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IMPROVING MULTI-CHANNEL WAVE-BASED V2X COMMUNICATION TO SUPPORT ADVANCED DRIVER ASSISTANCE SYSTEM (ADAS)

Y. H. KWON*

Department of Electronics Computer Engineering, Hanyang University, Seoul 04763, Korea

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ABSTRACT−The advent of vehicle-to-everything (V2X) communication has opened the opportunity to design advanced driver assistance systems (ADAS) that collect information from sensors in neighboring vehicles and roadside infrastructure. IEEE and ETSI have designed network protocol standards for V2X communications. Despite the differences between the vehicular wireless communication architecture defined by ETSI and the IEEE protocol stack, the two standards have multi-channel operations as a main commonality, with some channels dedicated to safety-critical applications and others to non-safety services. Some recent studies have demonstrated that these standards might not provide sufficient channel utilization for reliable exchange of information in mid- and heavily congested scenarios. In this paper, we propose and evaluate the performance of a driver-assistance system to reduce the connectivity gaps between vehicles and roadside units (RSUs). This cooperative system of multi-service channel allocation will improve radio channel utilization. We also show that the required latency for this inter-vehicle communication can be obtained using the IEEE-WAVE standards and dedicated short-range communication (DSRC) proposed for vehicular environments. Simulation results show that the proposed scheme can improve the average throughput by up to 15 % in various traffic density conditions compared with the dynamic channel allocation method.

KEY WORDS : Vehicular ad hoc network (VANET), Intelligent transport system (ITS), V2X, ADAS

1. INTRODUCTION

With the development of various types of sensors, researchers at Google and elsewhere are using advanced global positioning system (GPS) and operating-computing technologies to automate full vehicle control by developing autonomous or self-driving cars that could become commercially available within a few years. Today's self-driving cars are equipped with expensive but critical technology, such as light detection and ranging (LIDAR) sensors, radar, and high-precision GPS coupled with highly detailed maps. Among the different environments for self-driving cars, highways tend to be the most orderly and predictable, due to the well-maintained roads and well-marked lanes. In contrast, residential or urban driving environments are characterized by the presence of unexpected obstacles and inconsistent lane markings. Therefore, many automakers have been designing autonomous vehicles under the assumption that other vehicles are the only potential obstacles they need to consider.

To reduce the potential risk of accidents, the first highway auto-pilot solutions are designed to mitigate driver stress and fatigue and to provide additional safety features. For example, certain advanced-driver assistance systems (ADAS) can both keep cars within their lane and perform front-view car detection (Yenikaya *et al.*, 2013). Existing ADAS include lane keeping assistance systems, adaptive cruise control (ACC), and automatic emergency braking systems (AEBS). All those technologies increase the safety and convenience of driving modern automobiles. ADAS use multiple sensors to automate vehicle systems for safety and better driving. Thus, ADAS technology can be based on vision/camera systems, sensor technology, and connected-vehicle systems based on communications that guarantee information exchange among elements of cooperative systems in the nearby environment.

IEEE 1609 family and IEEE 802.11p standards (IEEE STD 1609.4, 2011; IEEE STD 1609.3, 2011; IEEE STD 802.11p, 2010) and the ITS-G5 suite (ETSI, 2012) have developed ADAS protocols. The IEEE standard for wireless access in vehicular environments (WAVE) is currently considered the most promising technology for vehicular networks. The WAVE system contains elements to allow vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication (collectively known as V2X). Dedicated short-range communication (DSRC) at 5.9 GHz frequency uses standards such as both SAE J2735 (ETSI, 2012) and the IEEE 1609 suites (IEEE STD 1609.3, 2011; IEEE STD 1609.4, 2011). The multiple channels in WAVE/DSRC are divided into one control channel (CCH) and four service channels (SCHs). The CCH is used for

**Corresponding author.* e-mail: phylio@hanyang.ac.kr

periodic information about the vehicles and emergent message to support vehicle safety. Non-safety data can be exchanged over an SCH for transport efficiency or information, respectively. In the service channels, WAVE provides the priority-access category (AC) service based on message types same as IEEE 802.11e MAC layer with four AC that have different contention-window size in four different queues(IEEE STD 802.11p). The WAVE system based on DSRC is built over two basic units (Kenney, 2011): the roadside unit (RSU) and the onboard unit (OBU). Vehicles with an OBU collect and store sensor data in a buffer and transmit those data to RSUs. The RSUs collect and use those data to warn drivers, about traffic conditions or menacing situations. Each vehicle alternates between a CCH and an SCH during its CCH interval and SCH interval to check for control and safety messages with single antenna (IEEE STD 1609.4, 2011). IEEE 802.11p defines a WAVE Basic Service Set (WBSS) as a unique identifier for delineating a communication zone governed by a certain wireless service provider (e.g., RSU, belonging to the roadside infrastructure, or a vehicle OBU). To initiate a WBSS, a wireless service provider periodically spreads WAVE service advertisement (WSA) beacons over the CCH. The WSA frame contains one of the four SCH's information which is chosen by the WBSS during the next SCH interval (SCHi). The WSAs are repeatedly broadcast to neighbor nodes during each 100ms sync period. If other nodes within the range of the WSAs' broadcasting are interested in the services offered by the provider, they join the WBSS after receiving WSA frame and switch to the relevant service channel after the current CCH interval (CCHi) to the same SCH specified in the WSA frame.

If the RSU can play the role of a WAVE service provider and offer connectivity services to vehicles in its coverage area, ADAS based on V2X communication should be able to give drivers useful and up-to-date information about traffic from other vehicles or roadside infrastructure in a restricted connection time. The information gathered from the ADAS system is real-time data, which is transmitted through the SCHs.

The IEEE 802.11p/WAVE protocol stack suggest selecting the least congested channel for data delivery based on multi-channel operations; however, it is not clear in specification how to select the least congested channel among them. Also, since all channel control message transmitted on the CCH are broadcasted, which implies that receiving nodes do not send back acknowledgments, it is not possible to know whether a frame transmission is successful or not. Hence, there is no way to reduce the large number of collisions that arise when traffic load increase. Therefore, IEEE 1609.4 standard cannot assign all SCH resources during the CCH interval. However, the efficient use of multiple channels is particularly important because of the absence of central coordination, and the unstable, distributed, and quickly changing nature of wireless links uniquely challenge the coordination of multi-channel activities. The limited spectrum allocation in the current IEEE standards challenges least-congested multi-channel assignment. It is not a problem that RSUs act as service providers, but it is a problem when vehicles act as service providers because that channel selection is more stimulating (Campolo and Molinaro, 2013; IEEE STD 1609.4, 2011). In fact, non-safety data exchange over the SCHs can only occur after the preliminary WBSS advertisement by the RSU over the CCH after the successful reception of WSA messages by vehicles under the RSU coverage. The reception of these advertisements could be hindered by channel impairments and collisions with interfering traffic delivered over the CCH. Vehicles missing WSAs frames from the RSU during a given CCHi are not allowed to join the advertised WBSS during the subsequent SCHi. This is leading to introduce a start-of-interval collision flooding problem, and, consequently, to severe performance degradation of applications delivered on the SCH.

Recently, many studies have focused on developing a safety-message dissemination algorithm and enhancing safety-message transmission performance using multi-channels on the WAVE platform under increasing vehicle density (Ding and Zeng, 2009; Wang *et al*., 2012; Lu *et al*., 2010; Bi *et al*., 2008; Tie *et al*., 2006; Omar *et al*., 2013; Tomar and Verma, 2012; Han *et al*., 2012; Cheng *et al*., 2011; So and Vaidya, 2004). However, little attention has been paid to service channel distribution in the exchange of non-safety messages, although the utilization of the service channels could donate to the entire network adeptness in IEEE 802.11p/WAVE.

In this paper, we investigate a multi-channel allocation problem among the service channels in IEEE 802.11p/WAVE and design an RSU-assisted queuing model to improve overall network throughput. This work serves the following purposes: 1) characterizing the multiple access and channel assignment mechanisms in the context of a multi-channel V2X communication scenario and 2) evaluating the performance of this type of communication under increasing vehicle density with RSU coverage and could benefit from the connectivity services it provides during the SCHi.

The rest of this paper is organized as follows. Section 2 provides an overview of the background and related work, and Section 3 describes our proposed scheme in detail. Section 4 illustrates a non-safety message delivery scenario through extensive simulations that consider the IEEE 802.11p/WAVE environment and presents performance evaluation results, and Section 5 provides concluding remarks

2. BACKGROUND AND RELATED WORK

The first generation of ADAS introduced into the market was ACC. ACC systems are based on a front looking sensor that uses LIDAR or microwave radar with a maximum detection range of around 100 m. The microwave radar sensors operate in the 76 ~ 77 GHz band, which has been reserved for automotive obstacle detection applications. Based on front vehicle information, mainly distance and speed, the ACC system regulates the vehicle speed by acting on the engine control and braking system. In this way, ACC is an extension of the standard cruise control system with the extra ability to adapt the speed of the vehicle to conditions. ACC with lane centering can detect un-indicated lane departures from detected lanes; the system helps the car stay on course near the center of the lane. The camera can recognize the lines on certain types of roads and help a driver keep within the lines. The system is designed to act like a human driver during a specific driving task. The driver gets processed information from the ACC system, which consists of sensors for recognition of driver and vehicle behavior and the driving environment, including the road and possible objects on it.

The combined application of ACC-like controllers and vehicular wireless communication is commonly known as platooning (Robinson *et al*., 2010). Platooning links vehicles in a high-efficiency group, in which a lead vehicle drives a line of other vehicles like a train. Each car measures the distance, speed, and direction and adjusts to the car in front. Vehicle platooning, as started by the SARTRE Project (2015) makes it possible for vehicles to travel close together to improve their safety, efficiency, and fuel mileage. Once drivers in the SARTRE system have joined a platoon, they can do something else while their vehicle travels toward its destination.

Much research has proposed different algorithms and protocols for multi-channel allocation in VANETs. The recent works include numerous highly reputable surveys that lay out the state of the art and extensively present the problems of multi-channel access in vehicular networking (Campolo *et al*., 2011). Therein, the authors enumerate several technical approaches that could lead to the solution of each of the identified problems. So far, except for a few publications, the literature lacks rough mathematical modeling and analysis of WAVE multi-channel operations.

The authors (Campolo and Molinaro, 2013) highlighted the severe effect of WAVE channel switching on communication reliability and provided design guidelines for improving the performance of WAVE's multi-channel broadcast mechanism. The limitation of their paper lies in the assumptions that the authors' proposed broadcasting process must work without hidden terminal nodes and in an ideal wireless medium.

In recent work, a dedicated multi-channel MAC (DMMAC) protocol (Ball *et al*., 2013) was proposed with adaptive broadcasting on the MAC layer in VANETs. DMMAC is designed to provide collision-free transmissions with reduced delay for safety applications in various traffic environments. DMMAC is similar to the WAVE 802.11p MAC in that it segments its CCH into 100 ms synchronized intervals and creates an SCH interval of 50 ms. Although the occupied slots for broadcasting can be adaptively adjusted, the released channel resources will not be used for data transmission. Therefore, the actual channel utilization might not be very efficient.

Many works (Taliwal *et al*., 2004; Kai *et al*., 2011; Ding and Zeng, 2009; Cheng *et al*., 2011) try to solve the channel coordination problem in the presence of an RSU. One work (Taliwal *et al*., 2004) proposed a DSRC MAC protocol to support multi-channel operation and thereby offer potentially high bandwidth for non-safety applications using roadside infrastructure without compromising the safety communication occurring in another channel. This approach also complements existing ad hoc schemes when an RSU is unavailable. However, each device must be equipped with different protocols for both ad hoc mode and infrastructure mode in the MAC and network layers. Consequently, the complexity of device implementation increases dramatically. The work of authors (Kai *et al*., 2011) proposed an RSU-assisted multi-channel coordination MAC (RAMC) scheme to allow parallel transmission on both SCHs and CCH in transferring safety messages. By monitoring all safety messages under the RSU-centric scheme, a vehicle can achieve high throughputs for non-safety messages. But RAMC still lacks a channel allocation and scheduling scheme. In the cluster-based time-division channel allocation scheme proposed in Ding and Zeng (2009), the protocol channel allocation scheme is transferred to the RSU to obviate channel contention for reliable delivery of messages despite different vehicle speeds and density. This technique also avoids the hidden and exposed node problems during communication, but it ignores the priority between different non-safety services and thus cannot provide differentiated QoS for them. N. Cheng *et al.* proposed a QoS-provision SCH allocation algorithm (Cheng *et al*., 2011). They considered data rate adaptation policies, under an EDCA parameter, that rely on position information during the SCH interval to select the data rate for packet transmission. However, the size of the network is incompatible with real traffic in urban situations. Nonetheless, the authors showed a time-varying multipath channel solution that avoids performance degradation caused by rate under selection when the link conditions are good and not saturated.

3. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Figure 1, we consider a free-flow traffic model for vehicles moving along a straight highway. Vehicles within an RSU's communication range cover a road segment of length d (in meters) and are made aware of the RSU presence whenever they successfully receive an RSU-generated WSA. According to other works (McShane and Roess, 1990; Khabbaz *et al*., 2012), under free-flow traffic conditions, the road segment is part of a longer highway. If the vehicular ad hoc network is considered to

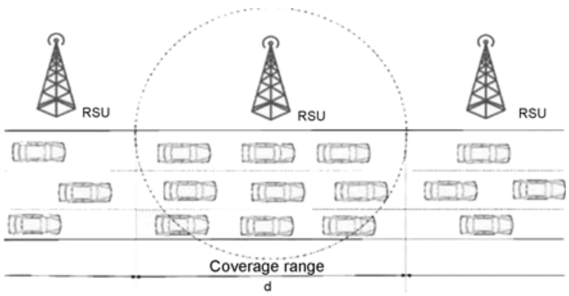

Figure 1. Typical highway V2X communication scenario.

be one-dimensional (1D) and the number of vehicles in a lane is Poisson distributed with parameter ρ(vehicle density), the probability $P(x, \rho)$ of finding x vehicles in a length l is given by:

$$P(x, l) = \frac{(\rho l)^x}{x!} e^{-\rho l} \quad (1)$$

Under those conditions, according to (Khabbaz *et al.*, 2012), each vehicle maintains a constant speed during its navigation along a segment of length d. The vehicle's residence time within the RSU's communication range has the probability density function (pdf) of an arbitrary vehicle's velocity.

This paper was assumed that wireless nodes (vehicles) arrive in the network (the coverage area of an access point) in batches and according to a Poisson arrival rate and exponential service times, namely M/G/m. We have a Poisson stream of service requests with arrival rate λ, giving independent inter-arrival times. The service rate of a server in the system is μ, giving service times that are exponentially distributed. We will let the number of wireless channel connections/servers be m, providing service independently of one another. Under the first-come-first-out policy, the vehicle service demands are taken in the order of arrival.

The total traffic intensity ρ also depends on the number of vehicles N within the transmission range of the RSU and is defined as:

$$\rho = \frac{N\lambda}{m\mu} \quad (2)$$

The probability that no jobs are in service, which is also the probability that the queue is empty in such a system, is given by Newell (1982):

$$P_0(m, \rho) = \left[\frac{(m\rho)^m}{m!(1-\rho)} + \sum_{n=0}^{m-1} \frac{(m\rho)^n}{n!} \right]^{-1} \quad (3)$$

The total traffic intensity ρ also depends on the number of vehicles N within the transmission range of the RSU and is defined as: The probability that a newly submitted service request must wait because all servers are busy (referred to as Erlang's second formula) is given by:

$$P_D(m, \rho) = \frac{\rho^m}{m!} \cdot \frac{m}{m-\rho} P_0 \quad (4)$$

The expected exponential response time for jobs that have to wait in the system is given by:

$$T = \frac{1}{\mu}\left(1 + \frac{P_D}{m(1-\rho)}\right) \quad (5)$$

The distribution of service time (T) in the above queuing model is the distribution of the time period during which an incoming batch of vehicles is going to be in the range of the access point. The vehicles' residence time within the RSU communication range has the pdf of an arbitrary vehicle's velocity. We define the distribution of vehicle velocities (v) within the RSU's communication range where $f_v(\cdot)$ is a pdf as random variable $R = (d/v)$. Then the $f_R(t)$ distribution of T can be formulated as

$$f_R(t) = \frac{R}{t^2} f_v\left(\frac{R}{t}\right), \ t \in [R_{min}; R_{max}] \quad (6)$$

where $R_{min} = (d/v_{max})$ and $R_{max} = (d/v_{min})$ are the minimum and maximum vehicle residence times within the RSU's communication range, respectively.

Most unicast ad hoc routing protocols need a facility by which a node can broadcast its locally gathered information to its neighboring nodes. Such dissemination usually works well on single-channel radios, such as mobile ad hoc networks (MANETs). However, because in WBSS-based vehicular networks OBUs operate on multi-channel radios, it is not guaranteed that all neighboring OBUs are operating on the same channel when an OBU is broadcasting/ transmitting its local information. In addition, because the connectivity of a VANET could change frequently at high speed, the provider does not know whether its neighboring OBUs have joined its WBSS and are ready to receive its messages before it transmits them. This problem is critical to unicast ad hoc routing protocols because the inconsistency of nodes' local information can cause them to generate inconsistent routes and routing loops.

To solve this problem for the scenario in Figure 1, the RSU is equipped with a service request queue (SRQ). If the SRQ is empty, an incoming request from a vehicle causes it to calculate the expected completion time for each channel condition based on WSAs. It then sends the job to the best channel and starts receiving its service. Otherwise, service requests remain in the SRQ until a channel becomes available. Observe that, while a request is waiting in the SRQ, the vehicle that requested the service could leave the RSU's range. Consequently, that service request has to be immediately discarded. The collection of RSUs within an area represents a distributed computing system that provides spectrum assignment services to cars.

Each RSU informs the cars of contention locations along their paths with the associated additional spectrum that they can use. Each RSU thus maintains a channel allocation matrix that keeps current information about assigned and free channels. It also maintains a table that stores information about which channel is given to which particular source vehicle along with a time stamp and the mode of transmission. To benefit from this service, a car in proximity of an RSU will subscribe to a WBSS generated by the RSU and advertised during the CCHi. During the next service channel interval, the car will provide the RSU with all records stored since the last time it passed an RSU. In addition, the car will inform the RSU about the next expected RSU on its path. This information will enable the RSU to provide the car with a table of information about the path the car will follow along with contention locations and the additional spectrum associated with them. In fact, the RSU locally stores a set of tables that correspond to direct next hop RSUs. These tables are updated and maintained in each RSU's local memory. Upon receipt of the next hop information from a car, the RSU forwards the corresponding table, thus enabling the car to extend its spectrum to additional channels at specific contention locations along the way. The node and its receiver must be on the control channel to exchange the SCH messages and reserve a service channel. The main steps of the proposed scheme are given next.

Step 1: A vehicle sends a WSA message that includes a service request (SR) to an RSU within the CCHi during *T*, which is computed based on equation (5). The SR message contains the source and destination id, application type, current speed, timestamp, relative distance, and direction of motion.

Step 2: During the CCHi, the RSU calculates the expected completion time for each channel using the channel data rate. The data rate to be used by vehicles for transmission during the SCHi is adaptively set according to the estimated distance from the RSU. The RSU updates the channel allocation matrix with the expected completion time based on Equation (6). In more detail, a user n selects the data rate for the ongoing transmission by comparing its distance through SR. The RSU assign a channel to the vehicle in close order. The RSU maintains a channel allocation matrix that preserves information about the currently assigned and free channel information. If request is for a broadcast, the packets are allocated to the SRQ. The RSU will serve first the packet in the queue with the minimum (i.e., earliest) deadline.

Step 3: After updating the channel table, the RSU sends a WSA that includes the channel allocation table to the car during the CCHi. The car receiving the WSA allocates service to the current channel. The user registration and transmission opportunities (TXOPs) negotiation does not use CCH resources in vehicles, so that critical safety messages broadcasting can be preserved.

Step 4: During the SCHi, a vehicle communicates with another vehicle and the RSU using the assigned service channels. After channel selection, the RSU monitoring communication maintains a channel allocation matrix of information about currently assigned and free channels.

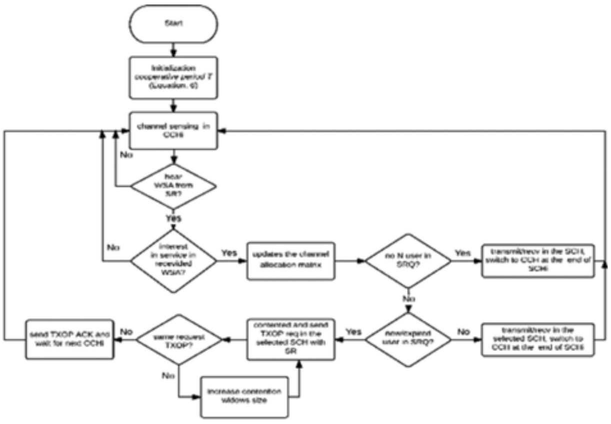

Figure 2. Flow chart of the proposed schema.

Step 5: To prevent the hidden terminal problem, if a vehicle asks the RSU to communicate with a neighbor who is already in communication with another vehicle, the RSU refuses to allocate any channel to the requested vehicles.

Step 6: When the RSU gets a WSA with SR information identical to the vehicles' requested service channel allocation with the same information, the RSU increases the contention window size and cancels the SR after the SCH's 7 sync intervals following the IEEE 802.11p standard (IEEE STD 802.11p, 2010).

Step 7: After disconnection, the RSU and vehicle delete the channel allocation matrix for the SR, and the vehicle sends a new WSA message to request a new service channel.

Step 8: The vehicle sends a transmission completion packet to the RSU.

Step 9: The RSU marks the channel free in its information database.

The flowchart of the proposed schema in the multi-channel WAVE-based V2X Communication to support ADAS is shown in Figure 2.

4. SIMULATION RESULTS AND ANALYSIS

In this section, we evaluate the proposed channel allocation schemes with the network simulator 3 (NS-3 Network Simulator, 2015). We compare the performance of the proposed scheme with that of the recently published IEEE 1609.4 multi-channel model that switches among the active service channels in a round robin (RR) way (Ghandour *et al.*, 2012; Wang *et al.*, 2012).

The simulation scenario is a 10 km highway with three lanes and 120 vehicles randomly distributed across them. 10 RSUs are placed 400 m from one another along the road. The mobility models assume vehicles' velocity between 20 and 40 m/s in free traffic flow in one direction. After 4 minutes a sudden traffic jam in the middle of the equipped road segment forces the velocity to drop to 3 ~ 8 m/s. For the next 4 minutes vehicles queue on the highway in one direction. RSUs receive beacons from vehicles in any lane, but they extract only relevant beacons for further processing. Every vehicle is equipped with an IEEE 802.11p transceiver and GPS receiver so it knows its position and can communicate with other vehicles. The transmission range of each vehicle is 250 to 300 meters, and the transmission rate is 6 Mbps. Each SCH has 10 slots and 100 slots are available in the reservation period and safety period. Each car broadcasts one safety message within the CCHi. Each vehicle has a safety message and WSA to send in every CCH period and tries to reserve a slot in a service channel to send data to a selected receiver in every sync interval. We use the Nakagami-m fading channel model with path-loss model as suggested in other works (Torrent-Moreno *et al*., 2006; Taliwal *et al*., 2004) for the highway simulation scenario. We generate each of the traffic data randomly and unicast packets with different priorities in addition to WSA'S service-provider table so that total generation time is 60 seconds of the overall 180 seconds of simulation time. Moreover, to consider the vehicle-traffic density within a transmission range, we change the active number of vehicles exchanging non-safety data using SCHs from 5 to 30 per lane during the simulations. The rest of the major simulation parameters are chosen from the IEEE 802.11p/WAVE standards. Generally, the TCP/IP protocol, based on Ethernet, can allow only 1500 bytes, which is called the maximum transmission unit (MTU); the MTU totals 1518 bytes (IEEE STD 1609.3, 2011) with the addition of a header and the cyclic redundancy code (CRC). The IEEE 802.11 family can handle this MTU with no problems; its payload is 2304 bytes (IEEE STD 802.11p, 2010), big enough for a distribution system. Although people would like to increase the wireless MTU, that is unlikely, not only because current applications rely on the TCP/IP suite for networking but also because of the infeasibility of making the MTU too large, especially for wireless communication. The parameters of the simulation are summarized in Table 2. In the following, we focus on a scenario in which each node sends its packets to a destination in the unicast mode.

Figure 3 depicts the non-safety message delay as the

Table 1. Simulation parameters and their values.

Parameter	Value
IEEE 802.11p data rate	6 Mbps
Channel bandwidth	10 MHz
Packet generation rate	5 packets/s
Packet size	1500 Bytes ~ 2000 Bytes
Transmission range	250 m ~ 300 m
Propagation model	Nakami-m fast fading (m = 3)
SCH and CCH interval	50 msec (each)
Simulation time	180 seconds

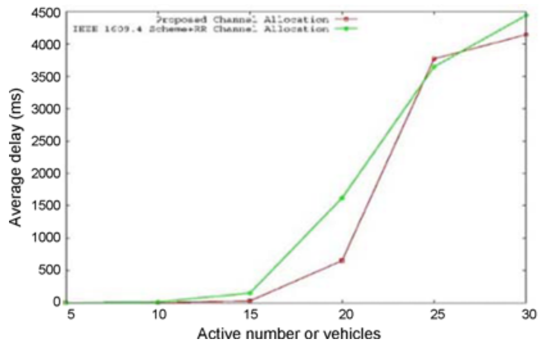

Figure 3. Average delay comparison for different vehicle densities (vehicles/per lane).

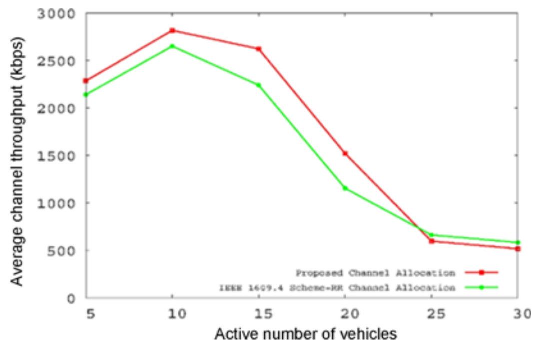

Figure 4. Average channel throughput comparison for different vehicle densities (vehicles/per lane).

number of active vehicles increases. As shown in Figure 3, the proposed scheme can greatly reduce the delay of non-safety-messages during increasing congestion thanks to channel allocation management by the RSUs.

Figure 4 presents the simulation results for average channel throughput per SCH as the number of active vehicles increases. As with the first simulation, when the congestion is medium (medium vehicle density), the proposed scheme performs better than the IEEE 1609.4 +RR scheme. However, when the congestion is high, the proposed scheme performs slightly worse than the IEEE scheme.

Note that our proposed scheme has lower average delay until the simulation reaches 25 active vehicles. The IEEE 1609.4+RR scheme has slightly less delay when the number of active vehicles per lane reaches 30. The proposed scheme does not perform quite as well in a high vehicular density scenario because it is a non-work-conserving policy. As defined in queuing theory (Bhat, 2015), a work conserving policy never leaves a server idle if jobs are waiting for service. Our proposed scheme might leave a slow channel idle while waiting for a fast channel. This decision wastes some of the system's inherent capacity. Second, as the vehicle density increases, WSA frames might collide with beacons transmitted by the vehicles. In an IEEE 1609.4 network, the average throughput per SCH is relatively low due to the limitation of accessing time

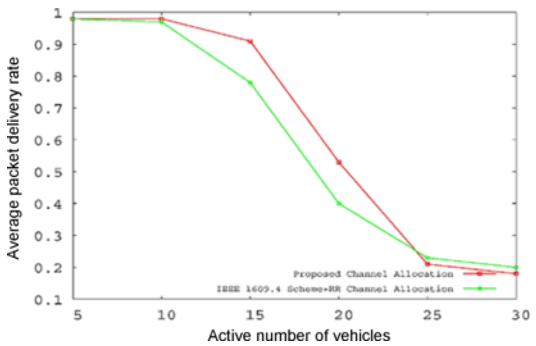

Figure 5. Non-safety message delivery rate comparison for different vehicle densities (vehicles/per lane).

slots. Within each 50 ms SCH interval, the contention level on CCH is too high in dense network, there are only few transmission. This poor performance is obtained by reflecting the weakness of adopting fixed CCH and SCH intervals in IEEE 802.11p MAC. However, as shown in Figure 4, the proposed scheme still provides better performance in most cases. Therefore, we conclude that the proposed scheme has better throughput performance than the IEEE 1609.4+RR scheme in VANETs, even when the active number of vehicles increases.

Figure 5 shows the results of the packet delivery rate (PDR) as the number of active vehicles increases. The PDR starts at a high value. However, as the number of nodes increases, the PDR decreases. Collisions occur in the unicast scenario because the retransmission limits of the MAC protocol (7 in IEEE STD 802.11p) are exceeded. However, our scheme improves the PDR of the IEEE 1609.4+RR scheme by 9.11 %. When the channel condition degrades at 30 active vehicles per lane, the IEEE 1609.4+RR scheme outperforms our proposed scheme by 1.9 %.

Figure 6 depicts the average packet loss rate with high priority packet, which worsens for both schemes as the number of vehicles increases. For the same reason as in the simulation result depicted in Figure 4, the performance values with more than 25 vehicles show few differences. However, the proposed scheme outperforms the IEEE 1609.4+RR scheme by 5 % ~ 15 % with fewer than 25

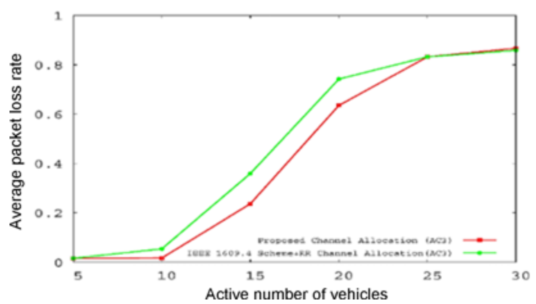

Figure 6. Non-safety packet loss rate comparison for different vehicle densities (vehicles/per lane).

vehicles. As shown in the simulation results, the proposed scheme achieves a low packet loss rate, low average packet delay, and high achievable channel throughput.

5. CONCLUSION

In this paper, we proposed the RSU-assisted multi-service channel allocation method to maximize channel use by efficiently assigning different service channels to support non-safety communication based on IEEE 802.11p/WAVE, and DSRC. With the assistance of an RSU, vehicles in a highway scenario do not need to periodically monitor service channels for non-safety transmissions. Through a detailed analysis and simulations, we have demonstrated the correctness and effectiveness of our proposed scheme. We have also implemented our proposed scheme on an NS-3 simulation platform to verify its practicality. Simulation results have shown that the proposed scheme outperforms the IEEE 16094+RR multi-channel scheme in terms of system throughput, packet delivery rate, and collision rate on SCH for vehicular networks in a highway scenario, though the proposed scheme shows a slightly degraded performance when the vehicular density is very high.

Recommendations for further work include carrying out a network performance analysis based on a more accurate simulation model under realistically varying urban traffic models, for example, routes with a greater number of segments. Because intersection traffic is more complicated in an urban traffic model than in a highway traffic model, further analyses should focus on reducing the computation and time complexity of the proposed scheme and increasing its adaptability in high mobility networks.

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