Mobility-Aware Interference Avoidance Scheme for Vehicular WLANs

Laihyuk Park[1], Woongsoo Na[1], Gunwoo Lee[1], Chang Ha Lee[1], Chang Yun Park[1], Yong Soo Cho[2] and Sungrae Cho[1]
[1]School of Computer Science and Engineering, Chung-Ang University
Seoul, Korea
[e-mail: {lhpark, wsna, gwlee}@uclab.re.kr, {chlee, cypark, srcho}@cau.ac.kr]
[2] School of Electrical and Electronics Engineering, Chung-Ang University
Seoul, Korea
[e-mail: yscho@cau.ac.kr]
*Corresponding author: Sungrae Cho

Received April 27, 2011; revised September 26, 2011; accepted November 28, 2011; published December 31, 2011

Abstract

Communication technology of future networks is predicted to provide a large variety of services including WiFi service in vehicular network. In this paper, we assume that vehicles are embedded with WiMAX antenna and in-vehicle terminals receive WiMAX traffic through WiFi interface. This assumption will impose severe performance degradation due to interference among mobile BSSs when WiFi access points (APs) are densely located. Existing interference avoidance techniques cannot properly resolve the above problems and do not cope with dynamically moving vehicular scenario since they focus only on the fixed network topology. In this paper, we propose a mobility-aware interference avoidance scheme for WiFi services. The proposed scheme computes the interference duration by exploiting mobility vector and location information of neighboring APs. If the interference duration is not negligible, our scheme searches for another channel in order to avoid interference. However, if the interference duration is negligible, our scheme continues to use the channel to reduce switching overhead. To measure the effectiveness of the proposed scheme against other existing techniques, we evaluated performance by using OPNET simulator. Through the simulation, we obtained about 60% reduction in the maximum interference frequency and about 67% improvement in throughput. Furthermore, our scheme provides fair channel usage.

Keywords: BSSs, WiFi, access point, vehicle, interference avoidance, IEEE 802.11, mobility

This research was supported by the KCC (Korea Communications Commission), Korea, under the R&D program supervised by the KCA (Korea Communications Agency)(KCA-2011-09913-04002)

DOI: 10.3837/ tiis.2011.12.001

1. Introduction

WiMAX mobile devices are known to have severe communication qualities due to signal degradation in cell boundaries and shaded areas [1]. To solve this problem, various researches attempt to increase signal sensitivity in those areas [1][2]. For instance, vehicles can be equipped with WiMAX antenna on the roof or glass of the vehicle so that the mobile devices can increase receiver signal sensitivity. Through this approach, a large variety of applications can be created by passing the WiMAX traffic to mobile devices in the vehicle. The vehicle might use a gateway (**Fig. 1**) that transparently distributes the WiMAX data to mobile users to augment the WiMAX data service. One of the potential technologies achieving this goal would be via wireless local area network (WLAN) such as IEEE 802.11[1] (we hereafter use AP and vehicle interchangeably for this reason). However, if a significant number of APs are densely located, the throughput of the mobile devices will be tremendously degraded due to interference among the WiFi networks.

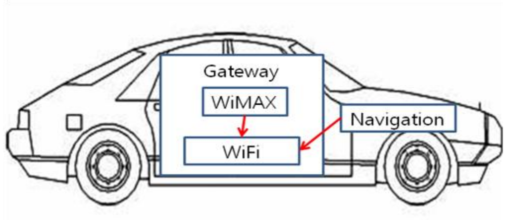


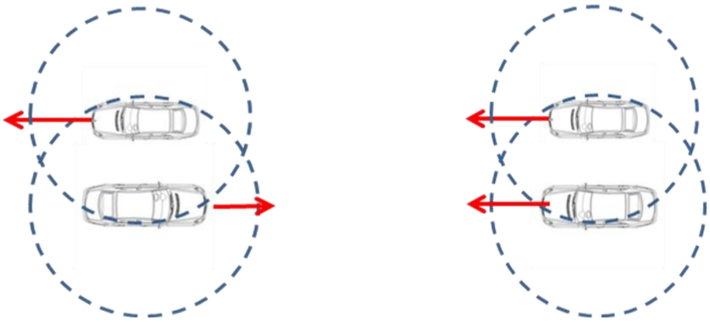
Fig. 1. Basic vehicle model

Interference avoidance techniques have been traditionally taken into account as a major research issue in wireless networks from physical to data link layers. There have been significant number of researches that use multi-channel [3][4][5][6][7][8][9][10], power control [11][12][13] or cooperative scheduling [14][15][16]. Unfortunately, there have been few proposals [3][4][5][6][7][8][9][10] to resolve interference using *channel hopping* or *selection* among access points (APs) in the WiFi WLANs. We can classify the prior interference avoidance techniques among APs into two categories: *proactive* [3][7][9] and *reactive* [4][5][6][8][10]. The former is an interference avoidance technique that presumably changes frequency channels to statistically reduce the chances having the same channel among APs. For instance, suppose two APs have the same channel. If they fix the channel during the entire lifetime of the channel, collision will always occur. With the proactive scheme, the probability of having the same channel will be relatively small in the next period even if the APs currently have the same channel. However, the proactive scheme will entail the synchronization among APs and also cause unexpected overhead since APs need to change frequency channel unnecessary even if the APs currently have different channels.

The latter is an avoidance technique that tries to resolve interference once it occurs. Unlike the former, this strategy can reduce unnecessary overhead since channel hopping occurs only when it is needed. Our mobility-aware interference avoidance scheme falls under the reactive approach. The related work under the both categories will be discussed in section 2.

[1]We assume in this paper that IEEE 802.11 WLAN is the technology distributing WiMAX traffic to in-vehicle mobile devices. However, any WPAN/WLAN technologies can be utilized for this purpose.

Considering mobile vehicular environment, topology of the WiFi WLAN will dynamically change. Furthermore, the signal to interference and noise ratio (SINR) will become severer and thus the throughput will exponentially decrease when two APs are densely located. The aforementioned techniques have been designed for fixed WLANs and thus they cannot be appropriate for the dynamically changing mobile WiFi vehicular network.



(a) Short interference duration **(b)** Long interference duration
Fig. 2. Different interference duration due to dynamicity of the topology

In this paper, we assume that vehicles are embedded with WiMAX antenna which distributes WiMAX traffic to WiFi in-vehicle wireless devices forming a basic service set (BSS). We propose a mobility-aware interference avoidance scheme among those BSSs which works well even under the situation that BSSs are densely located. Therefore, to cope with dynamicity of the topology, we exploit mobility vector and location information of neighboring APs from a global positioning system (GPS). Based on the location information, the proposed scheme computes the interference duration with neighboring APs. If the interference duration of the current channel is negligible as in **Fig.2 (a)**, it continues to use the channel. However, if the interference duration is not negligible as in **Fig. 2 (b)**, the AP searches for another channel in order to avoid interference. The rationale behind this approach is that channel hopping will impose unnecessary overhead when the AP interferes to other APs very short period of time. For the case that the interference duration is relatively long, the APs need to search for another channel. While searching, APs contend periodically among themselves to acquire a channel. For the contention, we provide a notion of priority where the AP with higher traffic volume will gain higher priority in order to increase overall network throughput.

The rest of this paper is organized as follows. In section 2, relevant interference avoidance techniques are discussed. Section 3 describes basic assumptions and a superframe structure. Section 4 presents the proposed mobility-aware interference avoidance technique. Performance of our scheme is evaluated and analyzed in section 5. Finally, we draw conclusions and suggest future directions in section 6.

2. Related Work

By the taxonomy mentioned in section 1, the slotted seeded channel hopping (SSCH) scheme [3] falls under the proactive interference avoidance approach. Based on the SSCH, each node maintains its own channel hopping schedule which is in turn shared with other nodes. As being a proactive scheme, it will incur unnecessary overhead of channel hopping even if the channel does not experience interference. Further, the SSCH technique was designed under a fixed network topology and thus it will suffer from performance degradation due to dynamically changing vehicular environment. Mishra *et al.* [7] proposed an interference avoidance scheme called MAXchop algorithm which aims at fair channel allocation for each AP. Similar to [3], it maintains a hopping sequence at a fixed network topology. However, since an extreme number of devices can be concentrated in hotspot, it will entail problem of finding the optimal min-max fair hopping sequence that is NP-hard for general graphs. Moreover, as a proactive scheme, the MAXchop scheme is not suitable for dynamically changing network topology and causes unnecessary overhead as in [3]. Ge *et al.*[9] suggested the channel allocation for hot spot in cognitive WLAN over fiber. This scheme divides two stages into online and offline stages. In the offline stage, AP computes and stores the lookup table. In the online stage, AP estimates the states of all the channels and looks up their index based on heuristic algorithm. Similar to other proactive scheme, it will be suffer from performance degradation due to dynamically changing vehicular environment.

Ihmig *et al.* suggested a reactive interference avoidance technique referred to as the distributed dynamic channel selection in chaotic wireless networks [4]. In this scheme, each AP collects channel information such as channel utilization, transmit queue length, and packet delay, and uses them for switching channels. This scheme only considers traffic volume for suitable channel selection while ours further takes into account channel interference duration and mobility.

Leith *et al*. [5] proposed another reactive scheme referred to as self-managed distributed channel selection algorithm for WLANs. This scheme assumes each AP is connected through wired backhaul links where each AP selects its channel according to aggregated network throughput. The aggregated throughput is computed by the signal-to-noise ratio (SNR) measured in each channel. The backhaul network is exploited for exchanging SNR of each channel. However, this scheme cannot be applied to vehicular environment since each AP is connected through wireline backhaul links. In our scenario, each AP is deployed in a mobile AP and the control information is shared by each AP wirelessly in a purely distributed manner.

Luo *et al*. [6] suggested the distributed dynamic channel selection algorithm which tries to improve throughputs of all devices through a reactive interference avoidance approach. By this scheme, every AP determines the best channel it should use in the next time slot, based solely on the number of WLAN stations associated with its neighboring APs and the channels used by them in the current time slot, and switches to that channel with a fixed probability. However, this scheme does not effectively resolve the situation that a significant number of devices are densely located where the traffic volume exceeds the maximum throughput. Furthermore, this scheme exploits the number of devices for measuring traffic volume to relate this to available throughput. However, this does not actually map to real traffic. Instead, our scheme exploits actual throughput generated from each BSS.

Gondran *et al.*[8] proposed the interference management in IEEE 802.11 frequency assignment. In this scheme, AP estimates real bit rate based on other AP's location, antenna pattern, azimuth, emitted power and frequency channel. AP performs channel assignment based on the estimation of real bit rate. However, this scheme cannot be applied to vehicular environment due to difficulty of real bit rate estimation in dynamically changing scenarios.

Abusubaih *et al.*[10] suggested a framework for interference mitigation in multi-BSS 802.11 WLANs. With this approach, interfering APs negotiate with other APs. When APs detect the interference, APs switch the mode from CSMA/CA to TDMA by negotiation. However, this scheme is not feasible in vehicle's scenarios since the negotiation in fast moving environment is not an easy task.

The aforementioned mechanisms try to resolve interference when selecting a channel, reactively or proactively. However, they do not take AP mobility into consideration where in-vehicle APs can randomly and dynamically move in any direction. Therefore, interference avoidance scheme for WLAN AP in mobile environment must consider the AP mobility. There have been a tremendous number of researches on vehicle-to-vehicle or vehicle-to-infrastructure network considering mobility in the notion of vehicular ad hoc network (VANET) [17][18][19][20][21][22][23][24]. They focus on how to communicate among vehicles. However, this type of research is not applicable to our scenario since we are targeting an application where vehicles should not interfere among themselves[2].

In order to consider the AP mobility, in this paper, we exploit mobility vector and location information of neighboring APs to explore the interference duration. Depending upon the interference duration, our scheme determines channel hopping or keeps using the current channel, which may reduce the unnecessary channel hopping overhead. Moreover, our scheme does not necessitate control channel for delivering control information such as SNR [5], channel utilization [4], transmit queue length [4], and packet delay [4]. Furthermore, our scheme exploits actual throughput generated from each BSS which actually maps to real traffic.

3. Basic Assumptions and Superframe Architecture for the Proposed Mobility-Aware Interference Avoidance Scheme

In our scheme, each AP periodically contends each other for acquiring a channel. For the contention, our scheme maintains a superframe synchronized to WiMAX superframe boundary. Therefore, the proposed scheme does not require additional synchronization frame such as beacon. In the superframe, a contention phase is provided for channel acquisition during which each AP can determine channel access by sending a channel occupancy frame with the AP's priority level. Channel acquisition is obtained based on AP's priority which is computed from traffic volume generated from the AP's BSS. AP with higher traffic volume gains higher priority in order to increase overall network throughput. Any AP that has failed to occupy the channel due to its lower priority level determines whether it uses the already acquired channel or switches to another channel. This decision is based on traffic volume, mobility vector, and location information of the corresponding AP and the AP that already acquired the channel. For this purpose, the above information is contained in the channel occupancy frame. The relevant decision policy will be described in section 4.

3.1 Assumption

Our scheme considers the following service scenario: a vehicle behaves as a WiMAX terminal node which passes WiMAX traffic to mobile devices in the vehicle. The vehicle uses a gateway (**Fig. 1**) that transparently distributes WiMAX data to WiFi mobile devices to augment the WiMAX data service. The gateway then performs as an interworking unit between WiMAX and WiFi. Hence, the gateway is visible to WiFi mobile devices as an access point, and thus the WiFi network forms a basic service set (BSS). The proposed interference avoidance scheme will operate on both the access point and the mobile devices.

We assume all mobile devices in the vehicle including the access point are synchronized with WiMAX superframe boundary using WiMAX/WiFi dual interface. The precision of the

[2] Our scheme is not for communication among mobile APs as in VANET. Therefore, our scheme does not form a multi-hop ad hoc network nor single-hop ad hoc network.

WiMAX synchronization is known to be in order of microsecond resolution [25][3]. The size of frames and subfield in time of our scheme is more rough, e.g., in order of milliseconds. Further, our scheme resynchronizes the AP and devices with every WiMAX superframe. Therefore, clock drift and synchronization error will be negligible.

We assume further that the gateway is equipped with GPS and in-vehicle AP can obtain mobility vector and location information. This information is shared to other in-vehicle AP by transmitting channel occupancy frame. We can represent the location information of vehicles as a set of 2-dimensional vector. Let AP_i^c represent the *i*th AP that uses channel c. For instance, if AP_i^c is located at α_i in x-axis and β_i in y-axis, we describe the location information as $l_i(\alpha_i, \beta_i)$. In addition, we can represent the mobility vector of vehicles as a set of 2-dimensional vector. For instance, if AP_i^c moves with a speed of γ_i in x-axis and δ_i in y-axis, we can describe the mobility vector as $m_i(\gamma_i, \delta_i)$.

Moreover, we assume in-vehicle AP recognizes the total traffic volume generated from its BSS. Then, the priority[4] can be computed from Φ priority levels by the traffic volume, e.g., the priority can be set uniformly and inverse-proportionally based on traffic volume.

3.2 Superframe Structure

Each superframe per channel consists of the contention phase and the data transmission phase as in **Fig. 3**. We denote the length of the contention phase and data transmission phase by T_C and T_D, respectively while the length of the superframe is T_S.

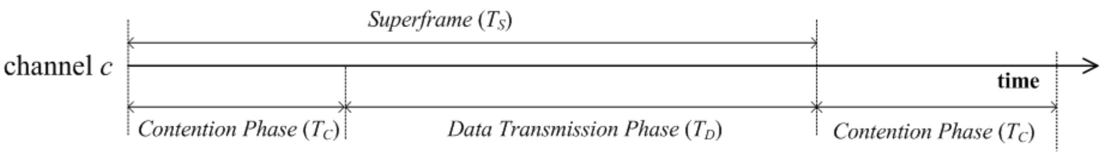


Fig. 3. Superframe structure

In the contention phase, each AP tries to transmit a channel occupancy frame whenever it has data to send. Each AP sets a random timer to transmit the channel occupancy frame based on its own priority level $x\,(1 \le x \le \Phi)$. If AP has priority level x, the AP sets its random timer from the range of $[(x-1)T_C/\Phi,\ x \cdot T_C/\Phi]$ to prioritize and avoid contentions when there are two or more APs have data to send. Whenever the random timer elapses, each AP tries to transmit the channel occupancy frame.

Suppose that the random timer from a vehicle (say vehicle *A*) is earlier than another vehicle (say vehicle *B*). By overhearing the occupancy frame from vehicle *A*, vehicle *B* can suppress its occupancy frame. If the AP (vehicle *A* in this example) receives an acknowledgement frame from any device associated with the AP[5], the mobile devices belong to AP's BSS (vehicle *A* in this example) can occupy the channel and transmit data during T_D. We refer the successful AP as the *leader AP* (vehicle *A* in this example) while the APs that fails to occupy

[3] The maximum synchronization error in our scheme is estimated as about 1 microsecond. Therefore, our scheme sufficiently meets the precision of the WiMAX synchronization in order of microsecond order [25].
[4] Using our priority assignment policy, priority level 1 gains the highest priority.
[5] The mobile device that needs to transmit the acknowledgement frame is indicated in the channel occupancy frame. This can conserve energy consumption by balancing the duty to transmit the acknowledgement frame.

the channel is called *follower AP* (vehicle *B* in this example). In contention phases, all of wireless devices in a BSS should be awake for listening the channel occupancy frame.

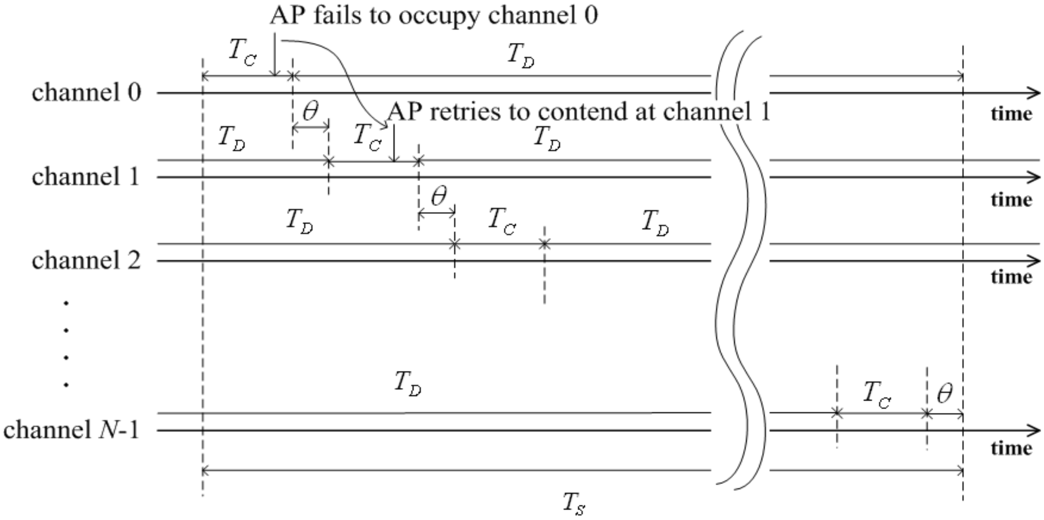


Fig. 4. Time relation between adjacent channels

After contention phase, follower AP that has failed to occupy the channel determines whether it either shares the channel with the leader AP (*contention mode*) or switches to another channel (*switching mode*) based on the interference duration. In contention mode, the follower AP shares the channel that is acquired by the leader AP. In the switching mode, the follower AP searches for the next channel sequentially as described in **Fig. 4**. Details of contention/switching mode decision policy will be discussed in section 4.

The above channel acquisition is performed in per-channel basis. When we observe the timing relation between adjacent channels, we can visualize the timeline as in **Fig. 4**. The contention phase is aligned with a timing margin θ between adjacent channel to accommodate channel switching delay. As in the figure, the length of the superframe exactly matches to $N(T_C + \theta)$ where N is the number of channels. By this alignment, follower APs that have failed to occupy the previous channel can immediately (of course after θ) start contentions, which greatly reduces the channel switching overhead. This also applies to the case of switching from channel $N-1$ to channel 0.

4. Mobility-Aware Interference Avoidance Scheme

In this section, we describe our proposed mobility-aware interference avoidance scheme for mobile WLAN APs. The major difference from the existing interference avoidance techniques is that our scheme takes AP mobility (from low to high mobility) into consideration, and thus our scheme would work well even under the situation that BSSs are densely located. As described in section 3, any follower AP that has failed to occupy a channel determines whether it shares a channel with leader AP (in contention mode) or switches to another channel (in switching mode). In the following, we describe the mode decision policy between contention and switching modes.

Remark: In order to select switching or contention mode, AP needs to obtain the interference duration based on mobility vector and location information. As we explained in section 3, an AP transmits the channel occupancy frame that contains the information such as traffic volume, mobility vector, and location information in the contention phase. Once the channel occupancy frame successfully transmitted, the AP that sends the frame will become a leader AP. The leader AP does not need to select the mode since it already acquired a channel. Only follower AP needs to obtain the interference duration. Since the leader AP transmits the channel occupancy frame including mobility vector and location information, the follower AP obtains this information by overhearing the frame.

4.1 Contention/Switching Mode Decision Policy.

To make a decision on the mode (contention or switching mode), the AP_i^c needs to consider the following two policies:

Policy 1: Whichever mode is selected, the benefit such as throughput of AP_i^c should be maximized and

Policy 2: The total traffic volume on channel c including traffic generated from AP_i^c should not exceed the maximum allowable traffic ($\lambda_{\max}$).

Denoting $\zeta_{i,j}$ the interference duration between AP_i^c and AP_j^c (where AP_j^c is the leader AP using channel c), the first policy is closely correlated with the following: *If $\zeta_{i,j}$ is negligible, AP_i^c continues to use channel c . However, if $\zeta_{i,j}$ is not negligible, AP_i^c searches for another channel in order to avoid interference*. This is because the throughput of AP_i^c increases as $\zeta_{i,j}$ becomes shorter. In other words, as the interference duration decreases, the available bandwidth of channel c for AP_i^c expands resulting in increased throughput. Moreover, when $\zeta_{i,j}$ is negligible, the channel switching will impose unnecessary overhead including switching cost and switching delay. Therefore, when $\zeta_{i,j}$ is negligible, the contention mode will be more effective.

Hence, for selecting contention mode, the following two conditions should be satisfied; otherwise, the switching mode will be selected, by rewriting the above policies.

Condition 1: The following condition should be met

$$\eta_C > \eta_S , \tag{1}$$

where $\eta_C = E[\text{Maximum Throughput} \mid AP_i^c \text{ decided the contention mode}]$ and $\eta_S = E[\text{Maximum Throughput} \mid AP_i^c \text{ decided the switching mode}]$, and

Condition 2: The total traffic volume on channel c including traffic generated from AP_i^c should not exceed the maximum allowable traffic ($\lambda_{\max}$), i.e.,

$$\lambda_i + \sum_{k \in \Omega_c} \lambda_k \le \lambda_{\max} \tag{2}$$

where Ω_c is the set of APs that uses channel c within communication range of AP_i^c. For condition 2, AP_i^c continuously measures its traffic volume, and the traffic volume of

AP_j^c $(j \neq i,\ j \in \Omega_c)$ is shared by overhearing the channel occupancy frame. The details on condition 1 will be explained in section 4.2.

4.2 Expected Maximum Available Throughput

Let η_N the network maximum throughput (or the maximum network bandwidth), then the expected maximum throughput (or the maximum available bandwidth) in switching mode (η_S) is the fraction of η_N . Since the percentage of actual data transmission is $T_D/(E[T_F]+T_D)$, η_S is given by

$$\eta_S = \frac{T_D}{E[T_F]+T_D} \times \eta_N \tag{3}$$

where T_F is the time until AP_i^c is able to start transmitting data as a leader AP, beginning from the contention phase after sequentially searching for the next channels. In other words, T_F can be considered as the search time until it becomes a leader AP. T_D is described in **Fig. 3**.

Denoting $\rho(x)$ the event that AP_i^c becomes a leader AP where the priority level of AP_i^c is x , T_F can be obtained as

$$\begin{aligned} E[T_F] &= E[T_F \mid \rho(x)]P[\rho(x)] + E[T_F \mid \overline{\rho(x)}](1-P[\rho(x)]) \\ &= T_C P[\rho(x)] + (E[T_F]+\theta)(1-P[\rho(x)]) \\ &= T_C - \theta + \frac{\theta}{P[\rho(x)]} \end{aligned} \tag{4}$$

Here, $P[\rho(x)]$ can be given by $P[\rho(x)] = 1 - x/\Phi$ where Φ is the number of priority levels. Then, (4) is rewritten by $E[T_F] = T_C + x\theta/(\Phi - x)$. T_C and θ are depicted in **Fig. 4**.

Now, we obtain the expected maximum throughput (or the maximum available bandwidth) given that AP_i^c decided the contention mode by

$$\eta_C = \begin{cases} \dfrac{(T_S - T_C)\times \lambda_i/(\lambda_i + \sum_{k\in\Omega_c}\lambda_k)\times \eta_N}{T_S}, & T_A \geq T_S \\ \dfrac{[(T_A, -T_C)\times \lambda_i/(\lambda_i + \sum_{k\in\Omega_c}\lambda_k) + (T_S - T_A)]\times \eta_N}{T_S}, & T_A < T_S \end{cases} \tag{5}$$

where T_A is the time until the leader AP does not interfere to AP_i^c because the leader AP fades away (out of interference coverage from AP_i^c). This computation can be explained by **Fig. 5**. If T_A is greater than or equal to T_S , AP_i^c shares channel c with the leader AP until the end of superframe. However, if T_A is less than T_S , AP_i^c shares channel c with the leader AP until the leader AP fades away from the interference coverage of AP_i^c, and then AP_i^c uses channel c exclusively up to the end of superframe boundary.

By a simple arithmetic, (5) can be reorganized by

$$\eta_C = \frac{[(\min(T_A, T_S) - T_C) \times \lambda_i / (\lambda_i + \sum_{k \in \Omega_c} \lambda_k) + \max(0, T_S - T_A)] \times \eta_N}{T_S} \tag{6}$$

where λ_i is continuously measured by AP_i^c and λ_k $(k \in \Omega_c)$ is shared by overhearing the channel occupancy frame. T_S and T_C are depicted in **Fig. 4**. Therefore, to compute η_C in (6), we should obtain the T_A.

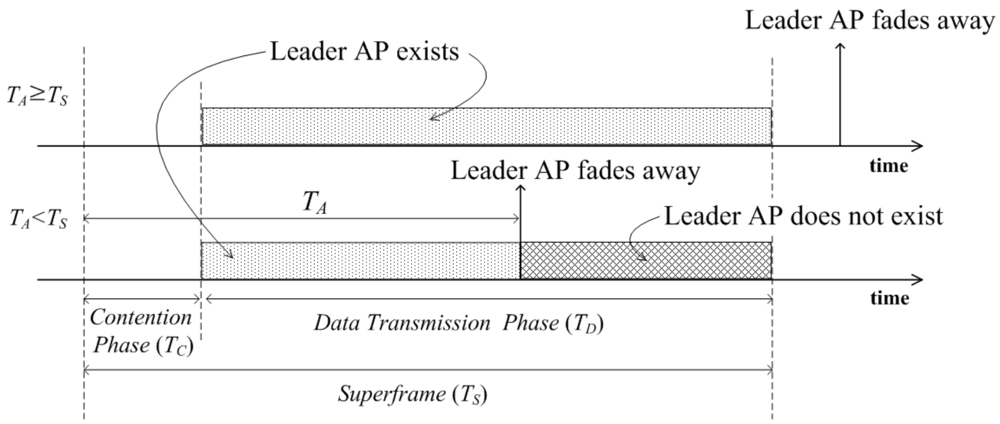


Fig. 5. Channel usage in contention mode

To compute T_A, we exploit the mobility vector ($m_i(\alpha_i, \beta_i)$, $m_j(\alpha_j, \beta_j)$), and location information ($l_i(\gamma_i, \delta_i)$, $l_j(\gamma_j, \delta_j)$) of AP_i^c and leader AP (denoted by AP_j^c), respectively. The location of AP_i^c after t time unit is $l_i(\gamma_i + t\alpha_i, \delta_i + t\beta_i)$ and location of AP_j^c after t is $l_j(\gamma_j + t\alpha_j, \delta_j + t\beta_j)$. Hence, we can obtain the distance (d_t) between AP_i^c and AP_j^c after t is given by

$$d_t = \sqrt{(\gamma_j - \gamma_i + t(\alpha_j - \alpha_i))^2 + (\delta_j - \delta_i + t(\beta_j - \beta_i))^2} \, . \tag{7}$$

We can lead the computation of T_A from (7). Based on the mobility vector, the distance between AP_i^c and AP_j^c may become shorter or longer. However, to compute T_A, we concentrate on the case that the distance become longer, i.e., the leader AP fades away (out of interference coverage from AP_i^c). If we consider d_t as the threshold distance that AP_j^c does not interfere to AP_i^c, we can obtain T_A by

$$T_A = \sqrt{d_t^2 - (\gamma_j - \gamma_i)^2 - (\delta_j - \delta_i)^2 + \left(\frac{(\gamma_j - \gamma_i)(\alpha_j - \alpha_i) + (\delta_j - \delta_i)(\beta_j - \beta_i)}{(\alpha_j - \alpha_i)^2 + (\beta_j - \beta_i)^2}\right)^2} - \frac{(\gamma_j - \gamma_i)(\alpha_j - \alpha_i) + (\delta_j - \delta_i)(\beta_j - \beta_i)}{(\alpha_j - \alpha_i)^2 + (\beta_j - \beta_i)^2} \tag{8}$$

where we assume the mobility vector is fairly stationary during T_S.

Substituting (3) and (6) into (1), condition 1 reorganized by

$$E[T_F] > \frac{T_D \times T_S}{(\min(T_A, T_S) - T_C) \times \lambda_i / (\lambda_i + \sum_{k \in \Omega_c} \lambda_k) + \max(0, T_S - T_A)} - T_D \qquad (9)$$

where $E[T_F]$ and T_A are obtained from (4) and (8), respectively.

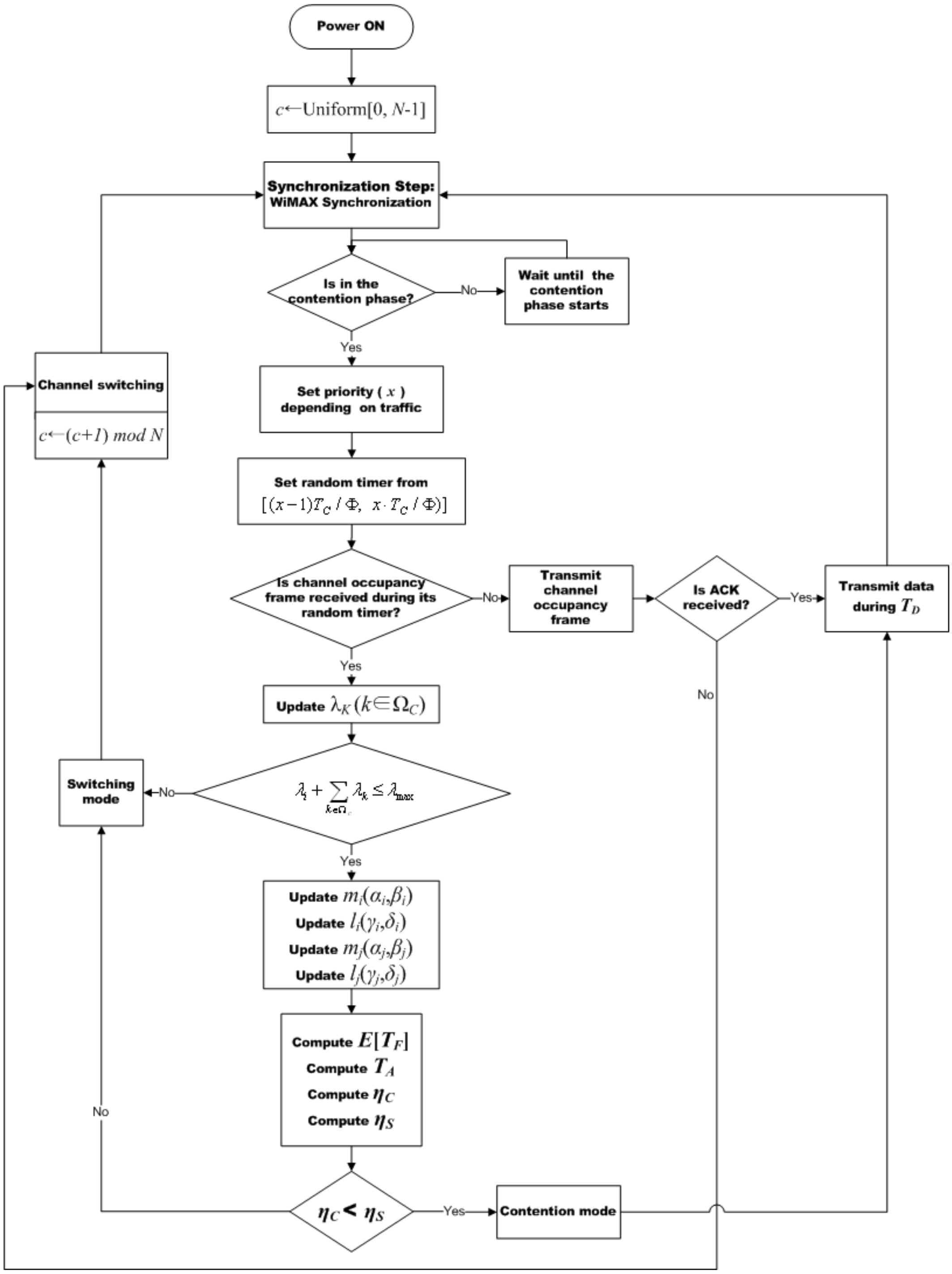


Fig. 6. Mobility-aware interference avoidance algorithm in AP

4.3 Algorithm

4.3.1 AP Behavior

The flowchart of the AP operation is given in **Fig. 6**. When AP_i^c turns on, AP_i^c is synchronized with a WiMAX superframe boundary. AP_i^c waits until the contention phase begins.

In the contention phase, AP_i^c performs mobility-aware interference avoidance scheme in order to occupy channel c. AP_i^c determines the priority based on the total traffic volume generated from its BSS. AP_i^c tries to occupy channel using its random timer based on its priority x.

If there is no channel occupancy frame overheard during its random timer, AP_i^c transmits the channel occupancy frame. If ACK is received, AP_i^c transmits data during T_D and then moves to synchronization step.

If AP_i^c overhears other channel occupancy frame, the AP_i^c will need to switch to the next channel (switching mode) or share channel c (contention mode) with the other AP. To decide the mode, the AP_i^c updates the parameter ($\sum_{k\in\Omega_c}\lambda_k$) from leader AP's channel occupancy frame. If $\lambda_i + \sum_{k\in\Omega_c}\lambda_k > \lambda_{\max}$, AP_i^c selects the switching mode and then performs channel switching. Otherwise, AP_i^c updates the mobility parameters ($m_i(\alpha_i,\beta_i)$, $l_i(\gamma_i,\delta_i)$, $m_j(\alpha_j,\beta_j)$, and $l_j(\gamma_j,\delta_j)$) and then computes $E[T_F]$, T_A, η_C, and η_S. If $\eta_C < \eta_S$, AP_i^c selects the contention mode and then transmits data in a channel c during T_D. Otherwise, AP_i^c selects the switching mode and then performs channel switching.

4.3.2 Mobile Device Behavior

The flowchart of the mobile device operation is given in **Fig. 7**. When the mobile device turns on, the mobile device associate with an AP. After the association, the mobile device is synchronized with a WiMAX superframe boundary. Then, the mobile device waits until contention phase begins. In the contention phase, if the mobile device receives a channel occupancy frame from the associated AP, it transmits data during T_D and then moves to synchronization step. However, if the mobile device does not receive any channel occupancy frame from its associated AP during the contention phase, it searches for the associated AP by scanning process of WiFi. If found, it transmits data during T_D and then moves to synchronization step. Otherwise, mobile device performs channel switching.

5. Performance Evaluation

In this section, we evaluate performance of the proposed scheme compared with the IEEE 802.11g and the distributed dynamic channel selection (DDCS) scheme [5] in densely located vehicular WLANs. Generally, the IEEE 802.11g rather statically fixes the channel of AP, which is determined at the initial setup. However, for our performance evaluation, we modify the IEEE 802.11g by randomly selecting initial channel for AP. Also, the DDCS algorithm exploits the MAC delay by continuously observing channel conditions where the channel switching occurs if the MAC delay exceeds a certain threshold. In our experiments, we set the threshold by 0.045 seconds which was shown as the best result in [5].

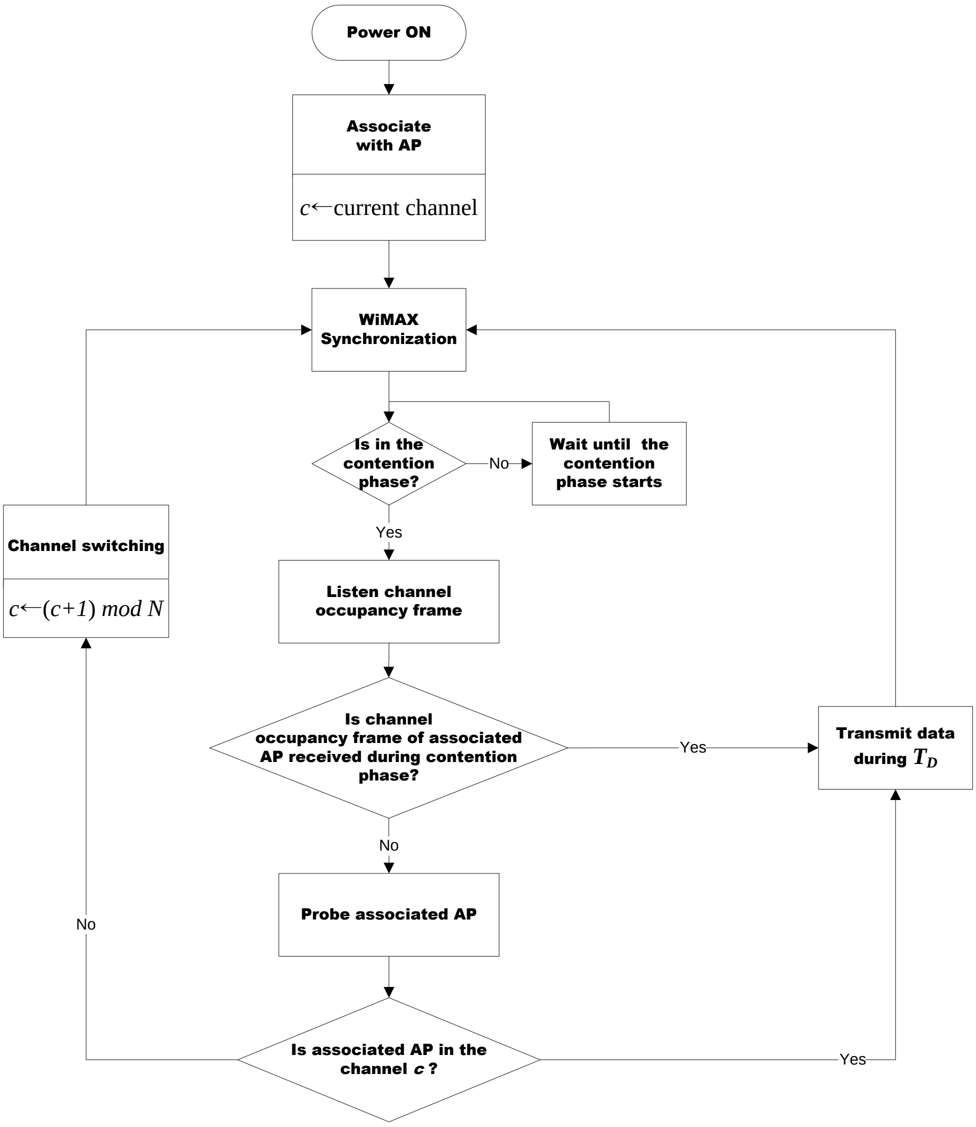


Fig. 7. Mobility-aware interference avoidance algorithm in mobile device

For performance evaluation, we use the OPNET modeler [26]. The simulation parameters are listed in **Table 1**. We apply a random walk [27], Manhattan [27], and highway [27] scenarios in a given topology and initial node positions are randomly selected. In these models, vehicles are allowed to move randomly in the random walk, on grid-like streets in the Manhattan (with probabilities of straight, left, and right are 0.5, 0.25, and 0.25, respectively), and only in straight and in reverse direction in the highway model. Vehicles move at 80~120km/h, 10~60km/h, and 60~140km/h in random walk, Manhattan, and highway, respectively. In the Manhattan model, block size is assumed to be 200m x 200m, and street width is assumed to be 10m. In the highway model, street width is assumed to be 10m. We simulate 4 jammers with short impulse (800mW) since a short impulse with high power could make the channel unstable for existing connections. In these traffic topologies, we measure the average aggregate throughput and the collision frequency defined by

- **Aggregate Throughput**: total sum of throughputs measured in each vehicle and
- **Collision Frequency**: the number of collisions per second in the network.

Table 1. Simulation parameters

Parameter	Value
Transmission Range	100 mW
Topology Size	2 km x 2 km (Random Walk, Manhattan) 10 m x 400 km (Highway)
Node Density	0~320 nodes/km^2
Traffic Type	VBR
Packet Size	1000~5000 Bytes (Uniform Distribution)
Packet Interarrival Time	25 msec
Number of Channels	3 (channel 1, 6, and 11)
Node Speed	0~140 km/h (Uniform Distribution)
d_t	158 m [28]
θ	1.35 sec
T_C	50 msec
T_S	4.2 sec

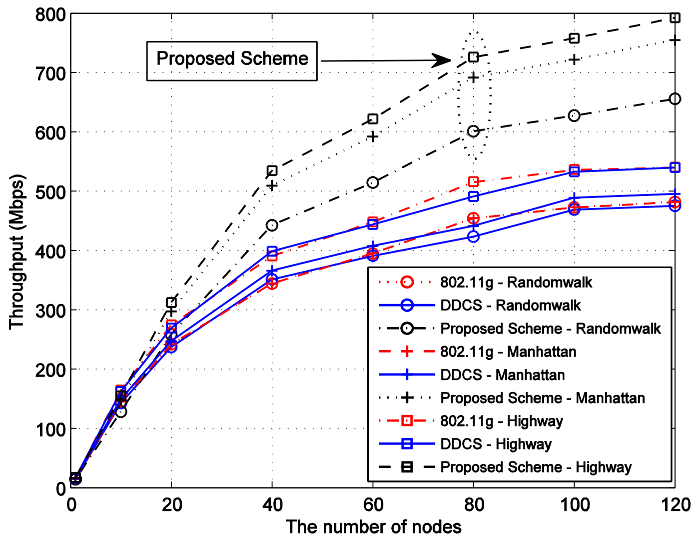


Fig. 8. The average aggregate throughput vs. the number of nodes for three topology models (traffic load = 40 frames/sec and Φ = 32)

5.1 Throughput

In this subsection, we measure the throughput by varying the number of nodes from 0 to 120

(**Fig. 8**), and the traffic load from 0 to 40 frames per second (**Fig. 9**).

Fig. 8 shows the throughput versus the number of nodes. This result was measured under the fixed traffic load of 40 frames/sec and $\Phi = 32$. As shown in the figure, the average aggregate throughput increases as the number of nodes increases for all three schemes and for all three mobility models. This is because growth of nodes generates more traffic load. In the region of 0~40 nodes, the throughput increases rapidly. In this region, the number of collisions from each AP will not be significant because the node density and the probability of interference are relatively small. However, in the region of 40~120 nodes, the aggregated throughput grows slowly since increasing node density causes more collisions. We will analyze the collision frequency in subsection 5.2 in more detail.

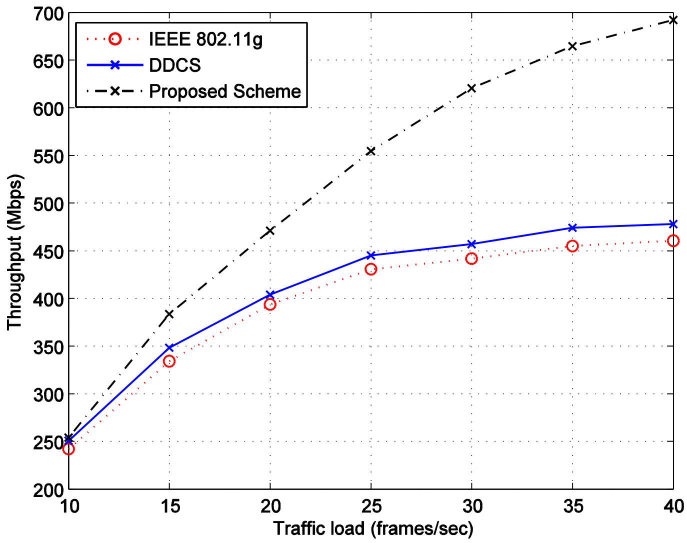


Fig. 9. The average aggregate throughput vs. traffic load (Manhattan) (The number of nodes = 80 and Φ = 32)

Also, from the figure, we observe that DDCS and IEEE 802.11g show almost similar results. This is because the DDCS scheme initiates channel switching when APs are densely located. Unfortunately, this channel switching is triggered in synchronized fashion in adjacent APs[6]. Therefore, the probability of having the same channel will not be negligible and thus the throughput of DDCS may become similar to that of IEEE 802.11g. Instead, our scheme reduces the probability of having the same channel since our scheme periodically contends for a channel. Furthermore, the DDCS and IEEE 802.11g are designed under the assumption of static node environment while our scheme exploits location information and mobility vector to achieve 67% higher throughput than the other two schemes.

One interesting finding is that the proposed scheme has relatively better performance in the Manhattan and highway models than in the random walk model compared with other schemes. This shows that the proposed scheme is feasible to a realistic road environment since our scheme considers direction of vehicles.

Fig. 9 shows the throughput versus the traffic load. This result was observed when 80 nodes are deployed and the $\Phi = 32$. As expected, the result is similar to previous experiments. The throughput increases as the traffic load increases for all three schemes. The proposed scheme

[6] When neighboring APs find interference, they vacate their channel and then switch to other available channel at the same time.

can achieve the throughput about 50% higher than the other two schemes in high traffic load (30~40 frames/sec).

To measure the effectiveness of our scheme versus the mode decision accuracy, we intentionally generate the mode decision error ε i.e., the AP erroneously switches to another channel even if the scheme had to determine the contention mode, or vice versa. Varying ε from 0% to 10%, we can observe the proposed scheme with ε =10% still outperforms the other schemes in **Fig. 10**.

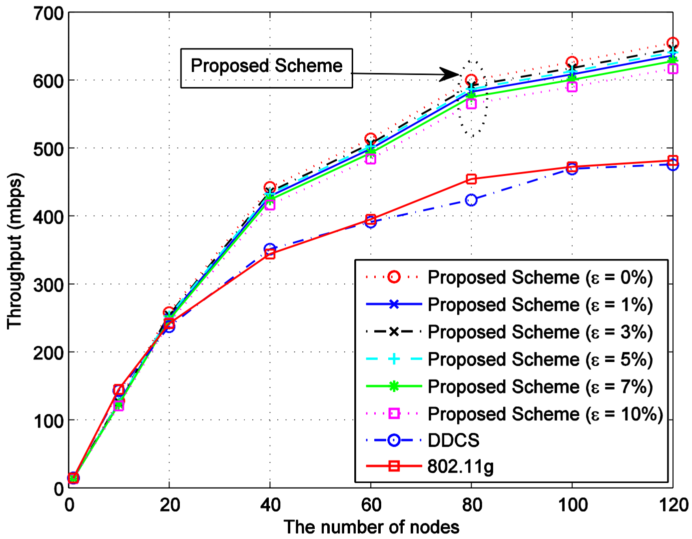


Fig. 10. The average throughput variation due to the mode decision errors vs. the number of nodes (Traffic load = 40 frames/sec and Φ = 32)

5.2 Collision Frequency

In this subsection, we measure the collision frequency (total collisions per second) as an interference indicator by varying the number of nodes from 0 to 120, and the traffic load from 0 to 40 frames per second. **Fig. 11** depicts the collision frequency depending on the number of nodes. As shown in the figure, the collision frequency increases as the number of nodes increases for all schemes. The result shows that our scheme has the collision frequency less than the other two by about 60%. Further, the IEEE 802.11g and DDCS schemes show almost the same collision frequency as explained in section 5.1. As we will see in **Fig. 13**, the number of collisions per channel of the DDCS scheme is not evenly distributed. This uneven number of collisions reflects that channels are not fairly allocated in DDCS. Although the DDCS scheme continuously switches the channel, the DDCS scheme incurs highly used channel which dominates the overall collision frequency. However, in our proposed scheme, the AP determines whether it shares the channel with other APs or it switches to another channel. Therefore, our scheme is expected to have evenly distributed channel usage.

Fig. 12 shows the collision frequency depending on the traffic load. This result was measured when 80 nodes are deployed and the $\Phi = 32$. As shown in the figure, the collision frequency increases as increasing the traffic for all three schemes since the probability of collision increases by generating high traffic load in densely located. Similar to **Fig. 11**, the result shows that the proposed scheme can achieve about 56% less collision frequency than the other two schemes.

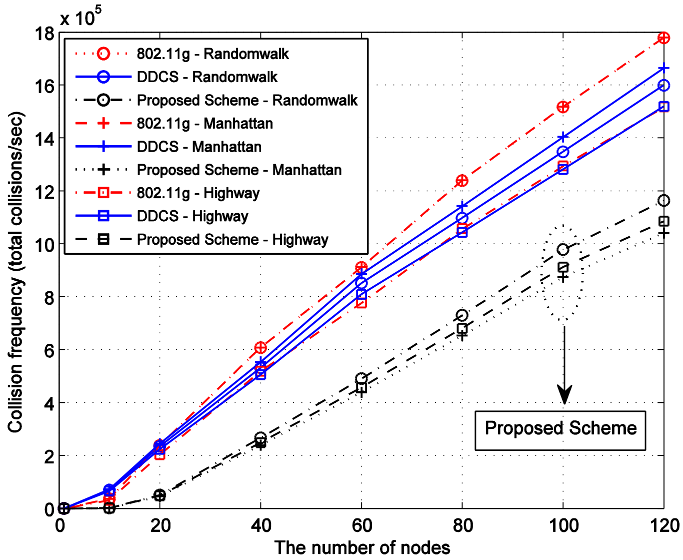


Fig. 11. Collision frequency vs. the number of nodes (Traffic load = 40 frames/sec and Φ = 32)

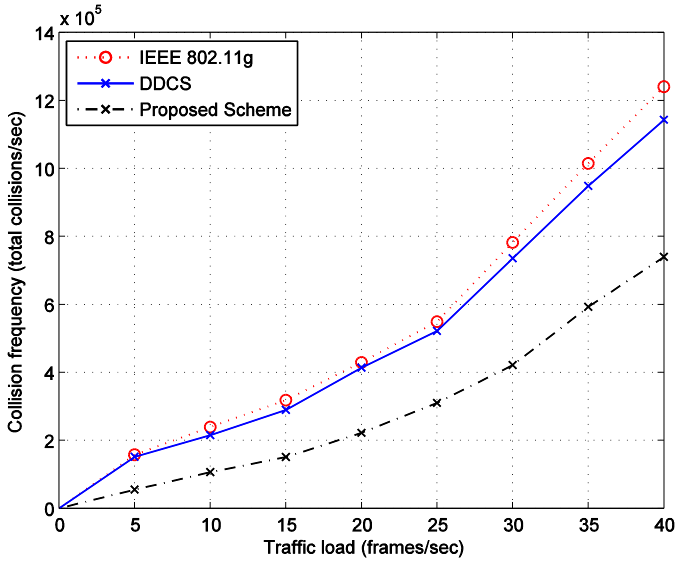


Fig. 12. Collision frequency vs. traffic load (Manhattan) (The number of nodes = 80 and Φ = 32)

5.3 Fairness

In this subsection, we measure the fairness of channel usage by observing the number of collisions at each channel for all three schemes. **Fig. 13** depicts the number of collisions at each channel. In this figure, IEEE 802.11g shows that the number of collisions of all channels are evenly distributed. However, the DDCS scheme shows imbalance on channel usage (i.e., channel 1 has been heavily used) because neighboring APs vacate their channel and then they switch to other available channel at the same time when they find interference. However, our proposed scheme shows fair channel usage as in Fig. 13 similar to the IEEE 802.11g.

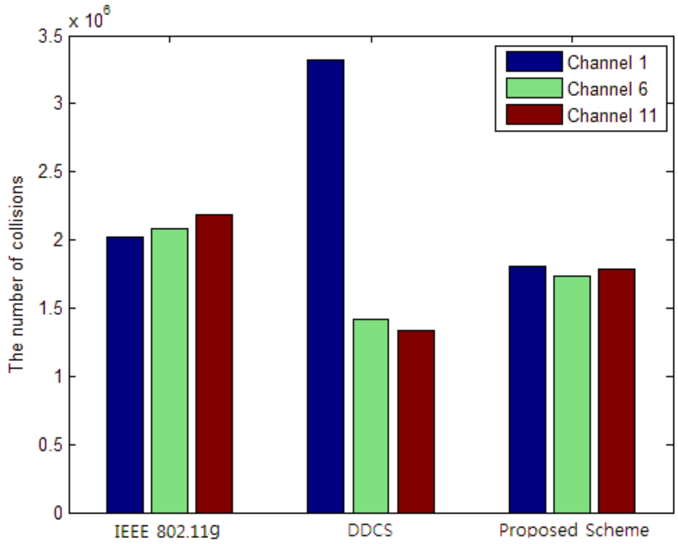


Fig. 13. Number of collisions per channel (The number of nodes = 80, Traffic load = 40 frames/sec, and Φ = 32)

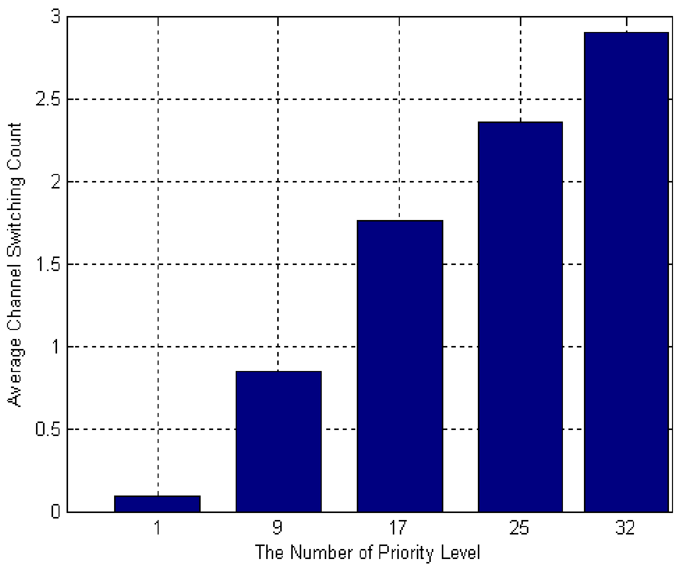


Fig. 14. The average switching counts vs. priority level (The number of nodes = 64)

5.3 Impact of Priority Levels

In this subsection, we measure the average switching counts per priority levels in Fig. 14. As shown in Fig. 14, the AP with priority level 32 switches channels about 3 times on average. However, the AP with priority level 1 rarely performs channel switching. As expected, an AP with higher priority will have a higher probability to become a leader AP, and thus AP with higher priority level will switch channels seldom. For an AP with higher priority, i.e., AP with higher traffic volume, it is difficult to find a spectrum hole by channel switching, and thus it is rather good idea for AP with lower priority to switch the channel.

6. Conclusions

In this paper, we addressed the problem of performance degradation in densely located vehicular network. Existing interference avoidance techniques cannot properly resolve the above problems and do not cope with dynamically moving vehicular scenario since they focus only on the fixed network topology. To consider dynamically moving vehicular network, we proposed a mobility aware interference avoidance scheme for vehicular WLANs. Our scheme exploits periodic competitions among BSSs. For the contention, we provide a notion of priority where vehicle with higher traffic volume will gain higher priority in order to increase overall network throughput. Moreover, the proposed scheme computes the interference duration by exploiting mobility vector and location information of neighboring APs. If the interference duration is not negligible, our scheme searches for another channel in order to avoid interference. However, if the interference duration is negligible, our scheme continues to use the channel to reduce switching overhead.

The simulation result shows that our scheme is very effective and provides significantly higher throughput by keeping the collision frequency low. Through the simulation with various mobility models, we obtained about 60% reduction in the maximum interference frequency and about 67% improvement in throughput against other existing schemes. Furthermore, our scheme provides fair channel usage compared with existing schemes.

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Laihyuk Park received his B.S. and M.S. degrees in Computer Science and Engineering from Chung-Ang University, Seoul, Korea in 2008 and 2010, respectively. He is currently pursuing his Ph.D. degree in Computer Science and Engineering at Chung-Ang University. His research interests include Cognitive Radio, Directional MAC, and Vehicular WLANs.

Woongsoo Na received his B.S. degree in Computer Science and Engineering from Chung-Ang University, Seoul, Korea in 2010. He is currently working towards the M.S degree in Computer Science and Engineering at Chung-Ang University. His research interests include Directional MAC and Vehicular WLANs.

Gunwoo Lee received his B.S. degree in Department of Computer Engineering from Myongji University, Yongin, Gyeonggido, Korea in 2006. He is currently working towards the M.S degree in Computer Science and Engineering at Chung-Ang University, Seoul, Korea. His research interests include Composite Context Awareness, Wireless Body Area Network, and Vehicular WLANs.

Chang Ha Lee received the B.S. and M.S. degrees in Computer Science from the Seoul National University, Korea in 1995 and 1997, and the Ph.D. degree from the University of Maryland at College Park in 2005. He is currently an assistant professor of Computer Science and Engineering at Chung-Ang University. Before joining Chung-Ang University, he was a research scientist at the National Capital Area Medical Simulation Center. His research interests include Geographical Information System, Computer Graphics, Visualization, and Medical Simulation.

Chang Y. Park received the B.S. and M.S. degrees in Computer Engineering from Seoul National University, Seoul, Korea in 1984 and 1986, respectively, and received the Ph.D. in Computer Science from the University of Washington, Seattle in 1992. He is currently a Professor in the School of Computer Science and Engineering, Chung-Ang University, Seoul, Korea. His research interests include Computer Networks, and Real-time Systems.

Yong Soo Cho received the B.S. degree in Electronics Engineering from Chung-Ang University, Seoul, Korea, the M.S. degree in Electronics Engineering from Yonsei University, Seoul, Korea, and the Ph.D degree in Electrical and Computer Engineering from the University of Texas at Austin, in 1984, 1987, and 1991, respectively. During 1984, he was a Research Engineer at Goldstar Electrical Company, Osan, Korea. In 1992, he joined Chung-Ang University, where he is presently a professor at the School of Electrical and Electronic Engineering.

Sungrae Cho received his B.S. and M.S. degrees in Electronics Engineering from Korea University, Seoul, Korea, and his Ph.D. degree in Electrical and Computer Engineering from the Georgia Institute of Technology, Atlanta, GA in 1992, 1994, and 2002, respectively. He is currently an associate professor in Computer Science and Engineering at Chung-Ang University, Seoul, Korea. Prior to joining Chung-Ang University, he was an assistant professor in Computer Science at Georgia Southern University, Statesboro, GA from 2003 to 2006. In 2003, he was a principal research engineer at Samsung Advance Institute of Technology, Keung, Korea. From 1994 to 1996, he was a member of research staff at Electronics and Telecommunications Research Institute, Daejon, Korea. He is a journal editor of Korea Information and Community Society as well as Korean Institute of Information Scientists and Engineers. He also served a TPC member of numerous international conferences including ICOIN 2010, 2011, 2012, ICUFN 2010, 2011, 2012, ICTC 2011, IEEE MASS2009, CSIE 2009, IEEE Tridentcom 2007, and IEEE MADWH 2005.