Master's Thesis
석사 학위논문

Traffic Flow Improvement Using V2X Communications

Seokjoo Koo (구 석 주 具 晳 柱)

Department of
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Advisor: Professor Ji-Woong Choi
Co-advisor: Professor Jeongho Kwak

by

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1]

07. 02. 2021

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(Co-Advisor)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Traffic Flow Improvement Using V2X Communications

Seokjoo Koo

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

05. 26. 2021

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ABSTRACT

Vehicle-to-Everything (V2X) communication is a wireless communication technology in which vehicles exchange traffic-related information with surrounding vehicles and road infrastructure in real-time. V2X communication is evaluated as an essential element for improving road safety and efficiency. V2X technology is divided into Dedicated Short-Range Communication (DSRC) and Cellular-V2X (C-V2X), and those technologies have distinct strengths and weaknesses. In this paper, firstly we compare the communication performance of DSRC and C-V2X in terms of reliability and latency in the highway road environment, using a MATLAB-based LTEV2Vsim simulator. As a result, we can see that DSRC is superior in terms of latency, and C-V2X is superior in terms of reliability. Then, we try to analyze whether V2X communication can have a positive effect on improving safety and efficiency in urban road environments. To this end, we conduct simple simulations to verify whether traffic congestion caused by traffic accidents in urban road environments can be alleviated by utilizing the vehicle path rerouting algorithm based on Wireless Access in Vehicular Environment (WAVE)-based V2X communication. Using OMNeT++, SUMO, and Veins, a DSRC/WAVE-based V2X network and urban road environments are configured, and V2X simulations are conducted after generating artificial accidents on specific roads. The average speed, the average driving time, and the average waiting time are used as indicators to evaluate the overall traffic flow. As a result of the simulations, it is shown that the application of path rerouting based on V2X communication can improve traffic flow by alleviating traffic congestion caused by accidents.

Keywords: V2X communication, DSRC, C-V2X, Traffic flow improvement

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Ⅰ. INTRODUCTION

Cooperative-Intelligent Transport System (C-ITS) means a system in which traffic elements such as vehicles and road infrastructure share surrounding traffic conditions and danger information in real-time. C-ITS can improve road safety and efficiency by integrating vehicular technologies and communication. It is evaluated as an essential system for realizing advanced autonomous driving in the future [1]. Vehicle-to-Everything (V2X) technology, in which vehicles exchange traffic information with surrounding vehicles and road infrastructure, is a wireless communication technology capable of realizing those visions of C-ITS. V2X communication technology is divided into two standards: Dedicated Short-Range Communication (DSRC), also known as Wireless Access in Vehicular Environment (WAVE) in USA, and Cellular-V2X (C-V2X). Each V2X standard has distinct pros and cons, and both standards are competing to take the lead in the automotive industry [2].

Active research on V2X technology for improving road safety and efficiency using V2X simulators is currently underway. For instance, the positive effect of dynamic route planning using V2X communication for reducing travel time from the vehicle's departure point to its destination in the realistic urban road was researched using network and road traffic simulators [3]. In this paper, we analyze V2X communication from two perspectives. Firstly, we aim to figure out which V2X technology is more suitable in terms of reliability and latency in the context of periodic beaconing under a general urban road environment, through several simulations. To this end, a MATLAB-based V2X simulator is utilized.

Secondly, we aim to analyze whether the vehicle path rerouting algorithm based on V2X communication can improve road safety and efficiency by mitigating traffic congestion when an unexpected hazard such as a traffic accident occurs on the road, through simple simulations. To this end, urban road environments for traffic flow simulations are constructed using an open-source network simulator and a road traffic simulator. The realistic road network created using actual road map and urban Manhattan grid road network are set as mobility maps. In addition, V2X communication based on DSRC/WAVE standard is adopted. Performance evaluation metrics are average speed, driving time, and waiting time of whole vehicles driving on the road.

The remaining parts of this paper are organized as follows. Section Ⅱ briefly introduces current V2X communication technologies. In section Ⅲ, we discuss the general communication performance of V2X technologies achieved through simulations. In section Ⅳ, several simulations and their results for analyzing the positive effect of V2X communication on traffic flow improvement in urban road environments are discussed. The conclusion of this paper is addressed in section Ⅴ.

Ⅱ. V2X COMMUNICATION TECHNOLOGIES

2.1 DSRC

The first concept of vehicular communication began to emerge from DSRC. DSRC is Wi-Fi-based wireless communication technology. Conventional DSRC supports low-speed wireless communication between vehicles and road infrastructure, such as automatic toll collection and simple traffic information services in ITS. It has a low transmission rate, low coverage, and only supports communication between vehicle and roadside infrastructure, so there is a limit to supporting next-generation ITS services.

To compensate for the shortcomings of the conventional DSRC, a new vehicular communication standard called WAVE was proposed mainly by the Institute of Electrical and Electronics Engineers (IEEE). WAVE is a kind of extended and advanced DSRC technology specialized to provide high-speed wireless communication between vehicles and vehicles (V2V), and between vehicles and infrastructure (V2I) in road environments where vehicles traveling at high speed. Recently, WAVE is generally regarded as DSRC for V2X communication, instead of conventional DSRC.

As mentioned above, WAVE is one of the main technologies to support V2X communications, based on DSRC. Figure 2.1 shows the WAVE layered architecture [4].

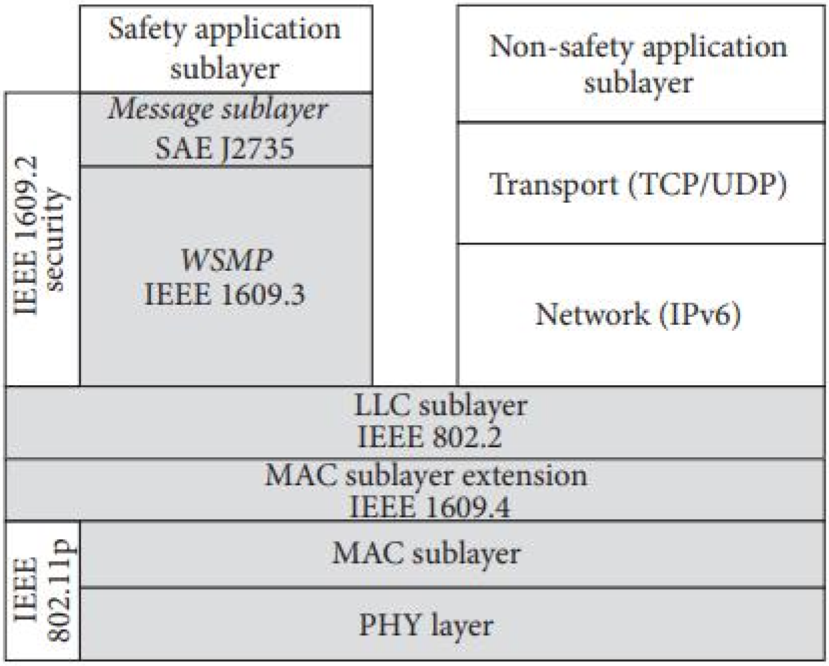

Figure 2.1 DSRC/WAVE layered architecture [4]

The physical (PHY) layer and MAC layer of DSRC/WAVE are defined based on the IEEE 802,11p standard, based on the IEEE 802.11a Wi-Fi standard. The PHY layer of DSRC/WAVE is defined based on IEEE 802.11a Orthogonal Frequency Division Multiplexing (OFDM). The operating frequency band of WAVE is fixed at a total of 75MHz from 5.850GHz to 5.925GHz, which was allocated as a DSRC operating band by the Federal Communication Commission (FCC) in the US in 1999 [5]. Figure 2.2 [6] shows the operating frequency band of DSRC/WAVE. Within this frequency band, 1 control channel (CCH) and 6 service channels (SCHs) occupying a 10MHz bandwidth per channel are utilized. In the corresponding 10MHz channels, by applying the modulation schemes of BPSK, QPSK, 16QAM, and 64QAM, data rates from 3Mbps to 27Mbps can be supported.

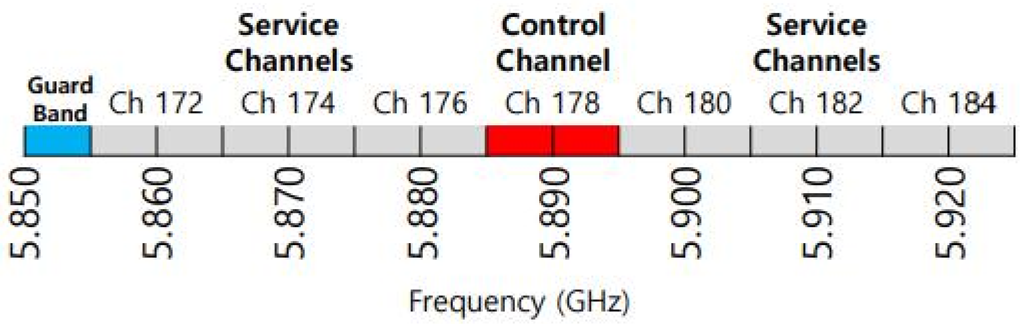

Figure 2.2 DSRC operating frequency band [6]

In the MAC layer of DSRC/WAVE, a contention and priority-based channel access mechanism is employed. The concept of data priority is added to the CSMA/CA channel access mechanism of the IEEE 802.11 MAC standard. This channel access mechanism is called Enhanced Distributed Channel Access (EDCA). Through EDCA, the data assigned a higher priority, the shorter the backoff time and inter-frame space, consequently the faster the data can be transmitted over the channel. In addition, time-division channel access to two or more different frequency channels using only a single DSRC/WAVE device can be possible, thanks to the multi-channel operation in IEEE 1609.4 standard additionally defined in the MAC layer.

The upper layers above MAC are defined based on the IEEE 1609.1 standard, which defines the Resource Manager (RM) for managing WAVE resources. The IEEE 1609.2 standard, which provides security services for DSRC/WAVE networks and applications. The IEEE 1609.3 standard defines WAVE Short Message Protocol (WSMP), a unique message transmission mechanism of DSRC/WAVE for V2X communication between

DSRC/WAVE devices. Additionally, the Society of Automotive Engineers (SAE) J2735 standard defines various V2X message types such as Basic Safety Message (BSM) and Signal Phase and Timing (SPaT) to support DSRC applications. In general, among those message types, the current driving information of each vehicle (e.g., driving speed, vehicle location, heading) are contained in a BSM message and broadcasted to other vehicles on the road at short intervals. Therefore, driving vehicles can receive driving information of other vehicles in real-time, thereby helping safe and cooperative driving on the road.

2.2 C-V2X

After the advent of DSRC technology, C-V2X, the other V2X communication technology based on cellular communication, appeared as 3GPP announced the Long-Term-Evolution (LTE)-based V2X standard in 3GPP Release 14 in 2016. Furthermore, recently commercialized 5G New Radio (NR) solutions have also been applied to C-V2X, called 5G NR-V2X. However, not long after the 5G NR-V2X appeared, there is no available 5G NR-V2X simulator so far. Therefore, this paper will only cover LTE-V2X technology.

There are two V2X communication methodologies in C-V2X. One is a methodology of performing V2X communication between vehicles or between vehicles and infrastructure through cellular communication network using a Uu interface between the base station eNodeB (eNB) and C-V2X devices. The other is a methodology of performing direct V2X communication through the PC5 interface, also known as sidelink. To meet the strict latency requirements of various V2X applications in road networks where vehicles travel fast, the latency of V2X communication must be reduced as much as possible. Therefore, in C-V2X communication, the latter methodology of performing direct V2X communication between V2X devices through the PC5 interface is preferred rather than the former methodology, which must go through the cellular network whenever messages are exchanged between V2X devices. As shown in Figure 2.3 [7], there exist two types of V2X communication modes through the PC5 interface defined in 3GPP Release 14, Mode 3, and Mode 4.

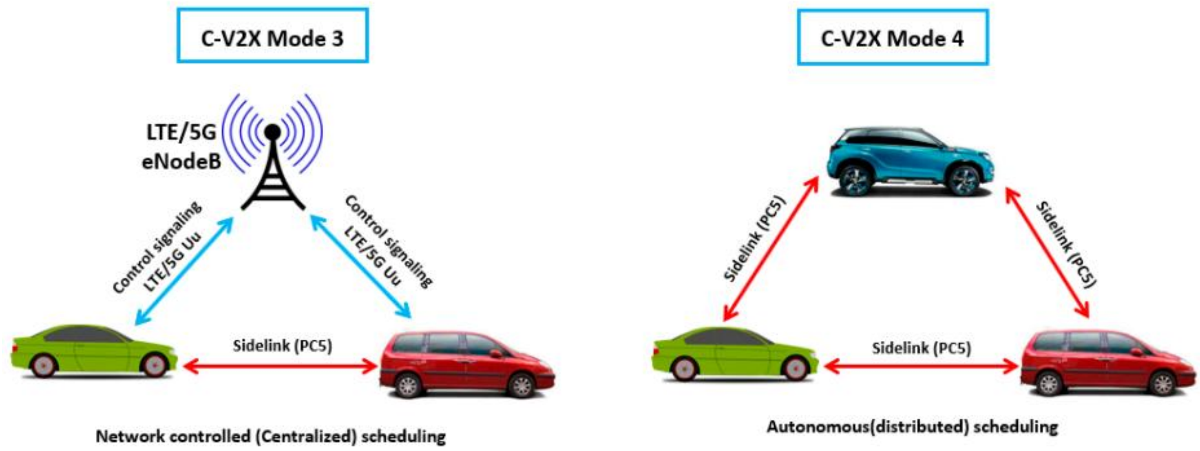

Figure 2.3 C-V2X communication modes [7]

When the vehicles are operating in Mode 3, vehicles request radio resources for V2X message transmission to the eNB through the Uu interface before performing V2X communication through the PC5 interface. When the eNB receives those requests, it collects information related to the current channel state and transmits information on the available radio resources to vehicles through the Uu interface. In other words, Mode 3 is a methodology in which the eNB manages and schedules radio resources to be used by vehicles for V2X communication. Mode 3 is available when vehicles are within the coverage of the eNB.

In Mode 4, the radio resources used during V2X communication are directly determined by the vehicles without the help of the eNB. In this mode, since vehicles directly grasp the current channel state and select available radio resources by themselves, V2X communication is possible even when the vehicles are outside the coverage of the eNB. Since Mode 4 is similar to the DSRC/WAVE in which vehicles select available resources and transmit V2X messages without the help of the network, it is determined that direct comparison between LTE-V2X Mode 4 and DSRC/WAVE is possible.

Next, we briefly introduce the radio resource scheduling scheme of LTE-V2X Mode 4. As mentioned above, while vehicles are operating in Mode 4, vehicles select radio resources for V2X communication by themselves. When vehicles directly select a transmission resource, they sense the transmission resource pool in advance and select a frequency resource not current used as the final transmission resource. This scheme is called the Sensing-Based Semi-Persistent Scheduling (SB-SPS) scheme. Figure 2.4 [7] shows the SB-SPS scheme. The execution process of SB-SPS is as follows.

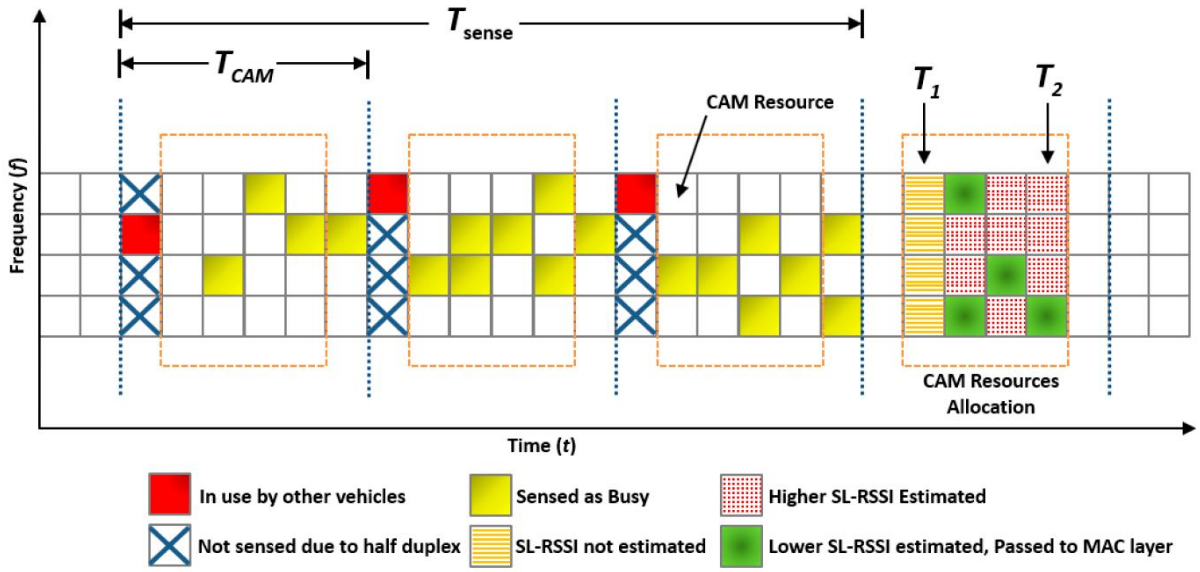

Figure 2.4 SB-SPS scheme in LTE-V2X Mode 4 [7]

Let us suppose that the vehicle needs to reserve a new transmission resource for V2X communication at the time T to transmit the message periodically. At this time, T, by setting the selection window, which is the size of the Resource Reservation Interval (RRI) of the vehicle, one of the Candidate Single-Subframe Resources (CSRs) in the selection window can be reserved. Also, Reference Signal Received Power (RSRP) and Reference Signal Strength Indicator (RSSI) thresholds to be used when selecting a transmission resource are set in advance.

First of all, the vehicle analyzes the information of whole resources received from other vehicles through the sidelink channel during the sensing window period of 1000ms size before T when it intends to reserve a new transmission resource. By analyzing the information in this sensing window, the vehicle determines which resources other vehicles have been using before and which resources will be used to transmit messages in the future. In addition, resources judged to be used by other vehicles are excluded from CSRs in the selection window.

After that, the vehicle measures the RSRP of the remaining resources. If the RSRP value of the resource is higher than the RSRP threshold, the resource is determined that it cannot be used for message transmission and is excluded from the CSRs. At this time, if the number of resources in the remaining CSRs set is less than 20% of the number of resources in total initial CSRs in the selection window, the RSRP threshold is increased by 3dB, and the previous resource selecting steps are repeated. If the number of resources in the remaining CSRs is greater than 20% of the total initial resources, the lowest average RSSI values of the resources in the corresponding set are measured. After that, resources with the lowest average RSSI value lower than the RSSI threshold are determined as final available resources, and an available resource list is created. Then, the list information is transmitted to the upper layer. Finally, the MAC layer randomly selects one candidate resource from the reported resource list as a resource for the first transmission.

After the resource is selected, message transmission occurs for a limited number of times called Reselection Counter (RC). The RC value is a randomly selected integer from the values in [5, 15] when the vehicle's transmission period is 100ms or more. When the RC value becomes 0, the probability of keeping the current resource (P) within the range of [0, 0.8] is used to select whether to continue using that resource or reserve another new radio resource.

A brief description of the LTE-V2X characteristics is as follows. Available modulation schemes in LTE-V2X are QPSK, 16QAM, and 64QAM. Unlike using OFDM in DSRC/WAVE, LTE-V2X employs Single Carrier Frequency Division Multiple Access (SC-FDMA) when performing carrier modulation to lower the peak-to-average power ratio (PAPR) of the signal and increase power efficiency. Furthermore, the 5.9 GHz band is adopted as a transmission frequency band, and channels with 10MHz or 20MHz bandwidth are used.

Each channel of LTE-V2X is divided into subframes, resource blocks (RBs), and subchannels. In the time domain, one subframe is 1ms long, and as shown in Figure 2.5 [8], 14 OFDM symbols are included in one subframe. When transmitting data, the minimum Transmission Time Interval (TTI) is 1ms, that is, one subframe. Unlike commercial LTE D2D operating in the 2.4GHz band, which includes two De-Modulation Reference Signals (DMRS) in one subframe, in LTE-V2X, to cope with the high doppler effect in the 5.9GHz band, four DMRSs are contained inside one subframe.

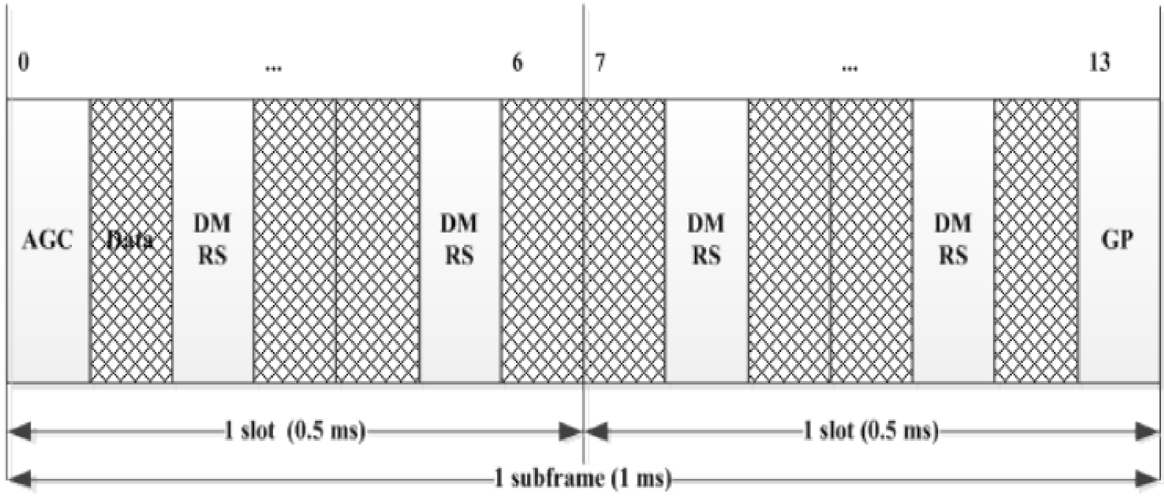

Figure 2.5 LTE-V2X subframe structure [8]

In the frequency domain, one RB occupies 180kHz, and each RB consists of 12 subcarriers, which means 15kHz subcarrier spacing. RBs grouped within the same subframe are called subchannel, and message transmission on a channel can be carried out in a subframe in the time domain and a subchannel in the frequency domain.

Ⅲ. PERFORMANCE COMPARISON OF V2X TECHNOLOGIES

It is important to identify which V2X technology is more proper to implement a V2X application that helps improve the traffic flow in an urban road environment. Therefore, in this section, we compare the general communication performance of DSRC and C-V2X in terms of reliability and latency when periodically broadcasting V2X message, through the MATLAB-based simulation using LTEV2VSim [9].

3.1 Simulation Setup

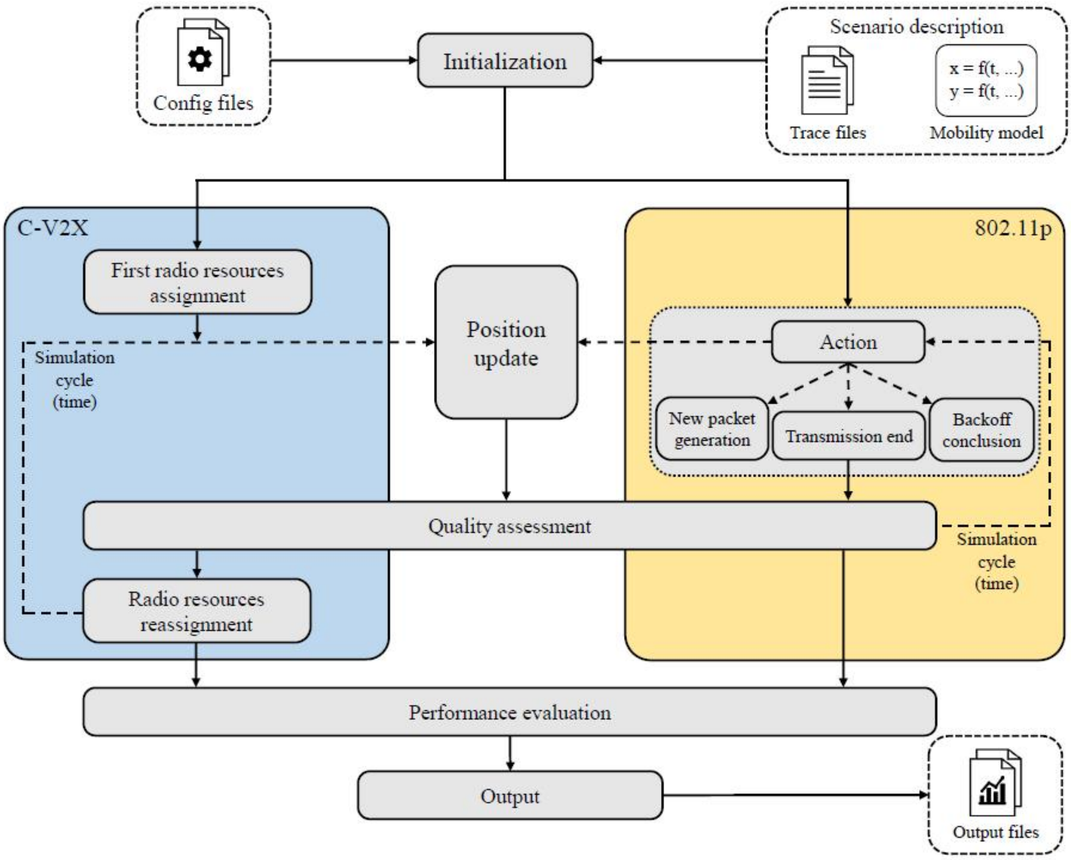

Figure 3.1 LTEV2Vsim block diagram [10]

In this section, a MATLAB-based LTEV2Vsim simulator is used to create an urban road traffic flow and carry out V2X simulations applying DSRC and LTE-V2X Mode 4 network. Figure 3.1 [10] shows the block diagram and workflow of the LTEV2Vsim simulator. LTEV2Vsim is a discrete-event V2X simulator that implements DSRC based on European Telecommunications Standards Institute (ETSI) ITS-G5 standard and LTE-V2X Mode 4 network. ETSI ITS-G5 is a European DSRC standard established on IEEE 802.11p similar to IEEE WAVE, a U.S. DSRC standard. One of the differences of ETSI ITS-G5 from IEEE WAVE is that each vehicle periodically broadcasts a Cooperative Awareness Message (CAM) type beacon instead of BSM to share the current driving and status information. As mentioned earlier, since ETSI ITS-G5 was established based on the IEEE 802.11p standard, variable settings such as operating frequency band, transmission power, and available data rate are very similar to IEEE WAVE.

Using this simulator, we constructed a 1 km highway road environment to compare the general communication performance of each V2X technology on an urban road. There are 2 lanes per direction, and the width of each lane is 3.5 m. In this environment, vehicles drive at an average speed of 100 km/h as shown in Figure 3.2 and Figure 3.3, and the vehicle density on the road is kept constant. Each dot on the figures represents the position of each vehicle on the highway. Figure 3.2 shows the traffic flow on the road when the vehicle density is 100 vehicles/km. Figure 3.3 shows when the vehicle density is 500 vehicles/km, a highly congested highway.

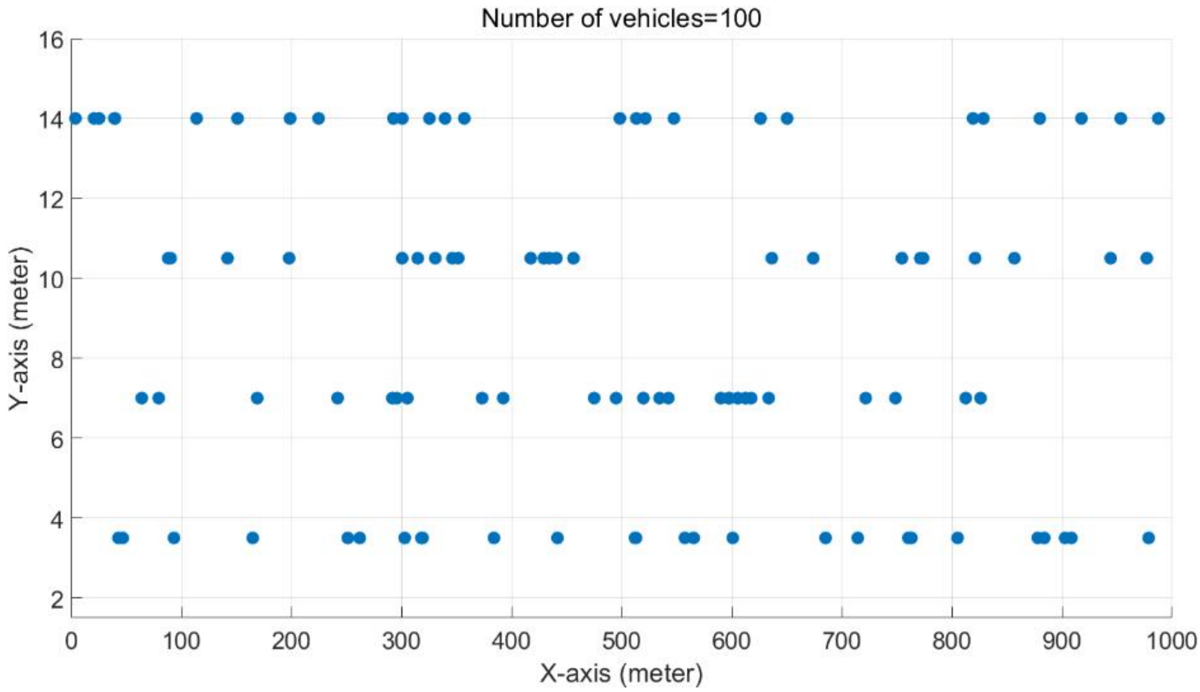

Figure 3.2 Traffic flow on the highway (100 vehicles/km)

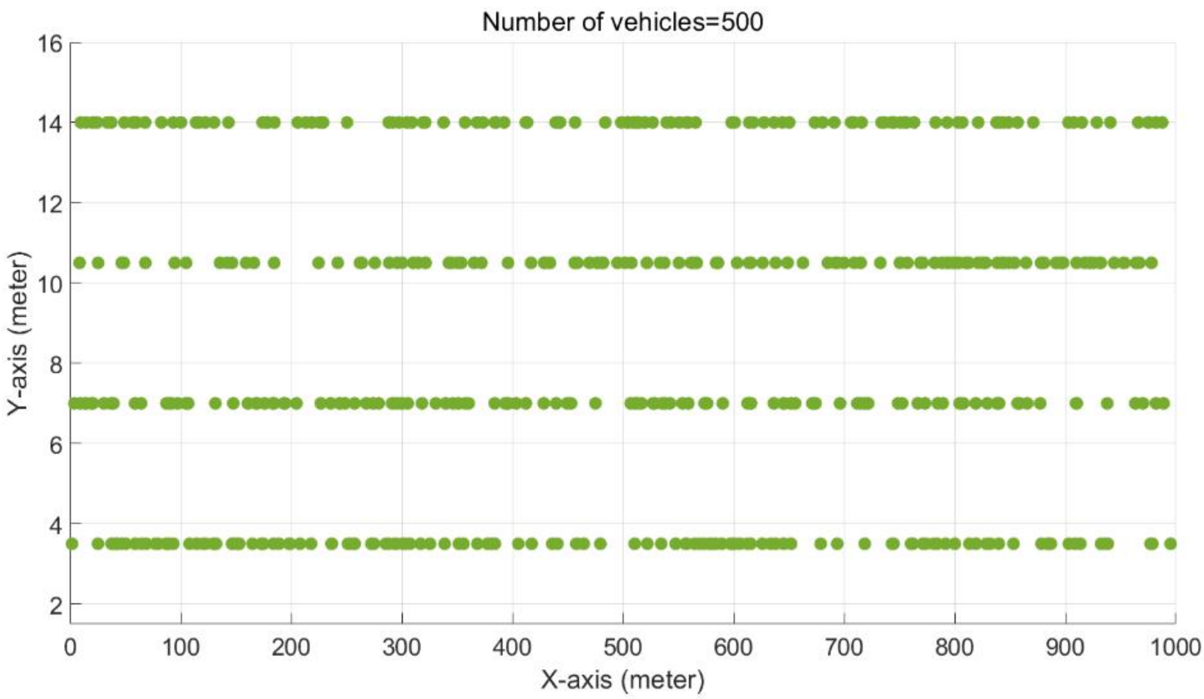

Figure 3.3 Traffic flow on the highway (500 vehicles/km)

In this scenario, to identify which technology is proper for V2X communication in common urban roads, we compared the performance of the two technologies by applying environmental settings and parameters of each technology as similar as possible. The simulation configuration parameters of the road environment and V2X technologies are set as shown in Table 3.1.

Table 3.1 Main simulation parameters and settings in LTEV2Vsim

Common parameters	
Parameter	**Value**
Simulation time	50 seconds
Road environment	Highway, 1 km
Average vehicle speed	100 km/h
Vehicle density	100 to 500 (Increased by 50)
Beacon period	100 ms
Beacon size	300 Bytes
Channel bandwidth	10 MHz
Transmission power	23 dBm
Transmitter antenna gain	3 dB
Receiver antenna gain	3 dB
Noise figure of the receiver	9 dB
Channel model	WINNER+ B1
Parameters related to DSRC	
Parameter	**Value**
Modulation and coding scheme (MCS)	3 (QPSK)
Parameters related to LTE-V2X Mode 4	
Parameter	**Value**
Modulation and coding scheme (MCS)	7 (QPSK)
Probability to keep the previously selected resource (probResKeep)	0.8

The simulation time is 50 seconds. For both DSRC and LTE-V2X Mode 4, we assume that each vehicle periodically broadcasts a 300 Bytes CAM message at 10 Hz (100ms per beacon). The channel bandwidth is 10 MHz, and the transmitter antenna gain and receiver antenna gain are set to 3 dB, respectively. The noise figure at the receiver is set to 9 dB. For the channel model, the WINNER+ B1 model [11] recommended in the 3rd Generation Partnership Project (3GPP) specifications is applied. To set the modulation order and coding rate of both V2X technologies as similar as possible, MCS of DSRC is adopted as 3, and MCS of LTE-V2X Mode 4 is adopted as 7. In addition, the probability to keep the previously selected resource, which is a value used for resource scheduling in LTE-V2X Mode 4, is set to 0.8.

3.2 Results and Analysis

To guarantee road safety and efficiency, it is necessary to exchange driving and status information among vehicles through reliable and low-latency communication. Therefore, the evaluation metrics used to compare the communication performance of V2X technologies on the highway road are as follows.

- **End-to-End Delay**: The time interval between the generation of the packet and its effective transmission. In other words, it represents the time interval between the generation time of the packet and the time when the packet is correctly received at the receiver.

- **Packet Reception Ratio (PRR)**: The average ratio between the total number of neighbor vehicles successfully received beacons in an awareness range and the total number of neighbor vehicles in an awareness range. In LTEV2Vsim, vehicles periodically broadcast beacon messages to all neighbor vehicles within a certain range. That range is called the awareness range.

3.2.1 End-to-End Delay

Since the main purpose of periodic beaconing is to exchange driving information in real-time with surrounding vehicles for safety and efficiency, we thought that it is inefficient to exchange information with vehicles that are relatively far apart. Therefore, we obtain end-to-end delay results adjusting the vehicle density and setting the awareness range to 200 m. Figure 3.4 shows the end-to-end delay of DSRC and LTE-V2X Mode 4.

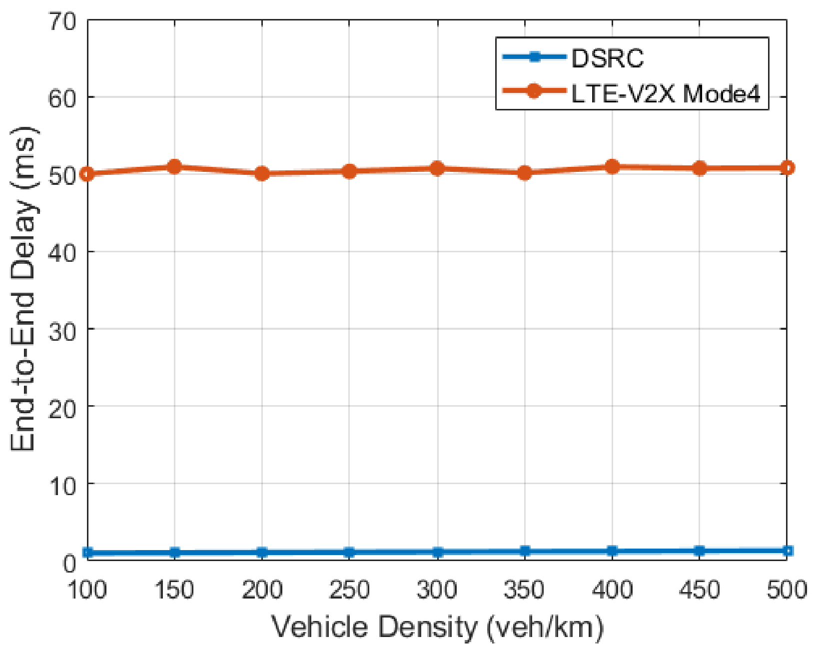

Figure 3.4 End-to-end delay adjusting the vehicle density

The end-to-end delay of DSRC is 1.07 ms when the vehicle density is 100 veh/km, and 1.37 ms when 500 veh/km. On the other hand, the latency of LTE-V2X Mode 4 is about 50 ms regardless of vehicle density. As shown in Figure 3.4, the difference in end-to-end delay of DSRC and LTE-V2X Mode 4 is very large, and

DSRC shows a much lower delay than LTE-V2X Mode 4. It is due to the difference in resource allocation mechanism between the two technologies.

DSRC uses CSMA/CA-based resource allocation method, and resource access time depends on the AIFS (58 μs) and backoff time (between 0 and 195 (15*13) μs) [12]. Therefore, as the vehicle density increases, the end-to-end delay increases due to the competition for resource allocation among vehicles. However, since the length of AIFS and time slot (15 μs) are basically short, the end-to-end delay is as low as 1 ms.

On the other hand, in LTE-V2X Mode 4, the available radio resource is randomly selected from candidate resources within a selection window of 100 ms based on SB-SPS. Therefore, the resource access time is constant at about 50 ms, which is about half of the length of a selection window, regardless of the vehicle density. As a result, in terms of end-to-end delay, DSRC is superior to LTE-V2X Mode 4.

3.2.2 Packet Reception Ratio

The quantitative results of the packet reception ratio are gathered adjusting the vehicle density and the awareness range. Firstly, we discuss the PRR versus vehicle density. Figure 3.5 shows the PRR when adjusting vehicle density and fixing the awareness range to 200 m, as previously set.

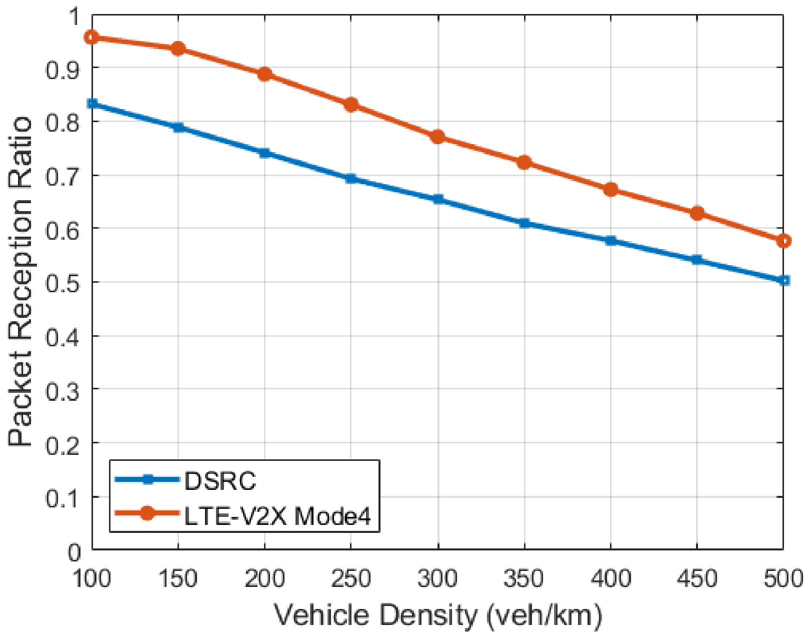

Figure 3.5 Packet reception ratio adjusting the vehicle density

Obviously, in both DSRC and LTE-V2X Mode 4, the PRR decreases as the vehicle density increases. In the case of DSRC, when the vehicle density is 100 veh/km, the PRR is already 0.832, which is less than 90 %, and decreases to 0.502 when the vehicle density is 500 veh/km. On the other hand, in the case of LTE-V2X Mode 4, the PRR is 0.956 at 100 veh/km, and it maintains a high PRR of over 90 % until the vehicle density approaches 200 veh/km, which is a remarkable result. Comparing the DSRC and LTE-V2X results, the two curves become closer for higher vehicle density. However, LTE-V2X Mode 4 shows higher PRR than DSRC, regardless of the vehicle density.

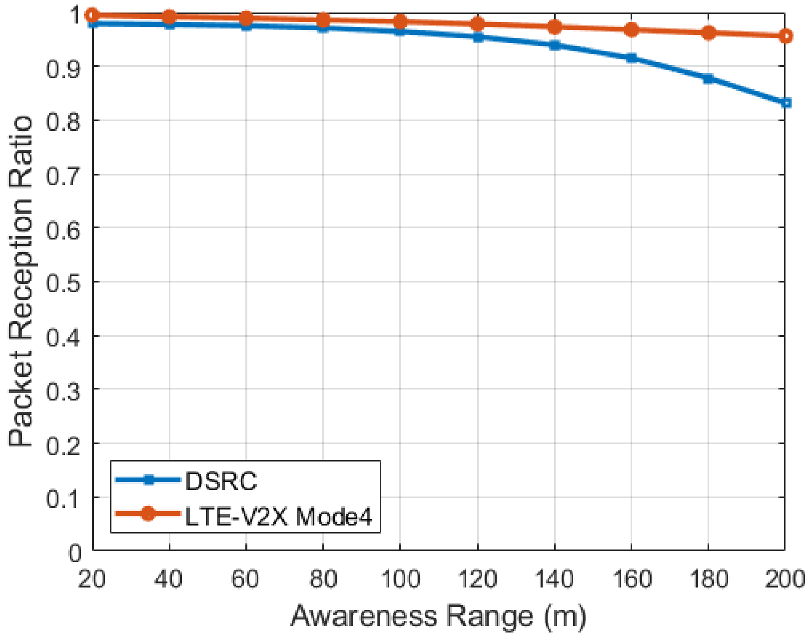

Figure 3.6 Packet reception ratio adjusting the awareness range (100 veh/km)

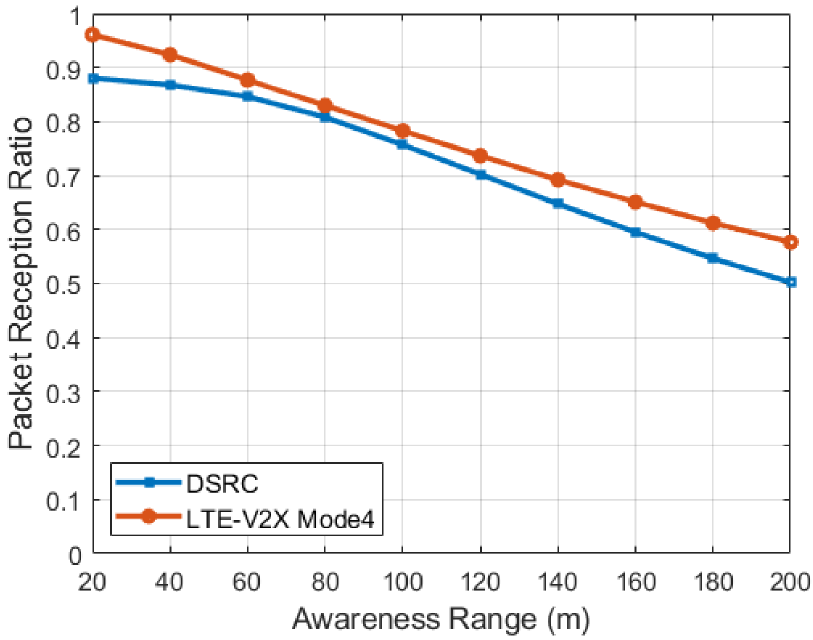

Figure 3.7 Packet reception ratio adjusting the awareness range (500 veh/km)

Next, we discuss the PRR results adjusting the awareness range and fixing the vehicle density. Figure 3.6 and Figure 3.7 show the PRR adjusting the awareness range when the vehicle density is 100 veh/km and 500 veh/km, respectively. In both figures, it can be seen that the PRR of LTE-V2X Mode 4 is higher than that of DSRC. In Figure 3.6, both DSRC and LTE-V2X Mode 4 show PRR over 0.8 even when the awareness range is 200 m. In the case of LTE-V2X Mode 4, the PRR when the awareness range is 200 m is 0.956, maintaining a high PRR over 95 % regardless of the range. However, in DSRC, when the range is more than 160 m, the PRR drops below 0.9. In the case of 500 veh/km in Figure 3.7, DSRC already shows the PRR of 0.881, which is less than 90 %, from a range of 20 m, whereas LTE-V2X Mode 4 shows a higher PRR than DSRC, such as the result of 0.924 at 40 m.

As a result, we can say that the LTE-V2X Mode 4 guarantees more reliable V2X communication than DSRC in a highway road environment. In LTE-V2X Mode 4, advanced techniques such as turbo coding and blind Hybrid Automatic Repeat Request (HARQ) are applied. On the other hand, DSRC has applied convolution coding and does not guarantee retransmission when broadcasting beacons. Therefore, LTE-V2X Mode 4 is better in terms of reliability because it has a greater link budget than DSRC.

Ⅳ. TRAFFIC FLOW IMPROVEMENT USING V2X

As we mentioned in the introduction, road safety and efficiency can be improved as each vehicle exchanges traffic-related information with surrounding vehicles and road infrastructure through V2X technologies in real-time. In section Ⅲ, we analyzed and compared the communication performance of each V2X technology in a general urban road environment. However, simply identifying which V2X technology is better in performance cannot guarantee that road safety and efficiency can be improved through V2X.

Therefore, we conducted additional V2X simulations closely related to traffic flow improvement to confirm that the above positive effects can be obtained by utilizing V2X communication in an urban road environment. The V2X technology considered for the simulation is DSRC/WAVE, which is evaluated as a rather more mature V2X technology than C-V2X so far. We considered two road environments. In each scenario, to check whether the application of V2X communication plays a positive role in alleviating traffic congestion, an accident is artificially modeled at a specific time and road spot to cause unexpected traffic jams. Then, the overall driving performance in the road environment is analyzed.

4.1 Simulation Environment

In this section, DSRC/WAVE-based integrated V2X simulation using Objective Modular Network Testbed in C++ (OMNeT++), Simulation of Urban Mobility (SUMO) [13], and Vehicles in Network Simulation (Veins) is executed. Figure 4.1 [14] shows the relationship and integrated architecture between each simulator.

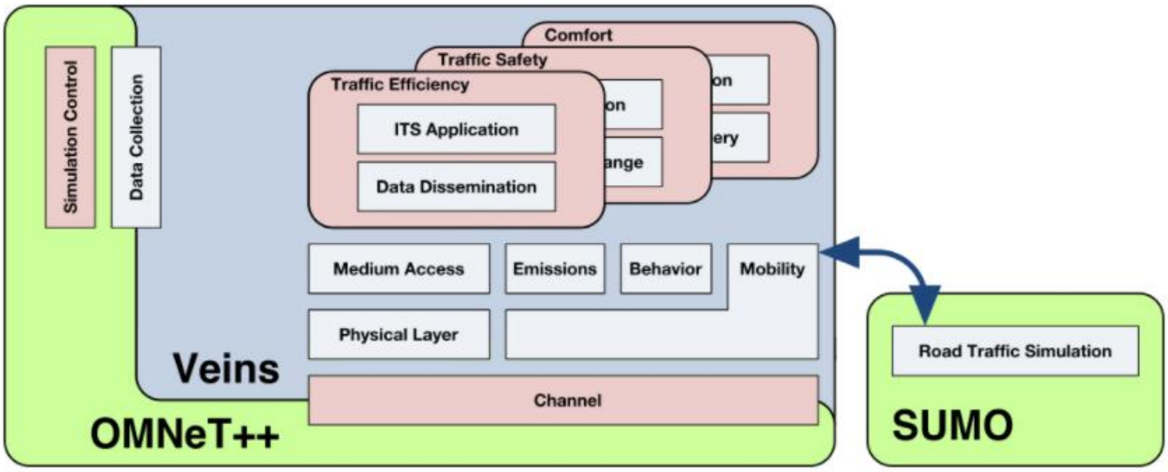

Figure 4.1 OMNeT++, Veins, SUMO architecture [14]

The LTEV2Vsim simulator used in the previous section makes it easy to compare the general communication performance of each V2X technology, but lacks indicators to evaluate the overall traffic flow of the road and the driving performance of vehicles. In addition, since LTEV2Vsim is basically a network simulator, it lacks a Graphic User Interface (GUI) function compared to the road traffic simulator that can check real-time traffic flow. Therefore, we try to complement the shortcomings of LTEV2Vsim by utilizing the above three simulators in parallel. The role of each simulator in this study will be briefly introduced below.

First of all, OMNeT++ is a C++-based discrete-event network simulator that enables V2X communication simulation considering the various wireless channel environment between V2X nodes, that is, vehicles (On-Board Unit, OBU) and roadside infrastructure (RoadSide Unit, RSU). SUMO is a road traffic simulator to model the road environment and traffic to be simulated and proceed with the road network simulation. Additionally, Veins is a vehicular network simulation framework that enables V2X communication to be conducted by mounting a DSRC/WAVE standard-based V2X network on V2X nodes created during the simulation in an OMNeT++ environment. Veins serves as an interface between OMNeT++ and SUMO environments to run simultaneous parallel V2X simulation. Suppose the parallel simulation is conducted on OMNeT++ and SUMO. In that case, communication-related simulation results such as end-to-end delay and Packet Delivery Ratio (PDR) can be collected on OMNeT++. Simulation results related to vehicular driving, such as average driving time and average driving speed, can be gathered on the SUMO simulator.

In the simulation setting step, the identical simulation environment must be applied to both simulators to apply the WAVE system to V2X nodes. The following simulation scenarios are applied equally to OMNeT++ and SUMO to proceed with DSRC/WAVE-based V2X simulations. In those scenarios, to confirm whether the application of the V2X communication network plays a positive role in mitigating traffic congestion, a traffic accident is artificially generated at a specific time and on the road, resulting in an unexpected traffic jam.

4.2 Vehicle Path Rerouting via V2X Communication

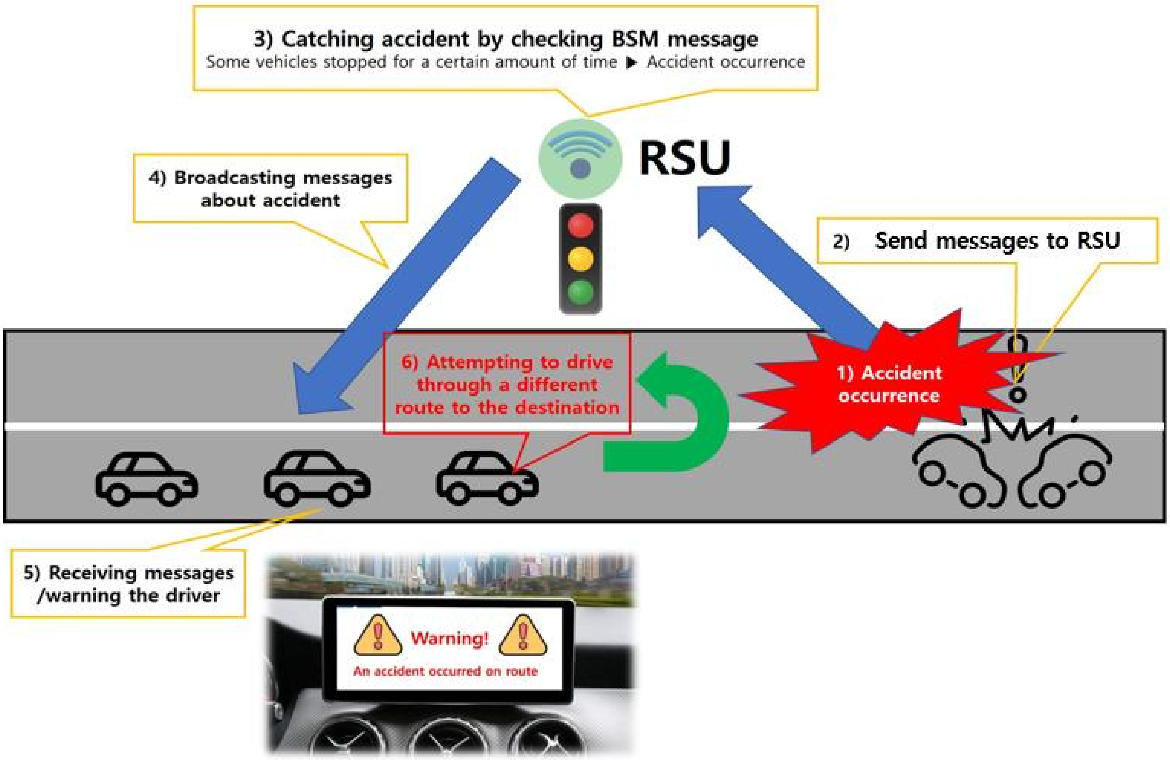

Figure 4.2 Workflow of V2X-based path rerouting algorithm

To verify the traffic congestion mitigation effect of vehicle rerouting based on V2X communication under an accident, artificial traffic accidents are modelled in V2X simulations. Veins framework provides a simple path rerouting algorithm that assigns a new driving path to vehicles based on the estimated driving time of vehicles on each road through V2X communication. In this study, path rerouting due to the accident is performed using that V2X-based algorithm as shown in Figure 4.2. It is assumed that the driver always makes an optimal judgment when receiving traffic information through V2X communication for convenience.

The procedures are as follows. First, when an accident occurs on the road, the vehicles stopped due to the accident send messages to RSU. In this message, there is a road ID information where an accident has occurred. The RSU receives those messages and can recognize the information about the accident. Then, the RSU broadcasts BSM messages about the accident to other vehicles normally driving on the road. As the vehicle receives BSM from RSU, it warns the driver and tries to drive an alternative route to the destination. In addition, vehicles with an initially set route that do not pass through the accident road do not change the initial route even if BSM is received. Also, to prevent redundant path changing of all vehicles, after the vehicle's initial route is changed to bypass the accident road, it is not changed twice even if BSM is received again.

4.3 Realistic Road

4.3.1 Simulation Setup

To analyze whether V2X communication can alleviate the traffic congestion caused by an accident under the realistic road environment, an actual road map is utilized. Figure 4.3 shows the artificially modelled actual road environment of Technopolis, the sub-center of Daegu Metropolitan City. As shown in Figure 4.3, the actual Technopolis road map is converted into a realistic simulation road environment on SUMO using the OpenStreetMap (OSM) program. Other factors such as traffic light arrangement and road speed limit that OSM cannot model are manually reflected in SUMO as closely as possible to actual roads.

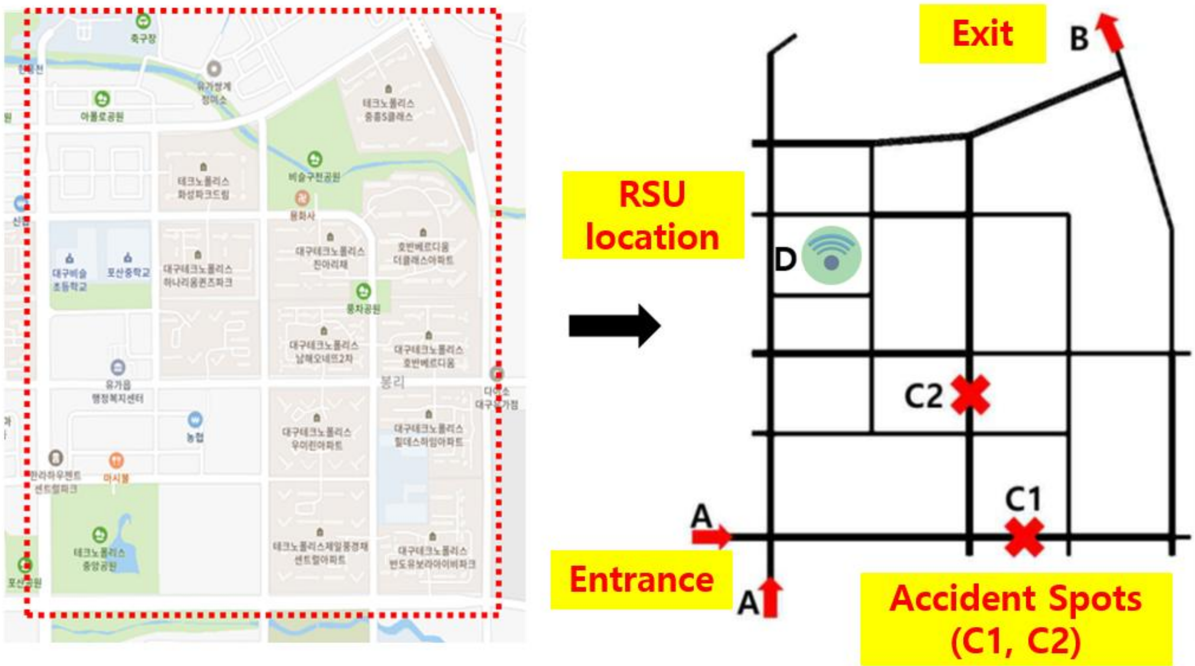

Figure 4.3 Technopolis road environment created using SUMO and OpenStreetMap

All vehicles placed in the simulation are generated at regular time intervals from the entrance A and drive to the destination B, a road connected to the downtown Daegu. It reflected that many vehicles from the Technopolis Industrial Complex headed for the downtown Daegu during the quitting time of work. The driving routes of vehicles are determined by the 'Duarouter' algorithm, which is an iterative route planning algorithm employed to apply the shortest path from entrance road to destination road in SUMO. To model traffic accidents, we artificially stopped several vehicles at points C1 and C2, setting those points as accident spots. Those two accident spots reflect the actual accident black spots of Technopolis road and high vehicular traffic spots in simulations. In the case of RSU, it is located at point D, where the schools are located. By utilizing the Veins framework in the road environment as modelled above, all vehicles and RSU can perform DSRC/WAVE-based V2X communication. The simulation parameters are shown in Table 4.1.

Table 4.1 Simulation parameters of realistic road scenario

Parameter	**Value**
V2X type	DSRC/WAVE, V2I
Transmission channel	CCH (Ch 178)
Message type	Basic Safety Message (BSM)
Transmission rate	10 Hz
Data rate	6 Mbps
Message size	300 Bytes
Transmission power	20 dBm (100 mW)
Channel model	SimplePathlossModel (= Free space model)
Speed limit	School zone: 30 km/h Public road: 60 km/h
Number of vehicles	600 to 1,800 (Increased by 200 vehicles)
Road network size	Same as actual Technopolis road
Simulation time	3,600 seconds

The RSU broadcasts a 300 Bytes size message (BSM) with a 10 Hz transmission period, and all messages are transmitted on the Control Channel (CCH) according to the DSRC/WAVE standard. In these simulations, the ‘SimplePathlossModel’ implemented in Veins framework, which is the same as the free space model, is applied as a channel model. To verify the positive effect of the application of V2X only in terms of overall traffic flow, the simplest channel model is used to ensure V2X communication without failure.

4.3.2 Results and Analysis

Table 4.2 Simulation cases in realistic road scenario

	Accidents at C1, C2	**Path Rerouting via V2X**
Case 1	X	X
Case 2	O	X
Case 3	O	O

In the realistic road scenario, simulations are conducted in three cases to analyze the effect of V2X communication on traffic flow, as shown in Table 4.2. Case 1 is when no accident occurs, and V2X communication is not applied. Case 2 is when an accident occurs at points C1 and C2, but V2X communication is not applied. Furthermore, Case 3 is where the path of the driving vehicle is reset by applying V2X communication when an accident occurs at points C1 and C2. The traffic flow is evaluated by adjusting the total number of vehicles created in the entire simulation time, and the traffic flow evaluation metrics are the average speed and average driving time of all vehicles driving from A to B, except for the accident vehicles.

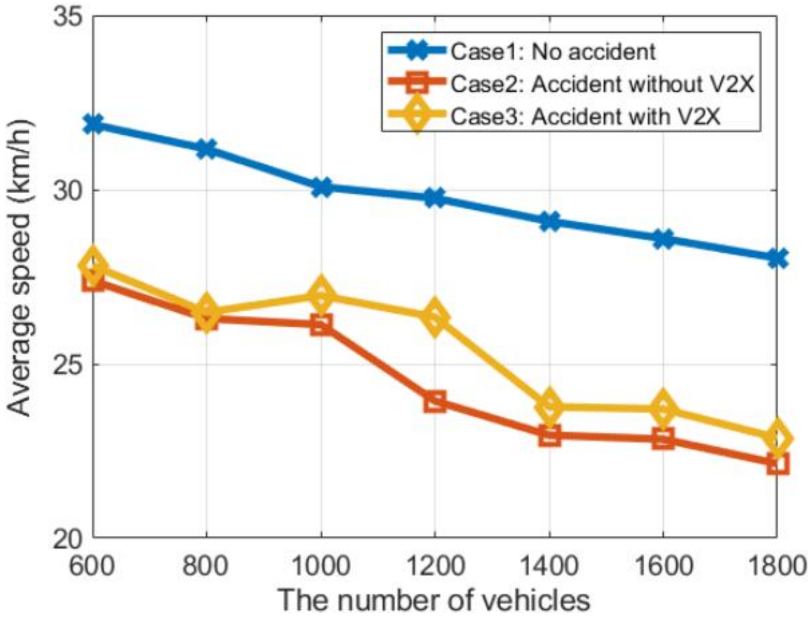

Figure 4.4 Average speed of vehicles adjusting the number of vehicles (Technopolis)

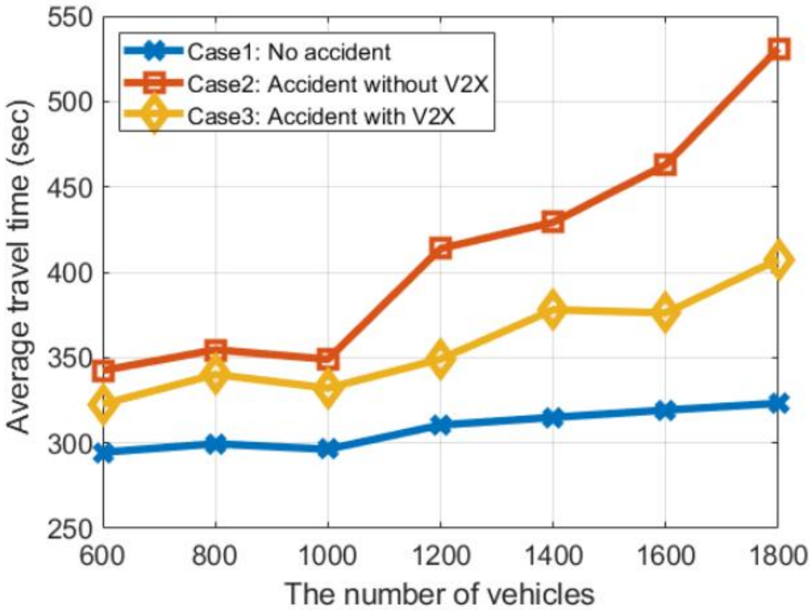

Figure 4.5 Average driving time of vehicles adjusting the number of vehicles (Technopolis)

Figure 4.4 and Figure 4.5 show the average speed and average driving time of all vehicles traveling from A to B, based on the Technopolis road shown in Figure 4.3. Obviously, as shown in Case 1 results, when no accident occurred, the average speed of all vehicles is the fastest while the average driving time is the shortest, representing the best traffic performance. From now on, we compare the average speed and driving time of Case 2 and Case 3, where the accidents occurred. When the vehicle routes are reset by recognizing accident information in advance through V2X communication between vehicles and RSU, the average speed always increases and the average driving time decreases regardless of the number of vehicles, compared to when the V2X is not applied. These results indicate that the overall driving performance of vehicles is improved due to path rerouting based on V2X communication. Therefore, it can be seen that the application of V2X communication can carry out a positive role in mitigating traffic congestion caused by accidents.

However, a key problem in these simulations is that more simulation results should be required to demonstrate the positive effect of V2X communication on the traffic flow more clearly. Also, we thought that it is insufficient to consider only situations where V2X is applied 100 % on the road or not at all. Therefore, considering the above points, we conduct additional simulations in the common urban road scenario, before running simulations on a realistically modeled road.

4.4 Urban Manhattan Grid Road

The road environment considered for the general urban road scenario is Manhattan grid road. As mentioned earlier, Manhattan grid road environment is one of the basic grid topologies that can be applied to analyze communication and driving performance of urban road in V2X simulations.

4.4.1 Simulation Setup

Figure 4.6 shows the 2 x 2 Manhattan grid mobility map created by using the SUMO simulator.

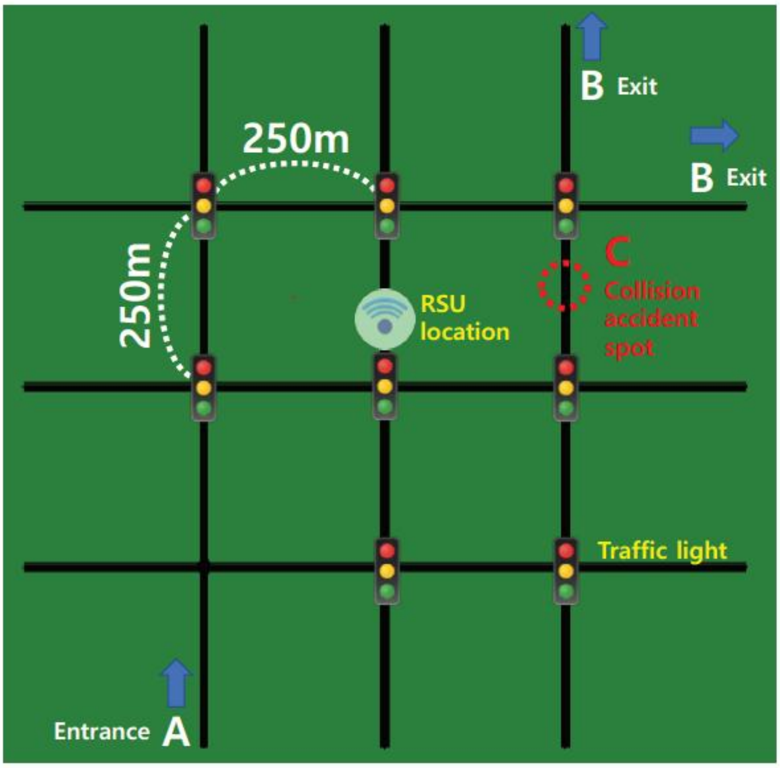

Figure 4.6 Urban Manhattan grid road environment created using SUMO

There are three vertical and three horizontal two-way roads where the distance between the roads is constant at 250m. All the roads are set as two lanes for each direction. In traffic flow, all vehicles are set to be created at regular time intervals at entrance A and to drive to the destination point B, as indicated in Figure 4.6. The vehicle's driving route is determined by the 'Duarouter' algorithm, all vehicles drive with the shortest route from entrance A to destination B. Traffic lights are installed at all intersections on the road except for the intersection in front of vehicle generation point A to prevent massive traffic congestion on the road where all vehicles are generated. All vehicles are set to drive at a maximum speed of 60km/h in consideration of the maximum speed limit of urban roads. Additionally, the point where the accident occurred artificially is point C as shown in Figure 4.7, obstructing 1 lane in 2 lane road. To simulate the vehicle collision accident causing the unexpected traffic congestion at that point, five vehicles are artificially stopped in a row at point C immediately after the simulation started. It is intended for traffic congestion caused by multiple collision accident on urban road.

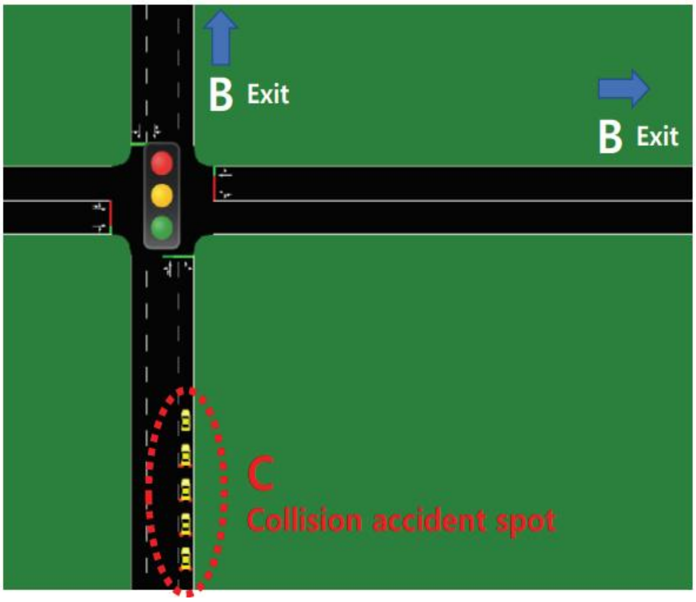

Figure 4.7 Multiple collision accident modeling

Table 4.3 Simulation parameters of urban Manhattan grid scenario

Parameter	Value
V2X type	DSRC/WAVE, V2I
Transmission channel	CCH (Ch 178)
Message type	Basic Safety Message (BSM)
Transmission rate	10 Hz
Data rate	6 Mbps
Message size	300 Bytes
Transmission power	20 dBm (100 mW)
Channel model	SimplePathlossModel (= Free space model)
V2X penetration rate	0 to 1 (Increased by 0.2)
Speed limit	60 km/h
Number of vehicles	200 to 800 (Increased by 200 vehicles)
Road network size	1,000m X 1,000m
Simulation time	3,600 seconds

Table 4.3 shows the overall simulation configuration parameters. All vehicles are equipped with OBU, and the RSU for periodically broadcasting BSM messages is located at the center intersection. Other communication-related parameters are set as same as in the realistic road scenario. Only the traffic-related parameters, such as road speed limit and the number of vehicles, are altered to reflect general urban road.

4.4.2 Results and Analysis

Table 4.4 Simulation cases in urban Manhattan grid scenario

	Accident	**Path Rerouting via V2X**
Case 1	X	X
Case 2	O	X
Case 3	O	O

In the urban Manhattan grid scenario, simulations are conducted in three cases as shown in Table 4.4, as same as the realistic road scenario. The traffic flow is evaluated by adjusting the total number of vehicles created in the entire simulation time and additionally adjusting the percentage of vehicles with V2X (V2X penetration rate). The increase in the V2X penetration rate means that the number of vehicles with V2X capability also increases. The adjustment of the percentage of vehicles with V2X can be executed in the simulation by adjusting a 'penetration rate' parameter in the Veins framework, enabling the V2X capability of a specific percentage of the vehicles. The traffic flow evaluation metrics are an average speed, an average driving time, and an average waiting time of all vehicles driving from A to B, except for accident vehicles. The additional metric, waiting time represents the total amount of time when the vehicle speed is below 0.1 m/s during the driving time from A to B. It is added to analyze the overall traffic flow in more detail.

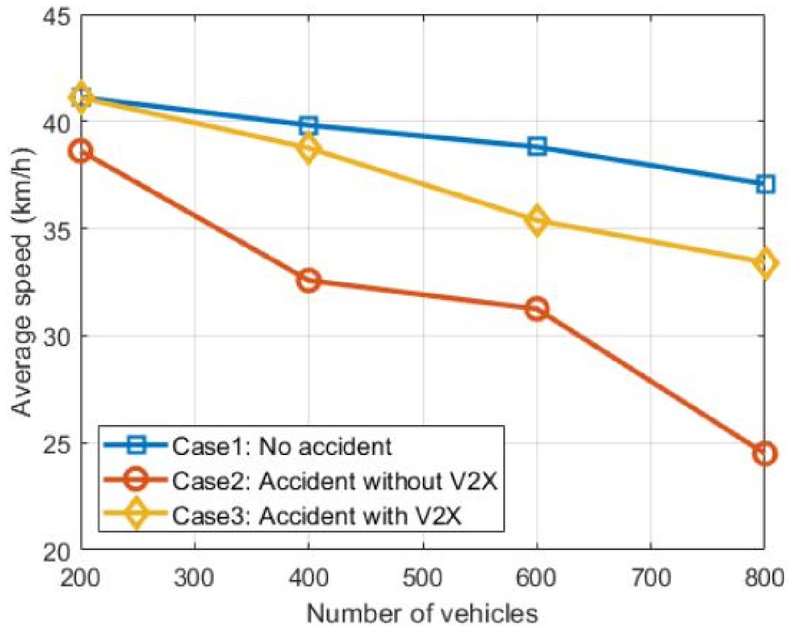

Figure 4.8 Average speed of vehicles adjusting the number of vehicles (urban Manhattan grid)

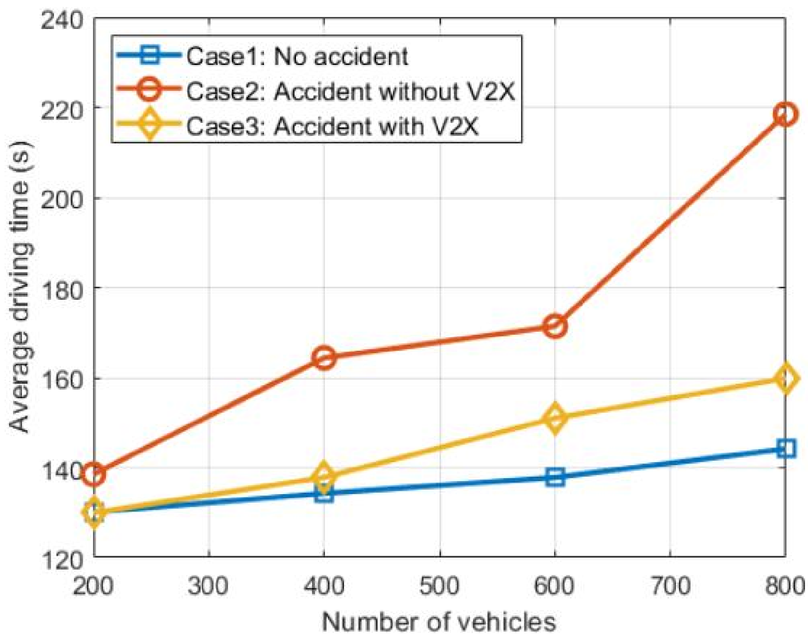

Figure 4.9 Average driving time of vehicles adjusting the number of vehicles (urban Manhattan grid)

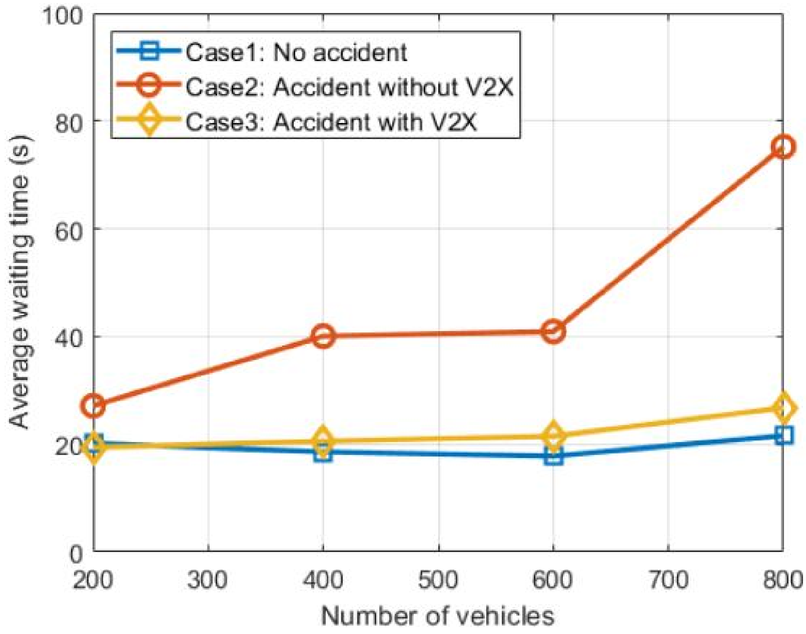

Figure 4.10 Average waiting time of vehicles adjusting the number of vehicles (urban Manhattan grid)

Figure 4.8, Figure 4.9, and Figure 4.10 are quantitative result graphs showing the average speed, driving time, and waiting time of all vehicles in each case when the number of vehicles is adjusted. First of all, it can be seen that in Case 1, where no accident occurred, the overall driving performance of vehicles is the best.

Then, we will analyze the results of Case 2 and Case 3 where the accident has occurred. In Case 2, V2X communication between the RSU and the vehicle is not carried out at all, so even though an unexpected accident occurred at point C, the RSU and the driving vehicles cannot recognize the accident information in advance. Since vehicles travel only on the initially set route in Case 2, traffic congestion on the accident road is more severe than in Case 3. Therefore, the average speed of vehicles is slower, and the average driving time and average waiting time are longer than in Case 3. On the other hand, in Case 3, where V2X communication is applied to the entire road, it can be seen that the driving performance of normally driving vehicles is significantly improved. Moreover, it is shown that the improvement in overall driving performance is even greater, as the number of vehicles is increasing. Accordingly, we can expect that vehicle path rerouting based on V2X can improve the overall traffic flow when accidents have occurred. We additionally need to consider the higher traffic density of urban roads. It is because the number of vehicles is up to 800 in these simulations.

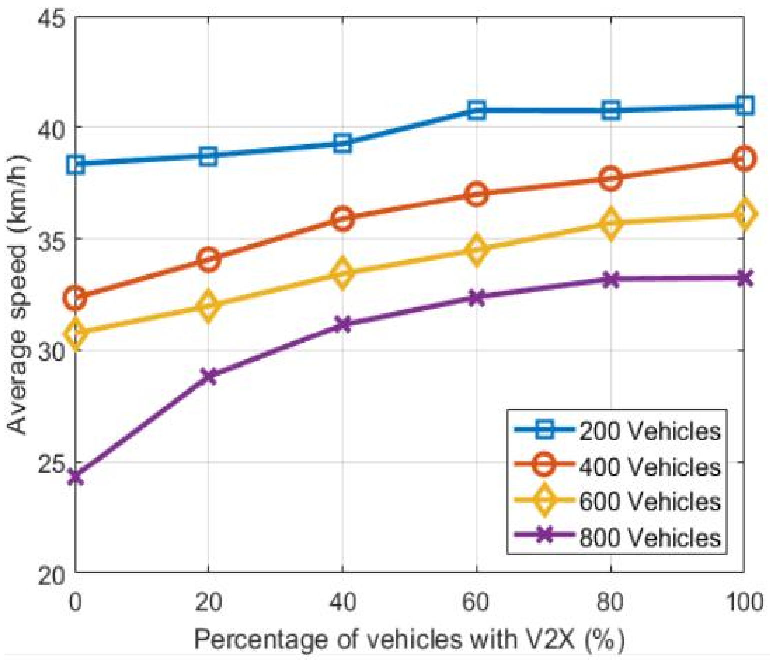

Figure 4.11 Average speed of vehicles adjusting the V2X penetration rate

Figure 4.11, Figure 4.12, and Figure 4.13 show the quantitative results adjusting the V2X penetration rate and fixing the number of vehicles. Simulations are conducted by adjusting the V2X penetration rate from 0 % to 100 %, in 20 % increments.

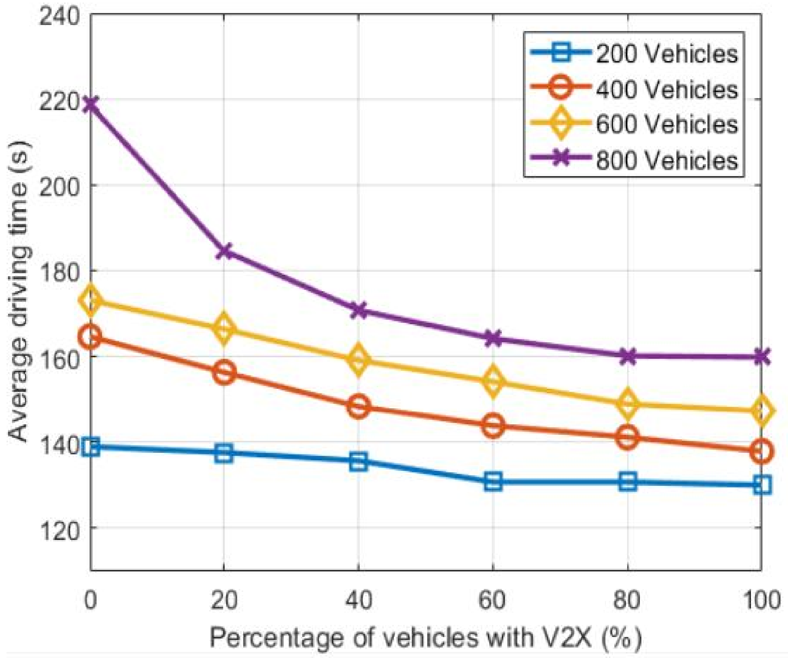

Figure 4.12 Average driving time of vehicles adjusting the V2X penetration rate

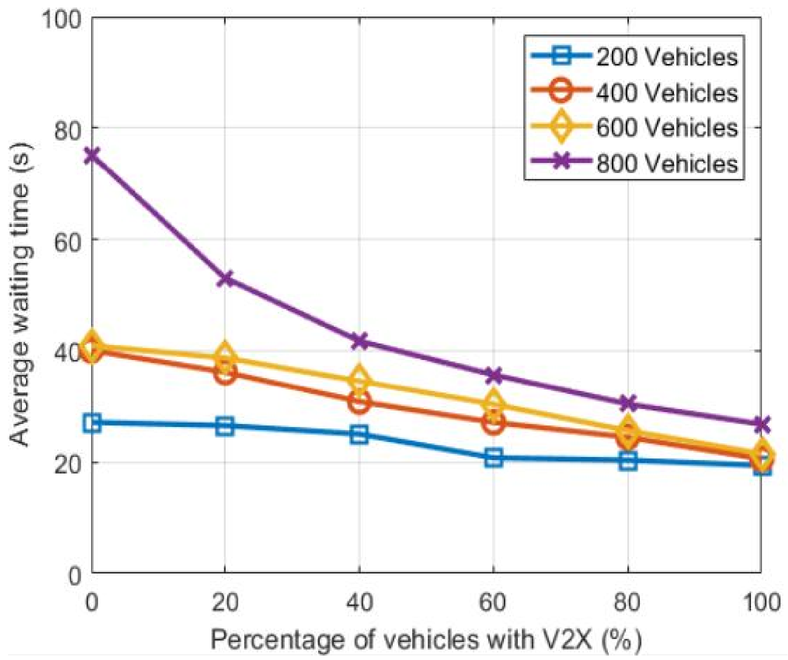

Figure 4.13 Average waiting time of vehicles adjusting the V2X penetration rate

As we mentioned earlier, the increase in V2X penetration rate means that the number of vehicles with V2X capability also increases. In other words, it indicates that the number of vehicles recognizing the accident in advance also increases. In the above result figures, as the V2X penetration rate of all vehicles increases, the average speed of vehicles also increases, while average driving time and waiting time decrease, regardless of the total number of vehicles. Moreover, the overall driving performance improvements due to the V2X are more noticeable when the number of vehicles is increasing. In the case of a total of 800 vehicles during the entire simulation time, when the V2X penetration rate is 100 %, the average speed of all vehicles increased by about 10 km/h and the average waiting time is reduced by less than half, compared to when the V2X penetration rate is 0 %. Therefore, we can say that the increase in the V2X penetration rate is helpful to improve the overall traffic flow under unexpected accidents on the road.

Ⅴ. CONCLUSION

In this paper, we conducted several V2X simulations from two perspectives. First, we analyzed and compared the general communication performance in terms of reliability and latency in highway road environment using MATLAB-based LTEV2Vsim. As a result, DSRC is superior to LTE-V2X Mode 4 in terms of end-to-end delay. On the other hand, in terms of packet reception ratio, LTE-V2X Mode 4 is superior to DSRC. These results revealed that each technology has distinct strengths and weaknesses, and there is not an optimal V2X technology for proper in every road environment.

Then, we tried to analyze whether the application of V2X communication can alleviate traffic congestion caused by unexpected traffic accidents and improve traffic flow. To this end, we carried out DSRC/WAVE-based V2X simulations in the realistically modelled Technopolis road and urban Manhattan grid road environments using OMNeT++, SUMO and Veins. In case of the accident in both road environments, V2X communication played the role of reconfiguring the vehicle route to bypass the accident road by broadcasting information about the accident location from the RSU to all driving vehicles. To verify the positive effect of V2X communication on the traffic flow, we compared the overall traffic performance in urban road environments when V2X is applied or not. As a result, the application of the vehicle path rerouting algorithm based on V2X can increase the average speed of vehicles, while reducing the average driving time and average waiting time. Accordingly, we confirmed that V2X communication applied on the road environment can mitigate severe traffic congestion due to the accident and improve the overall traffic flow by spreading the information about the accident in advance.

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요 약 문

V2X 통신을 활용한 교통 흐름 개선

Vehicle-to-Everything (V2X) 통신은 차량이 주위 차량 및 도로 인프라 등과 교통 정보를 실시간으로 교환하는 기술로, 도로 안전과 효율성을 향상시키고 고도의 자율 주행을 실현하기 위한 필수 요소로 평가된다. V2X 통신 기술은 Dedicated Short-Range Communication (DSRC)와 Cellular-V2X (C-V2X) 두 가지로 나뉘며, 기술들은 서로 상이한 장단점들을 가지고 있다. 본 논문에서는 우선 MATLAB 기반의 LTEV2Vsim 시뮬레이터를 활용하여 highway 도로 환경을 구성해 두 V2X 기술들의 성능을 통신 지연 (latency)과 신뢰성 (reliability) 측면에서 비교하였다. 시뮬레이션 결과, DSRC 는 지연 측면에서 더 우수하고, C-V2X 는 신뢰성 측면에서 더 우수함을 확인할 수 있었다. 이후, V2X 통신이 도심 도로 환경에서 안전과 효율성을 개선하는데 긍정적인 효과를 미칠 수 있는지를 검증하고자 했다. 이를 위해, 간단한 시뮬레이션을 통하여 북미 DSRC 표준인 Wireless Access in Vehicular Environment (WAVE) 표준 기반의 Vehicle-to-Everything (V2X) 통신을 기반으로 한 차량의 주행 경로 재설정 알고리즘을 활용함으로써 도로 환경에서 교통 사고로 인해 발생한 교통 혼잡을 완화할 수 있는지 분석하였다. OMNeT++, SUMO 시뮬레이터 및 Veins 프레임워크를 사용하여 무선 V2X 네트워크 및 도심 도로 환경을 구성하고, 특정 도로에서 인위적인 사고를 발생시킨 후 시뮬레이션을 수행했다. 교통 흐름을 평가하기 위한 지표로 차량의 평균 속도, 평균 주행 시간 및 평균 대기 시간을 활용했다. 시뮬레이션을 수행한 결과 V2X 통신 기반의 차량 주행경로 재설정 알고리즘의 적용이 교통 사고로 인해 발생한 교통 혼잡을 완화함으로써 교통 흐름을 개선할 수 있음을 보였다.

핵심어: V2X 통신, DSRC, C-V2X, 교통 흐름 개선