ARTICLE IN PRESS

Ad Hoc Networks xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Mobility impact in IEEE 802.11p infrastructureless vehicular networks

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
IEEE 802.11p
VANET
MAC
Mobility
Relative speed

ABSTRACT

Vehicular ad hoc networks (VANETs) are an extreme case of mobile ad hoc networks (MANETs). High speed and frequent network topology changes are the main characteristics of vehicular networks. These characteristics lead to special issues and challenges in the network design, especially at the medium access control (MAC) layer. In this paper, we provide a comprehensive evaluation of mobility impact on the IEEE 802.11p MAC performance. The study evaluates basic performance metrics such as packet delivery ratio, throughput, and delay. An unfairness problem due to the relative speed is identified for both broadcast and unicast scenarios. We propose two dynamic contention window mechanisms to alleviate network performance degradation due to high mobility. The first scheme provides dynamic level of service priority via adaptation to the number of neighboring nodes, while the second scheme provides service priority based on node relative speed. Extensive simulation results demonstrate a significant impact of mobility on the IEEE 802.11p MAC performance, the unfairness problem in the vehicle-to-vehicle (V2V) communications, and the effectiveness of the proposed MAC schemes.

1. Introduction

Recently, vehicular communication networks have received great attention from both industry and academia, due to their potential significance in various applications ranging from providing safety warnings to allowing on-road Internet access. In vehicular ad hoc networks (VANETs), vehicles communicate with roadside units (RSUs), referred to as vehicle-to-infrastructure (V2I) communications. In addition, vehicles can communicate with each other in an infrastructureless mode, referred to as vehicle-to-vehicle (V2V) communications. In general, the communication time of each link is very limited, due to high dynamics in network topology. One key issue in VANETs that has not been properly solved yet is how the mobile nodes should share the radio resources to ensure service quality. The IEEE draft standard 802.11p [1], included in the wireless access in vehicular environment (WAVE) protocol stack, is the only standard for MAC in V2V communications. Since the 802.11p uses the basic mechanism of the distributed coordination function (DCF) that was originally designed for low mobility networks, it does not operate efficiently for a high mobility communication scenario in VANETs.

The DCF operation mode has been extensively studied in the literature [2–5]. However, its behavior in VANETs differs from that in other networks because of VANET unique characteristics. In general, the performance of the 802.11 depends on network parameters (disregarding the type of networks) such as the number of communicating nodes, type of data traffic, backoff procedure, and carrier sensing range. In VANETs, the protocol performance is also affected by other factors such as the communication mode, vehicle density fluctuations, and node mobility. Node mobility can be characterized by node position, speed, acceleration, direction of movement, potential communication duration, and potential number of communication neighbors. All the factors are highly dynamic in VANETs, and difficult to predict especially in an extreme mobility

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1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2010.06.006

case. The IEEE 802.11p provides different levels of service priority based on traffic type, but does not address any of the preceding mobility factors.

The problem of fairness due to nodes having different speeds is intuitively explained in [11] for a V2I communication scenario. Basically, mobile nodes have different resident times in the coverage area of an RSU. The standard IEEE 802.11p does not take into consideration the resident time of each node. Moreover, if mobile nodes have different mobility characteristics (e.g., extremely high and low speeds), they do not have similar chances of channel access and, therefore, a fairness problem exists. Fig. 1a illustrates an example of the fairness problem in V2I communications for two mobile nodes. Similarly, an unfairness problem due to relative speed exists in a V2V communication scenario. Fig. 1b illustrates a simple case for three nodes communicating in a V2V mode. Node A moves with a similar speed as the sending node while node B moves with a much higher speed. It can be seen that, after some time, node B will be out of the active communication range while A can still communicate with the sending node. Due to the impact of relative speed in V2V communications, an effective MAC protocol should provide priority to node B to transmit before it moves out of the communication range.

In this paper, we define mobility metrics and study mobility impact on the performance of the IEEE 802.11p MAC protocol. Two new solutions are proposed for adapting the MAC protocol to the vehicular environment by providing different service priorities to nodes based on their mobility parameters. Numerical results show a significant impact of mobility on the node channel access time, and the effectiveness of the newly proposed solutions.

2. Related work

Even though the IEEE 802.11p has been extensively studied [6–10], to the best of our knowledge, there is no comprehensive evaluation that reflects the impact of user mobility on the IEEE 802.11p MAC protocol performance, especially for the V2V mode. Moreover, very limited work has been done to enhance the performance of the IEEE 802.11p via adaptation to the mobility factors. A VANET MAC should provide an efficient and fair channel access based on user mobility parameters. In [10], simulation results of the IEEE 802.11p standard show that a constant backoff window size does not guarantee the desired throughput in the V2I mode. Similar simulation results supported with analytical means indicate that the IEEE 802.11p suffers from an undesired decrease in throughput and an increase in delay in high node density scenarios [6]. Stibor et al. [7] evaluate the number of potential communication partners and the maximum communication time for a VANET using the IEEE 802.11p standard. In [9], the authors study the saturated performance of the 802.11 MAC in a single-hop network. It is shown that the delay requirement is always satisfied while the packet delivery

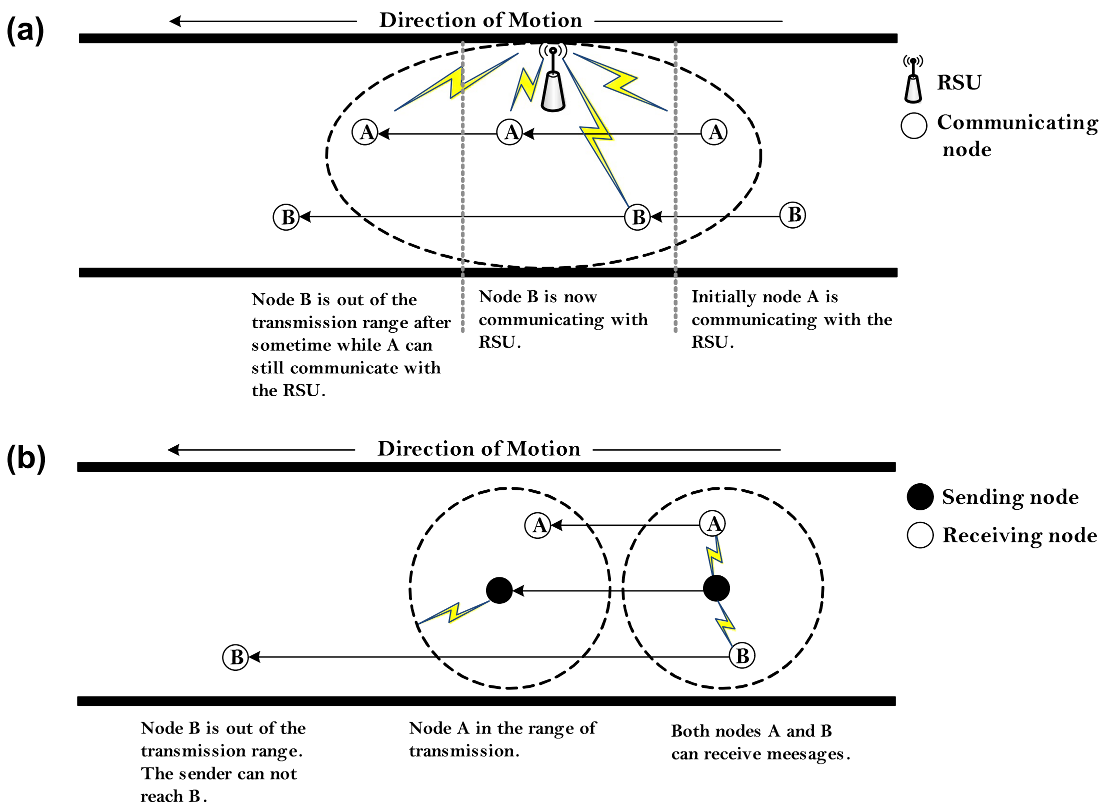

Fig. 1. The problem of unfairness due to nodes having different velocities.

ratio (PDR) decreases dramatically when the number of nodes increases. In [11], a modified version of the IEEE 802.11 DCF to enhance fairness is presented for the V2I communications.

3. System model

In the system model under consideration, mobile nodes communicate via a single channel in a pure ad hoc mode. Each node has a unique ID, based on its MAC address. Moreover, vehicle nodes cooperate in the ad hoc mode and relay packets whenever a multihop connection is established. Each node sends its packets to a specific destination according to a routing protocol. Here, we focus on MAC for single-hop transmissions.

Each vehicle is equipped with a Global Positioning System (GPS) receiver that can determine its position and speed. Each node maintains a list of its one-hop neighbors, and periodically broadcasts a HELLO message that includes its location and speed to the neighbors. All the neighboring nodes store the information for a certain time (e.g., 2–3 s [7]). If a node does not hear any information from a previous neighbor for a while, that neighbor will be removed from the neighbor list. At the end of a broadcasting period, each node calculates the total number of its one-hop neighbors, the average speed of itself and its neighbors, and the deviation of its speed from the average. The deviation from the average speed is used in the dynamic priority management in channel access (to be discussed in Section 4). Time is partitioned into frames of a constant duration. Fig. 2 shows the time frame for the periodic broadcasting and the IEEE 802.11p contention-based channel access period. At the beginning of a time frame, a cluster formation is performed. Each cluster is maintained by a clusterhead. A clusterhead broadcasts a message that assigns the mini-slots in the broadcasting period to the clustermembers. Every node that receives the clusterhead's message knows its mini-slot, and is synchronized with the other clustermembers. Therefore, there are no collisions during the HELLO broadcasting period.

4. MAC adaptivity to mobility

Here, we present two priority channel access schemes based on vehicle mobility. Both schemes aims at optimizing the backoff mechanism in the MAC protocol by assigning a dynamic contention window size based on node mobility parameters. The first scheme is a p-persistent carrier sense multiple access with collision avoidance (CSMA/CA) based backoff mechanism, while the second one is a dynamic priority management scheme based on node relative velocity.

4.1. Adaptation to the number of neighboring nodes

To provide adaptivity to the number of neighboring nodes, we model the backoff procedure of the IEEE 802.11p as a p-persistent CSMA/CA. The main difference between the p-persistent 802.11 and the standard IEEE 802.11p protocol is only in the selection of the backoff interval. In the standard protocol, the backoff interval is binary exponential. However, in the p-persistent CSMA/CA, the backoff interval is based on a geometric distribution with a specific probability of transmission, p. Therefore, the probability that a node stays idle when having a busy medium is $1 - p$. The p-persistent CSMA/CA provides a very close approximation to the IEEE 802.11 [3,4,12,13], and the memoryless backoff property makes it suitable for the purpose of analysis.

Based on the geometrically distributed backoff time, the probability of having a successful transmission after $n - 1$ failures is

$$P(X = n) = (1 - p)^{n-1}p, \quad n = 1, 2, \ldots, \tag{1}$$

where X is the number of total trials for a successful transmission. Accordingly, based on [3,4], the expected value of the random variable X can be used to determine the average contention window size $\overline{CW}$ as:

$$E[X] = \sum_{n=1}^{\infty} np(1 - p)^{n-1} = \frac{1}{p},$$
$$\frac{\overline{CW} + 1}{2} = \frac{1}{p}. \tag{2}$$

There are several important probabilities that we should consider. Let M the number of contending nodes, we have

$$P\{\text{no transmissions}\} = (1 - p)^M,$$
$$P\{\text{only one transmission}\} = Mp(1 - p)^{M-1},$$
$$P\{\text{at least one transmission}\} = 1 - (1 - p)^M.$$

Then, the probability of a successful transmission, P_s, and the probability of a collision, P_c, are given by:

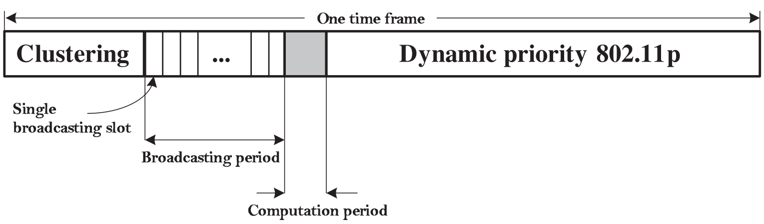

Fig. 2. Frame structure with periodic broadcasting of vehicle information.

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$$P_s = P\{\text{one node transmits}|\text{at least one node} \quad (3)$$

$$\text{has packets to transmit}\} = \frac{Mp(1-p)^{M-1}}{1-(1-p)^M}, \quad (4)$$

$$P_c = P\{\text{at least two nodes transmit}|\text{at least one node} \quad (5)$$

$$\text{has packets to transmit}\} = \frac{1-(1-p)^M - Mp(1-p)^{M-1}}{1-(1-p)^M}. \quad (6)$$

In [3], a virtual transmission time (V_T) is defined to be the time interval between two adjacent successful transmissions. It is possible to have a number of collisions in addition to one successful transmission, in a V_T. Let T_i denote the idle time during which no node transmits, T_s the time of a successful transmission, and T_c the total time of transmission collisions, within a virtual transmission time. Then, we have [13]

$$E[V_T] = E[T_i] + E[T_c] + E[T_s]. \quad (7)$$

For maximum system performance in terms of throughput, the value of V_T should be minimized. Let L, D and δ denote the packet transmission time, the DIFS time, and the slot time, respectively. Based on the probabilities of transmissions and a constant packet time L, mathematical expressions for $E[T_i]$, $E[T_c]$, $E[T_s]$ can be obtained [3,13], given by:

$$E[T_i] = \left[\frac{1-(1-p)^M - Mp(1-p)^{M-1}}{Mp(1-p)^{M-1}}\right]\left(\frac{1-p}{Mp}\right)\delta,$$

$$E[T_c] = \left[\frac{1-(1-p)^M - Mp(1-p)^{M-1}}{Mp(1-p)^{M-1}}\right](L+D)\delta,$$

$$E[T_s] = (L+D)\delta.$$

By using basic algebra, we have

$$E[V_T] = \left[\frac{(L+D)-(L+D-1)(1-p)^M}{Mp(1-p)^{M-1}}\right]\delta. \quad (8)$$

The optimal transmission probability, p_{opt}, which minimizes the value of $E[V_T]$, can be obtained by equating the first derivative of $E[V_T]$ with respect to p to zero. Given values of L, D, and M, p_{opt} can be numerically computed.

In the proposed MAC protocol, the p_{opt} value is used to tune the contention window size to reach the desired performance. To that end, each node that wants to transmit should already have the number of one-hop contending nodes, M. With p_{opt}, a suitable value for the minimum contention window size is assigned based on (2).

4.2. Adaptation to vehicle velocity

This proposed MAC scheme uses a relation between the relative speed and the level of service priority. Basically, the deviation of the node speed from the average speed of the neighbors is proportional to the level of channel access priority. In other words, over each constant observation interval, the share of the channel time for a node with the average speed is reduced and that of a node with an extremely low or high speed is increased. In this way, we want to achieve better fairness over a number of the observation intervals, in terms of how long each node shares the medium based on the estimated time that it spends in the active transmission range.

Table 1
Dynamic service priority assignment based on relative speed.

d	Priority	Access class
Small	Low	3
Medium	Medium	2
Large	High	1

For a cluster of M nodes contending for the channel, the share of node i accessing the channel is proportional to $\frac{p_i}{\sum_{j=1}^{M} p_j}$, where p_i is the transmission probability of node i.

One way to relate the channel access time to the node velocity is to adjust the contention window size to provide service priority. For a transmitting node, i, with a velocity, V_i, the deviation from the average speed, d, is given by:

$$d = |V_i - \overline{V}|,$$

where $\overline{V}$ is the average speed of the $(M-1)$ one-hop neighbors in the cluster.

For simplicity in implementation, vehicles are categorized into different classes based on their speed deviations from the average speed. An example is given in Table 1. Accordingly, each vehicle adjusts the values of the minimum and maximum contention window sizes, CW_{min} and CW_{max}, respectively.

5. Performance evaluation

To evaluate mobility impact on the standard IEEE 802.11p and the proposed dynamic priority management schemes, simulations are performed using Network Simulator (NS2) [14], version 2.31. The simulations are carried out for a 3-lane highway with a length of 5 km and a width of 10 m per lane. Vehicle velocity varies from 60 to 120 km/h. All vehicles have the same 802.11p MAC parameters. Vehicles move according to the freeway mobility model as described in [15].

In all the simulations, the system time is set to 100 s, and the transmission range of each vehicle is 250 m. Vehicles communicate in a V2V mode. Each packet has 1024 bytes and can be transmitted over 500 slots, at a rate of 1.2 Mbps. Channel reuse is permitted in different node clusters. The number of nodes contending for the channel varies from 20 to 250. We set the parameters of the IEEE 802.11p with time slot of δ = 13 μs, and SIFS time of 32 μs.

Consider two different communication scenarios in the evaluation. In the first one, each node broadcasts packets to its neighbors. In the second scenario, each node unicast packets to a destination, which may not be a one-hop neighbor. We use the Ad hoc On-Demand Distance Vector (AODV) routing protocol in the unicast scenario. Five minimal contention window sizes are used: $CW_{min} \in \{3, 7, 15, a, b\}$ where a is the value computed using the p-persistent scheme, and b is the value computed using the velocity adaptive scheme. Three maximal contention window sizes are used: $CW_{max} \in \{7, 255, 1023\}$.

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For the velocity adaptive MAC, the values for the speed deviation from average speed and the respective channel access priorities are given in Table 2. Accordingly, each node adjusts the values of CW_{min} and CW_{max}.

5.1. Mobility and performance metrics

In order to study the mobility impact, we use the communication duration as a mobility metric for network connectivity. We study the communication duration per each pair of nodes as a function of their relative speed and the distance between them. Furthermore, we study the distribution of one-hop neighbors, and the distribution of the communication duration of a link. For two vehicles i and j, the link distance l and relative speed v_r are defined as:

$$v_r = |v_i - v_j|,$$
$$l = |x_i - x_j|,$$

where v_i and v_j are the velocities of vehicles i and j respectively, and x_i and x_j are the x-axis (along the road) positions of vehicles i and j respectively.

The PDR, system throughput, average number of retransmissions per packet, average delay, and Jain fairness index [16] are used to measure the network performance at the MAC level. System throughput is the total number of bits successfully transmitted over the system time. These measurements indicate the efficiency of the system in terms of the ratio of delivered packets, the level of contention for channel access, and the level of fairness in channel access.

5.2. Evaluation of mobility impact on the IEEE 802.11p

5.2.1. Broadcast scenario

First, we evaluate the number of potential communication neighbors within the transmission range as shown in Fig. 3. It can be seen that the number of neighbors varies and does not follow a specific pattern. However, it is obvious that the distribution shifts to the right when the number of nodes increases. This indicates that, when the number of nodes increases, the connectivity of the network nodes increases.

Fig. 4 shows the cumulative distribution function (CDF) of the communication duration of network links. For more than 40–50% of all occurrences, the communication time is less than 1 s. This indicates that the communication time is very limited due to differences in node velocity.

For the effect of the relative speed on the channel access time, Fig. 5a shows the accumulated fraction of channel access time for different node densities and different relative speeds. It shows that most of the channel time is allocated for the nodes with relative speed less than 1 m/s, and then

Table 2
Dynamic assignment of parameters according to relative speed.

Speed deviation (m/s)	Priority	CW_{min}	CW_{max}
0–3	Low	15	1023
3–10	Medium	7	255
10–17	High	3	7

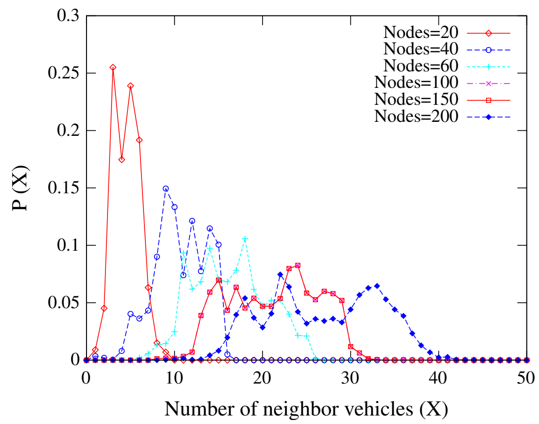

Fig. 3. Probability mass function of the number of neighbors.

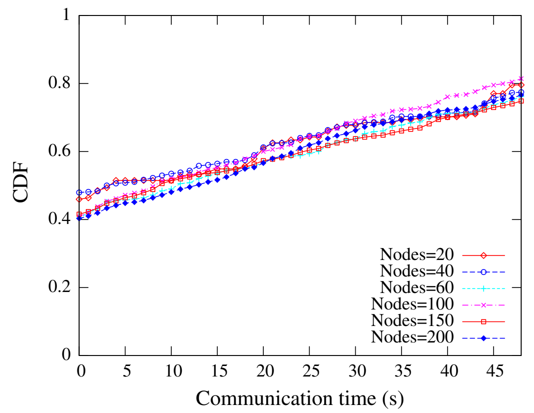

Fig. 4. CDF of the communication duration of a link in the broadcast scenario.

the access time decreases with very small fluctuations until it reaches zero at a relative speed higher than 17 m/s. Therefore, the channel access time is unfairly distributed among the contending nodes according to their relative speeds.

In contrast to the impact of the relative speed on the medium access, the distance between a transmitter and a receiver does not have such a huge impact, as shown in Fig. 5b. Once a node is in the transmission range of the sender/receiver, it is given a channel time that depends on the other mobility factors. Fig. 5b indicates that, the channel access time is spreaded over the link distance.

5.2.2. Unicast scenario

In the unicast scenario, each vehicle sends its packets via the routing protocol to a destination that may not be a one-hop neighbor. Each source and destination pair is selected randomly. The distribution of the number of communication neighbors for each node is illustrated in Fig. 3, with the same mobility scenario. However, the effect of the other mobility factors on the MAC performance differs as follows. First, we evaluate the CDF of the link communication duration for different node densities. Fig. 6a

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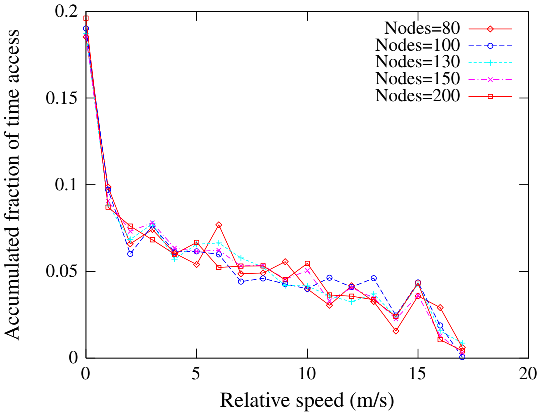
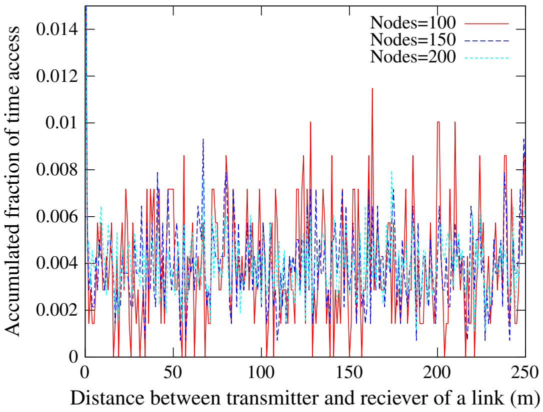
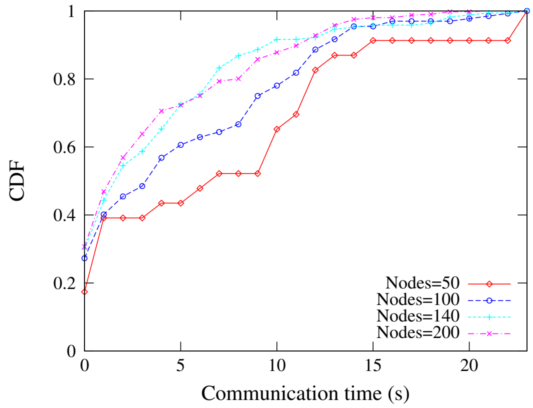


(a) Accumulated fraction of access time versus relative speed.

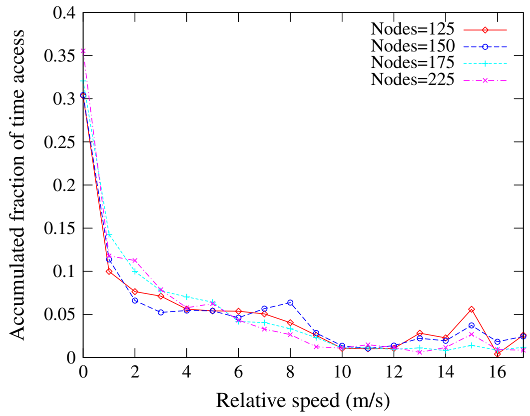


(b) Accumulated fraction of access time versus distance.

Fig. 5. Evaluation of channel access time in the broadcast scenario.



(a) CDF of the communication duration of a link.



(b) Accumulated fraction of access time versus relative speed.

Fig. 6. Mobility impact at the MAC layer in the unicast scenario.

shows the CDF of the link communication duration in the unicast scenario. Among 38–45% of all occurrences, vehicles have less than 1 s to communicate. Moreover, vehicles with a relative speed less than 1 m/s receive the most of the channel time as Fig. 6b shows. Also, node position does not have a great impact on the medium access as in Fig. 7. The channel access time is spreaded over the link distance. However, the channel access time tends to a fraction of time less than 0.004 at link distance of 50 m or lower, and forms a bell shape at a link distance of 100–150 m. However, once a node is in the transmission range of the sender/receiver, it is given a channel time that depends on the other mobility factors.

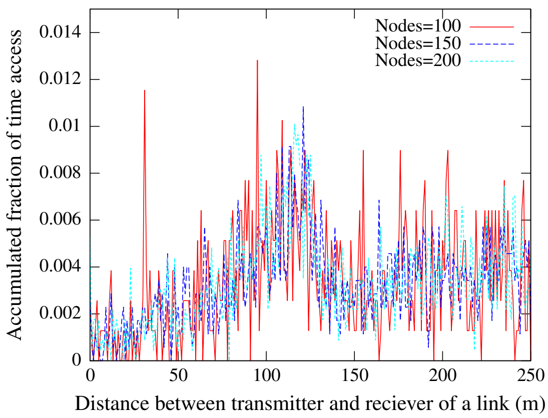
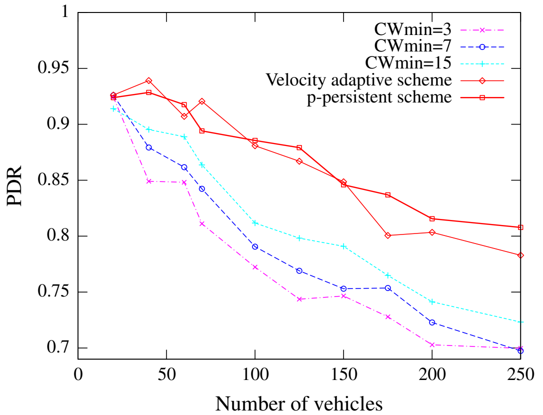


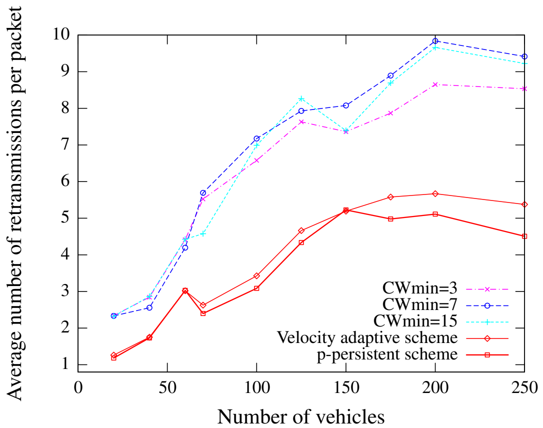
Fig. 7. Accumulated fraction of access time versus distance.

5.3. IEEE 802.11p performance evaluation

In the previous subsection, we provide performance evaluation of the IEEE 802.11p MAC from the perspective of mobility impact. Here, different performance metrics are used to evaluate the performance in V2V communications. In the following, we focus on the scenario that each node sends its packets to a destination in the unicast mode. First we measure the PDR for different access categories, as shown in Fig. 8a. The PDR starts at a high value. However, when the number of nodes increases, the PDR drops to below 75% due to the frequent network partitions and lack of adaptivity to mobility factors in MAC. Collisions occur in the unicast scenario because of the hidden terminal problem and/or exceeding the number of retransmission limits of the MAC protocol (which is 7 in the IEEE 802.11p). The average number of retransmissions per packet is low with

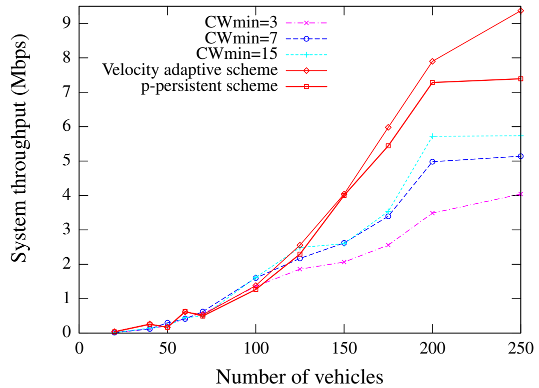


(a) PDR

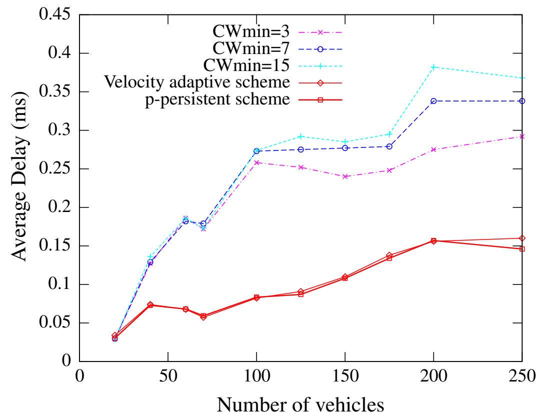


(b) Average number of retransmissions

Fig. 8. Performance of the IEEE 802.11p and the dynamic priority schemes.



(a) Throughput



(b) Transmission delay

Fig. 9. Performance of the IEEE 802.11p and the dynamic priority schemes.

a small number of nodes, but increases drastically from 50 nodes, as in Fig. 8b. A large number of retransmissions indicates that the level of contention on channel access is severe.

Fig. 9a shows that the throughput of the system increases as the number of nodes increases. This is a normal behavior of the network since more transmitting nodes leads to more delivered packets. Fig. 9b shows that the per-hop delay of the successfully delivered packets at the MAC level is under 0.4 ms.

Interestingly, Jain fairness index [16] indicates poor fairness at a low number of nodes, as shown in Fig. 10. This is due to the frequent fragmentation of the network which causes some nodes to have less connectivity than the others. At a higher node density, the fairness index increases. It is obvious in Fig. 10 that all the three contention window sizes of the standard IEEE 802.11p reveal a similar fairness behavior. This is due to the absence of the mobility consideration in the IEEE 802.11p.

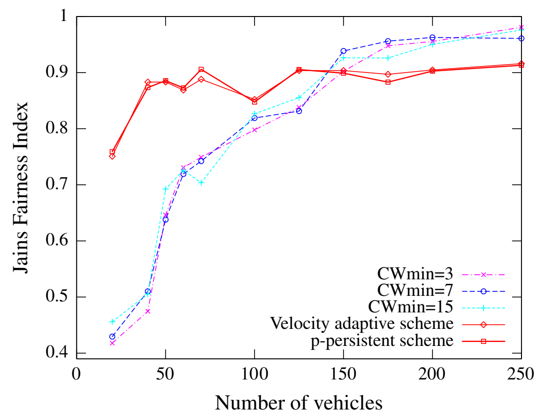


Fig. 10. Jain fairness index.

5.4. Performance evaluation of the adaptive schemes

Fig. 8a shows that the *p*-persistent MAC protocol results in a higher PDR than the IEEE 802.11p standard. Allowing different service priorities based on the neighbor number shows obvious alleviation of the number of dropped packets. The average number of retransmissions in the pro-

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posed *p*-persistent MAC protocol is lower than that in the IEEE 802.11p, as in Fig. 8b. As the severity of contention on channel access is significantly reduced, the number of collisions is reduced. The *p*-persistent scheme reveals close performance to that of the IEEE 802.11p in terms of throughput with number of node not larger than 125 as shown in Fig. 9a. However, at a node number of 150 or higher, the *p*-persistent scheme outperforms the IEEE 802.11p. The average transmission delay over each hop is significantly reduced with a maximum value of 0.15 ms as Fig. 9b shows.

Even though the velocity adaptive MAC does not use the exact relative velocity between vehicles, simulation results show performance improvement in terms of PDR and the number of retransmissions as can be seen in Fig. 8. The main improvement is that the protocol reduces the number of high priority packets that cause packets collisions [6] and alleviates the network performance degradation. The velocity adaptive scheme outperforms both the *p*-persistent scheme and the IEEE 802.11p standard in terms of system throughput at a node number of 150 or higher. The average transmission delay is improved over that of the IEEE 802.11p, as Fig. 9a shows.

Interestingly, Fig. 10 shows that the two proposed schemes achieve better fairness at a node number less than 150 nodes, in comparison with IEEE 802.11p. For the number of nodes equal to 150, 200, and 250, the IEEE 802.11p provides slightly better fairness.

Overall, both newly proposed schemes outperform the IEEE 802.11p. However, the two schemes have similar performance, each providing better performance in certain scenarios, due to the fact that each MAC protocol is adaptive to one of the significant mobility parameters. For the packet delivery ratio, when the node number is large, the *p*-persistent scheme performs better than the velocity adaptive scheme. For system throughput and the number of retransmissions, the velocity adaptive scheme outperforms the *p*-persistent scheme at the node number of 80 or higher as in Figs. 8b and 9a. Both schemes reduce the level of contention by reducing the number of high priority packets through the dynamic assignment of service priority. By reducing the contention level, the number of collisions is reduced, the packet dropping rate is decreased, and the throughput is increased. Reducing the level of contention results in better performance than that in the IEEE 802.11p, but to maximize the performance, the MAC protocol should incorporate the other mobility parameters in VANETs.

6. Conclusions and future work

In this paper, we evaluate the impact of mobility on the infrastructureless IEEE 802.11p MAC performance by investigating certain mobility factors. Simulation results show that relative speed has a significant impact on channel access at the MAC layer, disregarding the number of communicating nodes. In addition, the number of one-hop neighbors has a significant impact on the degree of contention. As a solution, we propose two dynamic priority schemes to reduce the severity of contention and improve the packet delivery ratio. The first scheme provides priorities based on the number of neighboring nodes, while the second one assigns channel access priority based on relative speed. Both schemes improve the network performance by increasing system throughput, reducing the number of dropped packets, the average transmission delay, and the average number of retransmissions.

Further research is necessary to investigate the performance of the adaptive schemes with respect to more than one mobility factor, and to jointly design the MAC and routing protocols.

Acknowledgment

This research was supported by a scholarship from Umm Al-Qura University at Saudi Arabia.

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Please cite this article in press as: W. Alasmary, W. Zhuang, Mobility impact in IEEE 802.11p infrastructureless vehicular networks, Ad Hoc Netw. (2010), doi:10.1016/j.adhoc.2010.06.006

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Please cite this article in press as: W. Alasmary, W. Zhuang, Mobility impact in IEEE 802.11p infrastructureless vehicular networks, Ad Hoc Netw. (2010), doi:10.1016/j.adhoc.2010.06.006