Model, analysis, and improvements for inter-vehicle communication using one-hop periodic broadcasting based on the 802.11p protocol

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Tseesuren Batsuuri, Reinder J. Bril, and Johan Lukkien

Department of Mathematics and Computer Science
Eindhoven University of Technology
Eindhoven, The Netherlands

Abstract

Many future vehicle safety applications will rely on one-hop Periodic Broadcast Communication (oPBC). The key technology for supporting this communication system is the new standard IEEE 802.11p which employs the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism to resolve channel access competition. In this work, we first aim at understanding the behavior of such oPBC under varying load conditions by considering three important quality aspects of vehicle safety applications: reliability, fairness, and delay. Second, we investigate possible improvements of these quality aspects. We start with a clear mathematical model which gives the foundation for making an accurate simulation model as well as for defining new appropriate metrics to judge the aforementioned quality aspects. We evaluate oPBC with a strictly periodic broadcasting scheme, i.e., each vehicle broadcasts messages in a strictly periodic manner. The evaluation reveals that the hidden terminal, or Hidden Node (HN), problem is the main cause of various quality degradations especially when the network is unsaturated. To be more specific, the HN problem reduces the message reception ratio (i.e., reliability degradation) and causes unfair message reception ratios for vehicles (i.e., fairness degradation). Moreover, it causes long lasting consecutive message losses (i.e., delay degradation) between vehicles while they are encountering each other, i.e., entering their Communication Ranges (CRs). In some serious cases, a certain vehicle could not successfully deliver any of its messages to a particularly destination vehicle throughout an entire encounter interval of these two vehicles. We propose three simple but effective broadcasting schemes to alleviate the impact of the HN problem. Though these solutions do not affect the message reception ratio (i.e., reliability) of the entire network, they do improve the fairness and delay aspects. These solutions are fully compatible with the IEEE 802.11p standard, i.e., they are application-level solutions and can be easily introduced in practice.

1 Introduction

A rapid progress in mobile and wireless technologies in the last decade enables a wide spectrum of applications in the Intelligent Transportation System (ITS) domain targeting vehicle safety, transportation efficiency, and driver comfort. In recent years, many industry/government consortiums are formed around the world to carry out projects to investigate such applications: the Vehicle Safety Communications consortium in the US [1], the Car2Car Communication consortium in Europe [2], and the Internet ITS consortium in Japan [3]. As a result of these efforts, many interesting vehicle safety application scenarios are identified and their communication requirements are carefully examined. It is now becoming clear that most of these applications will rely on broadcast communication that comes in two flavors: event-driven and time-driven. In the event-driven (or emergency) case, a vehicle starts broadcasting a safety message for a certain duration periodically when a hazardous situation is detected and, hence, these messages are not sent in a normal situation. In the time-driven case, each vehicle continuously performs one-hop periodic broadcast communication (oPBC) to pro-actively deliver a beacon message with its status information (e.g., position, speed) to the neighboring vehicles. The key idea of such oPBC is to make each vehicle aware of its vicinity such that future vehicle safety applications running on the vehicle will leverage this information to detect any hazardous situation in a timely manner. A lane change advisor and a forward collision warning application [1] are two typical examples that rely on this oPBC. These applications require a frequency of 10 messages per second with a maximum no message interval (or a tolerance time window) of [0.3sec,1.0sec] [1, 4, 5]. In addition, these applications pose a strict fairness requirement on oPBC [6, 7], where each vehicle should have equal opportunity for using the shared channel. In this type of system, message loss is unavoidable (we explain the causes below); however, it must not be the case that one or a few vehicles take all the loss, because this would result in these vehicles becoming a danger to their surrounding vehicles.

In this work, we focus on this oPBC from the vehicle safety application perspective. Particularly, we are interested in oPBC which is addressed in the IEEE 802.11p [8], IEEE 1609 standards [9], [10], [11], [12], and Society of Automotive Engineer (SAE) J2735 [13]. The 802.11p standard has been designed specifically for inter-vehicle communication. Besides the regular support for higher-layer protocols like IP, the 802.11p Medium Access Control (MAC) supports a short message protocol called WSMP (WAVE Short Message Protocol, IEEE 1609, where WAVE stands for Wireless Access in Vehicular Environments). Among other uses, this WSMP protocol together with the SAE J2735 addresses the transmission of Basic Security Messages (BSM) also known as beacon messages that are used by a vehicle to inform other vehicles about its status and condition. The BSM (in the rest of paper, we simply call it message) is sent periodically, in broadcast mode, with a typical frequency of 10Hz.

In general, the members of the 802.11 family, where the 802.11p is one of the newest members, of wireless standards support two communication modes: a managed mode called *Point Coordination Function (PCF)* where a base station manages access to the channel and an ad-hoc mode called *Distributed Coordination Function (DCF)* where stations collaborate to manage channel access [14]. In DCF, stations employ the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism to resolve channel access competition. For point-to-point communication, stations repeatedly perform channel sensing followed by a random Back-off (Bf) period selected from an increasing Contention Window (CW). Bf is used to reduce the probability of a contention problem which occurs when two or more stations that exist in each other's Communication Range (CR) incidentally happen to start transmission at the same time causing collisions. In addition, Request To Send/Clear To Send (RTS/CTS) signaling is used to resolve the hidden terminal, or Hidden Node (HN), problem which occurs when two stations that are outside each other's CR have overlapping transmissions in time interfering with their common neighbors in the intersection of the CRs. On top of this, a MAC level acknowledgement can be used to resolve the remaining message losses. An initial channel access delay, namely Arbitration Inter Frame Space (AIFS), allows discriminating among several priority classes. When stations broadcast messages rather than sending them point-to-point the situation in DCF is quite different. First, CW from which a Bf period is drawn is fixed, and Bf is at most done once [14]. Second, RTS/CTS signaling and MAC layer acknowledgement do not work since there is

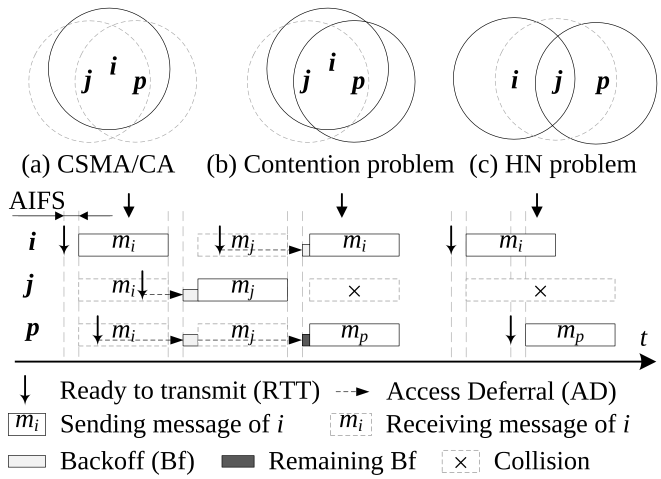

Figure 1: *the 802.11p MAC CSMA/CA in broadcast mode. (a) shows the contention protocol that serializes three stations. A station, which wants to transmit, first must check if the channel is free for a duration of Arbitration Inter Frame Space (AIFS). In case the channel is found active during this duration, the intended transmission is deferred and a Bf is performed. (b) shows a message collision due to a contention problem which happens if incidentally, two stations start transmission at the same time (mainly because their Bf periods expire at the same time), i.e., a Neighboring Node (NN) collision. (c) shows a message collision due to the Hidden Node (HN) problem, i.e., a HN collision: two stations that cannot sense each other's transmission may cause message collisions in the intersection of their Communication Ranges (CRs).*

no particular destination for a message. As a result, when all stations use broadcast-based communication, the collision problems, i.e., the contention and the HN problems increase. Figure 1 gives an overview of the 802.11p communication behavior in broadcast mode and illustrates the collision problems.

The purpose of our research is to understand the behavior of this oPBC based on the 802.11p DCF. We want to understand message losses due to the contention and HN problems under varying load conditions. In particular we want to understand oPBC by considering three quality aspects which are important for vehicle safety applications: *reliability* (i.e., successful message reception ratio), *fairness* (i.e., distribution of successful message reception ratio over vehicles) and *delay* (i.e., no message interval that is the longest interval in which a vehicle that is in the CR of another vehicle doesn't receive a message from that latter vehicle.). In addition, we want to investigate possible improvements.

Our first step is to develop a mathematical model of the 802.11p behavior under oPBC. This serves three purposes. First, it makes the discussion unambiguous. Second, it gives the foundation for a simulation model and third, it allows us to develop new relevant metrics (criteria) to judge communication quality for the above aspects. Standard performance metrics like a successful message reception ratio of the entire network or an average end-to-end delay fall short in this environment. Our second step is to simulate according to this model and to determine the values of the given metrics. This gives us insight in shortcomings of this oPBC and gives directions for improvements.

The contributions of this work are fourfold. First, we give a novel timing model of oPBC under the 802.11p DCF. Second, we define several new metrics for judging the quality of oPBC. Third, we simulate oPBC under several different circumstances showing problems and shortcomings. Namely, the simulation reveals that the HN problem is the main cause of various quality degradations when the network is unsaturated. It reduces the message reception ratio of the entire network (i.e., *reliability* degradation) and causes unfair message reception ratios for vehicles (i.e., *fairness* degradation). Moreover, it causes long lasting consecutive message losses (i.e., *delay* degradation) between vehicles while they are encountering each other, i.e., entering their CRs. In some serious cases, a certain vehicle could not successfully deliver any of its messages to a particularly destination vehicle throughout an entire encounter interval of these two vehicles. Fourth, we identify application-level improvements. We propose three simple but effective broadcasting schemes to alleviate the impact of the HN problem. These solutions are fully compatible with the IEEE 802.11p standard, i.e., they are application-level solutions and can be easily introduced in practice.

The remainder of the paper is organized as follows. Section 2 introduces the mathematical model of oPBC. Section 3 presents an evaluation study of oPBC by means of simulations which are carried out according to the model and Section 4 presents our solutions for the collision problems. Section 5 covers recent studies most relevant to our work. Finally, Section 6 gives a summary of the main results and presents an outlook on future work. In addition, Appendix A gives a detailed overview of CSMA/CA in broadcast mode and Appendix B gives a short overview of a signal reception model which is chosen for our simulation model.

2 Models of oPBC

In this section, we introduce our model of oPBC. Based on the model, we show how the appropriate metrics are defined for evaluating the three quality aspects of oPBC (i.e., *reliability*, *fairness*, and *delay*).

2.1 Two models

In our analysis of communicating vehicles we encounter two aspects: a simulation of the movement of the vehicles and a simulation of the behavior of the wireless communication as a function of the position of the vehicles. Thus we have the *traffic model* which yields the position of vehicles as a function of time and the *communication model* that describes the communication events between vehicles as a function of time and vehicle location. Hence, the communication model depends on the traffic model (but not the other way around).

The interface between the two models is formed by the location of the vehicles. Together with the radio channel model this yields the *neighborhood* structure viz., a set of vehicles that each vehicle can transmit to or receive from at any point in time. The traffic model can be very advanced, even to the extent that life traces are simulated [15, 16]. In this work we are not concerned, however, with the traffic model. For our simulations we stick to a simple highway model, represented as a stretch of several kilometers with three lanes per direction and periodic boundary conditions (which makes it, in fact, a loop). Speeds per lane are assumed to be fixed. In simulations the main concern of the traffic model is to simulate with a small enough time step to have a realistic and sufficiently accurate description for the communication model. The motivation for this restriction is that we want to study just the communication model under varying load conditions.

2.2 The communication model

The communication model consists of two parts: First, we describe the communication of the 802.11p standard and the radio channel model that generates the events. Second we model timing and events in the system consisting of communicating vehicles to define the concepts of interest.

2.2.1 The 802.11p communication and the radio channel model

We restrict ourself to describing the broadcast mode of the 802.11p MAC. In Appendix A, Figure 21 gives an extended flowchart of the broadcast procedure taken from [17] and Figure 22 describes the corresponding state machine diagram. In our simulation model, every vehicle is implemented according to this state machine. Besides, we take a Signal to Interference plus Noise Ratio (SINR) based signal reception model of the updated NS-2 implementation of the 802.11p [18] and a brief description of this model is given in Appendix B. In addition, we choose the Two-Ray Ground (TRG) signal propagation model in order to study solely the effect of message collisions. The main configuration parameters of the 802.11p and the TRG model are chosen as in Table 1.

Table 1: *The 802.11p parameter settings*

Parameters	**Values**
Date rate	6Mbps
A slot duration	13μs
AIFS	6 slots
CW size	7 slots
T_h (Preamble length)	40μs
Antenna gain	0dB
Antenna height	1.5m
Noise floor(nF)	-99dBm
Power Sense threshold($PsTh$)	–92dBm
Carrier sense threshold ($CsTh$)	-85dBm
SINR threshold ($SrTh$)	8dB

2.2.2 The timing model

We assume a set V of N vehicles $v_1, v_2, ...v_N$ periodically broadcasting messages. The behavior of the system is described as a series of events happening at certain times. As a convention we use a superscript to denote a k^{th} occurrence or instance. For example, $e^{(k)}$ denotes the k^{th} occurrence of an event e and $m_i^{(k)}$ denotes the k^{th} message of v_i. In addition, we often do not name the event but only the time of occurrence using a similar notation, as explained next.

The activation time $a_i^{(k)}$ is the time at which v_i becomes ready to broadcast $m_i^{(k)}$. The start time $s_i^{(k)}$ and finish time $f_i^{(k)}$ are the times at which v_i actually starts and finishes the transmission of message $m_i^{(k)}$, respectively. Note, from a receiver vehicle's perspective, the start time and the finish time at which the vehicle starts and finishes receiving the message $m_i^{(k)}$ are $s_i^{(k)} + \delta$ and $f_i^{(k)} + \delta$, respectively. δ is an air propagation delay that is relatively small[1], therefore

[1] $\delta \ll 1\mu s$ [19, 20]

we neglect this in our model.

The transmission interval $tI_i^{(k)}$ of message $m_i^{(k)}$ is defined as

$$tI_i^{(k)} \stackrel{\text{def}}{=} [s_i^{(k)}, f_i^{(k)}) \ . \tag{1}$$

We require that

$$a_i^{(k)} < s_i^{(k)} \le f_i^{(k)} \le a_i^{(k+1)} \tag{2}$$

holds. Message transmission is assumed to be periodic. If a message is not sent at all or is delayed such that the remaining part of the interval is not enough for successful completion we say that the message is dropped. This may mean a partial message transmission or, in the extreme case, no transmission at all ($s_i^{(k)} = f_i^{(k)}$). In both cases, we define $f_i^{(k)} = a_i^{(k+1)}$ and we take that as the condition of message dropping.

Moreover, we define transmission power $Pt_i(t)$ of vehicle v_i and its reception power at vehicle v_j as $Pr_{ij}(t)$ and cumulative reception power $cPr_j(t)$ of vehicle v_j at time t. Note, we always assume that $i \neq j$ holds whenever we talk about two vehicles v_i and v_j. We require that $Pt_i(t) > 0$ holds during $tI_i^{(k)}$ and its value is determined by the application. $Pr_{ij}(t)$ is determined by a given signal propagation model, by $Pt_i(t)$ and by the distance between sender and receiver at time t. $cPr_j(t)$ is determined by all receiving signal strengths at v_j at time t plus a noise floor, nF, as follows

$$cPr_j(t) = nF + \sum_{v_i} \{Pr_{ij}(t) | Pr_{ij}(t) \ge PsTh\}, \tag{3}$$

where $PsTh$ is a Power Sense threshold of the receiver. Given these notions, we define the neighborhood of a vehicle. At any time t, each vehicle v_i has a target neighbor set of other vehicles, $Nb_i(t)$, where $v_j \in Nb_i(t)$ means that v_j is in the CR of v_i at time t. It is defined as follows

$$v_j \in Nb_i(t) \stackrel{\text{def}}{=} \frac{Pr_{ij}(t)}{nF} \ge SrTh, \tag{4}$$

where $SrTh$ is a SINR threshold for receiving the message successfully. Note, CR is the reception range, the places where the message could be received disregarding interference of other stations. A necessary condition for receiving a message is that the receiving vehicle must be in the CR of the sending vehicle for the duration of the message transmission. A sufficient condition for a message reception is that the receiving signal power must be equal to or greater than $SrTh$ with respect to the cumulative power of all other signals for the entire duration of the message transmission. This is defined as follows

$$\forall t : t \in tI_i^{(k)} \ \wedge \ \frac{Pr_{ij}(t)}{(cPr_j(t) - Pr_{ij}(t))} \ge SrTh. \tag{5}$$

We extend the concept of a neighborhood to intervals by

$$\downarrow Nb_i(I) = \bigcap_{t \in I} Nb_i(t) \ . \tag{6}$$

This interval represents all vehicles that have been in the CR of vehicle v_i during the entire interval I. Changes of neighbor sets are represented by enter and leave events. Entering time $e_{ji}^{(k)}$ is the time at which v_j enters the CR of v_i for the k^{th} time while leaving time $l_{ji}^{(k)}$ is the time at which v_j leaves the CR of v_i for the k^{th} time. The k^{th} encounter interval $eI_{ij}^{(k)}$ of v_j with v_i is defined as

$$eI_{ij}^{(k)} \stackrel{\text{def}}{=} [e_{ji}^{(k)}, l_{ji}^{(k)}) \ . \tag{7}$$

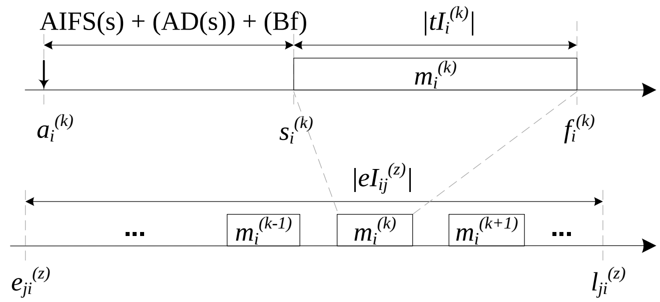

Figure 2: *Vehicle v_j enters the CR of v_i at $e_{ji}^{(z)}$ and leaves it at $l_{ji}^{(z)}$. During this encounter interval, v_j receives a sequence of messages from v_i. A vehicle v_i becomes ready to broadcast its k^{th} message at $a_i^{(k)}$ but it actually starts the transmission at $s_i^{(k)}$ and finishes at $f_i^{(k)}$. The distance between $a_i^{(k)}$ and $s_i^{(k)}$ depends on the channel condition. In the best case, it can be only an AIFS. In the worst case, it can be multiple AIFSs + multiple ADs(Access Deferrals) + Bf.*

During $eI_{ij}^{(k)}$ we say that there is a link from i to j and we call that the k^{th} such link. Figure 2 gives a schematic of these notions.

Message loss The most important concern is whether messages are actually received by vehicles that could receive them. Considering message $m_i^{(k)}$ there are three reasons why another vehicle v_j might not receive it.

- *(OOR) Out Of Range.* In order for a vehicle v_j to receive $m_i^{(k)}$ it must be in the neighborhood of v_i for the duration of the transmission. When $v_j \notin \downarrow Nb_i(tI_i^{(k)})$, v_j does not receive $m_i^{(k)}$.
- *(MD) Message Dropping.* This happens, as described above, if the back-off interval becomes so long that the message transfer time does not fit in the remaining part of the period. In our model this is equivalent to

$$f_i^{(k)} = a_i^{(k+1)} \ . \tag{8}$$

  No vehicle will receive message $m_i^{(k)}$.

- *(MC) Message Collision.* The message is transmitted but not received by v_j since other vehicles may transmit at the same time to v_j and their interferences are strong enough to corrupt the receiving message of v_i. This is defined as follows

$$\exists t : t \in tI_i^{(k)} \ \wedge \ \frac{Pr_{ij}(t)}{(cPr_j(t) - Pr_{ij}(t))} < SrTh. \tag{9}$$

Given these reasons for loss we define the *transmission condition* of message $m_i^{(k)}$ and, accordingly, the *reception condition* of $m_i^{(k)}$ by a vehicle v_j as follows

$$Tc_i^{(k)} = \begin{cases} MD & \text{if (8)} \\ XMT & \text{otherwise} \end{cases} \tag{10}$$

$$Rc_{ij}^{(k)} = \begin{cases} OOR & \text{if } v_j \notin \downarrow Nb_i(tI_i^{(k)}) \\ MC & \text{if } v_j \in \downarrow Nb_i(tI_i^{(k)}) \ \wedge \ (9) \\ Tc_i^{(k)} & \text{otherwise.} \end{cases} \tag{11}$$

If $Tc_i^{(k)} = XMT$, message $m_i^{(k)}$ is broadcast successfully. If $Rc_{ij}^{(k)} = XMT$, the message is received by vehicle v_j at time $f_i^{(k)}$ successfully.

Metrics We define the most appropriate metrics that can judge the communication quality in the three most important aspects of the safety applications: *reliability*, *fairness* and *delay*.

For the *reliability* aspect, we use the fraction of successfully delivered messages (*SMR*, successful message ratio). This concept can be refined to links between vehicles and to individual messages. To start we define the number of received messages from v_i by v_j in a given interval, as well as the number of times that such message could have been received. The ratio is the successful message ratio in that interval.

$$\begin{aligned} Rs_{ij}(I) &= |\{k \mid tI_i^{(k)} \subseteq I \wedge Rc_{ij}^{(k)} = XMT\}| & (12) \\ Ns_{ij}(I) &= |\{k \mid tI_i^{(k)} \subseteq I \wedge Tc_i^{(k)} = XMT \wedge v_j \in \downarrow Nb_i(tI_i^{(k)})\}| & (13) \\ SMR_{ij}(I) &= \begin{cases} \frac{Rs_{ij}(I)}{Ns_{ij}(I)} & \text{if } Ns_{ij}(I) > 0 \\ 0 & \text{if } Ns_{ij}(I) = 0 \end{cases} & (14) \end{aligned}$$

Generalizing this by summing over the receiving vehicles gives the successful message ratio of v_i in an interval.

$$SMR_i(I) = \begin{cases} \frac{\sum_{v_j} Rs_{ij}(I)}{\sum_{v_j} Ns_{ij}(I)} & \text{if } \sum_{v_j} Ns_{ij}(I) > 0 \\ 0 & \text{if } \sum_{v_j} Ns_{ij}(I) = 0 \end{cases} \tag{15}$$

As a special case, $SMR_i(tI_i^{(k)})$ is the *SMR* of $m_i^{(k)}$. Again, generalizing by summing over the sending vehicles we obtain the *SMR* of the entire network during that interval.

$$SMR(I) = \begin{cases} \frac{\sum_{v_i,v_j} Rs_{ij}(I)}{\sum_{v_i,v_j} Ns_{ij}(I)} & \text{if } \sum_{v_i,v_j} Ns_{ij}(I) > 0 \\ 0 & \text{if } \sum_{v_i,v_j} Ns_{ij}(I) = 0 \end{cases} \tag{16}$$

At the network level an interesting question is: how does $SMR([0, T))$, where T represents a time of consideration, behave as a function of vehicle density?

From the *fairness* perspective, the behavior of individual vehicles is more important than the average. This is why we also analyze SMR_i to see whether losses are distributed evenly (or fairly) over the vehicles. The cumulative distribution function shows this; a fair distribution would give a transition from 0 to 1 within a short interval.

$$cdfSMR(I, x) = \frac{|\{v_j \mid SMR_j(I) \leq x\}|}{N} \text{ , for } 0 \leq x \leq 1 \tag{17}$$

In addition, plotting SMR_i as a function of time gives insight in the visibility of v_i for other vehicles.

Finally, from the *delay* perspective, an important further question is how losses of a particular vehicle are distributed in time and across vehicles: do losses happen in sequences and do they affect the same links? To that end we define the concept of a "No Message Interval" between two vehicles during a given interval I which is the length of the longest subinterval of I without a successful message transmission. In addition, the "First Delay" is the length of the longest initial subinterval and represents a delay in discovery in case we apply it to an encounter interval.

$$NoM_{ij}(I) = \sup \{|J| \mid J \subseteq I \wedge Rs_{ij}(J) = 0\} \tag{18}$$

$$FD_{ij}([a,b)) = \sup \{x \mid [a, a+x) \subseteq [a,b) \wedge Rs_{ij}([a,a+x)) = 0\} \tag{19}$$

In our analysis we look at genuine *NoM* and *FD*, viz., those that correspond to encounter intervals. These are examined as a function of their length and plotted as a density (histogram) or as a cumulative distribution.

3 Evaluation of oPBC under CSMA/CA coordination

In this section, we evaluate oPBC using the newly defined metrics. We implemented a simulator according to the model and verified its correctness against the updated NS-2 implementation of 802.11p [18]. The following subsections describe the simulation setup, results, and analysis.

3.1 Simulation Set Up

For the purpose of this evaluation, two different scenarios are simulated. In the first scenario (single domain (SD)), vehicles are deployed at fixed locations within a single CR viz., all vehicles can receive each others messages. This scenario allows us to study the collisions caused only by the contention problem, i.e., NN collisions since there are no HNs. In the second scenario (multi domain (MD)), vehicles are deployed on a 3km long highway with three lanes per direction. This scenario allows us to study both HN and NN collisions. By having these two scenarios, we can compare the impact of these two types of collisions. The vehicles at the three lanes have fixed velocities of 20, 30, and 40 m/s respectively. In both scenarios, different inter-vehicle spacings are used in order to create different *Vehicle Densities* (*VD*). We assume a single channel, a fixed broadcasting period and initially, a random phasing within this period as

$$a_i^{(k)} \stackrel{\text{def}}{=} \phi_i + kT_i. \tag{20}$$

Thus, each v_i has a broadcasting period $T_i \in \mathbb{R}^+$ and an initial broadcasting phase $\phi_i \in \mathbb{R}^+$, where ϕ_i is uniformly selected from an interval of $[0, T_i)$. Moreover, we assume the same signal

Table 2: *Simulation settings*

Parameters	Values
Message size	555 bytes
CR	300m
Broadcasting Period (T)	0.1 seconds
Simulation length	60 seconds

strength, the same broadcasting period, the same message size fixed over time for all vehicles. Table 2 presents the values of the simulation parameters.

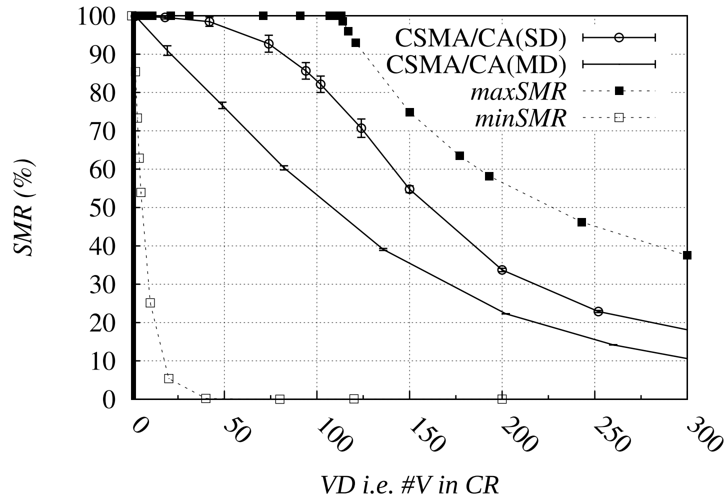

Figure 3: *Successful Message Ratio (SMR) of the entire network with respect to the vehicle density (VD) shows the communication reliability. maxSMR is the maximum possible SMR calculated analytically. minSMR is the minimum possible SMR obtained by means of simulations in which all vehicles have approximately the same phases for broadcasting. SD (Single Domain) case shows SMR degradation only due to the contention problem, where all the vehicles are deployed at fixed locations within a single CR, therefore, there are no HNs. MD (Multi-Domain) shows SMR degradation due to both the contention and HN problems, where all vehicles are deployed on a 3km long highway with three lanes per direction. Both cases show average values of ten simulations with a 99% confidence interval.*

3.2 Simulation results and analysis

First, we study the *reliability* by means of the successful message reception ratio metric, i.e., $SMR([0,60))$. The SMR of the overall network with respect to VD of the SD and MD cases are shown in Figure 3. For each different VD case, we performed ten simulations with a different random seed for selecting the initial phases. Figure 3 presents the average values of these simulations with a confidence interval of 99%. In addition, the theoretical maximum SMR ($maxSMR$) is plotted to show the upper boundary. This $maxSMR$ is given by

$$maxSMR(VD) = \begin{cases} 1 & \text{if } VD \leq SP \\ SP/VD & \text{otherwise} \end{cases}, \tag{21}$$

where SP is the channel saturation point, i.e., the maximum capacity of the channel in terms of the number of vehicles that can fit in one period duration without any overlap in time for broadcasting. SP is given as

$$SP = \frac{T}{T_s + T_d}, \tag{22}$$

where T_s is the inter-frame space, i.e., an $AIFS$ duration, and T_d is the time to transmit a single message. *When all vehicles are optimally synchronized over the period for broadcasting, the SMR should approach this maxSMR level.* Besides, we obtained the minimum possible SMR level ($minSMR$) by means of simulations in which we defined approximately the same phases for all vehicles.

From Figure 3, the HN problem appears to be the main cause of SMR degradation when the

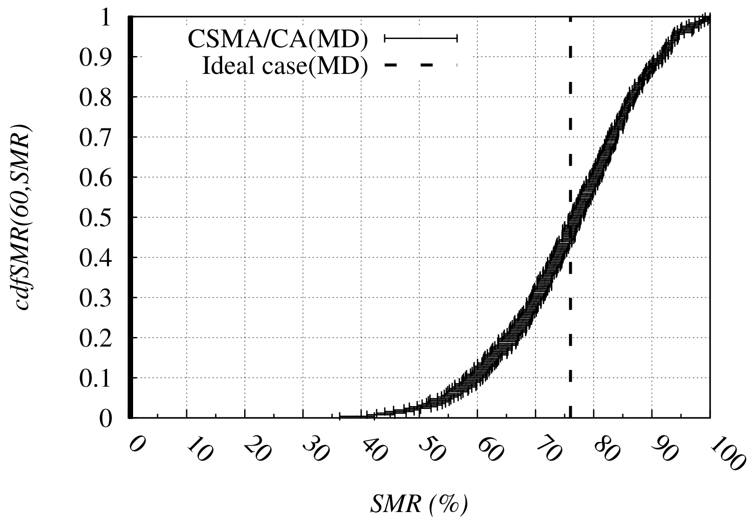

Figure 4: *This shows the fairness through CDF of vehicles by their SMR, when VD is about 50. In the graph, a point indicates that y% of vehicles have at most x% SMR. The result shown is an average of ten simulations with a confidence interval of 99%. In an ideal fair case, the dashed line is expected where all vehicle should have the same SMR that is equal to SMR of the entire network.*

network is unsaturated. Once the network load exceeds its maximum capacity, the NN collisions start occurring in bursts thus yielding lower *SMR*.

We now continue our study at individual vehicle level to investigate the *fairness*. Here, we select an unsaturated network condition where the traffic density is sparse, i.e., *VD* is about 50 vehicles (that corresponds to about 85 vehicles per km over 6 lanes in our settings). Figure 4 shows a relatively unfair distribution of message receptions over vehicles where some vehicles have a high *SMR* whereas others have a relatively low *SMR*. In an ideal fair case, the dashed line is expected where the distance between the best and worst cases should be close to 0, i.e., a transition from 0 to 1 within a short interval. In this case, however, the distance between the best case and worst cases is approximately 65%.

Figure 5 shows how *SMR* of an individual vehicle evolves over a time interval of 15 seconds. We take only an interval of 15 seconds from a simulation of 60 seconds for better visibility. The graph shows two specific cases of vehicles with the best *SMR* and the worst *SMR*. From this graph, we can conclude that vehicles remain in one condition (a certain *SMR* level) for a relatively long period of time if we ignore some fluctuations there. In addition, we can say that the best and the worst vehicles performances are clearly distinguished.

Figures 6 and 7 show the impact of the collision problems on the *delay* aspects at the link level through a cumulative distribution of links by their *NoM* and a histogram of links by their *FD* respectively. During 60 seconds of simulation (*VD*=50, i.e., vehicles in total for a simulation), approximately 53000 links are established in total. Note, the link is an one-way relationship. Some vehicles join the CR of a vehicle whereas some may leave the CR due to the relative speed between the vehicle and its neighbors. From Figure 6, we can see that almost 30% of links experience more than one second of *NoM*. This implies that a certain vehicle does not receive a sequence of messages from another vehicle although the vehicle could have received these messages in the absence of interferences. From Figure 7, many vehicles, i.e., about 350±50 are seen that did not even discover some of their one-hop neighboring vehicles for their entire

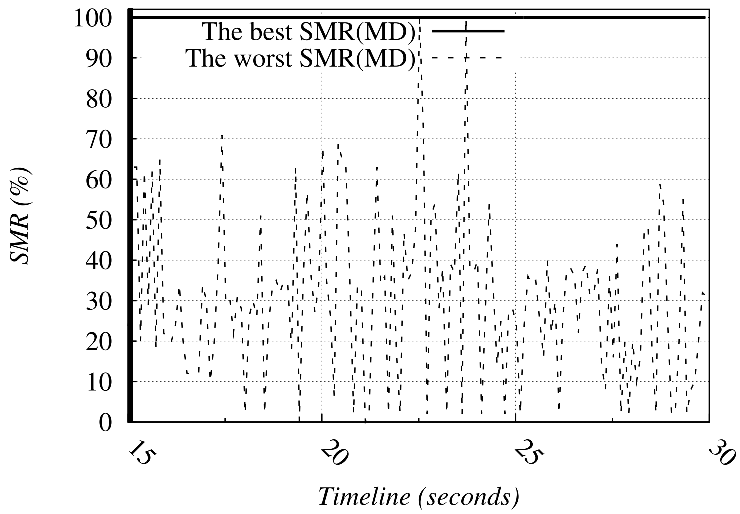

Figure 5: *SMR fluctuations over time of two individual vehicles that experience the best and the worst SMR, respectively, when VD is approximately 50. It shows that there is a clear difference between the best and the worst cases. The graph shows the results of an arbitrary simulation.*

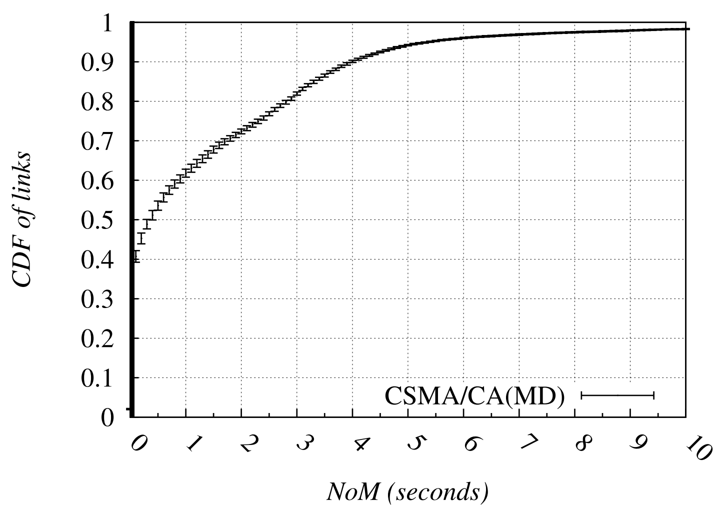

Figure 6: *CDF of links by their NoM (the longest no message interval), when VD is approximately 50. In the graph, a point indicates that y% of links have at most x seconds of NoM. The result shown is an average of ten simulations with a confidence interval of 99%.*

encounter interval.

3.3 Summary of the evaluation

This section summarizes the main findings of the evaluation. We conclude the following:

- The HN problem is the main cause of the *SMR* degradation when the network is unsaturated. Once it is saturated, the NN problem reduces the *SMR* dramatically. Therefore, the latter one is more a network congestion problem. In fact, this congestion problem is well-known and addressed in many works, e.g., [5], [7], and [21]. The main approaches are

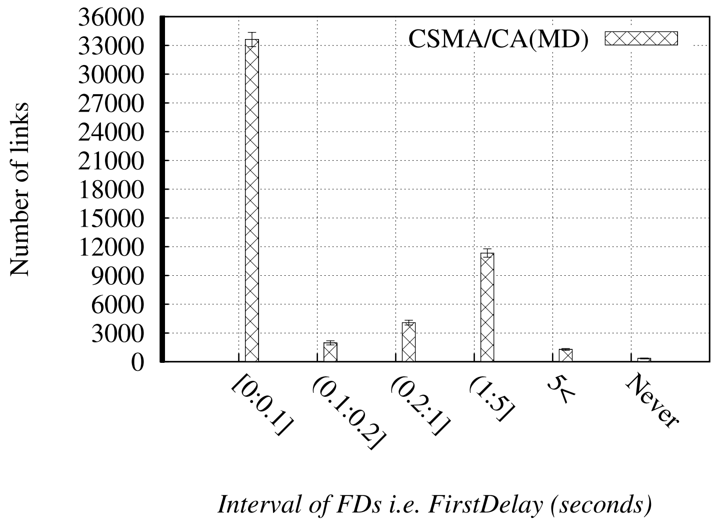

Figure 7: *Distribution of links by their FD (delay to discover a new neighbor), when VD is approximately 50. The graph presents 5 different intervals of FD. The last interval "Never" means that some vehicles never discover its neighbors. The number of links for "5<" and "Never" are 1280±95 and 350±50, respectively. The result shown is an average of ten simulations with a confidence interval of 99%.*

to reduce beacon generation rate, beacon size, or to reduce the CR which are indeed all derived from (22).

- The impact of the HN problem is clearly revealed by an unfair *SMR* distribution and the delay characteristics such as long lasting no message interval and first delay.
- The aforementioned quality impacts are mainly due to synchronized HNs, because vehicles traveling on a highway, particulary those traveling in the same direction could have a rather static topology for a relatively long period, i.e., in the order of multiple seconds[2]. In that topology, some vehicles could be incidentally synchronized as HNs which leads to a systematic message loss. It can be explained by a simple scenario where two vehicles are moving forward in the same direction as illustrated in Figure 8. Assume further that the difference between the message broadcasting phases (ϕ) of the vehicles is less than a message transmission time that they do not have any contenders (i.e., no vehicle in the CR with the same phase). In that scenario, both vehicles would remain broadcasting nearly at the same time and the messages would always collide at receiving vehicles in the intersection of the CRs as described in Figure 1c.

4 Solution study on the collision problem in oPBC

We are interested in the collision problems, particularly the HN problem, when the traffic density is moderate or sparse, i.e., when the network is unsaturated. We assume that in that situation message loss is even more serious in terms of vehicle safety since the vehicles can have relatively

[2]When CR is 300m, two vehicles approaching each other from the opposite directions with a relative speed of 80m/s will have an encounter interval of 7.5s.

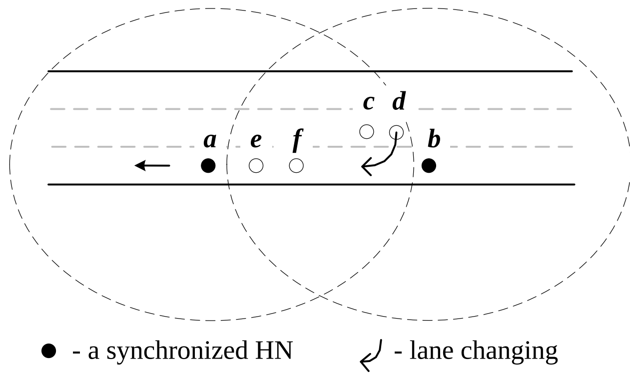

Figure 8: *This figure illustrates two examples of dangerous situations caused by synchronized HNs. Vehicles "a" and "b" are synchronized HNs. In the picture, vehicle "d" is changing lanes assuming it is safe to do so. Because "b is synchronized with "a", the driver of "d" is not informed about "b". Another case is a forward collision situation, where vehicle "a" is slowing down but "e" and "f" are not aware of this.*

high speeds. Therefore, such traffic conditions should have even stricter requirements on the communication. In the following sections, we look into three broadcasting schemes that can alleviate the impact of the collision problems. The key idea of these schemes is to break the synchronization between vehicles as much as possible to prevent the systematic message loss.

4.1 Scheme-1: Elastic scheme

The first approach is what we call the elastic scheme in which the initial phase of broadcasting is changed at a regular basis. In this scheme, the message activation time is defined as follows

$$a_i^{(k)} \stackrel{\text{def}}{=} \begin{cases} \phi_i & \text{if } k = 0 \\ a_i^{(k-1)} + T_i & \text{if } k > 0 \wedge (k + \phi_e) \bmod er_i \neq 0 \\ a_i^{(k-1)} + r(2T_i) & \text{if } k > 0 \wedge k \bmod er_i = 0 \end{cases} \tag{23}$$

where er_i is the elastic rate that defines how often the phase should be changed and r is a function that returns a random value within the given interval. This value defines how much the phase should be changed. ϕ_e is a phase for starting elasticity and it is given as $\phi_e = \lfloor r(er_i) \rceil$. To keep the expected number of generated messages the same as the strict periodic scheme, $2T_i$ is selected as the interval. The worst case delay between two messages is $2T_i$.

Figure 9, 11, and 12 show the results of this scheme in which we use the same er for all vehicles. From these graphs, we can make several interesting observations.

First, it is clearly seen that the more often the phase is changed, the better the elastic scheme improves the fairness and the delay characteristics. Particularly, the fairness is improved drastically even at the higher value of er. The reason for this result is the frequent change of phasing in the elastic scheme which affects the channel condition of the vehicle. Under the frequent change of the channel condition, the lifetime of a synchronized period of the vehicles (also a period of favorable channel condition of the vehicle) becomes shorter, i.e., highly likely to be at most the er period. Figures 10 and 11 reflect the effect of the short living synchronization when er is 6; we see somewhat discrete and step-like effects. As a result, each vehicle experiences more or less the same fluctuating channel conditions in the long run.

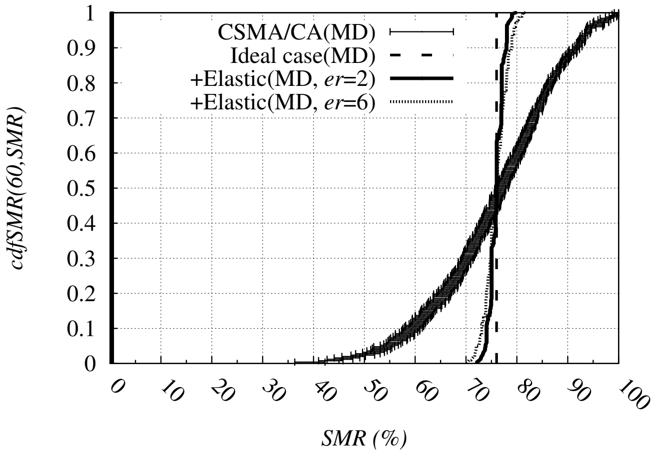

Figure 9: *The elastic scheme improves the fairness drastically, when VD is approximately 50. The result shown is an average of ten simulations with a confidence interval of 99%. For the elastic scheme, the confidence interval is* ± 0.3.

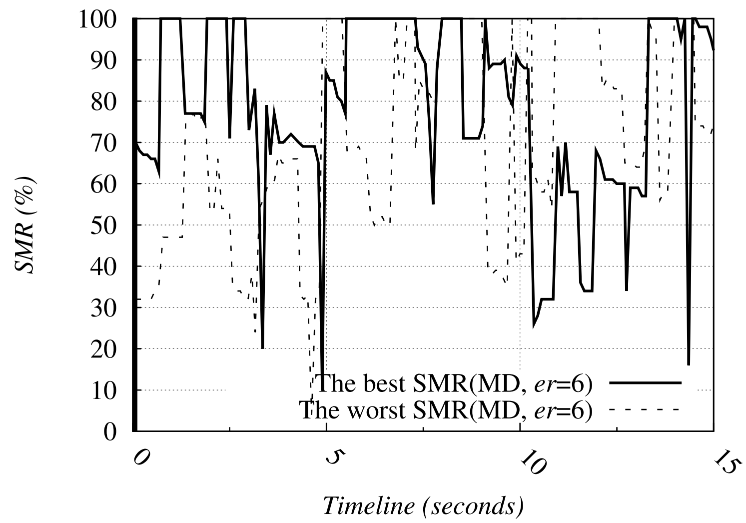

Figure 10: *SMR fluctuations over time of two individual vehicles that experience the best and the worst SMR, respectively, when VD is approximately 50. Compared to the pure CSMA/CA case, it is now hard to see any difference between the best and the worst cases. The graph shows the results of an arbitrary simulation.*

Second, in Figure 9 we can see that the elastic scheme does not affect SMR of the entire network. It only affects SMRs of individual vehicles. For example, in the case of pure CSMA/CA, roughly half of the vehicles shows SMRs between 75-100%, while the other half shows SMRs between 40-75%. But, in the case of elastic scheme, this is completely changed and all vehicles show more or less the same SMRs that is closer to SMR of the entire network. This is also seen in Figure 10 where the difference between the best and the worst cases are now hardly distinguishable.

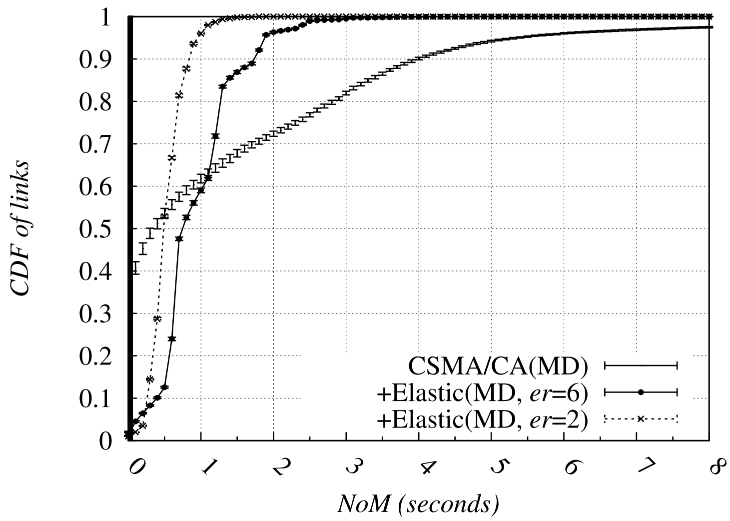

Figure 11: *The elastic scheme improves the NoM significantly, when VD is approximately 50. The result shown is an average of ten simulations with a confidence interval of 99%.*

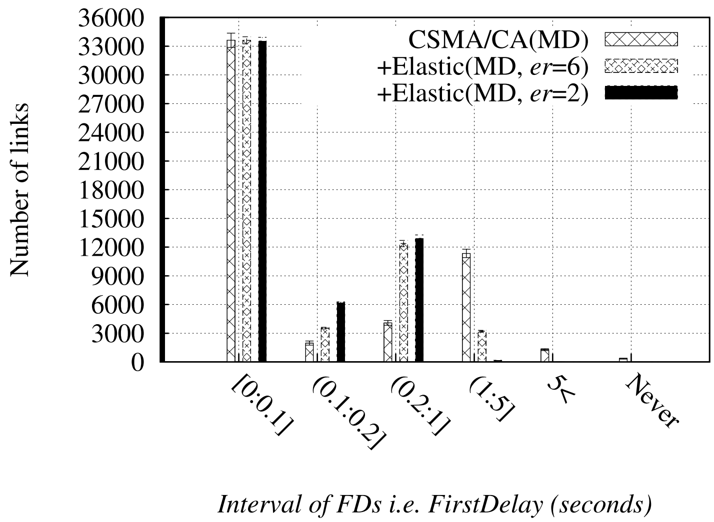

Figure 12: *The elastic scheme improves FD significantly, when VD is approximately 50. In case of "er=6", the number of cases for "5<" and "Never" are 15±7 and 0, respectively. In case of "er=2", the number of links for "5<" and "Never" are both 0. The result shown is an average of ten simulations with a confidence interval of 99%.*

4.2 Scheme-2: Jitter scheme

The second approach is what we call the jitter scheme in which the activation time is defined as

$$a_i^{(k)} = \phi_i + kT_i + AJ_i - r(2AJ_i), \tag{24}$$

where AJ_i is an activation jitter that has a granularity of one message transmission time (i.e., $AJ = N \leftrightarrow AJ = NT_d$). The worst delays between messages of this scheme, therefore, is equal to $T_i + 2AJ_i$.

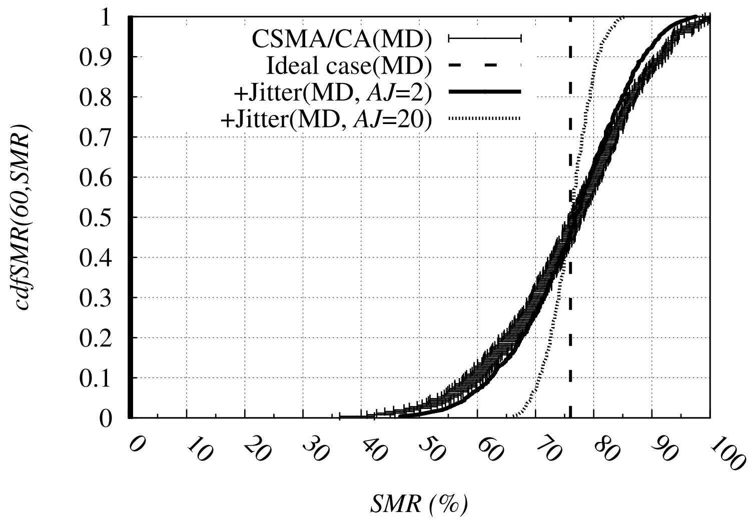

Figure 13: *The jitter scheme improves the fairness, when VD is approximately 50. However, it shows that a small jitter does not help much for improving the fairness. The result shown is an average of ten simulations with 99% confidence interval. For the jitter scheme, the confidence interval is* ± 1.0.

Again, we can make a number of observations. First, similar as the elastic scheme, the jitter scheme improves the *fairness* and the *delay* characteristics as shown in Figure 13, 14, 15 and 16. We chose the same AJ for all vehicles. The bigger AJ is chosen, the better the jitter scheme works. Note that a small jitter size does not show much improvement. Compared to the elastic scheme, the jitter scheme needs a bigger jitter size to improve the fairness though a small jitter size already works pretty well on the delay characteristics. This indeed makes sense, because, in the jitter scheme, the channel condition of a vehicle does not change completely compared to the elastic scheme. Let's say there are two vehicles synchronized with each other causing message collisions on their receivers. For the elastic scheme, we showed that the lifetime of such synchronization becomes relatively short. But, in the jitter scheme, the two vehicles would remain synchronized during their entire encounter interval. The jitter only sometimes helps to prevent the message collisions happening. In addition, we can say that the jitter scheme works better than the elastic scheme on the delay characteristics. Particularly, from Figure 16 we learn that the number of links on a 0.2-1s interval is much lower than the elastic scheme result.

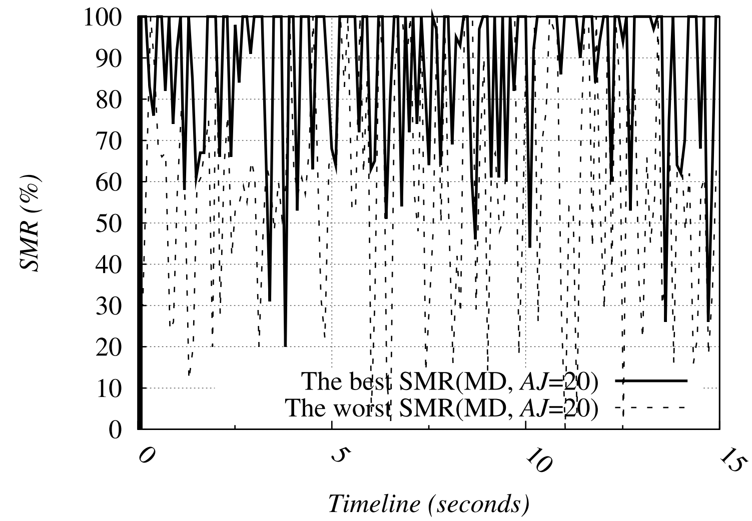

Figure 14: *SMR fluctuations over time of two individual vehicles that experience the best and the worst SMR, respectively, when VD is approximately 50. Compared to the elastic scheme, it looks more volatile. The graph shows the results of an arbitrary simulation.*

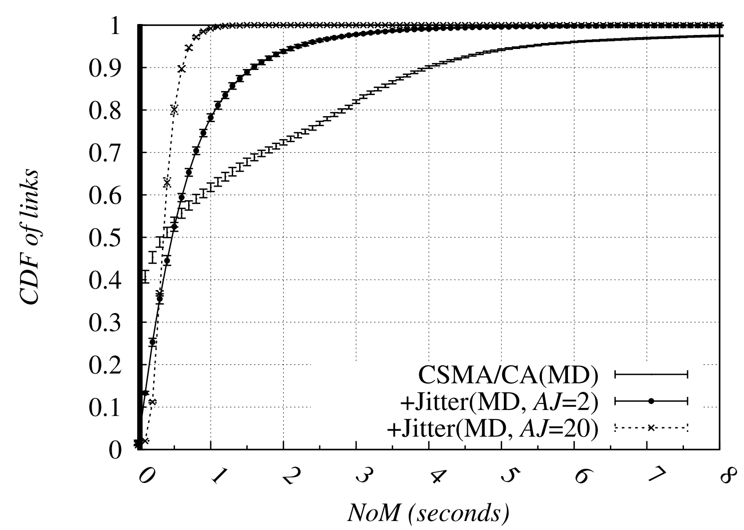

Figure 15: *The jitter scheme improves the NoM significantly, when VD is approximately 50. The jitter scheme performs better than the elastic scheme for this metric. In case of AJ=20, 60% of the links have less than 0.5s of NoM. The result shown is an average of ten simulations with a confidence interval of 99%.*

4.3 Scheme-3: Elastic + Jitter (EJ) scheme

In addition to the previous two schemes, we also look into a third approach which is a combination of the elastic and the jitter schemes. We call this scheme as the EJ scheme and it is defined

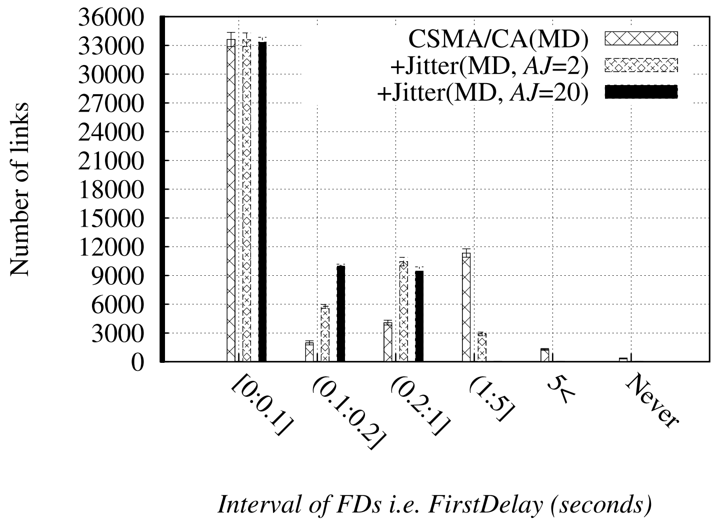

Figure 16: *The jitter scheme improves the FD significantly, when VD is approximately 50. In case of AJ=2, the number of cases for "5<" and "Never" are 31±6 and 29±9, respectively. In case of AJ=20, the number of cases for "5<" and "Never" are both 0. It shows that the jitter scheme performs better than the elastic scheme. In case of AJ=20, the number of the links in an interval of (0.2:1] is much lower. The result shown is an average of ten simulations with a confidence interval of 99%.*

as

$$a_i^{(k)} \overset{\text{def}}{=} \begin{cases} \phi_i & \text{if } k = 0 \\ a_i^{(k-1)} + T_i + AJ_i - r(2AJ_i) & \text{if } k > 0, (k + \phi_e) \bmod er_i \neq 0 \\ a_i^{(k-1)} + r(2T_i) + AJ_i - r(2AJ_i) & \text{if } k > 0, k \bmod er_i = 0 \end{cases} \tag{25}$$

As hoped, this solution outperforms both previous schemes as shown in Figure 17, 18, 20, and 19. This third solution features the advantages of both schemes. Similar as the elastic scheme, it does improve the fairness drastically. Similar as the jitter scheme, it improves the delay characteristics to a greater extent.

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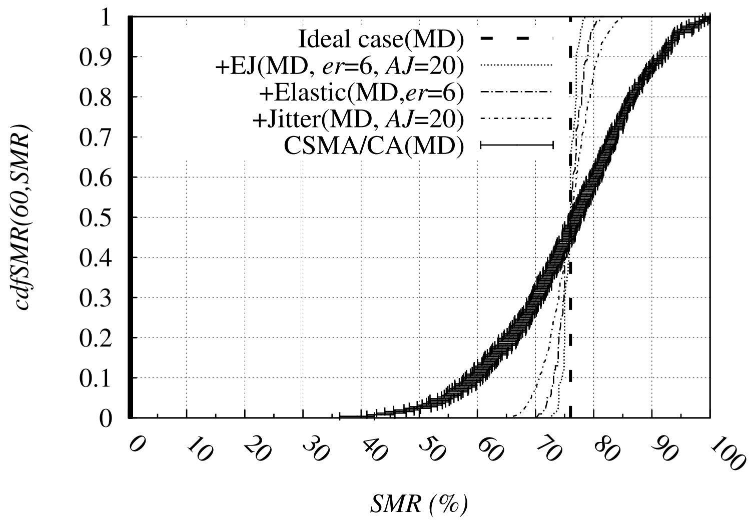

Figure 17: *The EJ scheme outperforms the jitter scheme and it is slightly better than the elastic scheme for improving the fairness. The result shown is an average of ten simulations with a confidence interval of 99%. For the elastic scheme, the confidence interval is* ± 0.3.

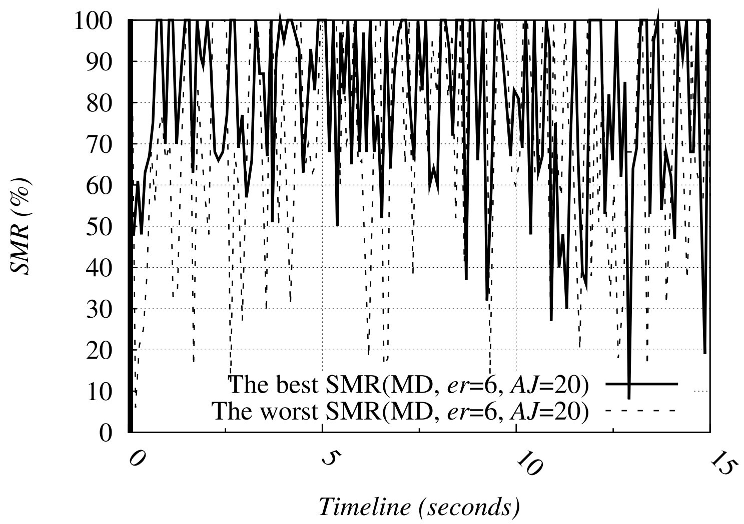

Figure 18: *SMR fluctuations over time of two individual vehicles that experience the best and the worst SMR, respectively, when VD is approximately 50. The graph shows the results of an arbitrary simulation.*

5 Related works

Performance studies of oPBC under CSMA/CA are carried out in many works. Here, we discuss the most relevant to our work. Computer simulation studies are done in [22, 17, 23] , analytical models for analyzing performance of oPBC are proposed in [20, 19] and a real-world experiment is carried out in [4]. In [22], J. Yin et al., measured message throughput and latency under an unsaturated network condition. The throughput is defined as the long-run average percentage of single-hop neighbors who successfully receive a broadcast message (*SMR* of the entire network).

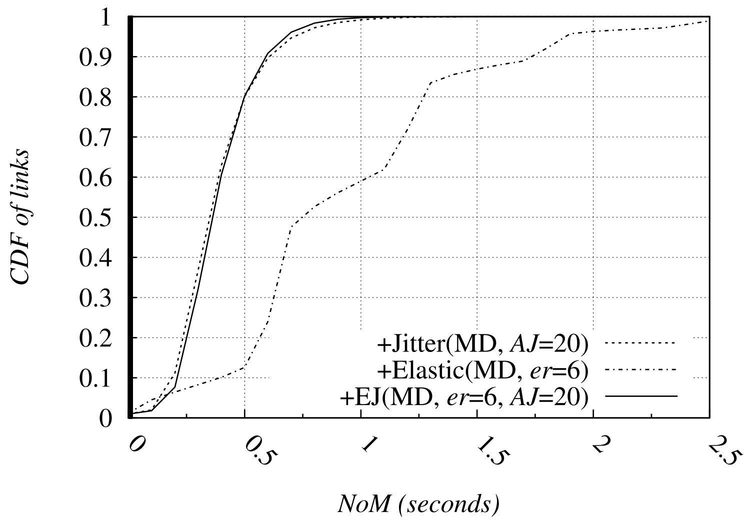

Figure 19: *The EJ scheme improves the delay characteristic by reducing NoM similar as the jitter scheme, when VD is ap- proximately 50. The result shown is an average of ten simulations with a confidence interval of 99%.*

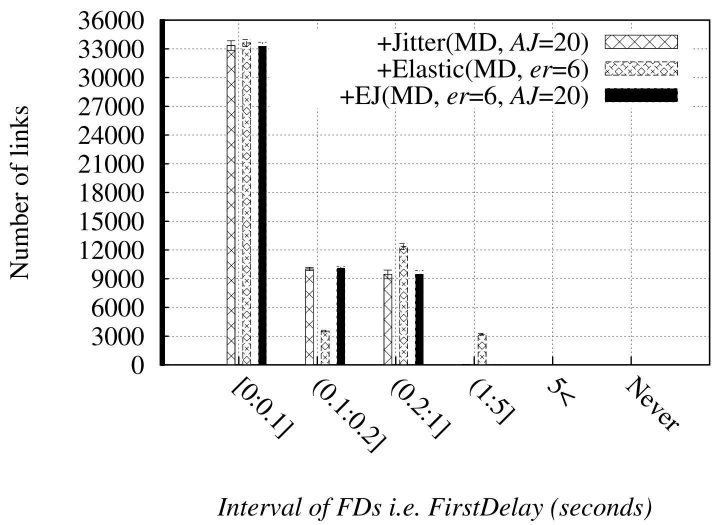

Figure 20: *The EJ scheme improves the delay characteristics similar as the jitter scheme. when VD is ap- proximately 50. In case of EJ scheme, the number of links for "5<" and "Never" are both 0, respectively. The result shown is an average of ten simulations with a confidence interval of 99%.*

The latency is defined as the long-run average time elapsing between sending a message at the source and successfully receiving ($f_i^{(k)} - s_i^{(k)} + \delta$) that message at a single-hop neighbor. They conclude that the latency is reasonably good whereas the throughput is moderate and needs improvement. It is not clear from their work what caused the moderate throughput. In [17], K. Bilstrup et al., analyzed a highway scenario with periodic broadcast of beacon messages. They particularly studied the "channel access time" ($s_i^{(k)} - a_i^{(k)}$) under saturated network conditions showing that a specific vehicle is forced to drop over 80% of its beacon messages because no channel access was possible before the next message was generated. As a result, they confirmed that some vehicles become invisible to surrounding vehicles for up to 10 seconds. Notably, the analysis is done at vehicle level rather than entire network level. They did not, however, consider the reception of messages. We think that "channel access time" is not a sufficient metric since the successful channel access does not guarantee the successful message delivery due to the collision and environmental problems. Also, it is more relevant to consider unsaturated conditions. In [23], T. Kuge et al., points out the impact of the HN problem on successful message reception in oPBC under unsaturated network conditions. They used a metric that is defined as "the rate of the messages which are received correctly against all the messages that are generated during measurement time (*SMR* of the entire network)". They confirmed that the number of message collisions that are caused by the HN problem is higher than that are caused by the contention problem. Moreover, they showed that changing CW size helps to reduce the collisions caused by contention. But, it has no effect on the collisions caused by the HN problem. Instead, they showed that the collision rate can be reduced to up to one-third of the conventional CSMA scheme by using a spread spectrum (SS) scheme. They do not provide any analysis on delay characteristics.

Xiaomin Ma et al., propose an analytic model in [19] for analyzing performance of emergency message transmission as well as oPBC. In their model, they take the 802.11 backoff counting process, the HN problem, unsaturated network, fading channel, and mobility into account. They use two metrics: a message reception rate that is defined as the ratio of the number of messages successfully received by all vehicles within the range of a sending vehicle to the number of messages transmitted (*SMR* of the entire network), and a message transmission delay that is the average delay a message experiences between the time at which the message is generated and the time at which the message is successfully received ($f_i^{(k)} - a_i^{(k)} + \delta$). With their model, they confirmed that the message delivery delay (less than 2ms) meets the requirement of the safety applications (500ms). However, the obtained message reception rates fail to meet reliability requirements for the safety critical messaging. A. Vinel et al., propose an analytic model in [20] for analyzing performance of oPBC under both saturated and unsaturated network conditions by two metrics: beacon message successful reception probability (*SMR* of the entire network) and mean beacon message transmission delay that is the time from the moment the beacon was issued until it has been transmitted ($f_i^{(k)} - a_i^{(k)}$). With the model, they found that the delay requirements are met, but the probability of successful message reception is rather low in typical scenarios. It is not clear whether they considered the HN problem in their model.

A very interesting real-world experiment is performed by F. Bai et al., in [4]. The work studied the environmental impact (e.g., fading, doppler, multi-path effect) on reliability of the 802.11p by an experimental set-up that includes a fleet of only three vehicles equipped with the 802.11p communication system. With this setup, the probability of having the collision problems is almost 0. In that sense, our work is complementary to this work since we study the impact of the collision problems (i.e., the other main reason of message loss besides the environmental impacts) on the quality of oPBC. The work judges the reliability of 802.11p using distribution of consecutive message losses (similar to NoM. Note, NoM is the longest no message interval.) together with the general metric "message delivery ratio". The message delivery ratio is calculated as a ratio of the number of data messages received at the receiver to total number of messages transmitted at the sender within some pre-defined time window ($SMR_{ij}(I)$). The work shows that the reliability of the 802.11p is adequate in a wide variety of traffic environments. Most importantly, they observed that the message losses do not occur systematically viz., there are almost no consecutive message losses between two certain vehicles even under the harsh freeway traffic environment.

All in all, we conclude the following: Two common metrics are widely used in these works. The first one is *SMR* of the entire network and the second one is an end-to-end delay (e.g., some define it as $f_i^{(k)} - s_i^{(k)} + \delta$ and some define it as $f_i^{(k)} - a_i^{(k)} + \delta$ or as $f_i^{(k)} - a_i^{(k)}$). These common metrics do not show or quantify the exact causes of a certain problem (e.g., the contention and HN problems). Namely, *SMR* of the entire network cannot show the fairness aspect and the end-to-end delay metric cannot show no message interval between two vehicles which is more relevant to vehicle safety applications that rely on oPBC. In addition, most of these works are a lack of formality.

6 Concluding remarks

In this final section, we summarize the main findings and achievements of this work. In addition, we shed some light on future research directions.

6.1 Main contributions

We regard the following four results as the main contributions of the paper. Among these, the biggest contribution of the work are the repairing schemes for improving the quality of oPBC.

First, a novel timing model of oPBC in the context of the 802.11p MAC has been defined. This model gives the foundation for a simulation model and for defining new more appropriate metrics to judge the communication quality from the perspective of the safety applications. Among others, we introduce concepts of "neighborhood of a vehicle", i.e., set of other vehicles that could receive its messages and "link", i.e., an encounter interval that starts when a vehicle B enters the Communication Range (CR) of another vehicle A and ends when vehicle B leaves the CR of vehicle A.

Second, new metrics based on the above concepts have been defined for judging the quality of oPBC in three of the most important aspects: Successful Message Ratio (*SMR*) for the *reliability*, cumulative distribution of *SMR* per vehicle for the *fairness*, No Message interval (*NoM*) (i.e., the longest interval in which no message is successfully delivered in a link), and First Delay (*FD*) (initial NoM) for the *delay* aspects respectively.

Third, an evaluation of oPBC is performed according to the simulation model under a strict periodic broadcasting scheme, i.e., each vehicle broadcasts messages in a strictly periodic manner. The evaluation reveals that the HN problem is the main cause of various quality degradations especially when the network is unsaturated. Once the network is saturated, the contention problem already reduces the *SMR* dramatically. A detailed evaluation is conducted on an unsaturated network condition where the traffic condition is sparse, i.e., 85 vehicles/km on a highway with three lanes per direction. We selects such condition because we assume that it is a typical highway condition. Besides, this condition is even more stringent in terms of vehicle safety since then vehicles have relatively high speeds. Such traffic condition, therefore, will have even stricter requirements on the communication quality, particularly, on the delay aspect. The evaluation results suggest that the HN problem causes unfair *SMR* distribution where the difference between the best and worst vehicles by their *SMR* is 65% in a simulation. Moreover, it causes long lasting consecutive message losses in a link of two vehicles. In some serious cases, a certain vehicle could not successfully deliver any of its messages to a particularly destination vehicle throughout an entire link interval. These quality issues are mainly due to synchronized HNs that can occur under the strict periodic scheme.

Fourth, we propose three simple but effective broadcasting schemes (i.e., elastic scheme, jitter scheme and a combination of these two schemes) to alleviate the impact of the HN problem. Though the three solutions do not affect the SMR (or reliability aspect) of the entire network, they do show significant improvements on the fairness and the delay aspects. Particularly, the combined scheme features the advantages of other two schemes for improving the communication quality in terms of the fairness and the delay aspects. These solutions are fully compatible with the 802.11p, i.e., they are application-level solutions and can therefore be easily introduced in practice.

6.2 Future directions

We are projecting the following future directions as our next steps:

- investigation of further broadcasting schemes (e.g., location and direction based scheduling) particularly for avoiding the collision problems;
- investigation of further combinations of different broadcasting schemes and their compatibility to each other (e.g., location based + jitter + predictive coding scheme);
- investigation of more adaptive schemes for the network congestion problem (e.g., dynamic message size or dynamic channel allocation i.e., switching between control and service channel);
- testing the proposed solutions with realistic traffic simulations and different traffic conditions (e.g., real traces of highway or urban roads);
- generalization of the solutions to domains (e.g., Mobile Ad-hoc Network or Wireless Sensor Networking).

7 Acknowledgement

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Appendices

A CSMA/CA

This section explains how CSMA/CA operates in periodic broadcast mode. Figure 21 shows a basic flowchart and Figure 22 gives a corresponding state machine diagram. According to CSMA/CA, when a station becomes ready to broadcast (Ready To Transmit (RTT)), the station must first check the channel for a duration of AIFS. If the channel has been idle for longer than AIFS, the station starts its transmission immediately. If the channel is busy or becomes busy during AIFS, the station must wait for the channel to become idle. 802.11 refers to this wait as *Access Deferral*. If access is deferred, the station first waits for the channel to become idle for AIFS again. If the channel is idle, the station must perform Bf procedure by starting a Bf timer which is set to a random number drawn from an interval of {0,1,. . . ,CW}. The timer has the granularity of a slot time and is decremented every time when the channel is sensed to be idle for a slot time. The timer is stopped in case the channel becomes busy and the decrementing process is resumed when the channel becomes idle again (i.e., idle for a duration of AIFS). The station is allowed to transmit its message when the Bf timer reaches zero. Depending on the channel condition, a station may experience multiple AIFS plus access deferrals. Note that the Bf counting is at most done once. If a new message arrives from the upper layer, then the current message must be dropped and the new message transmission will start.

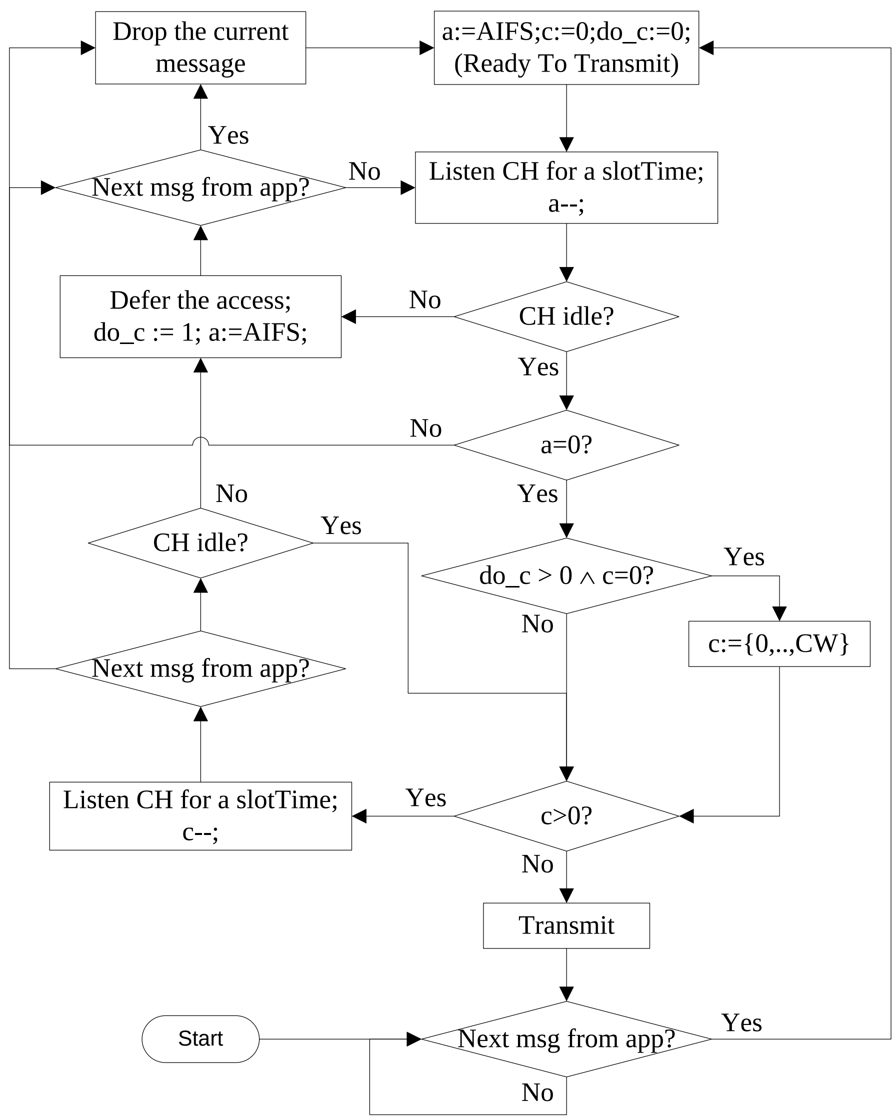

Figure 21: *CSMA/CA procedure in periodic broadcast mode*

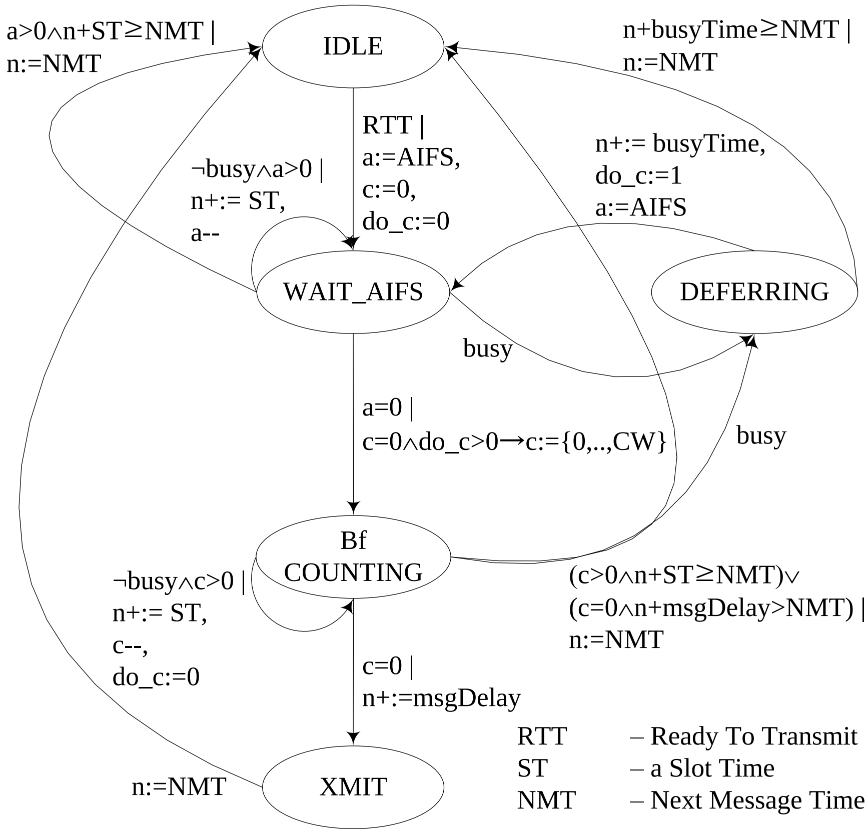

Figure 22: *CSMA/CA state machine*

As shown in the state machine diagram in Figure 22, each station is in one of the five states: IDLE, WAIT_AIFS, DEFERRING, Bf COUNTING, and XMIT. The station is in the IDLE state when it is neither in transmission nor RTT. In this diagram, we use several variables and constants to show the state transition conditions and timing changes.

- The "n" holds the current time.
- The "a" holds the current value of the AIFS counting.
- The "c" holds the current value of the Bf counting.
- The "do_c" is a boolean variable to indicate whether the station should perform the Bf counting.
- The "busyTime" is the duration of the channel being busy.
- The "msgDelay" is the duration of one message transmission.
- The "Next Message Time (NMT)" is the time at which the station becomes ready to transmit its next message.
- The "busy" to indicate the busy channel.
- The "AIFS" is the number of slots for the AIFS waiting and it is given by the standard.

- The "CW" is the number of slots for the Bf and it is given by the standard.
- The "a Slot Time (ST)" is the duration of one slot time and it is given by the standard.

B Signal reception model

There are generally two methods used for physical layer (or PHY) modeling in network simulations, namely SINR threshold based and Bit Error Rate (BER) based [22]. Under the former method, the receiver accepts the message when the computed SINR value is above the SINR threshold for a particular modulation scheme. The method based on BER decides whether or not a message is received successfully based on the message length and bit error rate deduced by the pre-computed BER versus SINR curve for every modulation scheme at the receiver.

In our case, the signal reception model is taken from the NS-2 implementation of 802.11p [18], where the signal reception decision is based on SINR ratio. In this model, three basic signal threshold concepts play a role. The first one is a Power Sense Threshold, $PsTh$.[3] If any receiving signal is equal to or greater than $PsTh$, the PHY will try to decode the signal. In addition, any signal equal to or greater than $PsTh$ is considered to be strong enough to interfere with any other signal. Therefore, such signal is added into the cumulative signal level of the receiver. The second threshold is the SINR threshold (or receiving threshold), $SrTh$. To receive a message successfully, the preamble must be received successfully. While a station is not transmitting nor receiving any signal, namely the PHY is constantly searching for a preamble and if a new signal arrives with a signal strength that is equal to or greater than $SrTh$ with respect to all other interfering signals plus noise, then the station will start receiving the signal as the preamble. If this SINR ratio holds for the entire duration of the preamble length, the PHY can finish the preamble reception successfully. Once the preamble is received successfully, the PHY will inform the MAC layer that the PHY is receiving a message and will continue until the complete payload has been received regardless of whether the signal level is greater or less than $SrTh$, unless the frame capturing feature is enabled. Note, the preamble includes information about payload (the length of payload, modulation scheme etc). In addition, if the receiving signal strength becomes less than $SrTh$ during the payload reception, PHY layer puts an error in the payload such that when the MAC layer checks the CRC of the received message it will not send the message to the application layer.

The third threshold is a carrier sense threshold, $CsTh$. If the cumulative power level of the receiver is equal to or greater than $CsTh$, then the PHY layer will inform the MAC layer that the channel is busy. From this, we can see that the MAC layer is informed about the channel status in two different ways. First, no matter what if the cumulative power is equal to or greater than $CsTh$, then the MAC is informed the channel is busy. Second, if the PHY layer successfully receives a preamble viz., start receiving a payload, the MAC layer is informed the channel is busy.

[3] Some concepts are rather misleading. In the document provided there are a RX threshold and a carrier sense threshold. But in the implementation there are a SINR threshold, a power sense threshold and a carrier sense threshold.