C-V2X Assisted mmWave V2V Scheduling

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***Abstract*—mmWave V2X (Vehicle-to-Everything) communications can support enhanced V2X applications for connected and automated vehicles. The design of mmWave V2X communications is though not exempt of challenges as a result of propagation and highly dynamic vehicular networks and topologies. To address some of these challenges, the authors propose decoupling the mmWave MAC control and data planes, and utilize sub-6GHz V2X communications for the control plane of mmWave V2X. In this context, this study evaluates the feasibility of using C-V2X as mmWave control plane. In particular, the study proposes and analyzes two mmWave V2X scheduling schemes that utilize C-V2X to schedule mmWave transmissions. The proposed schemes are evaluated considering periodic and aperiodic C-V2X beacons. The conducted evaluation shows that an adequate design of the scheduling scheme can reduce the impact of aperiodic beacons, and facilitate the use of C-V2X as a control plane for mmWave V2X communications.**

Keywords—mmWave, C-V2X, Cellular V2X, LTE-V, LTE-V2X, IEEE 802.11ad, MAC, scheduling, V2X, vehicular networks, aperiodic, non-periodic.

I. INTRODUCTION

V2X (Vehicle to Everything) communications have been initially designed to support active safety and traffic management services. To this aim, first V2X standards were based on IEEE 802.11p; e.g. ITS-G5 in Europe or DSRC in USA. An LTE-based standard for V2X communications has also been developed by the 3GPP. The standard is usually referred to as C-V2X, Cellular V2X, LTE-V or LTE-V2X. Current standards mainly plan to operate on the 5.9GHz band, and most services are based on the broadcast transmission of small beacon messages (known as CAM in ITS-G5 or BSM in DSRC). These beacons include relevant information such as the vehicle's location, direction, speed and acceleration.

The development of more advanced connected and automated applications require the exchange of larger amounts of data. For example, cooperative perception or sensing will require vehicles to exchange raw or processed data of their built-in sensors (cameras, LIDAR, radar, etc.) to improve their perception of the surrounding environment. Supporting the data rates and throughput required by this type of advanced applications can be a challenge for sub-6GHz V2X standards. mmWave V2X communications can address this challenge and support bandwidth-demanding applications [1]. However, operating at mmWave frequencies (30-300GHz) is not exempt of technical challenges, in particular under highly dynamic vehicular scenarios. mmWave communications are easily blocked and suffer from higher propagation pathloss. This can be (partially) addressed using highly directional communications with beamforming. This requires aligning the beams between transmitter and receiver. Such alignment can be a challenge in vehicular scenarios due to the high mobility of vehicles. In fact, [2] showed that current mmWave standards (in particular IEEE 802.11ad) are not capable to efficiently support mmWave V2X communications. This is due to difficulties experienced in the beam alignment and tracking processes as well as in the scheduling of transmissions. To address them, studies have proposed using side information (from sensors or even sub-6GHz V2X) to obtain the relative position of neighboring vehicles and facilitate the mmWave beam alignment and tracking [1]. In line with this approach, the authors proposed in [3] a novel sub-6GHz assisted MAC for mmWave V2X communications. The proposal includes decoupling the mmWave MAC control and data planes, and offloading mmWave MAC control functions (e.g. beamforming and scheduling) to sub-6GHz V2X communications. The authors showed in [3] that such decoupling is highly beneficial to schedule mmWave V2X transmissions since we can exploit the broadcast, omnidirectional and larger range of sub-6GHz V2X communications and improve the operation of the mmWave MAC.

The proposal in [3] was based on IEEE 802.11p for sub-6GHz V2X communications. Some studies claim that C-V2X outperforms IEEE 802.11p due to a potentially better link budget, the use of redundant transmissions, and the characteristics of the defined sensing-based semi-persistent scheduling [4]. In this context, this paper analyzes the potential to utilize C-V2X as the control plane of future mmWave V2X communications. In particular, we propose and analyze two schemes that schedule mmWave V2X data transmissions using the C-V2X beacons as control plane. It is important noting that although C-V2X replaces the IEEE 802.11p MAC and PHY layers, it reutilizes the upper layers developed by SAE, IEEE and ETSI, including the facilities to generate beacon messages. The evaluation is done considering periodic and aperiodic beacons' traffic. This is an important aspect since there is some debate on whether a semi-persistent scheduling scheme would work correctly with aperiodic beacons [5]. Recent studies have empirically shown that beacons (or CAMs) are not generated periodically by the European ITS-G5 standard [6]. This study shows that aperiodic traffic can impact the C-V2X operation. However, this study also demonstrates that one of the proposed C-V2X assisted scheduling schemes for mmWave V2X data transmissions can counteract the impact of aperiodic beacons on C-V2X operation, and significantly improve C-V2X assisted mmWave V2V communications.

II. C-V2X COMMUNICATIONS

C-V2X was developed under 3GPP release 14 to support V2X communications. C-V2X organizes radio resources in 1ms-long sub-frames and 180kHz-wide Resource Blocks (RB). RBs can be grouped in the same sub-frame to define a sub-channel. Vehicles use the sub-channels to transmit data (a.k.a. Transport Block, TB) and control information (a.k.a. Sidelink Control Information, SCI) (Fig. 1). The TB contains beacon messages (or other type of messages) while the SCI includes the necessary information to decode the TB (e.g. the modulation and coding scheme used to transmit the TB).

C-V2X defines two communication modes to support V2V communications. In Mode 3, the cellular network selects and manages the radio resources used by the vehicles for their direct or sidelink V2V transmissions. On the other hand, vehicles autonomously select and manage these resources under Mode 4. This work focuses on Mode 4 so that V2V communications do not depend on the availability of cellular coverage. C-V2X Mode 4 uses the sensing-based Semi-Persistent Scheduling (SPS) mechanism for vehicles to select and reserve their radio resources. The mechanism uses the resource reservations of other vehicles and the signal level detected in each sub-channel to select the sub-channels within a *Selection Window*[1]. The maximum length of the *Selection Window* is defined by the *maximum latency* a message can tolerate. For example, if beacons are generated at 10Hz, then the *Selection Window* is lower or equal to 100ms. C-V2X can then introduce a delay between the generation of a message to be transmitted and the time the message is transmitted. This is illustrated in Fig. 1 where a beacon is generated at $t=t_G$ and its transmission is delayed until $t=t_{TX}$. t_{TX} corresponds to the transmission time of the sub-channels SC_1 selected by the sensing-based SPS scheme within the *Selection Window*.

Vehicles can reserve the selected sub-channels for up to *Reselection Counter* transmissions. The *Reselection Counter* is randomly selected between 5 and 15. After each transmission, the *Reselection Counter* is reduced by one. When the counter is equal to 0, vehicles have to execute again the sensing-based SPS scheme to select new sub-channels. Vehicles inform their neighboring vehicles about the selected and reserved sub-channels using the SCI. The reserved sub-channels are separated by a time *Resource Reservation Interval* (*RRI*) indicated in the resource reservation field of the SCI. Following the example illustrated in Fig. 1, if a vehicle uses the sub-channels SC_1 at time instant $t=t_{TX}$, it will inform nearby vehicles through its SCI that it is also reserving SC_1 at time instant $t=t_{TX} + RRI$. This is done to avoid two vehicles selecting the same sub-channel at the same time. The reserved resource is finally utilized for the following transmission if the *maximum latency* is again guaranteed. In the example of Fig. 1, when a new beacon is generated (e.g. at $t=t_{G2}$), the vehicle uses the reservation made at $t=t_{TX} + RRI$ if $t_{TX}+RRI-t_{G2}$ < *maximum latency*. Otherwise, the vehicle has to execute again the C-V2X SPS mechanism.

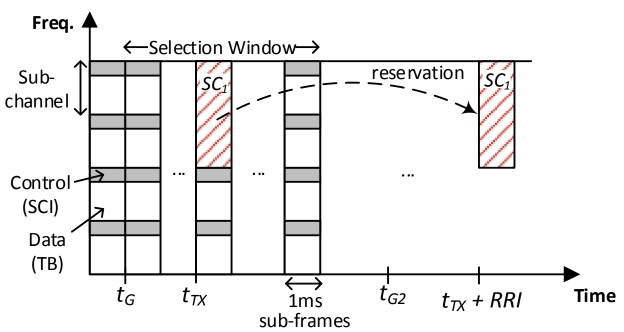

Fig. 1. C-V2X time-frequency grid and SPS resource reservation.

III. C-V2X Assisted mmWave V2V

This paper proposes using C-V2X to implement MAC functions for mmWave V2V communications. Following [3], we offload mmWave beam alignment and tracking, link availability identification, and scheduling control functions to C-V2X. The proposed C-V2X assisted MAC uses the location information included in the C-V2X beacons to align and track beams. This information is also used to identify available mmWave links. Such links are identified by detecting the visibility conditions (i.e. LOS or NLOS) between vehicles given the mmWave sensitivity to blockage. Beacon messages are also used to schedule mmWave transmissions. In particular, this paper proposes and evaluates two C-V2X assisted mmWave V2V scheduling schemes. Both schemes use C-V2X beacons as logical Request-to-Send (RTS) or Clear-to-Send (CTS) messages to schedule mmWave V2V transmissions. The proposed schemes utilize existing C-V2X beacons and do not require transmitting new or additional messages for scheduling mmWave V2V transmissions.

A. Scheduling Scheme 1 based on RTS+CTS exchange

The first scheme is based on the RTS/CTS exchange defined in IEEE 802.11 CSMA/CA to address the hidden terminal problem. In IEEE 802.11, the RTS (sent by the sender) and CTS (sent by the receiver) packets are used to inform neighboring nodes of the scheduled transmission and alert all nodes not to transmit during this period. The first proposed C-V2X assisted mmWave V2V scheduling scheme uses similarly the RTS and CTS messages. To explain its operation, let's consider the example illustrated in Fig. 2. Let's suppose a scenario with four vehicles (A, B, C, D). The vehicles transmit their C-V2X beacons represented in Fig. 2 as vertical arrows. These vehicles can require mmWave V2V transmissions at any time. For example, vehicles A and B detect the need to start a mmWave V2V transmission at t=40ms. Vehicle A uses its first beacon at t=60ms (as an RTS-like message[2]) to announce the mmWave neighbors it wants to communicate with (e.g. vehicles D, B and C in Fig. 2). The RTS-like beacon also includes the duration of the mmWave transmission to each vehicle (e.g. 50ms for all vehicles in Fig. 2), and the delay to the start of the mmWave transmission to each of neighboring vehicle (50, 100 and 150ms for vehicles D, B and C in Fig. 2). The transmitting vehicle (vehicle A) orders the mmWave transmissions to its neighboring vehicles based on the order it expects to receive the next beacon from each one of its neighbors. This is the case because the neighbors addressed in the RTS-like beacon need to acknowledge the reception of the RTS-like message in their next beacon (i.e. a CTS-like beacon) before the mmWave transmissions can start. The established order guarantees then that the mmWave transmissions are scheduled as soon as they can take place. The mmWave transmitter can identify the order it expects to receive the next beacon from each one of its neighbors using the SPS reservation information included in the SCI of the C-V2X beacons previously transmitted by its neighbors.

The CTS-like beacon messages include information about the scheduled mmWave transmission to inform neighboring vehicles in case they did not receive the RTS-like beacon message from vehicle A. For example, D is the first neighbor addressed by A's RTS-like beacon. D uses its first beacon after the RTS-like beacon from A as a CTS-like message. This message includes the ID of the mmWave transmitter (i.e. A), the delay to the start of the mmWave transmission from A to D (*Delay*=0ms), and the duration of the mmWave transmission (all this information was received

[1] Readers are referred to [7] for detailed information on the operation of sensing-based sub-channels selection.

[2] The RTS message is appended to the beacon message.

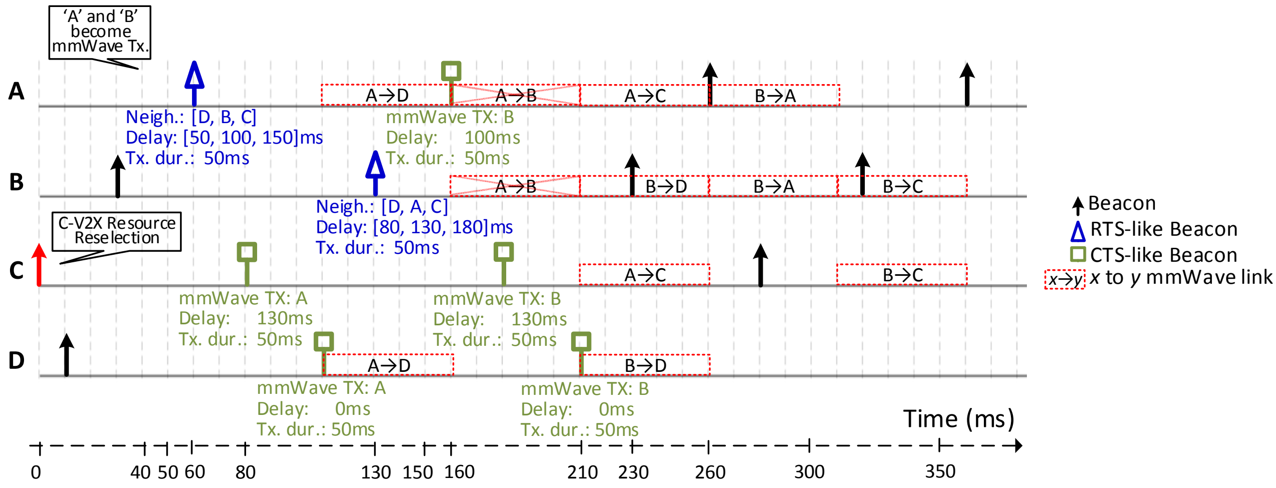

Fig. 2. Illustration of the scheduling *Scheme 1* based on RTS+CTS exchange.

in A's RTS-like beacon). The A→D mmWave transmission starts when A receives D's CTS-like beacon. Fig. 2 shows the 50ms interval allocated for this transmission.

B is the second neighbor addressed in A's RTS-like beacon in Fig. 2. It should then use its next C-V2X beacon as a CTS-like message. However, B also identifies it wants to start a mmWave transmission at *t*=40ms in Fig. 2. B uses then its next beacon at *t*=130ms as an RTS-like beacon to schedule its own mmWave transmissions[3]. B establishes the order of its mmWave transmissions following the process previously explained and the other scheduled mmWave transmissions to avoid any conflicts. Vehicle B is aware of such scheduled transmissions from the RTS-like and CTS-like beacon messages. For example, Fig. 2 shows how B schedules its transmission to A at *t*=260ms since A is previously busy with its own mmWave transmissions.

C is the third neighbor addressed in A's RTS-like beacon. However, if we look at the timing of the beacons in Fig. 2, C should have been the first scheduled transmission since it is the vehicle that transmits first a beacon after the RTS-like message from A. However, Fig. 2 illustrates an example where vehicle C has to reselect new sub-channels after its beacon at *t*=0ms since its *Reselection Counter* reached a value equal to zero. C cannot then indicate in its beacon at *t*=0ms any resource reservation for its next beacon. Since A does not know when C will transmit its next beacon, A schedules the mmWave transmissions to C after all other mmWave transmissions have finished[4]. C confirms with its RTS-like beacon at *t*=80ms the start of the A→C mmWave transmission at *t*=210ms. This scenario illustrates how the proposed scheme supports spatial sharing: the A→C and B→D mmWave transmissions take place at the same time.

1) Scheduling Scheme 2 based on CTS

The second scheduling scheme is an adaptation of the proposal presented in [3] by the authors. The original proposal was designed for IEEE 802.11p, and it is here adapted to C-V2X. Similarly to the first proposal, vehicles announce their mmWave transmissions using their beacons as an RTS-like message. The RTS-like beacon message also includes the duration of the mmWave transmission to each neighbor. The difference with the first scheme is that the RTS-like beacons of the second proposal do not specify when the mmWave transmissions to each neighboring vehicle should start. It is actually the neighboring vehicles the ones that schedule the transmissions in a distributed manner. To this aim, the neighbors addressed in an RTS-like beacon use their next beacon after receiving the RTS-like message as a CTS-like message to respond to the RTS. In these beacons, the addressed neighbors indicate the ID of the mmWave transmitter and the delay to the start of the mmWave transmission. To identify such delay, the addressed neighbors take into account all previous CTS-like messages transmitted by other addressed neighbors. This allows for a distributed scheduling operation while avoiding scheduling conflicts between vehicles under their sub-6GHz communication range (since beacons are transmitted with C-V2X). A detailed example of the operation of this scheduling scheme can be found in [3].

IV. Performance Evaluation

A. Scenario

The proposed C-V2X assisted mmWave V2V scheduling schemes are evaluated using simulations under ns-3.26. The simulation scenario emulates a highway with 4 lanes, and a vehicular density of 125vehicles/km. Each vehicle is equipped with a C-V2X interface at the 5.9GHz band (10MHz channel) and a mmWave one (IEEE 802.11ad) at the 60GHz band (2.16GHz channel). The C-V2X interface has been implemented by the authors in ns-3 based on [7], while the IEEE 802.11ad implementation is based on [8] and [2]. The IEEE 802.11ad interface is configured with a 14-sector directional antenna, a transmission power of 10dBm, and a modulation and coding scheme that allows a data rate of 693Mbps. The mmWave propagation loss is modelled following [2]. The C-V2X interface uses an omnidirectional antenna, and the transmission power is set to 15dBm. The sub-6GHz propagation loss follows the WINNER+ B1 model (σ =3dB for the shadow fading standard deviation) [10]. The noise figure is set to 9dB and the in-band emissions

[3] This is done instead of replying to A's RTS-like beacon which is why the A→B transmission is crossed out in Fig. 2. B does not use either its beacon at *t*=230ms to reply to A's RTS-like beacon. This is the case because this response would be too late as the A→B mmWave transmission was scheduled between *t*=160ms and *t*=210ms.

[4] This approach reduces the likelihood that A schedules the mmWave transmission to C before C can transmit its CTS-like beacon.

are modelled following [10]. The 10MHz C-V2X channel is divided into 4 sub-channels of 12 RBs each.

The evaluation considers a scenario where mmWave transmitters want to communicate with all their neighboring vehicles under LOS conditions[5]. Evaluations have been done considering that {15, 20, 25, 30, 35, 40}% of vehicles (R_{TX}) in the scenario can be mmWave transmitters. The analysis considers that mmWave transmissions last 10 or 50ms. During a mmWave transmission, a vehicle sends 12000 packets (of 1600 bytes each) per second. The packet size is chosen to emulate a collective perception use case following [11]. All vehicles also transmit C-V2X beacons of 300 bytes[6]. We have implemented periodic [10] and aperiodic [9] beacon generation traffic models following the 3GPP recommendations. The periodic one considers that vehicles transmit beacons every T_{GEN}=100ms. The time between beacons for the aperiodic model is equal to (in ms) 50+exp(λ), where exp(λ) is an exponential distribution with average λ (λ is set to 50 based on [9]). We assume for both models that the C-V2X *RRI* is equal to 100ms and that the *Selection Window* is also set to 100ms.

Sufficient simulations have been done to ensure the statistical accuracy of the results that are reported in the next sub-section as average values.

B. Results

Fig. 3 depicts the time elapsed (or delay) between the time instant a vehicle becomes a mmWave transmitter and the start of the mmWave tranmissions to the scheduled neighbors. For clarity, Fig. 3 plots the delay only to the 1st, 3rd, and 5th scheduled neighbors. Results are reported for the scheduling schemes with periodic (Fig. 3-left) and aperiodic (Fig. 3-right) traffic. Fig. 3 shows that the delay to the scheduled mmWave neighbors increases with the ratio R_{TX} of mmWave transmitters in the scenario. This is the case because when the number of mmWave transmitters in the scenario increases, there are more potential scheduling conflicts. The proposed schemes postpone then certain mmWave transmissions in order to avoid scheduling conflicts. Fig. 3 also shows that aperiodic traffic increases the delay. It is though important to highlight that such increase is smaller with *Scheme 2* that actually outperforms *Scheme 1* in terms of delay under all simulated conditions. The distributted mmWave scheduling defined in *Scheme 2* results in that the neighbors establish the order to communicate with the mmWave transmitter upon the generation of their beacons. This explains why *Scheme 2* limits the impact of aperiodic traffic on the operation and performance of the C-V2X assisted mmWave V2V communications.

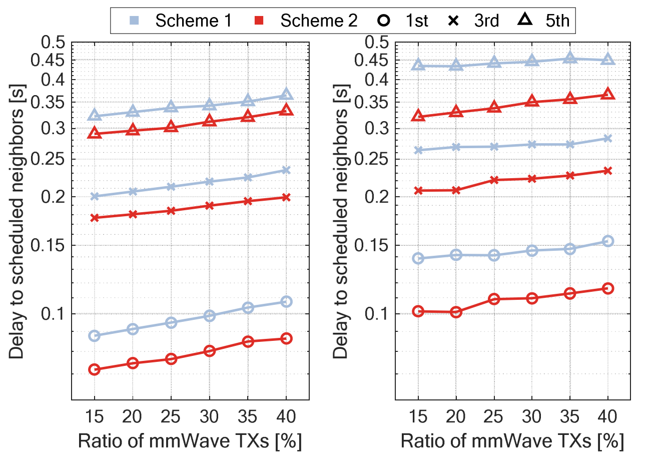

Fig. 3. Delay to contact the 1st, 3rd and 5th mmWave neighbors when the beacons are generated periodically (left) and aperiodically (right). The mmWave transmissions last for 50ms (similar trends are observed when the mmWave transmissions last for 10ms).

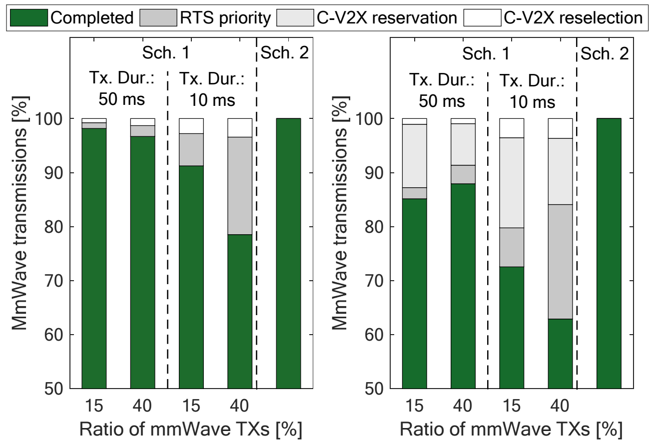

Fig. 4. Status of mmWave transmissions with periodic (left) and aperiodic (right) beacon traffic when using Scheme 1. The performance achieved with Scheme 2 is shown as a benchmark. Scheme 2 completes all 10ms and 50ms mmWave transmissions for all values of R_{TX}.

Fig. 4 compares the percentage of completed and not completed mmWave transmissions for the two scheduling schemes. A mmWave transmission is considered to be completed if the mmWave transmitter can finalize its data transmission in the allocated time interval (10 or 50ms). Fig. 4 clearly shows that *Scheme 2* can successfully complete all mmWave data transmissions. This result is achieved for all R_{TX} values and for 10ms and 50ms mmWave transmissions. On the other hand, *Scheme 1* is not capable to complete all mmWave V2V transmissions. For example, 91.2% and 72.5% of the scheduled 10ms mmWave transmissions are not completed with *Scheme 1* when C-V2X transmits periodic and aperiodic beacons respectively, and there are 15% of mmWave transmitters in the scenario[7]. When R_{TX} increases to 40%, this percentage decreases even further to 78.5% and 62.9% respectively. *Scheme 1* cannot complete a mmWave data transmission if:

- The addressed neighbor cannot transmit its CTS-like response to an RTS-like beacon before the start of the scheduled mmWave transmission. This can occur because the addressed neighbor is also a mmWave transmitter, and it utilizes its next beacon to transmit an RTS-like beacon (to schedule its own mmWave transmissions) rather than transmitting the expected CTS-like response. This case is referred to as 'RTS priority' in Fig. 4.
- The addressed neighbor has to select new sub-channels before transmitting the CTS-like beacon, and the newly

[5] Each vehicle has on average 5.5 neighboring vehicles under LOS in the simulated scenario.

[6] The beacons are transmitted using MCS 7 (QPSK and ½ coding rate), and hence require 20 RBs or 2 sub-channels.

[7] Fig. 4 shows a higher percentage of completed mmWave transmissions for *Scheme 1* when the mmWave transmissions last for 50ms compared to when they last 10ms. A duration of 50ms increases the time intervals allocated for mmWave transmissions. This delays the start of each scheduled transmission for at least 50ms (Fig. 3), but gives more time for the addressed neighbors to send their CTS-like beacons.

selected sub-channels are planned to start later than the beginning of the scheduled mmWave transmission. This reduces the amount of resources available to complete the transmission in time. This case is referred to as "C-V2X reselection" in Fig. 4.

- The addressed neighbor does not utilize the reserved sub-channels to transmit the CTS-like beacon, and hence does not have access to sufficient resources to complete the transmission in time. This can occur with aperiodic transmissions. To explain it, let's consider the example illustrated in Fig. 1 when a beacon is generated at $t=t_G$. The SPS mechanism selects sub-channels at $t=t_{TX}$ within a *SelectionWindow* so that $t_G < t_{TX} < t_G + SelectionWindow$. The sub-channels are reserved every *RRI* ms for the following *Reselection Counter* transmissions. If the beacons are generated periodically, all reservations are utilized since $t_G + T_{GEN} < t_{TX} + RRI$. However, if the generation of beacons is aperiodic the previous inequality might not be always satisfied. This happens if the beacon is actually generated after the reservation has passed. In this case, the reserved sub-channels are not used and the beacon has to be transmitted using the following reserved sub-channels. This increases the time between transmitted beacons to 2**RRI*. For the simulated scenario, 17.4% of the reserved C-V2X resources are not utilized with the aperiodic beacon traffic. This case is referred to as 'C-V2X reservation' in Fig. 4.

The delay (Fig. 3) and reliability (Fig. 4) benefits obtained with *Scheme 2* over *Scheme 1* are at the origin of the higher aggregated mmWave throughput observed for *Scheme 2* in Fig. 5. This figure depicts the aggregated mmWave throughput for a varying ratio R_{TX} of mmWave transmitters in the scenario, the two beacon traffic models, and the scenarios where the mmWave data transmissions last 10 or 50ms. The aggregated mmWave throughput at a given point in time is defined as the sum of the throughput measured between simultaneous mmWave transmissions. Fig. 5 shows the average of the aggregated mmWave throughput over the simulation time. Fig. 5 shows that aperiodic traffic reduces the aggregated mmWave throughput following the previously described inefficiencies. However, *Scheme 2* can better cope with these inefficiences than *Scheme 1*, and Fig. 5 shows that the throughput degradation with aperiodic traffic compared with periodic one is smaller for *Scheme 2* than *Scheme 1*. Fig. 5 also shows that the

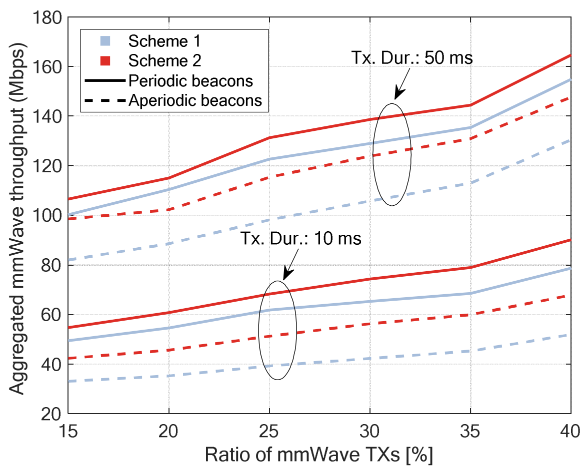

Fig. 5. Aggregated mmWave throughput.

aggregated throughput increases with R_{TX}. This is the case because mmWave exploits the antenna directionality to support multiple simultaneous mmWave transmissions between different pairs of vehicles (a.k.a. spatial sharing). Finally, it is relevant noting that higher throughput values are obtained with 50ms transmissions than with 10ms ones. This is the case since longer transmissions maximize the utilization of the mmWave channel for data transmissions.

V. CONCLUSIONS

This paper has analyzed the feasibility of using sub-6GHz C-V2X as the control plane for mmWave V2X communications. In particular, the paper has proposed and evaluated two scheduling schemes that use C-V2X to schedule mmWave V2V transmissions. The conducted analysis has shown that C-V2X can be utilized to support control functions for mmWave V2X communications. To this aim, it is important to adequately design the scheduling schemes in order to reduce delay, increase throughput and ensure all scheduled mmWave transmissions can be completed. An adequate scheduling scheme can also mitigate the negative impact that aperiodic messages can have on the operation of C-V2X communications.

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