Proceedings of the 2008 IEEE International Conference on
Vehicular Electronics and Safety
Columbus, OH, USA. September 22-24, 2008

IEEE 802.11p Performance Evaluation and Protocol Enhancement

Yi Wang, Akram Ahmed, Bhaskar Krishnamachari and Konstantinos Psounis
Viterbi School of Engineering
University of Southern California
Los Angeles, CA 90089, USA
{wangyi,akramahm,bkrishna,kpsounis}@usc.edu

Abstract— **The IEEE 802.11p Wireless Access in Vehicular Environment (WAVE) protocol providing for vehicle-to-infrastructure and vehicle-to-vehicle radio communication is currently under standardization. We provide an NS-2 simulation study of the proposed IEEE 802.11p MAC protocol focusing on vehicle-to-infrastructure communication. We show that the specified MAC parameters for this protocol can lead to undesired throughput performance because the backoff window sizes are not adaptive to dynamics in the numbers of vehicles attempting to communicate. We propose two solutions to this problem. One is a centralized approach where exact information about the number of concurrent transmitting vehicles is used to calculate the optimal window size, and the other is a distributed approach in which vehicles use local observations to adapt the window size. We show that these schemes can provide significant improvements over the standard MAC protocol under dense and dynamic conditions.**

I. INTRODUCTION

IEEE 802.11p, also known as Wireless Access in Vehicular Environment (WAVE), is a draft amendment to the IEEE 802.11 standard that adds applications to fast changing vehicular networks. In this paper, we aim at studying the MAC features and throughput performance of the IEEE 802.11p protocol. In addition, new methods are suggested to improve the performance by modifying the original IEEE 802.11p MAC protocol in such a manner that each transmitting vehicle could adjust its backoff window size in order to achieve higher throughput based on channel feedbacks.

We first propose a centralized enhancement algorithm, which is based on the study in [5] and [15] by modeling IEEE 802.11p as p-persistent CSMA. Instead of using a window based back-off mechanism, p-persistent CSMA divides the time into slots with equal length and each node chooses wether to transmit in the coming time slot with certain probability. A closed-form equation for the average Virtual Transmission Time [1] (VT) is proposed in Section V based on the analysis in [5] and [15]. Using this model, the throughput of the network can be maximized by choosing the transmission probability such that average VT length is minimized.

A critical assumption of the centralized algorithm is that the number of transmitting vehicles is always known in order to compute the optimal transmission probability. Since this is not always true in practical scenarios, we have also proposed a distributed enhancement algorithm where a node only uses local channel information to change its backoff window size. Specifically, a transmitting vehicle will measure the channel busy proportion and compare it with the ones obtained previously. Based on the changing amount of the busy proportion, a vehicle will consider whether the number of transmitting stations is increased or decreased and change its backoff window size accordingly. We simulate the algorithm under different scenarios and show that our algorithm, which controls the backoff window size in real time, can achieve better throughput.

The remainder of the paper is structured as follows. In Section II we present the related work. The MAC features of IEEE 802.11p protocol are discussed in Section III. The performance of the original IEEE 802.11p standard is studied in Section IV. Then, in Section V we propose the centralized enhancement algorithm that assigns optimal transmission probability to each vehicle. We also propose and discuss a distributed enhancement algorithm to increase throughput performance in Section VI. Finally, we give the conclusion and future work directions in Section VII.

II. RELATED WORK

The capacity analysis of several CSMA based wireless networking MAC protocols and tuning mechanisms has been extensively studied in the literature such as [3], [5], [4], [15], [14], [2], [12]. For example, Bianchi *et al.* [4] investigated the capacity of IEEE 802.11 and showed that the contention window of each transmitter has to be dynamically chosen in order to increase the throughput. Cali *et al.* [5] modeled the IEEE 802.11 protocol by p-persistent CSMA where each transmitting station transmits with a certain probability after collision rather than choosing a back-off window uniformly from $[0, CW+1]$. The authors showed that in order to reach the theoretical throughput limit of IEEE 802.11, the transmitting probability has to be adaptive to the channel condition such that the time between two consecutive transmissions is minimized. In a similar study [15], Yedavalli and Krishnamachari conducted optimality analysis of network throughput and energy consumption and proposed an enhancement algorithm to increase the throughput and reduce the power cost for IEEE 802.15.4 for high density sensor networks. The IEEE 802.11 protocol has also been studied via simulations in previous works such as [8] and [13].

On the other hand, however, the performance of IEEE

---

[1] Note that the authors of [5] define a Virtual Transmission Time (VT) as the time between two consecutive successful transmissions.

978-1-4244-2360-6/08/$25.00 ©2008 IEEE.

AC	CWmin	CWmax	AIFSN
VI	3	7	2
VO	3	7	3
BE	7	225	6
BK	15	1023	9

TABLE I
PARAMETER SETTINGS FOR DIFFERENT APPLICATION CATEGORIES IN IEEE 802.11P

802.11p has not been widely studied. Eichle [9] analyzed the capabilities of the IEEE 802.11p standard and gave an overview on both the capabilities and the limitations of the technology. Stibor *et al.* [11] evaluated the number of potential communication partners and the maximum communication duration for a vehicular ad-hoc network using a highway scenario, and showed that the number of neighboring vehicles is an important input parameter for algorithms that choose the optimal next transmitter in a multi-hop communication scenario. However, none of the existing works focuses on the MAC performance of IEEE 802.11p and the possibility of enhancing the IEEE 802.11p MAC protocol.

III. 802.11P MAC FEATURES AND DISCUSSION

The Medium Access Control protocol in IEEE 802.11p uses the Enhanced Distributed Channel Access (EDCA) mechanism originally provided by IEEE 802.11e [7]. Different Arbitration Inter Frame Space (AIFS) and Contention Window (CW) values are chosen for different application categories (ACs). There are four available data traffic categories with different priorities: background traffic (BK), best effort traffic (BE), voice traffic (VO) and video traffic (VI). Table I shows the default parameter settings used in IEEE 802.11p for different application traffic types.

In wireless medium access control (MAC) protocols such as CSMA/CA, a window based backoff mechanism is used such that a node willing to transmit will sense the medium first, and if the medium is not free it will choose a backoff time uniformly at random from the interval $[0, CW+1]$ where the initial CW value equals CW_{min}. The interval size will grow (doubled) if the subsequent transmission attempt fails until CW value equals CW_{max}.

From Table I, it can be seen clearly that voice and video traffics can be served with higher priority by picking lower backoff window size and shorter inter-frame space time. As a result, the throughput of these types of traffic can be increased by choosing small backoff window which reduces the waiting time to be served. However, sometimes the number of concurrent transmitting vehicles is large in vehicular networking environment, and hence making nodes highly aggressive will lead to low throughput due to the high probability of collision. In other words, a vehicle should increase the length of backoff time intervals rather than using $CW_{min} = 3$ and $CW_{max} = 7$ when there exist other contending nodes. In order to verify this observation, we have conducted simulations in NS-2, aiming to show that fixing protocol parameters (e.g.: Table I) usually leads to undesired performance, especially when the number of transmitting vehicles is large and backoff window size is small. The results are presented in the next section.

IV. 802.11P PERFORMANCE EVALUATION

We first present some simulation preliminaries and settings as follows:

- We focus on the infrastructure mode of IEEE 802.11p, i.e.: multiple vehicles transmit packets to a central base station. This scenario can be easily found in real life where many vehicles send data to a base station which serves as a central storage/relay node.
- Each vehicle adopts IEEE 802.11p MAC protocol. The parameter settings of IEEE 802.11p in NS-2 are based on the MAC and PHY modules designed in [6]. [2]
- Vehicles generate a single category of Constant Bit Rate (CBR) traffic with a fixed packet size.
- Channel data rate is 3Mbps.
- The transmission range of each vehicle is about 80m, and the largest distance between a vehicle to the base station is set to be 20m, which ensures that each transmitting vehicle can hear all others.
- In each simulation the number of concurrent transmitting vehicles is fixed and simulation length is $t = 50$ seconds.

Figure 1 plots the average throughput with respect to different number of transmitting vehicles for different backoff window sizes. The data arrival rate at each vehicle (denoted by R) is 1.6Mbps (saturated channel) and 0.32Mbps (non-saturated channel). It can be seen that under both saturated and non-saturated channel conditions, picking suitable backoff window size will have big impact on the network throughput.

We've also examined the network throughput under different number of transmitting vehicles, but with fixed *network data arrival rate*, that is, the value of per vehicle data arrival rate times the number of vehicles is constant(1.6Mbps in our study). Figure 2 shows that the network throughput decreases with number of vehicles. This observation is quite interesting and suggests that with the same network data input rate, the overall network throughput decreases with number of transmitting vehicles. This is because with more nodes transmitting, the chance of collision increases therefore vehicles will spend more time backing off. Moreover, Figure 2 also verifies the fact that choosing the correct backoff window size can significantly increase network throughput.

The above observations indicate that it is necessary to design an algorithms to adjust the backoff window size for each vehicle 'on the fly' in order to be adaptive to the environmental changes and achieve better throughput performance. In the next two sections we propose both a centralized and a distributed enhancement algorithm on IEEE 802.11p MAC such that each transmitting vehicle will be more aggressive when the number of transmitting nodes is small, and less aggressive when the number of contending nodes is large.

---

[2] The new modules have overcome some significant shortcomings in the previous MAC and PHY functionalities.

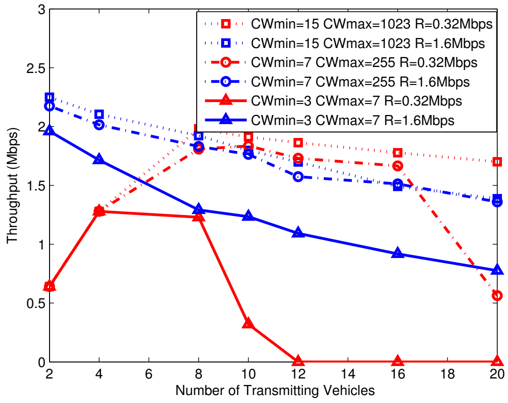

Fig. 1. Saturation and non-saturation throughput for different window sizes.

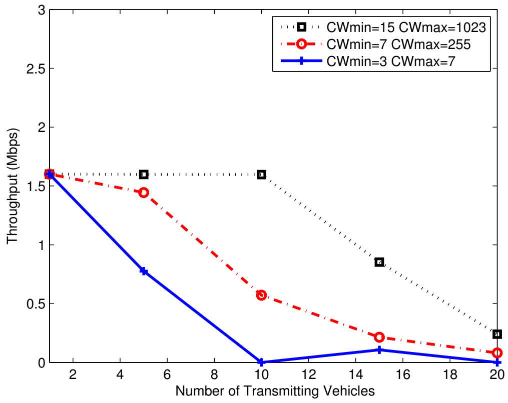

Fig. 2. Compares the average throughput for different backoff windows where the network arrival rate is fixed (1.6Mbps).

V. CENTRALIZED ENHANCEMENT ALGORITHM

A. Analysis and Algorithm

When observing the medium, the time interval between two successful transmissions is defined as a *Virtual Transmission Time* (VT) [5]. The VT is made up of idle times, collision times and successful transmission time. The idle times are defined as the time where no station is transmitting and hence the medium is free. Collision times, on the other hand, are defined as the time where more than one stations are transmitting which causes collision. Finally, successful transmission occurs at the end of the VT where the packet is delivered to its destination. Note that in order to achieve higher throughput, the time between two subsequent successful transmissions (VT) has to be minimized.

We model the IEEE 802.11p MAC as slotted p-persistent CSMA. It has been shown that p-persistent CSMA model can closely approximate the IEEE 802.11 protocol [5]. The main difference between the p-persistent CSMA and the original IEEE 802.11p protocol is the selection of the backoff interval. Instead of using the window based backoff mechanism, the backoff interval of p-persistent CSMA is determined by the transmission probability p such that a station chooses to transmit with probability p and stays idle with probability $1-p$ in each subsequent time slot when the medium is sensed busy. Note that although p-persistent CSMA model is suitable for analysis purpose due to its memoryless backoffs, the window based backoff mechanism in IEEE 802.11 standard does not have this feature.

In our study, a time slot in p-persistent CSMA is the same as IEEE 802.11p standard with length $t_{slot} = 0.000013s$. The transmission probability p is chosen such that the mean backoff time is equal to the window based backoff mechanism, i.e.: $\frac{1}{p} = \frac{CW+1}{2}$.

The average length of Virtual Transmission Times $E[VT]$ is suggested by [5]:

$$E[VT] = E[T_{totalidle}] + E[T_{totalcoll}] + E[T_{succ}] \qquad (1)$$

where $E[T_{totalidle}]$ is the average total length of idle times in each VT, and $E[T_{totalcoll}]$ is the average total length of collision times in each VT and $E[T_{succ}]$ is the average successful transmission time length, which is at the end of VT.

Define L and D as the packet size and the length of DIFS in terms of number of time slots. Also let M and p be the number of vehicles and transmission probability of a node. Based on the analysis in [5], [15], the average VT length can be written as:

$$\begin{aligned} E[VT] &= \left(\frac{1-(1-p)^M}{Mp(1-p)^{M-1}} - 1\right) \cdot (L+D) \cdot t_{slot} \\ &\quad + \left(\frac{1-(1-p)^M}{Mp(1-p)^{M-1}} - 1\right) \cdot \frac{(1-p)^M}{1-(1-p)^M} \cdot t_{slot} \\ &\quad + (L+D) \cdot t_{slot} \\ &= \frac{(L+D)-(L+D-1)\cdot(1-p)^M}{Mp(1-p)^{M-1}} \cdot t_{slot} \qquad (2) \end{aligned}$$

When M, L and D are known, $E[VT]$ can be minimized by choosing an optimal transmission p_{opt} such that:

$$p_{opt} = \underset{p}{\operatorname{argmin}} \left\{ \frac{(L+D)-(L+D-1)\cdot(1-p)^M}{Mp(1-p)^{M-1}} \cdot t_{slot} \right\} \qquad (3)$$

The centralized enhancement algorithm is then given as Algorithm 1. It assumes that the base station knows the number of concurrent transmitting vehicles in the communication range Γ and will update this information to all the transmitting vehicles by broadcasting periodically. Once a vehicle received such a broadcast, it will be able to calculate the optimal transmission probability based on Equation 3. Note that although Algorithm 1 is designed to be executed in real time, the p_{opt} for different L, M and D values can be calculated *a priori*; therefore, the desired window size can be updated in real time using table look-ups.

Algorithm 1 CEA: Centralized backoff window updating mechanism for vehicle v

```
while $v$ is in $\Gamma$ do
    if $v$ receives base station's broadcast containing the number of concurrent transmitting vehicles M then
        Calculate $p_{opt}$ based on Equation 3
        Set $CW_{min} = CW_{max} = CW = \frac{2-p_{opt}}{p_{opt}}$
    else
        Use previous CW
    end if
end while
```

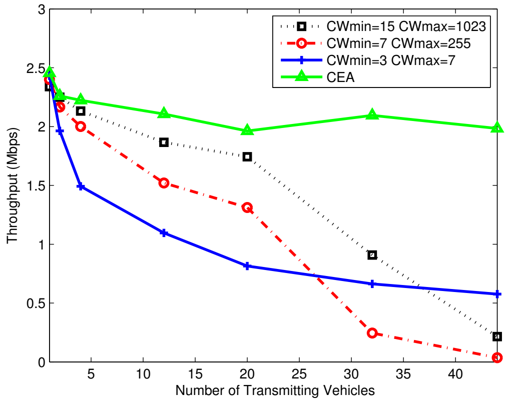

Fig. 3. Compares the throughput under Centralized Enhancement Algorithm with the original IEEE 802.11p settings.

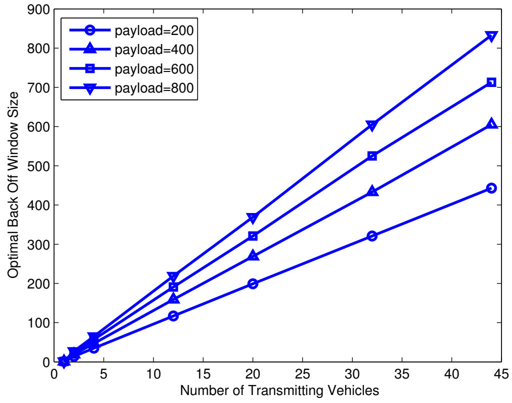

Fig. 4. Shows the optimal backoff window size for different payload sizes based on CEA.

B. Evaluation

The Centralized Enhancement Algorithm (CEA) is evaluated through simulations in NS-2. The following list shows some important features of the simulation settings:

- Each vehicles generates a single type of CBR traffic with packet sizes 600 bytes every 0.0015 second.
- The number of transmitting vehicles is varied as $\{1, 2, 4, 12, 20, 32, 44\}$.
- Four types of backoff window sizes are examined: (a) $CW_{min} = 15$, $CW_{max} = 1023$ (b) $CW_{min} = 7$, $CW_{max} = 255$ (c) $CW_{min} = 3$, $CW_{max} = 7$ (d) CW is calculated based on Algorithm 1. Note that the first three types are defined by the original IEEE 802.11p standard.
- Each transmitting vehicle is able to hear all others, i.e.: no hidden terminal.
- Simulation length is 50 seconds and the number of transmitting vehicles remains the same.

Figure 3 shows the average throughput for the several scenarios listed above. It can be seen that although CEA performance is similar to the original protocol when the number of transmitting vehicles is small, it is much better when the number of transmitting vehicles is large.

The optimal backoff window sizes are shown in Figure 4. It can be seen that as the number of vehicles and the payload size grows, the backoff window will increase such that each node becomes less aggressive to reduce the probability of collision.

For CEA implementation, certain types of road sensors or monitoring system are required to obtain the number of vehicles within the communication range. A beacon based mechanism can also be used such that each vehicle will broadcast its existence to the base station who can in turn count the total number of transmitting nodes. Indeed, most of the time it is difficult to know 'how many cars are around' from an infrastructure node point of view and a centralized MAC enhancement algorithm might fail if the base station is relaying wrong information to the transmitting vehicles. As a result, we proposed a distributed enhancement algorithm in the next section where each transmitting station only uses its local channel information to estimate the trend of the changing vehicle density and adjust its MAC backoff window accordingly in order to achieve higher throughput.

VI. DISTRIBUTED ENHANCEMENT ALGORITHM

A. The Algorithm

It has been suggested in [5] that one can observe the idle time within each virtual transmission time to estimate the number of transmitting vehicles M. However, the estimation variance could be very high due to the fact that the time of one VT is extremely short and may have huge randomness [3]. In our study, instead of trying to estimate the number of vehicles, we design an algorithm that captures the dynamics of number of nodes such that each node will enlarge its backoff window size when the number of vehicles is considered increased, and *vice versa*.

The distributed enhancement algorithm is based on the observation that when more nodes are contending for the channel, the ratio of channel busy time increases. Instead of identifying each VT, we define an *observation interval* (OI) which is much larger than a VT such that the observation randomness can be reduced. Each vehicle updates its backoff window size at the end of each OI. During an OI, a station simply keeps counting the amount of time a channel is busy and updates the proportion of busy time at the end of OI. At time interval i, the station compares the current busy proportion with the previous one and computes the difference which is denoted by α_i. The parameter α_{thres} is introduced to reduce the sensitivity of the window update algorithm, such that if α_i is positive and larger than some threshold α_{thres}, the vehicle will consider that more transmitting vehicles are injected into the communication range, and hence will increase its window size by $\frac{\alpha}{\alpha_{thres}}$. On the other hand, if α_i is negative and the absolute value of α is larger than α_{thres}, it will consider that the number of concurrent transmitting nodes is decreased, and hence reduce its current window size by $\frac{\alpha}{\alpha_{thres}}$. The linear updating method is based on heuristic and it simply suggests that as more vehicles join the communication range, the backoff window should

---

[3] We find through simulations in NS-2 that the estimation is not very accurate for IEEE 802.11p. E.g.: for 12 concurrent transmitting vehicles, the estimated result is 5

become larger proportionally to the previous window size. We plan to study and test other window updating methods such as AIMD to our future work. Note that there can be other ways of choosing the α_{thres} value as well. In this paper we will let $\alpha_{thres} = \frac{\alpha_1+\alpha_2+\ldots+\alpha_n}{n}$, that is, α_{thres} is the average of all alpha values observed by the current transmitting vehicle since it enters the communication range. One may argue that α_{thres} may become large due to big α_i value, which may refrain the vehicle from updating its window size. This is not true because the observation frequency is much larger compared to the speed of vehicle density change, thus n will be large enough to keep α_{thres} at a reasonable value. The detailed contention window size updating mechanism can be found in Algorithm 2.

Algorithm 2 DEA: Distributed backoff window updating mechanism for vehicle v

```
$CW = CW_{init}$
while $v$ is in $\Gamma$ do
    if end of $i^{th}$ OI then
        $r^i_{busy} = \frac{T^i_{busy}}{T^i_{OI}}$
        $\alpha_i = r^i_{busy} - r^{i-1}_{busy}$
        if $|\alpha_i| > \alpha_{thres}$ then
            if $\alpha_i > 0$ then
                $CW = CW \times \frac{\alpha_i}{\alpha_{thres}}$
            else
                $CW = CW \div \frac{|\alpha_i|}{\alpha_{thres}}$
            end if
        else
            CW remains unchanged
        end if
        $T^i_{busy} = 0$
        $\alpha_{thres} = \frac{\alpha_{thres}\cdot(i-1)+|\alpha_i|}{i}$
        $CW_{min} = CW_{max} = CW$
    else
        Use previous CW, keep observing
        $T^i_{busy} = T^i_{busy} + T^i_{newbusy}$
    end if
end while
```

The distributed enhancement algorithm only uses local channel information rather than computing the optimal transmission probability based on the knowledge of number of transmitting vehicles. DEA can be easily implemented on the communication component of each vehicle, since the MAC layer in IEEE 802.11p has a Reception Module that can identify the end of each OI by counting the number of ACKs received. The accumulation of busy time within each OI can be achieved by physical layer indication.

In the next subsection we will evaluate the distributed enhancement algorithm by simulations.

B. Evaluation

1) Adaptiveness to sudden changes: We first look at the case where there is a raise or a drop in number of concurrent transmitting vehicles. The basic settings and parameters of our simulations are given as follows:

- Each vehicles generates a single type of CBR traffic with packet size equals to 600 bytesevery 0.0015 seconds.
- The total simulation time is 50 seconds, and the number of concurrent transmitting vehicles is changed at $t = 25$ second. Specifically, the topology changes in number of vehicles are: 4 to 16, 4 to 32, 12 to 4 and 32 to 4.
- Again, each transmitting vehicle is able to hear all other transmitting vehicles, i.e.: no hidden terminal.
- Four types of backoff window mechanisms are tested: (a) $CW_{min} = 15$, $CW_{max} = 1023$ (defined by the original IEEE 802.11p protocol) (b) the centralized enhancement algorithm (CEA) (c) the distributed enhancement algorithm (DEA) with $CW_{init} = \{40, 50, 500, 500\}$ (d) No enhancement algorithm (NON-ALG) with the same initial window $CW_{init} = \{40, 50, 500, 500\}$.

Table II compares the throughput for different scenarios simulated. It can be seen that both CEA and DEA can lead to a big performance increment over the original protocol with CEA performing a little better than DEA. Furthermore, DEA performs better than NON-ALG, which uses the same initial window sizes as DEA. This is because DEA is able to identify the topology change and adjust the backoff window sizes accordingly.

2) Adaptiveness to smooth changes: Naumov *et al.* proposed a new mobility model for VANET (Vehicular Ad Hoc Networks) in [10], which is generated by a traffic simulator based on real road maps. The details of the traffic simulator and their project can be found at [1]. In our study, we use one of the vehicular mobility traces from [1] by observing a traffic cross point for 5 minutes and identify the traffic dynamics in that region. A central base station is placed at the traffic cross point and each vehicle passing by will transmit data continuously to it. Figure 5 plots the vehicle density change over time (5 minutes). It can be seen that the transition of number of transmitting vehicles is very smooth with maximum number of 4 vehicles difference per second. We have tested all the previous mechanisms including the original standard, CEA, DEA and NON-ALG. Moreover, network throughput with different OI lengths are compared for DEA.

The second column of Table III shows the number of successfully received packets at the base station. It can be seen that both DEA and CEA outperform the original IEEE 802.11p.

Interestingly, DEA performance is not always better than NON-ALG as it can be seen that the throughput of DEA is worse than NON-ALG under short OI length. Recall that DEA works by observing the channel busy proportion and estimating the change in number of vehicles, which might be biased due to the random access nature of each node. Hence, the algorithm with a short observation interval may be influenced by the randomness of channel access where the busy proportion observed may not represent the current medium condition exactly. In this case a station may 'think' that the medium is busier and increase its own backoff

Topology Change	Original Protocol Results (Mbps)	CEA Results (Mbps)	CEA Gain Over Original	DEA Results (Mbps)	DEA Gain over Original	NON-ALG Results (Mbps)
4 → 16	1.807584	2.180064	21%	2.045856	13%	1.828416
4 → 32	1.235040	2.093568	70%	1.936032	57%	1.823808
12 → 4	1.129632	2.210208	97%	2.005152	79%	1.887618
32 → 4	1.869504	2.093568	12%	2.022912	7%	1.870848

TABLE II

Throughput comparison for DEA, non-DEA and original IEEE 802.11p

Simulated Cases	Number of packets successfully received
Original IEEE 802.11p	76246
CEA	127966
DEA (OI = 1000 VT)	91602
DEA (OI = 3000 VT)	116359
DEA (OI = 5000 VT)	119327
NON-ALG	103528

TABLE III

DEA performance comparison for different OI lengths

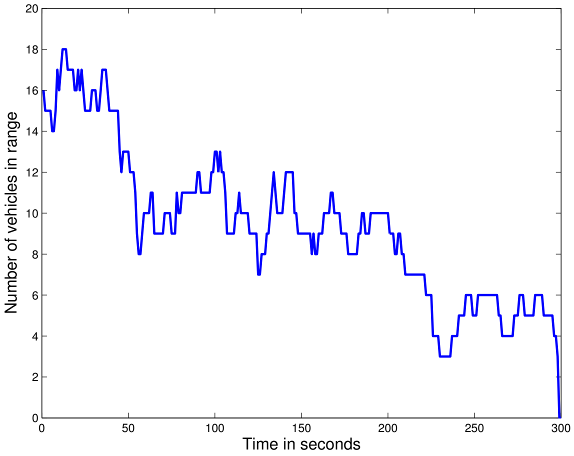

Fig. 5. Plots the number of concurrent transmitting vehicles in 5 minutes from vehicular traffic trace.

window size which is unnecessary and causes some amount of throughput drop. However, as the observation interval is enlarged, the randomness will be reduced such that each station is able to adjust its contention window size to the right direction to increase the throughput.

VII. Conclusions and Future Work

In this paper, we show that the infrastructure data collection mode of IEEE 802.11p (WAVE) standard, which will be released soon, does not perform well under the current static backoff schemes. We simulate the current protocol and show that fixing the backoff window sizes will lead to undesired throughput under dynamically changing vehicular communication environment. We propose both a centralized algorithm and a distributed algorithm to enhance the protocol and increase the network throughput. The centralized enhancement algorithm assumes that the base station knows the number of transmitting vehicles and calculate the optimal transmission probability in order to increase throughput. In the distributed enhancement algorithm, each vehicle only needs local medium information and selects the backoff time depending on the channel condition. We show that both the centralized and distributed enhancement algorithms provide significant network throughput increase compared to the original IEEE 802.11 standard.

In future work, we plan to study and test other window update rules for DEA. The effect of choosing different observation interval sizes can also be systematically studied and tested on various categories of vehicular traces. Possible ways of reducing the oscillations in window updating mechanisms also need to be considered. We also consider to design other kinds of enhancement approaches and compare the performance with the current ones.

References

[1] Realistic vehicular traces, http://lst.inf.ethz.ch/ad-hoc/car-traces/index.html.

[2] A. Banchs and L. Vollero, "Throughput analysis and optimal configuration of 802.11e EDCA," *Computer Networks*, 50(11):1749–1768, August 2006.

[3] G. Bianchi, "IEEE 802.11 - saturation throughput analysis," volume 2, pages 318–320, December 1998.

[4] G. Bianchi, L. Fratta, and M. Oliveri, "Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 wireless LANs," October 1996.

[5] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *Networking, IEEE/ACM Transactions on*, 8(6):785–799, 2000.

[6] Q. Chen, F. Schmidt-Eisenlohr, D. Jiang, M. Torrent-Moreno, L. Delgrossi, and H. Hartenstein, "Overhaul of IEEE 802.11 modeling and simulation in ns-2," pages 159–168, October 2007.

[7] Standards Committee, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: Amendment 8: Medium access control (MAC) quality of services enhancements," 2005.

[8] B. P. Crow, I. Widjaja, L. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," *Communications Magazine, IEEE*, 35(9):116–126, 1997.

[9] S. Eichler, "Performance evaluation of the IEEE 802.11p WAVE communication standard," Baltimore, USA, September 2007.

[10] V. Naumov, R. Baumann, and T. Gross, "An evaluation of inter vehicle ad hoc networks based on realistic vehicular traces," May 2006.

[11] L. Stibor, Y. Zang, and H. Reumerman, "Neighborhood evaluation of vehicular ad-hoc network using IEEE 802.11p," April 2007.

[12] Y. C. Tay and K. C. Chua, "A capacity analysis for the IEEE 802.11 MAC protocol," *Wirel. Netw.*, 7(2):159–171, 2001.

[13] J. Weinmiller, H. Woesner, J. P. Ebert, and A. Wolisz, "Analyzing and tuning the distributed coordination function in the IEEE 802.11 DFWMAC draft standard," Feb 1996.

[14] Haitao Wu, Xin Wang, Qian Zhang, and Xuemin Shen, "IEEE 802.11e enhanced distributed channel access (EDCA) throughput analysis," In *Communications, 2006. ICC '06. IEEE International Conference on*, volume 1, pages 223–228, 2006.

[15] K. Yedavalli and B. Krishnamachari, "Enhancement of the IEEE 802.15.4 MAC protocol for scalable data collection in dense sensor networks," Technical report, USC Technical Report CENG-2006-14, 2006.