3**.

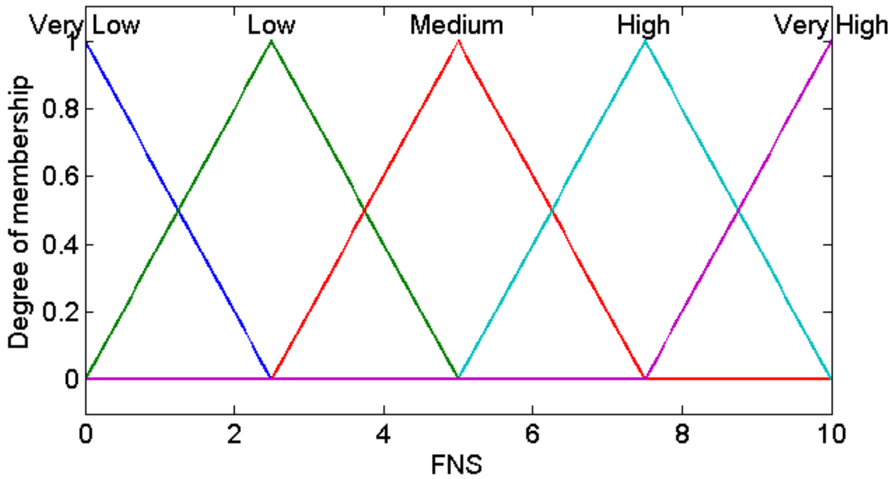

Figure 3.3. Membership function of fuzzy network stability.

3.1.3. Rule-based Fuzzy Inference

The fuzzy inference system is designed using the rule-based fuzzy inferences, or called fuzzy if-then rules. The fuzzy inference is performed based on the defined fuzzy rules to integrate the input variables (NC and SS) and output variable (FNS). 15 fuzzy inference rules are defined totally, shown as **Table 3.1**.

Table 3.1. Fuzzy inference rules of fuzzy network stability.

If			**Then**
Rule	**VANET Network Connectivity**	**Signal Strength**	**Fuzzy Network Stability**
1	Low	Very Weak	Very Low
2	Low	Weak	Very Low
3	Low	Medium	Low
4	Low	Strong	Medium
5	Low	Very Strong	High
6	Medium	Very Weak	Very Low
7	Medium	Weak	Low
8	Medium	Medium	Medium
9	Medium	Strong	High
10	Medium	Very Strong	Very High
11	High	Very Weak	Medium
12	High	Weak	Medium
13	High	Medium	High
14	High	Strong	Very High
15	High	Very Strong	Very High

3.2 Two-Level Roadside Units Deployment Scheme using GA with Extended Fuzzy Network Stability

The 2-level roadside units deployment scheme that is based on the GA with extended fuzzy network stability is described in this section. The deployment scheme aims to find the optimized roadside units deployment strategy based on the extended fuzzy network stability, described in previous section. The deployment of RSUs at a specific position is not necessary if the network at that position is stable enough. It means that if the network stability of VANET is good enough, the vehicles can transfer data packets via vehicle-to-vehicle communications. Similarly, if the signal strength from the base stations is good, the vehicle can transfer the data packets through the cellular network base stations. If the network stabilities of both VANET and cellular network are good at the same time, the vehicle can choose one of the wireless interfaces to access the Internet. It is normally better to access the Internet via VANET wireless interface because the Wi-Fi communication fee is normally lower.

Because the number of possible roadside units deployment strategies is too immense, it is not easy to calculate the wireless communication performance of all combinations of deployment strategies of the urban scenario. As the example scenario shown in **Figure 3.4**, however, all CDPs can be labeled from 1 to n, and the deployment strategy can be considered as a permutation combination of a sequence of 0 and 1. The 0 for RSU is not deployed and 1 for RSU is deployed. Hence, the generic algorithm (GA) can be used to find the optimized deployment strategy based on the proposed fuzzy network stability (FNS).

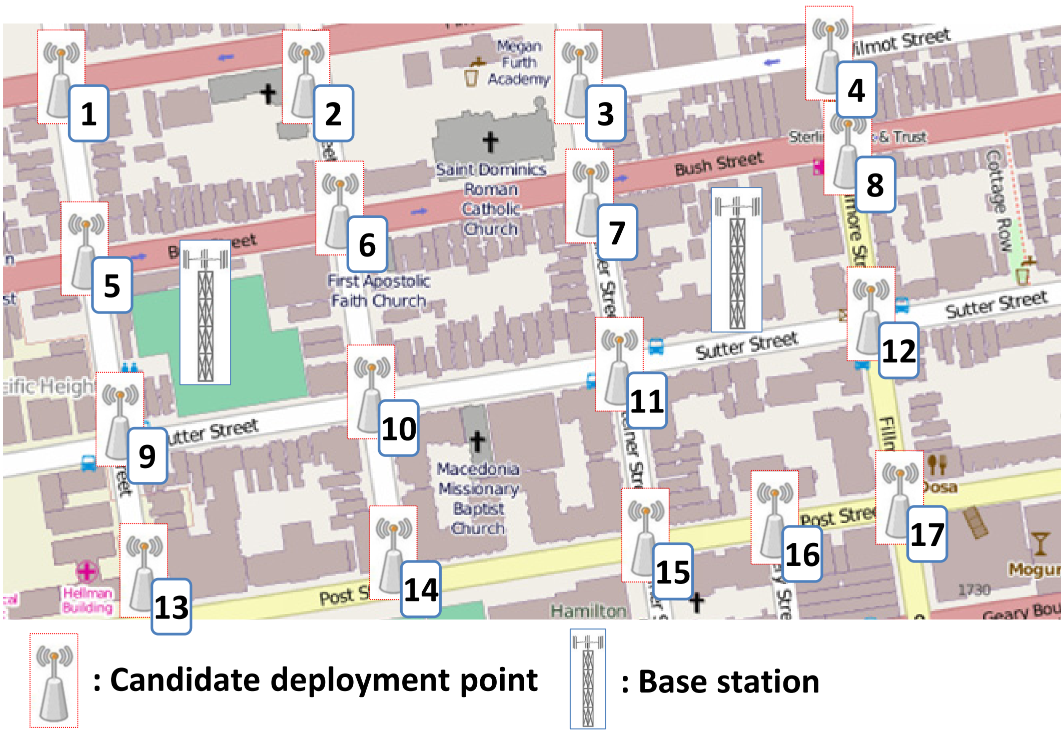

Figure 3.4.   Example candidate deployment positions of RSUs.

3.2.1. Outline of Two-Level Roadside Units Deployment Scheme

The outline of the proposed scheme is shown in **Figure 3.5**.

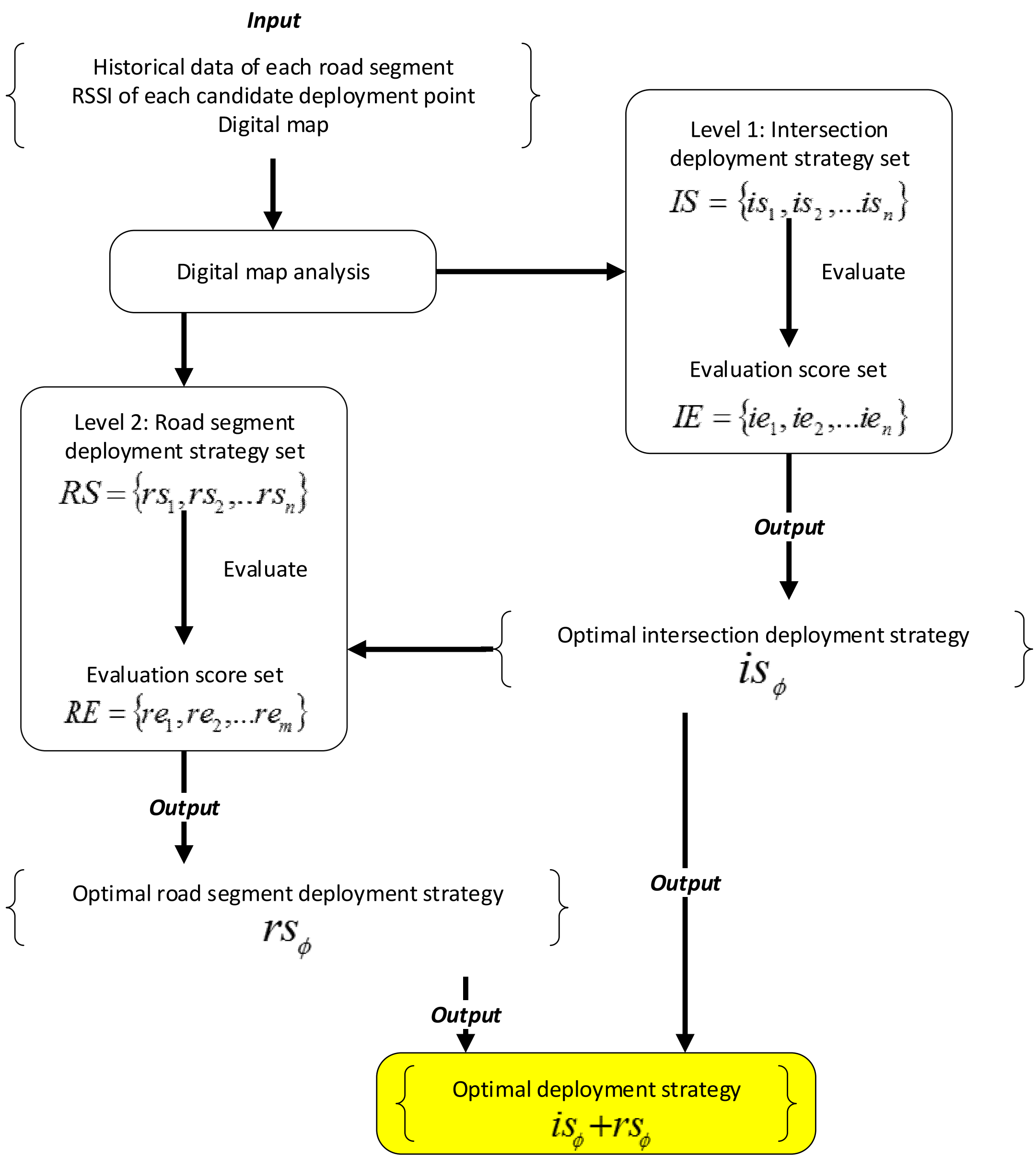

Figure 3.5. Outline of GA with fuzzy network stability based 2-level roadside units deployment scheme.

The proposed scheme includes 2 levels, i.e., intersection deployment optimization and road segment deployment optimization. The reason to divide the deployment into 2 levels is that the intersection always connects multiple road segments; the calculation of the VANET network connectivity of a specific intersection is different with the calculation for road segments. Furthermore, the vehicle will stop at the intersection when the traffic light is red, i.e., spent more time at the intersection, so both of VANET network connectivity and signal strength from base stations are important at the intersection. The vehicle, however, is almost moving when it is on the road segments, it leaves its current position soon. Therefore, the signal strength is not so important for a fixed position of the road segment. Hence, a 2-level deployment scheme is designed. The fitness function is defined based on the fuzzy network stability (FNS) in level 1, and the fitness function is designed based on the VANET network connectivity (NC) in level 2.

For the overall system flow, first, the inputted digital map is analyzed to decide all of the CDPs. Then, based on the input data, which consists of historical data of each road segment, RSSI of each CDP, and digital map, the proposed scheme produces various intersection deployment strategies in level 1, called intersection deployment optimization. These intersection deployment strategies can be expressed as a set $IS = \{is_1, is_2, ...is_n\}$, where each element of the set IS describes an intersection deployment strategy. An evaluation set $IE = \{ie_1, ie_2, ...ie_n\}$ is generated for the set *IS*, where ie_i represents the corresponding evaluation score of intersection deployment strategy is_i. An optimal strategy is_φ, which has the maximum evaluation score ie_φ, can be found.

Then, the output of intersection deployment optimization, i.e., optimal intersection deployment is_ϕ, is used as the input of level 2, called road segment deployment optimization. The same with level 1, the road segment deployment strategies can be expressed as a set $RS = \{rs_1, rs_2, ...rs_m\}$, where each element of the set *RS* describes a road segment deployment strategy. Also, an evaluation set $RE = \{re_1, re_2, ...re_m\}$ is generated for a set *RS*, where re_i represents the corresponding evaluation score of road segment deployment strategy rs_i. The optimized road segment deployment strategy rs_φ, can be obtained. Finally, the optimal deployment strategy, including is_φ and rs_φ, is obtained. The detail of digital map analysis, intersection deployment optimization, and road segment deployment optimization are described in the following subsection.

3.2.2. Digital Map Analysis

The first step of the GA with fuzzy network stability based 2-level roadside units deployment scheme is digital map analysis. It is executed to decide the basic positions of CDPs. First, all intersections are labeled from left to right and from up to down, shown as **Figure 3.4**. Then the transmission coverage of each CDP is compared. If the transmission coverages of two CDPs are overlapped, and they are in a straight line, then the CDP with larger label numbers will be removed from the CDPs list.

For example, as shown in **Figure 3.6 (a)**, the transmission coverage of CDP_2 is overlap with the CDP_1's, so the CDP with larger label numbers, i.e., CDP_2, is removed from the CDPs list. After the digital map analysis, the example result is shown as **Figure 3.6 (b)**. Although some of the road segments are not completely covered by RSUs if some CDPs are removed, the vehicles travel on those road segments still can access the Internet via the cellular network or V2V communication.

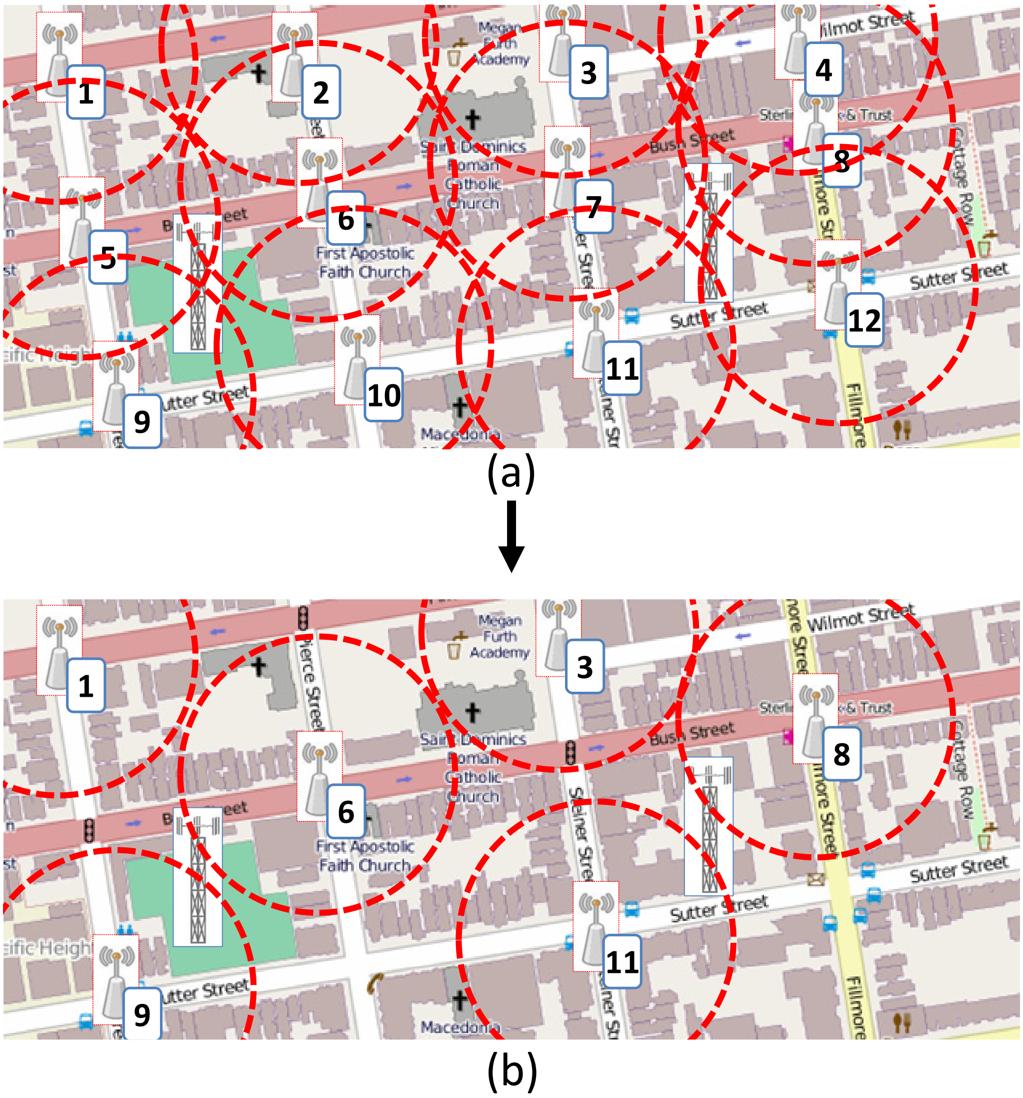

Figure 3.6. Example of digital map analysis, (a) before digital map analysis, (b) after digital map analysis.

3.2.3. Level 1: Intersection Deployment Optimization

Because the vehicles will certainly go through the intersections when it wants to travel to a specific destination and stop at the intersections when the traffic light turns to the stop signal. Therefore, the intersections are considered as the most important locations to deploy the RSUs. The objective of level 1 is to optimize the deployment of RSUs at the intersections.

The genetic algorithm is used to optimize the intersection deployment strategy of RUSs. Supposing 0 means the RSU is not deployed and 1 means a RSU is deployed at a specific CDP. The intersection deployment strategy is encoded into a chromosome comprised by a sequence of 0 and 1, as shown in **Figure 3.7**. Each bit represents whether a RSU is deployed at the CDP. The chromosome represents an intersection deployment strategy is_i in the areas. The chromosomes in the initial populations are generated randomly. Multi-point crossover is used to generate new generations of chromosomes. After generating new chromosomes, mutation process is performed. The mutation process involves the codes changing at randomly chosen points, from 0 to 1 or from 1 to 0, based on a mutation rate. It can avoid the situation of local optimum.

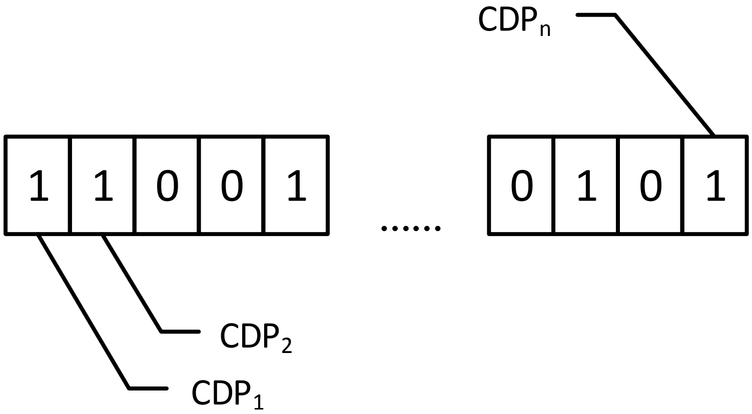

Figure 3.7. Encoded chromosome for an intersection deployment strategy.

One intersection may connect to multiple road segments, called adjacent road segments. For example, the CDP_6 connects to 4 road segments in **Figure 3.6**, so there are 4 adjacent road segments. The VANET network connectivity (NC_i) of a specific intersection i is the average of the network connectivity of each adjacent road segment. It is calculated as

$$NC_i = \frac{\sum_{r=1}^{n} NC_r}{n}, \qquad (3.2)$$

where NC_r is the VANET network connectivity of the adjacent road segment r, and n denotes the total number of adjacent road segments that connects to the intersection i. Then, the *FNS* of each CDP can be calculated using fuzzy network stability proposed in **section 3.1**. After generating new chromosomes, all RUSs deployed at the intersection are considered as the vehicles with maximum velocity on each adjacent road segment. The VANET network connectivity (NC_i) of each road segment and intersection are re-calculated for the next generation. The GA is executed to optimize the deployments, and it will stop if no different deployment strategy is generated after a fixed number of generations.

To evaluate each new intersection deployment strategy generated by the genetic algorithm, the fitness function is defined as

$$fitness = \sum_{i=1}^{m} FNS_i - d. \qquad (3.3)$$

The m here represents the total number of CDPs, FNS_i means the fuzzy network stability of CDP_i, and d is the number of RSUs deployed.

3.2.4. Level 2: Road Segment Deployment Optimization

After deploying the RSUs at all necessary intersections, level 2 road segment deployment optimization is performed. As shown in **Figure 3.5**, the output of level 1 is used as the input parameter. It is used to check whether the deployment of RSUs on the specific road segment is necessary. The road segment that needs to be deployed RSUs, called candidate road segment, is inserted into candidate road segment list. One candidate road segment may include multiple CDPs. If the length of road segment is smaller than two times as long as the transmission range and the RSUs are deployed at two adjacent intersections, the road segment will be fully covered by the transmission range of the two RSUs. In this situation, the deployment of the RSUs on the road segment is not considered. The road segment is removed from the candidate road segment list. Hence, only the road segments that are not wholly covered by the transmission range of RSUs will be considered to deploy the RSUs. Then, the deployed RSUs in level 1 are considered as vehicles with maximum speed, and the VANET network connectivity of each road segment is calculated.

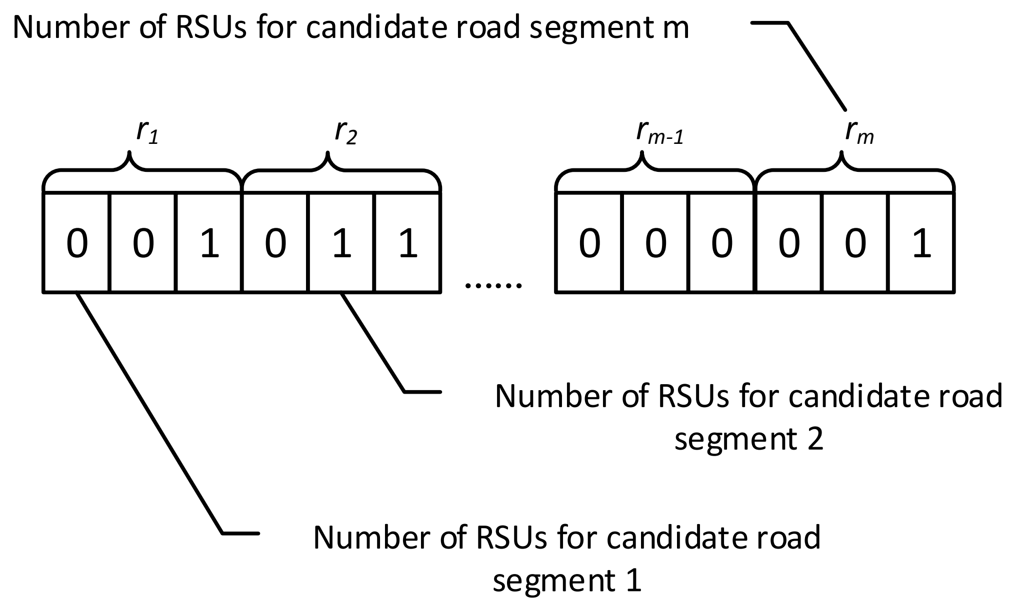

Figure 3.8. Encoded chromosome for road segment deployment strategy.

In level 2, the number of deployed RSUs on the candidate road segment is adjusted based on the VANET network connectivity. The chromosome is encoded for all candidate road segments stored in the candidate road segment list. The numbers of deployed RSUs at the candidate road segment are represented as three bits binary numbers, shown as **Figure 3.8**. As shown in **Figure 3.8**, for example, 1 RSU is deployed on the road segment 1, 3 RSUs are deployed on the road segment 2, and so on. If only one RSU is deployed, it will be deployed in the center of the road segment. If two RSUs are deployed, they will be deployed to divide the road segment into three equal parts. Therefore, if there are *n* RSUs deployed, they will be deployed to divide the road segment into *n*+1equal parts. In this proposal, the maximum value of *n* is 7.

The same with level 1, the chromosomes in the initial populations are generated randomly. The multi-point crossover and mutation process are executed to optimize the deployment strategy. In this step, the RUSs deployed on the road segment is also considered as vehicles with maximum velocity. The VANET network connectivity (NC_i) of each road segment is calculated after generating new chromosome. The fitness function, defined as

$$fitness = \sum_{r=1}^{m} NC_r - d, \qquad (3.4)$$

is used to evaluate the new chromosome. The NC_r is the VANET network connectivity of road segment *r*, and d is the total number of deployed RSUs. The *m* is the total number of candidate road segments. Because the value of NC_r is from 0 to 1, the value of fitness will be much smaller when more RUSs deployed. The chromosome with highest fitness value is the best deployment strategy.

3.3 Roadside Units Deployment Simulation, Network Transmission Simulations, and Discussions

The simulations and various performance analyses are conducted to verify the efficiency of the proposed road side unit deployment scheme in this section. Various deployment strategies, including no road side units deployment, fully deployment strategy, level 1 only deployment, level 1+ level 2 deployment, the hybrid approach in [43], and D-RSU deployment policy [44], are compared.

3.3.1. Experiment Environment and Network Simulator Setting

It is assumed that each vehicle is equipped with OBUs that contains dual communication interfaces in this proposal: the first one is a VANET wireless interface, and the second one is a cellular network interface (e.g., LTE). Each vehicle uses its VANET interface to communicate with its neighboring vehicles and RUSs. The VANET wireless link can only be established if the distance between two nodes is less than their transmission range. Furthermore, each vehicle uses its cellular network interface to connect to the cellular networks. When one vehicle wants to transfer data packets, it can choose one of the two communication interfaces. In the simulation, if the data packets cannot be transferred directly to RSUs or forwarded via other neighboring vehicles to RSUs, the vehicle will transfer the data packets through cellular networks. Similarly, after a vehicle receives data packets from another vehicle, it also can choose one of the two interfaces to forward it. It is also assumed that the average number of vehicles, average speed of each road segment, and the RSSI at each candidate deployment point can be obtained from historical data, which is randomly generated for the simulation.

The open source tool NS2 (Network Simulator 2) is used to simulate the wireless data transmission. The TraNS (Traffic and Network Simulation Environment) and the digital map, obtained from OpenStreetMap [75], are used to generate more realistic mobility trace of vehicles with a random routes generation module. The digital map used in the simulation is San Francisco city, shown as **Figure 3.9**. The source codes of TraNS are modified to make it compatible with the latest version of the simulation of urban mobility (SUMO). The traffic density for different road segments and travelling speed of vehicles for different routes are randomly generated using TraNS and SUMO according to the different setting of vehicle numbers. The generated vehicle movement trace data is used as the historical data and experimental data for the simulation.

The programming language used is C++ and Tcl/OTcl in NS2. Each vehicle is equipped with a VANET wireless interface with a transmission range of 250m. The number of vehicles considered in this simulation varying between 200 and 400. Four topology sizes, including 1000m x 1000m, 2000m x 2000m, 3000m x 3000m, and 4000m x 4000m, are simulated. All vehicles are travelling at an average velocity between 0 and 80 km/h. Four cellular network base stations are deployed with cell sizes 5 km. The maximum connection number is limited to 150 for vehicles for the reason that the resources of base stations are shared with normal mobile device, such as mobile phones, in a realistic urban environment. If the connection number is larger than the limit, the data packet will be dropped. The important simulation parameters used in the simulations are summarized in **Table 3.2**.

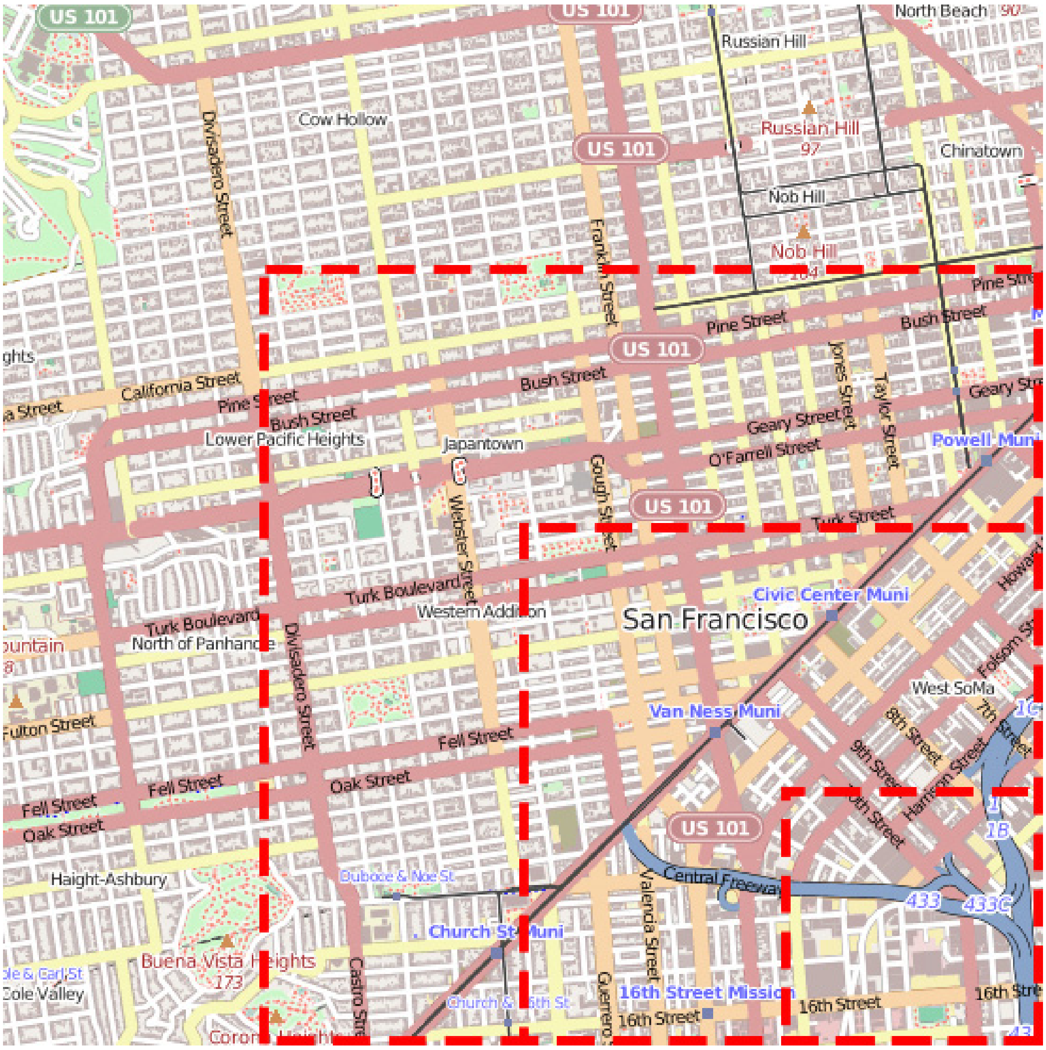

Figure 3.9. Digital map of San Francisco city obtained from openstreetmap.

Table 3.2. Network simulator parameters.

Parameter	Value
Simulation Time	300 Sec.
Topology Size	1000m x 1000m, 2000m x 2000m, 3000m x 3000m, and 4000m x 4000m
Number of Vehicles	200~400
Source	Random (200~400 connections/second)
Destination	Road side units or base station
Propagation Model	Two-ray ground
Transmission Range of VANET Wireless Interface	250 m

Cell Sizes of Base Station	5 km
Data Packet Type	Constant Bit Rate
Packet Size	512 bytes
Packet Rate	8 packets/second per. connection

The performance of the proposed scheme is evaluated by varying the size of topology, vehicle numbers, and deployment types. Various deployment strategies are compared, including no road side units deployed, the road side units fully deployment, level 1 only deployment, level 1 + level 2 deployment, the hybrid approach, and the D-RSU deployment policy. The fully deployment means the RSUs are fully deployed to cover all of the road segments to provide a seamless communication environment. The level 1 only means only level 1 optimization, i.e., intersection deployment optimization, of the proposed scheme is performed. The hybrid approach in [43] first selects RSU candidates with a manner of its greedy approach, then it applies the dynamic approach to optimize the number and position of RSUs. The detail algorithm of hybrid approach is shown in the algorithm 3 in [43]. The D-RSU deployment policy [44] places RSUs using an inverse proportion to the expected density. For example, if authorities have in mind to deploy a total number of 100 RSUs in the urban area, and the expected traffic density in a specific area of this city is about 60% of the vehicles, according to the D-RSU deployment policy, 40% of RSUs should be installed there, and the rest of the RSUs should be deployed in the rest of the area. Various metrics are used to verify the performance, including the number of RSUs indicating the deployment cost, loading of base station, and data packet delivery ratio.

3.3.2. Simulation Results and Discussions

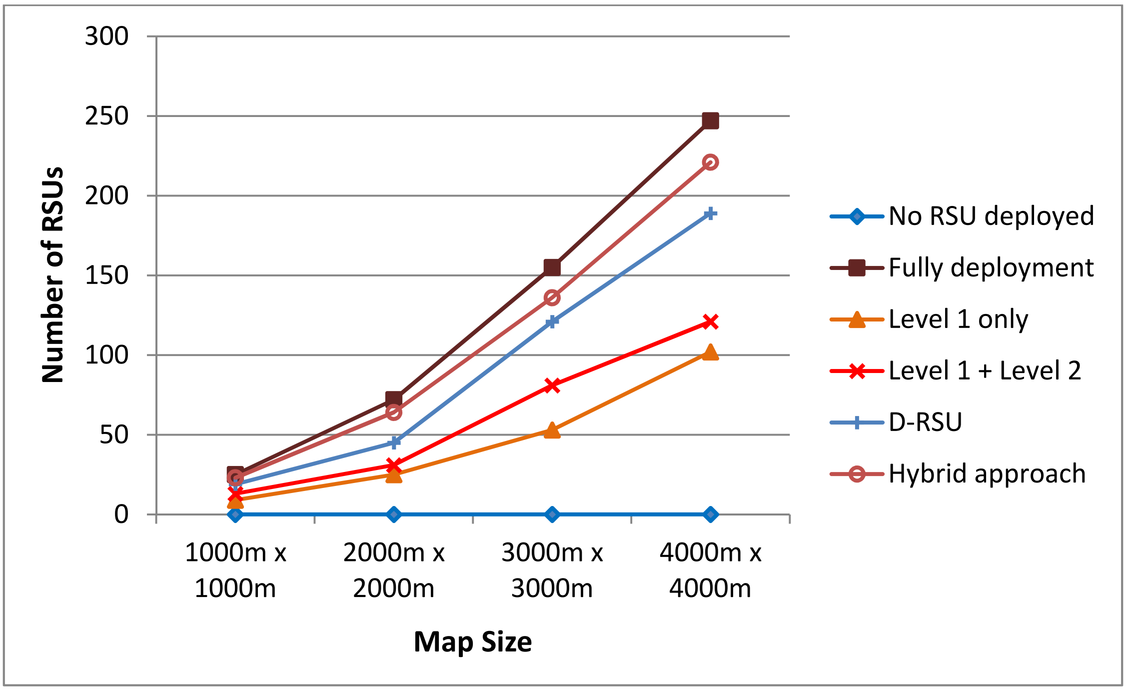

Figure 3.10. Number of RUSs deployed in different map sizes.

The comparison of the number of deployed road side units in different map sizes, including 1000m x 1000m, 2000m x 2000m, 3000m x 3000m, and 4000m x 4000m, and different deployment types is shown in **Figure 3.10**. As can be seen, the result shows that a lot of RSUs are necessary to fully cover all road segments to provide better connectivity. Of course, the numbers of deployed RSUs are increased if the map size is increased. Because the D-RSU and hybrid approach did not consider the network stability of VANET and cellular network, the decreased numbers of RSUs are not so much. After the level 1 optimization is performed, the numbers of deployed RSUs are significantly reduced, and it is smaller than one-half of fully deployed result.

As shown in **Figure 3.11** and **Figure 3.12**, however, the results show that after optimizing the deployment of RSUs on each road segment, the network performance is better than just level 1 optimization used. This is because that after executing the level 2 optimization, RUSs is deployed at some road segments whose network stability is not good. Therefore, it is clear that the 2-level road side units deployment scheme can produce a much better performance. Furthermore, because the proposed scheme considers the signal strength of base station, it decreases the number of deployed RSUs more than the result of D-RSU. The number of deployed RUSs in 2-level deployment is a little larger than only level 1 optimization performed.

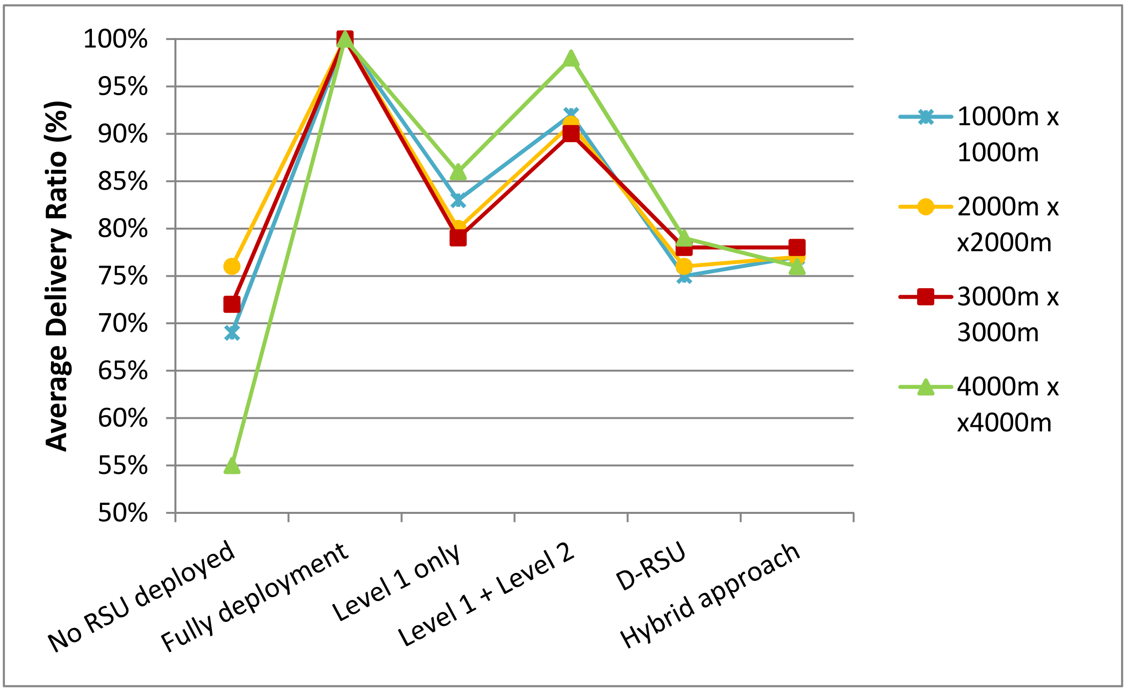

Figure 3.11. Average delivery ratio in different map sizes.

The number of vehicles in the comparison of **Figure 3.11** and **Figure 3.12** are 300. The result in **Figure 3.11** shows that if there are no RSUs deployed, the delivery ratio is poor. This is because the connection number over the maximum connection limit of the cellular network base stations. Some of the data packets will be dropped if the total connection number is larger the connection limit of base stations. When the RSUs are fully deployed, almost all vehicle transfers directly the data packets through the RUSs, rather than through the cellular network base stations. Hence, the delivery ratios are almost 100%. To fully deploy RSUs, however, it will cause more deployment costs, as shown in **Figure 3.10**. The delivery ratio is increased by using proposed scheme because it optimized the deployment of RSUs according to the network stabilities. One of the two communication interfaces is selected to transfer the data packets. The D-RSU deploys RSUs based on only the density of vehicles. The network stability of VANET or cellular network is not considered in the D-RSU, so the packets are dropped when the network is not stable enough. For the same reason, the result of hybrid approach is almost the same with the D-RSU.

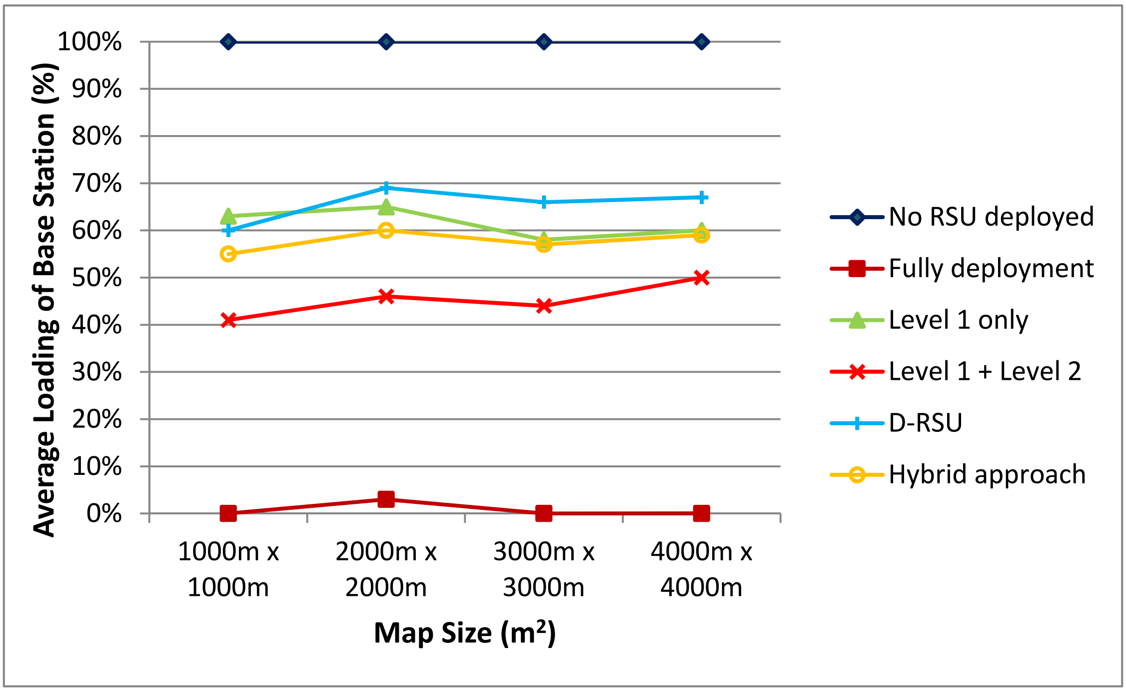

Figure 3.12. Loading of base station in different map sizes.

In **Figure 3.12**, the comparison of the loading of base station is represented. 100% means the number of the data packets transferred to the base station is larger than connection limit of the cellular network base stations. It is shown that if no RSUs are deployed, all of the vehicles will access the Internet via cellular network; therefore, the loading of base station will be 100% in this situation. In contrast, if the RSUs are fully deployed, almost all of the data packets are transferred through the RSUs; hence, the loading of the base station is close to 0. The D-RSU decreases the loading of base station by only about 30% because it did not consider the network stability. The level 1 only deployment decreases the loading of base station about 40% because the network stability is considered for the deployment of RSUs. Some of the data packets are transferred via RSUs, rather than base station. The hybrid approach gets better results than level 1 only by deploying more RSUs. The 2-level road side units deployment scheme decreases the loading more than 50% because the RSUs are deployed on the road segments whose network stability is not good. More data packets are transferred directly though the RSUs when the VANET network connectivity is stable.

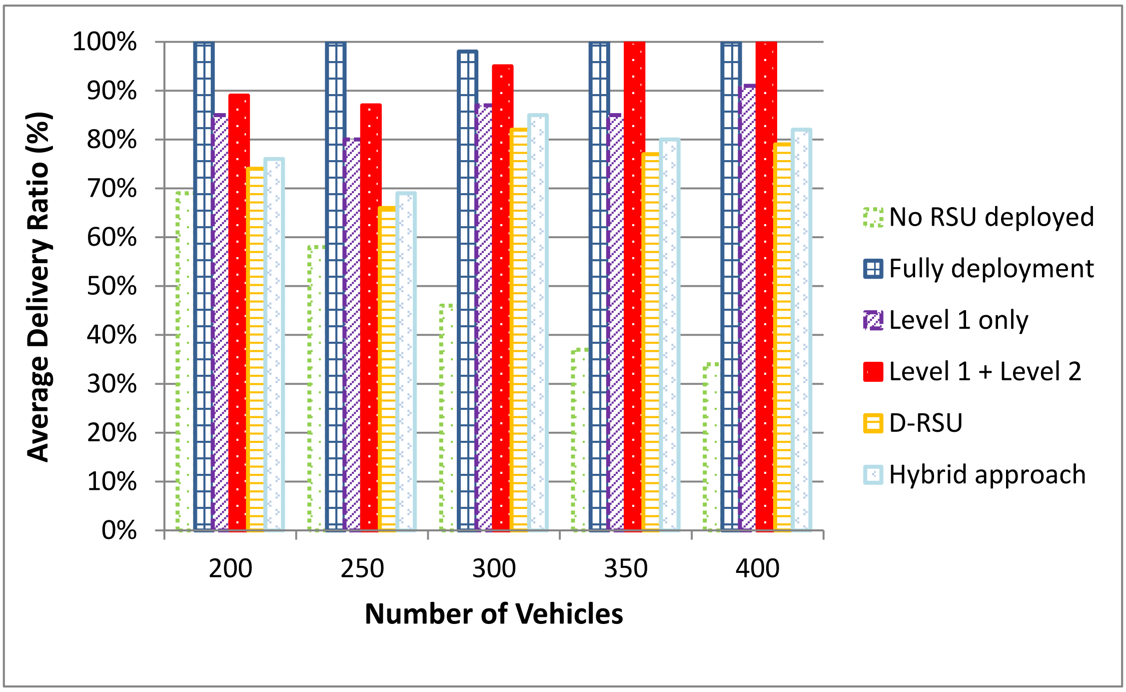

Figure 3.13. Delivery ratio in different number of vehicles.

The comparison of delivery ratio in different number of vehicles is shown in **Figure 3.13**. The map size of this comparison is 3000m x 3000m. As shown, the average delivery ratios of no RSUs deployed are significantly decreased when the numbers of vehicles are increasing. The results of D-RSU and hybrid approach are not stable, and their average delivery ratio is close to 75%. On the other hand, the proposed scheme provides a high delivery ratio because it deploys RSUs at necessary positions only. When the number of vehicles is larger than 350, the delivery ratio is almost the same as fully deployment.

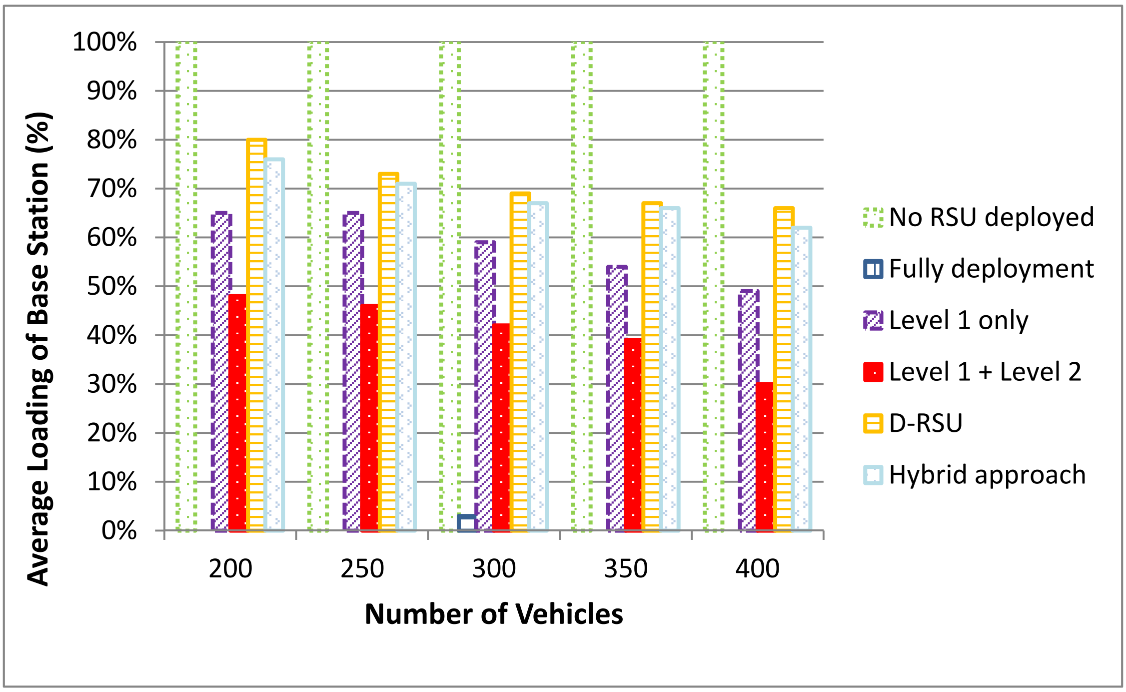

Figure 3.14. Loading of base station in different number of vehicles.

Furthermore, the proposed scheme decreases the loading of base station. The loading of base station decreases as of the number of vehicles increases, shown as **Figure 3.14**. If just using level 1 optimization, the loading is decreased about 50%. After the level 2 is performed, it can decrease the loading of base station more than 60%.

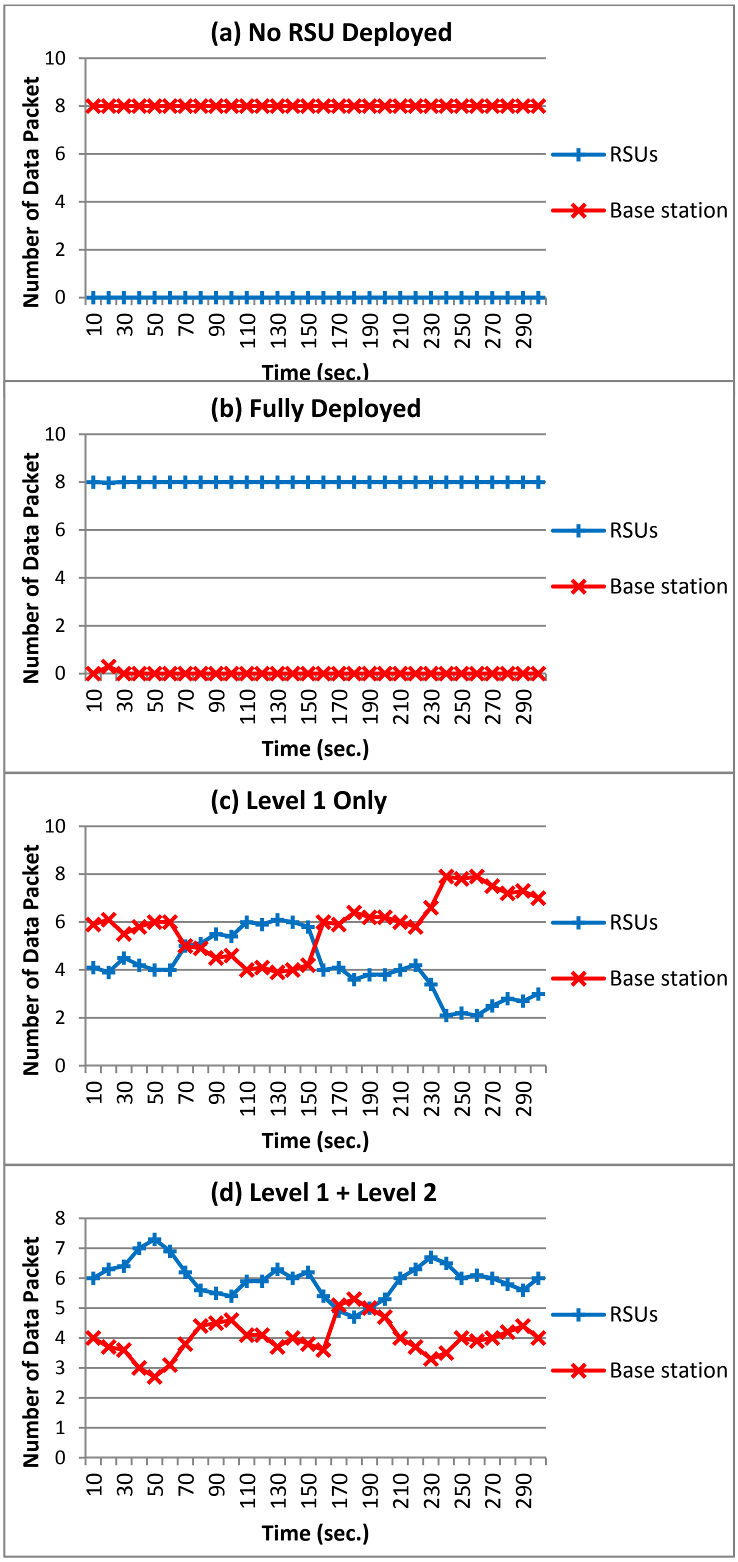

Figure 3.15. Number of data packets transmit to roadside units and base station.

For further discussion, the interfaces used to transfer data packet are analyzed, as shown in **Figure 3.15**. One of the vehicles is selected to be analyzed. In this analysis, the map size is 3000m x 3000m, and the total numbers of vehicles are 300. The result, shown as **Figure 3.15 (c)**, shows that after level 1 optimization, the data packets transmitted to the base station are decreased. During 150 seconds to 300 seconds, however, the packet number transferred to the base station is much larger than RSUs. This is because the vehicle is going through some road segments that not covered by any RSUs and the VANET connectivity also not good. Hence, the vehicle transfers the data packets via cellular network. As shown in **Figure 3.15 (d)**, after optimizing the deployment of RSUs on each road segment, the packets transferred via VANET interface are increased. Therefore, the loading of the base station can be further decreased.

According to the results shown above, after extending the roadside units deployment problem from VANET environment into cellular-VANET heterogeneous wireless network environment, the deployment cost can be further reduced. Furthermore, the network will be more stable because two communication interfaces exist. Some gateway selection method [48, 52] can be used to make the network loading more balance.

Chapter 4

Common Driving Notification Protocol based on Classified Driving Behavior for Cooperation Intelligent Autonomous Vehicle

A real-time optimal-drivable-region and lane detection system for autonomous driving [76] is proposed to ensure that the vehicle is driven safely in any kind of road conditions and tested using standalone autonomous vehicle. A real-time path-planning algorithm [77] provides an optimal path for off-road autonomous driving with static obstacle avoidance and is applied to the autonomous vehicle for testing. The VisLab's approach [78] for autonomous cars, including considerations on hardware and software, provides high integration level and a low-cost sensor suite, which are mainly based on vision. An environment-detection-and-mapping algorithm for autonomous driving in [79] shows good performance in obstacle detection using a standalone test vehicle. An optimization-based path planner [80] addresses the particular problem of probabilistic collision avoidance for autonomous road vehicles, and it allows for a more aggressive driving style than planning a single path without compromising the overall safety. Although the previous studies propose various algorithms for autonomous driving, it is still not enough. The driving behavior of vehicles driving on the road is always affected by other vehicles. However, the autonomous driving proposed in previous researches [76, 77, 78, 79, 80] are standalone, and the driving decision information of other vehicles is not considered. That means autonomous vehicles did not cooperate with each other to make a more suitable driving decision. The cooperation means transfer/receive information to/from other vehicles and adjust their driving decisions. According to [3], we can know that 60 percent of accidents could be avoided if the vehicle were provided with information half a second before the moment of collision. To realize the autonomous driving in our daily life, the cooperation between vehicles is necessary. To achieve cooperation, the most important thing is driving information exchange. On the other hand, the vehicular ad-hoc network (VANET) [12, 13, 14, 15, 16, 17, 18, 19, 20] provide the capability for vehicles to communicate with each other. The emergency message [17] is proposed to provide emergency warning. However, the accident warning is just a part of the reason affecting the driving decisions of vehicles. In [81], the vehicle control algorithms for cooperative driving is proposed. The four trajectory planning algorithms [82] determine the driving plans to avoid collision at crossings using inter-vehicle communication. The cooperative driving in [81, 82] can satisfy special situations and usages. However, to achieve autonomous driving in various driving situations, more detail driving information and standardized common protocol for each car manufacturer are necessary. The normal driving decision information of other vehicles is the key for autonomous vehicle to make a more suitable driving decision and avoid accidents. If the emergency warning message is considered as the treatment, the normal driving information will be the prevention. There is, however, no standard protocol to disseminate the normal driving decision information for autonomous driving to improve the driving safety and achieve cooperated autonomous driving. Therefore, the objective of this proposal is to propose a common message protocol for autonomous vehicles.

4.1 Common Driving Notification Protocol (CDNP)

4.1.1. Concept and Objective of CDNP

The main reason causing the car accident is unsafe driving, e.g., changing driving lanes without making sure there are no cars next to itself, changing its driving speed suddenly, and turning the driving direction without any signal. The driving decisions of vehicles are always affected by other vehicles. Therefore, the cooperative driving is necessary.

The human driver can notify other driver about his/her driving actions by flashing the car light or sounding the horn. The human driver can also determine the driving actions of other vehicles by identifying the car light signal of other vehicles or hearing the sound of the horn. For the autonomous, however, the image processing algorithm is necessary to identify the car light, and the digital audio processing algorithm is necessary to identify the horn. These algorithms may not work well if the environment is full of interference, e.g., heavy rain, noise environments. When one autonomous vehicle perform its driving decision, if it is possible to notify other autonomous vehicle about the driving decision using another support method, the autonomous driving environment will be safer.

As described in chapter 2 and chapter 3, it is known that vehicles can communicate, i.e., V2V communication and V2R communication, with each other via VANET technology [7, 8, 9, 10, 11]. Those VANET technologies can be utilized to realize the communication between vehicles.

To achieve the cooperative driving, the most important thing is to let vehicle efficiently identify the driving decision of other vehicles. Just like as the human driver can judge the information from the car light. Hence, the CDNP is proposed to make the notification more reliable and efficient.

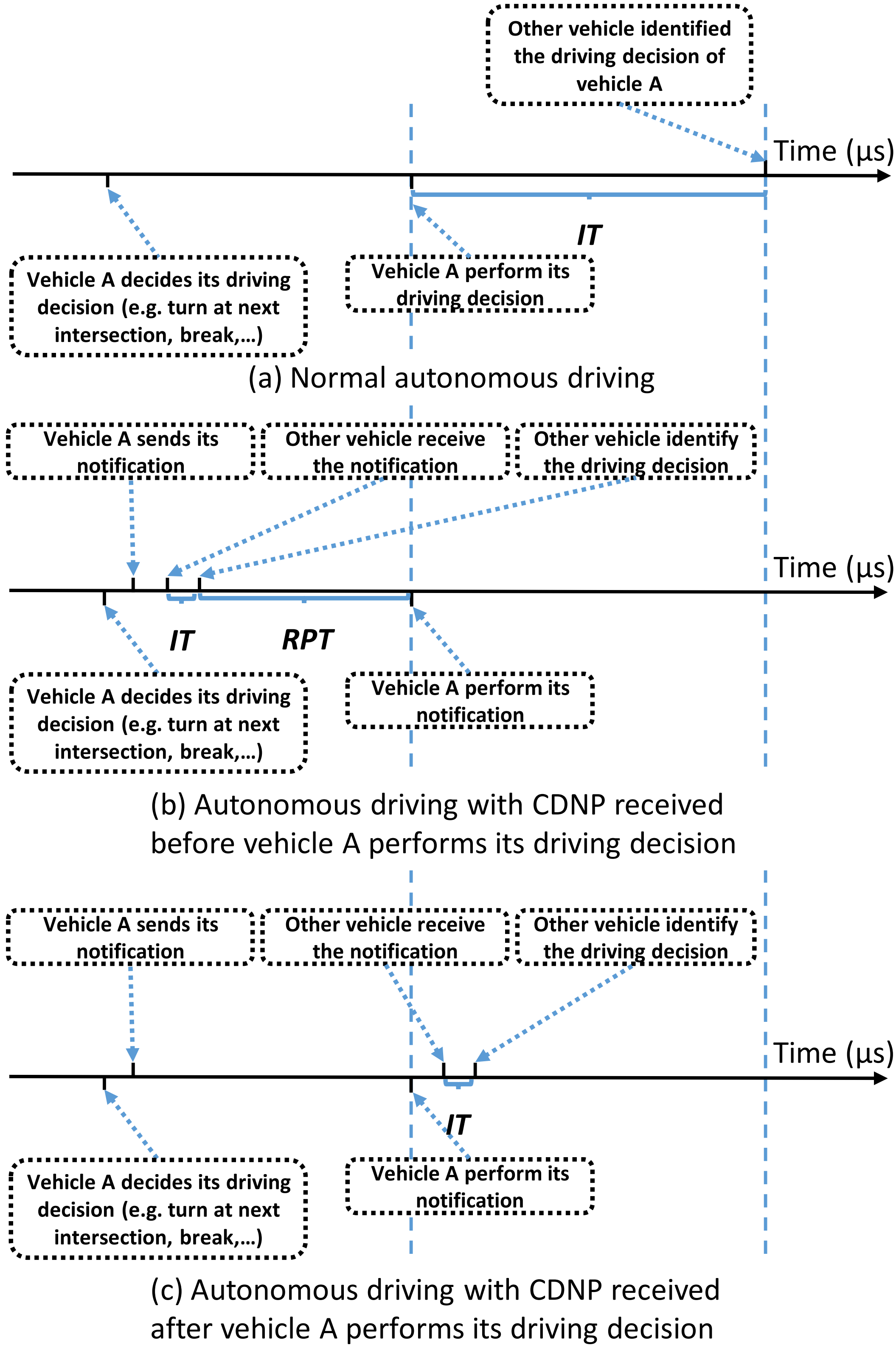

Figure 4.1. Comparison between normal autonomous driving and autonomous driving with the common driving notification protocol (CDNP).

In **Figure 4.1,** the comparison between normal autonomous driving and autonomous driving with CDNP is shown. It is shown that a longer processing time delay is necessary for other vehicles to identify the driving decision of vehicle A using its sensors and the image processing/ digital audio processing algorithm. The CDNP is designed to be immediately transferred just after the driving decision is decided. If the CDNP packet is received by other vehicles before the driving decision is performed, there will be enough processing time for the autonomous driving system to make a suitable control of the vehicle. Even though the CDNP packet is received after the driving decision of vehicle A is performed. The identification time (IT) will still shorter than the image / digital audio processing time. In the worst case, if the CDNP is received after the image / digital audio algorithm finished. The autonomous vehicle can still use the result obtained from the algorithm. Therefore, the CDNP provides another reliable method to identify the driving decisions of other vehicles. In this proposal, it is focus on the CDNP notification. The autonomous driving control, e.g., obstacle avoidance, keep a safe distance, decision conflicts avoidance, is out of range of this thesis.

4.1.2. Architecture of CDNP

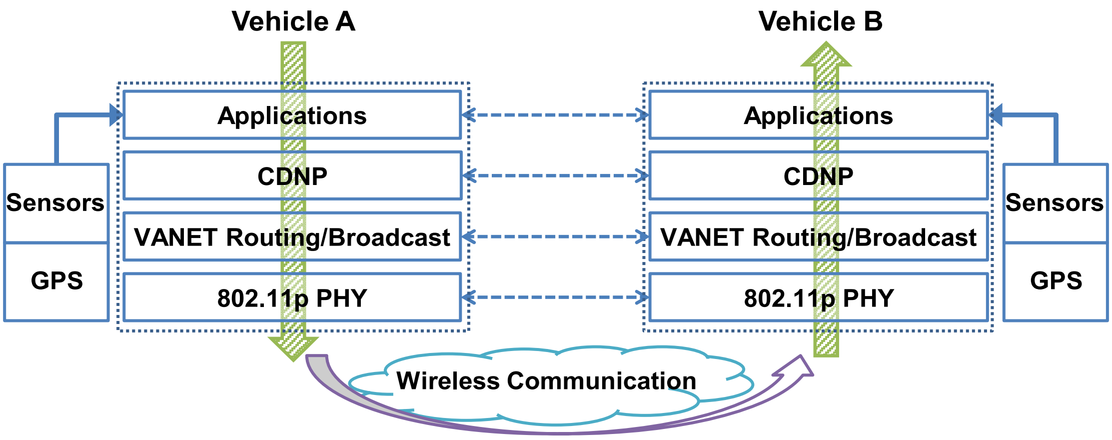

Figure 4.2. Architecture of the common driving notification protocol (CDNP).

The architecture of CDNP is shown in **Figure 4.2**. The Common Driving Notification Protocol (CDNP) is proposed based on classified driving behavior and designed below the application layer. The position of CDNP is designed to compatible with the facilities layer of ITS station architecture standardized in ISO/ETSI [83]. The function of CDNP is to provide the application support and information support. Therefore, it is easy to integrate the CDNP into the architecture of ITS. It plays an important role to make the vehicle understand what the other vehicles notify. The CDNP is designed to exchange common messages between vehicles using the VANET technology, including routing protocols, broadcast protocols, or unicast. The VANET beacon mechanism, i.e., basic safety message (BSM) [84, 85, 86, 87], is enabled so that each vehicle can know the related geographic position, velocity and direction of neighboring vehicles. The beacon messages are periodically exchanged with neighboring vehicles in a broadcast function. The information contained in the beacon message can be temporarily stored in the memory space of the vehicle received the message. The related position information is used for the vehicle to decide the destination of the CDNP packet.

When one vehicle wants to perform some driving decisions, such as changing the driving lane, driving direction, speed, etc., the autonomous driving system can create the CDNP message, including the type and code, according to the corresponding driving decision. Then, the CDNP message is stored in the CDNP header. The vehicles that send the CDNP packets are called source vehicles (SV), and the vehicles received the CDNP packets are called the current vehicles (CV) in this proposal. First, the CDNP header is encapsulated for data routing or broadcasting, and then, it is encapsulated into MAC frame. Finally, The CDNP packet is transmitted via VANET wireless interface, e.g. 802.11p. After one vehicle receiving the CDNP packets, it can de-capsulate the packets, resolve the notification using the cooperative driving control system installed in its vehicle telematics system, and decide some reactions, e.g., sent a reply CDNP packet. Under the CDNP layer, some protocols can be used to ensure the data reliability of VANET wireless transmission, e.g., [88]. Normally, the CDNP is used to notify the other vehicles near to itself using unicast or broadcast. It, however, can also be transferred to remote vehicles for special usage, e.g., traffic management of specific roads by urban traffic management system. The urban traffic management center can use the CDNP to manage the traffic flow of the urban area; in this case, the CDNP packets will be transferred to specified vehicles on specified road segment using VANET routing protocols, and the location service [66] is used to determine the destination. The traffic management is not discussed in this thesis.

4.1.3. Header Format of CDNP

Table 4.1. Formats of header fields of CDNP packet.

0	8	16 31
Type	Code	Checksum
Optional Data		

To make the vehicles understand what another vehicle notifies, a specific common message format is necessary. Therefore, the format of the header fields of CDNP packets is defined and shown as **Table 4.1**. The different types and codes are simultaneously used to identify different driving notifications in CDNP. The value of type field indicates the different main categories of driving decisions. Each type includes its corresponding codes to indicate which driving decision the vehicle wants to notify. The same with many Internet protocols, the checksum here is also used for error checking and verifying the correctness of packets. The value of checksum is calculated from the type field of the CDNP packet to the end of optional data optional data. The length of optional data field is varied according to the value stored in type and code. This makes the CDNP flexible and extendable.

4.1.4. Types and Codes of CDNP Header

In **Table 4.2**, all types and codes defined in the CDNP are listed, including its types, type names, descriptions, codes, and code names. There are totally 9 types. They are defined based on classified driving behavior. They can be classified into four main categories: special type (type 0x00), different driving behavior (from type 0x01 to type 0x05), vehicle emergence warning information (type 0x06 and 0x07), and urban traffic management (type 0xFF). For each type, different corresponding codes are defined according to different driving decisions, descripting in the following. The CDNP packet contained type n and code m is denoted by $CDNP_{(n, m)}$ packet and called type n code m CDNP packet.

Table 4.2. Types and codes of CDNP packet.

Type	Type Meaning	Description	Code	Code Meaning
0x00	Special type	Reserved for special types of vehicles, such as police car, ambulance, fire engine, etc. It is only set for emergency situations, e.g., pursuing an escaped prisoner, and cannot be used by normal vehicles.	0x00	Associate with type 0x01
			0x01	Associate with type 0x02
			0x02	Associate with type 0x03
			0x03	Associate with type 0x04
0x01	Changing lanes notification	Used when one vehicle wants to change its driving lanes and may affect the other vehicles.	0x00	Left
			0x01	Right
0x02	Changing speed notification	Used when one vehicle wants to dramatically change its driving speed for special purposes and may affect the other vehicles.	0x00	Speedup
			0x01	Speed-down
			0x02	Emergency brake
			0x03	Back a car
0x03	Changing direction notification	Used when one vehicle want to change its driving direction and may affect the other vehicles. Normally used before the intersections, and it can also be used in the situation of turning the direction to parking spaces.	0x00	Left
			0x01	Right
0x04	Overtake	Used when one vehicle wants to overtake other vehicles.	0x00	Overtake notification
0x05	Unsafe reply to the notification	Used to warn another vehicle about the driving decision.	0x00	Unsafe
0x06	Breakdown notification	Used when one vehicle breakdown.	0x00	Minor failure
			0x01	Medium failure
			0x02	Hard failure
0x07	Environment emergency warning	Used to alert other vehicles about the environmental emergency.	0x00	Minor emergency
			0x01	Medium emergency
			0x02	Hard emergency
0xFF	Global command	Reserved for global traffic flow control. It can only be used by the urban traffic management system in special situations, such as decrease the traffic flow of specified road segments or block specified road segments in some emergency reasons.	0x00	Associate with type 0x01
			0x01	Associate with type 0x02
			0x02	Associate with type 0x03

The type 0x00 is reserved for special types of emergency vehicles, e.g., police car, ambulance, and fire engine, in emergency situations. The special type vehicles have the highest priority to go through the road in the emergency situations, such as the police car pursues an escaped prisoner or ambulance transports the injured. When an emergency situation occurs, the special vehicles can set the type to 0x00 and insert necessary information into optional data. The format of optional data is different according to the different types, describing in the following subsection. The type 0x00 must be associated with type 0x01, 0x02, 0x03, or 0x04, and the code field is used to indicate which type is associated. The corresponding codes for the associated type is also stored in the optional data field.

The type 0x01, 0x02, 0x03, or 0x04 are used for normal driving behaviors, such as, changing driving lanes notification, changing speed notification, changing driving direction notification, overtake notification.

The type 0x06 is used for the notification of breakdown degrees when some part of one vehicle fault. The detail of the breakdown information is stored in the optional field. The breakdown information can also be instantly transferred to the repair center for further supports (e.g., take the control of autonomous driving, troubleshooting). The type 0x07 is used to notify other vehicles about the emergency degrees when one vehicle detects some environmental emergency using its sensors. The emergency information is stored in the optional field. The emergency information can also be instantly transferred to the urban traffic management center for further controls.

The type 0xFF is reserved for global traffic flow control. It can only be used by the urban traffic management center in special situations, such as decrease the traffic flow of specified road segments or block specified road segments in some emergency reasons. It cannot be used by any vehicle.

4.1.5. Optional Data Format of the CDNP Header

The optional data field is varied according to the type value stored in the CDNP header. The common formats of optional data field for each type are defined for correctly encapsulating and de-capsulate the packet header. The formats of optional data fields of the CDNP header are shown from **Table 4.3** to **Table 4.6**.

- Optional Data Format

Table 4.3. Formats of optional data fields of type 0x00 and 0xFF CDNP packet.

<table>
<tr><th>0</th><th>8</th><th>16</th><th>31</th></tr>
<tr><td>Type</td><td>Code</td><td colspan="2">Checksum</td></tr>
<tr><td colspan="2">Sequence Number</td><td colspan="2">Sequence Number of Associated CDNP</td></tr>
<tr><td colspan="4">Notification Timestamp</td></tr>
</table>

The **Table 4.3** shows the optional data definition for type 0x00 and 0xFF. Because the type 0x00 and 0xFF CDNP header should associate with other types and codes, the optional data field includes the information about the associated type and the sequence number of associated CDNP packet. Those fields are used by the vehicle which received the notification to match the associated CDNP packet. The notification timestamp field stores the timestamp when the source node transfers the CDNP packet.

When the CV received the type 0x00 CDNP packet and the associated CDNP packet, it will know that the special vehicle is performing special work. The associated CDNP packet will be considered as a request. It is like the human driver hear the sirens of police car. If the received CDNP is type 0xFF, the CV will know the message is from the urban traffic control system, and the autonomous driving system will follow the instruction.

Table 4.4. Formats of optional data fields of type 0x01, 0x02, 0x03, and 0x04 CDNP packet.

0	8	16	31
Type	Code	Checksum	
Sequence Number		Unused	
Speed-X		Speed-Y	
Notification Timestamp			
Execution Timestamp			

The **Table 4.4** shows the optional data definition for type 0x01, 0x02, 0x03, and 0x04. If this CDNP packet is associated with type 0x00 or 0xFF CDNP packet, the sequence number will be filled using the same number stored in the "sequence number of associated CDNP" field of previous 0x00 or 0xFF CDNP packet header. Otherwise, a new sequence number will be generated. The speed-X and speed-Y field stores the speed of the vehicle that sent the notification. When the source node wants to transfer the CDNP packet, the timestamp transferring the CDNP packet is stored in the notification timestamp field. The execution timestamp stored the timestamp that the driving decision may be performed if it is calculable. Otherwise, 0 will be stored. For example, if the one autonomous vehicle wants to change its driving direction at the next intersection, it is easy for the autonomous driving system to predict the necessary time period to drive to the intersection. It is useful to warn the vehicles which are near to the intersection. If the execution timestamp is larger than 0, the SV will re-transmit the same notification 1 packet/second to ensure the other vehicles surely receive the notification. This is because the vehicles are always moving. The CV received the notification, which execution timestamp is larger than 0, can also predict the relative position to judge whether it is necessary to pay attention to the driving decision. If it is not necessary, the CV can just drop the CDNP packet.

Table 4.5. Formats of optional data fields of type 0x05 CDNP packet.

<table>
<tr><th>0</th><th>8</th><th>16 … 31</th></tr>
<tr><td>Type</td><td>Code</td><td>Checksum</td></tr>
<tr><td colspan="2">Sequence Number</td><td>Unsafe CDNP Sequence Number</td></tr>
<tr><td colspan="3">Reply Timestamp</td></tr>
</table>

The **Table 4.5** shows the optional data definition for type 0x05 and 0x06. The "unsafe CDNP sequence number" field is the same with the sequence number stored in the notification packet that the CV wants to notify to. Its' function is like the human driver honk the horn to warn other drivers.

Table 4.6. Formats of optional data fields of type 0x06 and type 0x07 CDNP packet.

<table>
<tr><th>0</th><th>8</th><th>16 … 31</th></tr>
<tr><td>Type</td><td>Code</td><td>Checksum</td></tr>
<tr><td colspan="2">Identifier</td><td>Emergency Information</td></tr>
<tr><td colspan="3">Notification Timestamp</td></tr>
</table>

The **Table 4.6** shows the optional data definition for type 0x06 and type 0x07. For type 0x06, the identifier indicates the failure parts of the CV, and the parts of the vehicle are not discussed in this thesis; the emergency information stores the information for the manufacturer. For type 0x07, the identifier indicates the emergency situations that the vehicle detected using its sensors, including accidents, slippery road surfaces, road surface pit, chatter bump, static obstacle, moving obstacle, animal, etc. The emergency information stores various emergency situations information in type 0x07.

4.2 Concept of Cooperation Intelligent Autonomous Driving based on CDNP

4.2.1. Cooperation Intelligent Autonomous Driving

In this section, the concept application of CDNP, cooperation intelligent autonomous driving based on CDNP, is introduced. All autonomous vehicles can understand what the other vehicles notified according to the standard message format, types, and codes defined in CDNP.

It is assumed that autonomous driving technologies are already embedded in each vehicle. It also is assumed that each autonomous vehicle equips with global positioning system (GPS) device and numerous sensors with such techniques as radar, lidar, and computer vision to sense their surrounding environment for safety autonomous driving. In this proposal, only the vehicle driving decision information transmission is discussed; the autonomous driving technologies, such as however to control the vehicle, lane detection, and obstacle avoidance, etc., are out of the range of this proposal, so they are not discussed in this proposal. The VANET wireless interface is also installed. The VANET wireless interface is used to transmit or receive the data packets from other vehicles or infrastructures. The vehicle driving control application that is the application layer user interface is also available for passenger to input his driving requirements, such as the destination, in a hurry or not, etc.

4.2.2. CDNP Sending Procedure of Cooperation Intelligent Autonomous Driving

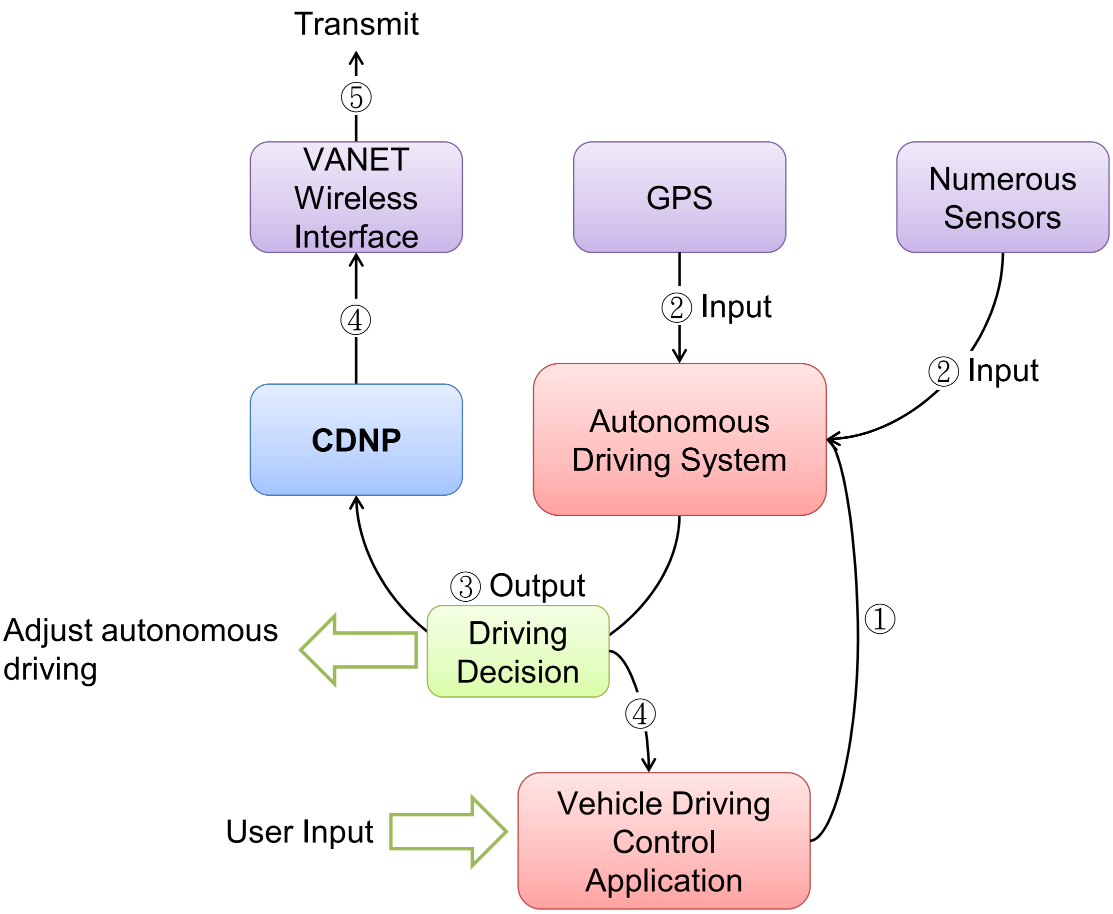

Figure 4.3. Sending procedure of the cooperation intelligent autonomous driving with the common driving notification protocol (CDNP).

The flow of sending procedure of the cooperation intelligent autonomous driving based on the CDNP is shown as **Figure 4.3**. When the vehicle received driving request inputted by passengers using the vehicle driving control application, the driving command information will be forwarded to the autonomous driving system. Then, the autonomous driving system will decide a most suitable driving decision according to the information, gathered from the GPS and various sensors to ensure the driving safety. The driving decision is used to adjust the autonomous driving of the vehicle. At the same time, the CDNP packet is generated. The CDNP packet is transmitted using the VANET wireless communication to notify other vehicles about the driving decision. It is like the human driver can notify other drivers using car light. Because the geographic positions of neighboring vehicles are available via the beacon mechanism, the CDNP can be transmitted to specific vehicles using unicast. Broadcast can also be used to notify a group of vehicles, e.g., all vehicles near to the intersection. In the case of broadcast, the CDNP will not be re-broadcast by other vehicles. Hence, there is no broadcast storming problem. To ensure the reliable CDNP packet transmission, the TCP liked protocol, such as TFRC-FC-SACK [89], which has better performance in VANET environment, can be used in the transport layer.

4.2.3. CDNP Receiving Procedure of Cooperation Intelligent Autonomous Driving

The flow of receiving procedure of the cooperation intelligent autonomous driving based on the CDNP is shown as **Figure 4.4**. When the CV received the packets transferred from other vehicles, it will de-capsulate the packet and check whether the packet is a CDNP packet. If it is, the CDNP packet will be forwarded into autonomous driving system. Then the system can judge whether it is necessary to perform some reaction or not. If it is necessary, the autonomous driving system can decide a suitable driving decision according to the type and code stored in the CDNP header and the information gathered from the GPS and various sensors. After the driving decision is decided, the decision will be used to adjust the autonomous driving of the vehicle and display some information for the passengers about the driving decision if necessary. Of course, if the autonomous driving system detects the possibility of unsafe driving decision, it can also transmit unsafe reply CDNP to the vehicle which sends the notification. It is like the human driver honk the horn to warn other drivers.

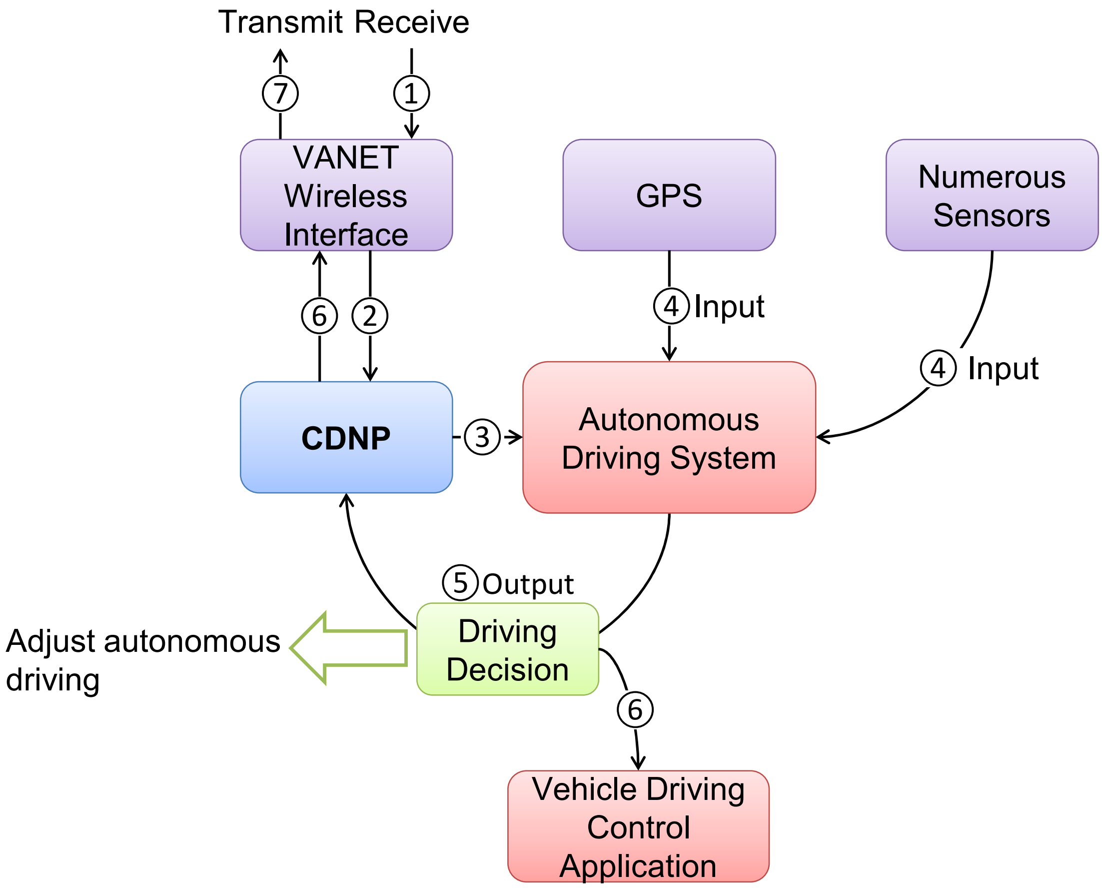

Figure 4.4. Receiving procedure of the cooperation intelligent autonomous driving with the common driving notification protocol (CDNP).

4.2.4. CDNP based Autonomous Driving Compared with Normal Autonomous Driving and Human Drivers

The **Table 4.7** shows the comparison of CDNP based autonomous driving, normal autonomous driving and human driver. The normal autonomous driving means the autonomous driving just depends on the sensors and various algorithms to control the vehicle.

Table 4.7. Comparison driving decision identification between CDNP based autonomous driving, normal autonomous driving, and human driver.

CDNP based Autonomous Driving	**Normal Autonomous Driving**	**Human Driver**
Not tired	Not tired	Long-distance driving will be tired
No processing time	Longer processing time for image/audio processing	No processing time
Data transmission time is necessary	No data transmission time	No data transmission time
Easy to locate the driving lane of the source far behind it	Not easy	It's a dangerous driving
No sensor necessary	Various sensors are necessary	No sensor necessary
Operable range of approximately 250 m	Long distance may not work properly due to the image resolution	Depend on the vision

According to the **Table 4.7**, it is known that the CDNP notification can provide human liked driving decision identification than normal autonomous driving technologies. Of course, it is better to integrate the CDNP and normal autonomous driving technologies at the same time to provide a safer driving environment for passengers.

4.2.5. Transfer Sequence Different between Type 0x00 (or 0xFF) CDNP and Other Types

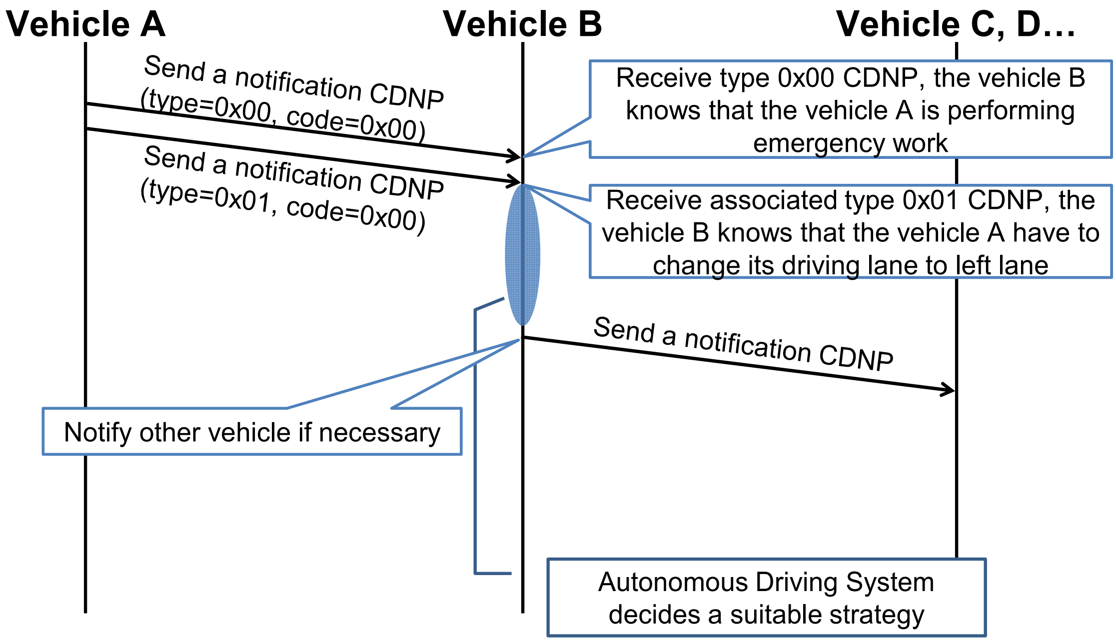

Figure 4.5. Example scenario of type 0x00 CDNP (associate with type 0x01, change driving lane).

The type 0x00 and type 0xFF are special types designed for special usages. The type 0x00 is used to increase the notification priority. It makes other vehicles know that the source vehicle is a special vehicle and it is performing a special work. The CDNP packet associated by the type 0x00 will be regarded as a request. The **Figure 4.5** shows an example scenario of type 0x00 notification. In this example, the vehicle A is a special vehicle, such as police car, and it is performing emergency work. Therefore, it transmits the type 0x00 CDNP packet to associate its driving lane change notification.

The vehicle received the notification will consider the notification as a high priority request. It is like the police car uses its siren to request other vehicles to make way in emergency situations.

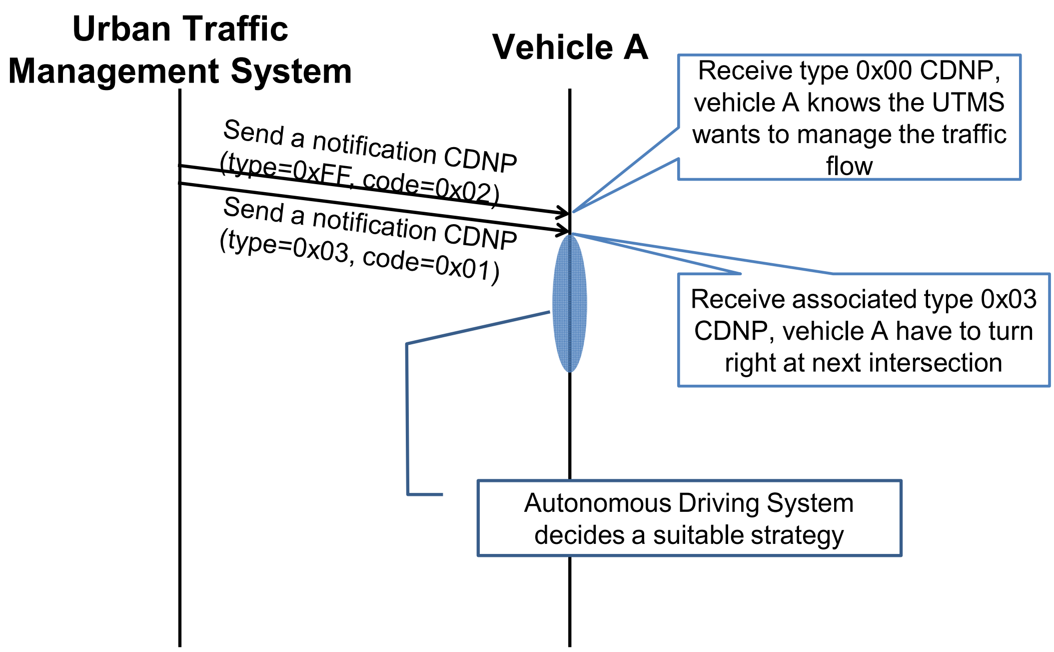

Figure 4.6. Example scenario of type 0xFF CDNP (associate with type 0x03, change driving direction).

The type 0xFF is reserved for the urban traffic management system to perform the traffic management. It changes the notification into the command. The associated CDNP packet is regarded as a command. All of the vehicles received the type 0xFF CDNP will follow the instruction from the urban traffic management system. This is useful if specific road segments must be blocked in special emergency situation. The **Figure 4.6** shows an example of type 0xFF CDNP notification.

4.3 Common Driving Notification Protocol Simulations and Results

The simulations and performance analyses are conducted to verify the efficiency of the proposed common driving notification protocol in this section. Because there still are no autonomous vehicles driven in our daily life, the simulators are used to simulate the cooperated driving concept of the autonomous vehicles. In the simulations, each autonomous vehicle equipped with OBUs that contains VANET wireless communication interface with a transmission range of 250m, so that autonomous vehicles can communicate with neighboring vehicles. The VANET wireless link can only be established if the distance between two nodes is less than their transmission range, and the beacon mechanism is enabled. The simulation environment, simulation scenarios, and metrics are introduced in the following.

4.3.1. Simulation Environment

The open source simulation tools, including NS-3 [90] and simulation of urban mobility (SUMO) [68, 69], are used to simulate the wireless data transmission and vehicle movement. The programming language used is C++.

- NS-3: the NS-3 is a discrete-event network simulator for building Internet systems, including wired and wireless communication. It is used to simulate the wireless data transmission of VANET.
- SUMO: the SUMO allows to simulate the realistic vehicle movement, which consists of vehicles moves through a given road network. Numerous of the car

following model are implemented in SUMO for more reality vehicle movement simulation. It can be connected with other applications through a TCP-based client-server architecture using Traffic Control Interface (TraCI) [91]. The TraCI in SUMO allows other application to retrieve values of simulated objects, e.g., vehicles, traffic lights, lane status, and to manipulate their behaviors, e.g., change driving lane, change driving speed, change driving route, change traffic light, and stop the vehicle. Therefore, through the TraCI, the NS-3 can achieve online interaction with SUMO.

The CDNP and simple basic capability of autonomous driving system are implemented as a sub-module of NS3. The component implementations are shown as **Figure 4.7**.

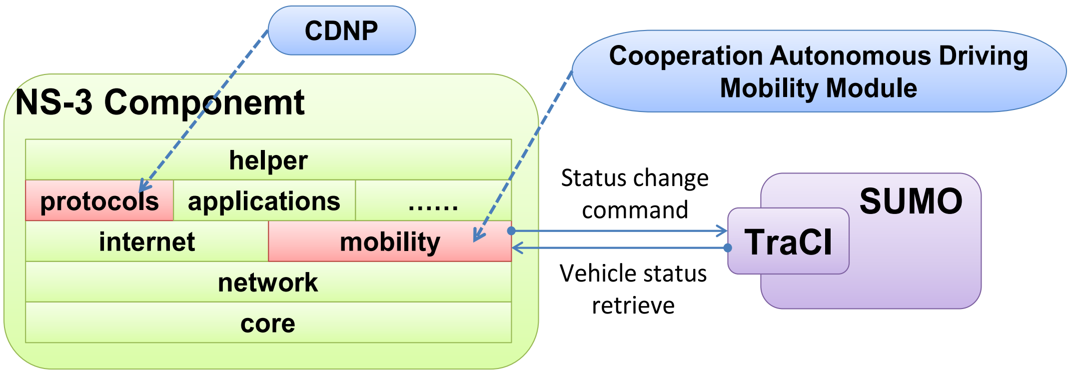

Figure 4.7. Component implementation of CDNP and cooperation autonomous driving mobility model.

- CDNP: the CDNP is implemented as a protocol component in NS-3.
- Cooperation Autonomous Driving Control Mobility Model: it is implemented as a mobility module to online interaction with the SUMO. It transfers control

command to SUMO to handle all vehicles' driving decision and retrieve the new vehicle statue from SUMO through the TraCI. It calculates the relative position of each vehicle to adjust their driving status, including change driving speed, change driving lane, change driving route, and stop, etc. After transferred the command to adjust the vehicle status, it also retrieve the new vehicle status from SUMO.

The important parameters and configurations are listed in the **Table 4.8**.

Table 4.8. List of important simulation parameters setting.

Simulation Time	400 sec.
Topology Size	Depend on the scenario described in the next subsection
Number of Vehicles	Depend on the scenario described in the next subsection
Destination Selection	According to the received beacon information stored in the vehicle memory
Media Access Control	802.11p
Transmission Range	250m
Propagation Models	TwoRayGroundPropagationLossModel
Data Packet Type	CDNP Packet
Data Packet Size	Changed according to different CDNP type.
TCP Liked Protocol	TFRC-FC-SACK
Beacon Message Interval	1 pkt. / sec.
Received Beacon Information Stored Threshold	30 sec.
Vehicles Movement	Randomly generated by SUMO
Traffic Light Interval	Randomly generated by SUMO

4.3.2. Maps and Scenarios

- Maps

The map of intersection scenario is shown in the **Figure 4.8**. The highway scenario is shown as **Figure 4.9**. The highway is four-lane two-way. The length of road is 4 km. The **Figure 4.10** shows the digital map used for the simulation of the urban scenario, and it is obtained from San Francisco city of the openstreetmap [75].

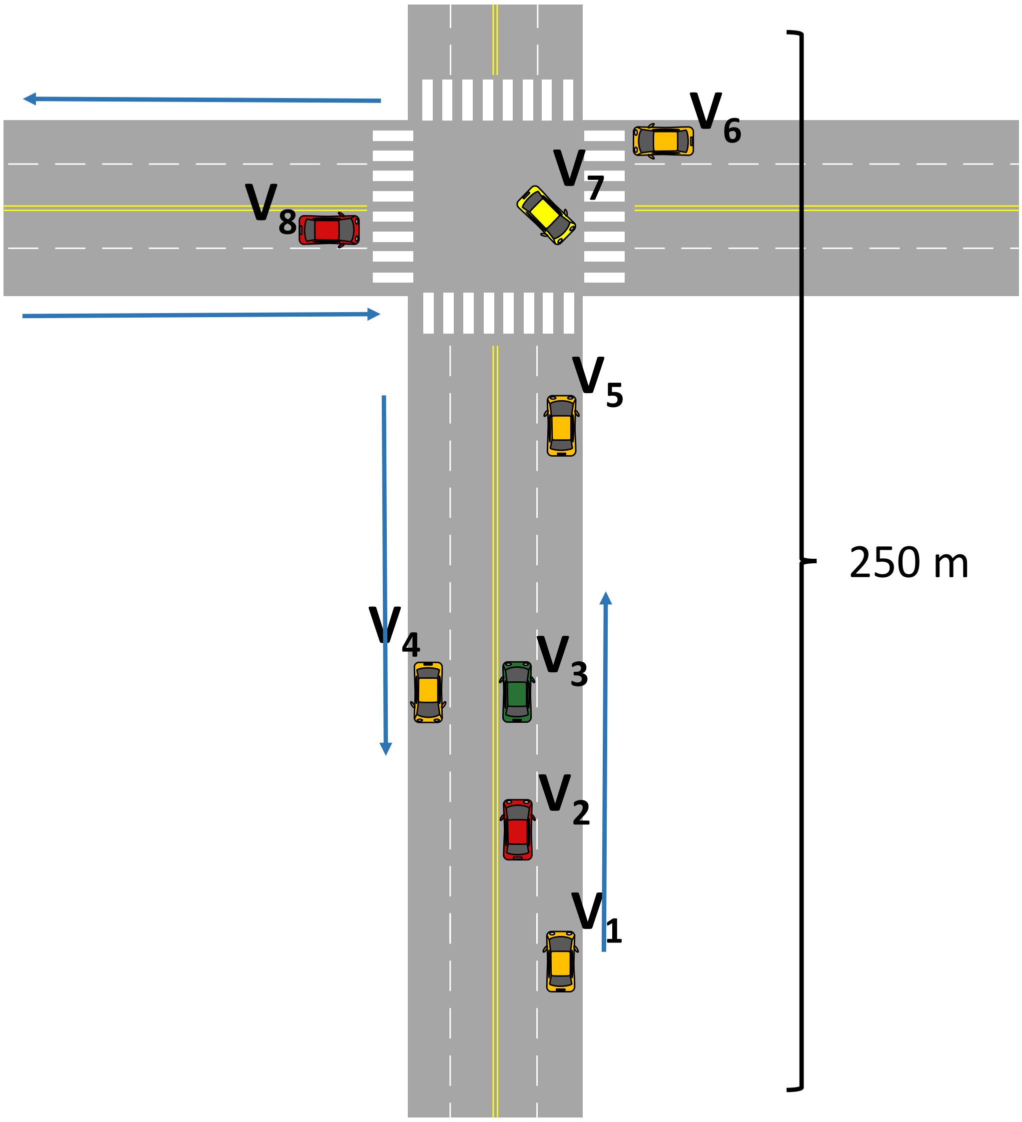

Figure 4.8. Intersection scenario.

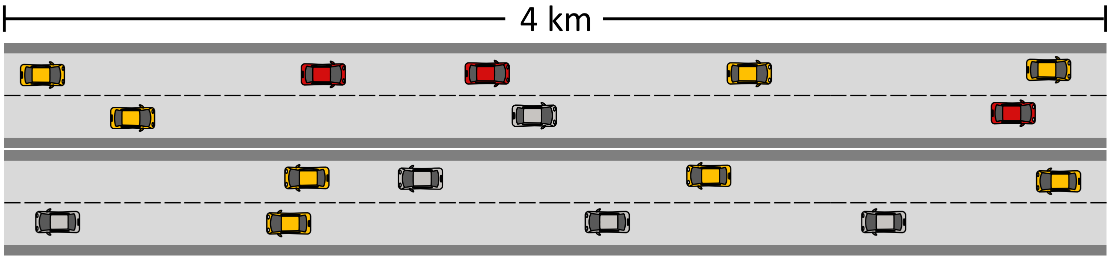

Figure 4.9. Highway with four-lane two-way.

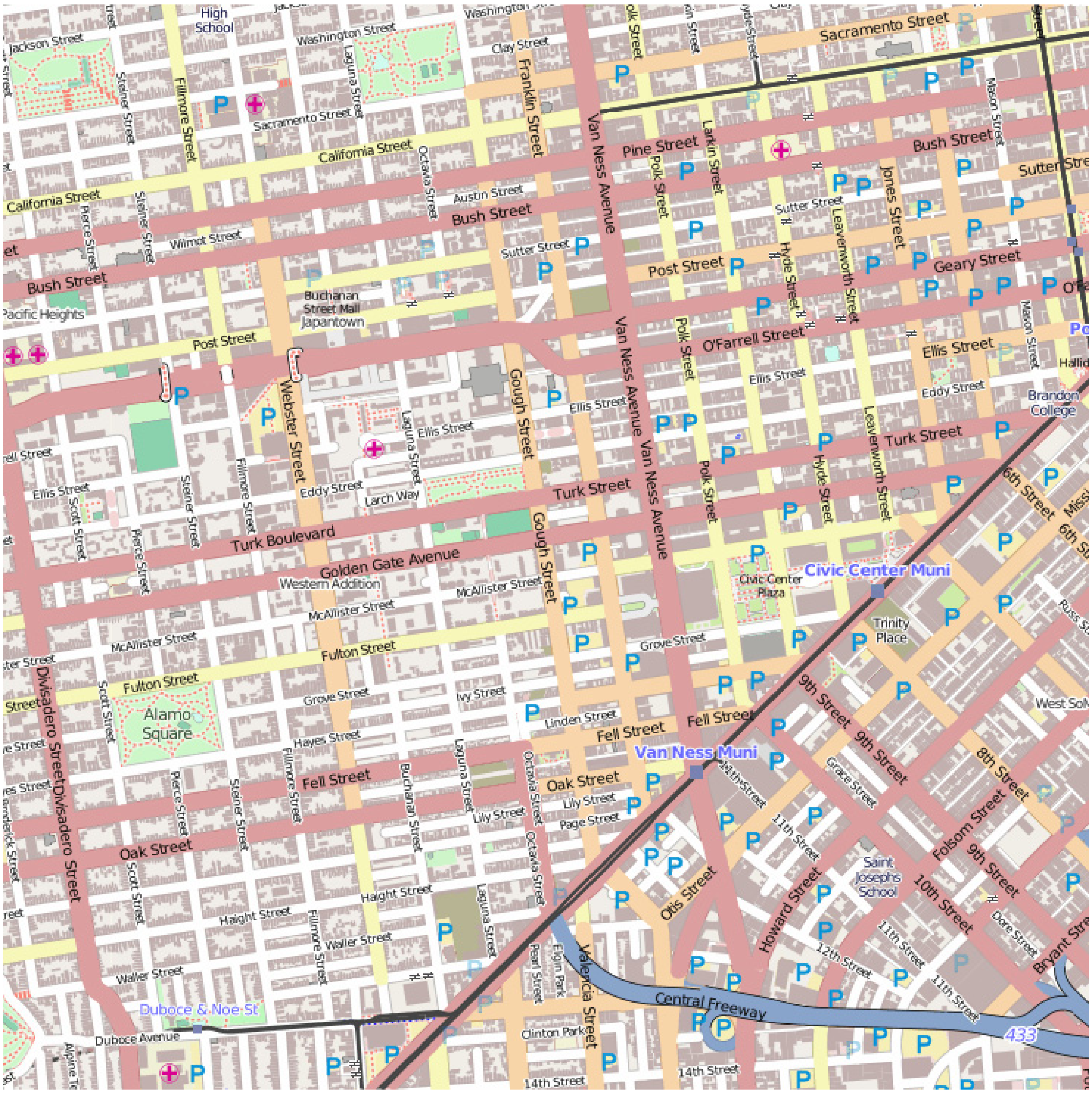

Figure 4.10. Digital map of San Francisco city used for the simulation of urban scenario.

- Scenarios

- Wireless Transmission Simulation

In this simulation, the intersection scenario, highway scenario, and urban scenario are used. The average number of vehicles is varied from 10 to 20 and the average speeds of each vehicle are randomly assigned between 0 km/h and 50 km/h in the intersection scenario. In the highway scenario, the average number of vehicles is varied from 40 to 80 and the average speeds of each vehicle are randomly assigned between 80 km/h and 110 km/h. In the urban scenario, the start point and end point of all vehicles are randomly selected. The average number of vehicles varies from 200 to 400, and the speeds of each vehicle are randomly varied between 50 km/h and 80 km/h. The movements of autonomous vehicles are statically generated by SUMO. The CDNP packets are transmitted according to the moving script generated from SUMO, e.g., the vehicle change driving direction, stop.

- Reaction Preparing Time Simulation

The intersection scenario and highway scenario are used. In intersection scenario, the vehicle 1 will turn left when it arrives the intersection. The navigation information can make the autonomous driving system know it has to turn left before it arrive the intersection. The speed of the vehicle 2 is larger than vehicle 3, and the vehicle 2 wants to overtake the vehicle 3. The vehicle 5 is slow-down because the vehicle 7 is turning its driving direction. Hence, the vehicle 5 has to notify the vehicle 1 about the slow-down information. This intersection scenario is generated as a static moving script for NS-3. In the highway scenario, the number of vehicles is setting to 60 and the average speeds of each vehicle are randomly assigned between 80 km/h and 110 km/h.

- Identification Time Simulation

The highway scenario is used in the identification simulation. The scenario setting is the same with the highway scenario of wireless transmission simulation. In order to compare with the image processing based driving, the vehicle image in difference is also used.

- Vehicle Traveling Simulation

Two scenarios, including highway scenario and urban scenario, are used in vehicle traveling simulation. The NS-3 is configured to online interaction with the SUMO to change the vehicle moving status, e.g., driving lane, direction, speed, through the TraCI. In the highway scenario, the average number of vehicles is varied from 40 to 80 and the average speeds of each vehicle are randomly varied between 80 km/h and 110 km/h. In the urban scenario, the start point and end point of the vehicle is randomly selected. The average number of vehicles varies from 200 to 400, and the speeds of each vehicle are randomly varied between 50 km/h and 80 km/h. The movements of autonomous vehicles are dynamically controlled by cooperation autonomous driving mobility module, TraCI, and SUMO.

4.3.3. Simulation Results and Discussions

- **Wireless Transmission**

In this simulation, the wireless transmission delay is compared. The result is shown as **Figure 4.11**. It shows that the end-to-end delay is varied within a certain range. This is because the CDNP is normally used to notify other vehicles in a certain range of the current vehicle when the driving decision may affect them. Therefore, the multi-hop transmission is usually not necessary. The end-to-end delay is short.

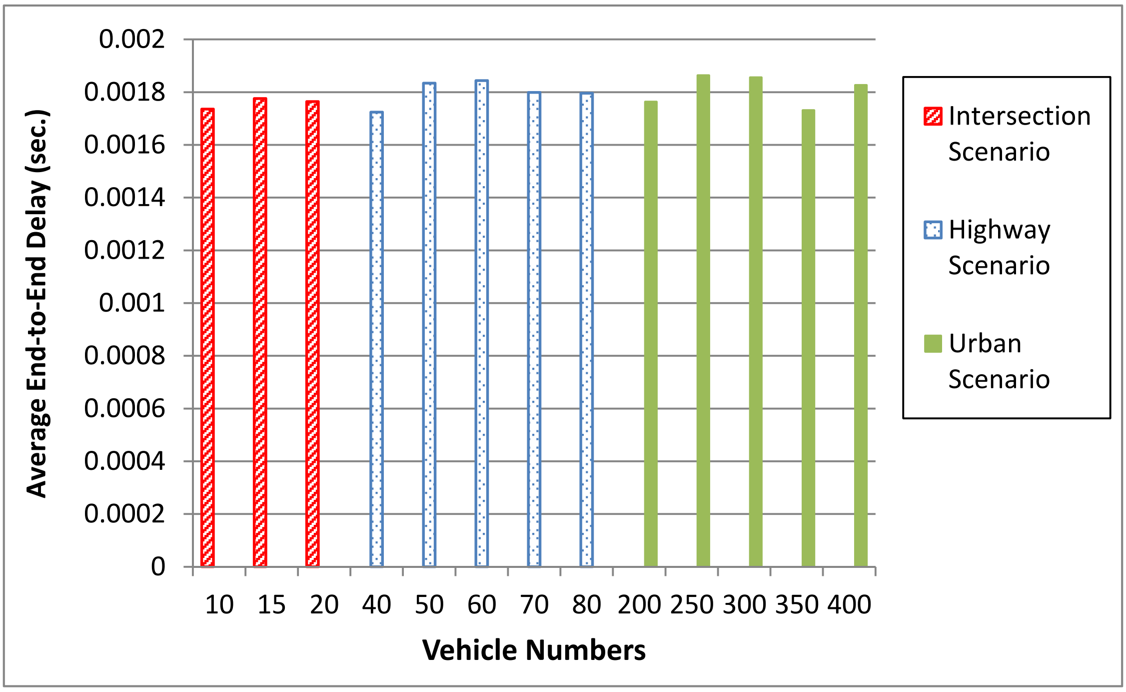

Figure 4.11. End-to-End delay of CDNP wireless transmission.

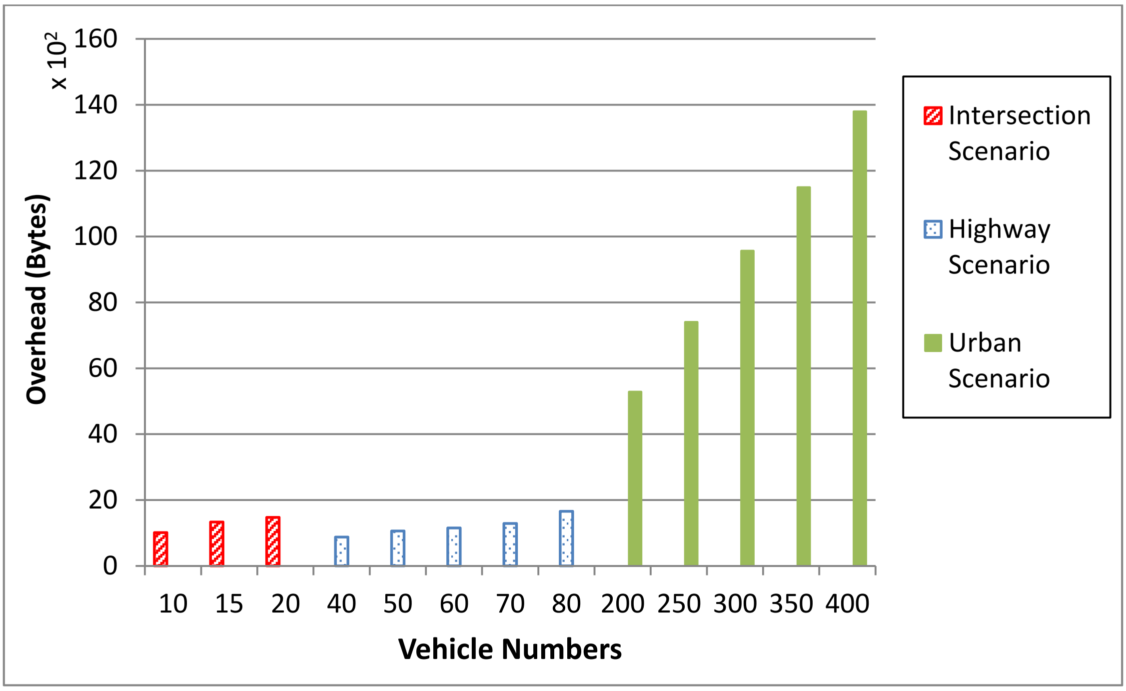

Figure 4.12. Overhead of CDNP wireless transmission.

In **Figure 4.12**, the transmission overhead of CDNP is shown. It is known that the CDNP will not cause large network overhead. The overhead of highway scenario is smaller than the intersection scenario. This is because the movement behavior of vehicles on highway is simpler than the movement near to the intersection.

- **Reaction Preparing Time**

According to the intersection scenario described in **section 4.3.1**, some autonomous vehicles have to transmit the CDNP notification. For example, the vehicle 2 will transfer overtake notification, the vehicle 5 will transmit slow-down notification, and the vehicle 1 will transmit turn left notification. The destination of each notification can be easily found from the stored beacon information. It can also predict the position if the driving decision is not executed immediately.

The **Figure 4.13** shows the RPT relations between vehicles. The $V_{a \to b}$ means the reaction preparing time for vehicle a to react to vehicle b before the driving decision of vehicle b is performed. The number is the RPT of vehicle b. The 0 means there is no reaction preparing time. After analyzing the simulation logs, it is known that the vehicle 1 transmits the notification before it arrives the intersection. The vehicle 5 transmits the notification and performs the slow-down driving decision at the same time. Hence, it is known that the RPT will depend on the usage of notification. It will also depend on the relative speed between two vehicles.

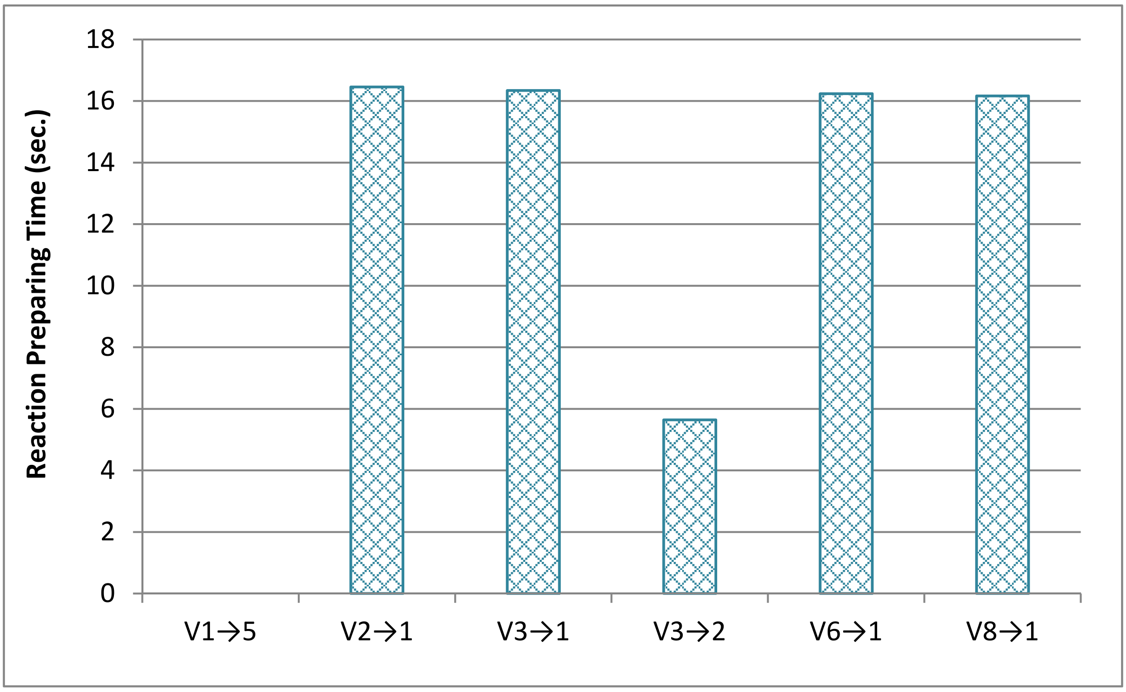

Figure 4.13. Reaction preparing time of intersection scenario.

To examine the relationship between RPT and the relative speed between two vehicles, the highway scenario is used. Each vehicle calculates the relative position when receiving the beacon message. The faster vehicle will transmit the overtake notification to the front vehicle that is slower than it. In the real world, the slower vehicle normally changes its driving lane to slow lane to let the faster vehicle passing when the driver notices the flashing car light or hear the horn. Hence, the RPT here is obtained by subtracting the time stamp that faster vehicle sent notification from the time stamp of faster vehicle close to the slower front vehicle's one meter range.

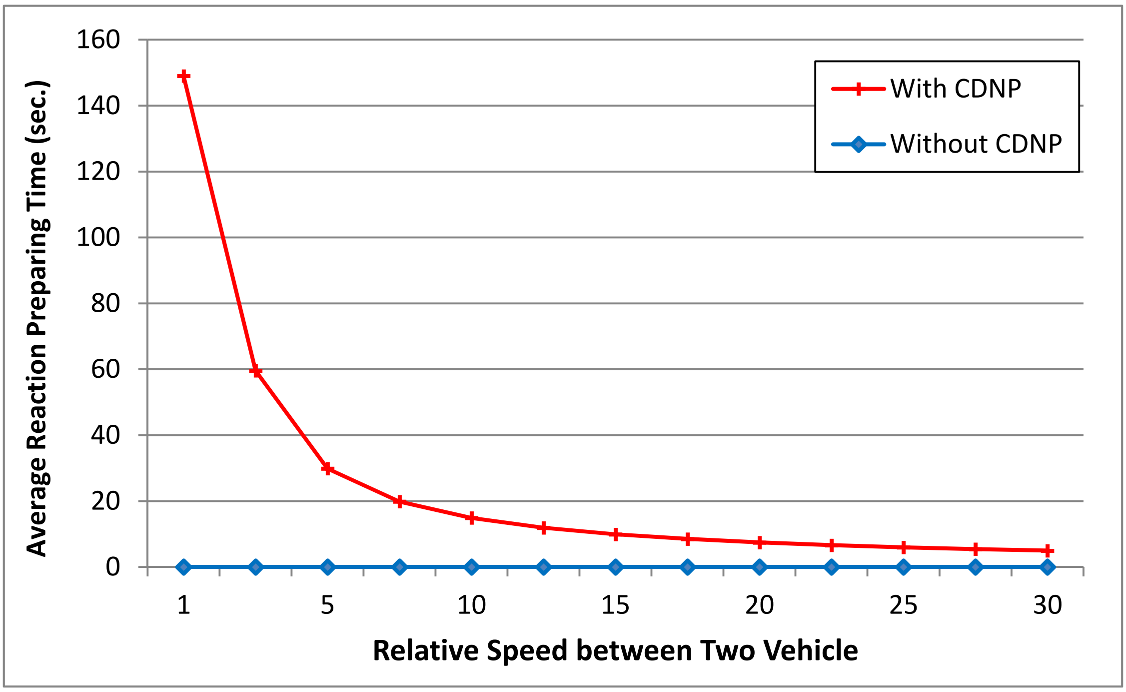

Figure 4.14. Reaction preparing time comparison in different relative speed between two vehicles.

The comparison of reaction preparing time when varying the relative speed between two vehicles is shown in **Figure 4.14**. It is shown that if the CDNP is available and the relative speed between two vehicles are close, the RPT will be long. When increasing the relative speed between two vehicles, the RPT is decreased. The RPT, however, may still long enough for the autonomous driving system to avoid possible accident. However, if the CDNP is not available, the driving decision cannot be transmitted. The autonomous driving system can just detect the driving decisions of other vehicles when some driving decisions have already performed. Therefore, the RPT without CDNP is 0.

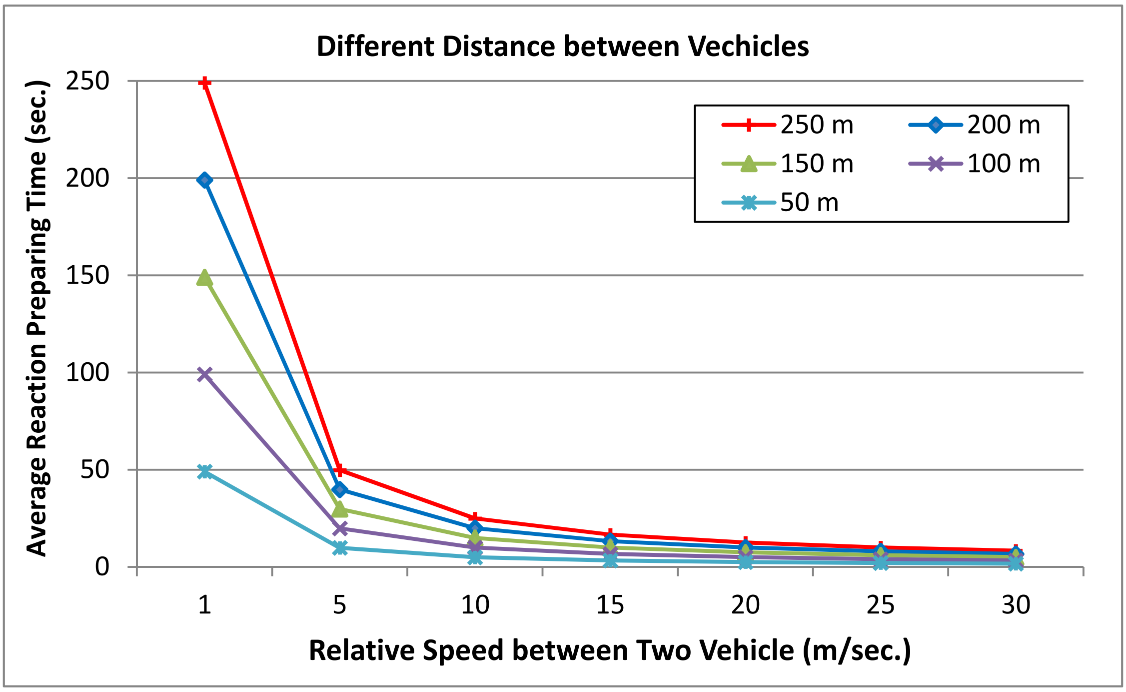

Figure 4.15. Reaction preparing time comparison in different distances between vehicles when the CDNP is transmitted.

In **Figure 4.15**, it shows the relationship between the RPT and the distance when transmit the CDNP. Although the RPT is decreased if the distance between two vehicles shorter. The CDNP still increases the RPT. If the CDNP is not available, the RPT is 0, and the autonomous driving system must react to all of the driving decisions of other vehicles after it detects the flashing car light or horn. From the results, it is known that the CDNP can increase the reaction preparing time with maximum value about 250 seconds if the transmission range of VANET is 250 m and the distance between two vehicles is 250 m.

- **Identification Time Simulation**

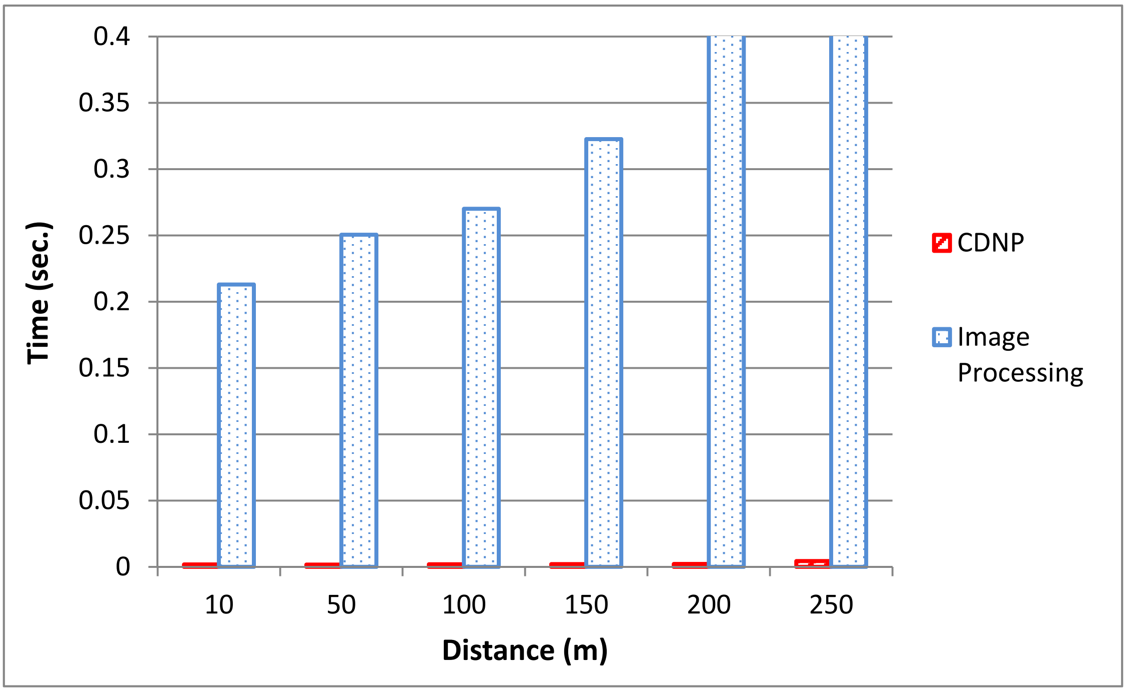

Figure 4.16. Identification time comparison.

The **Figure 4.16** shows the identification time comparison between CDNP and normal image processing based car light identification. Because the CDNP message is transmitted through the wireless technology, the transmission time is almost smaller than 0.002 seconds. Longer processing time is necessary for the image processing based identify to identification the car turn light correctly. The identifications of 200m and 250m are failed, so the processing times are infinity. Furthermore, although the image processing can still perform real-time identification, the image processing results may be incorrectly classified according to [57]. It will be dangerous if the result is incorrect. The CDNP identifies the driving decision according to the types and codes, so there is no incorrect identification.

● Vehicle Traveling Simulation

One vehicle is selected to be observed in the highway scenario, and ten vehicles are selected to be observed in the urban scenario. The selected vehicles are configured with highest driving speed. The vehicle transfer overtake CDNP notification if it finds a slower vehicle in the front. The position and speed of other vehicles can be got from the beacon message (or called basic safety message) [84, 85, 86, 87]. The vehicles which received the notification will calculate the relative position of surrounding vehicles and check whether it is possible to change its driving lane according to the safe distance rule. If it is not possible, the danger reply will be sent. If it is possible, the simulator changes the driving lane using TraCI. The results of this simulation are shown as **Figure 4.17** and **Figure 4.18**. It is shown that the CDNP can decrease the average traveling time. Actually, the purpose of this simulation is to show the possible driving concept. The CDNP can be used as the function of the car horn. Moreover, it is better than the function of car horn, because the relative position of source vehicle can be easily determined according to the content of beacon information and CDNP packet. This simulation results can be considered as that the ambulance transported the injured. It notifies other vehicles make a way. The actually implementation of autonomous driving control rules depends on the car manufactures, and also must follow the traffic law of each country.

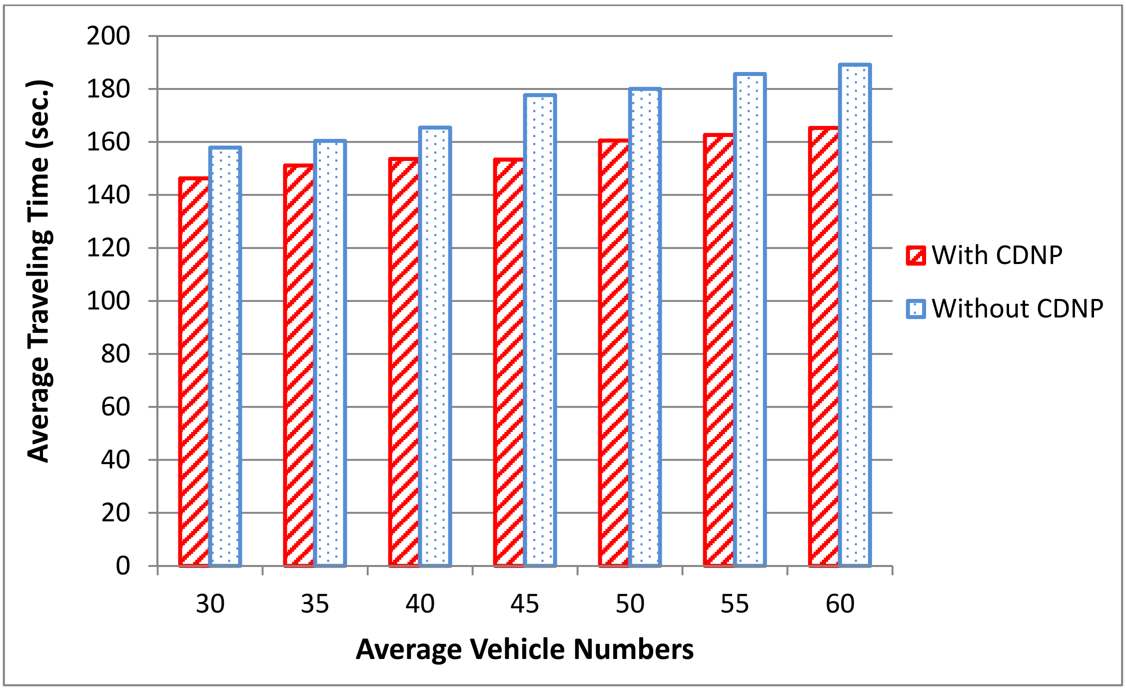

Figure 4.17. Traveling time of a vehicle traveling through the highway.

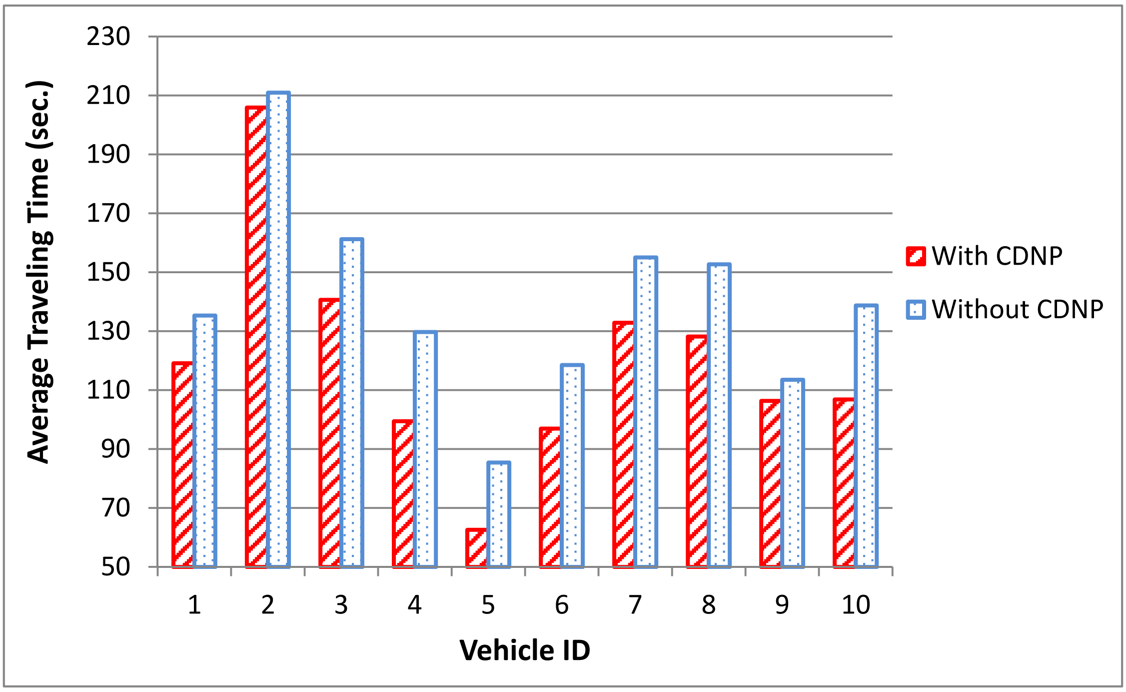

Figure 4.18. Traveling time of selected vehicles traveling from its start position to its end position in the urban scenario.

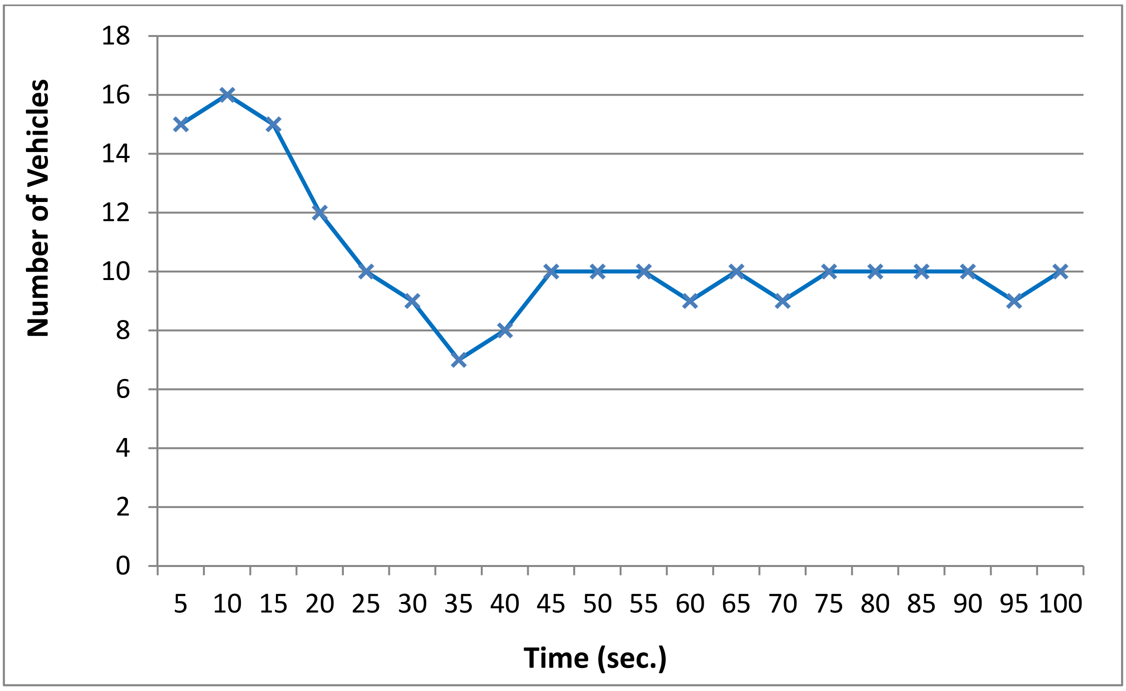

Figure 4.19. Number of vehicles controlled by urban traffic management center from 15 seconds.

In **Figure 4.19**, the number of vehicles on specific road segment is shown. The number of vehicles is under controlled and limited to 10 vehicles by urban traffic management center from 15 seconds. Hence, it can be seen that the number of vehicles is decreased from 15 seconds. Because some vehicles that want to enter the road segment are redirect to other road segments, the number of vehicles are lower than 10 from 25 seconds to 40 seconds and then close to 10 after 40 seconds.

The reaction preparing time and identification time can be considered as the safety index. Longer reaction preparing time and shorter identification time can increase the processing time for the autonomous driving control system to make a better control of the autonomous driving.

4.4 Discussion of Vehicle Moving Characteristics based on CDNP

In this section, the characteristics of autonomous vehicle movement related to the CDNP are described, including reaction time and traveling time.

Theorem: Let v_1 and v_2 be the speed of the vehicle 1 and vehicle 2 respectively, and the vehicle 1 runs after the vehicle 2. T_{range} is the transmission range of VANET. For the driving decisions, e.g., overtaking, braking, turning driving direction, of vehicle 1 / vehicle 2, the maximum reaction preparing time ($RPT_{\max}$) of vehicle 2 / vehicle 1 is given as

$$RPT_{\max} = T_{range} / (|v_1 - v_2|). \quad (4.1)$$

Proof: The transmission range of VANET technology is T_{range} meters, so each vehicle can communicate with other vehicles when the distance is shorter than T_{range} meters. Hence, the maximum reaction time is the time between the vehicles 1 / vehicle 2 enters the transmission range of the vehicle 2 / vehicle 1, until the vehicle 1 / vehicle 2 wants to perform its driving decision. Because length equals speed multiplied by time, obviously, the reaction time $RPT_{\max}$ will be $T_{range} / (|v_1 - v_2|)$.

Chapter 5

Conclusions and Future Perspective

5.1 Conclusions

Fuzzy Network Stability based Optimization Routing Protocol

In chapter 2, the NS2 and TraNS are used to do perform simulations and performance evaluation of the proposed routing protocol. The urban scenario is considered, and Manhattan street map is used. The topology size is 3000 m × 3000 m, the number of vehicles varies between 200 and 450, and the transmission range is 250 m. The optimization routing protocol is implemented in NS2, and the programming language used is C++ and Tcl/OTcl.

Because the vehicle to vehicle network connectivity of each road segment is calculated using the proposed fuzzy network stability, called fuzzy inference based vehicle to vehicle network connectivity model, it is not necessary to send any control packets to detect the real-time network connectivity situation. Furthermore, when network fragmentation occurs, the optimization routing protocol does not send any control packets to maintain and reconstruct the routing path. Therefore, the proposed protocol decreases the control overhead by 20%. Moreover, three adaptive strategies are used for different network connectivity, decreasing the probability of packet loss caused by frequent network fragmentation; therefore, the optimization routing protocol increases the delivery ratio by 15%. Because the optimization routing protocol finds the transmission with high network connectivity and avoids unsuitable next-hop selection, the end-to-end delay is also keep within a range, the average end-to-end delay is decreased by 75% in an unstable network environment. The experimental results show that the proposed routing protocol deals with the data packet forwarding well in the event of unstable network connectivity by selecting an appropriate packet-forwarding strategy. The simulation results also shows that the proposed protocol has lower control overhead then GyTAR and RTRP. Hence, with the primitive idea of proposed model, the optimization routing protocol will work well in any unstable network environment.

Two-Level Roadside Units Deployment Scheme

The same with chapter 2, two simulation tools, NS2 and TraNS, are used to do the simulations and performance evaluations of the proposed roadside units deployment scheme in chapter 3. The source codes of TraNS are modified to compatible with the latest version of the simulation of urban mobility to generate the realistic vehicle mobility traces. In the simulation, the urban scenario is considered and the street map of San Francisco obtained from openstreetmap is used to deploy the RSUs and simulate the data packet transmission. The simulation topology sizes include 1000m x 1000m, 2000m x 2000m, 3000m x 3000m, and 4000m x 4000m. The number of vehicles varies between 200 and 400.

The cellular networks (4G-LTE, 3G, HSPA, etc.) are already widely used in the world. Vehicles are also enabled to communicate among themselves (V2V) or via road side units (V2R) with VANET technology. To make the network connection to Internet of each vehicle more stable, it is necessary to integrate the VANET technology and cellular network. This proposal extends the roadside units deployment problem from

VANET environment into Cellular-VANET Heterogeneous Wireless Network. The two different network stability characteristics of two different wireless networks, i.e., cellular networks and VANET, are integrated by the proposed extended fuzzy network stability using fuzzy inference. Various metrics, including the number of deployed RSUs, loading of base station, and data packet delivery ratio, are used to verify and discuss the efficacy of the proposed scheme.

The experiment results show that although the full deployment strategy provides high network performance, the number of deployed RSUs is very large. Therefore, the fully deployment strategy is not suitable for the future development of VANET. Hence, some trade-off between the number of RSUs deployed and the network stability is necessary. The D-RSU policy does not consider the network stability of cellular network, so it does not decrease the number of RSUs so much. The simulation results indicate that this proposal, GA with fuzzy network stability based 2-level road side units deployment scheme, decreases the number of deployed RSUs by more than 50% in cellular-VANET heterogeneous wireless network environment without losing the network stability. This is because the proposed scheme only deploys RSUs at the necessary candidate deployment points whose network stabilities, including VANET and cellular network, are not good enough. This also improves the delivery ratio by 30% because the proposed scheme deploys the RSUs at the candidate deployment points whose network stability is not good. Furthermore, the experiment results also show that it scatters the data packets transferred to the base station when vehicles want to transfer data packets to the Internet, and it also decreased the loading of base station more than 60%.

The further analysis also indicates that after the level 2 optimization is performed, the deployed RSUs on the road segments are optimized; the data packets transferred to the base station are further decreased. Because the proposed scheme optimizes the deployment of RSUs according to the fuzzy network stability, if one vehicle wants to transfer data packets and the signal strength from the base station is weak, then it can transfer data packet through the VANET. Hence, the packet delivery ratio is increased. Some gateway selection method of heterogeneous wireless network, such as multi-metric QoS-balancing scheme, can be used to make the performance better and balance the loading of RSUs between cellular network base stations after optimizing the deployment of RSUs.

Common Driving Notification Protocol

In chapter 4, the open source simulator and tool are used in the simulation, including NS-3, and simulation of urban mobility (SUMO). The NS-3 is a simulator used to simulate the network communication, and the SUMO allows to simulate the realistic movement of vehicles through a given road network. The two simulation tools are used to simulate the movement and communications of each vehicle at the same time. The programming languages used are C++.

The wireless transmission simulation, reaction preparing time simulation, identification time simulation, and vehicle traveling simulation are done in the simulation. Three scenarios, including intersection scenario, highway scenario, and urban scenario, are used in the simulation. The length of road in highway scenario is 4 km, and the street map of San Francisco obtained from openstreetmap is used to perform the urban scenario simulations. The simulation topology size in urban scenario is 3000m^2.

The simulation results show that the CDNP message can be transmitted within 0.002 seconds using VANET technology. It also shows that the CDNP increases the reaction preparing time in some situations. This can provide one autonomous vehicle with enough computation time to make a better driving decision. The maximum value of the reaction preparing time is 250 seconds if the relative speed between two vehicles is very close. It also decreases the driving decision identification time that is longer if sensor based method is used. The CDNP changes the traditional passive detection of the driving decision of other vehicles into proactive notification to other vehicles about its driving decision. Furthermore, the simulation results also show the CDNP can decrease the traveling time in special case. It can be considered as the scenario that the ambulance transported the injured. It notifies other vehicles make a way. It also means the autonomous driving is smoother and the carbon dioxide emissions could be reduced in some situation. From the theorem, it is shown that the maximum reaction preparing time is $RPT_{\max} = T_{range} / (|v_1 - v_2|)$.

5.2 Future Perspective

The intelligent vehicular ad hoc networks (InVANET) and telematics technology, also known as ICT (Information and Communications Technology) are rapidly developing to improve the development of Intelligent Transportation System (ITS). More and more vehicles are going to equip with in-vehicle telematics systems (or VANET wireless interface) to provide the communication capability to gather information from other vehicles (V2V) or Internet (V2R). The communication capability provides the drivers with better driving experience, and it is the basis of the InVANET or intelligent transportation systems (ITS). The optimization of this thesis improves the performance of data packet routing and decreases the deployment cost of basic infrastructure of VANET. The CDNP protocol realizes more detail driving information exchange between vehicles. This thesis is useful to develop ITS applications, e.g., roadside unit deployment system, infrastructure-less real-time cooperative traffic-monitoring system, safety cooperative autonomous driving system, centralized urban traffic management system, using the embedded system to improve the future transportation environment and provide drivers a more safety and comfortable driving environment.

Roadside unit deployment system

The proposed roadside unit deployment optimization can find the optimal deployment strategy and decreases the deployment cost of RSUs in cellular-VANET heterogeneous wireless network environment, especially during the early development stages of VANET. It can be customized for using real world environment data for actual deployment of RSUs. Therefore, it is helpful to improve the future development of

VANET and Intelligent Transportation Systems. The roadside unit deployment optimization is going to support the Industrial Technology Research Institute (ITRI) in Taiwan to decrease the deployment cost of RSUs for real world testing of VANET technologies [47].

Infrastructure-less real-time cooperative traffic-monitoring system

The infrastructure-less traffic monitoring system is already implemented in NS2, using the optimization routing protocol to provide real-time traffic information. This kind of system is useful for providing real-time vehicle route planning to avoid congested areas and decrease the total average trip times, without any infrastructure to monitor each road segment. The traffic information of each road segment is separated by each vehicle using V2V communication and V2R communication. Moreover, because the traffic information is gathered by each vehicle, the deployment of fixed monitor infrastructure is not necessary. It means that there is no deployment cost. The protocol and traffic monitoring system is planned to cooperate with OEM manufacturers to develop real vehicle telematics device using embedded systems for further real world experiment.

CDNP based safety cooperative autonomous driving system

The autonomous driving and autonomous vehicle are important technologies for the future intelligent transportation system. To realize the autonomous driving in our daily life, the cooperation between vehicles is necessary. For the cooperation, the most important is information exchange. Unsafe driving decision, e.g. unsafe lane changes, unsafe overtake, or unsafe speed changes, will cause vehicle accidents; especially a vehicle suddenly performs those driving decisions. The CDNP standard provide the autonomous vehicles with the detail driving decision information about what driving decisions other vehicles want to perform. The future development of cooperative autonomous driving can be improved based on the CDNP standard. The CDNP can also be integrated with the normal autonomous driving technologies at the same time to provide a safer driving environment for passengers. The CDNP can be a globally consistent standard to be abided by all car manufacturers and research centers. All car manufacturers and research centers can implement their autonomous driving technologies based on the CDNP. The CDNP is going to be implemented as a module at the network protocol stack in the Linux kernel to provide the basic protocol capability.

Centralized urban traffic management system

The optimization routing protocol and common driving notification protocol (CDNP) can be used to develop a central traffic management system for the urban area. This kind of system can control and optimize the traffic flow of all road segments of the city. According to [1], the CO_2 produced during congestion is increased year by year. If all vehicles entering the city can be controlled by the centralized traffic management system, the movement of vehicles in the city will be more efficient. The emissions of CO2 can be reduced.

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Related Publications

Journal Papers

[J1] **Chehung Lin**, Fangyan Dong, and Kaoru Hirota, "Fuzzy Inference Based Vehicle to Vehicle Network Connectivity Model to Support Optimization Routing Protocol for Vehicular Ad-Hoc Network (VANET)," Journal of Advanced Computational Intelligence and Intelligent Informatics (JACIII), vol. 18 no. 1, pp. 9-21, 2014.

[J2] **Chehung Lin**, Fangyan Dong, and Kaoru Hirota, "GA with Fuzzy Network Stability based 2-Level Road Side Units Deployment Scheme for Cellular-VANET Heterogeneous Wireless Network", Telecommunication Systems, Springer (Submitted).

[J3] **Chehung Lin**, Fangyan Dong, and Kaoru Hirota, "A Common Driving Notification Protocol based on Classified Driving Behavior for Cooperation Intelligent Autonomous Vehicle using Vehicular Ad-hoc Network Technology", Journal of Artificial Intelligence and Soft Computing Research, Polish Neural Network Society (Accepted).

International Conference Papers

[C1] **Chehung Lin**, Fangyan Dong, and Kaoru Hirota, "Fuzzy Road Situation Model Optimization Routing (FRSMOR) in Vehicular Ad-hoc Network (VANET)," in 2012 6th International Conference on Soft Computing and Intelligent Systems (SCIS) and 13th International Symposium on Advanced Intelligent Systems (ISIS), pp. 532-537, Kobe, 2012.

[C2] **Chehung Lin**, Fangyan Dong, and Kaoru Hirota, "A Cooperative Driving Control Protocol for Cooperation Intelligent Autonomous Vehicle using VANET Technology", 7th International Conference on Soft Computing (SCIS) and Intelligent Systems and 15th International Symposium on Advanced Intelligent Systems (ISIS), pp. 275-280, Kitakyushu, 2014.