Vehicular Communication Simulation Platform (VCSim) for Traffic-oriented Environment

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Abstract

The vehicular communication network is a key technique to support Intelligent Transportation System (ITS) services. Due to high mobility and rapidly dynamic topology, it brings great challenges to the performance simulation. In this paper, firstly we give a brief overview of the heterogeneous vehicular networks (HetVNET) and the resource management in it. Then, the simulation methodology is discussed for HetVNET, which integrates the traffic and the network simulation. Finally, based on the simulation methodology, the vehicular simulation platform (VCSim) is built and simulation results show that the platform can reflect the traffic and communication behaviors well.

***Keywords**: Vehicular networks, Resource allocation, Simulation platform, Intelligent Transportation, heterogeneous vehicular*

1. Introduction

Vehicular communication networks have become one of the essential domains of Intelligent Transportation System (ITS) both in academic and industry communities. Lots of vehicular applications have been developed to enhance the safety of transportation and improve the drivers' experience via enabling vehicles to communicate with each other (V2V) or with the roadside units (V2I). The vehicles periodically broadcast and receive beacon messages including the position, velocity, status and so on via V2V communication. Moreover, the roadside units (RSUs) can provide Internet connectivity for drivers to improve the quality of experience using V2I communication.

Consequently, the study on vehicular communication networks becomes an important research issue. In the United States, FCC has allocated 75 MHz (5.850GHz-5.925GHz) radio bandwidth dedicated for vehicular communication in 1999 [1]. Meanwhile, IEEE has standardized the IEEE 802.11p/1609 protocol stack, also named WAVE (Wireless Access in Vehicular Environments), for vehicular communication networks [2, 3]. IEEE 802.11p specificate the PHY and MAC of WAVE protocol stack, which uses the CSMA/CA based EDCA as its medium access control mechanism [4]. At the same time, plenty of works have proposed solutions or designed protocol to deal with the defects of IEEE 802.11p, for instance, the high collision probability and low channel utilization in high dense node condition. A location-based channel congestion control scheme for V2I networks is proposed in [5] to handle the

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problem of access collision in high node density. In [7], some architectural enhancements have been proposed to fulfill the M2M service requirements, which can also be applied in vehicular communication. Therefore, a simulation platform which can effectively simulate the traffic and communication behaviors is badly needed to make the performance simulation for previous solutions or protocols.

Recently, many works have been done for the vehicular network simulation coupling traffic simulator and network simulator. The three ways of coupling these simulators are distinguished in [6], i.e., offline coupling (trace file), online one-way coupling, and online two-way coupling (feedback loop). The traffic simulators, such as Q-Paramics, SUMO [8], or TransCAD, are used to produce the trace file of movement for network simulators like ns-2 or OPNET in offline coupling mode. Online couplings eliminate the sequential file-based process via having both simulators run in parallel. In the online one-way coupling, the data is only sent from the traffic simulator to the network simulator, or vice versa. While in the online two-way coupling, the data can be shared with both simulators. In [6], an online two-way coupling is designed for an evaluation of the effects on traffic when vehicles react to the traffic light phase schedule information via traffic Control Interface (TraCI).

In this paper, we present a novel coupling platform which is developed by OPNET software. The traffic simulation is designed as a module in the platform, not fetching vehicle’s data from the traffic simulation software via interface. Thus, our platform can operate more efficiently than others. The main contributions of our work are summarized as follows:

- Proposal of a heterogeneous vehicular network which integrates3GLTE and IEEE 802.11p;
- Discussion on simulation methodology in vehicular communication networks;
- Build up a vehicular simulation platform which consists of the traffic model and the communication model.

The rest of our paper is organized as follows. In Section 2 the framework of heterogeneous vehicular networks is proposed. The problem of resource management in vehicular networks is stated in Section 3. The simulation methodology in vehicular networks is proposed in Section 4. The simulation results obtained through VCSim are shown in Section 5. Finally, conclusions and future research are provided in Section 6.

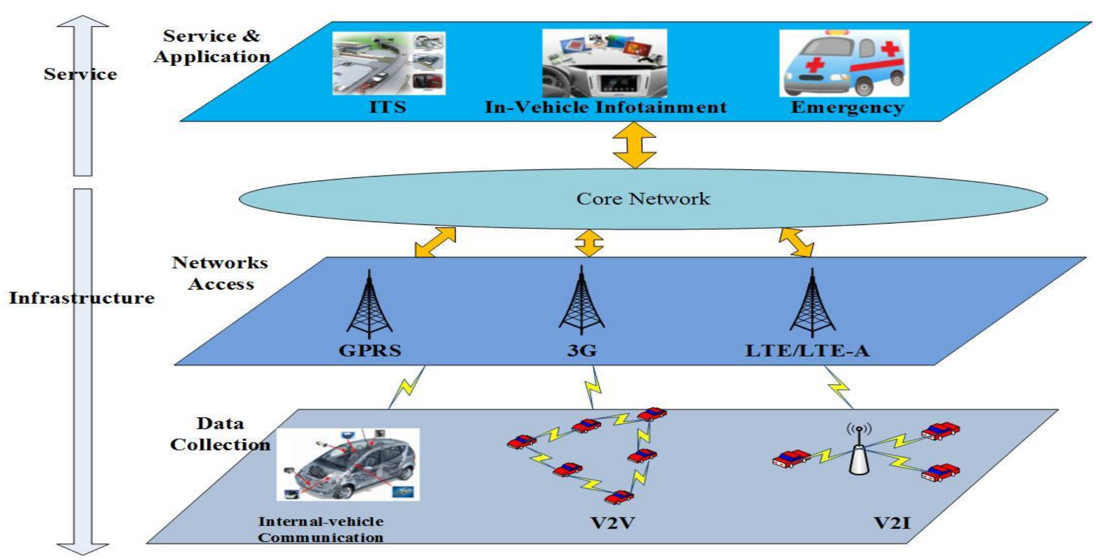


Figure 1. The Framework of HetVNET

2. Heterogeneous vehicular networks

In Intelligent Transportation System (ITS), two main types of services have been classified, i.e., safety services and non-safety services. The target of safety services is to reduce the occurrence of car accidents. Timeliness and reliability are highly demanded as the major requirements for this kind of services, i.e., the minimum frequency of safety messages varies from 1 Hz to 10 Hz and the maximum latency time is 50ms or 100ms. However, for non-safety services, which are mainly used for traffic management, infotainment and so on, the maximum latency time is 500ms and the minimum frequency of messages is 1 Hz [9].

However, due to the large-scale networks size, high mobility condition, dynamic network topology and unreliable connectivity, single wireless networks, i.e., cellular network or IEEE 802.11p can hardly satisfy the QoS requirements of ITS services. For example, with the increasing number of vehicular nodes, the performance of IEEE 802.11p decreases rapidly, e.g., the collision and end-to-end delay [10]. The same problem also occurred in cellular networks. In urban scenarios (high node density), 3G LTE suffers from larger delay and higher packet loss due to resource scheduling and other sequential activities.

To satisfy the QoS requirements of different services, heterogeneous vehicular network is the trend of vehicular communication. In this paper, a novel framework, termed as HetVNET, is designed for vehicular communication as shown in Figure 1. HetVNET is composed of the Radio Access Network (RAN), the Core Network (CN) and the Service Center (SC). The SC can provide a variety of services, i.e., road information, weather report, etc. used by the service provider. The main function of CN is management and gateway.

In the data collection section of the framework, there are three modes of communication, i.e., internal-vehicle communication, V2V communication and V2I communication. Internal-vehicle communication is a method to collect, through Bluetooth, the status of itself such as infrared communications or sensor techniques including velocity, position and so on. The statuses of other vehicles are collected by V2V communication. Moreover, the roadside unit (RSU) broadcasts local messages, for example, warning messages and traffic light information, to the vehicles nearby using V2I or I2V communication. The cellular network, i.e., GPRS, WCDMA, 3G LTE, is an effective method for vehicles to connect the core network.

2.1. V2I communication

The V2I communication provides the connections between the vehicles and RSU/eNB. In the United States, DSRC has been designed to support V2I communication, which uses IEEE 802.11p as its PHY and MAC layers [1]. Meanwhile, the 3G LTE networks have been proposed for vehicular services for many years [11]. However, there are several reasons for LTE applicability for V2I communications [12]. Firstly, LTE relies on capillary deployment of eNodeBs organized in a cellular network infrastructure offering wide area coverage. This would solve the issue of poor, intermittent, and short-lived connectivity in IEEE 802.11p, and would particularly indicate LTE for V2I communications even at high node speeds. Secondly, a higher penetration rate is expected to be achieved by LTE compared to IEEE 802.11p. Moreover, LTE can offer high downlink and uplink capacity (up to 1 Gbps for LTE-A in Rel.11), while IEEE 802.11p only offers a data rate up to 27 Mbps. Finally, the centralized architecture of LTE natively supports the V2I communication which is a infrastructure-based framework. Therefore, LTE is one of the most suitable communication ways for V2I communications.

2.2. V2V communication

V2V communication acts as an effective solution to provide the direct communication between vehicles, which is suitable for safety message broadcasting. IEEE 802.11p is proposed for V2V communication. However, the research is ongoing to enable direct device-to-device (D2D) communication in LTE-A [13]. D2D communication is also a method for local data exchange among vehicles, but there are several challenges that should be addressed. On one hand, the interference between eNBs and D2D need an effective solution to handle. On the other hand, the fast moving speed and severe vehicular environments degrade the performance of D2D. To sum up, IEEE 802.11p is a better choice for V2V communication compared to D2D communication.

3. Resource management in HetVNET

Through cooperative communication between LTE and IEEE 802.11p, HetVNET can perform resource management functions to achieve the maximum throughput while meeting the QoS requirements for vehicular services. Since safety services are usually delay-sensitive, while infotainment services, such as multimedia or download, require high throughput or data rate, the resource management schemes should be designed for different objectives. Extensive researches on resource management in HetVNET have been done to deal with the downlink transmission with the following optimization objectives.

A HetVNET with N vehicles on the road for downlink scenario is considered in this paper. Each vehicle equipment (VE) can establish direct link with the Base Station (BS) similar to the normal user equipment (UE) in LTE networks. Beyond that, every VE can help anther VE to forward data or not, depending on their channel quality and networks requirements via V2V communication. Therefore, the links between BS and VEs can be established directly or via 2-hop cooperative relaying. The throughput gain can be achieved by cooperative relaying if the data rate of 2-hop is higher than that of direct transmission.

3.1. Direct or 1-hop communication

In the 1-Hop communication mode, the VEs establish direct links with the BS via LTE networks. As specified in LTE specification [11], the entire radio resources are divided into resource blocks (RBs) along the time and frequency domain, which can be shared among all VEs depending on different scheduling algorithms. Thus, the achievable data rate of the i-th V2I link is expressed by

$$\eta_{B,i} = N_i \log_2(1 + SINR_i),\ 1 \le i \le N, \tag{1}$$

where N_i is the number of RBs allocated to i-th VE depending on current scheduling scheme and $SINR_i$ is the receiving Signal-to-Interference-plus-Noise Ratio of the i-th VE from the BS.

3.2. Cooperative or 2-hop communication

When the VE is traveling at the edge of the cell with poor channel conditions, its data may be forwarded by another VE in proximity to the BS via out-of-band relaying communications using the IEEE 802.11p. For simplicity, we assume that one VE can help only one VE at a time, and vice versa. Thus, the equivalent achievable data rate of cooperative communication can be given by

$$min\{\eta_{B,i},\eta_{i,j}\},1\le i,j\le N,i\ne j, \tag{2}$$

$$\eta_{i,j}=N_{i,j}\log_2(1+SINR_{i,j}), \tag{3}$$

where $\eta_{i,j}$ is the data rate between i-th VE and j-th VE when $N_{i,j}$ RBs are allocated on this link and $SINR_{i,j}$ is the receiving SINR of the j-th VE from the i-th VE.

Different scheduling schemes only differ in the choice of N_i and $N_{i,j}$ and the selection of relaying VE. For instance, a cooperative scheduling scheme is proposed in [14], which is based on the graph theory. In this algorithm, the scheduling on both V2I links and V2V links adopts the Round Robin (RR) algorithm. Then Kuhn-Munkres (KM) algorithm is employed to solve the problem of maximum sum throughput with considerably computational complexity. Performance evaluation shows that the KM scheme performs higher throughput and achieves better fairness.

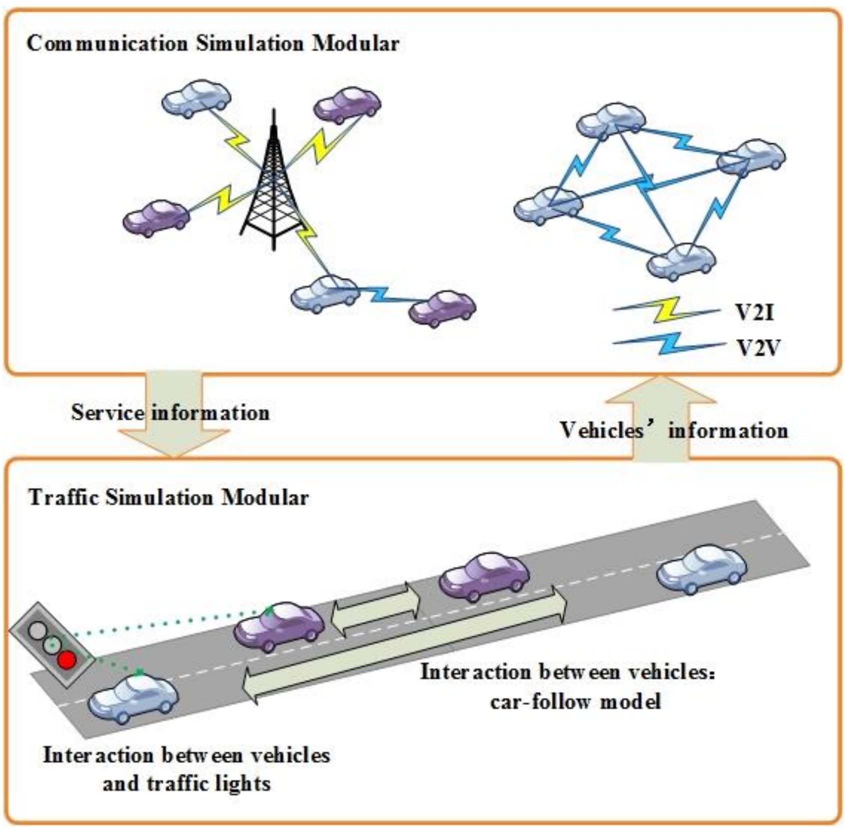


Figure 2. Interaction between traffic and communication simulators.

4. Simulation methodology in vehicular communication networks

In this section, we discuss the method to build up a novel simulation platform for vehicular networks, which consists of the traffic simulator and the network simulator as illustrated in Figure 2. The two components of the platform exchange information in real-time. The traffic simulator sends vehicle information, i.e., vehicle speed, location, direction and status, to the communication simulator to calculate the available path and pathloss more precisely. Meanwhile, the network simulator gives feedback of the scheduling information to the vehicles for reasonable path scheduling.

4.1. Traffic simulator

According to the different extent that the details of traffic flow can be resolved, which ranges from average quantities down to individual vehicle motion, modeling traffic flow can be classified into three classifications: macroscopic traffic simulation, microscopic traffic simulation, and mesoscopic microscopic traffic simulation [21]. Macroscopic traffic simulation is employed to describe the overall averaged quantities of the system, like vehicle density and average speed, while the microscopic models address the subject by describing individual vehicle dynamics, pedestrian and signal lights' status. The third model, mesoscopic model, describes the traffic flow using a mixture of macroscopic and microscopic models. A short overview about these model classes will be given.

4.1.1. Microscopic traffic simulation

The main idea of microscopic modeling is to describe the dynamics of each individual object, i.e., vehicles, pedestrians and signal lights. Therefore, the car-following model, modeling of human behavior and signal light model have to be considered.

a) Car-following model

There are much more sophisticated approaches for describing car-following model, i.e., the classical car-following model [15] and the optimal velocity model [16]. But in this section, we will give a description of simplest car-following model which assumes a road with only one lane. The car-following model is derived from a quite reasonable assumption that a change of the velocity is performed only if the momentary velocity does not coincide with the desired velocity v_{des}, which is determined by safety considerations, legal restrictions and so on [21]. The features of the car-following model are that it’s continuous in space, discrete in distance and accident-free. The velocity of the vehicle depends on the preceding vehicle as illustrated in Equation 4,

$$v(t) = max\{0, rand[v_{des}(t) - \varepsilon a, v_{des}(t)]\}, \tag{4}$$

Where

$$v_{des}(t) = min\{v_{safe}(t), v(t-\tau) + a\tau, v_{\max}\}, \tag{5}$$

$$v_{safe}\left(t\right) = v_p\left(t\right) + \frac{g\left(t\right) - v_p\left(t\right)\tau}{\bar{v}/b + \tau}, \tag{6}$$

where $g\left(t\right)$ denotes the distance between the current vehicle and its preceding vehicle, $v_p\left(t\right)$ is the velocity of the preceding vehicle, τ is the update interval of the simulator, a and b are the acceleration and deceleration respectively, $v_{\max}$ is the maximum velocity that legal restrict and ε is the driver's response time.

b) Modeling of human behavior

Most human behavior models are based on extremely simplified ideas about the way humans behave in traffic environment [21]. For instance, based on the simple idea that drivers only react, when certain perception thresholds are exceeded, an action-point-model is proposed in [17]. A completely different approach is proposed by Rekersbrink [18], who modeled the driver-vehicle system using fuzzy controllers. However, all human models are computationally expensive and not suitable for large networks.

c) Signal light model

The signal model is simple, which changes regularly. In this paper, four-state is used to describe the transformation of lights in an intersection based on OPNET software as shown in Figure 3.

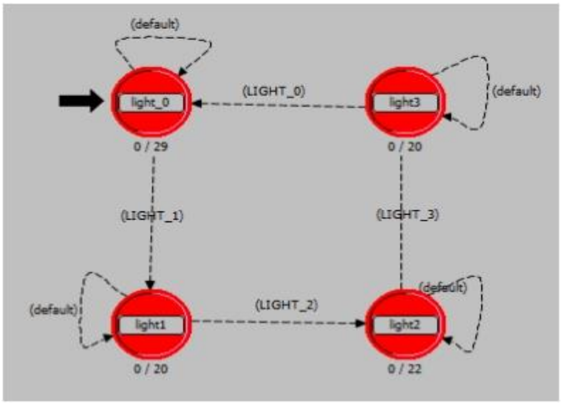


Figure 3. Four-state signal model.

4.1.2. Macroscopic traffic simulation

In macroscopic approaches it is not the dynamics of individual vehicles that is considered, but the dynamics of quantities that only have a macroscopic meaning. Generally in this model, the vehicle density $\rho(x,t)$ and average velocity $v(x,t)$ are the main parameters to manage traffic, which is the function of both space x and time t. These quantities are achieved by averaging over a region of sufficiently large spatial extent. The number of vehicles in a certain segment only depend on the vehicles entering and leaving the segment, so based on the idea the following equation can be obtained, i.e.,

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \tag{7}$$

Eq. 7 describes the relationship between density and velocity. Different models only differ in the choice of ρ and v. For example, the simplest model of this kind was proposed by Lighthill and Whitham [19], in which the velocity was assumed to be a function $V(\rho)$ of the density, causing the balance equation to evolve to

$$\frac{\partial \rho}{\partial t} + c(\rho)\frac{\partial \rho}{\partial x} = 0, \tag{8}$$

where

$$c(\rho) = \frac{d}{d\rho}(\rho V(\rho)). \tag{9}$$

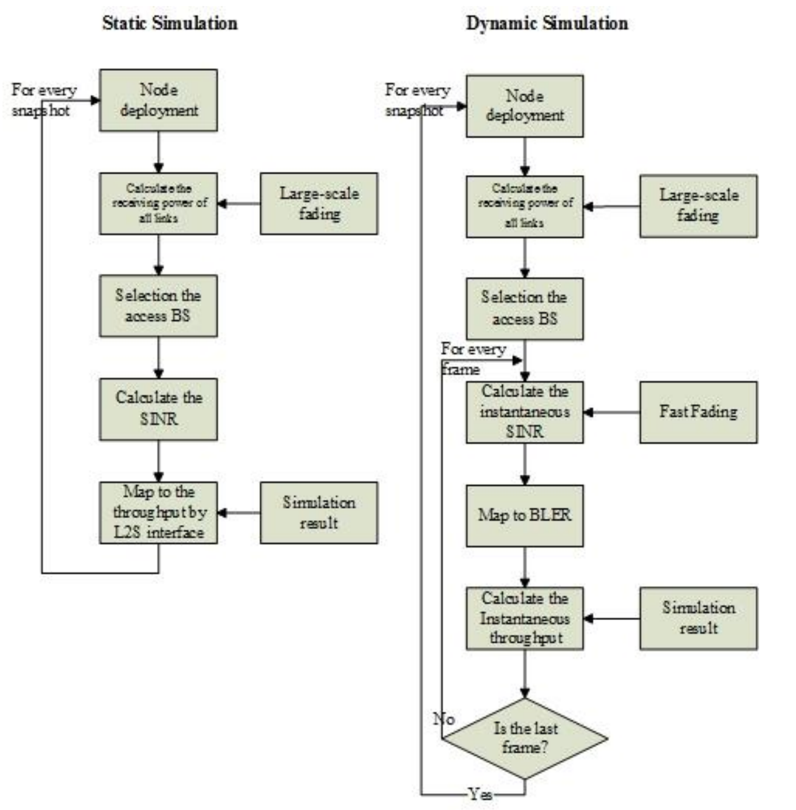
The model describes kinematic waves, but it is not capable of describing the properties of clusters in traffic flow correctly.

4.1.3. Mesoscopic traffic simulation

The mesoscopic model is a mixture model which combines the macroscopic and microscopic models. The individual vehicles in this model are moving according to dynamic laws governed by macroscopic quantities [21]. These models combine the computational efficiency of macroscopic models with the opportunity to derive properties that refer to individual vehicles, like emissions, probability distributions for accelerations, individual travel times and so on.

4.2. Network simulator

In wireless communication networks, network simulation is a technique where a program models the behavior of a network either by calculating the interaction between the different network entities (Base Station (BS), User Equipment (UE), etc.). According to the different extent that the details of simulation can be resolved, the simulation can be classified into link-level simulation and system-level simulation. The link-level simulation mostly concerns the performance of every link, while the system-level simulation cares about the performance of the overall system. Therefore, the network simulator is system-level simulation. Two kinds of network simulation, static simulation and dynamic simulation, are introduced to evaluate the performance of vehicular networks.



(a) (b)

Figure 4. The static and dynamic flow diagram, (a) is static simulation and (b) is dynamic simulation

4.2.1. Static simulation

In the static simulation, the statuses of the system at different sampling time are independent, which are discrete in time domain. Therefore, the static simulation is only applied to analyze the "static performance," e.g., coverage of wireless communication systems, the voice capacity and so on. In the wireless network planning, the static simulation is used to verify whether the performance metrics like coverage and capacity reach the standard or not. The static simulation can also be called Monte Carlo simulations based on snapshots as described in 3GPP TR 36.942 [22]. The Monte Carlo simulation is a classical method which is widely used in the study of "static performance." This method simulates many aspects including the transmission power of BS and UE, the load of BS and so on. The flow diagram of static simulation is depicted in Figure 4 (a). It divided the operation range into several intervals and between every two intervals there is the sampling time of a snapshot. Make a record of all the results of every snapshot and analyze them with the statistical method and we get the final result we expected.

4.2.2. Dynamic simulation

Dynamic simulation in wireless communication is the use of a computer program to model the time varying behavior of the system. Unlike the static simulation, the correlation of continuous frames is taken into consideration. As shown in Figure 4 (b), the large-scale fading and the fast fading are both considered when calculating the instantaneous SINR. Then mapping the SINR to Block Error Rate (BLER), and checking the receiving packet. Discarding the receiving packet and denoting the instantaneous throughput as 0 when the packet is wrong. Otherwise, calculating the instantaneous throughput according to the current Modulation and Coding Scheme (MCS). The dynamic simulation can obtain more precise performance with more complexity of the implementation.

5. Results in Simulation Platform

Table 1. Simulation parameters

Parameter	***Value***
Cell radius	500 m
VE number	50
Traffic model	Microscopic model in [21]
Max drive speed	126 km/h (35m/s)
Acceleration	2.6 m/s²
Deceleration	-4.5 m/s²
Length of time slot	1 ms
Link scheduling interval	1 s
Carrier frequency	2 GHz (V2I)/5.9 GHz (V2V)
Bandwidth	40 MHz (V2I)/5 MHz (V2V)
Transmit power	52 dBm (V2I)/20 dBm (V2V)
Path loss model for V2I link	$P(d)=l+37.6\log_{10}\left(\frac{d}{1000}\right)$, $l=128.1\text{-}2GHz$
Path loss model for V2V link	$P(d)=P(d_0)+10\gamma\log_{10}\left(\frac{d}{d_0}\right)+X_\sigma$

In this subsection, a simulation platform is designed by OPNET software to evaluate the performance of the vehicular networks. As illustrated in Figure 5, seven cells are considered in the platform and within the coverage of them are nine intersections. The vehicles travel along the lanes according to the traffic law and the traffic light model is presented to regulate the traffic flows. The highway has six lanes that are 3.5 meters wide. The car-following model and lane-changing model are considered. The configuration of the vehicle is listed in Table 1.

Two modes of communication, i.e., 3G LTE and IEEE 802.11p, are designed in the platform. The V2I communication is based on 3G LTE, while the V2V communication is based on IEEE 802.11p. Direct communication and cooperative communication are proposed. In the direct mode, all vehicles communicate with the eNB through 3G LTE. However, in the cooperative mode, the vehicles in the edge of the cell can randomly select vehicles as relays to forward the data using V2V communication. The main parameters of the networks are listed in Table 1.

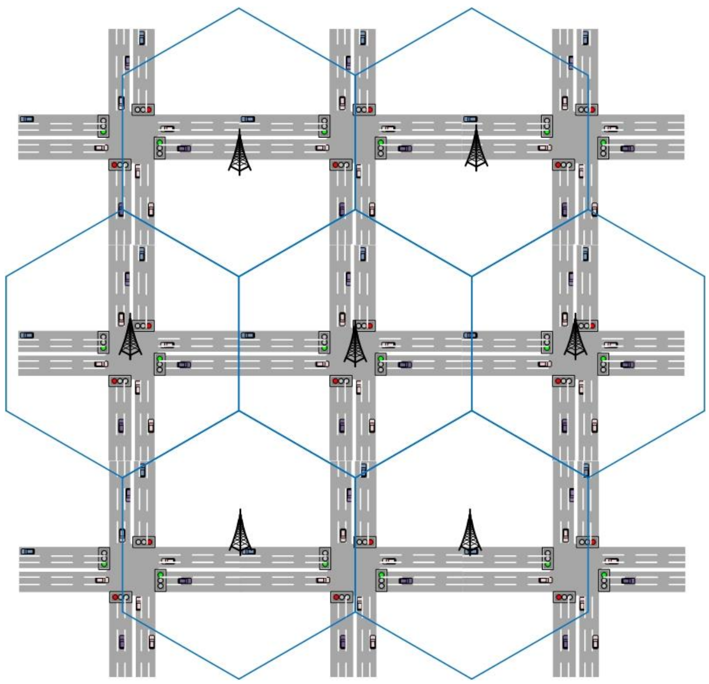


Figure 5. Illustration of simulation scenario of platform

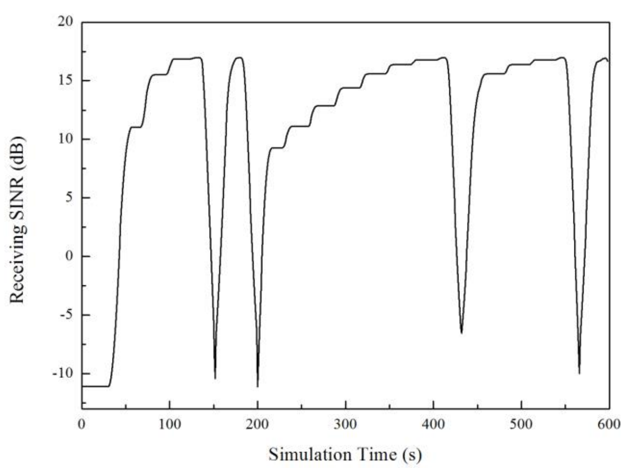


Figure 6. The receiving SINR of vehicle.

Figure 6 presents the receiving SINR from the access eNB. The curve fits the movement of vehicles well. The lowest point of the curve corresponds to the edge of the cell, while the highest point corresponds to the location of the cell center. The action of waiting for the green light in the intersection holds the receiving SINR nearby a constant value for a certain time. Figure 7 plots the average data rate of direct and cooperative communication. As shown in Figure 7, the cooperative communication achieves higher data rate due to the diversity gain.

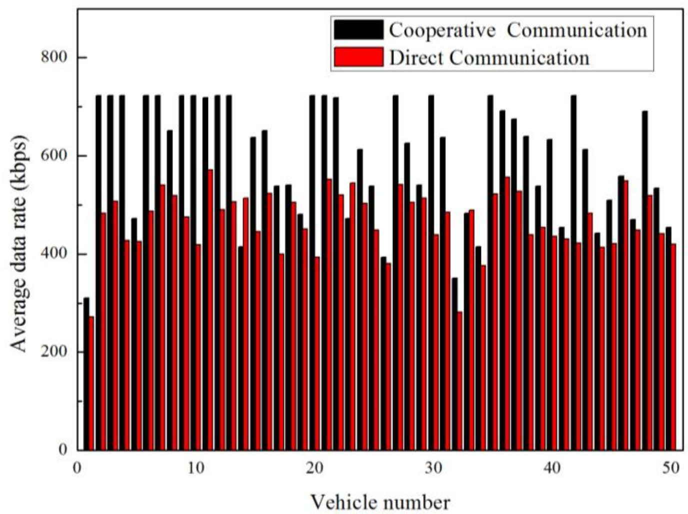


Figure 7. The average statistical data rate of direct and cooperative communications.

6. Conclusion

Vehicular network is a key technique to support the ITS services varying from safety to non-safety services. In this paper the framework of heterogeneous vehicular networks integrating 3G LTE and IEEE 802.11p is proposed. The resource management in heterogeneous vehicular networks is also given. Moreover, in order to evaluate the performance of vehicular networks more realisticly, we implemented the methodology of traffic and network behavior in our platform. Finally, the platform including seven cells and nine intersections was designed to verify the effectiveness of our works. The platform we build up can be used to estimate the performance of current protocol stacks and verify the advantage of proposed solutions in the vehicular environments.

7. Acknowledgments

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8. References

[1] J. B. Kenney, "Dedicated Short-Range Communications (DSRC) Standards in the United States," *Proceeding of the IEEE*, Vol. 99, No. 7, pp. 1162–1182, July 2011.

[2] IEEE Standard for Wireless Access in Vehicular Environments: Networking Services, IEEE Std. 1609.3-2010, Dec. 2010.

[3] IEEE Standard for Wireless Access in Vehicular Environments: Multi-Channel Operation, IEEE Std. 1609.3-2010, Dec. 2010.

[4] IEEE 802.11p-2010, “Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments,” IEEE Standards Association, 2010.

[5] Z. Zeng, H. Zhao, X. Xin, and K. Zheng, “A Novel Location-Based Channel Congestion Control Scheme in V2I Networks,” in Proc. of the 8th International Conference on Communications and Networking, Guilin, China, Aug. 2013, pp. 1–7.

[6] A. Wegener, H. Hellbruck, C. Wewetzer, and A. Lubke, “VANET Simulation Environment with Feedback Loop and its Application to Traffic Light Assistance,” in Proc. of the IEEE GLOBECOM Workshops, New Orleans, LA, Dec. 2008, pp.1–7.

[7] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, “Radio resource allocation in LTE-advanced cellular networks with M2M communications,” *IEEE Communications Magazine*, Vol. 50, No. 7, pp. 184–192, 2012.

[8] D. Krajzewicz, M. Bonert, and P. Wagner “The Open Source Traffic Simulation package Sumo,” in RoboCup 2006 Infrastructure Simulation Competition, Bremen, Germany, 2006.

[9] ETSI TR102638, Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Definition, ETSI Std. ETSI ITS Specification TR 102638 version 1.1.1 2009.

[10] C. Han, M. Dianati, R. Tafazolli, R. Kernchen, and X. Shen, “Analysis Study of IEEE 802.11p MAC Sublayer in Vehicular Networks,” *IEEE Trans. on Intelligent Transport System*, Vol. 13, No. 2, pp. 873–886, 2012.

[11] 3GPP TS 36.211, V10.4.0. (2011, Dec.). Technical Specification Group Radio Access Network [Online]. Available: http://www.3gpp.org

[12] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, “LTE for Vehicular Networking: A Survey,” *IEEE Communication Magazine*, Vol.51, No. 5, pp. 148–157, 2013.

[13] 3GPP TS 22.368 “Service Requirements for Machine Type Communications,” Rel. 12, Dec. 2012.

[14] K. Zheng, F. Liu, Q. Zheng, W. Xiang and W. B. Wang, “A Graph-based Cooperative Scheduling Scheme for Vehicular Networks,” *IEEE Trans. Vehicular Technology*, Vol. 62, No. 4, pp. 1450–1458, 2013.

[15] L. A. Pipes, “An Operational Analysis of Traffic dynamics,” *J. Appl. Phys*. 24, 274, 1953.

[16] M. Bando, K. Hasebe, A. Nakayama, A. Shibata, and Y. Sugiyama, “Structure Stability of Congestion in Traffic Dynamics,” *Japan J. Indust. Appl. Math*. Vol. 11, No. 2, pp. 203–223, 1994.

[17] E. P. Todosiev and L. C. Barbosa, “A Proposed Model for the Driver-vehicle-system,” *Traff. Eng.* Vol. 34, pp. 17–20, 1963

[18] A. Rekersbrink, “Simulation mit Hilfe der Fuzzy-Logic und einem Konzept potentieller Kollisionszeiten,” Ph.D. dissertation, University of Karlsruhe, Germany, 1994.

[19] M. J. Lighthill and G. B. Whiteham, “On jinematic waves II: A theory of traffic flow on long crowded roads,” in Proc. of the R. Soc. London A229, 1955, pp. 317–345.

[20] L. Cheng, B. Henty, D. D. Stancil, F. Bai, and P. Mudalige, “A fully mobile, GPS enabled, vehicle-to-vehicle measurement platform for characterization of the 5.9 GHz DSRC channel,” in Proc. of the IEEE International Symposium on Antennas and Propagation, Honolulu, Hawaii, June 2007, pp. 1847–1850.

[21] S. Krauβ. (1998, Mar.). Microscopic Modelling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics [Online]. Available: http://e-archive.informatik.uni-koeln.de/319/

[22] 3GPP TS 36.942. (2011). Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios [Online]. Available: http://www.3gpp.org/