# Bringing Connected Vehicle Communications to Unlicensed Spectrum

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## 1. Problem

"Connected vehicle" technology allows vehicles to communicate directly with each other, with roadside infrastructure, and even with cyclists and pedestrians over short-range wireless communications links. This technology could greatly improve roadway safety, bring a wide range of valuable new services to drivers and passengers, and perhaps eventually facilitate the deployment of autonomous vehicles, all without involvement of any cellular operator.

Until 2021, the United States had 75 MHz of spectrum allocated for connected vehicles in what is known as the *intelligent transportation systems* (ITS) band. The U.S. Federal Communications Commission (FCC) took 60% of that spectrum away from ITS and reallocated it to unlicensed devices [1, 2], leaving 30 MHz. The FCC simultaneously changed the technology allowed in the ITS band from dedicated short-range communications (DSRC) to cellular vehicle to everything (C-V2X) [3]. This brought U.S. spectrum policy for connected vehicles more in line with many nations, including the European Union and China. The stated goal of reallocating ITS spectrum was to make possible the deployment of the next generation of Wi-Fi, known as Wi-Fi 6. Until this change, no spectrum band had all the properties desired for Wi-Fi 6, including at least 160 MHz of contiguous spectrum that can be accessed without a license. There is reason to hope that Wi-Fi 6 will bring great benefits, but this change creates a problem. The U.S. Department of Transportation opposed the move, arguing that there would not be enough spectrum for connected vehicles [4], and many organizations involved with connected vehicles agreed [5]. To meet long-term needs, regulators may need to make more spectrum accessible to connected vehicles.

This paper proposes an alternative strategy that could meet the needs of both connected vehicles and Wi-Fi 6 by allowing them to share spectrum under an appropriate set of coexistence rules. This could be achieved through changes in spectrum regulations, modest changes in technology for those C-V2X devices that operate in the shared band, and no changes to Wi-Fi. This would give C-V2X devices access to spectrum that is adjacent to the ITS band (which was part of the ITS band until recently), while giving Wi-Fi 6 devices the contiguous 160 MHz that they need, all without modification to devices that have already been deployed. For simplicity we talk of "C-V2X" in this paper, but our approach is likely to apply similarly to successors of C-V2X, starting with 5G NR-V2X [6]. Our approach also supports sharing between C-V2X and unlicensed devices other than Wi-Fi, although this may require some change in how those devices access spectrum.

While users of both types of devices would prefer to have spectrum resources to themselves, the spatial and temporal characteristics of their spectrum access are conducive to sharing. Vehicles communicate when they are outside on roads, and many Wi-Fi devices operate indoors, a safe distance from any road. Also, both connected vehicle and Wi-Fi devices transmit sporadically. When DSRC was the dominant technology for connected vehicles, the FCC launched a proceeding that would consider exploiting these characteristics by possibly allowing unlicensed devices to access ITS spectrum on a secondary basis, i.e. an unlicensed device could transmit in the ITS band after sensing the channel and determining that a transmission at that particular time and place was unlikely to interfere with any connected vehicle devices [7]. Spectrum efficiency is improved because unlicensed devices gain access to spectrum, at no cost to connected vehicles.

Our previous work [8, 9] went further, by showing that even when DSRC and Wi-Fi share spectrum on a co-equal basis, this increases spectrum efficiency. While there can be mutual interference between DSRC devices and Wi-Fi devices, the amount of spectrum required to achieve a given quality of service for Wi-Fi and a given quality of service for DSRC with a given density of these device types is smaller when spectrum is shared between Wi-Fi and DSRC than if one block of spectrum is allocated exclusively for DSRC and another exclusively for Wi-Fi. Sharing can therefore benefit both types of devices. However, this beneficial coexistence occurs in part because Wi-Fi and DSRC are similar technologies based on listen-before-talk (LBT), so they inherently avoid collisions with each other. (A "collision" occurs when a receiver is unable to decode an incoming packet because two or more packets are arriving at the same time.) In contrast, C-V2X and Wi-Fi are quite different from each other, which means a different form of coexistence is needed to make sharing efficient. This paper presents a solution to this problem.

In our proposed solution, spectrum close to roads is used sometimes by C-V2X with little interference from Wi-Fi, and sometimes by Wi-Fi with little interference from C-V2X. From most locations that are not near roads or that are indoors, Wi-Fi devices operate as if there are no C-V2X devices in the band.

## 2. Background on C-V2X and Wi-Fi

Before creating a method for C-V2X and Wi-Fi to share spectrum, we must first consider how C-V2X and Wi-Fi access spectrum. As stated above, Wi-Fi uses LBT to reduce the probability collisions. If a Wi-Fi device detects an energy level that exceeds a certain level, the device will back off for a randomly selected duration before attempting to transmit again. This occurs regardless of whether the energy is from a Wi-Fi transmission or a C-V2X transmission or something else. This mechanism therefore helps protect C-V2X from interference from Wi-Fi when the two share spectrum, but it cannot protect Wi-Fi from C-V2X, since C-V2X does not use LBT.

Even with just Wi-Fi devices in a band, collisions can still occur when there are "hidden terminals," and this has implications when we add C-V2X to the picture. For example, Wi-Fi device A wants to transmit to Wi-Fi device B. Device C is currently transmitting, creating a lot of interference at Device B, but C's transmission is hidden from A because of a wall between A and C. In this case, LBT does not prevent Device A from transmitting and causing a collision at Device B. The Wi-Fi standard provides a solution to this hidden terminal problem. In this example, after Wi-Fi Device A senses that the channel is free, it would send a Request-to-Send (RTS) message to Wi-Fi Device B, which includes an indication of how long Device A would like to transmit to Device B. If Wi-Fi Device B too senses the channel to be free, then B would send a Clear-to-Send (CTS) message that tells A it is OK to send for the requested duration. If instead B does not sense the channel to be free, as is the case with a hidden terminal, then B would not send a CTS. When A does not receive a CTS within the allotted time, A concludes that it cannot transmit to B, and backs off. This mechanism is useful for preventing one Wi-Fi device from interfering with another Wi-Fi device when there is a hidden terminal, but since C-V2X devices do not send RTS or CTS packets, this does not prevent Wi-Fi from interfering with C-V2X or vice versa.

C-V2X is different [3]. C-V2X is based on the direct device-to-device mode of long-term evolution (LTE). Like DSRC, C-V2X supports direct communications between devices without the need for a cellular operator or any other entity that provides centralized control. (Although government agencies and cellular operators can share infrastructure cost-effectively [10, 11].) This is achieved using the decentralized "mode 4" of C-V2X, in which each device decides when and how to access spectrum based only on what it can sense.

A C-V2X device that wishes to transmit selects a resource block (RB). Each RB is characterized by its sub-frame, which is a timeslot within a future time interval that is called the *selection window*, and sub-channel, which is a range of frequencies within the accessible spectrum band. Scheduling is *semi-persistent*, meaning that if a device chooses the RB that uses the j'th sub-frame and k'th subchannel in one selection window, it will choose the same RB in subsequent windows until it has nothing to send, or until a randomly selected time. Consequently, an RB that had little interference in the recent past is much more likely to offer good performance in the near future. Whenever a C-V2X device must choose a new RB, it tries to pick an RB that has been lightly used in recent observation (i.e. in its "sensing window"). That approach works well when all other devices in the band also use similar semi-persistent scheduling, but it is worthless or worse with devices like Wi-Fi that do not use semi-persistent scheduling.

In summary, Wi-Fi devices are designed to avoid collisions with other Wi-Fi devices with LBT, and C-V2X devices are designed to avoid collisions with other C-V2X devices with semi-persistent scheduling, but these collision avoidance schemes are problematic when dissimilar devices share a band.

## 3. Approach

We need mechanisms that prevent Wi-Fi from unduly degrading performance of C-V2X, and vice versa. Degradation comes in two forms: transmissions that must be delayed, and transmissions that occur but are not correctly decoded at an intended receiver because of interference.

Because Wi-Fi devices back off when the channel is in use and C-V2X devices do not, a Wi-Fi device may be unable to transmit for a very long time, as it waits until the many transmissions from C-V2X devices finally subside. This leads to the first kind of performance degradation described above: delays to accessing the spectrum. To prevent this kind of harm, we add the concept of "*on periods*" and "*off periods*" to the basic C-V2X standard when C-V2X devices operate in the shared band. C-V2X devices would alternate between on periods during which C-V2X devices may transmit, and off periods during which C-V2X transmissions are not allowed. Wi-Fi devices are guaranteed regular access to spectrum during these off periods, which prevents starvation of Wi-Fi.

To implement this feature, every C-V2X device simply identifies the subframes in its selection window that coincide with off periods, and refrains from selecting any resource blocks that use these subframes. Stand-alone low-power LTE devices have used on and off periods in a somewhat different manner as part of the Carrier Sense Adaptive Transmission (CSAT) algorithm which is also intended for use in unlicensed spectrum. Important work has been done to make coexistence fair to Wi-Fi as well as LTE (or its successor) (e.g. [12, 13, 14]) by adjusting on and off periods, but that kind of fairness would not provide adequate throughput protection for safety-critical V2X applications that use semi-persistent scheduling, so we take a different approach.

Moreover, unlike standalone unlicensed LTE devices, for on and off periods to work for connected vehicles where there can be hundreds of autonomous devices within range, all C-V2X devices in a region must begin their on and off periods at the same time, or at least close to the same time. C-V2X devices already synchronize the beginning of every subframe. They can do so using timing signals from GPS. This can be expanded to synchronize the beginning of on periods. The C-V2X standard could specify the time of a reference subframe that is the beginning of an on period, and then every k subframes after that would be the beginning of another on period for some constant $k$ that is specified in the standard.

The other kind of performance degradation occurs because of collisions, i.e. when the transmission period of a Wi-Fi packet overlaps with the transmission period of a C-V2X packet, preventing an intended receiver from decoding one or both packets. Because Wi-Fi uses LBT and C-V2X does not, most collisions occur when a C-V2X device begins transmitting at a time when a nearby Wi-Fi device is already transmitting, and not the other way around. This can degrade performance for both C-V2X and Wi-Fi. This risk is increased when Wi-Fi devices use frame aggregation, i.e. they transmit multiple frames consecutively within the same Aggregate MAC (media access control) Protocol Data Unit (A-MPDU), as this causes a Wi-Fi device to transmit longer without stopping to sense the channel. When all devices use LBT, frame aggregation improves efficiency, but when some use LBT and some do not, it increases risk of collision which can degrade efficiency.

We prevent most collisions by preventing Wi-Fi devices from transmitting during the C-V2X on period, so in locations near busy roads on periods are mostly for C-V2X and off periods are mostly for Wi-Fi. The challenge is to do this without requiring modification to the Wi-Fi standard. This can be achieved by adding another feature to C-V2X when devices use the shared band. It exploits the RTS/CTS mechanism that was discussed in the previous section, but in a different way. In the first subframe of every on period, all C-V2X devices send a "CTS to self" [15], i.e. a CTS packet that is not in response to any RTS. A Wi-Fi Device X that observes this CTS will conclude that another Wi-Fi device is about to transmit, so this Wi-Fi device will refrain from transmitting for a period specified in the CTS packet. Thus, C-V2X communications should no longer experience interference from Wi-Fi. If CTS packets are transmitted at an appropriate power level, then Wi-Fi devices that are close enough to any C-V2X device to cause harmful interference will not transmit during the on period, but Wi-Fi devices that are not close to any C-V2X devices will not receive CTS packets, and will continue transmitting unimpeded. This is critical for efficient sharing.

The CTS packet can be transmitted 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 $j$, and then another CTS would be sent again 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 [6, 16]. Thus, no useful time is wasted by transmitting CTS packets.

The CTS packet sent by all vehicles will be exactly the same, meaning each C-V2X device will use the same source and destination address values, which are established in the new standard. Because clocks are synchronized, and identical content is sent at the same time over short distances, CTS transmissions will reinforce rather than interfere with each other. The requirement that C-V2X devices be capable of sending this Wi-Fi packet does add complexity, but devices would only have to send this one specific sequence of bits, and they would not have to receive these packets, or follow the RTS/CTS protocol in any way.

This use of CTS packets should prevent most collisions between Wi-Fi and C-V2X, but collisions still occur when a Wi-Fi device begins transmitting during an off period and is still transmitting when the on period begins. These collisions can be prevented by turning the first subframes in an on period into guard periods. That reduces packet error rate, but it does so by wasting a subframe, so may or may not be worthwhile.

The fraction of spectrum resources going to C-V2X roughly corresponds to the *C-V2X on-off fraction*, which we define as the (on period) / (on-off interval), where *on-off interval* is defined as the on period plus the off period. Clearly, to make sure both device types have reasonable access to spectrum, the C-V2X on-off fraction cannot be too close to 0, or too close to 1. The C-V2X on-off fraction could be a fixed number, established in the standard, and ultimately codified into regulation. This would be simple to implement, and fully transparent, so makers of Wi-Fi devices and makers of C-V2X devices know what they have. Alternatively, this ratio could be chosen dynamically, such that the C-V2X on-off fraction is high at times and places where there is a high density of vehicles communicating, such as near a six-lane highway during rush hour, and the C-V2X on-off fraction is small at times and places where there are few, such as a remote road in the middle of the night. If dynamic, each vehicle could choose its own C-V2X on-off fraction based on spectrum activity it has observed. We are exploring both static and dynamic.

The on-off interval is another important design decision. Making the interval longer (while holding C-V2X on-off fraction constant) has advantages. As discussed above, collisions can occur in the first subframe of a new on period. Increasing the on-off interval will make that problem less frequent, which slightly improves achievable throughput if that first subframe is turned into a guard period, and slightly improves packet loss rate otherwise. On the other hand, increasing the on-off interval also increases packet latency. For example, Wi-Fi packets will wait longer on average for transmission if on and off periods are 50 ms each than if on and off periods are 25 ms each.

## 4. Methodology

To quantitatively assess the viability of spectrum sharing between Wi-Fi and C-V2X, both with and without our proposed modifications, we developed and used a software system that simulated behavior of both. We built this system on top of LTEV2Vsim, a dynamic simulator written in MATLAB by researchers at the University of Bologna to investigate resource allocation in C-V2X [17, 18]. We added new mechanisms to C-V2X, including our proposed on and off periods, and CTS.

In the simulations discussed in this paper, mode 4 C-V2X devices are deployed as follows, which is consistent with the *highway scenario* as specified by 3GPP [19]. We consider an infinitely-long straight east-west highway with three lanes of traffic in each direction. Each lane is 3 meters wide. Vehicles are distributed across each lane of the highway according to a Poisson point process with uniform density. All vehicles are equipped with C-V2X devices with 1 ms subframes, and 100 ms selection windows. The on-off interval is also 100 ms, and no subframes are used as guard periods. Each vehicle generates a 200-byte packet to be scheduled for transmission every 100 ms. (For example, 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 requires one C-V2X resource block, and is transmitted with a power of 23 dBm. These C-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 are placed near the highway – one 10 meters to the north and one 10 meters to the south. Thus, each Wi-Fi device contends for spectrum with one other Wi-Fi device, and however many C-V2X devices are within range. At each Wi-Fi device, packets are generated independently according to a Poisson process. Wi-Fi packet transmissions consume the entire shared 10 MHz (and possibly spectrum in adjacent bands outside this 10 MHz as well). It takes 2 ms to transmit a Wi-Fi packet, which is reasonable for a Wi-Fi hotspot using frame aggregation. The transmit power is 20 dBm. The Wi-Fi sensing threshold is -78 dBm, 20 dB above noise. The arbitration inter-frame spacing (AIFS) is 152 µs. Both Wi-Fi and C-V2X signals attenuate according to the WINNER+ path loss model.

## 5. Findings

### 5.1. Quality of Service with Today's C-V2X

First, we consider how well C-V2X and Wi-Fi share spectrum in the highway scenario described in the previous section if there is no modification to C-V2X. Let the load from each Wi-Fi device be 20%, i.e. any given Wi-Fi device is transmitting 20% of the time. Fig. 1 shows how Wi-Fi quality of service is affected by the presence of C-V2X. The Y axis is the packet error rate of Wi-Fi, i.e. the percentage of packets received with SINR below threshold. The X axis is the density of vehicles and thus C-V2X devices, i.e. the number of vehicles per km on each lane of the highway. This shows that the presence of C-V2X devices on a busy highway can degrade Wi-Fi quality of service to unacceptable levels.

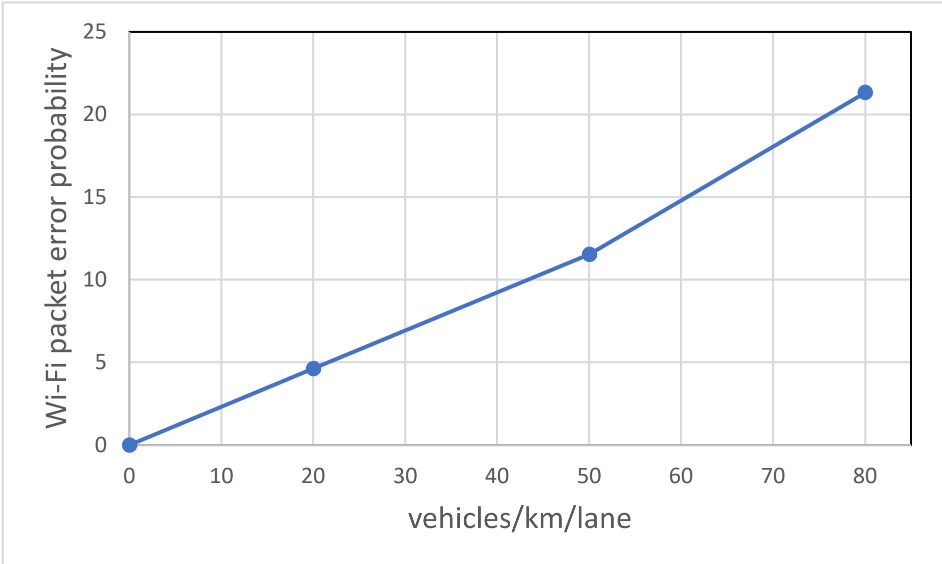


Fig. 1: Wi-Fi packet error rate vs. vehicle density. Load from each Wi-Fi device is 20%.

Fig. 2 shows how C-V2X quality of service is affected by the presence of Wi-Fi. The X axis is the same as in Fig. 1, and the Y axis is C-V2X packet reception ratio (PRR), which is the fraction of C-V2X packets that are correctly received (because their SINR is above threshold) averaged across all vehicles within 150 meters of the transmitter. This is an important measure of quality of service for C-V2X messages that are broadcast to all neighbors. The blue curve shows C-V2X PRR with Wi-Fi, and the orange curve shows C-V2X PRR if the Wi-Fi devices are removed. This figure shows that the presence of Wi-Fi devices with a 20% load can degrade C-V2X quality of service by over 15%, reaching a level that is unacceptable for many safety-related applications.

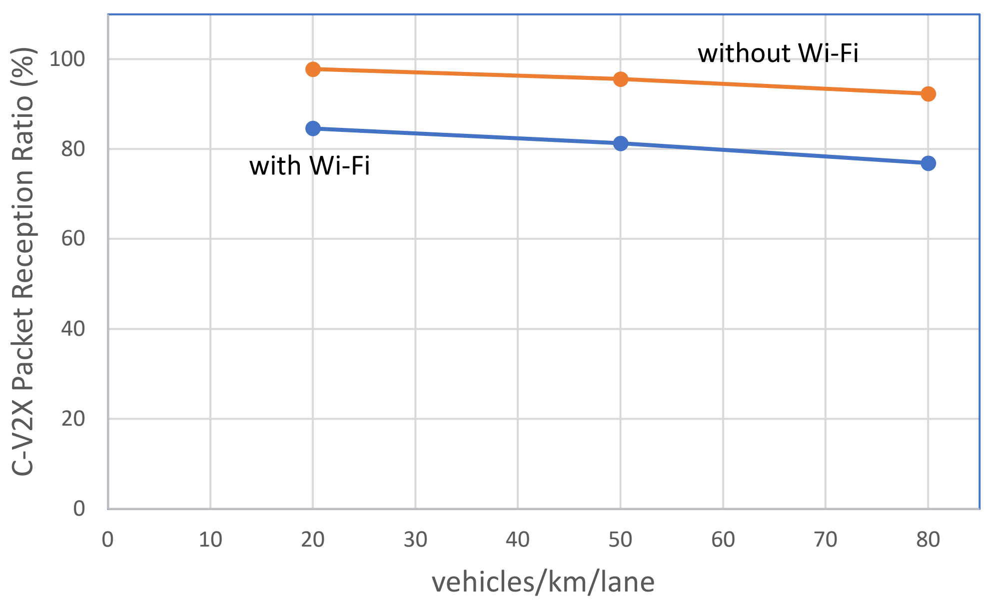


Fig. 2: C-V2X packet reception ratio vs. vehicle density. In blue curve, load from each Wi-Fi device is 20%. In red curve, there is no Wi-Fi in the band.

## 5.2. Quality of Service with Modified C-V2X

We now show how adding on-off periods and CTS packets to C-V2X affect quality of service in shared spectrum. Fig. 3 shows C-V2X PRR vs. C-V2X on-off fraction for different vehicle densities in three important scenarios: (i) when there are no Wi-Fi devices in the band (black), (ii) when there are Wi-Fi devices and C-V2X has on-off periods but not CTS packets (red), and (iii) when there are Wi-Fi devices and C-V2X has both on-off periods and CTS packets (green). At all three vehicle densities, Fig. 3 shows that if C-V2X devices use CTS, then for any given on-off fraction, C-V2X PRR is roughly the same when spectrum is shared with Wi-Fi as when there is no Wi-Fi. PRR without CTS packets is considerably worse. This unfortunately indicates that if spectrum is shared using the on-off periods alone for protection, which would be simpler, then C-V2X communications must tolerate lower quality of service. Fig. 3 also shows that the introduction of on-off periods does not significantly degrade performance for C-V2X as long as the C-V2X on-off fraction is not too low. How low this ratio can go depends on the vehicle density. With 20 vehicles per km per lane, C-V2X performance is quite good with an on-off fraction of 40%, but that is not sufficient for a vehicle density of 80.

To observe the effect of C-V2X on Wi-Fi quality of service, we show how Wi-Fi throughput changes with Wi-Fi load both with and without the presence of C-V2X devices. In Fig. 4, the Y axis is the number of Wi-Fi packets per second that are correctly received at each receiver, i.e. with SINR above threshold. The X axis shows 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 C-V2X on-off fraction is 50%. For the blue curve, there is only Wi-Fi, i.e. there are no C-V2X devices in the band. Not surprisingly, roughly twice the throughput can be achieved at high loads when there is no C-V2X. However, as long as Wi-Fi load is not too high, C-V2X does not appreciably affect Wi-Fi throughput.

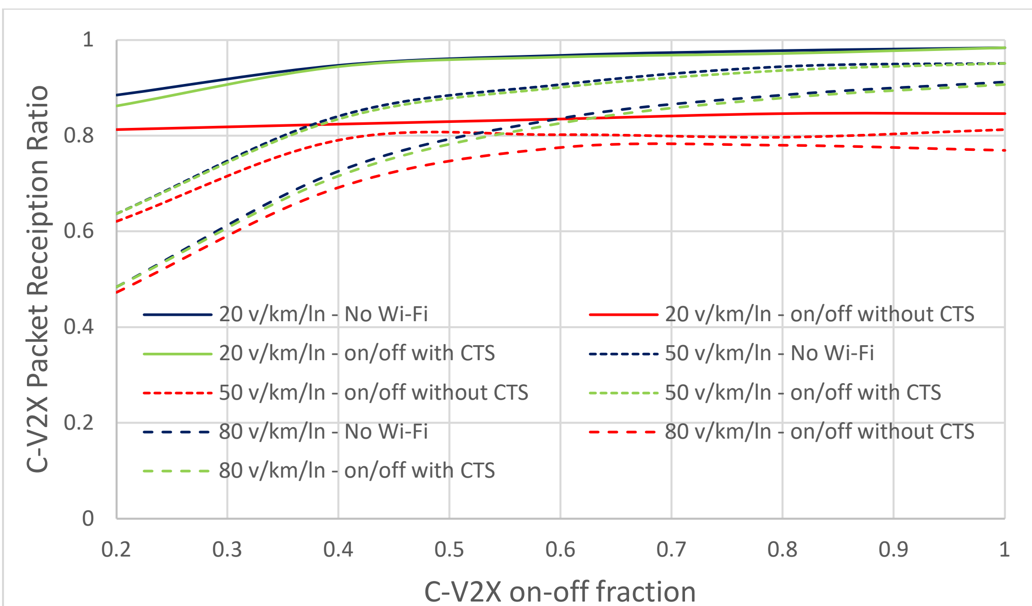


Fig. 3: C-V2X packet reception ratio vs. C-V2X on-off fraction. Curves are shown for vehicle densities of 20, 50 and 80 vehicles per km per lane (v/km/ln), and in three scenarios. In scenarios with Wi-Fi, Wi-Fi load is 20% per device.

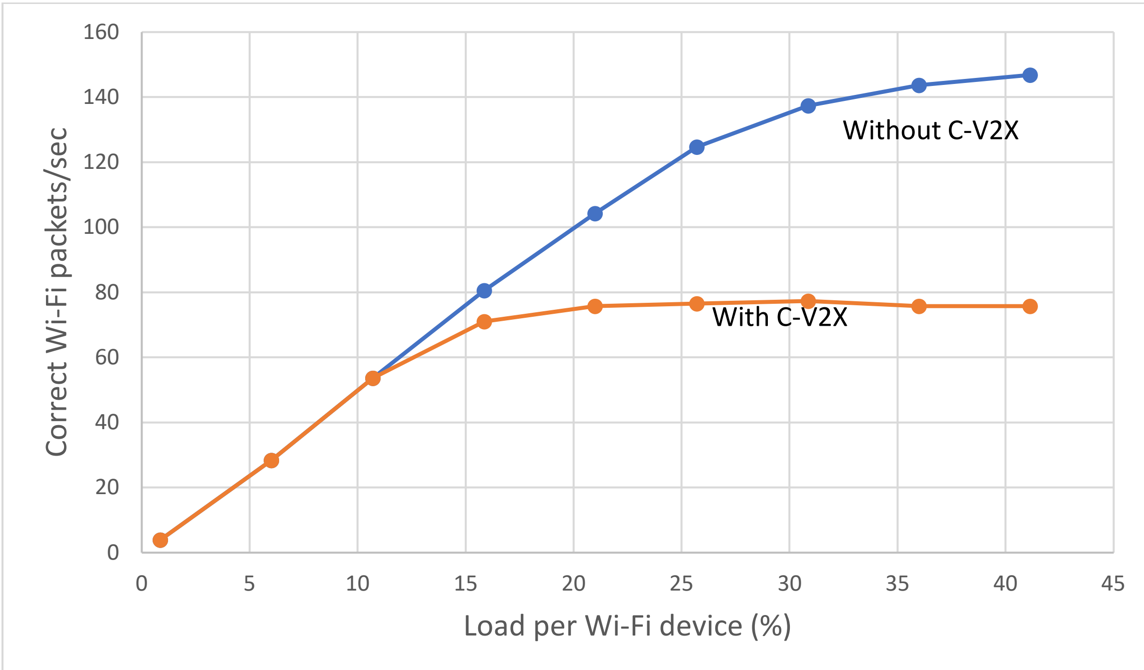


Fig. 4: Wi-Fi packets/second received correctly vs. Wi-Fi load per device. Orange curve is with 20 vehicles equipped with C-V2X per km per lane and on-off fraction of 50%. Blue curve is with only Wi-Fi, no C-V2X.

There is an obvious trade-off when setting the C-V2X on-off fraction. Increasing the ratio benefits C-V2X and decreasing it benefits Wi-Fi. However, it is often possible for both types of devices to perform well. Fig. 5 shows this trade-off, where the Y axis is C-V2X PRR and the X axis is Wi-Fi throughput. Wi-Fi load is 20% at each Wi-Fi device. Curves are shown for two vehicle densities, where every point along the curve has a different on-off fraction. Not surprisingly, it is possible to achieve better performance for both when vehicle density is lower. The fact that both curves resemble the corner of a square means that with the right on-off fraction, PRR for C-V2X will be only slightly worse than optimal, and throughput for Wi-Fi will be only slightly worse than optimal. There are some differences between the curves. With a vehicle density of 20, an on-off fraction of 40% serves C-V2X devices well, but with a vehicle density of 40, an on-off fraction of 50% or 60% is more appropriate.

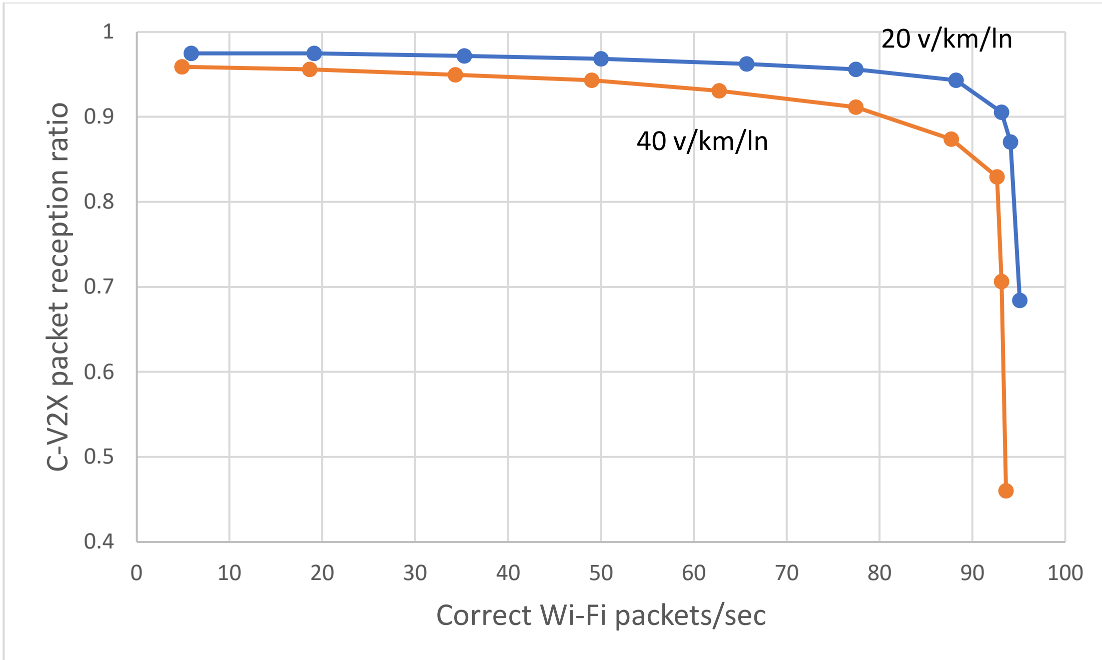


Fig. 5: C-V2X packet reception ratio vs. Wi-Fi packets/second received correctly. Wi-Fi load is 20% per device. Blue and orange curves have vehicle densities of 20 and 40 vehicles per km per lane, respectively.

Now we consider the case where 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 close to the corner of a square, but even under this heavy load, it is possible to operate at a point on the curve at which C-V2X PRR is well protected and Wi-Fi throughput is significant.

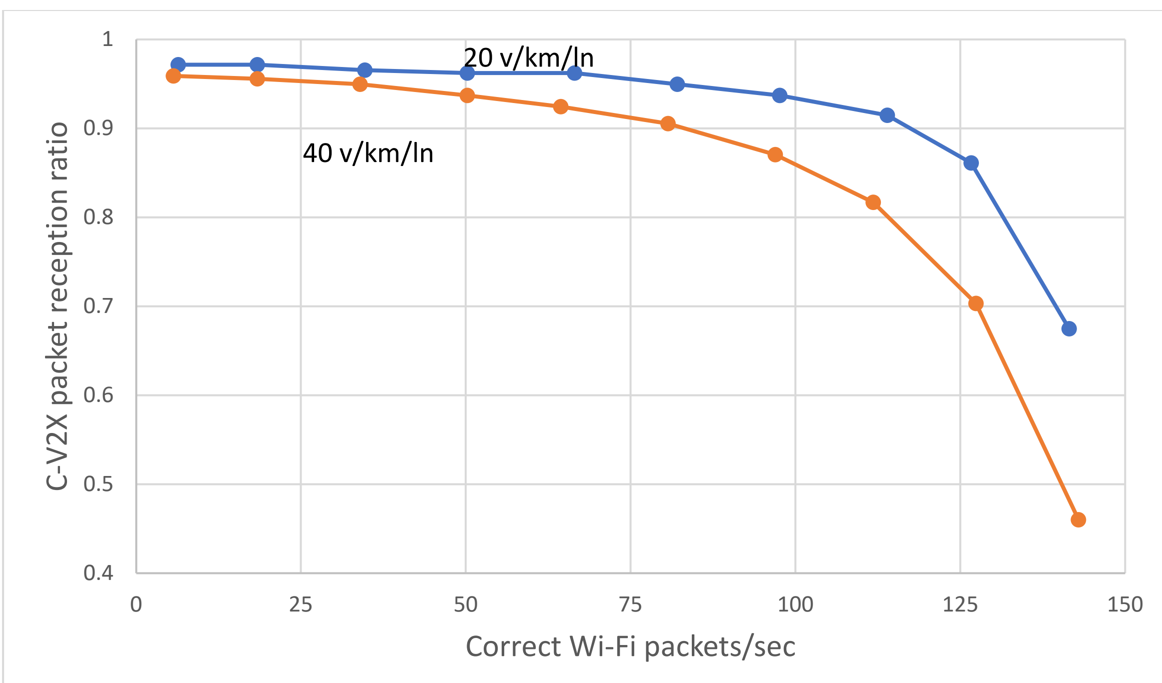


Fig. 6: C-V2X packet reception ratio vs. Wi-Fi packets/second received correctly. Wi-Fi load is 100% per device. Blue and orange curves have vehicle densities of 20 and 40 vehicles per km per lane, respectively.

## 6. Conclusions and Future Work

This paper shows that C-V2X and Wi-Fi can share spectrum in a way that meets the quality-of-service needs of both. All we have to do is add on-off periods and the ability to send CTS packets to the C-V2X standard for when these devices operate in shared spectrum. This allows C-V2X to operate with a quality of service that is comparable to what can be achieved in dedicated ITS spectrum, which means shared spectrum is a viable option to support even safety-critical applications if and when 30 MHz of dedicated spectrum becomes insufficient. The fact that there is now unlicensed spectrum with relatively low utilization directly adjacent to the ITS band makes this approach especially attractive, although these techniques can be used in other unlicensed bands as well.

This approach requires no modification to Wi-Fi devices if they comply with the standard, since it builds on the LBT approach that is already at the heart of Wi-Fi. This paper shows that the proposed approach still allows Wi-Fi devices that share spectrum with connected vehicles to achieve high levels of performance. Even more important, Wi-Fi devices that are not close enough to roadways to share spectrum operate as if there were no C-V2X devices in the band. It is likely that this will include many Wi-Fi devices, especially among those Wi-Fi devices that operate indoors. That alone makes this form of spectrum sharing extremely efficient.

Unlicensed bands can include many types of devices, and our approach can be extended to many of them, as long as they follow the same LBT approach as Wi-Fi, and they back off after observing CTS packets. Unlike Wi-Fi, this could require some modifications to how they access spectrum, but it is possible.

All of these benefits are possible with a fixed C-V2X on-off fraction. However, this paper has also shown that optimal on-off fraction depends on circumstances, e.g. utilization from C-V2X and Wi-Fi devices, and these factors vary from place to place and from time to time. In future work, we will present and assess options for dynamically changing the C-V2X on-off fraction based on recent observations of spectrum utilization. That work will also present and assess options for changing the on-off interval. These techniques can lead to even greater spectral efficiency, although with greater complexity.

## 7. Recommendations for Standards and Spectrum Policy

To make use of this spectrum-sharing approach, action is required from spectrum regulators and technical standards organizations. Obviously, a version of the C-V2X standard must be created that addresses operation in a band that is shared with unlicensed devices. This version would include on-off periods and CTS packets. This would require a committee that draws expertise both from the IEEE 802.11 committee which produces standards related to Wi-Fi, and the 3GPP organization which produces standards related to C-V2X.

Spectrum regulators must then establish the coexistence rules of a band shared by connected vehicles and unlicensed devices. Coexistence rules can have a tremendous impact on spectrum efficiency and quality of service, and can be simple or complex [20]. (Such rules can even give device designers incentive to use spectrum more efficiently by making certain parameters dependent on past spectrum utilization [20-25].) With the approach proposed in this paper, unlicensed devices operating in the shared band would be required to use LBT and to respond to CTS packets in a manner consistent with the IEEE 802.11 committee's standard, even if those unlicensed devices are not Wi-Fi. The C-V2X devices operating in the shared band would be required to use on and off periods in a manner consistent with the standard developed by the committee described above that draws from both IEEE 802.11 and 3GPP. We also expect that the coexistence rules would allow C-V2X devices to transmit CTS packets at a somewhat higher power than Wi-Fi devices are allowed to transmit.

For the unlicensed band that is directly adjacent to the ITS band, a spectrum regulator could take additional steps. To make sure that both connected vehicles and 160 MHz Wi-Fi 6 have access to the spectrum they need, the regulator can limit the unlicensed devices that operate in this band in two ways. One way is to restrict mobile and possibly outdoor unlicensed devices. For many indoor devices, there is little risk that interference to or from C-V2X devices will be a problem, because signals must travel between roads and buildings and pass through building walls. Interference is a greater risk for outdoor unlicensed devices, and is worst for battery-powered mobile devices such as cellphones that might operate inside vehicles. If the regulator only allows unlicensed devices in the shared band indoors, or at least limits this spectrum to stationary unlicensed devices that do not operate on battery power, this would allow more resources to go to connected vehicles. Further research and perhaps a Notice of Proposed Rulemaking would be needed to determine the impact of this limitation on the market for Wi-Fi 6 and other unlicensed devices, and whether this limitation is worthwhile overall.

If the primary purpose of moving spectrum from ITS to unlicensed was really to provide 160 MHz of contiguous spectrum for Wi-Fi 6 and its successors, then another possibility is for the regulator to prevent unlicensed devices that transmit in 80 MHz of spectrum or less from operating in the portion of the unlicensed band that is shared with connected vehicles, or to prevent unlicensed devices other than Wi-Fi from using this band, or both. Again, further research and perhaps a Notice of Proposed Rulemaking are needed to assess this idea.

## 8. Expanding the Transportation Workforce

This project has sought to expand the transportation workforce by contributing to the education of engineers regarding connected vehicles. We have presented some material from this work in graduate courses at Carnegie Mellon University. This research has also provided opportunities for one Ph.D. student, one MS student, and one post-doctoral Fellow at Carnegie Mellon University to learn about connected vehicles, and related transportation issues.

## 9. References


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