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Wireless access vehicle environment (WAVE) architecture of intelligent transportation system has been standardized in IEEE 802.11p standard and it is going to be widely deployed in many roadway environments in order to provide convenient services. However, the IEEE 802.11p contention-based medium access control protocol would significantly downgrade transmission efficiency between roadside unit (RSU) and on-board units (OBUs) because the number of OBUs served by a RSU could be large and the transmission rate between RSU and an OBU may be different from the others. This paper proposes a simple vehicular grouping access (VGA) strategy to reduce access latency and opportunities of collisions on a service channel (SCH) by equally distribute vehicles onto multiple SCHs. Since the RSU periodically broadcast the WAVE service advertisement (WSA) frames on the control channel (CCH), the proposed VGA strategy makes an OBU determine to join an appropriate SCH according to the RSSI threshold information of each SCH, which is carried in WSA frame, and the signal strength indicator (RSSI) while receiving WSA frame. Using appropriate RSSI thresholds, the system could equally allocate OBUs to all available SCHs. This paper further investigates the appropriate thresholds for three popular roadway scenarios to achieve the goal of load balancing. Simulation results demonstrate that the proposed VGA strategy not only improves the channel capacity but also provides useful information on roadway planning in IEEE 802.11p wireless vehicular networks.

Keywords: CSMA/CA, grouping, IEEE 802.11p, RSSI, WAVE

1. INTRODUCTION

With the matured wireless communication technology, the new demand on wireless applications is toward the concept of deploying wireless devices on transportation systems such as buses, trains and vehicles. Wireless devices used in vehicle side and road side are named as on-board-unit (OBU) and road-side-unit (RSU) respectively. The cooperation between OBU and RSU provides fancy intelligent transportation system (ITS) services such as vehicle positioning, electrical toll collection, parking lot payment, cargo tracking, road condition warning, traffic information, intersection collision warning, and so on. Nowadays, the concept of intelligent vehicles with wireless devices becomes more practical and realizable.

Dedicated short range communications (DSRC) technology [1] is a short to medium range communication service and it supports both public safety and private operations in roadside to vehicle (R2V) and vehicle to vehicle (V2V) communication environments.

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DSRC technique has been formally defined by American Society for Testing and Materials (ASTM) association couple years ago and, currently, the DSRC standardization process has been smoothly transferred to the IEEE 802.11p working group [2] for the consideration of world-wide market and regulatory. Moreover, some documents released from IEEE 1609 Working group (e.g., IEEE 1609.3 [3] and IEEE 1609.4 [4]), which name the DSRC system as wireless access vehicular environment (WAVE), have defined that the wireless communication technique among vehicles and roadside system mainly inherits from IEEE 802.11a physical (PHY) layer and IEEE 802.11 carrier sense multiple access with collision avoidance (CSMA/CA) medium access control (MAC) protocol [5]. Because this paper focuses on the performance improvement on services of vehicular internet access, all the ensuing discussions apply for the R2V applications only, unless otherwise noted.

In order to make sure the communication reliability and privacy in WAVE, all messages are transported on 5.9GHz ITS licensed frequency band (from 5850MHz to 5925MHz), which is comprised of one control channel (CCH) and several service channels (SCHs). The RSU broadcasts system information and urgent short messages on CCH and an OBU accesses SCH(s) to communicate with the RSU after it synchronizes with RSU and receives system information from CCH. In other words, the WAVE employs multi-channel access strategy rather than single-channel access scheme used in IEEE 802.11 standard and adopts additional operating rules. The RSU will functionally serve as the base station or access point for traffic to/from OBUs of vehicles which move within its service area. When the RSU or OBU equips one transceiver only, frequent switching between CCH and SCH is required for processing the broadcast system information and transportations of user data. As a solution, the RSU divides the timeline into contiguous ‘channel cycle’, each of which consists of a fixed CCH interval (\(T_{CCH}\)), a fixed SCH interval (\(T_{SCH}\)) and a fixed short turnaround time gap before switching to CCH and SCH (\(T_{GI}\)). A channel cycle is started with a cell-wise beacon frame, which is broadcasted from RSU and is used for all OBUs to synchronize with RSU and collect system information, and followed by urgent short messages (if any) and SCH interval. The IEEE 802.11p standard does not specify or suggest any method for an OBU to select SCH, as it is an implementation issue and beyond the scope of standard. However, as a lot of RSUs randomly camp on a certain SCH, the actual performance of WAVE may fall short of our expectations because the RSU serves OBUs on SCH using contention-based CSMA/CA protocol and the competing OBUs may use different data transmission rates based on the signal to noise ratio of channel, thereby it is desired to have a better load balancing strategy for the IEEE 802.11p networks.

Papers [6, 7] have revealed that the primary reasons of the capacity efficiency deterioration in popular IEEE 802.11 system are twofold: the number of competing nodes and the multi-rate transmission opportunities to the competing nodes when all nodes experience similar channel conditions. However, varying and unstable indoor channel condition drives the 802.11 standard to support multiple data transmission rates to exploit the tradeoff between throughput and reliability. That is, senders use proprietary rate switching algorithm to select proper data rates suitable for receivers’ current channel conditions. Such unpredictable behavior can result in considerable rate diversity, particularly when the network is congested. Under such conditions, throughput-based fairness can lead to drastically reduced aggregate throughput. Regarding to the multi-rate communication
problem, it can be easily solved when the RSU assigns the required data rate operating on each SCH. Such solution will be addressed later.

In literatures, various enhanced protocols have been proposed to improve the transmission efficiency in single-channel single-rate wireless networks. For example, authors of paper [8] have proposed an enhanced MAC protocol, named as GDCF, to improve the performance of IEEE 802.11 distributed coordination function (DCF). The GDCF defers the contention window (CW) back to the minimal value after successful transmission. Station with GDCF is permitted to reduce CW by a specified value after it has successfully and consecutively transmitted a sufficient number of data frames. However, the strategy of suspending and decreasing CWs cannot completely alleviate contention situations, especially on a crowded channel.

One of intuitive approaches to resolve collisions is grouping, which partitions stations into multiple groups and assigns dedicated resource to each group of stations. Paper [9] and [10] have proved that using grouping strategy is able to efficiently minimize the hidden-node and normal collisions and improve system throughput in IEEE 802.15.4 Zigbee wireless personal area networks and IEEE 802.11n wireless local area networks respectively. This paper adopts the similar grouping concept to alleviate the contention situation in IEEE 802.11p multi-channel networks. The proposed strategy, named as vehicular grouping access (VGA) strategy, has the capability to improve the average access latency and reduce the amount of collisions on a service channel (SCH) by smartly distributing vehicles into multiple available SCHs. Because the RSU periodically broadcasts the beacon frame, which carries the WAVE service advertisement (WSA) information, on the CCH, the proposed VGA strategy makes an OBU determine to join appropriate SCH according to the received signal strength indicator (RSSI) of beacon frame reception and the announced RSSI threshold information of SCHs. Based on such strategy, the OBUs with high and low RSSIs will access the SCH, which serves OBUs in the inner cell, and the SCH, which serves OBUs in the donor-shape outer cell, respectively. This paper further investigates the appropriate thresholds for three different scenarios of roadways (such as roundabout, crossroad and straight roadway) to achieve the goal of actual load balancing. Simulation results demonstrate that the proposed VGA strategy can not only improve the performance in terms of throughput, access delay and packet loss rate but also provide useful information on roadway planning in IEEE 802.11p wireless vehicular networks. To our best knowledge, this study is the first investigation to concentrate on the load balancing strategy for IEEE 802.11p multi-channel wireless vehicular networks from the practical roadway scenarios.

The rest of this paper is organized as follows. The description of current IEEE 802.11p MAC protocol and vehicular grouping access (VGA) strategy is provided in section 2, aiming to supply necessary background and motivate of the discussions. The threshold analysis and three popular scenarios of the roadway planning are then elaborated in section 3. The throughput analysis results are presented in section 4. Section 5 presents the simulation model and results in order to evaluate the performance of the VGA, followed by the conclusion remarks in section 6, which completes the paper.

**2. VEHICULAR GROUPING ACCESS (VGA) STRATEGY**

In IEEE 802.11p network, the MAC protocol coordinates operations on the CCH
and several SCHs. Recall that CCH and SCH intervals of fixed duty cycle appear alternatively and the CCH is used to transport broadcast information and urgent emergency messages, which are typically produced from backbone or backhaul servers, and the SCH is used to transport IP data packets which are typically produced from user applications. Before accessing SCHs, all OBU{s} have to listen to CCH for receiving beacon frames, which carry WSA information and are broadcasted by RSU during CCH intervals. This paper first focuses on taking advantage of broadcast WSA information so that the coordination becomes more smart and efficient, and then the proposed VGA strategy is introduced for accomplishing the load balancing in order to improve overall system performance.

2.1 WSA Frame Structure

The WSA is an information element (IE) embedded in beacon frames. Fig. 1 portrays a WSA frame structure which consists of two components: provider service table (PST) and WAVE routing advertisement (WRA). The PST information is preceded by a version control field, provider count and channel count respectively indicate how many services and channels that RSU provides in WAVE system. Provider service information further consists of several important fields which are information length, provider contents, provider service identifier (PSID), provider service contents, service priority, service IP address, port number, MAC address and corresponding channel number. In addition, channel information includes information length, channel contents, channel number, an adjusted flag, data transmission rate, and transmission power level. A RSU needs to issue a complete WSA frame to all OBU{s} within the cell so that each OBU realizes how to access the SCH(s). It is interesting to highlight that the information of data transmission rate per SCH is sufficient to avoid the multi-rate transmission situation, but it is insufficient to perform load balancing if two or more SCHs designate the same transmission rate.

![Fig. 1. Frame structure of WAVE service advertisement (WSA).](image)

2.2 Vehicular Grouping Access (VGA) Strategy

During CCH, the RSU broadcasts the WSA frame with the channel information on
CCH to invite OBUs to join network. Upon an OBU receiving WSA frame from RSU, it checks whether the PSID is matched or not. If yes, it determines which SCH to access according to channel information carried in WSA frame and the measured RSSI while receiving WSA frame. For the sake of conciseness, the WAVE system that provides two SCHs with the same services and designated data transmission rate is considered. Therefore, the RSU announces channel and service information of two SCHs by means of WSA frame broadcasting and consequently an OBU can access any one of two SCHs to obtain the service. If most of OBUs choose one certain SCH in random manner, the CSMA/CA MAC protocol can result in server channel contentions and collisions. To resolve the capacity efficiency deterioration problem, it is intuitive to bipartite the set of OBUs into two subsets of equal size, one subset for each SCH. However, it is hard for the RSU to equally bipartite the set of OBUs because the RSU does not have any information about active OBUs within the cell, as an OBU in WAVE system does not have the permanent MAC address or identity due to privacy protection. It is intuitive that random selection is one of possible solutions to balance the numbers of OBUs on two SCHs. However, it cannot guarantee the equal loading among SCHs at any time. In other words, random selection is a sensible design for load balancing, but by no means the most efficient one to achieve the real load balancing in multi-channel system.

![Fig. 2. Example of a WAVE system comprises one RSU and five OBUs.](image)

![Fig. 3. Example of a WAVE system with and without load balancing strategy.](image)
Recall that the easy way of solving the multi-rate issue on any SCH is to restrict the transmission rate on every SCH. For those SCHs designating the same data transmission rate, the proposed grouping strategy first groups OBUs with similar RSSI or signal to noise ratio (SINR) and then partitions grouped OBUs into multiple subgroups of equal size systematically. Fig. 2 portrays a WAVE network which comprises one RSU and five OBUs. Assume the WAVE network provides two SCHs, denoted as SCH(1) and SCH(2), which designate the same data transmission rate and provide the same service. Fig. 3 (a) shows that the RSU first broadcasts beacon frame with WSA IEs to OBUs during CCH interval and then all OBUs start accessing one of two SCHs according to a channel selection algorithm. If the channel selection algorithm does not take load balancing into consideration, the number of OBUs on a SCH may be larger than that of the other SCH. Fig. 3 (a) illustrates that there is one OBU on SCH(1) and there are four OBUs on SCH(2). If the channel selection algorithm takes load balancing into considerations, all the OBUs could be equally distributed to SCH(1) and SCH(2), as shown in Fig. 3 (b).

Because the RSSI estimated at OBU is inversely proportional to the distance between RSU and itself, the proposed strategy could easily separates all OBUs into two groups according to the derived RSSI from reception of WSA information at OBU. Considering the WAVE system shown in Fig. 2 again, we can see that two OBUs (OBU4 and OBU5), which are heading to right-hand side, are farther from RSU than three OBUs (OBU1, OBU2 and OBU3) which are heading to left-hand side. It is no longer difficult to accomplish the purpose desired if the RSSI thresholds for SCH(1) and SCH(2) are well assigned in WAVE system. Now, the problem has become how to find the appropriate threshold for each SCH, especially under different roadway scenarios. The following section first analyzes the distributions of OBUs in the scenarios of roundabout, crossroad and straight roadway, and then derives the appropriate threshold value for each scenario.

3. THRESHOLD ANALYSIS

In this section, we analyze the RSSI threshold, which is used to control the distribution of OBUs within the entire service area of RSU on all SCHs. Here, we assume that the WAVE system supports one CCH and two SCHs. For simplicity, the RSU is assumed to be located at the center of roadway and the location of RSU is the center (O) of the circle-shaped service area formed by the RSU with Omni-directional antenna. The radius of circle-shaped service area, denoted as $R_o$, is the maximum transmission/reception distance between RSU and OBU, which is depending on the transmission power of RSU and OBU, as a higher (lower) transmission power will result in a longer (shorter) transmission distance. For simplicity, reciprocity channel is assumed in the system, wherein the RSU and OBUs use the same transmission power. Without loss of generality, we further assume that all OBUs are scattered in the service area of RSU randomly, thereby the number of OBUs in an area is linear proportional to the area size.

According to the signal path loss, the RSSI value could be derived from the transmission distance between sender and receiver. Because the VGA strategy intends to utilize the RSSI threshold to bipartite the set of OBUs, the circle-shaped service area is logically partitioned as inner circle area and donor-shaped outer circle area. Let $A(In)$ and $A(Out)$ denote the sizes of inner circle area and donor-shaped outer circle area respec-
tively, and $R_i$ and $R_o$ are the radiuses of inner circle and whole circle respectively. The appropriate RSSI threshold for a certain roadway could be derived from the corresponding radius of the inner circle, $R_i$, which results in $A(In) = A(Out)$. That is, based on the $R_i$ value, the corresponding RSSI can be easily derived from pass loss equation.

In the following subsections, we will investigate the appropriate $R_i$ assignment for each of three different roadway scenarios, roundabout, crossroad and straight roadway.

### 3.1 Roundabout Scenario

Fig. 4 shows the roundabout scenario. The area sizes of outer circle and inner circle can be easily obtained:

$$A(Out) = \pi(R_o^2 - R_i^2), \quad \text{and} \quad A(In) = \pi \times R_i^2.$$  

To fairly allocate traffic loading on two SCHs, the radius of inner circle, $R_i$, shall be equal to $2R_o / \sqrt{2}$.

### 3.2 Crossroad Scenario

Because the movement of vehicle is always restricted on the roadways, four corners of an intersection should not be counted into the service area. As a result, the overall service area of a RSU would be affected by the width of roadway ($W$). Based on the relationship between $R_i$ and $W$, there are three possible cases in crossroad scenario, i.e., $R_i < \sqrt{2} \cdot W/2$, $R_i = \sqrt{2} \cdot W/2$ and $R_i > \sqrt{2} \cdot W/2$, as shown in Fig. 5. It is worthwhile to note that the $R_o$ is always larger than $\sqrt{2} \cdot W/2$ in crossroad scenario; otherwise, such scenario shall be categorized as roundabout scenario.

Figs. 5 (a) and (b) show the scenarios of $R_i < \sqrt{2} \cdot W/2$ and $R_i = \sqrt{2} \cdot W/2$ respectively. For these two cases, it is not difficult to obtain the area size of inner circle. We obtain $A(In) = \pi \times R_i^2$. On the contrary, it is a little bit difficult to calculate the area size of outer circle. From Figs. 5 (a) and (b), if we desire to derive the precise area size of outer circle, we have to first estimate the overlapping area of outer circle and four corners of intersection. Let $\theta_1$ denote the angles formed by lines $OB$ and $OC$, and let $\theta_2$ denote the angles...
formed by lines $\overline{OA}$ and $\overline{OB}$, where notations $A$, $B$ and $C$ denote the anchor point of corner and two intersections of outer circle and road, respectively. We have

$$\theta_1 = \pi - 2 \cos^{-1}\left(\frac{W}{2R_O}\right), \ \text{and} \ \theta_2 = \cos^{-1}\left(\frac{W}{2R_O}\right) - \frac{\pi}{4}.$$ 

Thus, the area size of outer circle could be derived by the following equation:

$$A(Out) = 4(R_I R_O \sin \theta_2 - R_I^2 \theta_2) + 2\theta_1(R_O^2 - R_I^2).$$

From the equilibrium of $A(In)$ and $A(Out)$, the appropriate radius for the inner circle is derived from the following equation:

$$R_I = \frac{4 \sin \theta_2 R_O + \sqrt{16R_O^2 \sin^2 \theta_2 + 4(4\theta_2 + 2\theta_1 + \pi) \cdot 2\theta_1 R_O}}{2(4\theta_2 + 2\theta_1 + \pi)}, \ \text{where} \ 0 < R_I \leq \frac{\sqrt{2}}{2} W.$$

Fig. 5 (c) shows the scenario of $R_I > \frac{\sqrt{2}}{2} \cdot W/2$. We can see that the inner circle overlaps with four corners as the outer circle does. Notably, the value of $\theta_1$ is the same as that in above cases but the value of $\theta_2$ is different from above cases. According to trigonometry, we have

$$\theta_2 = \cos^{-1}\left(\frac{W}{2R_O}\right) - \cos^{-1}\left(\frac{W}{2R_I}\right).$$

Then, the area sizes of inner circle and outer circle could be derived by the following equations:

$$A(Out) = 4(R_I R_O \sin \theta_2 - R_I^2 \theta_2) + 2\theta_1(R_O^2 - R_I^2), \ \text{and}$$

$$A(In) = 2R_O W \sin\left(\frac{\pi - \theta_2}{2}\right) - 4R_I R_O \sin \theta_2 - W^2 + 2R_I^2(2\theta_2 + \theta_1).$$
Obviously, it is another challenge on the derivation of the close-form of $R_I$ from parameters $\theta_1$, $\theta_2$, $W$ and $R_O$. From the aspect of numerical analysis, the precise $R_I$ could be solved using numerical techniques, such as Newton’s method. However, using time-consuming numerical techniques is not convenient and acceptable for operator to deploy the WAVE system. Thus, instead of figuring out the precise $R_I$, we desire to find out the close-form equation in order to approximate the precise $R_I$. To do this, we simply assume that the aggregation of areas of four overlapping sectors at corners is a circle. Therefore, the approximate $R_I$ is able to be obtained from the following simplified equation:

$$R_I \approx \frac{\sqrt{2W \cdot R_O + \frac{1}{2}W^2}}{2\sqrt{2} \cdot W}.$$  

3.3 Straight Roadway Scenario

Fig. 6 (a) shows the scenario of $R_I < W/2$. Owing to $\pi = \theta_1 + 2\theta_2$, we have

$$\theta_1 = \pi - 2 \cos^{-1}\left(\frac{W}{2R_O}\right), \text{ and } \theta_2 = \cos^{-1}\left(\frac{W}{2R_O}\right).$$

The area sizes of inner circle and outer circle are separately derived from the following two equations:

$$A(Out) = 2R_O^2 \cos \theta_2 \cdot \sin \theta_2 - 2\theta_2 R_I^2 + \theta_1 (R_O^2 - R_I^2), \text{ and } A(In) = \pi \cdot R_I^2.$$

Fig. 6. Three cases in straight roadway scenario according to the relationship between $R_I$ and $W$. 
From the equilibrium of $A(In)$ and $A(Out)$, the appropriate radius for the inner circle is obtained from the following equation:

$$R_I = R_O \cdot \sqrt{\frac{2 \cos \theta_2 \sin \theta_2 + \theta_1}{\pi + 2\theta_2 + \theta_1}}, \text{ where } 0 < R_I < \frac{W}{2}.$$  

Fig. 6 (b) shows the scenario of $R_I = W/2$. It indicates that the diameter of inner circle is equal to the width of roadway. Evidently, the values of $\theta_1$ and $\theta_2$ are the same as that in above case. So, the area sizes of inner circle and outer circle can be easily derived from the following two equations:

$$A(Out) = R_O^2 [\sin(2\theta_2) + \theta_1] - R_I^2 (2\theta_2 + \theta_1), \text{ and } A(In) = \pi \cdot R_I^2.$$  

Similarly, we can derive the proper radius for the inner circle by the following equation:

$$R_I = \frac{W}{2}.$$  

Fig. 6 (c) shows the scenario of $R_I > W/2$. We can see that the inner circle is over the range of roadway. Notably, the value of $\theta_1$ is the same as that in above cases but the value of $\theta_2$ is different from above cases. According to trigonometry, we have

$$\theta_2 = \cos^{-1}\left( \frac{W}{2R_O} \right) - \cos^{-1}\left( \frac{W}{2R_I} \right).$$  

Then, the area sizes of inner circle and outer circle could be derived by the following equations:

$$A(Out) = 2(R_I R_O \sin \theta_2 - R_I^2 \theta_2) + 2\theta_1 (R_O^2 - R_I^2), \text{ and }$$

$$A(In) = R_I^2 [\theta_1 + \theta_2 + \sin(\pi - 2\theta_2 - \theta_1)].$$  

Apparently, it is not easy to derive the close-form of $R_I$ from parameters $\theta_1$, $\theta_2$, $W$ and $R_O$. Instead of figuring out the precise $R_I$, we use the following equation to derive the approximate $R_I$

$$R_I \approx \frac{\sqrt{2W \cdot R_O + \frac{1}{2} W^2 + \frac{W^2}{\pi}}}{2\sqrt{2W}}.$$  

4. THROUGHPUT ANALYSIS

To concentrate on the system throughput gain contributed from proposed VGA strategy, every OBU in WAVE network has one transceiver only and the RSU in the WAVE network has one or two transceivers. In paper [11], author has designed an accurate throughput model for single-channel IEEE 802.11 network. Because the IEEE 802.11p
WAVE system inherits the CSMA/CA MAC protocol as its MAC protocol, the throughput model designed for IEEE 802.11 network can be applied directly. The main difference between IEEE 802.11 WLAN network and 802.11p WAVE network is the number of operating channels, as the standard IEEE 802.11 WLAN network operates on single channel and the standard IEEE 802.11p WAVE network is designed to operate on multiple channels. However, when the RSU uses one transceiver to operate in a multi-channel WAVE system, it is required for RSU and OBUs to perform frequency hopping between CCH and SCHs. Therefore, the maximum channel capacity of system is limited as single-channel capacity. On the other hand, if the RSU has two or more transceivers, it can serve OBUs on multiple SCHs in order to improve the system performance.

This paper first analyzes the system throughput of multi-channel WAVE network when the RSU uses single transceiver. Based on the derived result, we then estimate the system throughput of multi-channel WAVE network when the RSU uses multiple transceivers.

Let $T_{PS}$ denote the throughput of the multi-channel WAVE network, which comprises of one RSU and $N$ OBUs, under single transceiver constrain. Referring to paper [12], the throughput is expressed as the following equation:

$$T_{PS} = \frac{E[DP]}{E[FP]} \times DTR,$$

where $DTR$ is the data transmission rate, $E[DP]$ is the expected value of data payload, and $E[FP]$ is the expected value of frame period. We also note that the average amount of payload information successfully transmitted in a slot time is equal $P_{TX} \cdot P_{S} \cdot R_{SCH} \cdot E[DP]$, where $P_{TX}$ is the probability that there is at least one transmission in the considered slot time, $P_{S}$ is the probability of successful transmission, and $R_{SCH}$ is the ratio of SCH interval and channel cycle (i.e., $R_{SCH} = \frac{T_{SCH}}{T_{CCH} + T_{SCH} + 2 T_{GI}}$). Hence, the throughput of single-channel system can be rewritten with new notations as

$$T_{PS} = \frac{P_{TX} P_{S} R_{SCH} E[DP]}{R_{CCH} \sigma + R_{SCH} (P_{TX} P_{S} T_{S} + (1 - P_{TX}) \sigma + P_{TX} (1 - P_{S}) T_{C})} \times DTR,$$

where $\sigma$ is the duration of a slot time, $T_{S}$ is the average time period that the channel is sensed busy due to successful transmission, $T_{C}$ is the average time period during which the channel is sensed busy by the non-colliding OBU, and $R_{CCH}$ is the ratio of control interval and channel interval (i.e., $R_{CCH} = \frac{T_{CCH}}{T_{CCH} + T_{SCH} + 2 T_{GI}}$).

If each frame is transmitted by means of the Request-to-send/Clear-to-send (RTS/CTS) access mechanism, collision may occur only on RTS frames. We obtain

$$T_{S} = R_{TS} + SIFS + \sigma + CTS + SIFS + \sigma + HDR + E[DP] + SIFS + \sigma + ACK + DIFS + \sigma,$$

and

$$T_{C} = R_{TS} + DIFS + \sigma.$$
where SIFS is the smallest gap between two successive frame transmissions, DIFS is the gap of SIFS plus duration of slot time, RTS, CTS and ACK respectively denote the sizes of RTS, CTS and acknowledgment frames, and HDR is the packet header (which consists of PHY header and MAC header).

In general, the values of PTX and PS can be separately derived by the following equations:

$$PTX = 1 - \frac{1}{S_{TX}} (1 - \tau)^N$$

and

$$PS = \frac{1}{PTX} \left( \frac{\binom{N}{1}}{\tau_1} (1 - \tau_1)^{N-1} \right)$$

where $\tau$ is the probability that an OBU transmits a frame in a randomly chosen slot time.

Referring to paper [12] again, it yields:

$$\frac{1}{N} = \sum_{j=0}^{B-1} (2p^j)$$

where $C$ is the minimal contention window size, $B$ is the maximum backoff stage, and $p$ is the probability that a transmitted packet encounters a collision (i.e., $p = 1 - (1 - \tau)^N$).

However, $\tau$ depends on the conditional collision probability $p$, which is still unknown. Due to the dependence between collision probability and the number of competing nodes, the probability $p$ is simply set as the ratio of the number of OBUs on a SCH and the total number of OBUs. For example, if the RSU uses single transceiver to serve all OBUs, then $p$ is equal to 1 because all OBUs access the same SCH on which the RSU provides the service. Now, let us consider a multi-channel WAVE network in which the RSU uses $M$ transceivers to serve OBUs on $M$ separate SCHs simultaneously. Let $THM(i), 1 \leq i \leq M$, denote the throughput of the $i$th SCH and $N_i$ denote the number of competing OBUs on the $i$th SCH. We have $N = N_1 + N_2 + \ldots + N_M$. Based on the above analysis, the throughput expression for the $i$th SCH is similar to the TP excepting the parameters PTX, PS, $\tau$, and $p$, which shall be recalculated according to the actual number of competing OBUs on the $i$th SCH (i.e., $N_i$). Moreover, according to the aforementioned assignment for parameter $p$, if the RSU has two transceivers to serve OBUs on two SCHs simultaneously, the values of $p$ for SCHs which servers OBUs in inner circle and outer circle are $A(In)/(A(In) + A(Out))$ and $A(Out)/(A(In) + A(Out))$ respectively. As a result, the total throughput of the multi-channel WAVE system is $THM(1) + THM(2) + \ldots + THM(M)$. From our observations, the maximum throughput would be obtained when $N_1 = N_2 = \ldots = N_M = N/M$, as the load balancing strategy can minimize the collisions.

5. SIMULATION MODEL AND SIMULATION RESULTS

5.1 Simulation Model

In order to compare the performance of the random assignment strategy and the proposed VGA strategy, the throughput, the access delay and the packet loss rate are used as primary metrics. To concentrate on the performance of VGA strategy, an error-free chan-
nel condition is assumed in the NS2 simulator [13-16]. The network under investigation only includes one RSU and a number of OBU{s (varying from 2 to 60), and there are one CCH and two SCHs, which designate the same data transmission rate. Moreover, network generates the uplink traffic (from OBU to RSU) only in order to evaluate the impact from different channel selection strategies. Moreover, suppose each OBU has buffer space of 100 packets and it always selects one of two SCHs to transmit packets during SCH interval. The key IEEE 802.11p PHY and MAC parameters used in evaluation are listed in Table 1. Here we also assume that OBU{s are randomly distributed in space of 600m × 600m, and the RSU is placed at center of space (i.e., at coordinate (300,300)). We also note that, for the roadway scenarios, the OBU{s located on sidewalk are reallocated until they are properly located on the roadway. The maximum transmission distance of RSU and OBU is 300m (i.e., RO = 300m) and the WAVE system is deployed in a metropolitan where the width of main road is 50m (i.e., W = 50m). Here, we also assume that packet arrival rate of OBU follows the CBR traffic with interval of 10ms and the length of produced frame is 1024 Bytes.

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<th>Table 1. Key PHY and MAC parameters.</th>
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<td>Parameter</td>
</tr>
<tr>
<td>Data bit rate</td>
</tr>
<tr>
<td>Time slot</td>
</tr>
<tr>
<td>SIFS/ DIFS</td>
</tr>
<tr>
<td>MAC/ PHY header</td>
</tr>
<tr>
<td>ACK/ RTS/ CTS</td>
</tr>
<tr>
<td>WSA frame</td>
</tr>
<tr>
<td>aCWmin/aCWmax</td>
</tr>
<tr>
<td>Max. retry count</td>
</tr>
<tr>
<td>CCH/SCH/Guard interval</td>
</tr>
</tbody>
</table>

5.2 Simulation Results

Figs. 7-9 depict three sets of simulation results of proposed VGA strategy and standard random strategy under roundabout, crossroad and straight roadway scenarios, respectively.

First of all, the analytical system throughout and system throughout derived from simulation results under three different scenarios are respectively portrayed in Figs. 7 (a), 8 (a) and 9 (a) as a function of radius of inner circle (i.e., RI) for the proposed VGA strategy. Evidently, the system throughout is affected by the radius of inner circle and the number of OBU{s. As the total traffic load of OBU{s is higher than the saturation point of system capacity, the radius of inner circle dominates the performance of system throughout, as the maximum throughout could be derived when RI = 225m, 175m and 175m under roundabout, crossroad and straight roadway scenarios, respectively. The proof of derivation of similar RI values from our analyses (addressed in section 3) will be provided later.

From Figs. 7 (b), 8 (b) and 9 (b), the adoption of new VGA strategy with all kinds of parameter RI (i.e., RI = 100, RI = 150, RI = 200 and RI = 250) always results in better
throughout, as compared to the random strategy. For example, the throughput improvement achieved by VGA strategy could be up to 100% when $R_I = 200$ and the number of OBUs ($N$) is 50. More specifically, when $R_I = 200$ and $N = 50$, the throughput obtained
by the proposed VGA strategy in each scenario is about 16 Mbps, but the throughput
obtained by the random strategy is only 8 Mbps.

Access delay, as another key performance improvement metric, has also been evalu-
ated in this paper, due to the interactive impression from vehicular subscribers. Figs. 7
(c), 8 (c) and 9 (c) further illustrate the relations among average access delay, the number
of OBUs and the value of \( R_i \). It can be observed that proposed VGA strategy can sustain
a more stable and lower access delay, even though it yields a little bit worse access delay
as the number of OBUs grows. In addition, it also indicates that both strategies have sim-
ilar performance if the traffic load is lower than the saturation throughput (i.e., \( N \leq 20 \)).
Nevertheless, this highly desirable feature of insensibility is particularly indispensable for
handling vehicular application, as the network operator might adopt any kinds of heuristic
experiences to deploy the WAVE system.

Investigation into the packet loss rate shows that the standard random strategy will
incur a certain ratio of packets of high packet loss rate, which is consistent with its low
system throughput and large access delay. Moreover, due to the fact that proposed VGA
strategy systemically and equally spreads OBUs onto two SCHs in order to possess the
advantage of multi-channel access, the packet loss rate reduction it can thus accomplish
is always better than random strategy.

As a conclusion, the random strategy, which is probably adopted in IEEE 802.11p
WAVE system, is harmful to the system performance in terms of throughout, delay and
packet loss rate. On the contrary, the proposed VGA strategy, which is designed to achieve
the load balancing, is able to maximize the system performance.
5.3 $R_I$ Assignment

Comparison among those figures indicates that the throughput enhancement, the access delay reduction and the corresponding packet loss rate improvement achieved by the proposed VGA strategy somewhat rely on the parameter $R_I$. A closer examination of the performance results reveals that as the $R_I$ is set below (beyond) the equilibrium point, it becomes more likely to partition most of the OBUs as the users in inner (outer) circle, thereby increasing the degree of contentions to a higher level. Assigning a proper $R_I$ for WAVE system is of importance and the fast way of figuring out the proper value of $R_I$ is the major contribution of this paper.

As discussed in section 3, to equally distribute OBUs onto two SCHs, it is hard to derive the precise $R_I$ in some scenarios. Instead of figuring out the precise $R_I$ by time-consuming numerical technique, we have derived the simplified equations to estimate the approximate $R_I$. Table 2 compares the values of precise $R_I$ and approximate $R_I$ for each scenario. It is quite evident that the values of precise $R_I$ and approximate $R_I$ for each scenario are close to each other. In addition, the simulation results shown in Figs. 7 (a), 8 (a) and 9 (a) also prove that these values of $R_I$ are able to obtain the maximum system throughput.

Table 2. The derived precise $R_I$ and approximate $R_I$ for each different scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>RO/W</th>
<th>Precise $R_I$</th>
<th>Approximate $R_I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundabout</td>
<td>300m/0</td>
<td>212.2m</td>
<td>212.2m</td>
</tr>
<tr>
<td>Crossroad</td>
<td>300m/50m</td>
<td>155.9m</td>
<td>158.8m</td>
</tr>
<tr>
<td>Straight roadway</td>
<td>300m/50m</td>
<td>170.7m</td>
<td>161.7m</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

This paper has revealed that the primary reason of the system throughput efficiency, the access delay and the packet loss rate deterioration in multi-channel IEEE 802.11p WAVE system is the unbalanced traffic load on SCHs. In this paper, we have proposed a novel load balancing strategy, namely VGA, to improve the system performance, while trying to minimizing the additional signaling overhead. The key concept of VGA strategy is to distribute OBUs into multiple SCHs by controlling the RSSI threshold of every SCH channel. An OBU automatically selects the SCH according to the RSSI threshold broadcast by RSU and the corresponding RSSI value while receiving beacon frame. This paper further investigated the appropriate thresholds for three popular roadway scenarios to achieve the goal of load balancing. Simulation results demonstrate that the proposed VGA strategy not only improves the overall system capacity but also provides useful information about roadway planning in IEEE 802.11p wireless vehicular networks.

REFERENCES


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