IEEE Open Journal of
Intelligent Transportation
Systems

Received 5 January 2023; revised 1 June 2023; accepted 26 December 2023. Date of publication 2 February 2024; date of current version 4 April 2024.

Digital Object Identifier 10.1109/OJITS.2024.3361473

Addressing Rare Outages in C-V2X With Time-Controlled One-Shot Resource Scheduling

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This work was supported by the Ford Motor Company's Initiative on Vehicular Communication Research.

ABSTRACT Cellular Vehicle-to-Everything (C-V2X) has become one of the most anticipated technologies for vehicular safety network. In LTE C-V2X Basic Safety Messages (BSMs) are transmitted on radio resources that are allocated with a periodic resource reusability. This allocation is based on a semi persistent sensing-based scheduling scheme (SPS) algorithm. But, due to this reuse of periodic resources, the possibility of loss of consecutive packets between the same vehicle pair is significant. This study discusses different approaches proposed to solve this consecutive loss problem. Based on this investigation, this article suggests an efficient One-Shot based solution with a new control parameter, that performs superior to the state-of-the-art solution that is standardized in SAE J3161/1 which this article analyzes and shows to have limitation in case of high-density scenario.

INDEX TERMS C-V2X, Mode-4, LTE, 3rd generation partnership project (3GPP), one-shot, SAE J3161/1, information age, IA.

I. INTRODUCTION

INTELLIGENT Transportation System (ITS) community has been undergoing research and development of basic vehicular safety communication technology for years since allocation of 5.9 GHz band for this purpose. The 2020 FCC [1] review of the progress shows a sense of urgency in that endeavor. 3rd Generation Partnership Long Term Evolution (3GPP-LTE) based Cellular Vehicle-to-Everything (C-V2X) is one of the major contenders of vehicular ad-hoc networking (VANET) technologies considered to be deployed in USA. This technology is considered superior to other similar technologies in performance and reliability. But studies like [2]–[4] show that this technology has limitations, such as, its susceptibility to a prolonged consecutive loss of information. This problem happens between pairs of communicating vehicles causing them to stay blind to each other from a network perspective for a long period of time. This phenomenon is investigated thoroughly from a system safety perspective in the following sections. Currently there are several proposals from different study groups as solutions to this blind scenario. Especially, the Society of Automotive Engineers (SAE) has already standardized a One-Shot based resource allocation scheme to mitigate this problem. This current article takes a deep dive into this solution which reveals the incompatibility of this scheme with the standardized congestion control algorithm, in case of high congestion traffic scenario. This detailed study leads to the discovery of a novel and robust One-Shot based solution, by introducing a time-controlled parameter to it. This introduction of this parameter results in improvement the performance of the algorithms, in terms of information quality and tracking of vehicular positions.

II. BACKGROUND AND MOTIVATION

V2X is a combined umbrella terms for features of Vehicle-to-vehicle (V2V), Vehicle-to-Network (V2N), Vehicle-to-Infrastructure (V2I) and Vehicle-to-pedestrian (V2P) technology as described in [5]. In 2017, 3GPP introduced vehicular communication as a separate feature in Long Term Evolution (LTE) release 14. It is known as LTE-V2X or more generally C-V2X. LTE is heavily dependent on

The review of this article was arranged by Associate Editor Emmanouil Chaniotakis.

network infrastructure in general. But C-V2X scheme allows special ad-hoc basic safety communication on road, with or without cellular coverage. For that purpose, 3GPP defines two special modes of communications, termed Mode-3 and Mode-4. The former allows Evolved Node B (eNodeB) assisted resource management while the latter one uses co-operative unassisted resource management for Vehicular User Equipment (VUE). The link level performance of C-V2X demonstrates a superiority over other technologies, due to its use of high efficiency coding [6]. Moreover, under heavy traffic and out-of-coverage scenarios, several research exhibits higher overall system performance for C-V2X based on different evaluations. But, as a distributed ad-hoc network, C-V2X Mode-4 cannot detect and avoid a collision before or during it happens. Hence, it must follow a distributed control architecture [7], where decision of transmission is based on measurement, estimation, and control input for each vehicle. Due to the probabilistic nature of this method, a rare but unique phenomenon of communication outage between nodes happens. This was discovered alongside. Toghi et al. in [4] demonstrated an exceptionally high Inter-packet-gap (IPG), as shown in Fig. 3 & 7 in [4], from near distance. In another work from the same authors in [8] shows a phenomenon of so called 'dead nodes' where, a pair of nodes never hears from each other, despite having a comfortably lower distance in between and considerable reception rate from other simultaneously communicating nodes. The most detailed understanding of this phenomenon is explored in [3] by Bazzi et al., where the term 'wireless blind spot' is used to describe and analyze the phenomenon. It showed an impact on performance metrics on statistical tail analysis due to those blind spots. Another study [2] comparing 802.11p based Dedicated short-range communication (DSRC) and C-V2X with congestion control exhibits similar performance degradation due to such rare outage events despite having a higher reception rate in case of the latter, as reproduced in the Fig. 1. The first published attempt by [3] to get rid of such blind nodes works for a non-congested scenario. But when under higher traffic density is considered, the solution does not satisfy the latency requirements, as demonstrated later in this study. Another solution suggested by [9] introduces a new resource allocation scheme namely One-Shot. But this solution suffers similarly under congested traffic. The focus of this study is to investigate this problem in greater detail and introduce a unique solution to the problem that improves performance without known pitfalls.

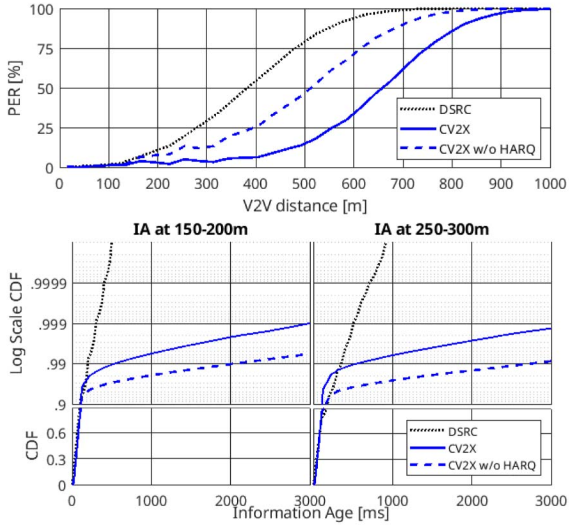

FIGURE 1. **Packet error rate (PER) and distribution of information age (IA) comparison between DSRC and C-V2X from low density traffic and Street Canyon Channel model simulation (detailed later).**

III. C-V2X: A SHORT INTRODUCTION

LTE C-V2X system follows the regular 3GPP LTE resource configuration. The 3GPP, in release 12, introduced LTE for device to device (D2D) communication as Proximity Services (ProSe) using PC5 radio interface, also known as Sidelink. C-V2X, which is developed using the same concept of ProSe technology [10], was first standardized by 3GPP release 14. The same standard is carried through the newer releases for broadcasting safety message, i.e., release 15 and 16. In these releases, some added features for other communication modes were also introduced which do not directly affect safety communications. Most importantly, release 16 introduces V2X for 5th Generation new radio devices, namely 5G NR-V2X. But this article focuses solely on the aspect of LTE system for V2X. Hence, limiting our scope of study and performance evaluation within 3GPP release-14 is adequate for this purpose. In LTE C-V2X, communication can happen under 4 different transmission (Tx) modes. One of those is Mode-4, which is designed for safety message broadcast specialized to facilitate a distributed resource allocation scheme. Any further references to C-V2X in this article assume the release 14 Mode-4 LTE C-V2X communication unless otherwise mentioned. This study also focuses mainly on transmission of BSMs. The following section discusses some relevant features of this C-V2X mode communication that will be used in this article.

A. RESOURCE BLOCK

In LTE standard, the whole radio bandwidth is abstracted into **Resource blocks (RB)**. In frequency domain each RB represents 180KHz radio bandwidth, which in time domain takes 1 ***subframe***. The time duration of 1 subframe for the C-V2X is defined as 1ms. With such division of resources, a 20 MHz bandwidth can host 100 RBs in a single 1ms subframe. For different Tx modes, these RBs can be grouped and used with different configurations. For C-V2X, the RBs are divided into several consecutive groups along frequency axis, which are called **subchannels**. Each subchannel consists of a fixed number of consecutive RBs on any given subframe. C-V2X standard forces the allocated resources for transmission of a single packet to reside within the same subframe, while each transmission may cover one or more subchannels within that subframe. For any such transmission, the first two RBs are used for transmitting

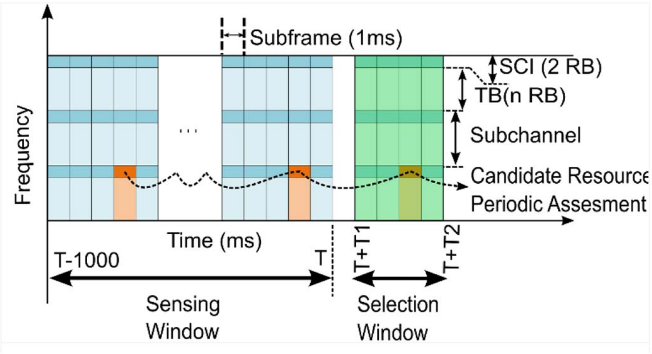

FIGURE 2. The SPS mechanism inside a simplistic visualization of resource block arrangements.

Sidelink control information (SCI). The remainder of the resources are for transmission of Transport Block (TB). SCI uses PSCCH (Physical Sidelink Control Channel), while TB is transmitted over PSSCH (Physical Sidelink Shared Channel). At the receiver side, the SCI must be decoded first to gain information about the frequency resources, i.e., number of RBs, etc. for successful reception of the TB part.

B. SEMI-PERSISTENT SCHEDULING MECHANISM

Optimization through minimizing collision among radio transmissions is a major goal of any Media Access Control (MAC) resource scheduling protocol. LTE C-V2X uses a semi persistent sensing-based scheduling scheme (SPS) for this purpose. The detailed procedure is discussed in [9]. Here we give a brief introduction to this procedure. In this scheme a VUE node reserves several future periodic resources using a single scheduling procedure for multiple expected transmissions. This scheduling mechanism requires channel sensing information and reception log of past 1000 subframes. This helps to predict the least busy resources in the future. With every packet data-unit (PDU) arrival from higher layer to MAC queue, the MAC decides to either request a new resource grant for it or reuse already allocated resources. In case of new resource grant, Physical Layer (PHY) performs SPS to schedule the required number of resources [9], [10]. As visualized in Fig. 2, the process selects a region of all eligible resources, termed 'candidate resource' $R_{x,y}$ in future, and put it in a 'CandidateList' with a predefined delay limit between $T1$ and $T2$, called selection window. Let's term the number of $R_{x,y}$ as N_c. $T1$ and $T2$ may vary from (0∼4ms) and (20∼100ms) respectively based on packet priority or QoS requirement. Each candidate resource contains 2-RB for SCI and n-RB for TB, where n depends on the respective packet size and configured Modulation and Coding Scheme (MCS). Now Each of the $R_{x,y}$ is matched to multiple resources from the 1000 subframe sensing window, based on a periodicity. This periodicity is determined from parameters P_{rsvpRX} and P_{step}.

$R_{x,y}$-s, for which any SCI was received at its corresponding sensed-resources, are removed from the list if Reference Signal Received Power (RSRP) at the PSCCH for any of that SCI reception $P_{RSRP-SCI}$ goes over a certain predefined SPS-threshold Th_{SPS}. The remaining resources R_{remain} are then sorted based on the average Received Signal Strength Indicator (RSSI).

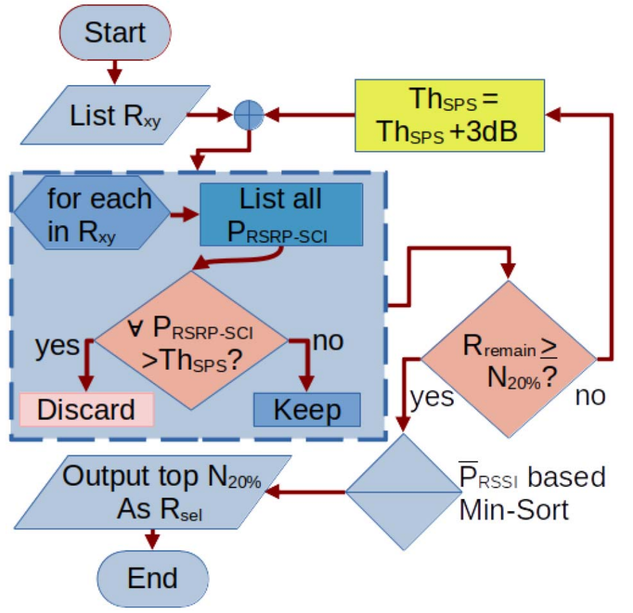

FIGURE 3. The SPS mechanism flow diagram.

There is hard requirement that, at least 20% of the initial $R_{x,y}$ needs to stay in R_{remain} after the removal. Otherwise, the procedure will be repeated using a 3dB higher SPS-threshold, until this R_{remain} reaches the required number of $N_{20\%} = N_c \times 0.2$ resources. Finally, $N_{20\%}$ resources with least RSSI average $\overline{P}_{RSSI}$ are reported as selected resource list R_{sel}. MAC randomly selects one or more resources from R_{sel} for a single packet transmission. These selected resources are then marked as *allocated resource grant* for future transmissions of same priority packets with a periodicity calculated from P_{rsvpTX}, i.e., 100ms. Fig. 3 shows the flow diagram for the SPS steps explained here.

In J3161/1, Higher Priority Messages (HPMs) are configured to be granted a single use resource allocation SPS, termed One-Shot. This resource is allocated through an individual but separate SPS queue, which is different from the regular periodic SPS resource flow.

C. RESOURCE RESERVATION MECHANISM

The periodic resources that are allocated for future transmissions have an expiration policy based on transmission requirement. This 'reservation' may expire anytime if the reserved resource amount becomes insufficient for transmission of a future packet. In that case, a new SPS would be required. There are a few other ways by which the reserved resource selection can be discarded, such as:

1) COUNTER BASED RESERVATION

A Sidelink Resource Reselection Counter (SLRRC) is used to track reusage of resources after each transmission. SLRRC

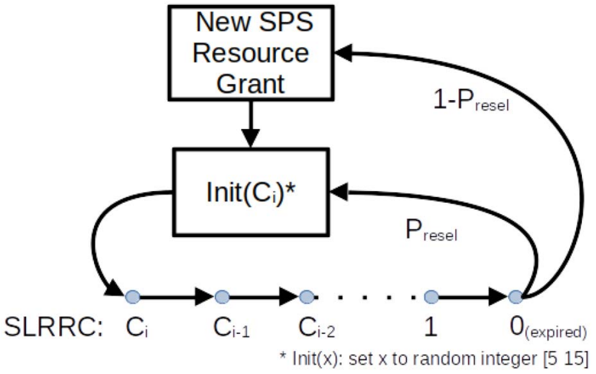

FIGURE 4. **The Resource Reuse and Reselection mechanism. C_i denotes SLRRC value and updates with each transmission reusing the SPS resource grant.**

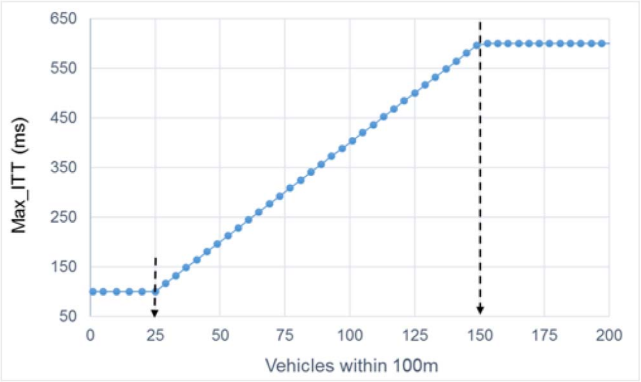

FIGURE 5. **Rate control in SAE J3161/1.**

resets to a random value initially selected between a range of integers, i.e., [5], [15], after the resource grant is obtained. This counter decrements with each Tx using that resource, until it reaches zero. On such expiration of SLRRC, the VUE MAC probabilistically attempts to re-schedule the same periodic resource for another batch of future transmissions. This probability of keeping the resource is termed **KeepResProbability** (P_{resel}). In case this random trial fails, the reserved resource pool gets discarded and a new SPS selection is scheduled for the next transmissions in future. This SLRRC mechanism is depicted in Fig. 4.

2) MISSED TRANSMISSION OPPORTUNITY BASED

If Tx opportunity at the allocated periodic SPS resource either remains unused longer than a predefined duration, i.e., 1sec, or missed a few numbers of times defined by **ResReselectAfter** consecutively**,** then the reserved resource grant gets discarded and new selection is required for next Tx.

For C-V2X, 3GPP allows up to 1 Hybrid Automated Repeat Request (HARQ) for adding redundancy in received codewords, making it total two transmissions per packet. Both transmission and retransmission (ReTX) resources are selected through the SPS as a single resource grant and reside within 15ms of each other.

D. CONGESTION CONTROL CHALLENGES IN C-V2X

Distributed Ad-hoc wireless connection technologies, such as connected vehicles, need to employ congestion control algorithms (CCA) to deal with high congestion scenarios. Compared to extensive line of research in CCA for DSRC (802.11p) optimization, CCA for LTE C-V2X is newer. In the USA, SAE has recently released its CCA as part of the standard, namely SAE J3161/1 [11] for C-V2X.

SAE J3161/1 lacks any Transmission Power Control (TPC) for its CCA, as studies such as [12] shows reducing Tx power at high network load, does not leave any positive impact on C-V2X system congestion. Instead in lower density, the reduced Tx power causes loss of packets due to reduction of signal interference to noise ratio (SINR). On the other hand, rate control (RC) based on vehicular density in C-V2X shows a significant gain in packet reception rate (PRR). Equation (1) denotes the RC for C-V2X-CCA in this study. RC works based on an estimation of local vehicle density N_s, defined as number of participating vehicles within 100m distance of a host VUE. Value of N_s is determined using the number of unique senders of successful BSM receptions (Rx) over a 5 sec sliding window (k). This value is evaluated every 1sec. The resultant rate of Tx is determined using Equation (1). The RC starts to take effect as soon as the $N_s$reaches a minimum threshold β, and the maximum inter-transmission-time (Max_{ITT}) of BSM. Max_{ITT} increases from 100ms to the calculated value from the equation. There is an upper limit for Max_{ITT}, beyond which any increase in N_s does not increase Max_{ITT}. That upper limit is selected to be $itt_{\max}$=600ms. It is worth noting that BSM may get transmitted even earlier than implied by this equation. For example, critical events may require sending BSM immediately or application may detect a higher loss phenomenon and may request immediate transmission of packets.

$$Max_{ITT}(k) = \begin{cases} 100, & \text{if } N_s(k) \le \beta \\ N_s(k)\frac{100}{\beta}, & \text{if } \beta < N_s(k) \le \frac{itt_{max}}{100}\beta \\ itt_{max}, & \text{if } \frac{itt_{max}}{100} \times \beta \le N_s(k) \end{cases} \tag{1}$$

CCA addresses a lossy channel condition by sending earlier than scheduled if a passive estimation of Tracking Error (TE) gives high value. This early probabilistic transmission is decided by the application at each Control Interval using the Equation (2). Here, k denotes the k^{th} Control Interval which usually matches the P_{step}. On special cases, higher priority messages (HPM) also ignore RC configuration to send immediate Tx packets.

$$p(k) = \begin{cases} 1 - e^{-a\times|err(k)-T|^2}, & \text{i}T \le err(k) < S \\ 1, & \text{if}eff(k) \ge S \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

IV. RARE PROLONGED COLLISIONS IN C-V2X

As discussed earlier in Section II-B, C-V2X uses periodic resources, allocated through SPS, for BSM transmission.

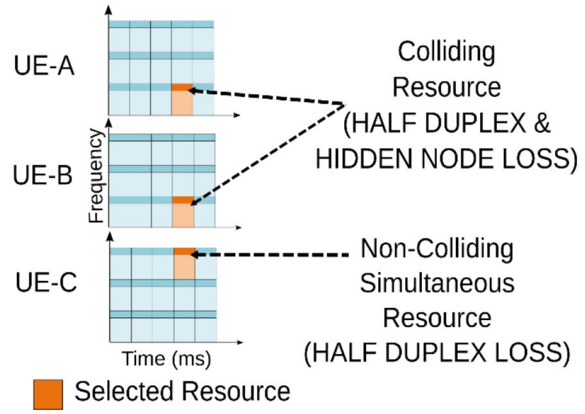

FIGURE 6. Near distance loss categories.

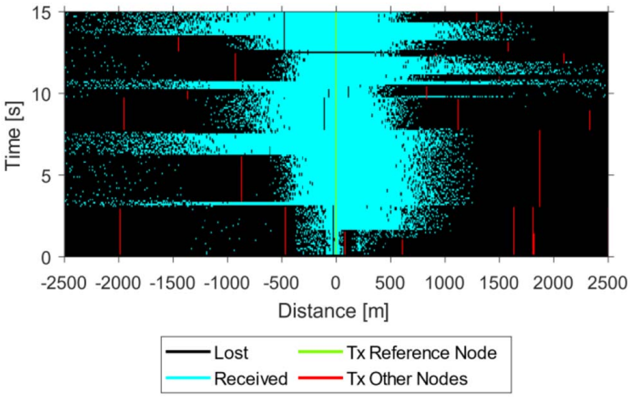

FIGURE 7. The reception status at different range for transmission from a reference node (node-250), in a low-density scenario with 10Hz transmission rate. Collision is depicted by Red lines and isolated blue lines shows half duplex incident.

For most transmissions, a resource is allocated prior to the generation of the respective packet, except those that trigger a new SPS. Once allocated, any resource gets periodically re-used by several subsequent transmissions by a particular VUE. Since there is no feedback mechanism, it cannot reassess resource quality and collision status for any transmissions from the sender side. Hence, this periodic reuse of resource can be termed as 'blind reservation'. Theoretically, this blind periodic reservation of the same resource grant can continue indefinitely if neither of the expiring conditions described in Section II-C is fulfilled.

BSMs are periodic and fixed size packets. Hence, expiration through missing Tx opportunity or failing size requirement is not expected. Hence, SPS remains a rather scarce phenomenon for any VUE. The initial SLRRC value range dictates a minimum count of resource re-use. But even after expiration of a specific SLRRC, the same resource can be renewed with a probability of P_{resel}. In this study, P_{resel} is set to 0.8 following recommendation from other studies such as [13]. High value P_{resel} increases predictability of future resource usage that should improve the performance of SPS.

But unexpectedly, such scarcity of new resource selection results in consecutive losses of packet between pairs of VUEs. Before analyzing the prolonged consecutive loss further, a concise overview of different kinds of packet loss in C-V2X is discussed in the following points.

A. HIGHER DISTANCE PACKET LOSS

In any wireless communication system, A packet loss occurs when a transmission, in this case from Remote Vehicle (RV), is either not detected or not successfully decoded by the receiver, at host vehicle (HV). From a system point of view, distribution of such loss depends heavily on channel condition and resource allocation. But regardless of such considerations, for Tx from a sufficiently long distance, the Received Signal Strength (RSS) at the Rx-end always deteriorates beyond the sensitivity level of the receiver. The 'Link-Budget' term can be used to describe such distances. Such loss can be modelled for a simple single Tx-Rx pair, considering a channel model, with path-loss, fading and noise figure (NF) of the channel and a receiver model containing Block Error Rate (BLER) and Signal to Noise Ratio (SNR) characteristic under specific HARQ situations. Having more vehicles in between considered VUE increases the chance of having interferences from other VUEs, which in turn increases packet loss. Loss due to low sensitivity tends to happen for higher distances only and independent of previous transmissions. Such losses can be ignored in this study, as it is an investigation of prolonged outage between two nodes that is sufficiently nearby. In other words, only those prolonged communication gaps between pair of VUEs that are unexpected or detrimental to vehicular safety measures is considered in this investigation.

B. NEAR DISTANCE PACKET LOSS

In case of near distance communication, losses can still happen if HV fails to either listen to a particular RV's transmission caused by simultaneous transmission by itself, or from other RVs resulting in higher interference. Such losses fall into two categories:

1) HALF DUPLEX PHENOMENON

As a C-V2X entity cannot transmit (Tx) and receive (Rx) at the same time, and must always use granted RB resource, a simultaneous use of same resource will end up in loss by all nodes using that resource. This is independent of channel condition. Theoretically, there is a finite range that can be covered without collision with other nodes given a traffic density.

2) HIDDEN NODE PHENOMENON

A VUE_A can lose connection with another VUE_C for long period of time, in case a third VUE_B transmits on the same resource. With transmission from two nodes VUE_A & VUE_B on the same resource, a VUE_C can receive packet from only one of VUE_A or VUE_B, depending on its relative proximity from both. Fig. 7 shows instances of transmissions (green) and its receivers' position (blue) for a transmitting reference vehicle, say VUE_A, located at 0m on the middle of x-axis. This scenario contains 500 stationary vehicles on a linear road length 5km. Each vehicle stands 10m apart. The transmission rate is 100ms for all VUEs without any CCA. Each point on this plot denotes either a transmission or reception, and covers 10m on x-axis and 100ms across y-axis, so that no gap is visible across points. The middle VUE Node-250 is selected as reference VUE_A and other VUEs are located over 2.5km on both sides. For each 100ms, only those instances of subframes (ms) are plotted across y-axis where there is a transmission from VUE_A as depicted by the green points at 0m, basically appears to be a line. For each of those green points, the blue points to its right and left denote the position and time of VUEs that received those transmissions from VUE_A. Black points show those VUEs' position, that failed to receive packets from green point. If investigated closely, the communication range, shown as blue region, is not symmetrical on both sides (right and left from the middle of x-axis) of the transmitter VUE_A. The reason is, there are other VUEs, denoted by red points transmitting using colliding resources simultaneously. Interestingly, the red points appear to be on a line, since, the C-V2X resource reuse algorithm allows this collision to happen consecutively for several times, as time progresses. Any red point represents a colliding node (VUE_B). Around any VUE_B, there is a region of black dots on right and left. This black region shows, a lack of receptions from the central reference node VUE_A. This is due to interference from that VUE_B transmission, that allows VUE_B to act as a shadow, for transmissions from VUE_A. This phenomenon happens in addition to the half-duplex loss between VUE_A & VUE_B, and as depicted at 0-3s time in the plot, can happen at very near distances.

C. COLLISION DISTANCE ESTIMATION BETWEEN TRANSMITTING NODES

The theoretical upper bound for radio-collision free distance that can be attained by any VUE depends on the number of available resources without overlap (N_{nocol}) from other VUEs and geographical distribution of the VUEs. Equation (3) gives the capacity of the system for no collision access, for a bandwidth configuration of N_{RB} resource blocks per subframe, and n_{RB} resource blocks required per packet per transmission. The 2 in the denominator signifies the fact that each packet is transmitted twice using HARQ. P_{step} is the periodicity of SPS managed resource grant measured in number of subframes (e.g., 100).

$$N_{nocol} = \frac{P_{step} \times N_{RB}}{2 \times n_{RB}} \tag{3}$$

Let's assume the VUEs are uniformly distributed on a linear road topology with VUE-density d per distance. The theoretical average distance between collision, meaning same resource is used by two VUEs is,$\frac{N_{nocol}}{d}$. So, on average, the distance achieved by any transmitting VUE expecting a perfect no collision stretch,$\frac{N_{nocol}}{2d}$, avoiding so called hidden node phenomenon. In practice, the SPS mechanism selects 20% of the resources with least busy estimation to go through a random selection (see Fig. 3). Since two VUEs from near vicinity holds similar sensing data from the resource pool history, the random chance for selecting the same resource remains significantly higher if the SPS resource allocation happens within the same transmission period. Let the channel pathloss P_{loss} is monotonically increasing by distance and fading and shadow effect γ ignored as having zero mean distribution. Now, let's consider a limited model of least interference linear one-dimensional scenario, where initially VUEs with colliding resources are distributed as farthest as possible. Hence, the distance of two VUEs using same resource is $\frac{N_{nocol}}{d}$. Despite the best optimization of estimation of future transmissions, Any VUE_A that attempts SPS resource selection would be forced to select a resource that is colliding with one of its 20% least interfering neighbors, because size of R_{sel} is $N_{20\%}$. The estimated index of the colliding VUE_C in terms of distance from the VUE_A is between, $m = (0.8N_{nocol} + 1)^{th}$ to $n = N_{nocol}^{-th}$ nearest neighbor. It is assumed that SPS has perfect initial condition and estimate of all future transmission from its neighborhood.

For a given average density of stationary UE, ρ on road length L, and width H ($H \ll L$), the distance $R_{k^{th}}$ for $k^{th} -$ *nearest* neighbor can be statistically calculated using simple Poisson point process approximation. Probability of finding k local point within area of radius r from host VUE, is given by Equation (4), if density is calculated along the road length, with per distance unit, $\rho_L = \rho H$.

$$P(Idx_r = k) = \frac{e^{-2rH\rho}(2r\rho_L)^k}{k!} \tag{4}$$

Using the same line of derivation from [14], the distance distribution for randomly selecting one of the neighbors between m^{th} and n^{th} with equal probability, can be expressed as generalized Erlang distribution in Equation (5)

$$f_{R^{th}_{[m,n]}}(r) = \frac{1}{n-m+1}\sum_{k=m}^{n}\frac{e^{-2\rho_L r}(2\rho_L r)^k}{rk!} \tag{5}$$

At this point, the calculation is considering two VUE's using the same colliding resource within the same subframe. But HARQ allows both VUEs to mitigate this loss by allowing another re-transmission using another resource. But, maximum time gap of the HARQ re-transmission of the same packet by a VUE is $SF_{gap} = [-15, 15]$ from the initial transmission. So, in case of a collision or simultaneous transmission. loss already happens between two VUE's for one transmission, there is a $\kappa_{HARQ} = (\frac{1}{30})$ chance of having another simultaneous HARQ re-transmission. In that case, the benefit of HARQ retransmission does not stay. However, in case of higher density there is a reduction of collision, due to congestion control (See Eq (1)). Despite SPS choosing the same periodic resource every P_{step}, those resources do not get used by the VUE every time, for increased gap between packet generation by Max_{ITT}. This increases the chance for two VUEs with colliding resource grants not to collide. This happens by one VUE_A choosing to transmit on alternating non overlapping subframes than other VUE_C by a factor of $\kappa_{CC} = (\frac{Max_{ITT}}{P_{step}})$. Here both reduction factors can be included in the UE density ρ_L, by assuming an increase in volume of the available resource pool by the same factor, since probabilistic sampling of a Poisson process is also Poisson process. The effective density becomes,

$$\rho_L = \rho H \kappa_{HARQ} \kappa_{CC} \tag{6}$$

From this simplified model, it turns out, the SPS tries to move collision further in distance to allow collision free transmission nearby. Fig. 1 & 3 in the study [3] of temporal behavior of C-V2X, it is shown that, as system load increases the SPS trades off the collision-free distance for close range optimization of resources by using more aggressive range control. Even with congestion control enabled, the lower bound of distance between such collision stays low, due to κ_{CC} based reduction.

In addition, the SPS mechanism is only designed to avoid colliding resources in both time and frequency, i.e., using same subframe and subchannel by co-operatively distributing the colliding resources between VUEs at furthest distance possible. But two neighboring nodes has a considerable chance that they would select resources from the same subframe in Time scale even though the subchannel selection in frequency scale is not the same. Thus, those VUEs will get into a cycle of half duplex loss, until either of them changes their resource through SPS. A simple approximation for such a half-duplex loss at any distance nearer than r can be obtained by splitting the Poisson process theorized so far with a probability of $\frac{1}{P_{step}}$ and using Equation (7) for finding the nearest $k = 1$ neighbor.

$$f_{sym}(r) = \left(\frac{2\rho_L}{P_{step}}\right) e^{\frac{-2r\rho_L}{P_{step}}} \tag{7}$$

The analysis for this Half-Duplex loss for different density of vehicles depicted in Fig. 8. It shows, at a distance 300m, the simultaneous collision in a moderately dense traffic reaches close to 1%, which is significant, considering the sheer number of packets transmitted in the system.

$$\rho_L = \rho H \kappa_{HARQ} \kappa_{CC}$$

V. ANALYSIS OF CONSECUTIVE LOSS IN C-V2X

Both half duplex and hidden node problems exist in other Technologies, e.g., in DSRC. But, in those cases radio resource selection for a particular transmission does not depend on previous transmission information, i.e., sensing data. In C-V2X, there exists a minimum resource retention period, governed by *SLRRC*. Moreover, keeping the same resource for indefinite numbers of SLRRC cycles is possible due the P_{resel}, which is the probability of re-assigning SLRRC for the same resource grant**.** This process of resource reuse can be described as a generalized renewal process with random stopping conditions. Considering a keep probability P_{resel}, and SLRRC limit $[S_1 S_2]$, the generating function for probability distribution of the lifespan of any resource grant is described by,

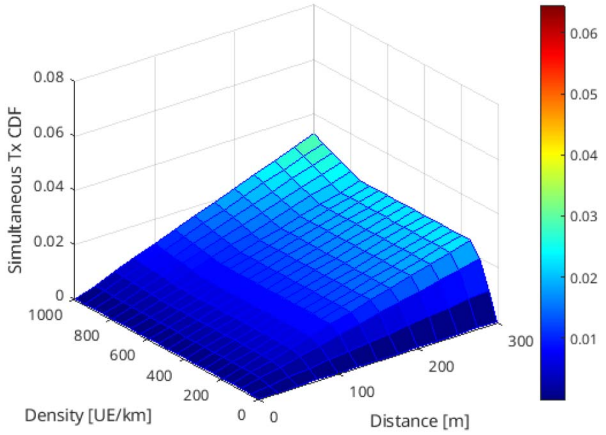

FIGURE 8. **Cumulative probability distribution of simultaneous transmission for any transmission pair resulting in Half-Duplex loss.**

$$G(x) = \sum_{n=1}^{\infty} P_{resel}^{n-1}.(1 - P_{resel})\left(x^{S_1}\left(\frac{1 - x^{S_2 - S_1 + 1}}{1 - x}\right)\right)^n$$

which can be simplified to do Taylor expansion,

$$G(x) = \frac{(1 - P_{resel})}{P_{resel}} \times \frac{x - 1}{x - 1 - P_{resel}\left(x^{S_2+1} - x^{S_1}\right)} \tag{8}$$

From equation (8), the probability of a transmission being the k^{th} using that resource grant is,

$$p_{index}(k) = \frac{G^{(k)}(0)}{k!} \tag{9}$$

Let's assume, transmission indices for two simultaneous transmissions from two separate VUEs, VUE_A & VUE_B are k_A and k_B using their respective resource grants. These two transmissions are independent of each other. The number of consecutive times these two VUEs are blind to each other due to half duplex phenomenon, can be expressed as a random integer variable (r.i.v.), $Z = min(K_A, K_B)$, where K_A and K_B represents the r.i.v. for k_A and k_B. Let's term this number as *consecutive collision index* (ccolIdx). The probability of *ccolIdx* holding a value z can be expressed by,

$$p_{colIdx}(z) = \frac{G^{(z)}(0)}{z!} \tag{10}$$

For a given ITT, enforced by congestion control, the SLRRC counter expiration (CET) will average to,

$$CET_{slrrc} = \frac{S_1 + S_2}{2} \times ITT \tag{11}$$

with a resource reselection probability P_{resel}, the average Resource retention time (RRT) becomes,

$$RRT_{avg} = \frac{CET_{slrrc}}{(1 - P_{resel})} \tag{12}$$

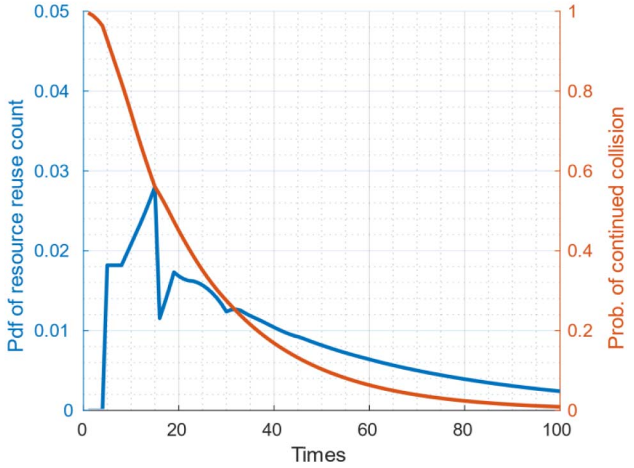

FIGURE 9. (Blue) Probabilistic distribution of resource reusage count (Red) Probability of continued collision number given first transmission of one of the colliding nodes.

For example, a 100ms ITT value and SLRRC range of [5], [15] and P_{resel} of 0.8, the average becomes 5sec. And if a pair of VUEs selects resource from same subframe, the average (Median) time for them to have continued collision can be shown in Fig. 9 to be 1.8sec.

It needs to be mentioned that this prolonged retention of the same resource does not depend on any other system phenomenon. If there is a regular generation of BSM packets by a VUE, this periodic resource reuse and grant reselection scheme continues independently. Hence, for a VUE-pair that are currently transmitting simultaneously, the possibility of continuous collision does not decrease over time. In other words, this is a renewal process from a statistical perspective.

A. IMPACT OF RATE CONTROL ALGORITHM ON CONSECUTIVE LOSS

CCA applies Transmission Rate Control (TRC) based on vehicular density estimation, which reduces the rate of packet transmission for higher traffic density following equation (1). Since the decrement in SLRRC depends directly on radio-transmission of BSM packets, TRC increases the RRT with the same factor, as it takes longer for SRRC to reach zero following equation (11). Which keeps the average number of consecutive collisions same, but the timespan for such persistent collision increases by a factor of κ_{MaxITT}.

In case of maximum allowed $ITT = 600ms$ with [5], [15] SLRRC and 0.8 P_{resel}, the average time jumps to 30 sec. Even with the random selection of minimum $SLRRC = 5$, and the first attempt of P_{resel} probabilistic grant reselection fails, the minimum RRT at this high ITT would cause the collision to go on for 3sec. Which means, each VUE that are colliding would wait at least 3sec before any chance of change in resource grant in heavy traffic scenario.

VI. C-V2X: STUDY SETUP

To investigate the rare outage scenario via prolonged consecutive collision, this study performed an extensive simulation campaign of C-V2X system. Some important details regarding that simulation setup are discussed in the following subsections. Other parameters such as packet size, MCS, RB etc. were selected following conventional values used in previous studies such as [2], [9], [14].

A. SIMULATOR

An in-house full-stack simulator for C-V2X Mode 4 is used for all simulations in this study, based on network simulator 3 (NS-3). The implementation of the simulator highly relies on NIST implementation of LTE in [16]. For Application module, the SAE J3161/1 is implemented as CCA for C-V2X complying 3GPP standards, whereas SAE J2945/1 is used for DSRC simulator.

B. CHANNEL MODEL

1) FOR ENSURING THE ROBUSTNESS OF THE SIMULATION RESULT, TWO SEPARATE CHANNEL MODELS ARE IMPLEMENTED. ITU-R P.1411 STREET CANYON UHF LOS MEDIAN WITH NAKAGAMI FADING

This channel model is developed by International Telecommunication Union (ITU) [13] to properly predict channel in Urban Street setting. For fast fading, Nakagami fading by variable m-value based on distance ranges, like the study had used. This channel model is selected to consider its high loss component in congested urban scenario.

2) UCF I-405 CHANNEL MODEL

UCF channel model [14] is a statistical model to emulate the realistic data collected by Crash Avoidance Metrics Partners LLC (*CAMP*). The path loss model contains three statistical models for very low, medium, and heavy traffic density. This model was improvised for this study, by investigating the medium density to be a statistical extension of low and heavy density Path loss. A new probabilistic selection of either low or heavy density path loss based on vehicular density is introduced to ensure continuous transition of Path loss from Line-of-Sight (LOS) to Non-Line-of-Sight (NLOS) traffic scenario.

The fast-fading model used for this channel is Nakagami fading with fixed m at different distances, statistically determined by the authors of [17]. Since this channel model is based on data ‘I405’-highway study, it is a more realistic experiment-based channel model for an actual simulation of highway scenario.

C. ERROR MODEL

The error model used in this simulation comes from NIST analysis of HARQ mechanism with BLER vs SINR characteristics in [16, p. 3]. In C-V2X maximum two transmissions are supported of the same packet through HARQ process, namely of redundancy version (RV) 0 and 1. Reception of the HARQ-0 follows the regular SINR to BLER error curves taken from [14]. But, for HARQ-1 reception, NIST proposed a formula for determining combined $BLER_{nist}$, given by

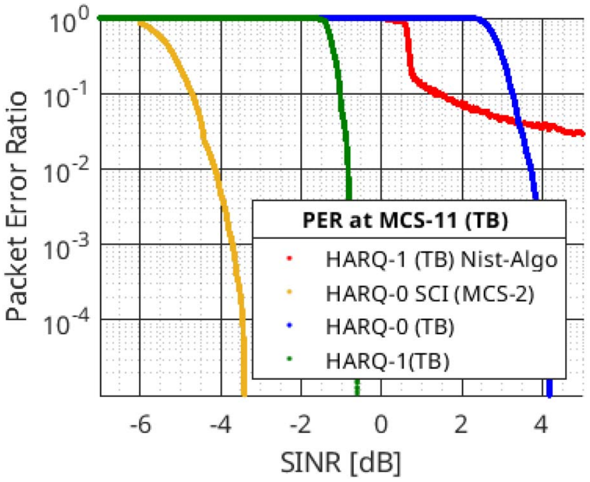

FIGURE 10. **BLER vs SINR characteristics for (Yellow) SCI MCS-2 (Red) HARQ-0 MCS-10 TB (Blue) HARQ-1 MCS-10 TB NIST proposed. (GREEN) Fixed HARQ-1 MCS-10 TB, $SINR_0$ is fixed to 0 dB.**

Equation (13). This combination depends on the individual SINRs and BLERs from both HARQ-0 and HARQ-1. The SINRs are denoted as $SINR_0$ and NR_1, and BLERs as $BLER_0$ and $BLER_1$, respectively. $SINR_{\max}$ and $SINR_{min}$ are respectively maximum and minimum between $SINR_0$ and $SINR_1$.

$$BLER_{nist} = \frac{BLER_0 + BLER_1 \times \frac{SINR_{max}}{SINR_{min}}}{1 + \frac{SINR_{max}}{SINR_{min}}} \tag{13}$$

The problem with this formulation is, if the resultant $BLER_{nist}$ is plotted against $SINR_1$, in many cases, BLER never goes down to zero regardless of high $SINR_1$ value, Fig. 10 (red) demonstrates this phenomenon for different $SINR_1$ values with an arbitrary fixed $SINR_0$=0dB. Which means, for some individual reception with 0% BLER, the combining HARQ BLERs adds more error instead of reducing it. For this problem, a corrected HARQ BLER calculation with simply averaging out SINR is used in this study. The corrected model follows the analytical BLER observations by NIST in [16], without wrongfully allowing packet loss at very high SINR. The (green) line Fig. 10 shows the resultant BLER using the modified version of the formula.

D. ROAD TOPOLOGY AND MOBILITY MODEL

Selecting a proper vehicular mobility model is important for a simulation that represents real life performance. The link level range of C-V2X communication is about 2.2km. Hence, to ensure a well distributed system, a 5km road is considered for this simulation, like other major studies. A 6-lane road topology is created with 3 lanes per direction for this simulation campaign, see Fig. 11. The number of lanes is selected to keep simplicity in the configuration, since, at a given system-wide density the increased lane count have little to no impact on the simulation using the selected Channel Models. The VUEs are placed with unform randomness in lanes. All vehicles have a constant speed of $30ms^{-1}$ in the direction of its lane. Vehicles are made to follow a wrap-around mobility model to avoid reduced density effect at the edge of the simulation. Which means the same vehicle re-appears on the same lane from the other end after reaching its end of the road.

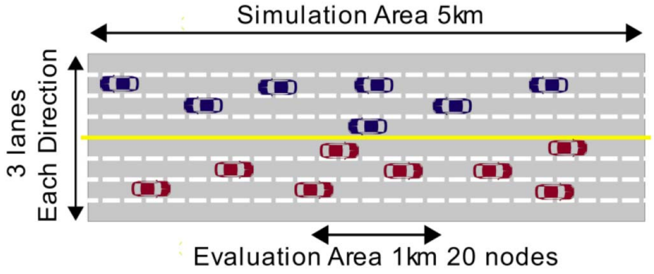

FIGURE 11. **Road topology for simulation setup.**

E. PERFORMANCE METRICS

For a communication system performance measure, overall average reception rate or throughput is given most attention. But, in current study, VUEs are dynamically moving objects too. The goal of the communication is to ensure the safety of the vehicle, by giving accurate information about neighboring vehicles. Hence, the performance measure should also consider the temporal and sequential performances of individual node pairs. Hence, some of the relevant measures that are used in this study are as follows.

- *Packet Reception Rate (PRR):* Packet reception rate is an average measure of reception success rate against transmitted packets. In this study, distance between communicating VUEs are used as control variables. The communication distances are divided into several distance bins. For each receiving VUEs, the transmitters are classified with their binned distance from that VUE. PRR is then calculated over all VUEs as transmitter in the system using equation (14) for any specific distance bin i:

$$PRR(i) = \frac{\sum_{bin_i} \text{successful receptions}}{\sum_{bin_i} \text{attempted transmissions}} \tag{14}$$

The complementary measure for PRR is Packet Error Rate (PER), as shown in Fig. 1.

- *Information Age:* The safety of a vehicle depends on the quality of received information. So, there should be a measure of such information quality. For a VUE, the awareness of its surroundings can be measured using the time passed after the last information update from each of its neighboring nodes. Information Age (IA) is the average age of updated information. As Fig. 12 shows, initially, at a particular VUE receiver, the IA of the reception from an RV remains undefined, when no reception is yet received. Then, IA drops to a minimum just after the moment of reception. The minimum value can vary due to the MAC delay at the RV transmission

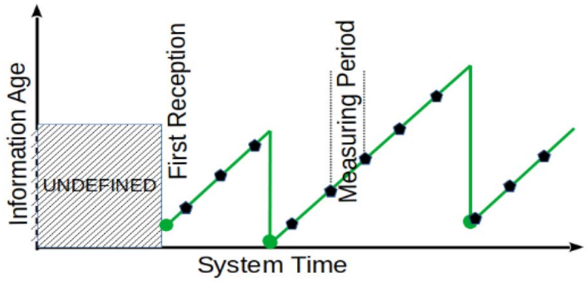

FIGURE 12. Information Age related to reception and measuring gap.

side. The IA increases linearly after that until another reception happens. The IAs are measured with a fixed 50ms period for all RVs. The plots presented in this article are the (cumulative distribution function) CDF or Counter-CDF (CCDF) of the all-IA measures for all VUE pairs having a particular distance-range between them, in any simulation.

- *Tracking Error:* The measure of success of a vehicular dynamic position-based communication system is the successful tracking of the nearby vehicle positions. The CCA application applies a linear estimation for dynamic tracking of vehicles, which considers the RV is moving at constant speed until another information update arrives. Hence, high dynamicity can cause error in tracking of neighboring VUEs if the information is not regularly updated. Especially in the case of long outages such as this current investigation, losing track of neighboring VUEs is an increased risk. For this study, the Tracking Error (TE) is defined the linear distance between a tracked position of a vehicle and its actual position at any instance of time.

VII. RARE OUTAGE MEASURE & POTENTIAL SOLUTIONS

Fig. 1 used in the beginning of this study, is a recreation of the simulation setup study of [2] with the in-house simulator used in this study. It shows PER and IA-CDF for DSRC, C-V2X (with HARQ enabled) and C-V2X w/o HARQ. That study uses J3161/1 as CCA-C-V2X, except the One-Shot scheme introduced by [9] standardized later. The PER measure suggests a huge advantage for C-V2X over DSRC at longer distance. Even for distances as short as 200m, C-V2X standard setup suffers half of the losses in comparison to DSRC. This advanced reception rate helps to attain better IA (for CDF higher curve is better) for 98% of the receptions. But C-V2X falls short significantly for the rest of 2% of the receptions so much so that, even with HARQ transmissions enabled, at 99.9%-tile the IA reaches 3sec at a short distance of 150-200m bin. This result shows the severity of this problem for BSM reception in C-V2X.

The solution to the problem of prolonged consecutive loss is to ensure that the outage does not happen for a long time as observed in previous studies. Several recent studies are discussed in the survey [6] as a solution to this problem. Researchers takes mainly two different approaches.

A. APPLICATION SIDE

In case of critical incidents, like hard break, C-V2X-CCA switches the transmission of BSM to HPM, which gets scheduled immediately. Since, HPM uses a One-Shot resource instead of regular SPS periodic allocations. So, the HPM should not get into the same consecutive collision streak. Using this advantage of HPM over regular BSMs, one possible solution from an application point of view is to request added numbers of HPM Transmissions, i.e., Event Packets, in case of high loss is predicted, such as in lane change or any other trajectory changing scenario. But it does not make the following regular BSM any less susceptible to consecutive loss. Secondly, Consecutive collision of resources is a lower-level phenomenon, which can't be determined from application level. And HPMs are bigger packets using BSM Part II [19, p. 27], which may add additional overhead on the network. So, this solution will not be an effective solution.

Another part that is manageable from the application side is the ITT matchup between VUEs. The longevity of consecutive collision streak increases in case of higher ITT. The allocated resource periodicity P_{step} is usually 100ms. As explained in earlier Section V-A, high-density vehicular traffic under CCA forces a long gap between transmissions happens due to high ITT, allowing in-between periodic resources remain unused. But nearby VUEs experience same vehicle density N_s for CCA, which means if two VUEs having high ITT, e.g., VUE_A and VUE_B gets stuck in a prolonged collision, the increased ITT does not help. Because, both VUE_A and VUE_B should have similar ITT and will end up colliding on every BSM transmissions, skipping periodic resource grant simultaneously. But the fact of skipping periodic resources can be used for the benefit of avoiding prolonged resource collision too. That is by changing the deterministic ITT scheme to a random ITT scheme, either selecting from a range of ITT-values or by adding a random jitter to the ITT value. Randomizing ITT would then allow diversify their instances of skipping resource grant, and thus allowing e.g., VUE_A and VUE_B to select different part of the ITT length for transmission. But there is a problem with this approach. Although it helps in case of high density runs, it does not help lower density scenario. Secondly, adding jitters in both directions eventually cause lack of information update, which may cause additional IA and TE. The reduction of predictability on BSM transmission also cause the SPS resource allocation to worsen performance. In short, although these measures are strictly from application layer, it does not fully address the problem adequately.

B. LIMITING SPS RESOURCE REUSE DURATION

Since, application layer measures are unable to address the problem sufficiently, another way to look at it, is to manage

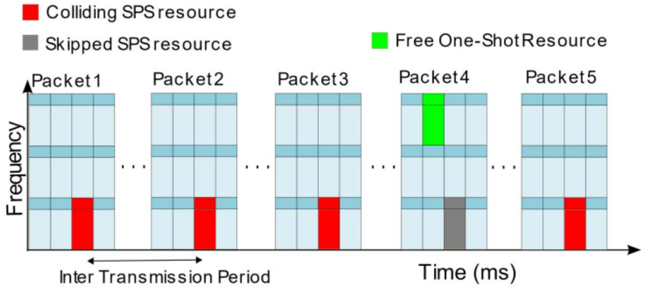

FIGURE 13. **A conceptual illustration of Interleaving consecutive collision using One-Shot SPS resource.**

the existing exceptionally long resource retention period using P_{resel} and SLRRC from the MAC layer.

Prolonged consecutive collision happens because the same colliding resource gets selected for a longer period. So, the best approach to this problem is not letting collision happen repeatedly within the same VUE-pair. In the study [3] the authors proposed to set a hard limit on the total number of reuses. While this approach is very effective containing the unbounded nature of IA, it removes the predictability of transmission and thus reducing the performance of SPS. In another study, [7] authors proposed a double allocation of resources in an alternating fashion. But, the HARQ procedure already serves a similar role, and fails to ensure enough robustness. Moreover, it adds a resource reservation overhead on the MAC layers, which may hamper the resource handling of other types of packets. Study [15] takes a similar approach.

So, the best way forward is to add a separate but occasional break-away resource for BSM transmission, which does not fall into the collision between same pair of VUEs. Fig. 13 explains the concept briefly. Now, it is safe to assume that for a certain kind of Data packet, here BSM, there should be only one periodic resource selection process possible. So, any secondary "collision-streak" breaking resource is best to be a temporary resource allocation by SPS. SAE J3161/1 already employs the same idea for HPM resource, "One-Shot". A One-shot resource is a single-use resource allocation by SPS, which can be used to transmit a packet once and immediately gets discarded. The study [9] applies this idea for BSM transmission too which already got included in the SAE J3161/1 standard that will be described in Section VIII.

The first part of this One-shot based BSM transmission scheme is, to keep track of BSM transmissions that uses regular consecutive and periodic SPS resources. After a certain number of times, skip one Tx-opportunity by asking for a new single-use resource allocation through a new SPS instead of the regular consecutive and periodic SPS resource. This new SPS mechanism should select the best resource for the immediate transmission. So, One-Shot resource transmission should avoid near distance losses except for one case. That is if both of two nearby VUEs, that are already under a prolonged collision, request for One-Shot SPS grant on the same transmission cycle and in this process both select resource from the same subframe. But, as One-Shot resources are just single use, the next One-Shot based transmission is unlikely to fall into the same collision, thus removing occasional failure to break the streak.

One possible complication from such a scheme is the loss of predictability for general SPS based resource selection due to additional single-use resources. Moreover, this additional interference from the One-Shot transmissions would force other VUEs, during their SPS resource allocation, to avoid these One-Shot transmission resources as busy. But luckily, in C-V2X standard, the SCI associated to any One-Shot transmission can hold the information of RRI to be zero, meaning non repetitive. Using this additional information in SCI, the impact of One-Shot resources over SPS quality gets significantly reduced.

VIII. SAE J3161/1: COUNTER BASED ONE-SHOT TRANSMISSION

Considering all the benefits of One-Shot resource-based solution, SAE J3161/1 proposes a counter-based approach for the C-V2X-CCA.

In this approach, the transmissions using regular SPS allocated resources are tracked using a One-Shot Interval Counter ($OsIC$), like SLRRC. The counter's initial reset value is determined randomly within a predefined limit of integers $U_{integer}[C_{1sMin}, C_{1sMax}]$. OSIC decrements after each BSM transmission using regular SPS periodic resource. Eventually the OSIC expires. Then the immediate next transmission of BSM, is forced to avoid the regular SPS resource grant. Instead, it needs to ask for a separate One-Shot Resource by SPS. SLRRC remains unchanged for this BSM transmission, using this new One-Shot Resource. After this, the OSIC gets reset to a new initial random value for the next cycle of transmissions using regular SPS resource grant.

This system of using two types of resources to transmit BSM can be modelled using an uncertain alternating renewal process, where the regular SPS transmission can be modelled as system 'Up' state with uncertainty distribution $\xi \wedge$the One-Shot transmission can be modelled as 'Down' state with uncertainty distribution η.

$$\begin{aligned} R_{\eta} &= \frac{\xi}{\xi + \eta} \\ E(\xi) &= \frac{1}{2}(C|1sMin + C_{1sMax}) = C_{1sAvg} \\ & \qquad E\big(\xi + \eta | \xi = C_{1sAvg}\big) = C_{1sAvg} + 1 \\ E\big(R_{\xi}\big) &= \frac{C_{1sAvg}}{C_{1sAvg} + 1} \end{aligned} \tag{15}$$

The time limiting theory for alternating renewal process gives the expected share of One-Shot Tx $E(R_{\xi})$ as a function of average of OSIC in Equation (15).

In [9], the authors demonstrated comparison of IA performance between a counter range [2], [6] and [5], [15]. For these configurations of OSIC, average number of SPS related consecutive transmission are limited to an expected value of $C_{1sAvg} = 4$ and 10, giving the ratio of 0.8 and 0.91,

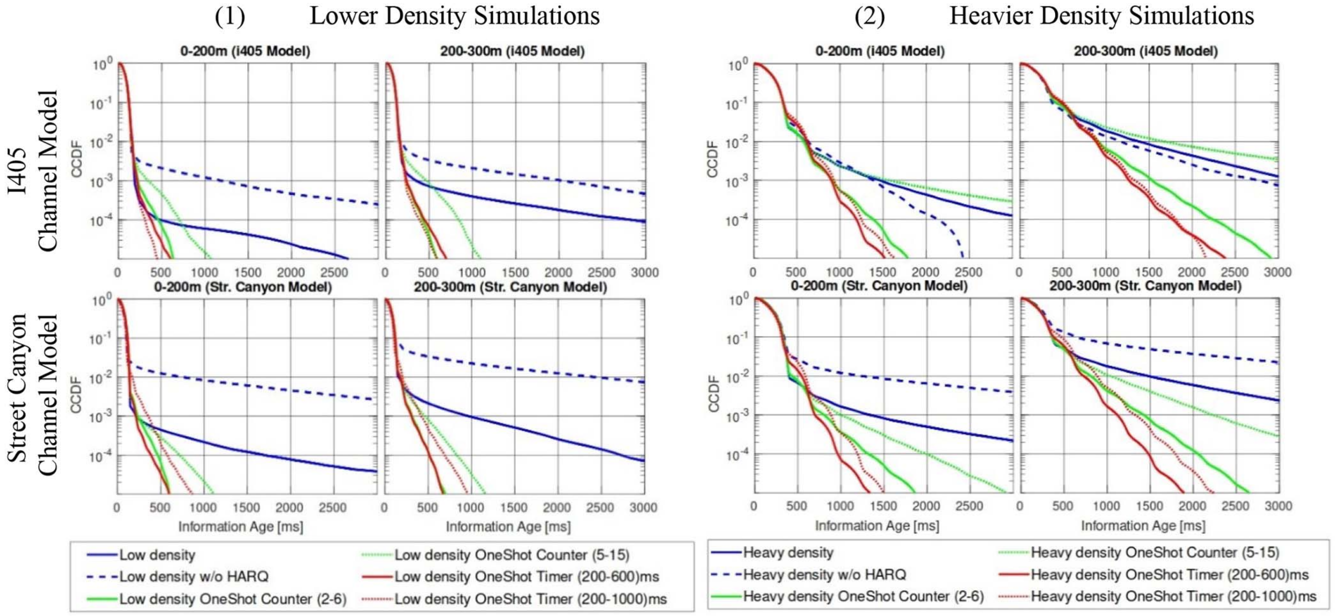

FIGURE 14. Information Age in Simulation results.

respectively. [2], [6] have higher number of transmissions with One-Shot resource, that negatively impacts SPS related resource quality. But that is surpassed by the benefit of average limiting of consecutive collision streak to a lower count. Which suggests that more frequent One-Shot helps break the streak of consecutive collision better, without reducing the SPS quality too much. In this study, the [2], [6] and [5], [15] are evaluated Fig. 14. [2], [6] counter demonstrated best performance.

A. LIMITATION OF COUNTER-BASED APPROACH

The counter-based approach does not work well enough in case of heavier scenario. Having a CCA helps reduce the load on the system and increase packet throughput. But, due to the long duration of SLRRC expiration time, a rare consecutive collision can stay much longer than lower density highest rate transmission scenario. A similar delay occurs in OSIC based One-Shot sequence breaking. In heavier density the ITT becomes multiple factors higher than regular 100ms interval, which can increase up to 600ms. Since OSIC does not differentiate between ITTs, the expiration of this counter gets delayed by the same factor of ITT, with similar factor κ_{MaxITT} as explained in Section V-A. So, as demonstrated in Fig. 15 where, in case of ITT=150ms, it takes $\kappa_{MaxITT} =$ 1.5time to interleave a consecutive collision. This delay in turn increases the IA.

IX. TIMER BASED ONE-SHOT TRANSMISSION

The problem of delay in counter-based approach for One-Shot transmissions, as described in previous section, is directly dependent on ITT increment by CCA. The best way to resolve this problem is to remove such dependency. So, this study proposes a timer-based trigger for One-Shot transmission.

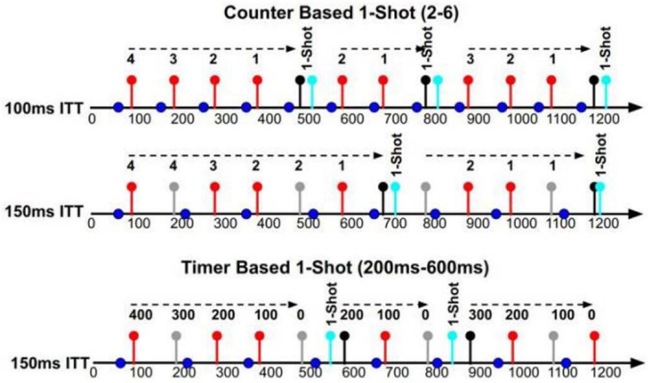

FIGURE 15. Heavier density of vehicles forces C-V2X CCA to have higher ITT and shifts the rare collision to higher IA.

In this timer-based approach, the transmission happens based on One-Shot Interval Timer (OSIT) with interval $U_{integer\times 100ms}[T_{1sMin}, T_{1sMax}]$, where the T_{1s} values are sampled at P_{step}=100ms granularity. The randomly selected *OSIT* is reset to a random initial value each time a One-Shot is triggered or, a new resource gets allocated for regular SPS. The Algorithm flow is detailed in Fig. 16. The resultant One-Shot count distribution is:

$$E(\xi) = \frac{\frac{1}{2}(T|1sMin + T_{1sMax})}{P_{step} \times \kappa_{maxITT}} = \frac{T_{1sAvg}}{P_{step} \times \kappa_{maxITT}}$$

$$E(\xi + \eta|\xi = E(\xi)) = \frac{T_{1sAvg}}{P_{step} \times \kappa_{maxITT}} + 1$$

$$E\left(R_{\xi}\right) = \frac{T_{1sAvg}}{T_{1sAvg} + P_{step} \times \kappa_{maxITT}} \tag{16}$$

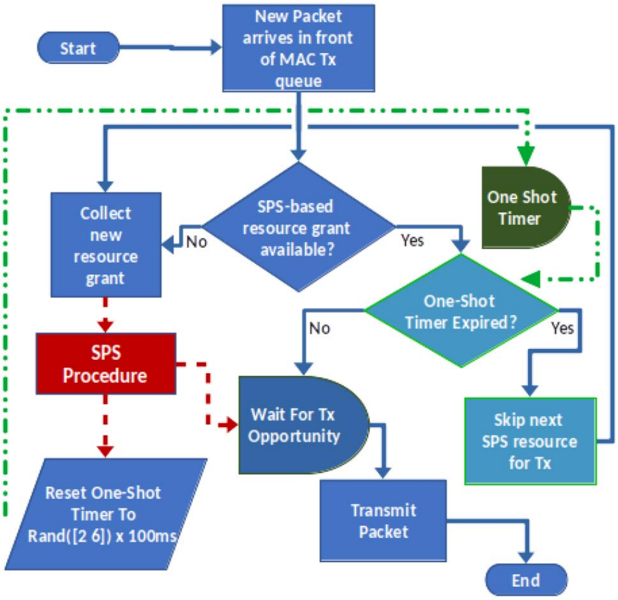

FIGURE 16. Algorithm for Timer based One-Shot.

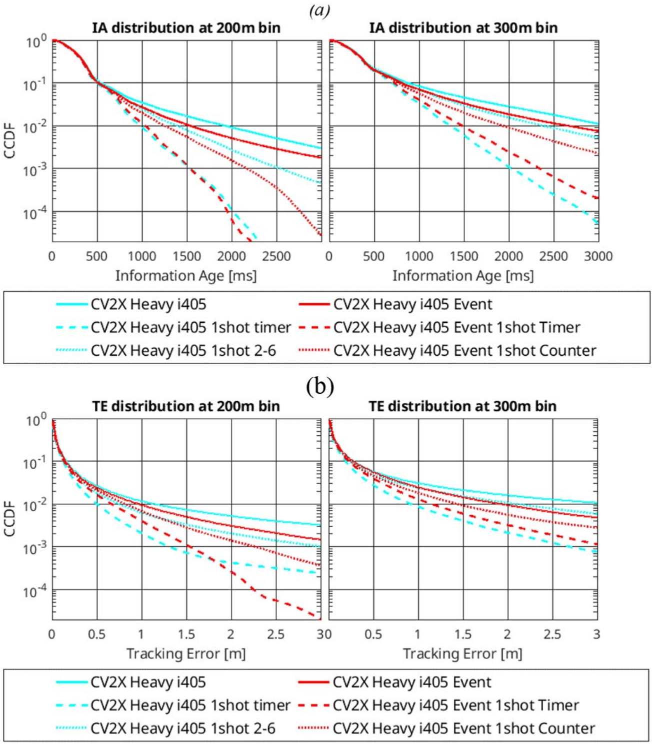

FIGURE 17. (a) Information Age (b) Tracking Error, for heavier density of vehicles simulation under realistic mobility and channel model.

As equation (16) suggests, for a lower density traffic scenario, the scheme should act exactly like of OSIC configuration [2], [6], when OSIT is selected between [200 600] ms. But, as ITT increases for higher density scenario, the timer improves the prolonged consecutive loss situation comparatively, as shown in Fig. 17. In case of very heavy density, with $P_{step} \times \kappa_{maxITT} = 600ms$, the $E(R_{\xi})$ settles at 50%.

TABLE 1. List of simulation parameters.

Configuration Parameter	Value	
Payload Size (BSM)	300 bytes	
MCS (SCI/TB)	2/7	
Carrier Freq	5.9GHz	
Bandwidth	20 MHz	
CBR threshold	-92dBm	
SPS threshold	-84.18dBm	
Propagation Loss Model	1. ITU-R P.1411 Street Canyon UHF Median 2. UCF I-405 Channel Model	
Fading Model	Nakagami	
Road Length	5000m (Highway 6 Lanes)	
Simulation Time	100sec	
Vehicular Traffic Scenario	**Density**	**$E(\kappa_{maxITT})$**
Low (316 veh)	63.5 v/km	1
Heavy (1995 veh)	399 v/km	3
Heavy Realistic Traffic (3200 veh)	666 v/km	4.5

X. RESULT ANALYSIS

To determine the best OSIT initialization, two different OSIT configurations are investigated. Since OSIT is supposed to improve over the Counter-based One-Shot, the corresponding OSIT is evaluated at [200 600]ms. Like OSIC value [5], [15] resulted worse, this study found similar degradation of IA for OSIT [500 1500]ms. For simplicity, the result for this configuration is not shown in this article. But, one additional configuration OSIT (200,1000) ms is simulated for getting additional insight about the Timer Based One Shot scheme.

The Fig. 15 shows the IA results for simulations done using constant speed vehicular mobility model as denoted by Low and Heavy in Table 1. Considering 99.99%-tile (as marked with 10^{-4}CCDF) as a reasonable ratio to measure One-shot benefit, the lower density scenario gives both counters based [2], [6], and timer based one-shot [200 600]ms and (200,1000)ms configurations almost the same improvement in long tail IA, in comparison to the without One-shot scenario. But, with 3 times of the ITT in BSM for heavy density scenario, the One-Shot counter-based approach deteriorates in IA by more than 350%, in respect to Lower density. While with timer-based approach although deterioration of IA happens to deal the increased load on the system, that bounds under 250% for both channel models. Between configurations of timer-based approach, [200 600]ms configurations of OSIT always performed better than [200 1500]ms. This is since, having lower average wait time helps more to break the streak of prolonged consecutive loss.

XI. FURTHER INVESTIGATION IN MORE DIVERSE SCENARIOS AND PERFORMANCE MATRIC

So far in the study, the simulation scenario is based on a simpler constant speed road traffic model. Although it gives the basic understanding of the IA matric and in turn the impact on prolonged loss distribution, it does not provide a clear picture on the dynamic nature of vehicular movements on real road topology. To address that limitation, the simulations are run using a realistic

Vehicular Mobility scenario. For Channel model, the UCF I-405 channel mode[12] is used for a realistic highway channel abstraction. The CCA under realistic traffic mobility, results in several artificial events driven HPMs, so called Event messages. The improvement of those event messages is more important to ensure successful information dissipation.

The simulation results show a promising improvement for both regular (blue) BSM and event driven (red) HPM in Fig. 17 (a). Since Event messages are transmitted using One-Shot resources themselves, the improvement seems similar for BSM, since the IA gets calculated starting from the first Event driven HPM. Which shows, reducing prolonged collision for regular BSM has a similar improvement for Event driven HPM IA.

Another important metric to investigate is TE under One-Shot scheme. Although TE is calculated using simple linear constant speed prediction model, the One-Shot implementation improved the tracking error by a large factor in case of high TE due to prolonged loss or blind nodes, as shown in shown in Fig. 17 (b). Considering 99.9%-tile (as marked with 10^{-3}CCDF) of TE, the improvement is almost 33% for timer-based approach over the counter-based approach. This TE study has a little measurement bias due to high numbers of unrealistic events simulated in the mobility model, which forces a higher minimum TE for several vehicular nodes. So, the study needs to be repeated in a refined mobility model with realistic number of events. Despite this limitation, the Timer based One-Shot implementation shows a clear improvement over the non-One-Shot and counter based One-Shot scenario.

XII. LIMITATIONS AND CHALLENGES

The study provides a detailed impact assessment of the newly proposed time-controlled One-Shot scheme. But, it only experimented with highway scenarios. Although the solution is generic in nature and expected to work in any scenario, further investigations are needed to assess its impact on city roads and intersections. Moreover, no accident scenario has been simulated in this article or any other study using One-Shot Scheme. Accident scenarios or near miss scenarios may provide newer insight into the actual impact of overall One-Shot solution the rare outage event. It also needs to be noted that, there are several challenges implementing the solution in the Radio devices. Although SAE J3161/1 is standardized, the One-Shot algorithm implementation requires changes to the default 3GPP based C-V2X radio system, in both original counter-based and proposed timer-controlled case. Finally, an overall adoption of C-V2X on real life is still a challenge. Hence, testing this solution with enough C-V2X enabled real-life vehicles is also another hurdle to cross, before fully realizing the value of this improvement.

XIII. CONCLUDING REMARKS

The study investigated the reason and impact of rare prolonged loss unique to C-V2X system in detail. The investigation successfully rationalized and evaluated the proposed state of the art One-Shot based solution to the blinding collision problem. It was discovered that the original One-Shot based solution is not generalized for higher density scenarios in presence of congestion control-based rate reduction. This study provides an alternative algorithm for the One-Shot decision, that is a timer-based approach. The timer based one-shot transmission demonstrated significant improvement over the state-of-the art solutions in both controlled scenario and realistic road topology and channel model. In controlled speed scenario, the new proposal improved information age measurement by 10% to 25% in 99.9%-tile under different channel condition in heavy vehicular density cases. In the realistic mobility scenario, information age was improved by 40% and tracking error was improved by 33% in 99.9%-tile cases of packet receptions for near distance.

ACKNOWLEDGMENT

This work was proposed for patent filing in United States. A patent application [20] is pending in USA and Germany related to the work in this article.

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