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Dynamic Beacon Distribution Mechanism for Internet of Vehicles: An Analytical Study

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Abstract: In the last decade, with the arrival of the 5G communication technology and the increasing numbers of vehicles being connected to the internet, conventional vehicle ad-hoc networks (VANETs) are evolving towards the internet of vehicles (IoV), which makes the co-existence of IEEE 802.11p and 5G-based technologies very important for the design of a heterogeneous IoV system that takes advantage of both. The IEEE 802.11p standard is still the best candidate to support direct communications for safety critical services. In fact, both the ETSI ITS-G5 and the IEEE 1609 standard families adopt the IEEE 802.11p standard as a medium access control (MAC) mechanism, and they require vehicles to exchange periodic awareness messages to avoid dangerous situations. When the density of vehicles increases, the MAC layer will suffer from radio channel congestion problems, and this may affect the various VANET applications, especially safety applications. Therefore, the decentralized congestion control (DCC) mechanism has been specified by ETSI to mitigate the channel congestion; this was achieved by adapting the transmission parameters, such as the transmit power and data-rate. However, many research studies have demonstrated limitations and a low performance of DCC, especially when the channel load is extremely high. To deal with this, in this paper, we investigate a new promising technique, called the transmission timing control (TTC), to control the channel load for periodic cooperative awareness. It consists of spreading the transmissions over time in order to avoid contention on the transmission channel. The objective of the paper is to propose an analytical study to calculate the probability of successful transmission using TTC. The demonstrated results show the efficiency of our timing control-enabled scheme to deal with the channel load on top of different conditions.

Keywords: internet of vehicles; beaconing; ETSI ITS-G5; IEEE 1609; decentralized congestion control

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1. Introduction

The internet of things is driving the evolution of the traditional VANETs into the IoV, which promises huge commercial interest and research value [1]. Therefore, researchers and scientists are continuously designing and developing advanced wireless technologies for vehicular communication. In this regard, the arrival of 5G provides additional spectrum resources to the wireless network for vehicle-to-everything applications, which enable massive data transmissions and low-latency communications. However, for the successful and timely transfer of data, vehicular communications still require direct short range communications (DSRC) to support safety-related applications, without the need for passing through an access point [2,3]. For a seamless network connectivity, combining short-range technologies (IEEE-802.11p/ITS-G5) [4] and long-range technologies (5G), it is becoming primordial to leverage the best of both so as to achieve enhanced vehicular communications [5–7].

Cooperative awareness is one of the most important use-cases concerning safety-related applications in the context of the IoV [8]. It is supported by a beaconing algorithm, which consists of vehicles periodically broadcasting a beacon message called a cooperative awareness message (CAM) in Europe [9], as standardized by the European Telecommunications Standards Institute (ETSI) [10] and basic safety message (BSM) in the USA used by the approved IEEE 1609.0 standard and known under the work name "wireless access in vehicular environment" (WAVE) [11,12]. CAM/BSM messages are transmitted with a frequency typically ranging from 1 to 10 Hz, where each vehicle shares its position, speed, and direction with its neighbors. This allows increasing the drivers' awareness, and having a real-time visibility of the neighborhood.

The control channel (CCH) is the typical frequency channel where the CAM/BSM is sent, so that every vehicle has to listen to data traffic in this specific channel. Of course, other communication channels are typically available for non-safety traffic, which are termed service channels (SCHs). Since vehicles share the same frequency channels, it becomes necessary to control the access to the medium to prevent/avoid frame collisions among vehicles located within the same collision area. The collision area of a vehicle can be defined as the radio range covering its 1-hop and 2-hop neighbors, which may cause known direct and hidden collision problems, respectively [5].

The MAC layer is responsible for controlling access to the communication medium, and plays a fundamental role for controlling channel usage. The best candidate for short-range vehicular communication is the MAC layer specified in the IEEE 802.11p standard [3]. It is a widely adopted contention-based MAC technique due to its simplicity, dynamicity, as well as its asynchronicity. It is a distributed channel access called enhanced distributed channel access (EDCA), which is the improved version of the distributed coordination function (DCF) mechanism used in 802.11. EDCA relies on the carrier sense multiple access/collision avoidance (CSMA/CA) technique, to reduce the probability of collisions between multiple vehicles accessing the medium. It is mainly based on carrier sensing (CS), backoffs, and retransmission schemes.

In North America, the WAVE architecture uses 802.11p/1609.4 standards for the MAC layer implementation, introducing a switching mechanism among multiple physical channels [13,14]. So, right after channel switching from SCH to CCH, many WAVE devices may simultaneously start the channel access contention period [15], causing the "start-of-interval contention" problem [16], which results in a high collision risk, especially when the network is dense. The only congestion control technique available in a WAVE system for safety message beaconing is the backoff mechanism, which is generated using small contention window (CW) sizes, and executed right after the guard interval. This mechanism is not enough to prevent different vehicles from accessing the channel at the same time. Thus, when attempting to support real-time applications, such as safety message beaconing under dynamic topologies, which requires high communication reliability and low latency, the current MAC layer functioning can generate serious problems.

In a previous study [17], we proposed a novel scalable random access MAC for vehicular networks with the objective to prevent the start-of-interval contention problem, which occurs upon switching to the CCH. It aims to provide an efficient one-hop broadcast access to the CCH, and attempts to minimize the risk of direct and hidden collision problems. The proposal is called CSSA MAC (carrier sense for slotted-ALOHA random multiple access MAC), which tries to combine the advantages and the simplicity of the two MAC mechanisms: CSMA and slotted-ALOHA [18]. It can be seamlessly integrated in IEEE 1609.4 on top of the IEEE 802.11p standard. Its main idea is to spread the transmission time of beacons of the contending vehicles, over a spreading window (SW) within the CCH interval. Therefore, the CCH period is virtually slotted, the same way as the S-ALOHA MAC method, where the virtual slots (Vslots) represent the possible start of transmission times of the beacons. The beacon spreading process relies on randomly selecting the Vslot from the SW by contending vehicles. Hence, with this mechanism, CSSA MAC aims to ensure a more efficient use of the limited bandwidth available.

The objective of this paper is to calculate the optimal size of the SW and CW that allows increasing the probability of successful transmission when adopting the CSSA MAC protocol. Thus, we provide a new analytical study on the transmission timing control (TTC), to control the channel load for periodic cooperative awareness. It consists of spreading the transmissions over time in order to avoid contention on the transmission channel. The objective of the paper is to propose a new method to calculate the probability of successful transmission using TTC. The demonstrated results show the efficiency of our timing control-enabled scheme to deal with the channel load on top of different conditions. For more readability, the used abbreviations in this paper, along with their definitions are provided in Table 1.

Table 1. List of used acronyms.

Acronyms	Meaning	Acronyms	Meaning
5G	Fifth Generation	IoT	Internet of Things
BSM	Basic Safety Message	IoV	Internet of Vehicles
CAM	Cooperative Awareness Message	MAC	Medium Access Control
CCH	Control Channel	OR	Occupancy Ratio
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance	SCH	Service Channels
CS	Carrier Sensing	SNR	Signal-to-Noise Ratio
CSSA	Carrier Sense for Slotted-ALOHA Random Multiple Access	SW	Spreading Window
CW	Contention Window	S-ALOHA	Slotted ALOHA
DCC	Decentralized Congestion Control	TBeacon	Beacon Transmission Time
DCF	Distributed Coordination Function	UTC	Coordinated Universal Time
DSRC	Direct Short Range Communications	VANET	Vehicular Ad-Hoc Networks
EDCA	Enhanced Distributed Channel Access	Vslot	Virtual Slots
ETSI	European Telecommunications Standards Institute	WAVE	Wireless Access in Vehicular Environment
ITS	Intelligent Transportation System		

The remainder of this paper is organized as follows: Section 2 provides an overview of some related studies found in the literature providing MAC layer solutions. Then, Section 3 describes the proposed CSSA-based MAC. The investigation of the beacon distribution is presented in Section 4, followed by the analytical study of the CSSA parameters on the successful transmission probability in Section 5. Finally, the paper is concluded in Section 6.

2. Related Work

Random medium access protocols have been extensively used in contention-based algorithms whenever multiple nodes share a common channel, and compete to access it in a way that can lead to conflicts. A refinement over pure ALOHA, called the slotted ALOHA (S-ALOHA), is a random medium access approach used in wireless local area networks thanks to its simplicity and ease of implementation [19]. Such a protocol requires time to be partitioned into slots of a fixed length that are exactly equal to the packet transmission time. Every packet transmitted must fit into one of these slots, which is randomly selected, by beginning and ending at slot boundaries with perfect synchronization. Thus, a packet to be transmitted at any given node must be delayed until the beginning of the next slot. If two or more nodes transmit their packets in the same slot, a collision occurs. The colliding packets are buffered and retransmitted after a random retransmission delay, calculated with probability P. Many methods have been proposed [20–23] to improve S-ALOHA by adapting the retransmission delay and the probability value. Nonetheless, these alternative solutions still offer a low performance in terms of throughput, mainly due to the weaknesses associated with their collision avoidance mechanism. Moreover, the higher the packet arrival rate, the higher the risk of experiencing collisions.

The CSMA/CA becomes the basis of the majority of the proposed asynchronous MAC for V2V under the IoV. This is thanks to its simplicity, distributed nature, freedom from a central coordinator, and effectiveness to deal with mobility and topology changes. However, its weaknesses become evident when the channel starts to become congested. Therefore, any improvement upon CSMA/CA remains meaningful. The classification of CSMA/CA-based proposed protocols is performed according to the mechanism which they act upon. These mechanisms can be categorized under two relevant classes: EDCA parameter adaptation mechanisms, and distributed congestion control (DCC) mechanisms.

Concerning the EDCA parameter adaptation mechanisms, these act exclusively on CSMA/CA parameters, such as the contention window, priorities, etc. The researchers working on the medium access issue mention that the CW, and the priorities values used in the standard, are not optimal [24–35]. Adapting these values, which can be increased or decreased according to the vehicular density, is a method experiencing a growing tendency in the context of random multiple access control. Several solutions based on a CSMA-like MAC have been extensively investigated in the literature [36–42] to improve the performance of beaconing in the context of vehicular networks. In particular, adapting the CW parameter is the most attractive approach in the context of a safety message beaconing system. This adaptation may consist in either increasing or decreasing the CW according to the network density. Researchers that have been working and tackling the backoff issue state that the CW value used in the standard is not optimal [43–50]. In that regard, a number of modified backoff algorithms have been proposed in the literature [51–57]. These mechanisms should take into account the optimal contention window size. Increasing the CW size can lead to the beacon expiration problem; in addition, decreasing its size may lead to an increased number of collisions. So, obtaining a good balance between these two issues becomes a challenging problem, and it is still not sufficient to decrease the risk of collision under high contention [58–65].

Regarding the second category, the main idea of distributed congestion control (DCC) mechanisms is to reduce the load on shared communication channels, and to coordinate a fair channel access among vehicles in the context of vehicular communication.

To that end, the congestion control algorithms usually adopt a method of dynamically adjusting one or more DCC transmission parameters, such as (1) the transmitted power, (2) the generation rate, (3) the transfer rate, and (4) transmission timing [66]. The European ITS architecture ETSI standard gives the opportunity to adapt these parameters through cross-layer design. Note that the transmission timing control is not standardized yet. A more general survey related to DCC-based techniques for vehicular environment is instead presented and classified in [67] with the aim to derive open challenges and future research directions.

Adjusting the beacon rate generation is the most obvious solution for controlling the channel load in a congested environment in vehicular networks. It can be achieved in a straightforward manner through cross-layer mechanisms. In a very dense environment, vehicles usually have low speeds, and the beaconing frequency could be reduced, which has proved to be an effective approach in congestion control. Zheyuan [68] examined the performance of ETSI DCC under a platooning scenario. He implemented a transmit rate control technique for DCC under highway scenarios with a static frequency (in his study, 10 Hz and 20 Hz). A linear message rate integrated control (LIMERIC) [69] is a distributed and adaptive linear control algorithm which remains nowadays as one of the most cited approaches. In LIMERIC, the message transmission rate of each vehicle is adapted with the aim of making channel congestion converge to a given target value. Yet, from time to time, the transmission rate is adapted according to a linear adaptive formula. Bansal et al. [70] extended the LIMERIC algorithm to adapt the message transmission to the vehicle's action. They introduced an error model based adaptive rate control (EMBARC) in which vehicles with higher dynamics have more transmission opportunities. In [71], Cheng et al. analyzed the performance of ETSI DCC and LIMERIC in a heterogeneous scenario, where some vehicles exploit ETSI DCC, while others vehicles implement the

LIMERIC algorithm. Several protocols have been proposed to improve LIMRIC, in terms of fairness and scalability [72–77]. In [78], the authors propose a model based on a game-theoretic approach that optimizes the rate and transmission power for each vehicle to enhance throughput by reducing re-transmissions. However, the rate adaptation of such beacons should be designed carefully because sending fewer messages can easily have the effect of damaging the performance of safety applications instead of improving them. The consequences of this adjustment on every safety application should be taken into account as it remains unclear if all applications could deal with such a reduction. Moreover, the maximum frequency of these messages is still an open research problem, and anticipating a maximum value between 5 Hz and 10 Hz could be a hindrance in some situations.

Adjusting the data rate is the third mechanism of DCC; it intends to reduce the transmission time of a message when the vehicular density increases in order to give more stations the chance to access the channel during a beacon period. It consists of speeding up the transmission time of a beacon by using high data rates at high vehicular densities. This practically means to use the signal modulation which occupies the channel for less time. Since LIMERIC decreases the message-rate to reduce congestion without increasing the channel capacity, authors in [79] proposed a data-rate DCC technique (DR-DCC) as an improvement for LIMERIC. DR-DCC increases the data-rate to reduce congestion, effectively making messages shorter in time and increasing the channel capacity. DR-DCC can easily result in unfairness where vehicles with similar channel load conditions can obtain different data-rate settings.

3. The CSSA MAC Overview

3.1. The Main Idea

The CSSA MAC protocol consists of randomly spreading the beacon throughout the Vslots of the entire SW time interval, aiming to prevent simultaneous channel access attempts. The size of the SW can cover the whole CCH interval, or part of it. At the beginning of each CCH interval, each vehicle updates the size of their SW according to the number of neighbors (or the local density (LD)) within a two-hop range. When the virtual slot is reached, each vehicle has a chance to access the channel, and attempts to transmit using the conventional IEEE 802.11p's CSMA/CA.

3.2. System Model

The system is formed by vehicles which can transmit, receive, and forward beacon messages to/from vehicles within two hops from each other. The communication links are assumed to be symmetric, and each vehicle in the network has the same communication range, which is fixed to a specified value. The carrier sensing range is assumed to be the same as the communications range. The system uses the MAC protocol, as defined in IEEE 802.11p/1609.4, and operates in one CCH which is used for the transmission of a beacon message, also known in the WAVE architecture as a BSM (CAM in the ETSI architecture). The beacon messages are always transmitted at the beginning of each CCH interval, B is the set of beacons, where $B = \{i/1 \leq i \leq m\}$. All of the vehicles transmit beacon packets of the same size, and at the same transmission rate λ, and they start at the same instant.

It is assumed that the transmission duration between two successive beacons is equal to the CCH interval, which is reasonable to limit the lifetime of a beacon message to one CCH interval. The time synchronization at the MAC layer is also required by our scheme, and it can be achieved in real deployments by relying on the coordinated universal time (UTC), which can be obtained easily using GPS timestamps. The CCH interval is partitioned into a variable number of virtual slots (Vslot), where their borders and size are calculated at the beginning of each CCH interval, according to the beacon size and the beacon transmission rate. Note that the $\text{VSlotset} = \{j/1 \leq j \leq N\}$ represents the set of virtual slots of the CCH interval where SW interval is equal or a part of it, i.e., $|\text{SW}| \leq |\text{VSlotset}|$, as shown in Figure 1.

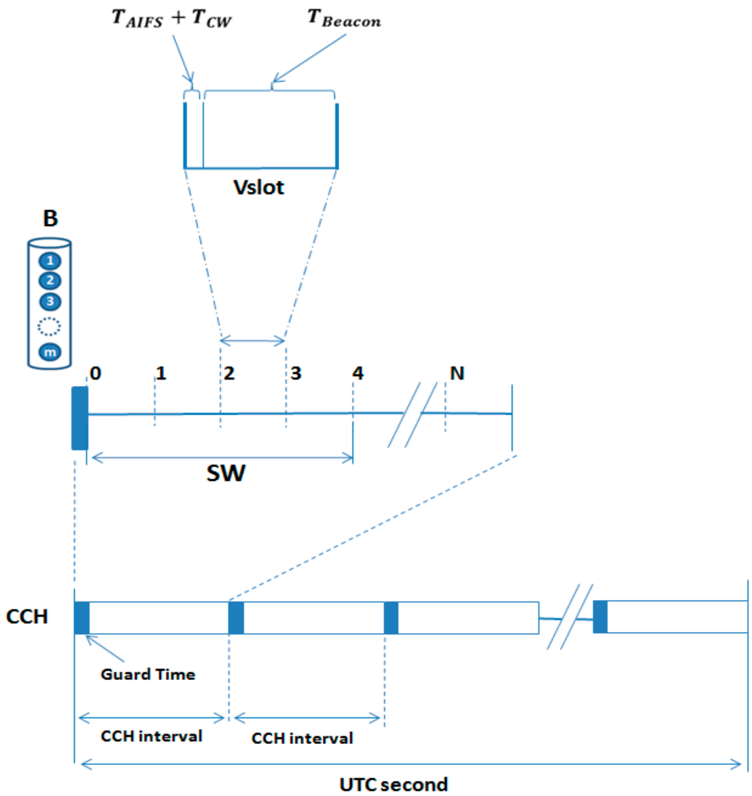

Figure 1. Virtual time slicing and SW size, compared to the CCH interval.

For that purpose, the protocol defines the duration of the Vslot for the beacon's transmission, as presented in Equation (1). It consists of a guard time T_{Guard}, which is a guard interval that accounts for the propagation delay and timing inaccuracy, an AIFS period, the minimum contention window (CWmin) interval, and the beacon transmission time (TBeacon). Note that the CWmin is used to ensure a competition between the vehicles that have selected the same Vslot, when they arrive at the MAC layer. The duration of the Vslot, used can be adjusted according to the CW value and the chosen beacon size, as follows:

$$\text{Vslot} = T_{Guard} + T_{AIFS} + T_{CW} + T_{Beacon} \tag{1}$$

Based on that, the control channel is slotted virtually, and the size of STT_{CHH} is calculated according to Equation (2), defined as follows:

$$|\text{Vslotset}| = \left[\left(\frac{1}{\gamma}\right) \text{div TTD}\right] \tag{2}$$

where γ refers to the beacon transmission rate (note that $\left(\frac{1}{\gamma}\right)$ is equal to the CCH interval).

4. Analytical Study of the Beacon Distribution

Spreading the beacons of vehicles over the SW interval results in a set of occupied Vslots where each of them receives at least one beacon. The spreading function is implemented in MATLAB under the name SWOccupancyDist (NB, SW), where (NBs) is the number of beacons and (SW) represents the spreading window, as shown in Figure 2. It is clear that the spreading is a random phenomenon where different beacon distributions are possible. In order to predict the number of occupied Vslots, as well as the number of beacons in each Vslot, this phenomenon should be modeled as an occupancy problem [68], where (m) distinguishable balls are randomly distributed into (n) distinguishable boxes, as shown in Figure 2.

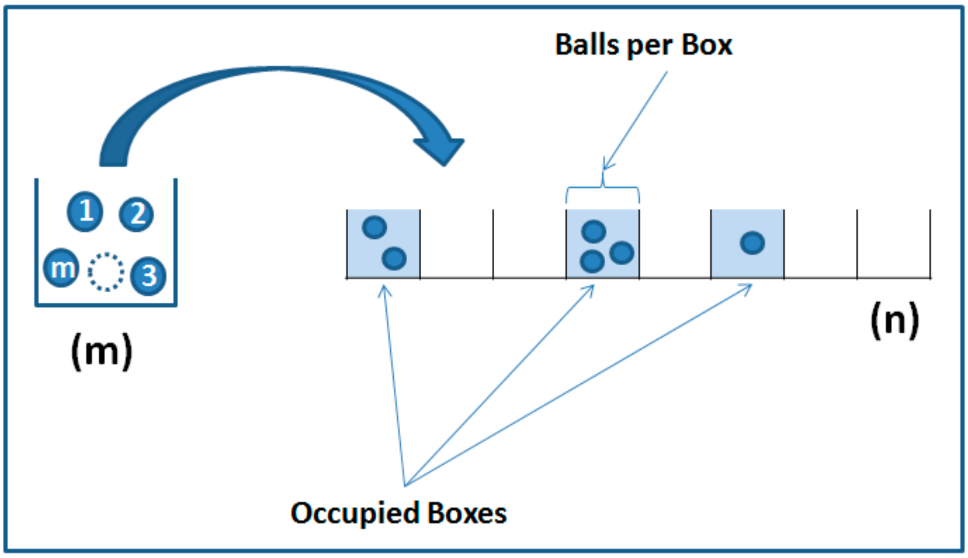

Figure 2. The occupancy problem modeling of the beacon distribution.

4.1. The Number of Occupied Vslots

To begin with, let $O_{m,n}$ be the random variable which determines the number of occupied boxes when distributing (m) distinguishable balls into (n) distinguishable boxes, and let $(O_{m,n} = k)$ be the probability that (k) boxes are occupied. It is extracted from the famous equation named "Stirling number of the second kind" [69]. The deduced probability can be written as:

$$P(O_{m,n} = k) = \frac{\binom{n}{k} \sum_{j=0}^{k} (-1)^{j} (k-j)^{m}}{n^{m}} \tag{3}$$

The graphs of Figure 3 are generated from the implementation of the Equation (3) in order to show the occupancy probabilities when varying the number of occupied Vslots for a NBs = 10. It also presents the impact of the SW size on the whole graph. It is noticeable that for all graphs, the occupancy possibilities do not have the same probability of appearance and for each SW size, there is one occupancy possibility which has the highest value denoted as the highest occupancy possibility (HOP). It represents the number of occupied Vslots which have the highest chances to appear when the beacons are spread over the SW. The graphs show that, when the SW increases, the whole graph shifts to the right, and the value of the HOP comes closer to the maximum number of beacons. This means that the occupied STTs will be receiving only one beacon as the SW becomes bigger.

A more general study about the impact of the SW on the HOP is needed to ascertain the previous results. Let HOP(NBs, SW) be the function which returns the HOP value when spreading the NBs over the SW. This way, the occupancy ratio (OR) can be defined in Equation (4), as follows:

$$OR(NB, SW) = \frac{HOP(NB,\ SW)}{NB} \tag{4}$$

$$\lim_{HOP \to 1} OR \cong 0, \quad \lim_{HOP \to NB} OR = 1,$$

The worst case takes place when the HOP is equal to 1, meaning that the occupancy is minimal. Moreover, the best case occurs when the HOP is equal to the number of beacons (NBs), in this case each occupied Vslot receives only one beacon. Now, let us define the average occupancy ratio (AvgOR) for a set of NB values, and for a given SW. The AvgOR can be determined in Equation (5), as follows:

$\forall$ SW $\in$ SWset, $\forall$ NB $\in$ NBset:

$$\text{AvgOR(SW)} = \frac{\sum_{\text{NB}} \text{HOP(NB, SW)}}{|\text{NBset}|} \tag{5}$$

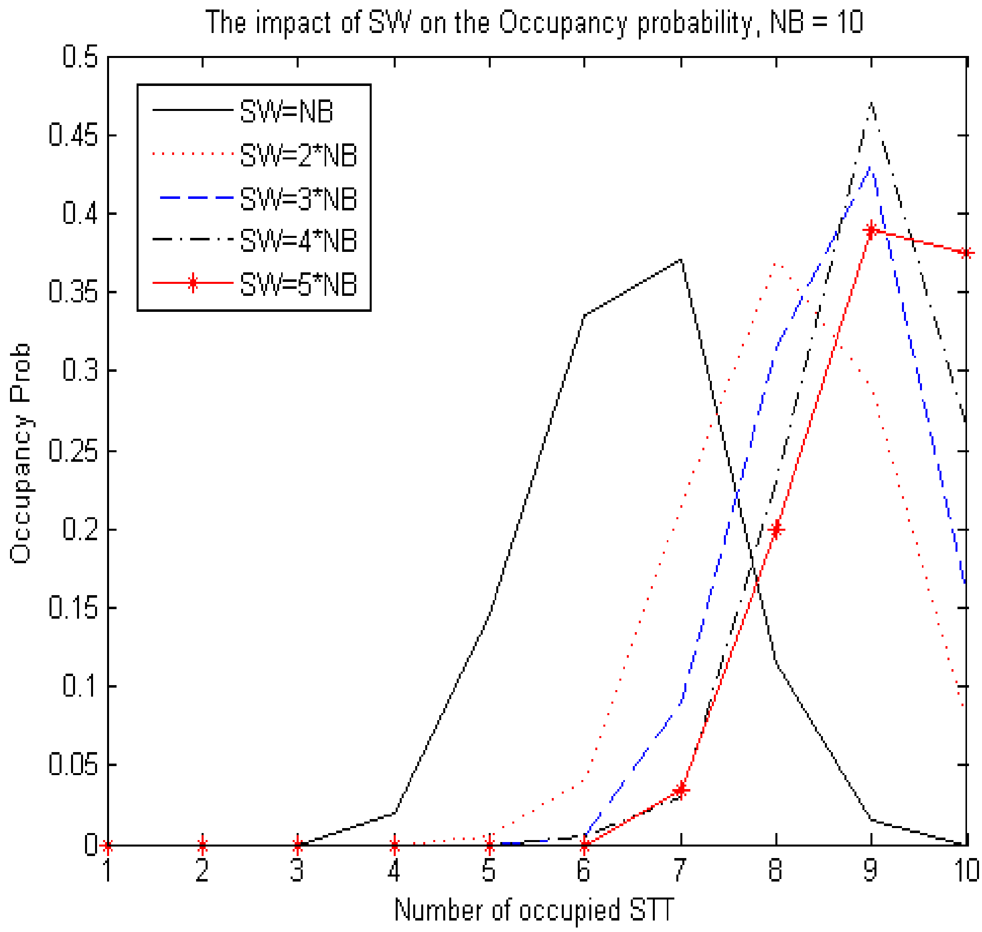

Figure 3. Impact of the SW size on the occupancy possibilities and on the HOP, for a number of beacons equal to 10.

Figure 4 shows the analytic and the simulation results of AvgOR, where the average results of different numbers of beacons are taken: NBset $= \{\text{i}/\ \text{i} = 10..\text{n and } \Delta\text{i} = 5\}$, for each SW size. The SW sizes taken represent a set of multiples of NBs, where SWset $= \{\text{k} * \text{NB}/\ \text{i} = [1, 3] \text{ and } \Delta\text{k} = 0, 5\}$. Note that, when multiple NB values are equal to zero (k = 0), it means that the SW has just one Vslot (SW = 1). It is remarkable from the graph, that the results of both analytic and simulation graphs are close, especially between 0 and 0.5, 2 and 2.5 where both graphs match each other. For the rest of the graph, there is a slight difference due to the randomness of the simulation which cannot generate the same results in each experiment. Despite that, the margin of error can be considered acceptable. Moreover, from an analytic point of view, the occupancy ratio increases when the SW size increases. It means that the probability of occupying a number of Vslots equal to the number of beacons (NBs) increase as the size of the SW becomes bigger, and this is what is shown in Figure 3. Moreover, the simulation experiments show stable probability results once the SW has a size bigger than 2.5, which means that in reality, it is slightly difficult to occupy a number of Vslots with the same number of beacons (NBs).

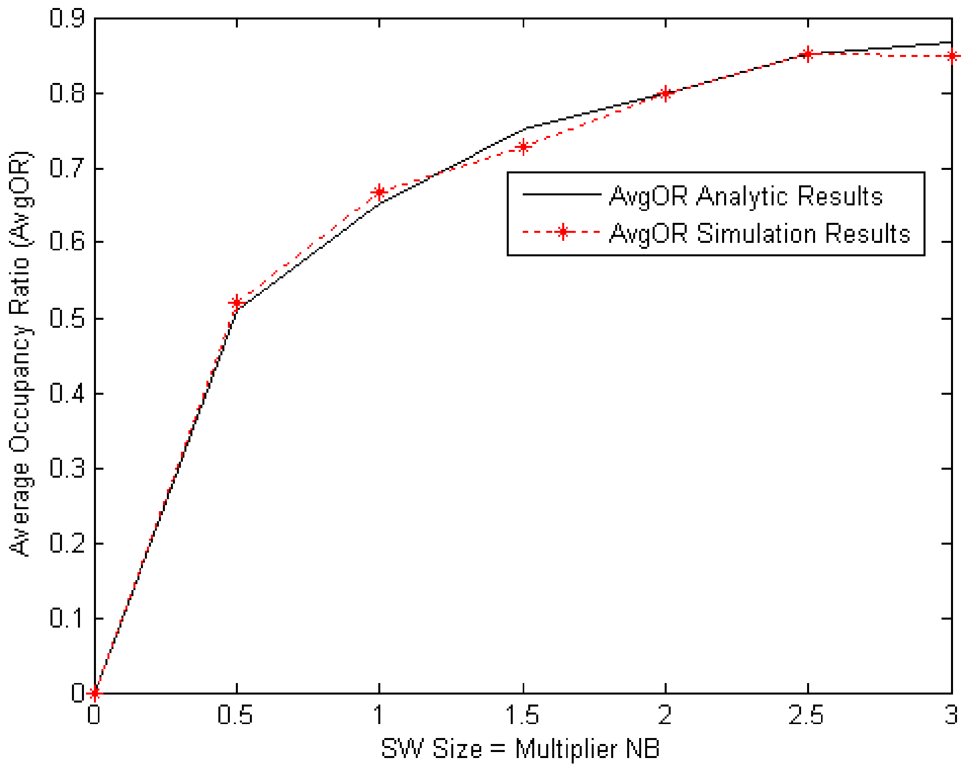

Figure 4. Impact of the SW size on the occupancy possibilities and on the HOP.

The results of the AvgOR graph can be used as a model to estimate and to predict the number of occupied Vslots, noted as HOP, for any number of beacons belonging to the NBset, spread over any SW size belonging to the SWset. The HOP can be extracted using Equation (6):

$\forall$ SW $\in$ SWset, $\forall$ NB $\in$ NBset:

$$\text{HOP}(\text{NB}, \text{SW}) = \text{Round}\left[\text{AvgOR}\left(\frac{\text{SW}}{\text{NB}}\right) * \text{NB}\right] \quad (6)$$

4.2. The Number of Beacons in the Occupied Vslots

In order to predict the number of beacons in each Vslot, the imbrical spreading function (ISF) is proposed. It performs the spreading process multiple times over the occupied Vslots, recursively in a nested loop. Following each round of beacon spreading, the function assigns one beacon to each occupied Vslot and, in the next round, the remaining ones are re-spread once again exclusively over the previously occupied Vslots. The process is repeated several times until there is no beacon left to be spread.

The ISF calculation is performed based on the highest occupancy possibility (HOP) function presented in Equation (3). The notification $\text{IFS}(\text{NB}, \text{SW})$ represents the recursive distribution of NBs over the SW. For that purpose, let $\text{HOPr}(\text{i})$ be the highest occupancy possibilities in the round (i) of spreading, and let $\text{RBr}(\text{i})$ be the remaining beacons in the round (i) of spreading, which can be defined as follows:

$$\text{HOPr}(\text{i}) = \text{HOP}(\text{NBr}(\text{i}),\ \text{SWr}(\text{i}))$$

$$\text{RBr}(\text{i}) = \text{SWr}(\text{i}) - \text{HOPr}(\text{i})$$

where $\text{NBr}(\text{i})$ represents the number of beacons to be spread in the round (i), and $\text{SWr}(\text{i})$ is the spreading window of the round (i).

The ISF can then be computed recursively as follows (cf. Algorithm 1):

Algorithm 1. The Imbrical Spreading Function Algorithm

Input: NB and SW
Output: Array of HOPr of the spreading rounds

NBr(1) = NB; SWr(1) = SW
i = 1;
While NBr(1) $\neq$ 0 Do
HOPr(i) = HOP(NBr(i), SWr(i))
RBr(i) = SWr(i) − HOPr(i)
NBr(i + 1) = RBr(i)
SWr(i + 1) = HOPr(i)
i = i + 1

end

Following the execution of the ISF function, the following information can be extracted. Let HOPset be the set of the highest occupancy possibilities of all rounds, and $\text{NVset}(\text{i})$ be the number of Vslots that receive (i) beacons, and finally let NVslotset be the set the occupied Vslots that have the same number of beacons. They can be defined as follows:

$$\text{HOPset} = \{\text{HOPr}(\text{i})/\ \text{i} = 1, 2 \ldots \text{n}\ \}$$

$$\text{NVset}(\text{i}) = |\text{HOPr}(\text{i}) - \text{HOPr}(\text{i}+1)|$$

$$\text{NVslotset} = \{\text{NVslot}(\text{i})/\ \text{i} = 1, 2..\text{n}\ \}$$

Table 2 shows the analytic results of an application example generated by the ISF with (NB, SW) = (10, 10) and (NB, SW) = (15, 15), respectively.

Table 2. Application example of the imbrical spreading function where (NB, SW) = (10, 10).

i	NBr	SWr	AvgOR	HOPr	RBr	NSTT
1	10	10	0.7	7	3	4
2	3	7	0.8	3	0	3
3	0	3	0	0	0	0

The information extracted from Table 2 is presented as follows:

- The $\text{HOPset} = \{7, 3, 0\ \}$
- $\text{NVset}(1) = |\text{HOPr}(1) - \text{HOPr}(2)| = 4$, it means that there are "4" STTs which receive "1" beacon
- $\text{NVset}(2) = |\text{HOPr}(2) - \text{HOPr}(3)| = 3$, it means that there are "3" STTs which receive "2" beacons.
- $\text{VNslotset} = \{4, 3\}$, It means that there are "4" STTs having "1" beacons and "3" STTs having "2 " beacons.

5. Impact of CSSA Parameters on the Successful Transmission Probability

In order to reduce the contention in the occupied Vslots and to reduce the risk of transmission collision, the value of the optimal CW has to be adjusted according to the maximum number of beacons received by one of the occupied Vslots. The latter is affected by the density of vehicles and the size of the SW. Therefore, the influence of these parameters on each other has to be studied. Figure 5 shows the variation of the maximum number of beacons per Vslot, which are generated by the ISF function, compared to the density of vehicles and the size of the SW. Note that the graphs present the value that has the high probability of occurrence. As expected, the higher the value of SW, the lower the number of beacons per occupied Vslot. This is due to the large number of Vslots when the SW becomes larger. Moreover, for each SW value, the maximum number of beacons remains the same for all vehicle densities. It is because of the SW size, which is chosen according to the number of vehicles.

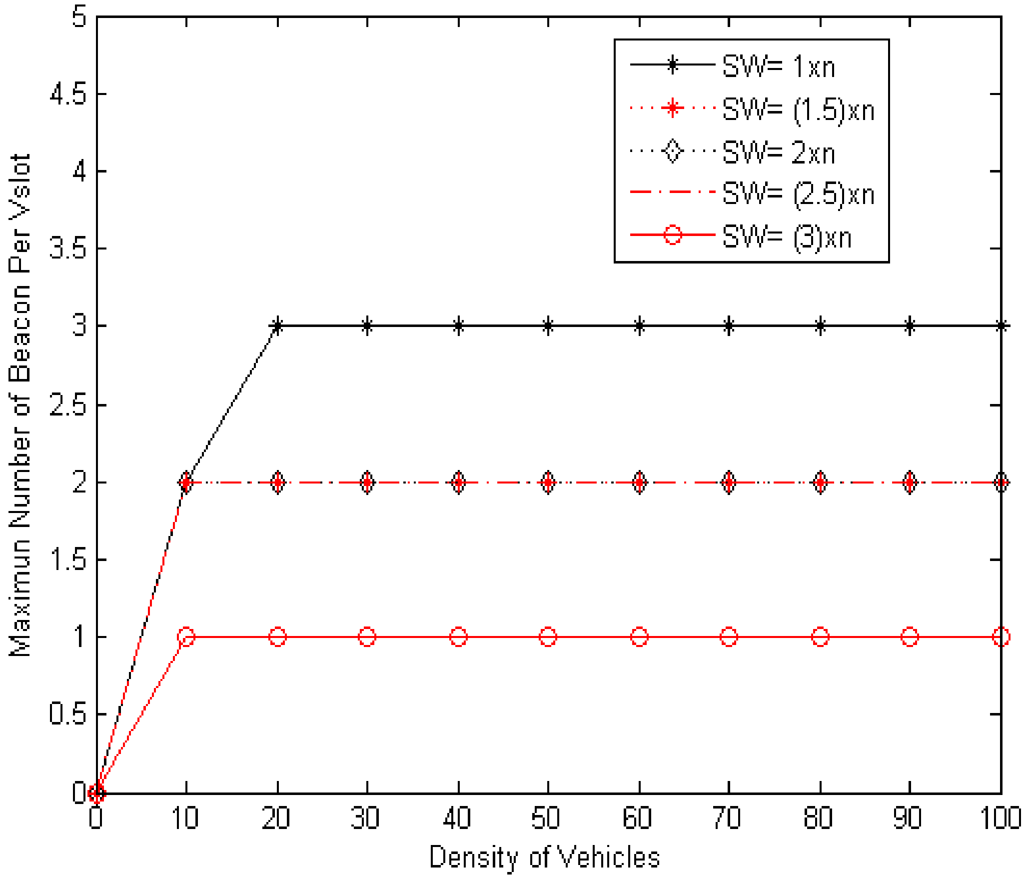

Figure 5. The maximum number of beacons per Vslot, compared to the density of vehicles and the size of the SW.

Figure 6 presents the percentage of the occupied Vslots which receive a different number of beacons for different vehicle densities. It is clear that the occupied Vslot of one beacon has almost the higher percentage of appearance for all of the graphs and the percentage becomes bigger when the size of the SW increases. Moreover, the Vslot with two beacons shows a considerably smaller percentage than those with one beacon and they decrease with the increase of the SW size. While the Vslot with three beacons appears only when the size of the SW is equal to the vehicle density, except in the case of the density of 10 vehicles. The reason for this is because the size of the SW, which has an impact on the distribution of beacons. The larger the size of the SW, the more the occupied Vslots probably receive just one beacon.

According to the CSSA MAC protocol, the access to the Vslot is based on the CSMA in which collisions happen when more than two or more nodes backoff their counters to zero at the same time. Therefore, the values of the SW and CW have a direct impact on the successful transmission probability. Notice that the successful transmission in each Vslot is considered only in two cases. The first one is if the STT contains only one beacon, the vehicle obtains access to the channel without contention, and in the second case, when only one of them sends its beacon exclusively. This means that the backoff of the winner has to be unique, compared to the other contenders, and expires before them, otherwise a collision will occur. This phenomenon can be modeled by Equation (7), defined as p(k, cw, d,v) [70]. It represents the probability that k vehicles generate beacon messages at the same time, and select the backoff counter from the contention window(CW), and (d-1) has passed from the counting down before the first transmission attempt, and that v<=k vehicles transmit in backoff number d.

$$P(k, cw, d, v) = \left(1 - \frac{d-1}{w}\right)^{k} \binom{k}{v} \left(\frac{1}{w-d+1}\right)^{v} \left(1 - \frac{1}{w-d+1}\right)^{k-v} \quad (7)$$

where:

- $\left(\frac{1}{W}\right)$ is the probability that a vehicle selects one of the backoff numbers d from w,
- $\left(1 - \frac{d-1}{w}\right)$ is the probability of not selecting a backoff number lower than d which represents the interval [0, d−1],
- $(1 - \frac{1}{w-d+1})$ is the probability of not selecting slot d among w − d + 1,
- $\binom{k}{v}$ represents all the possibilities where v among k vehicles can select d.

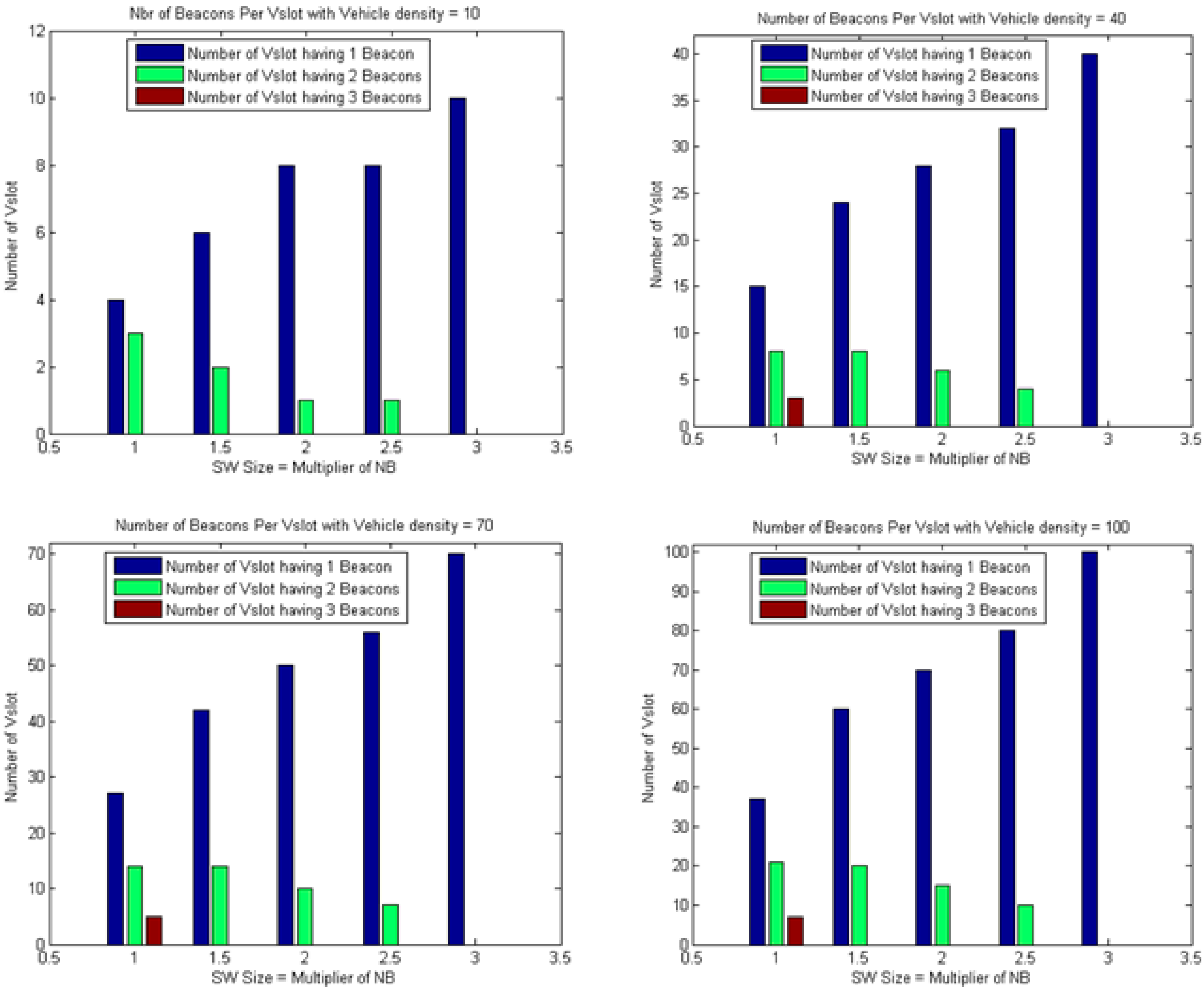

Figure 6. The maximum number of beacons per Vslot, compared to the density of vehicles and the size of the SW.

The probability of a successful transmission will be equal to "one" if one and only one vehicle (v = 1) can select the backoff number d. Let $T(k, w)$ be the random variation which counts the number of transmissions at one occupied STT among k contenders.

Therefore, $P(T(k,w)=1)$ represents the successful transmission probability of one occupied STT, as shown in Equation (8):

$$P(T(k,w)=1)=\sum_{d=1}^{w} P(k,w,d,1) \quad (8)$$

From that, the average successful transmission probability, denoted as AvgSTP(NB,SW,CW), applies to all occupied STTs during a SW interval with a given CW (contention window). It can be calculated, as presented in Equation (9):

$$AvgSTP(NB,SW,CW)=\frac{\sum_{i=1}^{|NSTTset|}\sum_{j=1}^{NSTT(i)} P(T(i,cw)=1)}{HOPr(1)} \quad (9)$$

where $HOPr(1)$ returns the number of all occupied STTs generated from the first spreading round by the ISF function, HOPset is the set of the different highest occupancy possibilities of the different spreading rounds, and $NSTT(i)$ represents the number of STTs which receive exactly i beacons.

Figure 7 shows the impact of the SW and CW size on the average theoretical successful transmission probability for the CSSA MAC protocol. The CW of the 802.11p standard achieves a low performance, since it uses a fix and small value of CW. Moreover, the more the CW becomes bigger, according to the maximum number of beacons in the occupied Vslots, the more the protocol shows a better successful transmission probability. This checks the efficiency of using an adaptive value of the CW. However, as the size of the SW becomes bigger, the protocol will have almost the same average of a successful transmission probability for different values of the CW. The reason is that, as shown in Figure 7, when the SW becomes larger the probability to receive only one beacon in each occupied Vslot becomes bigger too. Therefore, the transmission contention in the occupied Vslot is reduced and the size of the CW has no impact on the successful transmission of beacons. So the value of both parameters of the SW and CW should work in reverse, so that if one of them increases the other should decrease. However, it is a better to double the SW size for a good performance.

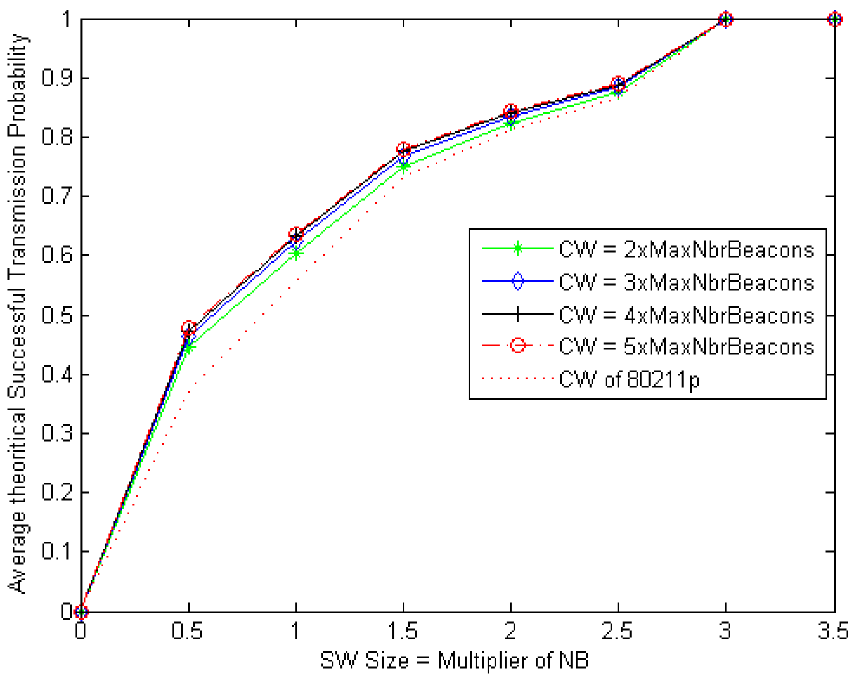

Figure 7. The impact of the SW and CW size on the average successful transmission probability for the CSSA MAC protocol.

6. Conclusions

The objective of this paper is to investigate through analytical study, the performance of the previously proposed protocol called CSSA MAC. It is a random medium access method aimed at increasing the successful transmission probability of the beacon message to support the cooperative awareness which is one of the most important use-cases concerning safety-related applications in the field of IoV. Its main idea is the adoption of a spreading technique for the beacons of vehicles over a SW interval which contains a set of Vslots, and it uses a contention period generated from a CW before sending in each occupied Vslot. For that, the imbrical spreading function (ISF) is proposed to predict the number of occupied Vslots from both the SW size and the number of contender vehicles, and then to estimate the number of beacons affected by each Vslot.

The analytical study performed in this paper proposes an adaptation of the two parameters, SW and CW, according to the number of contending vehicles, and show their impact on the probability of a successful transmission. The obtained results demonstrate that their values have to be adjusted in reverse to each other with the priority for the SW to be increased as high as possible for a better performance in terms of successful transmission probability. However, increasing the sizes of the SW has the side effect of reducing the efficiency of the protocol in the case of a low number of contending stations. It implies that a high fraction of the channel time is wasted before the last beacon can be sent. Thus, it is not suitable for the safety applications where the communications need to be in real time.

Regarding the limitations of the CSSA MAC scheme, while its method works randomly, meaning the risk that several vehicles pick a similar Vslot is still always possible. Moreover, the protocol relies on the IEEE 802.11p CSMA/CA procedure to reduce the risk of simultaneous transmissions. Obviously, when a vehicle succeeds to transmit in a given Vslot, the other vehicles around should again contend to transmit in the following Vslot which increases the risk of collision. In addition, the proposal does not add any additional signaling exchanges in order to reserve the Vslot, so, the vehicle that successfully transmits in a given STT will not keep transmitting at the same Vslot in the next CCH intervals. Thus, contention will necessarily take place in future occasions due to a lack of a memory mechanism. As future work, we are planning to deal with all of the aforementioned challenges as well as to leverage deep-learning based approaches in order to design intelligent and optimal schemes at the MAC level.

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