# A Comprehensive Analysis of Beacon Dissemination in Vehicular Networks

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***Abstract*—In many active safety applications, each vehicle must periodically disseminate a beacon message including the status information, such as position, speed, steering, etc., so that a neighbor vehicle can better perceive and predict the kinematics of the vehicle. However, a simple broadcasting of beacon message may lead to a low message reception as well as an excessive delay. To resolve this problem, we consider the application, the channel and inter-vehicle distance requirements in a highway scenario of vehicular networks. Based on these requirements, we analyze the impact of the following three key parameters of the beacon dissemination on the performance of vehicular networks: *beacon period*, *beacon transmit power*, and *contention window (CW) size*. We first derive a beacon period which is inversely proportional to the vehicle speed. Next, we mathematically formulate the maximum beacon load to demonstrate the necessity of the transmit power control. We finally present an approximate closed-form solution of the optimal CW size that leads to the maximum throughput of beacon messages in vehicular networks.**

## I. Introduction

Vehicular networks have been considered as the key technology of a *cooperative driving safety applications* that can significantly reduce a huge amount of economical and social loss originating from road accidents. With these applications, a driver becomes aware of road incidents in advance by virtue of *multi-hop delivery* of the information about road environments.

Vehicular safety applications run on the basis of message dissemination among nearby vehicles, either a safety message or a beacon message. A vehicle broadcasts a safety message to help other vehicles to avoid dangerous situation beforehand. On the other hand, a beacon message is periodically disseminated to neighbor vehicles in order to announce the status information, e.g. position, speed, heading, etc [4], [5]. This information is essential for neighbor vehicles to predict the traffic situation. However, a frequent beacon dissemination may significantly degrade the performance of a highly dense vehicular network. In such a situation, network may suffer from an excessive loss due to many frame collisions.

To alleviate this problem, the previous works have studied the key parameters of the beacon dissemination that affects the performance of vehicular networks [6]–[10]: *beacon period*, *beacon transmit power*, and *contention window (CW) size*. In [6], the authors present localization algorithms to exchange a beacon message so that the position prediction of a neighbor vehicle does not exceed a predefined threshold. In [7], Torrent-Moreno et al. propose a fair transmit power control algorithm not to exceed a predefined load of beacon message. In [8], the authors present some simulation results that demonstrate the needs of CW size adjustment depending on the vehicle density. However, all of the above works take into account only one parameter of beacon dissemination, so their approaches may achieve a locally optimal performance. On the other hand, the authors in [9], [10] consider both the beacon period and the beacon transmit power. In [9], they decide the beacon period on the basis of position estimate error of neighbor vehicles, while in [10] they focus on the efficiency of beacon message in the sense that the number of nodes receiving a beacon message should be maximized. However, as far as we are aware of, there is no work that considers the impacts of all three parameters on the performance of vehicular networks.

In this paper, we attempt to present a comprehensive analysis that accounts for the impacts of these parameters on the performance of vehicular networks. We first determine the beacon period $T_{BP}$ in which the position error of a neighbor vehicle does not exceed a predefined constant value, $D_{th}$. From this application requirement, we show that the beacon period is inversely proportional to the speed of vehicle $v$. We next derive the upper bound of vehicle density $\overline{\rho}$ based on the fact that the inter-vehicle distance should be at least a certain distance $D_{IV}$ which accounts for recognizing and decelerating against a exceptional situation. Then, we derive a mathematical formulation that determines the carrier-sensing range $D^*_{CS}$ of the beacon message so that the channel load of beacon message should not exceed a predefined threshold value $C_{b,\max}$. We finally present an approximate closed-form solution of the optimal CW size $W^*_{opt}$ that leads to the maximum throughput of the beacon message.

The rest of this paper is organized as follows. In section II, we define a network model and three requirements of beacon dissemination. Next, we present a comprehensive analysis that determines the three key parameters of beacon dissemination in section III. We finally conclude this paper in section IV.

## II. Preliminaries

In this section, we will describe the vehicular network model and three requirements imposed on the beacon dissemination in vehicular networks.

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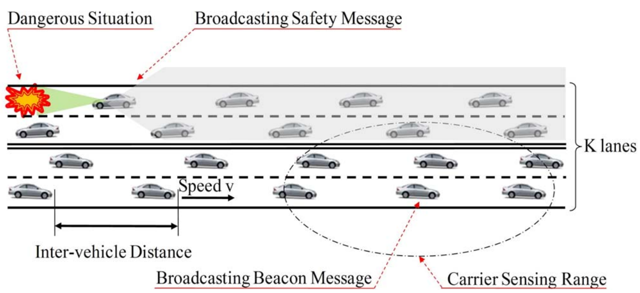


Fig. 1. An example of vehicular networks

### A. Network Model and Notations

Fig. 1 illustrates an example of vehicular networks in $K$-lane highway. There are two streams of vehicle traffic moving in the opposite directions, each of which drives at an average speed of $v$ along $\frac{K}{2}$ lanes. In this paper, we focus on the analytical aspects of beacon dissemination in the carrier-sensing range (CSR) of a vehicle. The CSR is the distance to which a vehicle's transmission can be detected; thus, a vehicle within this range is not allowed to access the channel in order to avoid the interference. For the analytical simplicity, we make an assumption that there is no hidden-node problem in the network. A vehicular network is designed to support active safety applications, such as cooperative adaptive cruise control (CACC), or emergency electronic brake light (EEBL) [1]. To achieve this challenging goal, a vehicle is assumed to exchange two kind of messages in a DSRC channel at 5.9 GHz [3]: a *beacon* message and a *safety* message. A beacon message is a *periodic* message conveying the kinematics information of a vehicle so that its nearby vehicles can trace the movement of the vehicle [3], [5]. Here, we denote by $L$ and $R$, the length and the data rate of a beacon message, respectively. On the other hand, a safety message is an *event-driven* message to alert rear-end vehicles to foresee a road incident, such as an icy road, a vehicle collision, etc. To attain a prompt dissemination of this information, it is evident that the safety message must be delivered with the highest priority in vehicular networks.

### B. Requirements of Vehicular Networks

In this paper, we impose three requirements on the beacon dissemination in vehicular networks. First, the beacon message should be frequently disseminated so that an active safety application of a nearby vehicle can successfully trace the kinematics of this vehicle, which is referred to as the *application requirement*. Second, the communication load of the beacon message at a DSRC channel should be less than a threshold value $C_{b,\max}$ so that a safety message can be timely delivered to the vehicles in the geographic area of concern, which is called the *channel requirement*. Finally, a driver maintains at least a distance from its head-end vehicle so that it can avoid a head-end collision, which is called the *inter-vehicle distance requirement*. We will address the details of each requirement in the remainder of this section.

*1) Application Requirements:* A beacon message is disseminated to neighbor vehicles so that they can update the kinematics of the vehicle. In the literature, there are two approaches to the period of beacon message, either *fixed* or *adaptive*. In the fixed scheme, each vehicle has to disseminate this information once a fixed time interval, e.g., every 0.1 sec [4], [5]. Unfortunately, this frequent beacon dissemination may dominate the capacity of wireless channel in case of road traffic congestion. On the other hand, in an adaptive scheme, a vehicle has an position estimator for itself as well as its neighbor vehicles; a vehicle disseminates a new beacon message once the difference between the real position and its estimate exceeds a given threshold [6], [9]. However, each vehicle should maintain a dedicated position estimator to each neighbor vehicle, which may result in a significant processing overhead in dense vehicular networks.

Contrary to the above approaches, we consider the *uncertainty* of GPS samples in application requirements. It is widely known that the root-mean square (RMS) error of a GPS sample, denoted by $D_{th}$, ranges around 10 m [11]. In other words, if multiple samples are obtained within $D_{th}$, it would be very hard to predict the movement of a vehicle due to the uncertainty of GPS samples. Therefore, in this paper, we assume that each vehicle disseminates its beacon message once it drives at least the RMS error of GPS samples $D_{th}$. The final remark on the exceptional case is that a beacon period of a *stopped vehicle* should be less than a certain value so that approaching vehicles can receive multiple beacon messages before they arrive at the position of the stopped vehicle.

*2) Channel Requirements:* As we stated before, a safety message should be disseminated to as many vehicles in the destined geographical area as possible. However, it is likely that the beacon load $C_b$ may dominate the capacity of a DSRC channel $C$ in dense vehicular networks ($C_b \approx C$). In this situation, a safety message experiences a significant performance degradation, i.e. increasing both frame loss rate and latency, due to frame collisions. To avoid this undesirable situation, the load of beacon message should be restricted to a fraction of the DSRC channel capacity, denoted by $\alpha$, i.e.,

$$C_b \;\leq\; C_{b,\max} = \alpha C, \qquad 0 \leq \alpha \leq 1. \tag{1}$$

To meet this requirement, we will present a mathematical formulation for the feasible value of the CSR in section III-B3.

*3) Inter-vehicle Distance Requirements:* The last requirement imposed on vehicular networks is originated from driving behaviors. That is, a driver usually keeps *at least* a distance from the head-end vehicle, which is referred to as the inter-vehicle distance (IVD) $D_{IV}$. The IVD is a function of vehicle speed $v$, and accounts for the displacement of a vehicle during the time of perception, reaction, and deceleration against road incidents. Then, the IVD is contributed by 1) vehicle length $D_v$; 2) the distance during perception-reaction time $D_r$; and 3) the distance during braking-deceleration time $D_b$, i.e.,

$$D_{IV} = D_v + D_r + D_b = D_v + \tau_r v + \frac{v^2}{2a_b}, \tag{2}$$

where $\tau_r$ is the perception-reaction time and $a_b$ is the peak deceleration rate. Based on the IVD requirement, we will derive the upper bound of vehicle density in section III-B1.

## III. Analysis of Beacon Dissemination

Given a network model with three requirements, in this section, we attempt to present a comprehensive analysis that provides a guideline for setting the three key parameters of beacon dissemination in vehicular networks: beacon period, beacon transmit power, and CW size. In addition, we examine the impacts of these parameters on the performance of vehicular networks.

### A. Beacon Period

As we stated in section II-B1, it is very important to determine the period of beacon message so that it can satisfy the application requirements while it does not incur the congestion problem. To meet this challenging goal, each vehicle is supposed to broadcast a beacon message, once its displacement from the last point of beacon transmission exceeds the RMS value of GPS samples $D_{th}$. Then, beacon period $T_{BP}$ of a vehicle at speed $v$ can be represented by

$$T_{BP} \quad = \quad \frac{D_{th}}{v}. \tag{3}$$

### B. Beacon Transmit Power

In this section, we first derive the upper bound of vehicle density from the IVD requirement. Based on this result, we examine the upper bound of the beacon load. We finally present a mathematical formulation for the CSR $D_{CS}$ to meet the channel requirement.

*1) Upper Bound of Vehicle Density:* The vehicle density is defined as the number of vehicles per unit length of a lane. As we stated in section II-B3, the IVD is the smallest distance between two consecutive vehicles at the same lane of a road. Then, it is clear that the upper bound of vehicle density $\overline{\rho}$ at speed $v$ is inversely proportional to the IVD, i.e.,

$$\overline{\rho} = \frac{1}{D_{IV}} = \frac{1}{D_v + \tau_r v + \frac{v^2}{2a_b}}. \tag{4}$$

In (4), we can observe that the upper bound of vehicle density decreases with the increase of vehicle speed, which matches with our daily experiences.

*2) Upper Bound of Beacon Load:* In this section, we focus on the beacon load in the CSR of a vehicle. Recall that each vehicle in this area broadcasts its own beacon message with period in (3). Thus, the beacon load of a vehicle can be represented by $L/T_{BP}$. From (4), we infer that the number of vehicles in the CSR is less than or equal to $2D_{CS}K\overline{\rho}$. Therefore, we can obtain the upper bound of beacon load $\overline{C_b}$ by multiplying these two values, i.e.,

$$\overline{C_b} \;=\; 2D_{CS}K\overline{\rho}\frac{L}{T_{BP}} \;=\; \frac{2D_{CS}KLv}{D_{IV}D_{th}}. \tag{5}$$

In (5), the upper bound of beacon load $\overline{C_b}$ is a function of CSR $D_{CS}$ and vehicle speed $v$.

From (1), the upper bound of beacon load should be less than or equal to the threshold beacon load, i.e., $\overline{C_b} \leq C_{b,\max}$.

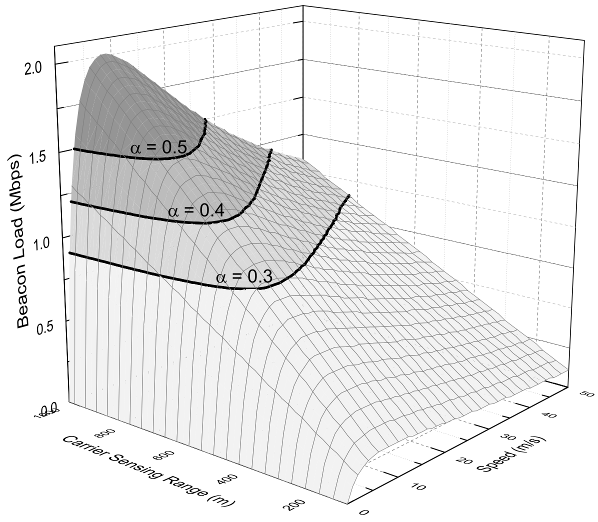


Fig. 2. The upper bound of beacon load $\overline{C_b}$ vs. CSR and vehicle speed.

Fig. 2 shows the upper bound of beacon load against vehicle speed and CSR with different $\alpha$ values, when $R = 3$ Mbps, $\tau_r = 1.5$ sec, $a_b = 7.5\ m/\sec^2$, $D_{th} = 12$ m, $L = 500$ bytes, and $K = 8$. We can observe that the upper bound of beacon load exceeds the threshold beacon load for all $\alpha$ values in the figure. This result demonstrates the necessity of reducing the beacon load to ensure fast and reliable delivery of safety messages. One possible solution is to adjust beacon transmit power to decrease the CSR $D_{CS}$, because the upper bound of beacon load is proportional to CSR in (5). We can also observe that, for a given CSR value, the upper bound of beacon load becomes a *concave* function of vehicle speed $v$ . This is also confirmed by substituting (4) into (5). By differentiating (5) with respect to $v$, we can obtain the vehicle speed $v^*_{peak}$ that maximizes the upper bound of beacon load $\overline{C_b}$, as follows:

$$v^*_{peak} \quad = \quad \sqrt{2a_b D_v}. \tag{6}$$

In (6), the speed $v^*_{peak}$ is independent of the CSR value $D_{CS}$, which can also be found in Fig. 2.

*3) Transmit Power Control:* In the literature, there are two key parameters used to control the beacon load in vehicular networks: the beacon period and the beacon transmit power [6]–[10]. Since an increase of beacon period results in the violation of the application requirement, we focus on the adjustment of the beacon transmit power to control CSR. Here, we make an additional assumption that the CSR monotonically increases with the beacon transmit power; thus, there is one-to-one correspondence between them. Then, the goal of this section is to find the maximum CSR value $D^*_{CS}$ that the beacon load does not exceed the threshold $C_{b,\max}$.

The maximum CSR $D_{CS,ch}$ to meet the channel requirement (CSR-CR) can be obtained by combining (1) with (5),

$$D_{CS,ch} \;=\; \frac{\alpha C D_{th} D_{IV}}{2LKv} \;=\; \frac{\alpha C D_{th}(D_v + \tau_r v + \frac{v^2}{2a_b})}{2LKv}. \tag{7}$$

In (7), we can see that the CSR-CR increases with the vehicle speed $v$. For the scenario with very high vehicle speed, the

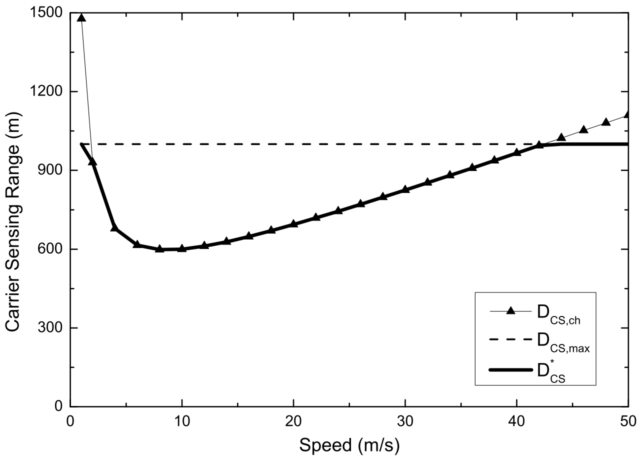


Fig. 3. The maximum CSR vs. vehicle speed $v$ when $D_{CS,\max} = 1$ Km.

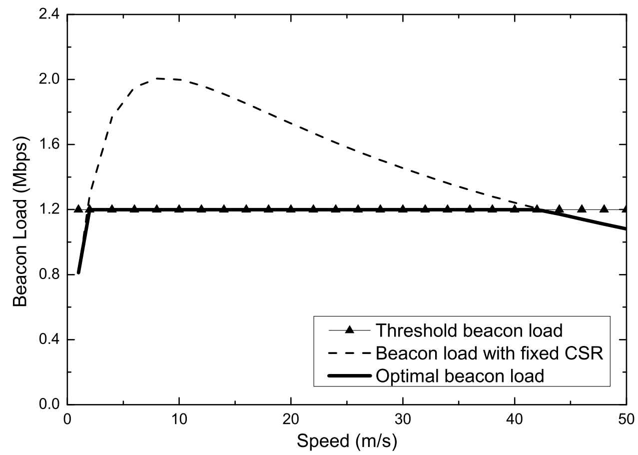


Fig. 4. The beacon load vs. vehicle speed

CSR-CR may exceed the CSR $D_{CS,\max}$ that can be obtained from the maximum STA transmit power in the IEEE 802.11p [3]. To avoid this exceptional case, we provide a safeguard to the maximum CSR value $D^*_{CS}$, as follows:

$$D^*_{CS} = \min\left(D_{CS,ch}, D_{CS,\max}\right). \tag{8}$$

Fig. 3 shows the maximum CSR values against vehicle speed when $D_{CS,\max} = 1$ Km. In the figure, a dashed line represents the CSR $D_{CS,\max}$ from the IEEE 802.11p; a solid line with a mark indicates the CSR-CR $D_{CS,ch}$; a thick solid line represents the maximum CSR value $D^*_{CS}$. We can observe that the CSR-CR is the limiting factor of the maximum CSR value for almost all practical values of vehicle speeds ($v \leq 40$ m/sec). This result demonstrates the needs for the adjustment of the beacon transmit power.

Fig. 4 shows the upper bound of beacon load against vehicle speed when $\alpha = 0.4$. Here, the dashed line indicates the upper bound of beacon load with fixed CSR ($D_{CS} = 1$ Km); a solid line with a mark represents the threshold beacon load $C_{b,\max} = 1.2$ Mbps; a thick solid line stands for the upper bound of beacon load with *adaptive* CSR in (8). In fixed CSR, we can find that the upper bound of beacon load can exceed the threshold beacon load $C_{b,\max}$, which may lead to unreliable transmission of safety messages. On the other hand, the upper bound of beacon load for adaptive CSR is always less than or equal to the threshold value by virtue of beacon transmit power control.

From the above results, we can conclude that the adjustment of beacon transmit power in (8) can lead to an optimal CSR value to meet the channel requirement.

### C. Contention Window Size

The IEEE 802.11 MAC standard provides an exponential backoff algorithm to resolve the collision of a unicast frame [2]. In the exponential backoff algorithm, the CW size doubles once a *unicast* frame is failed to reach its destination. On the other hand, there is no similar mechanism to resolve the collision of *broadcast* frame, e.g. the beacon frame. To overcome these limitations, it is utmost important to carefully determine the CW size: if the CW size is too small, then there are too many frame collisions; on the contrary, if it is too large, most of the mini-slots are not used for frame delivery. Therefore, in this section, we present an approximate close-form solution to the optimal CW size $W^*_{opt}$ that maximizes the throughput of a broadcast frame.

To simply our analysis, we make the following two assumptions: 1) there is no hidden-node problem; and 2) each vehicle has at least one frame to send at each contention period (*saturated*). We first denote by $N$ and $W$, the number of vehicles within the CSR and the CW size of a beacon frame, respectively. Recall that the maximum number of vehicles in the CSR can be represented by $N = 2D_{CS}K\overline{\rho}$. Depending on the number of frame transmissions, the status of each mini-slot is classified into three categories:

- *Idle slot*: No vehicle sends its frame at the mini-slot;
- *Success slot*: One vehicle successfully sends its frame at the mini-slot; and
- *Collision slot*: Multiple vehicles send their frames at the mini-slot resulting in a frame collision.

Here, we denote by $P_i$, $P_s$, and $P_c$, the probability of idle slot, success slot, and collision slot, respectively. Since each vehicle randomly selects a mini-slot in [0, $W$-1] at each contention period, the number of frame transmissions at a mini-slot follows the binomial distribution $B(N, \frac{1}{W})$. Let us denote by $p(k)$, the probability that $k$ vehicles sends beacon frames at a mini-slot. Then, the three probabilities can be obtained as follows:

$$P_i \;=\; p(0) \;=\; (1-\frac{1}{W})^N, \tag{9}$$

$$P_s \;=\; p(1) \;=\; \frac{N}{W}(1-\frac{1}{W})^{N-1}, \tag{10}$$

$$P_c = 1-p(0)-p(1) = 1-(1-\frac{1}{W})^N-\frac{N}{W}(1-\frac{1}{W})^{N-1}. \tag{11}$$

We also denote by $T_i$, $T_s$, and $T_c$, the time duration of idle slot, success slot, and collision slot in terms of mini-slots, respectively. Then, it is clear that the duration of idle slot is

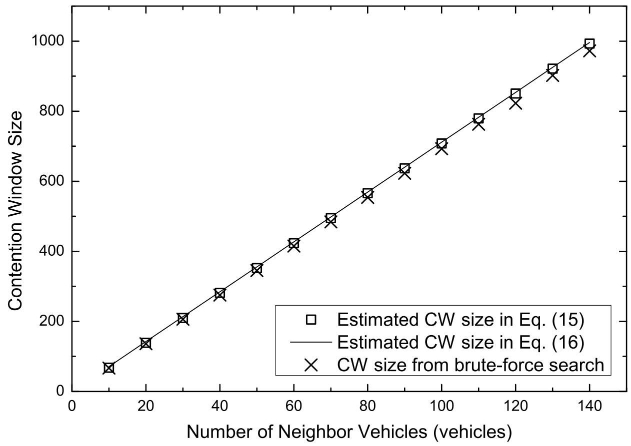


Fig. 5. The optimal CW size vs. the number of vehicles in the CSR

equal to 1 ($T_i = 1$). Since the beacon frame is assumed to be 500-byte long, the time needed to transmit a beacon frame becomes 88 mini-slots, i.e., $T_s = T_c = 88$.

Then, the throughput $S$ of beacon frame can be represented by

$$S = \frac{T_s P_s}{P_i + T_s P_s + T_c P_c}. \quad (12)$$

Notice that, for fixed number of vehicles in the CSR, the throughput of beacon frame can be seen by a function of CW size in (9)-(12), i.e., $S(W)$. To obtain the optimal CW size $W_{opt}$, we differentiate (12) with respect to $W$. Then, the optimal CW size $W_{opt}$ is the solution of the following polynomial equations:

$$(T_c - 1)(1 - \frac{1}{W_{opt}})^N + T_c(\frac{N}{W_{opt}} - 1) = 0. \quad (13)$$

Since $1/W_{opt} << 1$ for practical values of $N$, we can simplify (13) using the Taylor series expansion:

$$(1 - \frac{1}{W_{opt}})^N \approx 1 - \frac{N}{W_{opt}} + \frac{N(N-1)}{2W_{opt}^2} \quad (14)$$

Substituting (14) to (13), we can obtain an approximate closed-form solution of the optimal CW size, i.e.,

$$W_{opt} \approx \frac{N(N-1)(T_c - 1)}{-N + \sqrt{N^2 + 2N(N-1)(T_c - 1)}} \quad (15)$$

For a large value of $N$, we can further simplify (15) as follows:

$$W_{opt} \approx \frac{(T_c - 1)}{\sqrt{2T_c - 1} - 1} N. \quad (16)$$

Since the CW size is a positive integer, we can finally obtain the optimal CW size $W_{opt}^*$, as follows:

$$W_{opt}^* = \arg \max_{\lfloor W_{opt} \rfloor, \lceil W_{opt} \rceil} [S(\lfloor W_{opt} \rfloor), S(\lceil W_{opt} \rceil)] \quad (17)$$

Fig. 5 shows the optimal CW size against the number of vehicles in the CSR. Here, a cross mark indicates the optimal CW size obtained from a brute-force search; a square mark represents the CW size from (15) and (17); and a solid line stands for the CW size from (16). We observe that the approximate closed-form solution closely matches with the real value within 3 % difference. We can also observe that the optimal CW size $W_{opt}^*$ almost linearly increases with the number of vehicles in the CSR, which can be seen in (16).

## IV. Conclusion

In this paper, we present a comprehensive analysis that provides a guideline to set the beacon period, beacon transmit power, and the CW size. We also examine the impacts of these parameters on the performance of vehicular networks. From the application requirement, we first show that the beacon period is inversely proportional to the speed of vehicle $v$. We next derive the upper bound of vehicle density $\overline{\rho}$ based on the fact that the inter-vehicle distance should be at least a certain distance $D_{IV}$. Then, we derive a mathematical formulation that determines the maximum CSR $D_{CS}^*$ of the beacon message while meeting the channel requirement. We finally present an approximate closed-form solution of the optimal CW size $W_{opt}^*$ that leads to the maximum throughput of the beacon message.


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## References


[1] "Vehicle safety communications project, task 3 final report: Identify intelligent vehicle safety applications enabled by DSRC," Nat. Highway Traffic Safety Admin., Washington, D.C., 2005.

[2] IEEE Computer Society, "IEEE standard for information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2007*, 2007.

[3] IEEE Computer Society, "IEEE standard for information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 6: Wireless access in vehicular environments," *IEEE Std 802.11p-2010*, 2010.

[4] IEEE Vehicular Technology Society, "IEEE standard for wireless access in vehicular environments (WAVE). Multi-channel operation," *IEEE Std 1609.4-2010*, 2010.

[5] SAE International, "DSRC implementation guide: A guide to users of SAE J2735 message sets over DSRC," online available: http://www.sae.org/standardsdev/dsrc/DSRCImplementationGuide.pdf, Feb. 2010.

[6] A. Boukerche, C. Rezende, R. W. Pazzi, "Improving neighbor localization in vehicular ad-hoc networks to avoid overhead from periodic messages," *Global Telecommunications Conference (GLOBECOM 2009)*, pp. 1-6, December 2009.

[7] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-vehicle communication: fair transmit power control for safety-critical information," *IEEE Transactions on Vehicular Technology*, Vol. 58, No. 7, pp. 3684-3703, August 2009.

[8] R. Reinders, M. V. Eenennaam, G. Karagiannis, G. Heijenk, "Contention window analysis for beaconing in VANETs," *International Wireless Communications and Mobile Computing Conference (IWCMC 2011)*, pp. 1481-1487, August 2011.

[9] C. L. Huang, Y. P. Fallah, R. Sengupta, and H. Krishman, "Adaptive intervehicle communication control for cooperative safety systems," *IEEE Network*, Vol. 24, No. 1, pp. 6-13, Jan. 2010.

[10] Y. P. Fallah, C. L. Huang, R. Sengupta, and H. Krishman, "Analysis of information dissemination in vehicular ad-hoc networks with application to cooperative vehicular safety systems," *IEEE Transactions on Vehicular Technology*, Vol. 60, No. 1, pp. 233-247, Jan. 2010.

[11] E. Abbott and D. Powell, "Land-vehicle navigation using GPS," *Proceedings of the IEEE*, vol. 87, no. 1, pp. 145-162, Jan. 1999.