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A Fair Scheme for Multi-channel Selection in Vehicular Wireless Networks

Kuo-Lung Wang · Tsan-Pin Wang · Chien-Chao Tseng

Abstract In recent years, the IEEE 802.11p/1609 wireless access in vehicular environments standards adopt the dedicated short-range communications multi-channel architecture for vehicular wireless networks. To utilize the multi-channel architecture, each vehicle equipped with two sets of transceivers can operate concurrently on three different channels. For example, in cluster-based multi-channel schemes, a cluster head vehicle coordinates and assigns an appropriate channel to its cluster members. However, these schemes are unsuitable for a single channel device performing on only one RF channel at a time which would waste channel resource and increase time to allocate a channel. Another approach, called LEACH-based scheme, selects channels randomly and ensures that each channel is selected once within a round in each vehicle. However, this leads to a situation that different vehicles might select the same channel in short-term duration. In this paper, we propose a multi-channel selection scheme, called minimum duration counter (MDC) scheme, which could apply to a single channel device, while utilizing the multi-channel architecture of an 802.11p/1609 network. In addition, we compare the MDC scheme with pure random (PR) and LEACH-based schemes in terms of fairness index (FI) and utilization to emphasize the fairness and to balance the traffic of multi-channel usage. Furthermore, we analyze the counter overflow probability distribution and propose solutions to the MDC scheme. Numerical results show that our scheme outperforms the PR and LEACH-based schemes in terms of multi-channel usage, traffic balancing, and fairness.

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1 Introduction

In recent years, a variety of communications between vehicles, including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, have attracted considerable attention from the community, academia, and automotive industry. The IEEE 802.11p/1609 WAVE standards [1–5] provide a communication protocol stack for vehicular communication networks. The IEEE 802.11p standard [1] amends from the IEEE 802.11-2007 standard [6], and defines a new operation mode, called the WAVE mode, for V2V or V2I communications. In addition, the IEEE 802.11p WAVE basic service set (WBSS) uses ad hoc mode specifications to access independent basic service set (IBSS) networks and the physical layer (PHY) is expected in the 5.850–5.925 GHz DSRC [7] spectrum in North America, which is a licensed radio services band in the United States. Basically, the spectrum is divided into seven 10-MHz wide channels including one control channel (CCH) and six service channels (SCHs). These standards define the WBSS for vehicular ad hoc networks (VANETs) to implement V2V communications. However, the standards do not specify how to select a WBSS SCH that is less likely to be congested for vehicular communications. Therefore, we design a scheme to make best use of DSRC multi-channel architecture fairly and efficiently in vehicular networks.

Besides the IEEE standardization activities, much research focuses on a cluster-based multi-channel protocol for VANETs [8–10]. In the [8,9] schemes, each vehicle is equipped with two sets of transceivers, which can operate simultaneously on three different channels. But the requirement for simultaneous channel usage might be unsuitable for a single channel device that can perform on only one RF channel at a time. Furthermore, in the [8–10] schemes, a cluster head vehicle (like WLAN's Base Station) coordinates the channel status of the cluster and assigns an appropriate data channel to its cluster members after receiving the data channel requests. However, it could waste channel resource and increase time to get an allocation of the data channel. In [11], the proposed method is designed to guarantee that each cluster member will take turn as the cluster head in a probabilistic manner and could be modified for selecting channels in vehicular networks. The schemes used the method in [11] are referred to as LEACH-based schemes hereafter. In the LEACH-based scheme, each vehicle selects channels in a round-robin fashion in its local view. Thus, in the global view, different vehicles might select the same channel in short-term duration. This leads to unfair channel utilization. In this paper, we propose a multi-channel selection scheme called MDC scheme that could apply to a single channel device while utilizing the multi-channel architecture of an 802.11p/1609 network in both short-term and long-term duration. Moreover, we compare the MDC scheme with PR and LEACH-based schemes in terms of FI and utilization to emphasize the fairness and traffic balancing of multi-channel usage. In addition, we present the counter overflow problem, analyze the overflow probability distribution, and propose solutions to the MDC scheme.

The remainder of this paper is organized as follows. Section 2 reviews the concepts and describes the SCH selection schemes. In Sect. 3, we propose a mathematical model to evaluate the fairness and utilization of MDC, PR, and LEACH-based schemes. In Sect. 4, we analyze and compare the numerical results of MDC with PR and LEACH-based schemes. Section 5 considers the counter overflow problem and evaluates the probability of counter overflow. Finally, conclusions are given in Sect. 6.

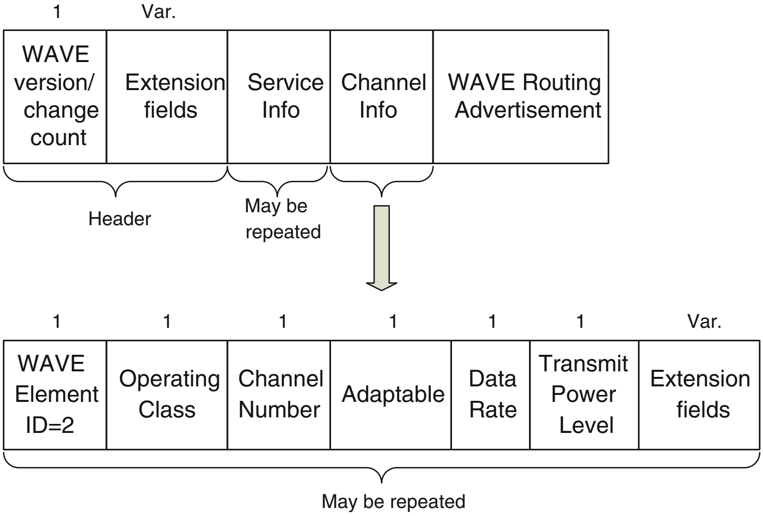


Fig. 1 Wave service advertisement (WSA) format

2 SCH Selection Schemes

2.1 WAVE Operations

In the WAVE mode, data packet transmissions are allowed to occur within a WBSS. A node that initiates a WBSS is called a WBSS provider, while nodes that join a WBSS are called WBSS users. When a provider wants to form a WBSS, it broadcasts a WAVE service advertisement (WSA) frame on the CCH during the CCH interval. The WSA frame carries the information about which one of the six SCHs is chosen for the WBSS during the next SCH interval. The WSA format [4] is shown in Fig. 1. The WSA consists of WAVE version/Change count, WSA header extension fields, Service Info, Channel Info, and WAVE Routing Advertisement.

WAVE version/Change count: This mandatory one-octet field carries the 6-bit version number that defines the format of this WSA. The version number of the current IEEE 1609.3-2010 Std. is 1. The remaining 2 bits are a modulo-4 content change counter. The sender shall increment the counter when it changes the contents of the WSA. This provides a receiver to filter out duplicate WSA.

WAVE service advertisement (WSA) header extension fields: The optional "extension field" provides flexibility for the WSA to omit or include an optional field and provides new extension fields that can be defined in the future. The total length of the WSA header extension fields should not cause the WSA header to exceed 255 octets. In the current standard, six extensions are defined such as "Repeat Rate", "Transmit Power Used," "2DLocation", "3DLocationAndConfidence", "Advertiser Identifier", and "Country String".

Service Info: There are 0–32 possible instances of Service Info segments in the WSA. Each Service Info segment advertises one service.

Channel Info: There are 0–32 instances of Channel Info segments in the WSA and one Channel Info segment is needed for each channel on which an advertised service is offered. A Service Info segment is linked to a Channel Info segment by the Channel Index in the Service Info segment. The Extension fields of Channel Info are variable length in bits. However, the total length of the Extension fields should not cause the Channel Info to exceed 255 octets.

WAVE Routing Advertisement: This is an optional field within the WSA. It provides information about how to connect the Internet, allowing a receiver to be configured to incorporate on the advertised IPv6 network.

2.2 Pure Random Scheme

The provider will always select the SCH randomly in the PR scheme. The major advantage of the PR scheme is its simplicity. Although all six SCHs are equally likely to be selected in the same probability, the PR scheme is not always the fairest. The PR scheme may lead to unfair in long-term selection since every selection is memory-less and independent. For this reason, the PR scheme may concentrate traffic in some channels. That is, the PR scheme may not always balance traffic among six SCHs. Therefore, the PR scheme may not take advantage of the DSRC multi-channel architecture to balance traffic.

2.3 LEACH-Based Scheme

The LEACH scheme is designed to guarantee that each cluster member will take turn as the cluster head in a probabilistic manner. In the following, we modified the LEACH scheme for selecting channels in vehicular networks. In the LEACH-based scheme, the SCH i, for $i = 1, 2, \ldots, 6$, chooses a random number between 0 and 1. If the chosen number is less than a threshold T(i), the SCH i will be the candidate channel in the current selection. If there is more than one candidate in the current selection, the LEACH-based scheme selects one SCH randomly from the candidates. The T(i) is set as follows.

$$T(i) = \begin{cases} \frac{\frac{1}{6}}{1-\frac{1}{6}(r \bmod 6)} & if\ i \in G \\ 0 & otherwise \end{cases} \tag{1}$$

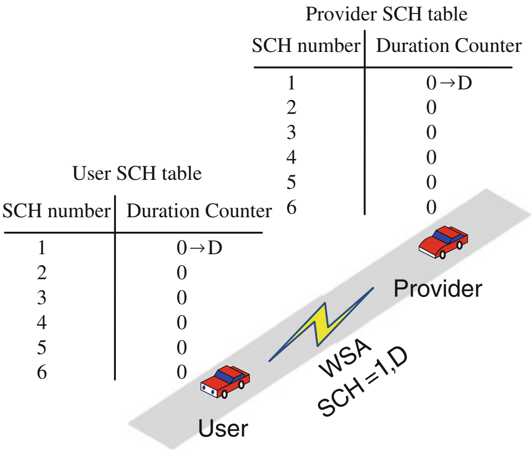
where r is the number of selection in this round and G is the set of SCHs which have not been selected in the last selections. By using T(i), each SCH will be selected within 6 selections. During the first selection (r = 0), each SCH has a probability 1/6 to be selected. The SCH which is selected in the first selection cannot be selected in the consequent selections. Similarly, during the second selection (r = 1), each SCH in G has a probability 1/5 to be selected. After 6 selections, all six SCHs are once again to become the selectable channels.

The used probabilistic selection scheme would guarantee that each channel is selected only once within a round for a vehicle. That is, in the LEACH-based scheme, the provider will always select each SCH once for every six selections within each vehicle. Consequently, each vehicle selects SCH in a round-robin fashion in its local view. However, in the global view, different vehicles in the radio range could still select the same channel in short-term duration. In the long-term duration, the LEACH-based scheme selects channels in a near round-robin fashion.

2.4 Minimum Duration Counter scheme

In the MDC scheme, the provider will always select the least-used SCH. To identify the least-used SCH, each vehicle maintains an SCH table that contains two fields: SCH number and duration counter as shown in Fig. 2. The SCH number field denotes the six SCHs and the duration counter field indicates the respective usage for each SCH among vehicles. Let $counter_i$

Fig. 2 Concept of the MDC scheme



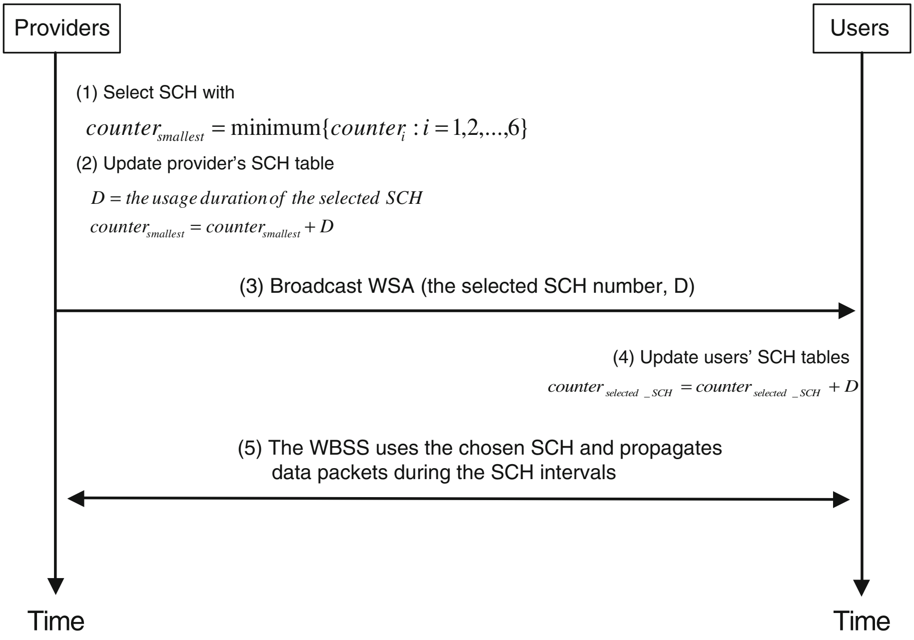


Fig. 3 MDC operations

denote the duration counter of SCH i, for i = 1,2,…,6. Assume that we could estimate the usage duration of the selected SCH for each transmission. In the IEEE Std. 1609.3-2010 [4], the Extension fields of Channel Info of WSA are variable bits in length. Thus, we could attach the usage duration of the selected SCH in the Extension fields of Channel Info of WSA as shown in Fig. 1. That is, the usage duration of the selected SCH is piggybacked in WSA. Consequently, the MDC scheme will not increase any extra traffic flow in WAVE operations.

The operations of MDC scheme consists of the following five steps (see Fig. 3).

Step 1: When a vehicle wants to create a WBSS and becomes a provider, it will select the SCH with the smallest duration counter in its SCH table. That is, the provider selects the SCH with $counter_{smallest} = \text{minimum}\ \{counter_i : i = 1, 2, \ldots, 6\}$.

Step 2: Suppose that the usage duration of the selected SCH is given for each transmission. Let D denote *the usage duration of the selected SCH*. After Step 1, the provider updates its SCH table with $counter_{smallest} = counter_{smallest} + D$.

Step 3: Then, the provider will broadcast the WSA frame that contains the corresponding SCH number and piggybacks the usage duration of the selected SCH in WSA on the CCH during the CCH interval. In other words, the provider broadcasts WSA (the selected SCH number, D).

Step 4: On receipt of the broadcasted SCH information in WSAs, WBSS users store and update the information in their SCH tables. Once an SCH is advertised in the WSA, the corresponding duration counter will be increased according to the usage duration of the selected SCH. That is, WBSS users update the duration counter with $counter_{selected\_}\mathrm{SCH} = counter_{selected\_}\mathrm{SCH} + D$.

Step 5: The WBSS uses the chosen SCH and propagates data packets during the SCH intervals.

If a duration counter reaches the maximum value called MAX, the duration counter will overflow next time. When the overflow occurs, the duration counter will be reset to zero that is always the smallest one. Consequently, the MDC scheme will select the corresponding SCH time after time. In other words, the overflowed SCH will be the only selected channel during the period when the overflow counter changes from zero to the smallest value among the other duration counters. For example, if all six duration counters of SCH reach the MAX, then a duration counter of SCH will overflow next time. Assume that the duration counter of SCH i overflowed. Then, the SCH i will be always the only selected channel during the period when the duration counter of SCH i varies from 0 to MAX. Thus, how to deal with the overflow problem is a challenge for the MDC scheme to provide better fairness for multi-channel utilization and selection.

3 Analytical Model

In this section, we propose an analytical model to evaluate PR, LEACH-based, and MDC schemes in terms of FI and utilization.

3.1 Fairness

We use the Jain's FI [12] to evaluate how fair an SCH allocation is as follows.

$$f(X) = \frac{\left[\sum_{i=1}^{a} X_i\right]^2}{\left(a \sum_{i=1}^{a} X_i^2\right)}, \tag{2}$$

where a is the number of SCHs. We define the fairness parameter X in the Jain's FI in the following way. Let X_i denote the value of the corresponding duration counter for SCH i and represent the measured allocations of SCH i under the PR, LEACH-based, and MDC schemes. Once an SCH i is allocated, X_i increases by the usage duration of SCH i. Note that the Jain's FI is always a real number between 0 and 1; the larger the FI value, the fairer the allocation. If all X_i are equal, then the FI value, f(X) will be equal to 1, which means the allocation of SCHs is fair. On the other hand, if f(X) is going to near 0, then the allocation of SCHs is unfair. In the following, we will analyze the fairness of MDC scheme first and then those of the PR and LEACH-based schemes.

In the vehicular wireless networks, most of the data transmissions are short messages except for entertainments. So, we could assume that the usage duration of each SCH is the same and equal to one time unit for simplification in our analytical framework. Let S(t) denote the number of channel selections during [0, t]. Suppose that S(t) forms Poisson distribution. Thus,

$$P[S(t) = s] = \frac{e^{-\lambda_s t}(\lambda_s t)^s}{s!}, \tag{3}$$

where λ_s is the channel selection rate. Let $\overline{f}_{MDC}(X)$ be the average FI of MDC scheme. In the MDC scheme, the SCHs will be allocated in a round robin manner. Conditional on s, we could obtain the following equation from Eqs. (2), (3).

$$\overline{f}_{MDC}(X) = \sum_{s=1}^{\infty} f(X) P[S(t) = s], \tag{4}$$

where $f(X)$ is the Jain's FI when $s = \sum_{i=1}^{6} X_i$.

Let $\overline{f}_{PR}(X)$ be the average FI of PR scheme. In the PR scheme, all possible cases occur in a probabilistic manner because every SCH selection forms a memory-less and independent random variable. Given S(t), let $H^6_{S(t)}$ be the total number of possible cases for allocating six SCHs in the PR scheme. Using combinations with repetition [13], we get

$$H^6_{S(t)} = C^{6+S(t)-1}_{S(t)}. \tag{5}$$

From Eqs. (2), (5), we could have

$$\overline{f}_{PR}(X) = \frac{\sum_{X_1=0}^{S(t)} \sum_{X_2=0}^{S(t)-X_1} \sum_{X_3=0}^{S(t)-X_1-X_2} \sum_{X_4=0}^{S(t)-X_1-X_2-X_3} \sum_{X_5=0}^{S(t)-X_1-X_2-X_3-X_4} \sum_{X_6=0}^{S(t)-X_1-X_2-X_3-X_4-X_5} f(X)}{\sum_{\mathrm{i}=1}^{\mathrm{s(t)}} H_i^6}, \tag{6}$$

where $f(X)$ is the Jain's FI.

Let

$$h(X_j) = S(t) - \sum_{i=1}^{j} X_i. \tag{7}$$

From Eqs. (6), (7), we obtain

$$\overline{f}_{PR}(X) = \frac{\sum_{X_1=0}^{h(X_0)} \sum_{X_2=0}^{h(X_1)} \sum_{X_3=0}^{h(X_2)} \sum_{X_4=0}^{h(X_3)} \sum_{X_5=0}^{h(X_4)} \sum_{X_6=0}^{h(X_5)} f(X)}{\sum_{\mathrm{i}=1}^{\mathrm{s(t)}} H_i^6}, \tag{8}$$

where $f(X)$ is the Jain's FI.

Let $\overline{f}_{LEACH}(X)$ be the average FI of the LEACH-based scheme. In the LEACH-based scheme, the SCHs will be allocated in a round robin manner within each vehicle. Suppose that there are m vehicles in the radio range, each vehicle has the same request rate of channel selections, and each channel selection is independent and identical distributed. Let P_j be a random variable and denote the channel usage rate of vehicle j, for j = 1, 2, …, m. So, $P_j = \frac{y}{6}$ for y = 0, 1, 2,…, 5 and y is uniformly distributed between 0 and 5. Suppose that the channel usage rate of each vehicle is uniformly distributed among m vehicles. That is,

P_j is uniformly distributed between $\frac{0}{6}$ and $\frac{5}{6}$ among m vehicles. If each P_j is given for m vehicles, we could drive the X_i using binomial distribution as follows.

$$X_i = \sum_{k=1}^{m} k C_k^m P_j^k (1 - P_j)^{m-k}. \tag{9}$$

From Eqs. (2), (9), we could have

$$\overline{f}_{LEACH}(X) = \frac{\left[\sum_{i=1}^{a} X_i\right]^2}{\left(a \sum_{i=1}^{a} X_i^2\right)}. \tag{10}$$

Assume that a round contains six channel selections within a vehicle. Therefore, if each one of m vehicles performs channel selections within a round in the radio range, it is referred to as short-term duration. The maximum number of total channel selections is $6m$ in a round for m vehicles because each vehicle has the same request rate of channel selections and there are m vehicles in the radio range. From Eqs. (4), (6) and (10), we could drive the following equations in the short-term duration.

$$\overline{f}_{MDC}(X) = \sum_{s=1}^{\text{6m}} f(X) P[S(t) = s] \tag{11}$$

$$\overline{f}_{PR}(X) = \frac{\sum_{X_1=0}^{\text{6m}} \sum_{X_2=0}^{\text{6m}-X_1} \sum_{X_3=0}^{\text{6m}-X_1-X_2} \sum_{X_4=0}^{\text{6m}-X_1-X_2-X_3} \sum_{X_5=0}^{\text{6m}-X_1-X_2-X_3-X_4} \sum_{X_6=0}^{\text{6m}-X_1-X_2-X_3-X_4-X_5} f(X)}{\sum_{\text{i}=1}^{\text{6m}} H_i^6} \tag{12}$$

$$\overline{f}_{LEACH}(X) = \frac{\left[\sum_{i=1}^{a} X_i\right]^2}{\left(a \sum_{i=1}^{a} X_i^2\right)}, \tag{13}$$

where $X_i = \sum_{k=1}^{m} k C_k^m P_j^k (1 - P_j)^{m-k}$.

If each one of m vehicles performs channel selections after many rounds in the radio range, it is referred to as long-term duration. Suppose that each one of m vehicles performs channel selections after z rounds. Using Eqs. (4), (6), (9) and (10), we could drive the following equations in the long-term duration.

$$\overline{f}_{MDC}(X) = \sum_{s=1}^{\text{6z+6m}} f(X) P[S(t) = s] \tag{14}$$

$$\overline{f}_{PR}(X) = \frac{\begin{array}{c}\sum_{X_1=0}^{\text{6z+6m}} \sum_{X_2=0}^{\text{6z+6m}-X_1} \sum_{X_3=0}^{\text{6z+6m}-X_1-X_2} \sum_{X_4=0}^{\text{6z+6m}-X_1-X_2-X_3} \\ \times \sum_{X_5=0}^{\text{6z+6m}-X_1-X_2-X_3-X_4} \sum_{X_6=0}^{\text{6z+6m}-X_1-X_2-X_3-X_4-X_5} f(X)\end{array}}{\sum_{\text{i}=1}^{\text{6z+6m}} H_i^6} \tag{15}$$

$$\overline{f}_{LEACH}(X) = \frac{\left[\sum_{i=1}^{a} X_i\right]^2}{\left(a \sum_{i=1}^{a} X_i^2\right)}, \tag{16}$$

where $X_i = z + \sum_{k=1}^{m} k C_k^m P_j^k (1 - P_j)^{m-k}$.

3.2 Utilization

Generally, the total utilization of six SCHs is close to the utilization of each SCH with the MDC, PR, and LEACH-based schemes. To simplify the modeling, we investigate the utilization of one SCH rather than that of six SCHs in MDC, PR, and LEACH-based schemes. Suppose that channel selections arrive at a 6-server service station forming a Poisson process with rate λ. That is, the time between successive arrivals is an independent exponential random variable with mean $1/\lambda$. We use an M/M/1 queuing model to investigate the utilization of one SCH in the MDC and PR schemes. Thus, we split the system rate λ into a single-server service station. The successive service time in a single-server service station is assumed to be an independent exponential random variable with mean $1/\mu$.

In the PR scheme, let m be the number of vehicles and the probability that we select the same SCH at least twice is equal to

$$\sum_{i=2}^{m} \frac{6 \times 1^{i-1} \times 5^{m-i}}{6^{m}} \times C_{i-1}^{m-1} = \sum_{i=2}^{m} \frac{5^{m-i}}{6^{m-1}} \times C_{i-1}^{m-1}. \tag{17}$$

Thus, the arrival rate is $\lambda \times \sum_{i=2}^{m} \frac{5^{m-i}}{6^{m-1}} \times C_{i-1}^{m-1}$. We explain the reasoning for Eq. (17) as follows. For example, let m is equal to 2. The probability that the two vehicles select the same SCH is $\frac{6\times 1}{6^2}$. Similarly, if m is equal to 3, the probability that the three vehicles select the same SCH at least twice is $\frac{6\times 1^1 \times 5^1}{6^3} \times C_1^2 + \frac{6\times 1^2}{6^3}$. In the same reasoning, we can derive the Eq. (17).

Let ρ_{PR} be the utilization factor and T_{PR} be the average time spent in the system of PR scheme. Using [14], let $\rho = \frac{\lambda}{\mu}$ and we could obtain

$$\rho_{PR} = \frac{\lambda}{\mu} \times \sum_{i=2}^{m} \frac{5^{m-i}}{6^{m-1}} \times C_{i-1}^{m-1} = \rho \times \sum_{i=2}^{m} \frac{5^{m-i}}{6^{m-1}} \times C_{i-1}^{m-1}, \tag{18}$$

where $0 \leq \rho_{PR} < 1$, and

$$T_{PR} = \frac{\frac{1}{\mu}}{1-\rho_{PR}} = \frac{\frac{1}{u}}{1-\rho \times \sum_{i=2}^{m} \frac{5^{m-i}}{6^{m-1}} \times C_{i-1}^{m-1}} = \frac{\lambda}{\rho\left(1-\rho \times \sum_{i=2}^{m} \frac{5^{m-i}}{6^{m-1}} \times C_{i-1}^{m-1}\right)}. \tag{19}$$

In the MDC scheme, all counters will increase in a round robin fashion. Consequently, the arrival rate will be $\lambda/6$. Let ρ_{MDC} be the utilization factor and T_{MDC} be the average time spent in the system of MDC scheme. Using[14], let $\rho = \frac{\lambda}{\mu}$ and we could have

$$\rho_{MDC} = \frac{\lambda}{6\mu} = \frac{\rho}{6}, \tag{20}$$

where $0 \leq \rho_{MDC} < 1$, and

$$T_{MDC} = \frac{\frac{1}{\mu}}{1-\rho_{MDC}} = \frac{\frac{1}{\mu}}{1-\frac{\rho}{6}} = \frac{6\lambda}{\rho(6-\rho)}. \tag{21}$$

Let ρ_{LEACH} be the utilization factor and T_{LEACH} denote the average time spent in the system of LEACH-based scheme. The value of T_{LEACH} will be ranged between T_{MDC} and T_{PR}because the LEACH-based scheme could select the same channel in short-term duration, while it works in a round-robin fashion in long-term duration. In the long-term duration, the analysis of LEACH-based scheme is the same as the MDC scheme. Therefore, we have $\rho_{LEACH} = \rho_{MDC}$ and $T_{LEACH} = T_{MDC}$.

4 Performance Results and Discussion

In this section, we compare PR, LEACH-based, and MDC schemes in terms of FI and utilization. Most of the existing channel selection schemes of MANETs focus their performance on utilization. In this paper, we focus on the fairness of channel selections. In our study, the LEACH-based scheme is the best channel selection scheme in terms of fairness in the literature. Therefore, we compare the proposed scheme with the LEACH-based scheme in this paper.

4.1 Simulation Environment

To validate the performance model, we write a Visual Basic program to simulate channel selections with the PR, LEACH-based, and MDC schemes. We use the random number generator of Microsoft Excel to generate one hundred thousand of random numbers to simulate the channel selections. Then we write a Visual Basic program to simulate the PR, LEACH-based, and MDC schemes using the generated random numbers. Furthermore, we calculate the numerical results of each case and calculate the average numerical results of all cases.

Suppose that the number of channel selections forms Poisson distribution with mean $\lambda_s t = m$, for $1 \leq m \leq 31$, in the short-term duration. In the simulation, the channel will be selected according to the rule of the LEACH-based, and the MDC scheme. In the PR scheme, we assume that the number of selection for each channel forms uniform distribution between 0 to $6m$, for $1 \leq m \leq 31$, where $\sum_{i=1}^{6} X_i = 6m$ in the short-term duration due to the nature of randomness. In the long-term duration, we assume that the number of channel selections forms Poisson distribution with mean $\lambda_s t = z$, for $100 \leq z \leq 1{,}000$. Moreover, the channel will be selected according to the rule of the LEACH-based, and the MDC scheme. On the other hand, in the PR scheme, the number of channel selections forms uniform distribution between 0 and $6z + 6m$, for $100 \leq z \leq 1{,}000$, where $\sum_{i=1}^{6} X_i = 6z + 6m$ due to the nature of randomness. Finally, to evaluate the impact of utilization on waiting time, we assume that the channel selections arrive at a 6-server service station form Poisson distribution with mean λ, for $\lambda \in \{1, 2\}$.

4.2 Fairness

Figure 4 plots the Jain's FI of MDC scheme in a round-robin fashion. That is, the allocation of SCH_i, for i = 1, 2,..., 6, is in a round-robin fashion. It could be observed that the FI increases and approximates to 1 as S(t) increases. That is, the MDC scheme achieves the fair usage of SCHs and balances the traffic between SCHs. A variety of possible SCH selections occur because the PR scheme selects the SCH randomly. Thus, we present the average FI to compare MDC scheme with PR scheme to evaluate how fair SCHs are allocated. In the short-term duration, the average fairness indexes of MDC, PR, and LEACH-based schemes are derived from Eqs. (11), (12) and (13) as plotted in Fig. 5. When m increases, the MDC scheme outperforms the PR scheme. The improvement on the average fairness indexes approximated to about 39 %. In most cases, the MDC scheme outperforms the LEACH-based scheme. When m increases, the improvement on the average fairness indexes between the MDC and LEACH-based schemes will be very close. The numerical results revealed that the $\overline{f}_{MDC}(X)$

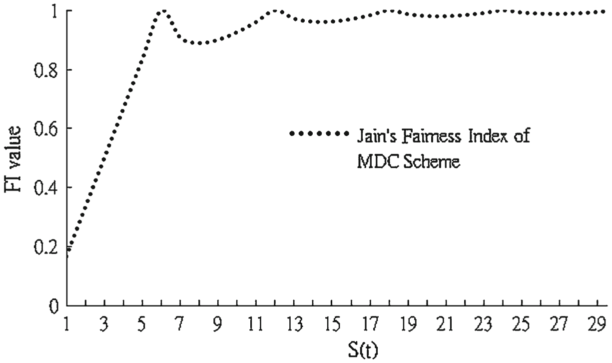


Fig. 4 Impact of S(t) on Jain's fairness index of MDC scheme

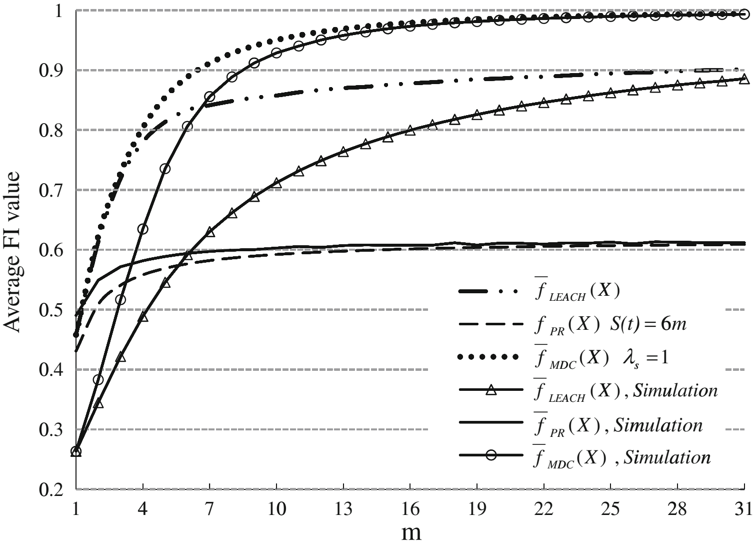


Fig. 5 Impact of on average fairness index in the short-term

is better than the $\overline{f}_{PR}(X)$ and $\overline{f}_{LEACH}(X)$. That is, the MDC scheme is much fairer than PR and LEACH-based schemes in allocating six SCHs. As shown in Fig. 5, the difference of average FI between the simulation and numerical results of the proposed model will be very close as m increases.

On the other hand, the long-term fairness of LEACH-based scheme, derived from Eqs. (14), (15) and (16), will approximate to 1 as z increases as shown in Fig. 6. Note that the LEACH-based scheme is as fair as the MDC scheme in allocating the SCHs in the long-term duration. The long-term fairness of PR scheme approaches slowly to 1 when the duration is long enough. Therefore, no matter how long the duration is, the MDC scheme performs not only with fairness of multi-channel usage but also with load balancing of multi-channel traffic in vehicular wireless networks. As shown in Fig. 6, the difference of average FI between the simulation and numerical results of the proposed model will be very close as z increases.

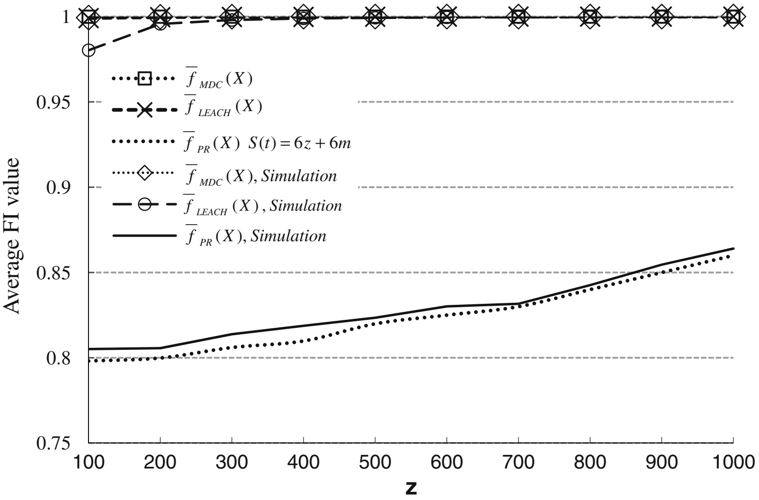


Fig. 6 Impact of z on average fairness index in the long-term duration with m = 30

4.3 Utilization

Figure 7 shows the impact of ρ on the average time spent in the system as described below. Firstly, ρ_{MDC} and ρ_{PR} increase as the ρ increases. In addition, T_{MDC} and T_{PR} increase as the utilization increases in the MDC and PR schemes, respectively. Because the MDC scheme will balance traffic among SCHs, the increase in T_{MDC} is less significant than that in T_{PR}. Secondly, the larger value the m increases, the more times the same SCH might be selected. This situation results in worse T_{PR}. Finally, the larger value the λ holds with the same ρ, the less time the T_{MDC} and T_{PR} will be. We observed that T_{MDC} is better than T_{PR}. The reason is similar to the first finding. As shown in Fig. 7, the simulation and numerical results indicate that the MDC scheme out-performs the PR scheme in terms of multi-channel utilization.

As mentioned above, in the short-term duration, the MDC scheme performs better multi-channel utilization than the LEACH-based scheme. Nevertheless, in the long-term duration, the LEACH-based scheme achieves similar multi-channel utilization with the MDC scheme.

5 Counter Overflow Problem

In this section, we consider the counter overflow problem and evaluate the probability of counter overflow due to the fixed size counter.

In the MDC scheme, let X_p be a random variable denoting the number of vehicular channel selections during [0, t]. Thus, let $P[X_p = s]$ be the probability of vehicular channel with s selections during [0, t]. Note that the MDC scheme always selects the SCH with the MDC. Consequently, from Eq. (3), we could obtain

$$P[X_p = s] = P[S(t) = s]. \tag{22}$$

Following Eq. (22), we could have

$$P[X_p \le n] = \sum_{s=0}^{n} P[S(t) = s]. \tag{23}$$

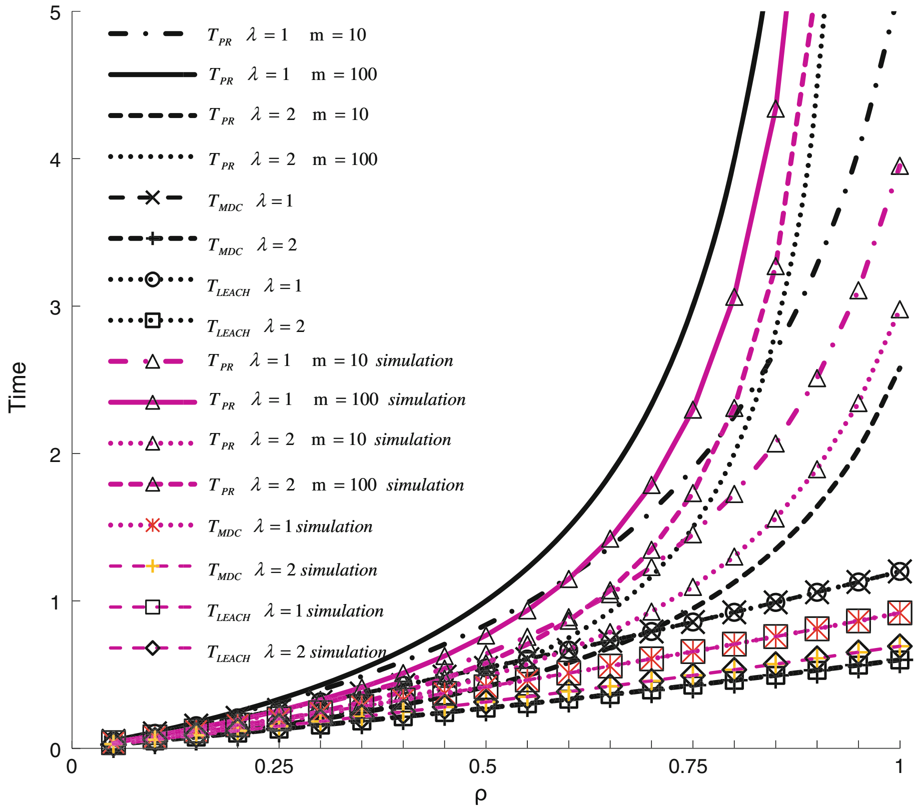


Fig. 7 Impact of ρ on average time spent in the system

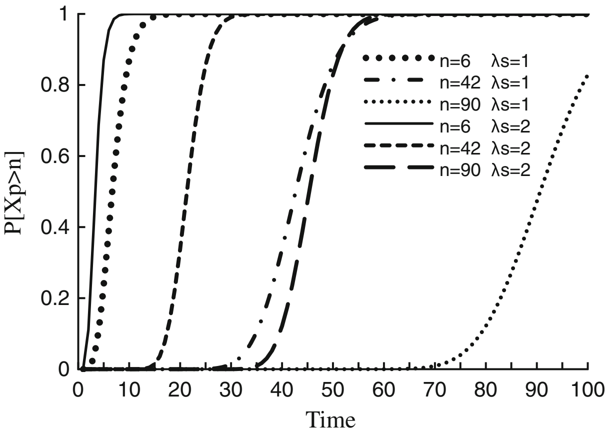
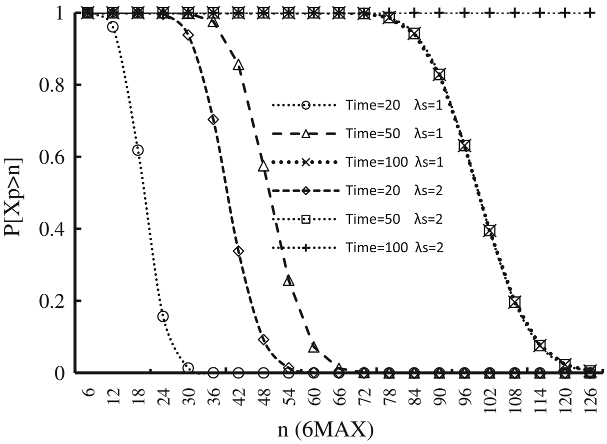


Fig. 8 Impact of time on overflow probability distribution

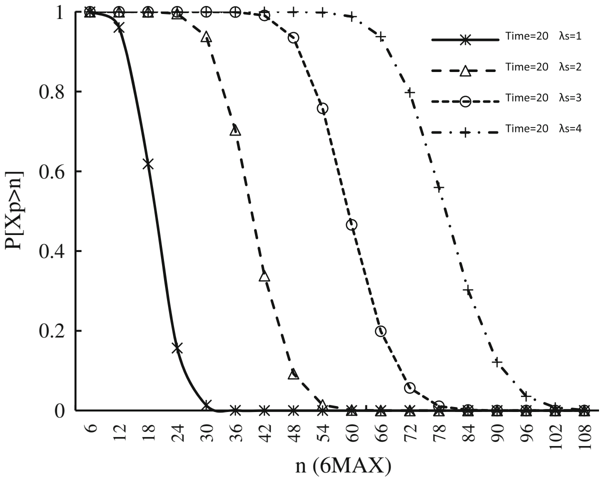
In other words, the probability distribution of counter overflow during [0, t] is

$$P[X_p > n] = 1 - P[X_p \leq n], \tag{24}$$

where n = 6MAX.



(a) Impact of time with $\lambda_s = 1$ or $\lambda_s = 2$.



(b) Impact of λ_s.

Fig. 9 The impact of n on overflow probability distribution with different time and λ_s.

Figure 8 shows the overflow probability as a function of time. Note that the overflow probability increases rapidly as the time increases. It is obvious that the larger value the MAX is, the more time the overflow probability reaches one. That is, an increase in the counter size is an increase in the time for the overflow probability reaching one. However, the time that the overflow probability reaches one is not too long no matter which counter size is. On the other hand, the channel selection rate (λ_s) is an inverse proportion to the overflow time. That is, the larger value λ_s is, the less time the overflow probability reaches one. Clearly, in any case, the counters will occur to overflow soon without proper handling.

Figure 9 shows the impacts of n on overflow probability distribution with different time and λ_s as described below. Firstly, at a fixed time and $\lambda_s = 1$ or 2, if we increase the MAX value, the overflow probability decreases quickly and then reaches to a small value near 0 (Fig. 9a). Secondly, if we increase λ_s by one ($\lambda_s = 2$), then we must enlarge the MAX value about double to maintain the same overflow probability as shown in Fig. 9b. That is, an increase in counter size is uneconomical. Instead of enlarging the counter size, we reset the counter to solve the counter overflow problem. In this work, once a counter reaches the MAX, we solve the overflow problem of MDC scheme by shifting all six counters 1 bit right, i.e., divided by 2. In this manner, resetting the counter will still achieve fairness in allocating SCHs since the SCHs allocations will be in a round robin manner in the MDC scheme.

6 Conclusions

In this paper, we propose a fair channel selection scheme which adopts a single channel device to exploit high utilization and fairness in the WAVE multi-channel architecture. The proposed scheme is simple and fair for allocating SCHs. With the MDC scheme, each vehicle maintains an SCH table which contains a duration counter. By using the SCH table, the vehicle selects the least used SCH to achieve fairness. Generally, duration counters may overflow from time to time. Consequently, we also propose a counter resetting scheme which not only deals with the counter overflow problem but also achieves fairness multi-channel usage at the same time. Moreover, we also propose an analytical model to compare the fairness of multi-channel usage and utilization of one SCH for different schemes. The numerical results show that the MDC scheme outperforms the PR and LEACH-based schemes in terms of multi-channel usage, traffic balancing, and fairness.

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