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RESEARCH ARTICLE

Vehicle-to-Everything (V2X) Communications in Unlicensed Spectrum Can Be Safe and Efficient

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ABSTRACT To meet the communications demands of connected vehicles, the wireless devices deployed in vehicles and on roadside infrastructure may need access to more spectrum than is available today. This paper proposes a novel approach that allows connected vehicle devices using V2X technology (e.g., C-V2X or NR-V2X) to share spectrum with Wi-Fi and other unlicensed devices, thereby gaining access to more spectrum. The proposed approach requires no change to Wi-Fi technology so there is no need to replace Wi-Fi devices that have been deployed, and only modest modifications to V2X which reduces cost and complexity. It uses a backward-compatible form of beaconing. Unlike previous work, the resources allocated to V2X are dynamically adjusted for greater efficiency. The approach also does not require involvement from a cellular operator or other centralized controller. One spectrum band where this approach could be especially beneficial is adjacent to the Intelligent Transportation System (ITS) band, where this approach could help meet the needs of both connected vehicles and Wi-Fi 6. Simulation results show that it is possible to protect quality of service for both V2X and Wi-Fi communications in a shared band, while greatly improving spectrum efficiency. This paper also describes steps that standards bodies (IEEE 802.11 and 3GPP) and spectrum regulators could take to advance this spectrum-sharing approach.

INDEX TERMS C-V2X, NR-V2X, unlicensed spectrum, spectrum sharing, Wi-Fi, connected vehicles, intelligent transportation systems (ITS), 802.11bd.

I. INTRODUCTION

Vehicle-to-everything (V2X) technology, which is also known as "connected vehicle" technology, gives vehicles the ability to communicate directly with other vehicles, roadside infrastructure, and devices carried by pedestrians over short-range wireless links. Widescale adoption of V2X could vastly improve safety on the roads, bring a variety of new and valuable services to passengers and drivers, and potentially facilitate operation of autonomous vehicles. Today's underlying V2X technology is related to cellular technology, but V2X communications is device to device, so no cellular operator is required.

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In the United States, V2X devices operate in the *intelligent transportation systems* (ITS) band. This band had 75 MHz of spectrum until 2021, when 60% of that spectrum was reallocated to unlicensed devices [14], [48], reducing ITS to 30 MHz. Concurrently, the U.S. Federal Communications Commission (FCC) decided to transition the technology allowed in the ITS band to C-V2X from dedicated short-range communications (DSRC) [18], which aligned U.S. policy more closely to that of many other countries, including China and the European Union. (For simplicity we often talk of "V2X" in this paper, referring both to the current generation which is C-V2X, and also successors of C-V2X, starting with NR-V2X [15], [16], [23] and possibly others that follow.)

The FCC's stated reason for reallocating 45 MHz of ITS spectrum was to enable a new generation of Wi-Fi, known as Wi-Fi 6. Wi-Fi 6 can be configured to use up to 160 MHz,

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and in 2021 there were no unlicensed bands with 160 MHz. While Wi-Fi 6 promises substantial benefits, this reallocation raises serious concerns. The U.S. Department of Transportation opposed the change, arguing that the spectrum allocated for V2X would be insufficient [40]. This view was echoed by many organizations in the sector [2], [21]. For example, the 5GAA Automotive Association wrote "it is clear that the 70-75 MHz of ITS spectrum in the 5.9 GHz band ... is needed to support the basic safety and advanced use cases under consideration today" [2]. To address long-term needs, regulators probably need to make more spectrum accessible for V2X communications.

This paper proposes a new strategy for making sufficient spectrum available for V2X communications by allowing V2X to share spectrum with Wi-Fi under an appropriate set of coexistence rules. It extends and builds upon our previous conference paper [49]. If used at 5.9 GHz in the spectrum recently taken from ITS, our proposed strategy would bring additional spectrum to V2X – and contiguous spectrum - while still meeting the objective of making 160 MHz of contiguous spectrum available to Wi-Fi 6. Moreover, this approach would use spectrum more efficiently than is possible in a band dedicated exclusively to ITS. In their current form, C-V2X and NR-V2X performance is inadequate when V2X devices share spectrum with Wi-Fi [39], and performance is bad for Wi-Fi too. Our new approach would solve that problem.

For sharing between V2X and Wi-Fi to be practical in this band, and in many other unlicensed bands as well, two additional requirements must be met. First, the sharing strategy cannot require unlicensed devices to operate in the shared band in a manner that is inconsistent with Wi-Fi standards. This would be impossible for those Wi-Fi 6 devices that have already been produced. Moreover, to reuse V2X technology developed for the ITS band, any differences between operation of V2X devices in the shared band and operation in the ITS band should be modest.

Second, the sharing mechanism should not require centralized control over devices operating in the band. When spectrum is licensed to a single entity such as a cellular operator, the license-holder typically controls transmissions in its spectrum, but there is no comparable entity that controls all devices in an unlicensed band. The introduction of V2X devices certainly cannot come with a requirement that all Wi-Fi devices be centrally controlled. The same is true for V2X devices. V2X communications is device-to-device, so centralized control is not necessary. The standards would allow either centralized control from a cellular operator (C-V2X mode 3, NR-V2X mode 1), or decentralized with no involvement from a cellular operator (C-V2X mode 4, NR-V2X mode 2). Our approach will work with both.

The decentralized case is more challenging, but it must be supported. Today's 5.9 GHz ITS band has no centralized controller. With decentralized control, there is no need for every vehicle to obtain service from a cellular operator. There is no need for any operator to deploy expensive infrastructure that guarantees truly ubiquitous access to the latest generation of cellular technology on every road. (In most countries, including the U.S., no single operator comes close to covering 100% of the nation by area, even with 4G and certainly not with 5G.) A car's inability to connect to a tower, whether it is due to lack of infrastructure or temporary outage or deliberate jamming, does not prevent the V2V exchange of messages that might prevent a deadly crash. In big cities, we may see the opposite problem: there are multiple operators with good coverage to choose from, but which of these operators would be the one to provide centralized control of V2X communications? Once vehicles are locked into this monopoly provider, what prevents that provider from charging excessive fees? For all of these reasons, while our approach should work with centralized control, it is essential that it work with decentralized control.

Section II of this paper describes the opportunities and challenges of sharing between V2X and Wi-Fi, and some prior work. Section III explains how Wi-Fi and V2X devices access spectrum, and why coexistence of these technologies is so problematic. Section IV describes how we propose to modify V2X to address those problems. Section V presents the experimental method used to evaluate this approach, and Section VI shows the quantitative results. Conclusions are summarized in Section VII. Finally, Section VIII describes how spectrum regulators and standards bodies could implement this approach.

II. SHARING BETWEEN V2X AND WI-FI

To bring spectrum to V2X beyond the current ITS band, 3GPP will standardize V2X communications at much higher frequencies in 5G, e.g. between 24 and 71 GHz [23], [50], [51], [67], where it is easier to obtain bandwidths much greater than 30 MHz. This spectrum is excellent for applications that require high data rates over short distances, such as the transmission of video from vehicle to vehicle in a convoy [24], or video to infrastructure for remote valet parking [3]. Data rates over 1 Gb/s have been achieved in mmWave-enabled V2X field trials [23]. Consequently, we have also been conducting research on the design of antennas that would be well-suited for V2X communications in this spectrum [4]. Although it may be useful for V2X, such spectrum is a poor substitute for 5.9 GHz spectrum for those applications that benefit from reliable communications across hundreds of meters, so this paper addresses unlicensed spectrum at these lower frequencies.

While users of both connected vehicles and Wi-Fi devices would prefer exclusive access to spectrum, sharing among these devices could be highly efficient, because of the temporal and spatial characteristics of their spectrum utilization. V2X devices transmit primarily when they are outdoors on streets, whereas most Wi-Fi devices operate indoors, too far from a street for there to be interference with V2X. Additionally, transmissions from both V2X and Wi-Fi devices occur sporadically. When Dedicated Short-Range Communications was the technology chosen for connected vehicles, the FCC initiated a proceeding to consider giving unlicensed devices access to ITS spectrum on a secondary basis, thereby exploiting these spatial and temporal characteristics. An unlicensed device would be allowed to transmit after sensing a channel in the ITS band and determining that transmitting at that specific location and time probably would not interfere with any V2X device [13]. This approach would enhance spectrum efficiency by granting unlicensed devices access to spectrum without adversely affecting connected vehicles. Researchers also considered this sharing between DSRC and Wi-Fi [9], [35], [38], [42], [60].

Our past research [30], [33], [34] went further than the FCC proceeding, demonstrating that DSRC can experience good performance and spectrum efficiency can be enhanced even when Wi-Fi and DSRC share as equals. While both Wi-Fi transmissions adversely affect DSRC and vise versa, we showed that it is possible to provide a specified quality of service for both Wi-Fi and DSRC at specified device densities using less spectrum when spectrum is shared by both device types than when one block of spectrum is allocated exclusively for DSRC and another block exclusively for Wi-Fi. Spectrum sharing is beneficial for both Wi-Fi and DSRC.

However, one reason that DSRC and Wi-Fi coexist efficiently is that both employ listen-before-talk (LBT), so transmissions rarely collide. (A "collision" is when two or more packets arrive simultaneously at a receiver, so the receiver is unable to decode either packet.) In contrast, Wi-Fi and C-V2X/NR-V2X are fundamentally different, necessitating a different coexistence strategy. This paper proposes a solution; spectrum is shared dynamically between Wi-Fi and V2X with each technology experiencing minimal interference from the other.

There has been previous research on the possibility of spectrum sharing between V2X and Wi-Fi [25], [26], [59], [61], [62], [63], [64]. All these papers assume that a centralized controller exists to manage V2X communications, and most [59], [61], [62], [63], [64] cannot function unless that centralized controller is available. All these papers also assume that V2X devices will be given the ability to sense the channel and employ LBT, similar to Wi-Fi. This aspect is consistent with Release 18 of the 5G standard which would allow LBT-based unlicensed sidelinks [15], [23], making this feature more viable for future NR-V2X devices. Many of these papers emphasize fairness, which often makes sense when LBT is employed in other contexts, but fairness is not an appropriate objective when some communications traffic is safety-critical and some is not. As will be discussed further in the next section, this LBT approach considered by 3GPP [15], [19], [23] can allow safety-critical messages to experience dangerously high latencies, which is not acceptable for safety-critical V2X. Thus, while this prior work has uses, it does not meet the constraints described in Section I.

III. WI-FI AND V2X SPECTRUM ACCESS MECHANISMS

Our new coexistence mechanism for Wi-Fi and V2X is designed around their respective spectrum access mechanisms. Wi-Fi uses LBT, as discussed above. When a Wi-Fi device receives energy at a level above a specific level, the device backs off for a randomly selected duration and then it tries again. This occurs regardless of the source of the energy, which could be Wi-Fi or V2X or anything else. Consequently, when Wi-Fi and V2X share spectrum, Wi-Fi's LBT mechanism helps to protect V2X from Wi-Fi. However, V2X does not use LBT, so this does nothing to protect Wi-Fi from V2X.

LBT alone cannot prevent collisions. A Wi-Fi transmission can still collide with another device's transmission when there are "hidden terminals." Consider the case where Wi-Fi Device A intends to transmit to Wi-Fi Device B. Meanwhile, Device C is transmitting, producing a signal that is strong when it reaches Device B. However, Device A is not aware of C's transmission because C is hidden, e.g. there is a wall between A and C. In this case, LBT does not stop Device A from transmitting, even though A's transmission causes a collision at Device B.

The Wi-Fi standard solves the hidden terminal problem through a mechanism involving Request-to-Send (RTS) and Clear-to-Send (CTS) messages. When Device A senses the channel is free, it sends an RTS message to Device B, indicating Device A's desired transmission duration. If Device B also determines that the channel is free, it sends a CTS message, granting permission for a transmission with the requested duration. If instead B considers the channel occupied, as would occur with a hidden terminal, then B does not send the CTS. In the absence of a CTS, Device A concludes it must back off from transmitting to avoid a collision. This RTS/CTS mechanism prevents interference between Wi-Fi devices in the presence of hidden terminals, but since V2X does not utilize RTS or CTS messages, this mechanism does not prevent Wi-Fi transmissions from interfering with V2X transmissions or vice versa.

V2X operates quite differently from Wi-Fi [18]. It is a variation of the direct device-to-device mode of long-term evolution (LTE), which is the mode that bypasses cell towers. Thus, like DSRC, mode 4 of C-V2X and mode 2 of NR-V2X allow devices to communicate without any centralized control from a cellular operator [18]. Each V2X device determines independently from what it can observe when and how it should access the spectrum. (Nevertheless, it is noteworthy that government agencies and cellular operators can reduce infrastructure costs by sharing infrastructure [27], [28], [29], [31], [32], as is possible when public safety shares infrastructure with cellular operators [17], [43], [45], [47].)

A V2X device intending to transmit must select a resource block (RB). Each RB is defined by its sub-frame, which is a timeslot within a future time interval that is called the *selection window*, and its sub-channel, which is a range of frequencies within the accessible spectrum band. The device uses that RB in a *semi-persistent* manner, which means that when a device chooses the RB in one selection window that has the j'th sub-frame and k'th subchannel, the device then chooses the same sub-frame and subchannel in every subsequent window until a randomly selected time or until the device has nothing left to send. When a V2X device selects a new RB, it attempts to choose an RB that has had low utilization within this device's recent ''sensing window.''

That approach works well when all devices use semi-persistent scheduling, because an RB that has not been used recently by neighboring devices is likely to remain unused. However, this approach is worthless or even detrimental when sharing spectrum with devices that do not use semi-persistent scheduling, such as Wi-Fi. This problem also occurs when sharing with DSRC [65].

In summary, V2X devices are designed to avoid collisions with other V2X devices through semi-persistent scheduling, and Wi-Fi devices are designed to avoid collisions with other Wi-Fi devices through LBT. Unfortunately, these mechanisms for collision avoidance fail miserably when dissimilar devices share a band.

To protect the performance of safety-critical V2X traffic in a band shared with devices that use LBT, V2X devices must transmit continuously for extended periods, so Wi-Fi devices do not see an opportunity to begin transmitting and then cause collisions. In a system with centralized control, the controller can schedule V2X transmissions in a way that achieves this, but centralized control of Wi-Fi as well as V2X is contrary to our assumptions.

When there are multiple independent V2X devices operating without centralized control, there will be gaps between V2X transmissions, leading to collisions. Moreover, if V2X devices adopt LBT to get the channel back from Wi-Fi, there is always a danger that Wi-Fi load will be so high that V2X devices cannot get sufficient access to meet their needs. A device can reduce that risk somewhat by transmitting when it has nothing to send just to hold the channel [25], [26], but this increases interference for useful V2X communications, and Wi-Fi devices will have even longer queues when they do get access to the channel [53], [54], [55].

IV. PROPOSED APPROACH FOR SPECTRUM SHARING

Mechanisms are needed to ensure that Wi-Fi does not substantially degrade the performance of V2X, and vice versa. Performance degradation might take the form of low throughput when there are few opportunities to transmit, or high packet error rate when transmissions occur but are subject to interference.

A. STATIC ALLOCATION OF RESOURCES

Because Wi-Fi devices back off when they sense energy and V2X devices do not, a Wi-Fi device may be unable to transmit for extended periods, while V2X transmissions dominate the channel. This causes the first form of degradation discussed above: lower throughput. To prevent this form of performance degradation, we propose to introduce ''*off periods*'' and ''*on periods*'' to the V2X standard. When operating in a shared band, V2X devices would alternate between on periods during which V2X transmissions are allowed, and off periods during which V2X transmissions are prohibited. This ensures that Wi-Fi transmissions can occur on a regular basis during off periods, thereby preventing Wi-Fi starvation.

To establish off periods, each V2X device simply identifies the subframes in its selection window that occur during off periods, and avoids selecting any resource blocks that correspond with these subframes. On and off periods have been used before, although in a somewhat different manner, within low-power unlicensed stand-alone LTE devices as part of the Carrier Sense Adaptive Transmission (CSAT) algorithm. Significant work has been done on setting on and off periods in a way that promotes fairness between Wi-Fi and unlicensed LTE (or its successor) (e.g. [6], [20], [58]). However, the fair CSAT approach would not provide adequate throughput protection for safety-critical V2X applications that use semi-persistent scheduling. Consequently, we use a different approach.

Moreover, unlike the case of a single standalone unlicensed LTE device in a customer premises, implementing off and on periods for V2X may involve hundreds of autonomous devices that are within communications range of each other. For this to work, all V2X devices in a region must synchronize their off and on periods to start at roughly the same time. V2X devices already synchronize the beginning of every subframe using timing signals from GPS, a technique that has achieved sub-microsecond accuracy. This function can easily be expanded to include the start of off and on periods. The V2X standard could specify the timing of a reference subframe that marks the beginning of an on period, with every k subframes thereafter work mark the beginning of a subsequent on period, where k is a constant that is also specified in the standard. (Note that Wi-Fi devices do not need GPS for synchronization because they use LBT in our approach. Indeed, Wi-Fi devices are not modified in any way for sharing.)

Another form of performance degradation is packet error, which occurs when the transmission of a Wi-Fi packet collides with the transmission of a V2X packet at an intended receiver. Since Wi-Fi uses LBT and V2X does not, most collisions happen when a V2X device begins transmitting while a nearby Wi-Fi device is already transmitting, rather than vice versa. These collisions increase error rate for both Wi-Fi and V2X. The risk of collisions is even greater when Wi-Fi devices use frame aggregation, where multiple frames are transmitted consecutively within the same Aggregate Media Access Control (MAC) Protocol Data Unit (A-MPDU), because frame aggregation causes a Wi-Fi device to transmit for longer periods without stopping to sense the channel. While frame aggregation improves efficiency when all devices use LBT, it increases collision risk and thereby reduces spectral efficiency when some devices use LBT and others do not. Most collisions would be prevented if Wi-Fi devices somehow could avoid transmitting during the V2X on period, but Wi-Fi devices do not know that on periods exist. If that were possible, on periods would be primarily for V2X while off periods would be entirely for Wi-Fi.

The challenge is to keep Wi-Fi transmissions out of the on periods without any modification to the Wi-Fi standard. We accomplish this by adding a new feature to V2X that leverages the Wi-Fi RTS/CTS mechanism discussed in the previous section, but in a different way. In the first subframe of every on period, all V2X devices send a "CTS to self" [10], i.e. a CTS message that is not in response to any RTS. A Wi-Fi Device that receives this CTS will interpret it as an indication that another Wi-Fi device is about to transmit, and will thus refrain from transmitting for the duration specified in the CTS message. Consequently, Wi-Fi transmissions should no longer interfere with V2X communications.

In effect, V2X devices would use CTS messages as a form of beacon to announce their presence, but it is a beacon that is backward-compatible because incumbent Wi-Fi devices are already designed to understand. Thus, this is cooperative sharing, in contrast to most unlicensed bands which are typically based on coexistent sharing schemes in which systems never explicitly communicate with each other [41], [44], [46], [52].

When CTS messages are transmitted at an appropriate power level, Wi-Fi devices close enough to any V2X device to cause harmful will be prevented from transmitting during an on period. Wi-Fi devices not in proximity to any V2X devices will not receive CTS messages, and will continue transmitting unimpeded. This is critical for efficient use of spectrum.

V2X devices can transmit the CTS message during the last symbol period of the first subframe in the on period to prevent Wi-Fi transmissions for the next *j* subframes for some integer *j*. They would send another CTS every *j* subframes until the end of the on period. In C-V2X and NR-V2X, the last symbol of a subframe is used as a guard period for transmitter-receiver timing adjustment [12], [16]. Thus, transmitting these short CTS messages at this time does not waste any useful transmission time.

The CTS message sent by all vehicles will be identical, with each V2X device using the same source and destination addresses, as specified in the new standard. With synchronized clocks and the simultaneous transmission of identical content over short distances, CTS transmissions will reinforce rather than interfere with each other. While the requirement for V2X devices to transmit this one new message adds some complexity, that complexity is minimal. Devices would not have to receive Wi-Fi packets, or follow the RTS/CTS protocol in any way.

This use of CTS messages will prevent most collisions between V2X and Wi-Fi. However, collisions still occur if a Wi-Fi device begins transmitting during an off period and has not completed the transmission when the on period begins. These collisions can be prevented by designating the first subframes of an on period as guard periods. That reduces packet error rate, but it does so by wasting subframes, so may or may not be worthwhile. Further study is required.

The fraction of spectrum resources allocated to V2X corresponds roughly to the *V2X on-off fraction (OOF)*, which we define as (on period)/(on-off interval), where *on-off interval* is defined as the sum of the on period duration and the off period duration. As long as OOF is not too close to either 0 or 1, both V2X and Wi-Fi devices are guaranteed regular access to spectrum. If OOF has a fixed value that is first specified in the standard and then codified in regulation, it would be straight-forward to implement, and fully transparent, providing clarity to producers of both V2X and Wi-Fi devices. This was our approach in a previous conference paper [49]. Alternatively, OOF could dynamically adapt to conditions, which we introduce for the first time in this paper, as shown in the next section.

Another significant design decision is the duration of the on-off interval. Extending the interval (while keeping OOF constant) has advantages. As previously discussed, collisions may occur in the first subframe of a new on period. Lengthening the on-off interval reduces the frequency of these collisions, which can slightly improve throughput if that first subframe is turned into a guard period, and slightly improve packet loss rate otherwise. However, extending the on-off interval also worsens packet latency. For example, Wi-Fi packets would wait longer on average to begin transmission if off and on periods are 50 ms each as compared to 25 ms each.

B. DYNAMIC ALLOCATION OF RESOURCES

Each vehicle could allocate resources between V2X and Wi-Fi dynamically by constantly adjusting the on-off fraction (OOF) based on the extent of communications activity that the vehicle has recently observed from these two types of devices. Observed communications will change dramatically as a car travels from a busy highway at rush hour to a quiet city park that is blanketed with outdoor Wi-Fi. Adjusting parameters based on those observations can yield greater performance and more efficient use of spectrum than the static approach we previously considered [49].

The dynamic OOF algorithm could be designed to favor connected vehicles, by making the OOF large enough to meet the quality needs of V2X communications but no larger, effectively giving Wi-Fi only the resources that V2X does not need. Conversely, the algorithm could be designed to favor Wi-Fi, making the OOF small enough to meet the needs of Wi-Fi but no smaller. Or the algorithm could be anything in between these extremes. In this paper, we consider algorithms that favor V2X, which is the most likely case because some V2X traffic is safety-critical whereas Wi-Fi traffic generally is not. However, connected vehicles systems could be designed to send their safety-critical messages on other bands, so that priority over Wi-Fi in this shared band is not necessary.

The algorithms considered in this paper are variations of how V2X works today, so as to facilitate implementation. In today's systems (which have no off periods), a V2X device that is choosing the best resource block for a new packet stream first finds an initial set of resource blocks that are likely to be unused in the coming selection window [11], [37]. (It then makes adjustments based on the size of that set, but we only use the initial set for our purposes.) Excluded from this initial set are resource blocks that other V2X devices have selected for likely future use through semi-persistent scheduling. Also excluded are resource blocks in which the device has received significant interference in the last second, even if the device cannot determine what produced that interference. In a shared band, this interference could come from V2X collisions or Wi-Fi or something else. Finally, for the purpose of our proposed algorithm which does have off periods, we also exclude resource blocks that occur during the current off period.

Let U be the number of resource blocks left in this set of resource blocks that appear to this V2X device to be unused. If U is large, this probably indicates that the OOF could be reduced without significantly degrading performance for V2X. Conversely, if U is small, it may be necessary to increase OOF to protect V2X performance.

In this paper, we will consider two algorithms designed to prioritize V2X. In the first, OOF is increased by 0.05 whenever U is below a constant threshold and decreased by the same amount whenever U is above the same threshold. In the second algorithm, decisions are made not based on the number of resource blocks that are unused but on the fraction of resource blocks within the current on period that are used. Thus, the duration of the OOF is increased if U/(number of resource blocks in the on period) is below a constant threshold and OOF duration is decreased otherwise. Neither heuristic is truly optimal, but we will show that either can make the new spectrum-sharing approach we propose in this paper effective.

For either algorithm, it can be useful to set a minimum value of OOF to ensure that some resources are always available for V2X, and a maximum value of OOF to ensure that some resources are always available for Wi-Fi, regardless of what has been observed.

V. METHOD OF ANALYSIS

To quantitatively evaluate the feasibility of spectrum sharing between V2X and Wi-Fi, both with and without our proposed modifications, we developed software that simulated behavior of both technologies. We built this system over LTEV2Vsim, a dynamic simulator written in MATLAB by researchers at the University of Bologna for investigating resource allocation in C-V2X [5], [7], [8]. We added new mechanisms to C-V2X, incorporating the use of CTS messages and the static version of our proposed on and off periods in our previous work [49], and the dynamic version of on and off periods for this paper.

In the simulations presented in the next section, mode 4 C-V2X devices are deployed as follows, which is consistent with the *highway scenario* as specified by 3GPP [1]. There is a straight infinitely-long east-west highway with three lanes of traffic in each direction. Vehicles are distributed across each lane of the highway according to a Poisson point process with uniform density. Each lane is 3 meters wide. All vehicles contain V2X devices with 1 ms subframes, and 100 ms selection windows. The on-off interval is also set to 100 ms, with no subframes designated as guard periods. Each vehicle generates a 200-byte packet every 100 ms to be scheduled for transmission. (This is typical for basic safety messages, which each vehicle regularly broadcasts to all of its neighbors to enable various applications intended to prevent vehicle crashes.) Each transmission occupies one V2X resource block, and is transmitted with a power of 23 dBm. These V2X transmissions occur in 10 MHz of spectrum that is shared with Wi-Fi devices.

Wi-Fi devices are deployed as follows. Every 200 meters along the highway, a pair of outdoor Wi-Fi devices is placed near the highway – one 10 meters to the north and one 10 meters to the south. Each Wi-Fi device contends for spectrum with the other Wi-Fi device in its pair, and any V2X devices within range. At each Wi-Fi device, packets are generated independently according to a Poisson process. The transmit power is 20 dBm. Wi-Fi packet transmissions utilize the entire shared 10 MHz (and possibly adjacent spectrum bands beyond this 10 MHz too). Each Wi-Fi packet transmission lasts 2 ms, which is reasonable for a Wi-Fi hotspot using frame aggregation. The arbitration inter-frame spacing (AIFS) is 152 μs. The Wi-Fi sensing threshold is -78 dBm, 20 dB above the noise level. Both Wi-Fi and V2X signals attenuate according to the WINNER+ path loss model [36].

VI. NUMERICAL RESULTS

A. QUALITY OF SERVICE WITH TODAY'S C-V2X

Our simulation results show that C-V2X without our proposed modifications does not coexist well with Wi-Fi. For example, with 20 vehicles/km/lane on the highway described in the previous section, and no Wi-Fi transmissions, V2X packet reception ratio (PRR) is 98%, where PRR is the fraction of V2X packets that are decoded correctly at a receiver because their SINR is above threshold at that receiver, averaged across all vehicles within 150 meters of the transmitter. Once we add a load of just 20% at each Wi-Fi device, the PRR falls to about 84%, which is dangerously inadequate for many safety applications. See [49] for more of our results on how sharing degrades quality with today's algorithms. These results are consistent with previous studies [39]. Wi-fi quality also suffers in this scenario, as 5% of Wi-Fi packets are lost due to collisions with V2X. If the band contained only Wi-Fi at these loads, packet loss rate would be negligible.

B. QUALITY WITH MODIFIED V2X, STATIC OOF

We now examine the impact of incorporating on-off periods and CTS messages into V2X on quality of service. Fig. 1 presents the V2X PRR versus the V2X on-off fraction (OOF) for different vehicle densities in three cases: (i) absence of Wi-Fi devices in the band (black), (ii) presence of Wi-Fi devices with V2X using on-off periods but not CTS messages (red), and (iii) presence of Wi-Fi devices with V2X using both on-off periods and CTS messages (green). Across all vehicle densities and all OOF values, Fig. 1 shows that when

V2X devices employ CTS messages and on-off periods, PRR is roughly the same when spectrum is shared with Wi-Fi as when there is no Wi-Fi at all. In contrast, even with on-off periods, PRR without CTS messages is considerably worse. This unfortunately indicates that relying solely on the on-off periods for protection, which is simpler, would result in lower quality of service for V2X.

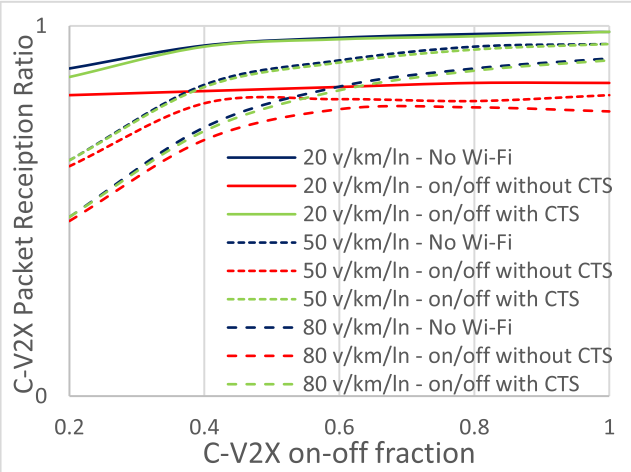

FIGURE 1. V2X packet reception ratio vs. V2X on-off fraction. Curves are shown for vehicle densities of 20, 50 and 80 vehicles per km per lane (v/km/ln), and in three scenarios. In scenarios with Wi-Fi, Wi-Fi load is 20% per device.

Fig. 1 also demonstrates that the implementation of on-off periods does not substantially degrade performance for V2X provided that the OOF is not too low. The acceptable threshold for OOF depends on vehicle density. For example, with 20 vehicles per km per lane, a 40% OOF yields very good performance, but 40% is too small when vehicle density is 80.

To evaluate the impact of V2X on Wi-Fi quality of service, we observe changes in Wi-Fi throughput as Wi-Fi load varies, both with and without the presence of V2X devices. In Fig. 2, the Y axis represents the number of Wi-Fi packets per second that are correctly received at each receiver, i.e. that are received with an SINR above the threshold. The X axis shows the load at each Wi-Fi device. (Wi-Fi devices are deployed in pairs, so if each device has a load of ρ, then Wi-Fi devices try to occupy the channel 2ρ of the time.) For the orange curve, there are 20 vehicles per km per lane, and the V2X on-off fraction is 50%. For the blue curve, only Wi-Fi is present, and there are no V2X devices in the band. Not surprisingly, approximately twice the throughput is achieved at high loads when V2X is absent. However, as long as Wi-Fi load is not too high, the presence of V2X does not significantly affect Wi-Fi throughput.

There is an obvious trade-off when setting the OOF. Increasing OOF benefits V2X, while decreasing it benefits Wi-Fi. However, it is often possible for both types of devices to perform well. Fig. 3 illustrates this trade-off, where the Y axis represents V2X PRR and the X axis represents Wi-Fi throughput. Wi-Fi load is 20% at each device. Curves

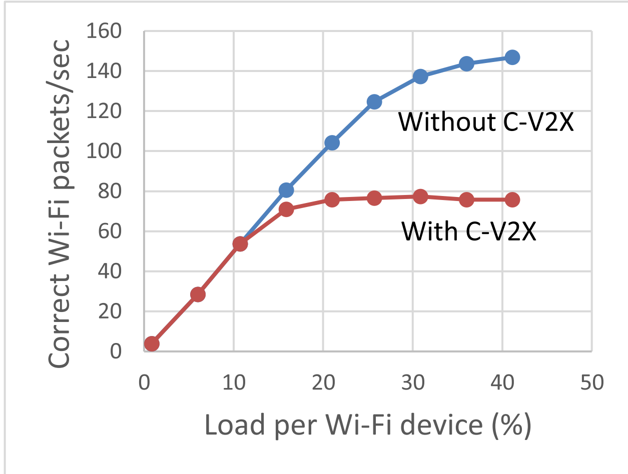

FIGURE 2. Wi-Fi packets/second received correctly vs. Wi-Fi load per device. Orange curve is with 20 vehicles equipped with V2X per km per lane and on-off fraction of 50%. Blue curve is with only Wi-Fi, no V2X.

are plotted for two vehicle densities, with each point on the curve corresponding to a different OOF. As expected, both types of devices achieve better performance at lower vehicle densities. The curves' resemblance to the corner of a square indicates that with an appropriate OOF, V2X PRR will be only slightly worse than optimal, and Wi-Fi throughput will be only slightly worse than optimal. There are noteworthy differences between the curves: at a vehicle density of 20 per km per lane, an OOF of 40% works well for V2X, but at a vehicle density of 40 per km per lane, an OOF of 50% or 60% is more appropriate.

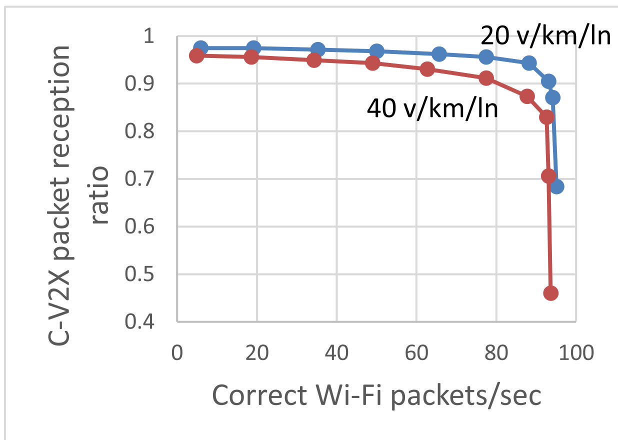

FIGURE 3. C-V2X packet reception ratio vs. Wi-Fi packets/second received correctly. Wi-Fi load is 20% per device. Blue and orange curves have vehicle densities of 20 and 40 vehicles per km per lane, respectively.

We now repeat the same scenario discussed above, except that load at each Wi-Fi device is 100% instead of 20%, so there are always Wi-Fi packets in each queue waiting for transmission. The curves are not quite as similar to the corner of a square, but even under this heavy load, it is possible to operate at a point on the curve where C-V2X

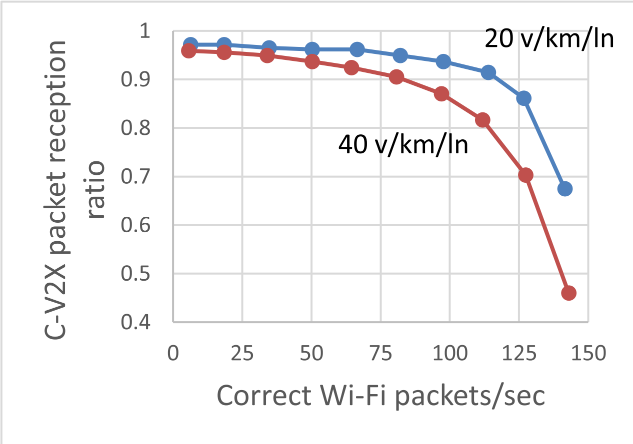

FIGURE 4. V2X packet reception ratio vs. Wi-Fi packets/second received correctly. Wi-Fi load is 100% per device. Blue and orange curves have vehicle densities of 20 and 40 vehicles per km per lane, respectively.

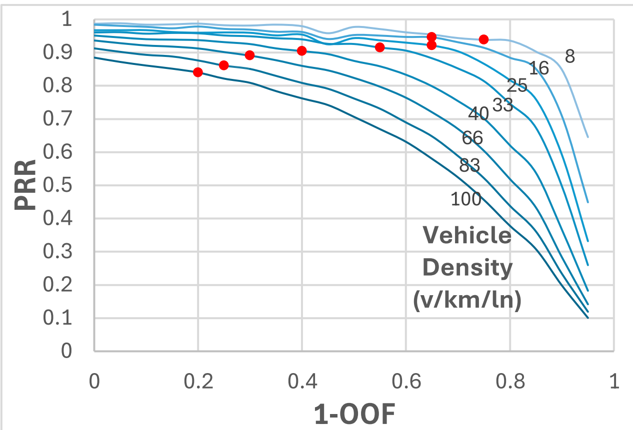

FIGURE 5. V2X packet reception ratio vs. (1 -on-off-fraction) at different vehicle densities. Red dots signify "ideal" values.

PRR is well protected while still maintaining significant Wi-Fi throughput, if an appropriate OOF is chosen.

C. QUALITY WITH MODIFIED V2X, DYNAMIC OOF

As the previous section shows, the most appropriate OOF depends on factors like V2X device density, load per Wi-Fi device, and other characteristics of observed channel use that change as a vehicle travels. That is strong motivation to give vehicles the ability to adjust OOF dynamically based on what they observe. We will now assess the two dynamic OOF algorithms that were presented in Section IV-B: one based on the number of unused resource blocks (henceforth called NUM), and one based on the ratio of unused resource blocks to the number of total resource blocks in the current on period (henceforth called RATIO). For both algorithms, we set a minimum OOF of 0.25, and a maximum OOF of 0.95.

For both algorithms, we will try to set the threshold to achieve an "ideal" OOF. There is no single definition of ideal, but for this paper we define the ideal value of OOF as the value that provides V2X traffic with a PRR in spectrum

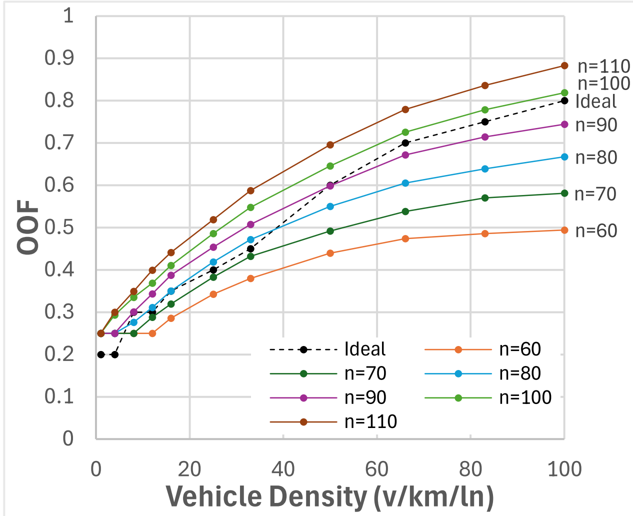

FIGURE 6. Mean steady-state V2X on-off-fraction vs. vehicle density. Dashed curve is ideal. Other curves for NUM OOF algorithm at different thresholds.

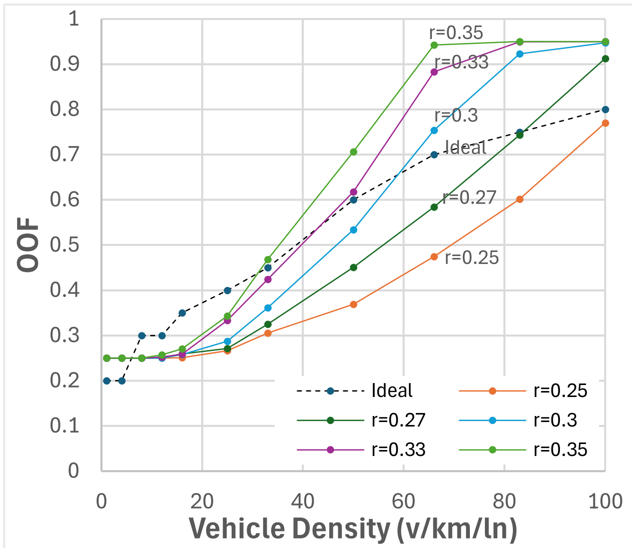

FIGURE 7. Mean steady-state V2X on-off-fraction vs. vehicle density. Dashed curve is ideal. Other curves for RATIO OOF algorithm at different thresholds.

shared with Wi-Fi that is 95% of the PRR that would be achieved in the absence of Wi-Fi. Fig. 5 shows PRR as a function of 1-OOF, where each curve corresponds to a different vehicle density, and the dots indicate the "ideal" values of OOF by this definition.

When setting parameters for a dynamic OOF algorithm, the goal is for every vehicle to select a OOF reasonably close to the "ideal" shown above at every vehicle density, which should yield a V2X performance close to what would be experienced without Wi-Fi in the band. Figures 6 and 7 show OOF averaged across all vehicles in the steady state versus vehicle density, for NUM and RATIO respectively. There are curves for different threshold values, and one curve representing the "ideal" OOF. While no threshold can ever

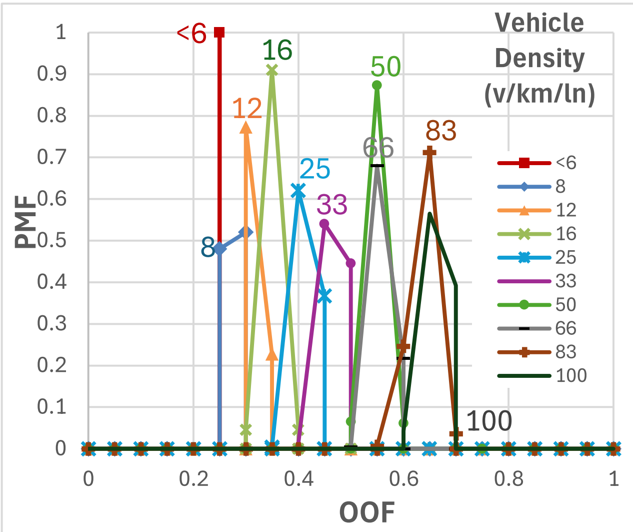

FIGURE 8. V2X Distribution of on-off-fraction at different vehicle densities, using NUM dynamic OOF algorithm at threshold 80.

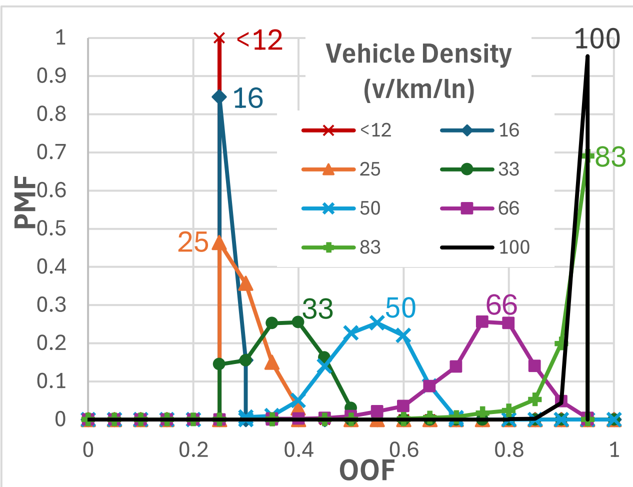

FIGURE 9. Distribution of on-off-fraction at different vehicle densities using RATIO dynamic OOF algorithm at threshold 0.3.

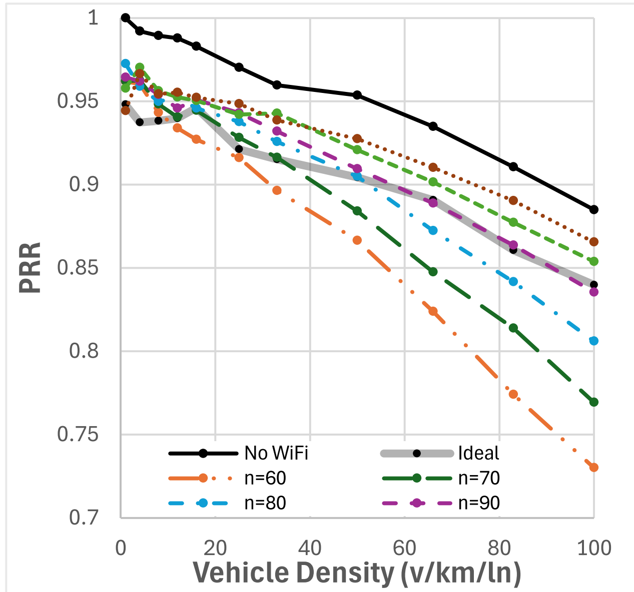

FIGURE 10. V2X PRR vs. vehicle density using NUM dynamic OOF algorithm at different thresholds.

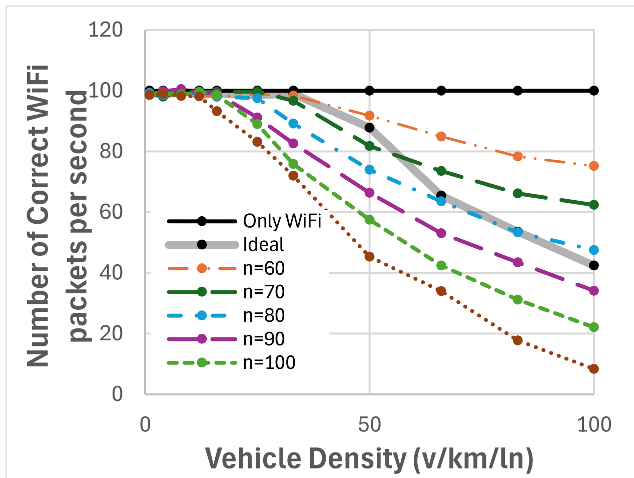

FIGURE 11. Wi-Fi correct packet/sec vs. vehicle density using NUM dynamic OOF algorithm at different thresholds.

be perfect, a threshold of 80 for NUM and 0.3 for RATIO work reasonably well. NUM appears to work slightly better across a broad range of vehicle densities by this criterion.

A good dynamic OOF algorithm should set the OOF close to the ideal for all vehicles. Consistency across vehicles is not guaranteed because there is no centralized control in a connected vehicle system; each vehicle chooses its own OOF based on what it observes in the channel. Thus, we also examine the distribution of OOF across vehicles.

Figures 8 and 9 show the distributions of OOF across vehicles for each vehicle density for NUM and RATIO, respectively. We expect some variation in OOF, because vehicles are randomly distributed across the highway according to a uniform Poisson point process, which means that some vehicles see greater density around them than others. Also, our algorithm never stops adjusting OOF up or down even when it is close to ideal. A future version of this algorithm could incorporate some hysteresis. However, a large variance would be problematic. With NUM, the variance is relatively small. With RATIO, the variance can be larger, except when OOF is close to the minimum and maximum values that the algorithm allows. Thus, we find that the NUM algorithm is better than RATIO by this criterion.

Ultimately, our goal is to achieve great performance for both V2X and Wi-Fi at any device density. For this paper, that means V2X PRR close to 95% of what is achievable without Wi-Fi and Wi-Fi throughput that is as good as possible under that constraint. Figures 10 and 11 show V2X PRR and Wi-Fi throughput, respectively, as a function of vehicle density for the NUM algorithm. Figures 12 and 13 show V2X PRR and Wi-Fi throughput, respectively, for the RATIO algorithm.

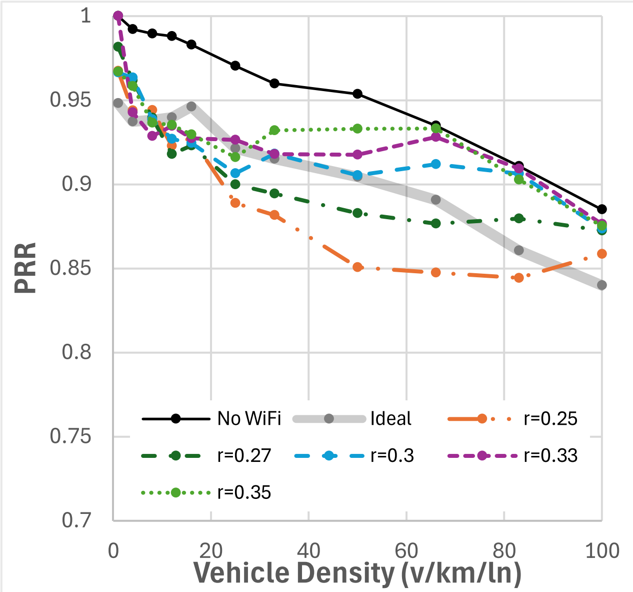

FIGURE 12. V2X PRR vs. vehicle density using RATIO dynamic OOF algorithm at different thresholds.

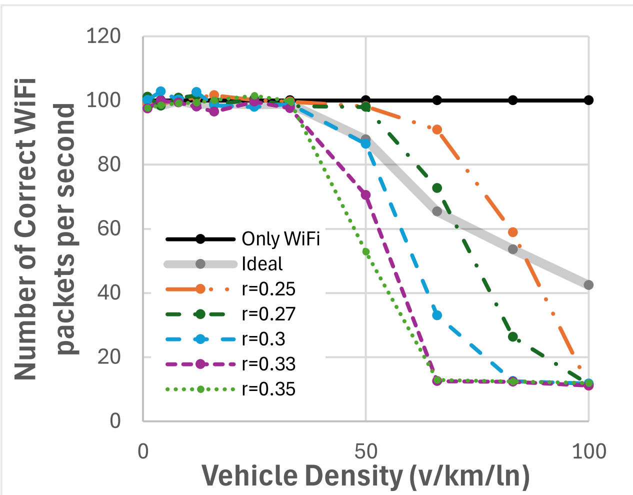

FIGURE 13. Wi-Fi correct packet/sec vs. vehicle density using RATIO dynamic OOF algorithm at different thresholds.

In the graphs showing V2X performance, the black solid curve shows the V2X PRR that could be achieved if there were no Wi-Fi, and the black dashed curve shows the "ideal" which is 95% of that. Similarly, in the graphs showing Wi-Fi performance, the solid black curve shows the Wi-Fi throughput that could be achieved if there were no V2X, and the black dashes curve shows the idea.

We find that our proposed dynamic OOF approach can be highly effective at all vehicle densities. The RATIO algorithm works well, but the best choice appears to be the NUM algorithm with threshold 80. The V2X PRR in shared spectrum is roughly 5% below what would be experienced in spectrum entirely dedicated to V2X, which was our target. Wi-Fi throughput is only slightly below what would be achieved in spectrum dedicated to Wi-Fi until vehicle density grows too large, so more resources must be allocated to V2X to protect PRR.

VII. CONCLUSION AND FUTURE RESEARCH

This paper demonstrates that C-V2X/NR-V2X and Wi-Fi can share spectrum in a manner that satisfies quality-of-service requirements for both technologies, and can greatly improve spectrum efficiency in the process. By incorporating the ability to send CTS messages and on-off periods into the V2X standard for use in shared spectrum bands, V2X can achieve a quality of service in shared spectrum comparable to that of dedicated ITS spectrum. This makes shared spectrum a viable option even for safety-critical applications. The presence of an unlicensed band with relatively low utilization directly adjacent to the ITS band makes this approach especially attractive, though these techniques are applicable in many other unlicensed bands as well.

This approach requires no modification to Wi-Fi devices that comply with the standard, since it builds on the LBT mechanism that is already integral to Wi-Fi. This paper demonstrates that the proposed approach still enables Wi-Fi devices that share spectrum with V2X to achieve high levels of performance. Even more importantly, Wi-Fi devices that are not close to streets operate as if there were no V2X devices in the band. This is likely to include many Wi-Fi devices, particularly those operating indoors, making this form of spectrum sharing highly efficient.

These results were achieved with a simple heuristic algorithm that dynamically adjusts OOF based on what a vehicle observes. While that heuristic performed well, thereby proving the viability of the approach, there is no reason to believe that this is the best possible heuristic. Each vehicle typically maintains a great deal of information about the channel utilization it has observed over the last second, and our heuristic does not make use of most of that data. The search for the best heuristic is worthy of further research. This future research should also experiment with other scenarios. (The highway scenario simulated in this paper is one of two scenarios standardized for V2X research [1].)

Unlicensed bands can accommodate a variety of device types other than Wi-Fi. Our approach can be extended to many, provided that they adhere to the same LBT approach as Wi-Fi, and they back off upon detection of a CTS message. While this may necessitate some modifications, it is often feasible.

Our proposed approach might also be useful someday if a successor to 3GPP's C-V2X technology must share spectrum with a successor to IEEE's DSRC, such as the emerging IEEE 802.11bd standard. Like DSRC, 802.11bd will carry V2X communications using an LBT approach, and RTS/CTS messages are an option [22], [66].

VIII. IMPLICATIONS FOR STANDARDS AND SPECTRUM POLICY

To implement this spectrum-sharing approach, both technical standards organizations and spectrum regulators must take action. A version of a V2X standard (e.g. C-V2X and/or NR-V2X) must be developed that addresses operation in spectrum shared with unlicensed devices. This version should incorporate CTS messages and on-off periods. Establishing such a standard would require a committee that draws expertise from both the 3GPP organization which produces standards related to C-V2X and NR-V2X, and the IEEE 802.11 committee which produces standards related to Wi-Fi.

Spectrum regulators must then establish the coexistence rules of a band shared by V2X and unlicensed devices. Coexistence rules can have a tremendous impact on spectrum efficiency and quality of service, and can be simple or complex [26], [44]. (Such rules can even incentivize device designers to use spectrum more efficiently by making certain parameters dependent on past spectrum utilization [44], [53], [54], [55], [56], [57].) Under the proposed approach, coexistence rules would require unlicensed devices operating in the shared band to use LBT and to respond to CTS messages as specified in the IEEE 802.11 standard, even if those unlicensed devices are not Wi-Fi.

These same rules would require V2X devices operating in the shared band to use off and on periods as specified in the standard developed by the IEEE-3GPP joint committee described above. Additionally, the coexistence rules should permit V2X devices to transmit CTS messages at a somewhat higher power level than Wi-Fi devices can under the rules.

There are additional steps that a spectrum regulator could take for the unlicensed band that is adjacent to the ITS band, to ensure that both V2X devices and 160 MHz Wi-Fi 6 devices have access to enough spectrum. One approach is to limit deployment of the types of unlicensed devices that are most likely to interact with V2X devices: especially mobile unlicensed devices, and possibly outdoor unlicensed devices. For many indoor devices, there is little risk that they will cause harmful interference to V2X communications or experience harmful interference from it. There is a greater risk of interference with outdoor unlicensed devices. The interference risk is greatest with battery-powered mobile devices such as cellphones because they might operate inside vehicles. By limiting the shared band to indoor devices, or at least precluding devices that can operate on battery power, spectrum regulators could make more resources available for V2X. To assess the impact of such restrictions, further research and probably a Notice of Proposed Rulemaking would be appropriate.

If the primary objective of reallocating ITS spectrum to unlicensed was really to provide 160 MHz of contiguous spectrum for Wi-Fi 6 and its successors, then it is possible to meet this objective while making even more spectrum available for V2X by preventing unlicensed devices that transmit in 80 MHz of spectrum or less from operating in the portion of the unlicensed band that is shared with V2X, or to by preventing unlicensed devices other than Wi-Fi from using this band, or both. Again, further research and probably a Notice of Proposed Rulemaking are appropriate to assess this idea.

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