Traffic-Aware Sensing-Based Semi-Persistent Scheduling for High Efficacy of C-V2X Networks

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***Abstract*—3GPP has introduced C-V2X technology in the Rel. 14 for improving road safety. There are two modes of vehicular communication in C-V2X viz., Mode 3 and Mode 4. Since Mode 4 allows vehicles to communicate with each other even outside the cellular coverage, it is acknowledged as the baseline mode. In Mode 4, vehicles select the best available least interfered radio resource by utilising Semi-Persistent Scheduling (SPS) in a distributed fashion. Medium Access Control (MAC) parameters like *pKeep* (probability of keeping a radio resource) and Resource Counter (RC) affect the duration of radio resource collision, so these need to be configured carefully for efficient C-V2X communication. This paper explicates the impact of *pKeep* and RC on the overall performance of C-V2X system. A new algorithm called Traffic-Aware SPS (TA-SPS) is then proposed, which optimally configures these parameters according to the current density of road traffic by estimating it from periodic Cooperative Awareness Messages (CAMs) broadcasted by the vehicles. By reducing the number of resource collisions, TA-SPS increases transmission reliability of the C-V2X system. Through extensive simulation studies, we show how TA-SPS outperforms the traditional SPS in mixed road traffic scenarios.**

I. INTRODUCTION

Rapid advancements in wireless communications, sensing technologies, and Machine Learning algorithms have made the development of Intelligent Transport System (ITS) possible. Two wireless technologies competing for ITS deployment are Dedicated Short Range Communication (DSRC) and Cellular-Vehicle-to-Everything (C-V2X) [1]. DSRC is based on IEEE 802.11p and allows communication among vehicles in a decentralized fashion. C-V2X has been introduced in Rel. 14 by 3GPP. It employs Long Term Evolution (LTE) architecture with a few Physical (PHY) and Media Access Control (MAC) layer enhancements for efficient inter-vehicle communication.

C-V2X operates in two modes for communication (Mode 3 and Mode 4) which are based on the scheduling decisions [2]. To support these two modes a new channel named sidelink is created for Uu/PC5 interfaces, distinguishing the flow of information from traditional uplink and downlink channels. In Mode 3, base station centrally manages the radio resources by collecting the channel quality information of vehicles via Uu interface and assists them in radio resource allocation. Mode 4 allows selection of the radio resources in a decentralised fashion using the PC5 interface, where vehicles manage their radio resources for direct vehicle-to-vehicle communication without requiring any base station and using a sensing-based Semi-Persistent Scheduling (SPS) scheme accompanied by congestion control mechanisms.

In C-V2X Mode 4, vehicles periodically broadcast Cooperative Awareness Messages (CAMs) [3] which include the vehicle's speed, acceleration, and trajectory. These messages require timely delivery for improving road safety. Collision of CAMs creates serious issues in SPS implementation, and negatively impacts the performance of safety applications because of wrong localisation of nearby vehicles. Therefore, careful configuration of SPS parameters plays an important role in reducing the number of collisions and ensuring timely delivery of safety related messages to the nearby vehicles. Motivated by this, the proposed work focuses on adjusting the MAC parameters of SPS according to the current density of road traffic to increase transmission reliability. The main contributions of this paper are enumerated below:

- Studying the effect of C-V2X MAC parameters i.e., *pKeep* (probability of keeping a radio resource) and Resource Counter (RC) on Packet Delivery Ratio (PDR) and Message Delay (MD) metrics, and the tradeoff between these two metrics.
- Proposing an enhancement to SPS called Traffic-Aware SPS (TA-SPS) which identifies the optimal values for *pKeep* and RC parameters while accounting for current density of road traffic.

The rest of the paper is organised as follows: Section II presents the related work. Section III explains the working of the SPS scheme in detail. Section IV presents the proposed TA-SPS algorithm. Section V illustrates the simulation setup. Section VI discusses the results, depicted through graphs. Section VII concludes the work with some future directions.

II. RELATED WORK

In the literature, there are some efforts on enhancing radio resource selection for C-V2X Mode 4. Molina-Masegosa et. al. [4] assessed the performance of SPS by presenting different types of transmission errors (with their distributions) under realistic traffic conditions. In [5], Bazzi et. al. analysed the performance of different parameters used in SPS. They found that by tuning *pKeep* in SPS, it is possible to control PDR and UD of the system. It was concluded that *pKeep* is enough to control the system performance and there is no necessity to modify the RC. In [6], Jung S.Y. et. al. proposed a Resource Alternate Selection (RAS) algorithm based on SPS for packet transmission. Multiple resources are chosen alternatively during the period of RC to reduce consecutive collisions. Benefits of RAS algorithm in terms of improvement

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in PDR and reduction in the number of consecutive collisions are shown by considering a 6-lane freeway scenario with 240 vehicles in a 2 KM road segment. In [7], He X. et. al. proposed a short-term sensing-based radio resource selection algorithm. This algorithm is shown to reduce the radio selection collisions and improve the PDR of C-V2X networks.

Unlike the previous works, this paper contributes to selecting both *pKeep* and RC parameters according to current density of road traffic to study their combined effect on PDR and MD metrics and the tradeoffs involved. To our best of knowledge, this is the first work that proposes an algorithm for adjusting the MAC parameters of SPS algorithm according to the current traffic for enhanced performance of PC5 based C-V2X networks.

III. C-V2X MODE 4 COMMUNICATION: AN OVERVIEW

This section presents a brief overview of the PC5 based C-V2X (Mode 4) standard. First, C-V2X Mode 4 Physical (PHY) layer specifications are detailed and then working of sensing-based SPS is elaborated.

A. PHY Layer of PC5 based C-V2X

Like LTE uplink, C-V2X technology uses Single-Carrier Frequency Division Multiple Access (SC-FDMA) and the radio resources are orthogonally divided in both frequency and time domain [8]. It supports both 10 MHz and 20 MHz channel bandwidths. A Resource Block (RB) is the smallest amount of radio resource that can be allocated to a vehicle. One RB is of 180 kHz with 12 subcarriers of 15 KHz each in frequency domain and one ms in the time domain. Each subcarrier has 14 symbols per subframe. Out of these 14 symbols, four are reserved for the DeModulation Reference Signals (DMRS) to counter doppler effect in high mobility environments. Group of RBs in the frequency domain forms a subchannel. A Transport Block (TB) contains a packet to be transmitted that can be transmitted in one or more subchannels. Each TB contains control information called Sidelink Control Information (SCI) which is transmitted using Physical Sidelink Control Channel (PSCCH), whereas TBs are transmitted in Physical Sidelink Shared Channel (PSSCH).

B. Semi-Persistent Scheduling in PC5 based C-V2X

SPS is designed for periodic traffic and thus suitable for C-V2X applications generating traffic with fixed periodicity. In SPS algorithm, vehicles autonomously select the radio resources in a distributed fashion without any assistance from base station and communicate with each other over PC5 interface. A vehicle is permitted to persistently reserve the selected radio resource for some consecutive transmissions controlled by RC and *pKeep* parameters [9]. The SPS algorithm is explained in the following steps:

1) Channel Sensing: After monitoring the Reference Signal Received Power (RSRP) and the Sidelink Received Signal Strength Indicator (S-RSSI) across all subchannels for T_{sense} duration (typically of one sec), the vehicle forms a list of Candidate Subframe Resources (CSR) within the Selection Window (SW). The bounds of the SW are from the time a new resource allocation is triggered (T1) to the maximum latency an application can tolerate (T2).

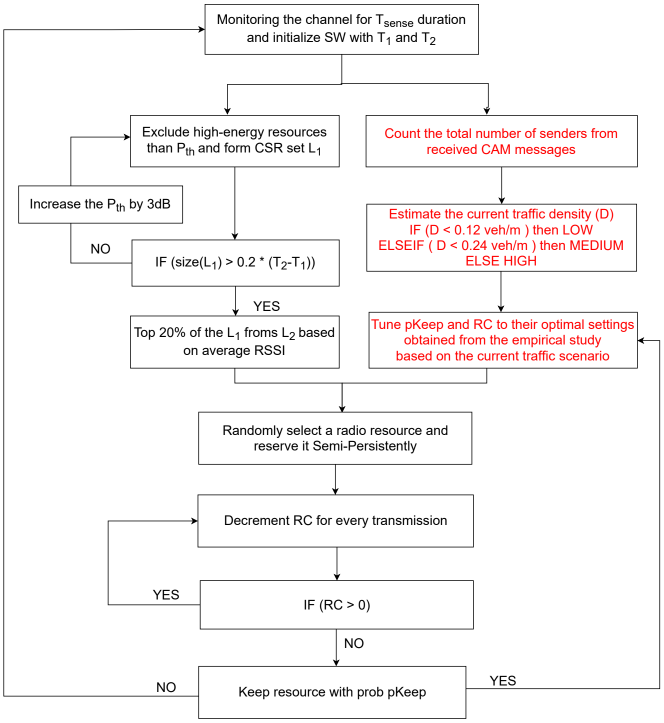

Fig. 1: Flowchart of the proposed traffic-Aware SPS algorithm.

2) Exclusion of Occupied Resources: A new CSR list (L1) is formed, including all the least interfered radio resources. The resources that are estimated to be utilised are then removed from the list. Excluded resources are dropped out on the following conditions:
   a) The vehicle cannot monitor the corresponding CSRs simultaneously as it is transmitting due to the Half-Duplex problem.
   b) SCI has been received from another vehicle, indicating that it would utilise this CSR in future during a slot in the selection window (SW), and
   c) The RSRP of subchannel(s) associated with the SCI is higher than the threshold value (P_{th}).

   After scanning through SW, if the L1 is not 20% of the total available CSRs, then the RSRP threshold is augmented by 3dB and Step 2 is repeated until the size of L1 is at least 20% of the total avaliable CSRs.
3) RSSI Calculation: The resource list L1 is then sorted based on the average RSSI. RSSI values are averaged over the previously transmitted subframes within the sensing window. Avg. RSSI = $\sum_{t=1}^{j} RSSI_{CSR-j*100}/j,\ j \in [1-10]$. Then top 20% of the entries forms the list L2, and the resultant list is then passed to the MAC layer.
4) Resource Reservation: A resource is chosen randomly from the list L2 by the MAC layer and reserved for

some consecutive transmissions.

IV. PROPOSED TRAFFIC-AWARE SPS ALGORITHM

Procedure for selecting a radio resource through SPS has been elaborated in Section III-B. The MAC layer parameters *pKeep* and RC determine the maximum duration to reuse the previously selected radio resources without rerunning the SPS algorithm for selection of radio resources by the vehicles. First, a vehicle chooses a random value from the RC range, say RC_x, and uses the same selected resource for RC_x consecutive transmissions. The value of RC_x is decremented every time a packet is transmitted by the vehicle. Once the RC_x becomes zero, then the second parameter *pKeep* decides whether to reuse the same resource or not for its subsequent transmissions.

Figure 1 shows the flowchart of proposed Traffic-Aware SPS (TA-SPS) algorithm. Modifications made to SPS while designing the TA-SPS are highlighted in the flowchart with red font. 3GPP has defined various ranges for MAC parameters of SPS algorithm. TA-SPS algorithm selects the best possible combination of these parameters for each traffic density scenario. TA-SPS, running inside C-V2X radio of each vehicle, analyses the CAM messages received from other vehicles in order to estimate the current traffic scenario based on unique MAC IDs. For the estimated traffic scenario, it sets the best possible combination of pKeep and RC for improving PDR while keeping MD within a limit. Selecting the best possible combination for this duplet and varying them accordingly to the nearby vehicles density enhances reliability of broadcast messages transmitted by the vehicles. Higher *pKeep* and wider RC range make the channel conditions steady by increasing the duration of resource usage. If the channel condition is almost unchanged from the last sensing period, it means that the vehicle can now precisely estimate the channel occupancy and will have higher PDR. Also, an additional advantage of the TA-SPS is that it does not incur any additional signaling overhead as it relies only on the periodic CAM messages sent by the other vehicles.

V. SIMULATION SETUP

A. Simulation Tools

We evaluate the performance of the proposed TA-SPS algorithm using a system-level simulator. The simulations are carried out using the OpenCV2X Mode 4 simulator [10], which is a combination of OMNeT++ , INET, SimuLTE, Veins, and SUMO. The OpenCV2X-Mode 4 is an open-source implementation of the Mode 4 C-V2X standardised by 3GPP in LTE Rel. 14. It is based on an extended version of the SimuLTE. OMNet++ is a C++ based simulation library and framework, and it provides a platform for building different communication networks. One such model library is INET which contains models for Internet stack and link-layer protocols for wireless networks. The SimuLTE is a module for LTE simulations. The Veins is a framework for administering vehicular network simulations with a complete suite providing inter-vehicle communications. Both SimuLTE and Veins internally use INET as the base. The SUMO is used to generate realistic traffic mobility for the considered simulation scenarios.

TABLE I: Simulation parameters

Parameter	**Value**
Application Layer	
Packet size	300 B
Transmission frequency	10 Hz
SPS MAC and PHY Layer Parameters	
pKeep	[0 - 0.8]
Resource Counter	[2, 7], [5, 15], [10, 30]
T_{sense}	1 sec
T1	4
T2	100
RSRP threshold (P_{th})	-92 dBm
Rsel	0.2
PHY Layer	
MCS	7
Propagation model	WINNER+ B1
Transmission power	23 dBm
Noise figure	9 dB
Shadowing variance loss	3 dB
Radio Reservation Interval	100 ms
Channel Settings	
Carrier Frequency	5.9 GHz
Channel bandwidth	10 MHz
Number of subchannels	2
Size of subchannels	24 Resource Blocks
PSCCH-PSSCH arragement	Adjacent

Table I shows various simulation parameters that are set in the OpenCV2X Mode 4 simulator. We consider a one KM highway with six lanes. A realistic vehicular mobility environment is created for the considered highway segment by varying number of vehicles, their speeds and directions using the SUMO simulator. Three traffic scenarios are simulated using the SUMO: low-density (0.12 vehicles/meter with an average speed of 86.4kmph), medium-density (0.24 vehicles/meter with an average speed of 46.8kmph), and high-density (0.36 vehicles/meter with an average speed of 28.8kmph). Vehicles are broadcasting CAMs of the fixed size with a periodicity of 100 ms.

B. Performance Metrics

Following metrics are used to study the performance of proposed TA-SPS:

1) Packet Delivery Ratio (PDR): The average of ratio of the total number of CAMs successfully received by the vehicle to the total number of CAMs broadcasted by its nearby vehicles i.e., PDR = $CAM_{received}$/CAM_{sent}.
2) Message Delay (MD): For a sender(s)-receiver(r) pair, the time difference between the last successfully received CAM (T_s^{j-1}) and the currently received CAM (T_s^j) gives the inter-message delay i.e., MD_r = T_s^j - T_s^{j-1}.

The effective distance while calculating these two metrics is set to 300 meters between sending vehicles and receiving vehicles. Rather than reporting average of message delays of all the vehicles in the system, we report the maximum value in 99.99% of inter-message delays from the sorted list as the MD metric in this work.

TABLE II: Variation in PDR and MD metrics for various *pKeep* + [RC] combinations in case of traditional SPS algorithm under different traffic scenarios

Traffic Density	Performance Metrics	Setting I	Setting II	Setting III	Setting IV	Setting V	Setting VI	Setting VII
		***pKeep*:0.0 RC: [5,15]**	**0.0 [10, 30]**	**0.4 [2, 7]**	**0.4 [5, 15]**	**0.4 [10, 30]**	**0.6 [5, 15]**	**0.8 [5, 15]**
Low Density	PDR(%)	93.10	96.65	94.19	95.95	97.10	**97.64**	98.08
	MD(sec)	2.2	2.8	2.5	2.7	2.9	**3.0**	3.5
Medium Density	PDR(%)	81.37	86.18	83.47	85.13	**88.67**	87.28	91.48
	MD(sec)	4.7	5.3	4.9	5.1	**5.5**	5.4	6.1
High Density	PDR(%)	67.02	**74.85**	69.22	71.08	77.18	75.8	79.29
	MD(sec)	5.0	**6.0**	5.3	5.8	6.5	6.3	7.2

VI. PERFORMANCE RESULTS

This section presents the performance of traditional SPS by varying MAC parameters under various traffic scenarios. First, the effect of C-V2X MAC parameters i.e., *pKeep* and RC on PDR and MD metrics is studied for low, medium and high density scenarios using traditional SPS algorithm. Then, comparison of TA-SPS with the traditional SPS is made in a time varying road traffic scenario.

A. Variation in pKeep and RC for different traffic scenarios

To study the affect of *pKeep* and RC values on the performance of C-V2X system which employs traditional SPS algorithm, the *pKeep* is varied from 0 to 0.8 while also varying RCs from [2, 7] to [10, 30]. Due to space constraints, only the predominant configurations are reported in Table II. As shown in the table, higher pKeep or wider RC achieve higher PDR but also increases the duration of resource collisions and delay between delivery of consecutive CAM messages. Therefore, the objective is to find such a duplet from our empirical study that gives higher PDR while keeping MD under an acceptable limit.

1) ***Low-Density Scenario****:* To simulate a low-density traffic scenario, 120 vehicles are considered over a one km road segment in the experiment. Exhaustive combinations of *pKeep* and RC are studied, and their results are tabulated above. The mean PDRs are 95.95%, 97.64% and 98.08%, for settings IV, VI, and VII, respectively. Higher *pKeep* stabilises the channel occupancy leading to accurate channel condition estimation and ultimately reducing radio resource collisions. Nevertheless, increment in mean PDR negatively affects the MD causing localisation errors because of outdated information. To balance these two metrics, setting VI is considered as the optimal for low-density traffic as it increases the overall PDR with minimal increment in MD compared with MD at setting IV.

2) ***Medium-Density Scenario****:* For this scenario, 240 vehicles are considered in the experiment. With setting I, the mean PDR is 81.37%, but with setting VII it has increased by $\sim 10\%$. MD has also increased by 1.4 sec. Here, setting IV is an intermediate solution with PDR of 85.13% and MD of 5.1 sec. If RC range is doubled according to the traffic scenario i.e., from setting IV to setting V, a significant difference is achieved in the system performance. This is because a wider RC makes the channel condition more predictable and increases the packet reception.

To find the optimal pair, we consider frequently used setting IV as the lower limit of system performance and setting VII as the upper limit. PDR has covered 55.7% of this range $(PDR_{SettingVII} - PDR_{SettingIV})$ in setting V by doubling the RC. While the increment in MD is minimal compared to MD at setting VII, which is just 40% of the range.

3) ***High-Density Scenario****:* For this scenario, 360 vehicles are considered in the experiment. By varying the *pKeep* from 0 to 0.8, keeping RC as constant at [5,15], PDR has improved by $\sim 12\%$ in setting VII when compared with setting I. Moreover, MD also got increased by 2.2 sec. For the intermediate setting (IV), PDR is 71.08% but MD is 5.8 sec, which is already high. In this high density scenario, the desirable MD is around the MD achieved with intermediate *pKeep* value because MD more than 6 sec is not acceptable by many safety applications. However, moving close to *pKeep* of 0.8 increases the MD drastically and does not serve our primary purpose. So, the best possible duplet for this high density scenario could be setting II. Along with low *pKeep*, RC should be widened enough to enhance the system performance by improving the PDR and keeping MD within the acceptable threshold.

To find the optimal pair, we consider setting IV as the lower limit and setting VII as the upper limit of system performance. It can be seen that MD is just 14.2% of this range $(MD_{SettingVII} - MD_{SettingIV})$ in setting II by doubling the RC, and the PDR has covered 45.9% of this range.

B. Evaluation of proposed TA-SPS algorithm

To evaluate TA-SPS performance under time varying traffic conditions during the simulation experiment, traffic traces are created by varying vehicle density from low to medium to high with time. When the proposed TA-SPS algorithm is employed by the vehicles, they choose the best possible combination of MAC parameters according to the current traffic density to optimize the system performance (as highlighted in Table II).

The proposed TA-SPS is compared with traditional SPS having different static *pKeep* and RC combinations. As shown in Fig. 2, compared to the intermediate and most frequently used static MAC combination i.e., *pKeep* of 0.4 and RC of [5,15], TA-SPS performs better with 4% improvement in the PDR with almost the same MD. Also, TA-SPS outperforms all other static combinations used in SPS in terms of combined

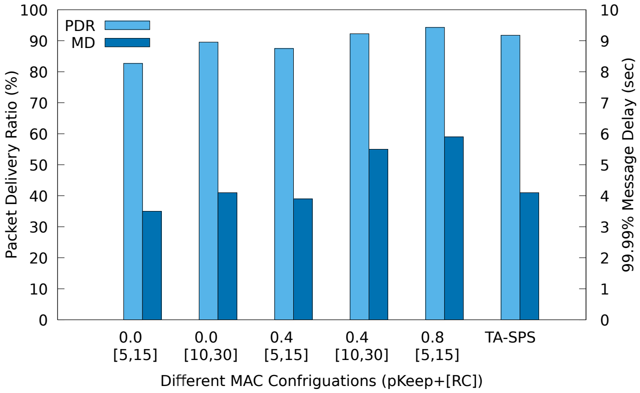

Fig. 2: SPS with different static MAC configurations vs TA-SPS in case of time varying traffic scenario.

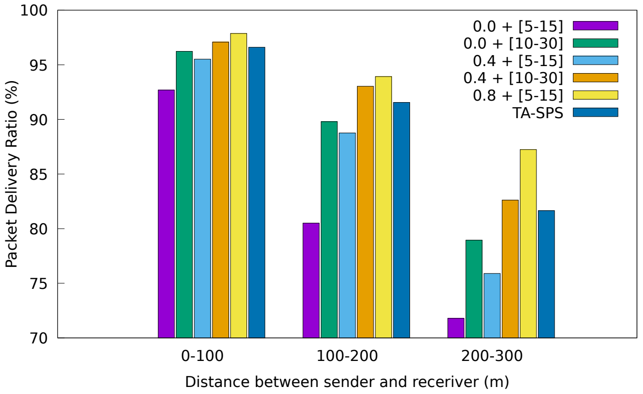

Fig. 3: PDR vs transmission distance for SPS with different static MAC configurations and TA-SPS.

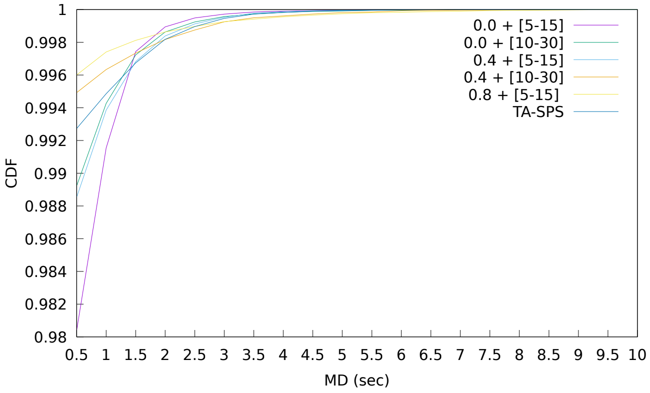

Fig. 4: CDF of MDs for SPS with different static MAC configurations and TA-SPS.

PDR and MD metrics. Fig. 3 shows PDR as a function of the distance between sender and receiver for various MAC configurations of SPS and TA-SPS. As the distance increases, PDR starts decreasing mainly because of radio resource collisions and the maximun difference is observed from 200m to 300m range. The TA-SPS is performing better than SPS with static 0.4+[5-15] MAC parameters from the beginning but the difference in PDR between SPS and TA-SPS is noticeable from 100m onwards. Fig. 4 explains the trend in MD for these configurations. CDF curve of SPS with static 0.0+[5-15] MAC parameters has steeper slope, that is why the maximum value of 99.99% MD for SPS with 0.0+[5-15] is 3.6 sec while it is 6 sec for SPS with 0.8+[5-15].

By adaptively choosing the best combination of MAC parameters, the proposed TA-SPS improves message delivery without increasing the message delay and therefore it helps in timely delivery of safety related messages.

VII. CONCLUSIONS

This paper studied the effect of different configurations of *pKeep* and RC parameters of SPS algorithm on the overall system performance in PC5 based C-V2X networks. Based on the study, a modified SPS scheme called TA-SPS is proposed, which adjusts these parameters according to the current traffic density. An improvement of 4% in PDR is achieved when using TA-SPS as compared with traditional SPS for time varying traffic scenarios. As *pKeep* and RC have an extensive range of combinations, depending on the performance requirements of ITS applications these values need to be configured appropriately.

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