Model, analysis, and improvements for V2V communication based on 802.11p

Tseesuren Batsuuri
SI Department
MCS electronics, MCS group
Ulaanbaatar, Mongolia
tseesuren.b@mcs.mn

Reinder J. Bril
Mathematics and Computer Science
Eindhoven University of Technology
Eindhoven, The Netherlands
r.j.bril@tue.nl

Johan J. Lukkien
Mathematics and Computer Science
Eindhoven University of Technology
Eindhoven, The Netherlands
j.j.lukkien@tue.nl

***Abstract*—Future vehicle active safety applications will rely on one-hop Periodic Broadcast Communication (oPBC) based on a new standard IEEE 802.11p. 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. Our evaluation reveals that the Hidden Node (HN) problem is the main cause of various quality degradations especially when the network is unsaturated. We propose three simple but effective broadcasting schemes to alleviate the impact of the HNs.**

***Keywords*-One-hop periodic broadcast; vehicle-to-vehicle communication, 802.11p**

I. INTRODUCTION

Vehicle safety applications will use two basic communications: event-driven and time-driven. In the former case, a vehicle starts broadcasting a message for a certain duration periodically when a hazardous situation is detected and, hence, the messages are not sent in normal situation. In the latter case, each vehicle continuously performs oPBC to pro-actively deliver a beacon message to the neighboring vehicles to make each vehicle aware of its vicinity such that safety applications will leverage this to detect any hazardous situation in a timely manner. A lane change advisor and collision warning applications [1] are two typical examples which require a frequency of 10 messages per second with a maximum no message interval of [0.3sec,1.0sec] [1], [2], [3]. In addition, the applications pose a strict fairness requirement [4], [5], where each vehicle should have equal opportunity. 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 invisible to their surrounding vehicles.

When stations broadcast rather than making peer-to-peer communication the 802.11p's DCF does not use its full functions [6]. As a result, when all stations use broadcast-based communication, the collision problems, i.e., the contention and the HN problems increase. The purpose of our research is to understand the behavior of this oPBC based under varying load conditions 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 between two vehicles that are in their CRs.). In addition, we want to investigate possible improvements. The remainder of the paper is organized as follows. Section II introduces the mathematical model. Section III presents our evaluations. Section IV presents our improvements and Section V gives a conclusion.

II. MODEL OF oPBC

Here, 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 uses the traffic model's output as one of its input parameters. 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 [7]. In this work we are not concerned, however, with the traffic model and 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. The communication model has two parts: First, communication and radio channel model that generates the events. Second, timing model of communicating vehicles to define the concepts of interest.

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1) The communication and the radio channel model: We restrict ourself to describing the broadcast mode of the 802.11p DCF. 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 [8]. In addition, we choose the Two-Ray Ground (TRG) signal propagation model in order to study solely the effect of message collisions.

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 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

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

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

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

[1] $\delta \ll 1\mu s$ [9], [10]

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

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

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

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

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

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

During $eI_{ij}^{(k)}$ we say that there is a link from i to j and we call that the k^{th} such link.

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

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

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

$$\mathit{Tc}_i^{(k)} = \begin{cases} \mathit{MD} & \text{if (8)} \\ \mathit{XMT} & \text{otherwise} \end{cases} \quad (10)$$

$$\mathit{Rc}_{ij}^{(k)} = \begin{cases} \mathit{OOR} & \text{if } v_j \notin \downarrow\!\mathit{Nb}_i(tI_i^{(k)}) \\ \mathit{MC} & \text{if } v_j \in \downarrow\!\mathit{Nb}_i(tI_i^{(k)}) \;\wedge\; (9) \\ \mathit{Tc}_i^{(k)} & \text{otherwise.} \end{cases} \quad (11)$$

If $\mathit{Tc}_i^{(k)} = \mathit{XMT}$, message $m_i^{(k)}$ is broadcast successfully. If $\mathit{Rc}_{ij}^{(k)} = \mathit{XMT}$, 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 following three aspects: *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.

$$\mathit{Rs}_{ij}(I) = |\{k \mid tI_i^{(k)} \subseteq I \wedge \mathit{Rc}_{ij}^{(k)} = \mathit{XMT}\}| \quad (12)$$

$$\mathit{Ns}_{ij}(I) = |\{k \mid tI_i^{(k)} \subseteq I \wedge \mathit{Tc}_i^{(k)} = \mathit{XMT} \wedge v_j \in \downarrow\!\mathit{Nb}_i(tI_i^{(k)})\}| \quad (13)$$

The ratio is the successful message ratio in that interval.

$$\mathit{SMR}_{ij}(I) = \begin{cases} \frac{\mathit{Rs}_{ij}(I)}{\mathit{Ns}_{ij}(I)} & \text{if } \mathit{Ns}_{ij}(I) > 0 \\ 0 & \text{if } \mathit{Ns}_{ij}(I) = 0 \end{cases} \quad (14)$$

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

$$\mathit{SMR}_i(I) = \begin{cases} \frac{\sum_{v_j} \mathit{Rs}_{ij}(I)}{\sum_{v_j} \mathit{Ns}_{ij}(I)} & \text{if } \sum_{v_j} \mathit{Ns}_{ij}(I) > 0 \\ 0 & \text{if } \sum_{v_j} \mathit{Ns}_{ij}(I) = 0 \end{cases} \quad (15)$$

As a special case, $\mathit{SMR}_i(tI_i^{(k)})$ 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.

$$\mathit{SMR}(I) = \begin{cases} \frac{\sum_{v_i,v_j} \mathit{Rs}_{ij}(I)}{\sum_{v_i,v_j} \mathit{Ns}_{ij}(I)} & \text{if } \sum_{v_i,v_j} \mathit{Ns}_{ij}(I) > 0 \\ 0 & \text{if } \sum_{v_i,v_j} \mathit{Ns}_{ij}(I) = 0 \end{cases} \quad (16)$$

At the network level an interesting question is: how does $\mathit{SMR}([0,T))$, 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.

$$\mathit{cdfSMR}(I,x) = \frac{|\{v_j \mid \mathit{SMR}_j(I) \leq x\}|}{N} \text{ , for } 0 \leq x \leq 1 \quad (17)$$

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.

$$\mathit{NoM}_{ij}(I) = \sup\ \{|J| \mid J \subseteq I \wedge \mathit{Rs}_{ij}(J) = 0\} \quad (18)$$

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.

$$\mathit{FD}_{ij}([a,b)) = \sup\ \{x \mid [a, a+x) \subseteq [a,b) \wedge \mathit{Rs}_{ij}([a, a+x)) = 0\} \quad (19)$$

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.

III. Evaluation of oPBC under CSMA/CA

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

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

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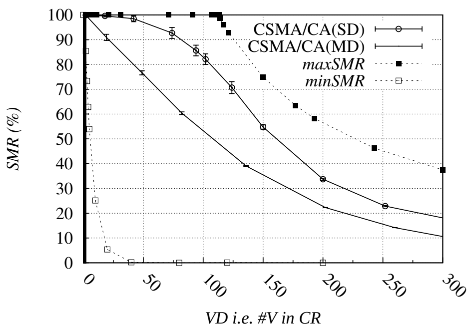

Figure 1. *Successful Message Ratio (SMR) of the entire network with respect to the vehicle density (VD) shows the reliability. maxSMR, minSMR are the max and min possible SMR, the former is calculated analytically and the latter is obtained through simulations. SD (Single Domain) case shows SMR degradation only due to the contention problem since all vehicles are deployed at fixed locations within a single CR (i.e., no HNs). MD (Multi-Domain) shows SMR degradation due to both the contention and HN problems (vehicles are deployed on a 3km long highway). CI = 99%.*

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 strength (300m), the same broadcasting period (0.1seconds), the same message size (555 bytes) fixed over time for all vehicles. The evaluation is based on 1 minute of simulation.

Simulation results: 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 1. For each different *VD* case, we performed ten simulations with a different random seed for selecting the initial phases. Figure 1 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

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

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

$$SP = \frac{T}{T_s + T_d}, \qquad (22)$$

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 roughly the same phases for all vehicles. From Figure 1, the HN problem appears to be the main cause of *SMR* degradation when the 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 2 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, however, the fact is 65%. Figures 3 and 4 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), 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 3, 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 4, many vehicles, i.e., about 350±50 are seen that did not even discover

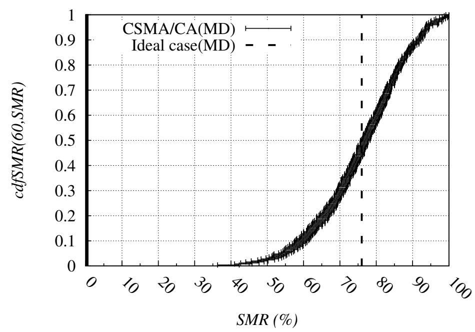

Figure 2. *This shows the fairness through CDF of vehicles by their SMR. In the graph, a point indicates that y% of vehicles have at most x% SMR. In an ideal fair case, the dashed line is expected where all vehicle should have the same SMR that is equal to SMR of the entire network.VD = 50, CI = 99%*

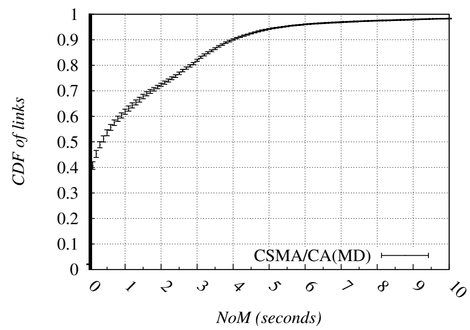

Figure 3. *CDF of links by their NoM (the longest no message interval). In the graph, a point indicates that y% of links have at most x seconds of NoM. VD = 50, CI = 99%.*

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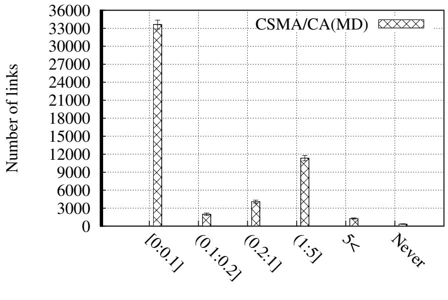

Figure 4. *Distribution of links by their FD (delay to discover a new neighbor). The graph presents 5 different intervals of FD. The last interval "Never" means that some vehicles never discover its neighbors. The number of links for "5<" and "Never" are 1280±95 and 350±50, respectively. VD = 50, CI = 99%.*

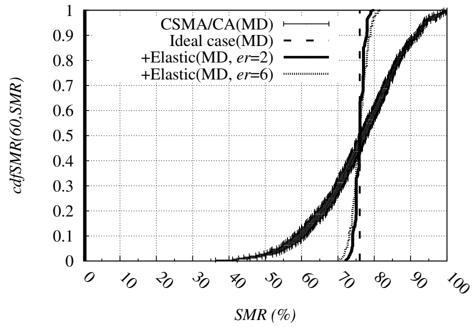

Figure 5. *ES improves the fairness drastically (VD = 50, CI of 99%, for ES, CI = ±0.3).*

some of their one-hop neighboring vehicles for their entire encounter interval. Based on the above results, we conclude that 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., [3], [5], and [11]. The main approaches are 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 *NoM* and *FD* 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 [2]. In that topology, some vehicles could be incidentally synchronized as HNs which leads to a systematic message loss.

IV. SOLUTION FOR IMPROVING THE QUALITY OF OPBC

We look at situations where the traffic density is moderate or sparse, i.e., unsaturated. We assume that in that situation message loss is even more serious in terms of safety since the vehicles have relatively higher speeds. Therefore, such situations should have even stricter requirements on the communication.

Elastic scheme (ES): In ES, the initial phase of broadcasting is changed at a regular basis. The message activation time is defined as follows

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

[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.

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 5, 6, and 7 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 which is in result of frequent change of phasing in the elastic scheme that changes the channel condition for the vehicle. Under changing 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. Figure 6 reflects 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. Second, in Figure 5 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.

Jitter Scheme (JS): In JS, 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 $T_i + 2AJ_i$. Again for observations, first, similar as ES, JS improves the *fairness* and the *delay*

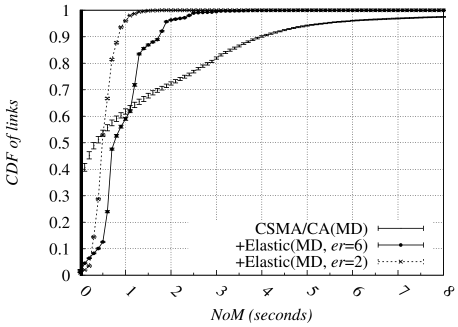

Figure 6. *ES improves the NoM significantly (VD = 50, CI = 99%).*

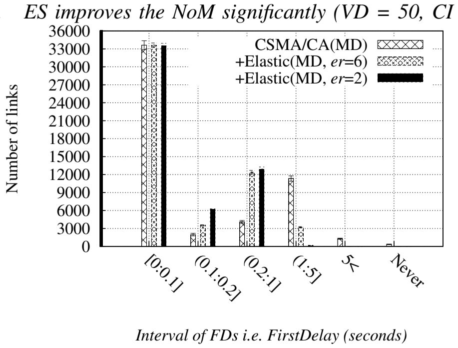

Figure 7. *ES improves FD significantly. When "er=6", the number of cases for "5<" and "Never" are 15±7 and 0, respectively while "er=2", these are both 0 (VD = 50, CI = 99%).*

characteristics as shown in Figure 8, 9 and 10. We chose the same AJ for all vehicles. The bigger AJ is chosen, the better JS works. Note that a small jitter size does not show much improvement. Compared to ES, JS 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 JS, the channel condition of a vehicle does not change completely compared to the ES. Let's say there are two vehicles synchronized with each other causing message collisions on their receivers. For ES, we showed that the lifetime of such synchronization becomes relatively short. But, in JS, 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 JS works better than ES on the delay characteristics. Particularly, from Figure 10 we learn that the number of links on a 0.2-1s interval is much lower than that of ES.

Elastic + Jitter scheme (EJS): 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, namely EJS defined as

$$a_i^{(k)} \stackrel{\text{def}}{=} \begin{cases} \phi_i & \text{if } k = 0 \\ a1 & \text{if } k > 0, (k + \phi_e) \bmod er_i \neq 0 \\ a2 & \text{if } k > 0, k \bmod er_i = 0 \end{cases} \qquad (25)$$

where $a1 = a_i^{(k-1)} + T_i + AJ_i - r(2AJ_i)$ and $a2 = a_i^{(k-1)} + r(2T_i) + AJ_i - r(2AJ_i)$, respectively. As hoped,

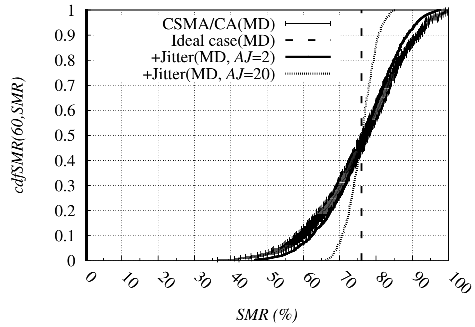

Figure 8. *JS can improve the fairness for bigger jitter size. (VD = 50, CI of 99%, for JS, CI = ±1.0)*

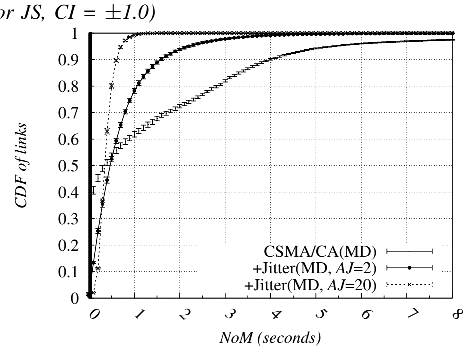

Figure 9. *JS improves the NoM significantly. In case of AJ=20, 60% of the links have less than 0.5s of NoM (i.e., better than ES). (VD = 50, CI = 99%).*

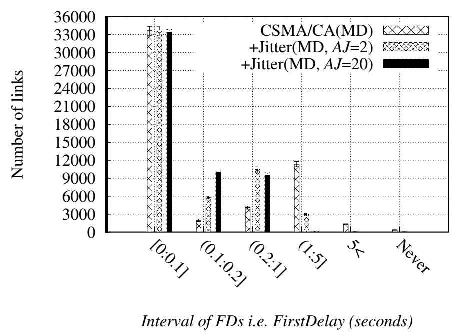

Figure 10. *JS improves the FD significantly. In case of AJ=2, the number of cases for "5<" and "Never" are 31±6 and 29±9, respectively. In case of AJ=20, these are both 0 and the number of the links in an interval of (0.2:1] is much lower. (VD = 50, CI = 99%)*

this solution outperforms both previous schemes as shown in Figure 11, 13, and 12. This third solution features the advantages of both schemes. Similar as ES, it does improve the fairness drastically. Similar as JS, it improves the delay characteristics to a greater extent. .

V. Concluding remarks

We regard the following two as the main contributions. The first is an evaluation of oPBC, where we reveal that the HN problem is the main cause of various quality degradations especially when the network is unsaturated. The detailed study shows that the (synchronized) HN causes unfair *SMR* distribution and long no message interval in a

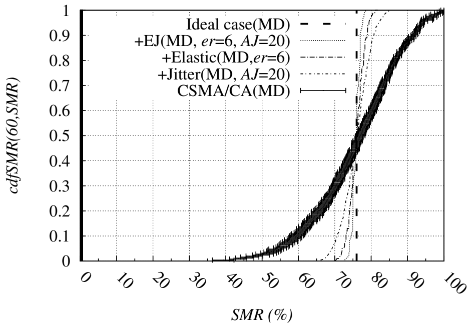

Figure 11. *EJS scheme outperforms JS and it is slightly better than ES for improving the fairness (CI = ±0.3, 99%).*

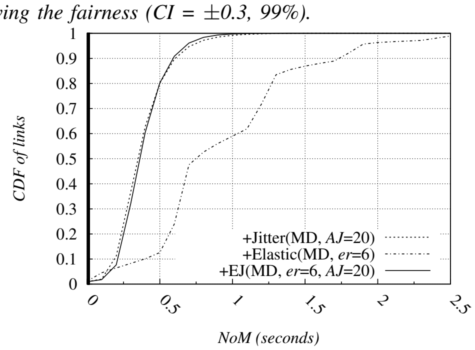

Figure 12. *EJS improves the delay characteristic by reducing NoM similar as JS (VD = 50, CI = 99%).*

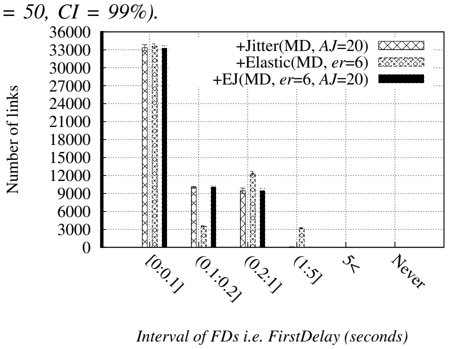

Figure 13. *EJS improves the delay characteristics similar as JS (In case of EJS, the number of links for "5<" and "Never" are both 0, respectively. VD = 50, CI = 99%).*

link of two vehicles. In some cases, such no message interval equals to an entire link interval. The second contribution is three simple but effective broadcasting schemes to fix the above issue that are fully compatible with the 802.11p and can be very applicable in practice. 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 delay aspects.

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