Adaptive Contention Window Design to Minimize Synchronous Collisions in 802.11p Networks

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Abstract. The vehicular ad hoc network (VANET) capable of wireless communication will enhance traffic safety and efficiency. The IEEE 802.11p standards for wireless communication in the US and Europe use a single shared channel for the periodic broadcast of safety messages. Coupled with the short contention window and inflexibility in window size adaptation, the synchronous collisions of periodic messages are inevitable in a large scale intelligent transportation system (ITS). To this end, we propose an adaptive contention window design to reduce synchronous collisions of periodic messages. The proposed design replaces the aggressive window selection behaviour in the post transmit phase of IEEE 802.11p with a weighted window selection approach after a successful transmission. The design relies on the local channel state information to vary contention window size. Moreover, in high density networks, the design gives prioritized channel access to vehicles experiencing dropped beacons. The proposed design can be readily incorporated into the IEEE 802.11p standard. The discrete-event simulations show that synchronous collisions can be reduced significantly to achieve higher message reception rates as compared to the IEEE 802.11p standard.

Keywords: VANET · Synchronous collisions · ITS · 802.11p · Congestion control · Media access control · Contention window · Adaptive contention window

1 Introduction

The research in Vehicular Ad hoc Network (VANET) has received much interest due to its potential to provide drivers not only with safety specific data but with information useful for traffic efficiency and passenger comfort [1–3]. The key concept of transmitting such information is the use of wireless communication technology based on IEEE 802.11p standard [4,5]. The transmission of safety information messages (i.e. beacons) is frequent and valid for a limited time period. It implies that the Medium Access Control (MAC) layer specification in IEEE 802.11p has to fulfill specific requirements for efficient operation of Intelligent Transportation System (ITS).

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Due to high frequency of beacons, one crucial requirement is to efficiently utilize the limited available wireless spectrum for reliable beacon delivery. In high density vehicular networks, the amount of periodic beacons increase. As a result, efficient operation of ITS suffers due to synchronous beacon collisions. The actual reason for synchronous collisions is the unscheduled channel access mechanism in the IEEE 802.11p [6,7]. In an ad hoc communication setting such as VANETs, the harmonized channel access becomes difficult due to the limited size of the contention window and the aggressive binary exponential back-off (BEB) mechanism. Note that, synchronous beacon collisions can be reduced by reducing the message transmission frequency. However, most of the safety applications have strict frequency requirements [8], therefore, reducing message frequency is not useful for safety applications [9].

It follows that the size of contention window for shared channel access mechanism in IEEE 802.11p must be properly adapted in order to bring time diversity in beacon transmissions by multiple vehicles. We argue that the contention window size adaptation should be based on the underlying channel conditions, given the variation of vehicular density. Moreover, the design should not incur transmission delays due to the increase in the contention window size.

Clearly, the objective of this paper is to provide reliable beacon transmission by minimizing synchronous beacon collisions. In this paper, we propose modifications at the IEEE 802.11p MAC layer that can potentially minimize beacon collisions to improve reliability. A weighted contention window selection is proposed, which replaces the standard BEB in the post transmit phase by using the local channel states. In high density networks, the design also gives prioritized channel access to vehicles experiencing dropped beacons.

The rest of the paper is organized in sections: In Sect. 2, we give necessary background on the IEEE 802.11p standard and presents some observations that lead to the design of the proposed approach. Section 3 describes the proposed weighted contention window adaptation, its behaviour and the algorithm. The evaluation is given in Sect. 3.2. Finally, Sect. 5 concludes the paper.

2 Background

This section gives necessary background on beaconing using the IEEE WAVE networks followed by the transmit power control approaches in the literature.

2.1 The IEEE 802.11p Standard

The IEEE WAVE is a family of standards including, among others: IEEE 1609.1-4 and IEEE 802.11p. The IEEE 802.11p allocates 10 MHz channels each for the Control Channel (CCH) and the Service Channels (SCH) in a 5.9 GHz band for safety and non-safety messages simultaneously. The WAVE devices, i.e. the On-Board Units (OBUs) and the Road Side Units (RSUs), can use both these channel alternatively by switching their radios to a channel defined by the IEEE 1609.4 standard [10]. The time duration to tune a radio to a particular channel is usually set at 50 ms. The CCH is reserved for the safety messages/beacons and it is used simultaneously by all the WAVE-enabled devices. Accordingly, the IEEE 1609.4 standard includes separate functions for different types of messages to be transmitted on the CCH and the SCH.

The most important of these functions is related to the shared channel access mechanism for transmission of beacons on the CCH as shown in Fig. 1. Every transmission is preceded by sensing the CCH. If the CCH is sensed as busy, the transmission is deferred. Otherwise, each transmitting vehicle observes different waiting times before transmission in order to minimize the chances of colliding with other vehicles. The Distributed Inter-frame Space (DIFS) is a time interval, which is observed before attempting to transmit on the CCH. On the other hand, Short Inter-frame Space (SIFS) is representative of a collective time, which includes the time to process a received as well as a response beacon. The beacons are immediately transmitted if the medium is found idle for DIFS duration. If not, the transmitting vehicles select back-off slots from the contention window. Usually, each back-off represents a 13 μs slot and it is selected with a uniform random probability from the current contention window. With the passage of every 13 μs, the back-off decrements by one. When the back-off hits 0, the transmitting vehicle transmits the beacon. If the channel is found busy, then according to Binary Exponential Back-off (BEB) the contention window size is doubled for the next back-off slot selection. Obviously, the probability of synchronous collisions is defined by the size of the contention window.

In the following section, we present some observations about the synchronous collisions in light of the MAC channel access mechanism in IEEE 802.11p standard.

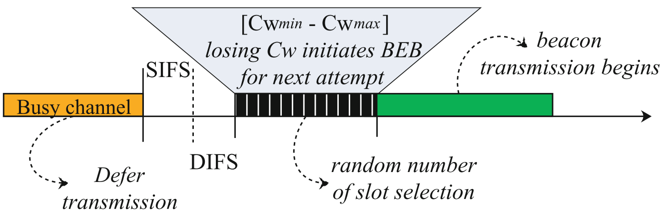

Fig. 1. The mechanism for shared channel access in IEEE 802.11p including the use of contention window and the binary exponential backoff.

2.2 Observations About Synchronous Collisions

Periodic beacons are transmitted using the access category VI as shown in Table 1, which is based on the 802.11e standard [11]. This access category provides a class of service, which has a minimum contention window size of 8 with $cw_{min} = 7$ and $cw_{max} = 15$. The reason for having a small cw_{min} is to transmit beacons before they expire in order to achieve high mutual awareness. Note that, the binary exponential back-off increases the window size upon deferred transmissions and reduces it to the minimum upon a successful transmission. It implies that after a successful transmission, the cw_{min} provides a collision free domain for only 8 vehicles, which causes a high number of synchronous collisions at the start of CCH.

It is also worth mentioning that the BEB was designed to improve the reliability of retransmissions in case of collisions. However, retransmission of beacons in VANETs is not useful due to (1) absence of acknowledgments, and (2) difficulty in judging beacon collisions, which are inherently broadcast in nature. Based on this context, the following observations must be incorporated in the proposed contention window adaptation design to reduce beacon collisions.

Table 1. Contention window sizes defined by the enhanced distributed channel access.

Access category	$cwin_{min}$	$cwin_{max}$
Background	15	1023
Best-effort (AC_{BE})	15	1023
Video (AC_{VI})	7	15
Voice (AC_{VO})	3	7
Legacy DCF	15	1023

Less Aggressive BEB. In IEEE 802.11p, a high-level perspective of a transmission success or failure is indicative of the channel state, that is, a deferred transmission indicates a saturated channel and a subsequent successful transmission indicates a free channel. In VANETs high channel saturation occurs in dense networks and the saturation is likely to persist as long as the vehicle remains a part of the dense network. Therefore, it is safe to say that the channel states are although highly variable in VANETs (defined by the vehicular density), but the change in channel states is not abrupt, as depicted by the aggressive BEB in IEEE 802.11p. Therefore, assuming a constant message frequency, we argue that a contention window adaptation must be less aggressive (i.e. especially after the successful transmission) and adaptive towards channel states, in order to minimize synchronous collisions and to enhance reliable delivery of messages.

Beacon Drops at Source. Another observation originates from the effects of contention window size on the short temporal validity of beacons. That is, the increase in contention window beyond a certain limit increases the probability of dropped beacons at the source, and hence increasing the update delays at the receiver. Also, the exact maximum window size for beaconing is difficult to determine, because contention window adaptation depends upon several dynamic and uncontrollable parameters such as transmission frequency, vehicular density, messages in the queue and channel conditions to name but a few. This notion is significant in adapting the size of contention window up to an extent, which does not affect dropped beacons.

3 The Weighted Contention Window Adaptation Design

Clearly, the weighted contention window adaptation introduces a less aggressive post transmit contention window selection approach by making use of the local information while making sure that increase in the window size does not affect dropped beacons at the source.

To ensure that window adaptation is indicative of the evolving channel conditions (i.e. deteriorating or improving over time) and the contention window adaptation is not aggressive during the post-transmission stage, the design employs two main strategies: (a) a channel congestion state metric to predict the evolving channel condition, and (b) a weighted selection of a suitable post-transmission contention window size for the next beacon.

We use the channel busy time *cbt* at the physical layer to capture the evolving state of the CCH. According to *cbt*, the channel is considered busy if the received signal strength is above a certain threshold (i.e. a signal received or collision detected). We record *cbt* for the previous synchronization intervals (synch-I) i.e. for 10 Hz message frequency, we use 5 synch-intervals. Moreover, the *cbt* for each synch-I is weighted such that the most recent *cbt* is weighted higher than the older ones, as follows.

$$cbt(t) = w_1(cbt)_i + w_2(cbt)_{i+1} + ... + w_n(cbt)_{i+(n-1)} \tag{1}$$

In order to map the $cbt(t)$ into meaningful weights for the contention window size selection, we introduce a middle contention window size (cw_{mid}) besides the default (cw_{min}) and (cw_{max}) such that $(cw_{min}) < (cw_{mid}) < (cw_{max})$. Then for every successful beacon transmission, the $cbt(t)$ is mapped to a selection probability associated with a contention window size in the post transmit phase as follows:

$$P_{cwin(mid)} = \mid 1 - [\sigma_t * \tau] \mid \tag{2}$$

$$P_{cwin(min)} = 1 - [P_{cwin(mid)}] \tag{3}$$

The $P_{cwin(mid)}$ and $P_{cwin(min)}$ are the probabilities of selecting the middle size contention window and the minimum windows for some value of $cbt(t)$. The σ_t is the inverse of $cbt(t)$ and τ is the threshold of the $cbt(t)$ beyond which weighted contention window selection is considered applicable. As the $cbt(t)$ increases beyond a threshold, the probability of selecting back-off from $cwin_{mid}$ for the next beacon increases. The default IEEE 802.11p BEB is used as long as the channel conditions remain suitable for transmission. That is, upon a successful transmission, the minimum contention window is selected. Moreover, the dropped beacon at the source also forces the proposed approach to select the minimum contention window.

$$cwin_{post-tx} = \begin{cases} cbt > \tau, cwin(mid) \\ cbt < \tau | beacondropped, cwin(min) \end{cases} \tag{4}$$

The following section further illustrates the behaviour of the proposed approach.

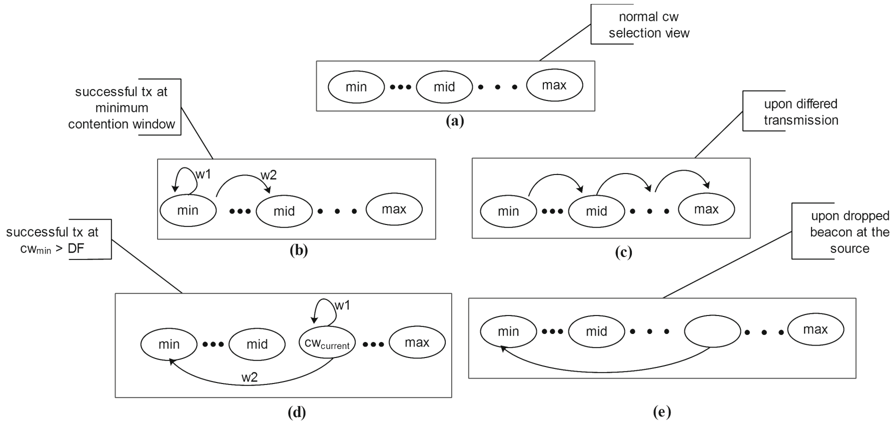

Fig. 2. Behaviour of contention window adaptation during different phases of beacon transmission

3.1 Behaviour at a Microscopic Level

The Fig. 2 illustrates the weighted contention window adaptation mechanism at the MAC layer during different possible stages of beacon transmission: (a) shows the view of the normal contention window with the minimum and maximum window size as defined in IEEE 802.11p standard and the middle contention window size as set by the proposed approach, (b) shows the probability of selecting the minimum window or the middle size upon successful transmission at $cwin_{min}$, defined by the weights $w1$, and $w2$ respectively, (c) shows the increase in window size by $2 * cwin_{current}$ upon a deferred transmission (the increase in window size is similar to the IEEE 802.11p standard), (d) in case of successful transmission at a contention window size, which is higher than the $cwin_{mid}$, the $cwin_{mid}$ is reset to the current window size and then the weights $w1$ and $w2$ are applicable as in Fig. 2(a), finally in (e) upon dropped beacon at the source, the window size is set to the minimum window size with the probability 1.

Note that, the selection of back-off from $cwin(mid)$ for a subsequent beacon after successful transmission has implications on dropped beacons at the source. That is, continuous transmissions at a higher contention window may result in longer waiting times in the queue and, as a result, dropped beacons before transmission. Under such conditions, as soon as a vehicle detects a dropped beacon, the back-off is immediately initialized to $cwin_{min}$ to reconcile for the delay incurred due to the loss of the dropped beacon.

For the sake of logical argument and to highlight the usefulness of the proposed approach, we consider the following example:

Without loss of generality, let's assume that two vehicle v_i and v_j have similar values for cbt, then the probability of simultaneous transmission by selecting same back-off is given by $P(v_i = v_j)$. Where $v_i = s$ for $s \in [all\ slots\ in\ cw_{min} \bigwedge cw_{mid}]$ containing initial and maximum contention windows sizes of c_{min} and c_{mid} respectively, then selecting s_i and s_j by v_i and v_j respectively are independent events. So, we have Eq. 5.

$$P(v_i = v_j) = \sum_{x=c_{def}}^{c_{mid}} P(v_i = s \mid v_j = s) \tag{5}$$

Since, $P(v_i = s) = P(v_j = s)$ for every slot in the contention window, therefore it is sufficient to calculate the $P(v_i = s)$. Hence, for $s \in [cw_{min} : cw_{mid}]$, we have the law of total probability:

$$P(v_i = s) = P(v_i = s \mid cw_{min}).P(cw_{min}) + P(v_i = s \mid cw_{min})$$
$$.P(cw_{mid}) = \begin{cases} \frac{1}{|cw_{min}|}.w_{cw_{mid}} + \frac{1}{|cw_{mid}|}.w_{def}, & s \in cw_{min} \\ 0.w_{cw_{mid}} + \frac{1}{|cw_{mid}|}.cw_{mid}, & s > cw_{min} \end{cases} \tag{6}$$

Thus, the probability of synchronous collision due to same back-off selection between two vehicles $P(v_i = v_j)$ with same $cwin_{min}$ and $cwin_{mid}$, is given by:

$$P(v_i = s) = \sum_x P(v_i = x, v_j = x) = \sum_a P(v_i = x)^2 \tag{7}$$

The benefit offered by the weighted contention window selection is the probabilistic post-transmission selection of $cwin_{min}$, which is a less aggressive approach and minimizes collisions at the start of CCH. In addition, vehicles experiencing high slot utilization can also select back-off from $cwin_{min}$ with certain reduced probability. It means that high slot utilization does not always allocate a large window size and presents an opportunity for vehicles to transmit using small window size. In addition, to avoid vehicles from continuous transmissions using a higher window size, the proposed approach uses a dropped beacon as an indication for very long waiting times at the source. Therefore, to provide prioritized channel access to account for the dropped beacon, the window size is initialized to $cwin_{min}$ for the next beacon transmission.

3.2 Algorithm: Contention Window Adaptation

The algorithm for contention window adaptation is given in Algorithm 1. The inputs to this algorithm are the beacons from the application layer, transmission status and the value of *cbt*. The algorithm gives the probabilities for selecting a contention window size upon each transmission attempt ($cwin_{(post-tx)}$). Initially, the algorithm demarcates the contention window sizes i.e. $cwin_{min}$, $cwin_{mid}$ and $cwin_{max}$ in line 1. Then the back-off for all beacons arriving from the application layer is selected using the function Backoff() at line 3. The arguments of this function are $P_{(cwin(mid)}$ and $P_{(cwin(min))}$, which specify the probability of selecting a post transmit back-off from $cwin_{mid}$ and from $cwin_{min}$, respectively. The line 5 through line 7 records the *cbt* during the back-off interval and in line 8 the beacon is transmitted. The algorithm from line 11 through line 25 is significant in order to record the transmission status and to convert the slot utilization into

Algorithm 1. Contention Window Adaptation
inputs: *beacons*, *transmission status*, $cbt(t)$
outputs: $cwin_{post-tx}$

1: set $(cwin_{mid}) \mid (cwin_{min}) < (cwin_{mid}) < (cwin_{max})$
2: **for** beacons from above **do**
3:     **procedure** BACKOFF $(P_{cwin(mid)}, P_{cwin(min)})$
4:         pick $backoff \leftarrow [cwin_{min} - cwin_{mid}]$
5:         **while** $backoff$ **do**
6:             record $cbt(t) \leftarrow equation\ 1$
7:         **end while**
8:         transmit
9:     **end procedure**
10: **end for**
11: **if** $(cwin_{current} > cwin_{mid})$ **then**
12:     $cwin_{mid} = cwin_{current}$
13: **end if**
14: **switch** *transmit status* **do**
15:     **case** *transmitted*
16:         calculate $cwin_{post-tx} \leftarrow equation\ 4$
17:         call Backoff()
18:     **case** $deferred$
19:         set $cwin_{current} \leftarrow ((cwin_{current}(v_i) + 1) * 2) - 1$
20:         calculate $cwin_{post-tx} \leftarrow equation\ 4$
21:         call Backof()
22:     **case** *Dropped*
23:         set $P_{cwin(min)} = 1$
24:         $P_{cwin(mid)} = 0$
25:         call Backoff()

meaningful weights that can be used to determine the contention window size for the next beacon transmission. First of all at line 11, the current contention window size is checked and if it is greater than the $cwin_{mid}$, then the $cwin_{mid}$ is reset to $cwin_{current}$, otherwise, the contention window size demarcation remains the same as in line 1. The transmission at line 8 may result in a successful transmission, a deferred transmission or a dropped beacon during the back-off. As such for a successful transmission, the $cwin_{(post-tx)}$ is calculated using Eq. 4. For deferred transmission, the contention window is increased as specified in IEEE 802.11p and then $cwin_{(post-tx)}$ is calculated. In either case, the calculated values for $P_{(cwin(min)}$ and $P_{(cwin(mid)}$ are used to call the Backoff() function at line 17 and line 21. Finally, if the beacon is dropped during the back-off, the value of $P_{(cwin(min))}$ is set to 1 and $P_{(cwin(min))}$ is set to 0. It indicates that for the next beacon transmission the back-off at line 4, will be selected from the $cwin_{min}$. This shows the prioritized channel access mechanism to make up for the previous dropped beacon.

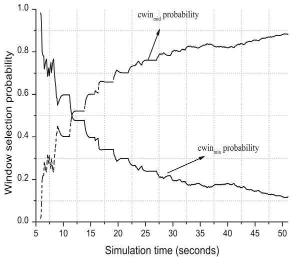

Fig. 3. Run-time selection probability of minimum contention window w.r.t CBT for the first few seconds of simulation

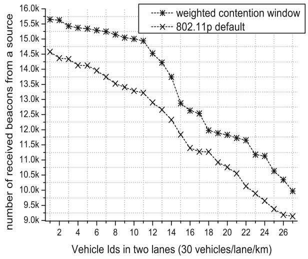

Fig. 4. Awareness quality measured as the number of received beacons in 50 veh/lane/km scenario

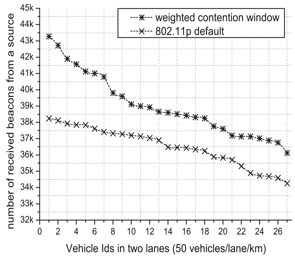

Fig. 5. Awareness quality measured as the number of received beacons in 30 veh/lane/km scenario

This concludes the specification of the weighted contention window adaptation approach which aims to reduce overall synchronous collisions in the network. In the next section, we evaluate the proposed approach.

4 Evaluation of Contention Window Adaptation

This section evaluates the weighted contention window approach proposed in this paper. First, we verify the correct functioning of the proposed design followed by a comparison with the de facto standard i.e. IEEE 802.11p.

The Veins framework – version 2.1, OMNeT++ – version 4.2.2 and sumo – version 0.17.0 is used for evaluation. The WAVE application layer is configured to generate beacons at 10 Hz. The MAC layer is responsible for acquiring channel states from the physical layer. The simulation scenario consists of the 1 Km 2 way and 4 way highways with varying number of vehicular densities freeway speeds.

4.1 Results

As aforementioned, when a vehicle transmits a beacon, the proposed approach monitors the channel states in order to associate a meaningful weight for contention window size selection. Therefore, the implementation of weighted contention window requires modifications at the MAC layer during the post transmit phase.

The logic behind weighted contention window is to associate probabilities with minimum and middle contention window sizes with respect to the increasing channel saturation. Therefore, it is important to verify this behaviour for vehicles in a simulated scenario. We configure a two lane highway which is heavily populated with vehicles that transmit beacons at a high frequency. In Fig. 3, for increasing vehicular densities, we record the window selection probabilities for minimum and middle window sizes in the post transmit phase. It could be observed that as the channel becomes saturated (here increase in time is representative of the increasing number of vehicles or otherwise more congestion), the probability of middle contention window approaches to 1. Accordingly, the with the exact same proportions, the minimum window selection probability approaches to 0. This behaviour verifies the evolution of weights for window sizes according to the design.

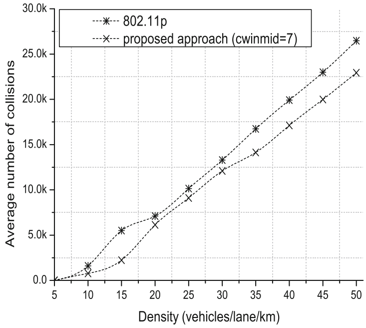

Fig. 6. Comparison of average number of collisions for varying levels of vehicular densities and window sizes with $cwin_{mid}$ set at 7

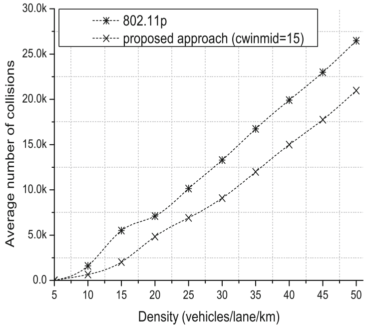

Fig. 7. Comparison of average number of collisions for varying levels of vehicular densities and window sizes with $cwin_{mid}$ set at 15

One way of measuring awareness is to measure the number of received beacons in a network. Clearly, high message reception means a high level of awareness of the local topology. In Figs. 4 and 5, the number of received beacons from a source vehicle is recorded on different vehicles. The receiving vehicles are arranged on x-axis with respect to their increasing distances from the source. By controlling the synchronous collisions, the awareness quality in terms of the proposed approach increases as compared with the IEEE 802.11p.

High message reception is achieved due to the less aggressive behaviour in selecting the $cwin_{min}$ and larger window sizes in the post transmit phase. The Figs. 6 and 7 shows the average number of collisions. Observe that, significantly fewer collisions are recorded for the proposed approach as compared with the IEEE 802.11p. Besides, for higher values of $cwin_{mid}$, the collisions are further reduced.

In a highway scenario of 50 vehicles/lane/km in a two lane road, we show the performance of the proposed approach using overall throughput. In Fig. 8, the results are compared with the standard IEEE 802.11p. It can be observed that initially for few seconds the throughput values remain similar. This is because initially the network has limited vehicles and the probability of selecting the minimum contention window remains very high. However, as the number of vehicles increase, the proposed approach starts to select $cwin_{mid}$ in the post-transmit phase for new beacons. Therefore, as a result of reduced collisions, a higher throughput can be observed.

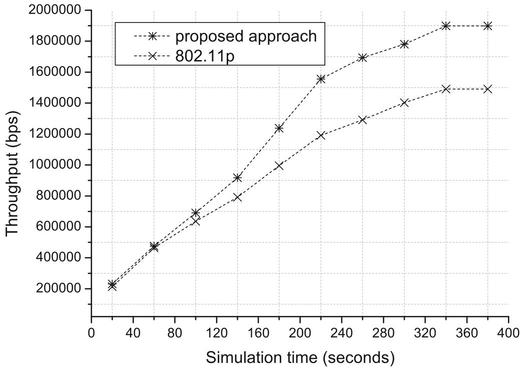

Fig. 8. Comparison of throughput variation of the proposed approach with the standard 802.11p

5 Conclusion

The stipulated amendments in the WAVE offer little relief to the problem of synchronous collisions. In this paper, we identified the limitations of the contention window size and the aggressive BEB as main reasons for synchronous collisions. The proposed contention window adaptation approach is proposed, which translates the channel busy times into meaningful weights for selecting the window size in the post transmit phase. After a successful transmission, the default aggressive behaviour of BEB is replaced such that a higher probability of selecting the minimum window is applicable in situations of less channel saturation and vice verse. Moreover, the window adaptation design also makes provisions for prioritized channel access to vehicles experiencing dropped beacons. The simulation results clearly demonstrates reliable beacon transmission as compared to the IEEE 802.11p standard.

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