Impact of Wi-Fi Transmissions on C-V2X Performance

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***Abstract*—The 5.9 GHz band has been earmarked in many countries for Intelligent Transportation Systems (ITS) applications. Cellular V2X (C-V2X)—a recently developed access technology for vehicle-to-everything (V2X) communications—is a candidate technology to provision ITS applications using the 5.9 GHz band. Due to the ever-increasing popularity of Wi-Fi and search for additional unlicensed bands, in the US and Europe, regional regulators have previously considered allowing co-channel Wi-Fi operations in the ITS band on a secondary basis to the incumbent ITS technology. Additionally, there are several Wi-Fi channel configurations, some already in operation while others still under consideration, which place Wi-Fi and C-V2X devices in adjacent bands. It is, therefore, likely that C-V2X users may be susceptible to interference from Wi-Fi devices operating both in co-channel scenarios and in adjacent bands. To make an informed decision on future Wi-Fi channelization in and around the ITS band, a detailed study on the impact of these Wi-Fi transmissions on the system performance of C-V2X is extremely essential. In this paper, through a comprehensive and systematic simulation study, we investigate the impact of Wi-Fi transmissions on the performance of C-V2X, both in co-channel and adjacent channel scenarios. Our simulations reveal that if Wi-Fi devices are to coexist with C-V2X in the same spectrum, existing mechanisms either fall short of sufficiently protecting C-V2X performance or render the spectrum unusable for Wi-Fi operations. On the other hand, all Wi-Fi channels that are adjacent to the ITS band can significantly degrade the system-wide C-V2X performance. In such scenarios, to adequately protect the C-V2X network performance, either certain restrictions need to be put in place on Wi-Fi operations, or the operations of Wi-Fi in such channels must be prohibited.**

I. INTRODUCTION

Connected vehicles have enormous potential in reducing accident-related fatalities and minimizing the social and economic impact resulting from vehicle crashes [1]. The emerging vehicle-to-everything (V2X) communications paradigm is envisioned to act as an additional sensor allowing V2X-capable vehicles to obtain a long-range non-line-of-sight "view" of its surroundings [1], thereby significantly enhancing vehicle and passenger safety. V2X encompasses the capability of a vehicle to communicate with other vehicles (V2V), roadside infrastructure (V2I), pedestrians (V2P) and the network (V2N).

The two key technologies that support direct vehicular communications are Dedicated Short Range Communications (DSRC) and Cellular V2X (C-V2X). Primarily designed for V2V and V2I, DSRC has been the *de facto* technology for connecting vehicles for over a decade. Borrowing its physical (PHY) and medium access control (MAC) protocols from the IEEE 802.11 standard, DSRC offers all those advantages that are available to Wi-Fi — simple and distributed medium access protocol, well-studied PHY and MAC layers, etc. While a large range of safety and non-safety applications can be supported by DSRC [2], factors such as its poor scalability and lack of commercial deployments have motivated the development of alternative technologies for V2X communications.

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C-V2X is a cellular-based V2X technology alternative to DSRC that can enable vehicular communications both in the presence and absence of cellular infrastructure. C-V2X was standardized by the 3rd Generation Partnership Project (3GPP) in its Release 14 [3] and uses the Long Term Evolution (LTE) *sidelink* (also referred to as the PC5) air interface.

Both DSRC and C-V2X are designed to operate in the 5.9 GHz Intelligent Transportation Systems (ITS) band. Even though this band was allocated for ITS applications in the US as early as in 1999, commercialization of V2X-capable vehicles has been slow. Citing this under-utilization, regulators in the US and Europe started considerations to allow unlicensed secondary operations, such as those from Wi-Fi devices, in the ITS band. In the US, the Federal Communications Commission (FCC) issued a Notice for Proposed Rulemaking (NPRM) [4] in 2013 that solicited proposals for unlicensed operations in the $5.85 - 5.925$ GHz band. The unlicensed Wi-Fi devices would operate as secondary users of the spectrum, transmitting only when its incumbent users did not occupy the band. In August 2013, the *DSRC Coexistence Tiger Team* was formed to investigate techniques for harmonious DSRC–Wi-Fi coexistence. In their final report [5], the Tiger Team proposed two mechanisms for DSRC–Wi-Fi coexistence. In Europe, on the other hand, the European Telecommunications Standards Institute (ETSI) has already standardized two mechanisms for DSRC–Wi-Fi coexistence [6].

In addition to the aforementioned co-channel operating scenario, ITS band (i.e., currently DSRC) devices are prone to interference from Wi-Fi devices operating in the adjacent bands due to out-of-band emissions (OOBE), especially if such Wi-Fi devices are located in the proximity of ITS band receivers. In the US, the ITS band spans from $5.85 - 5.925$ GHz. At the lower end of the ITS band lies the Unlicensed National Information Infrastructure 3 (U-NII-3) band ($5.725 - 5.85$ GHz), which is used by Wi-Fi devices to service wireless local area networks. Furthermore, to cater to the growing demand for unlicensed spectrum, the FCC in the US is considering a proposal to allow Wi-Fi operations in parts of the $5.925 - 7.125$ GHz band [7], which is, again, adjacent to the ITS band. At the lower end of this spectrum is the U-NII-5 band ($5.925 - 6.425$ GHz) where outdoor operations of Wi-Fi devices may be permitted. To make matters worse, one of the two Tiger Team proposals for DSRC–Wi-Fi coexistence mechanisms places Wi-Fi and DSRC devices in adjacent bands with no guard band!

It is, thus, clear that the efficacy of V2X communications is at risk from Wi-Fi-induced interference both due to co-channel and adjacent channel operations. Except for adjacent channel interference from U-NII-3 Wi-Fi devices, all other scenarios discussed above are still in the proposal phase. Thus, a detailed investigation of the impact of Wi-Fi transmissions on the performance of the V2X communications technology, which is precisely the subject of this paper, is critical.

Because C-V2X is a relatively new technology, studies that have looked at the impact of Wi-Fi transmissions on V2X communications' performance have, to this date, considered DSRC as the default V2X technology. However, it is arguable that C-V2X offers certain advantages over DSRC such as an increased communication range, eNodeB-assisted resource management, well-defined evolutionary paths etc [8]. While the merits and demerits of DSRC and C-V2X are still under debate, a scenario where Wi-Fi-like unlicensed devices coexist with C-V2X in and around the ITS band is a plausible one. Considering the new trends in the automotive industry, the popularity of Wi-Fi and development of new V2X use-cases, the FCC has started to take a fresh look at the 5.9 GHz band in the US [9]. Under these circumstances, knowledge of whether and how much Wi-Fi devices' operations in co-channel and adjacent channel scenarios impact the performance of C-V2X is critical in the regulatory decision-making process.

In this paper, through a systematic simulation study, we investigate the impact of Wi-Fi on C-V2X system performance. The main contributions of this paper are summarized below.

- We first study the suitability of mechanisms, which were previously developed for DSRC–Wi-Fi coexistence, for the coexistence of C-V2X and Wi-Fi. Naturally, it is expected that such coexistence mechanisms may be inadequate at protecting C-V2X receivers from Wi-Fi interference. Using simulation results derived from our network simulator-3 (ns-3) based simulator, we demonstrate that this indeed the case.
- Using the same simulation platform, we show that Wi-Fi devices operating in channels (both existing and proposed) adjacent to the ITS band can significantly raise the noise floor of C-V2X receivers, thereby causing a considerable loss in the C-V2X system performance.

To the best of our knowledge, ours is the first effort to study and quantify the impact of Wi-Fi devices on the system-level performance of C-V2X. In this paper, we keep our discussions limited to C-V2X devices using sidelink mode 4, i.e., C-V2X operations without assistance from the cellular infrastructure.

II. Related Work

The study of coexistence between Wi-Fi and the incumbent ITS technology has garnered considerable attention in the literature. However, existing studies almost exclusively consider DSRC as the ITS technology. At the time of writing this paper, therefore, studies on the coexistence of C-V2X and Wi-Fi are limited in the literature.

Existing research works predominantly study the impact of Wi-Fi on DSRC under co-channel operating conditions. For example, it has been shown in [10] that if Wi-Fi devices vacate the ITS band for 10 seconds as soon as any DSRC activity is detected, a sufficient degree of protection can be provided to near-by DSRC devices. This has been verified by the FCC in its initial phase of experimental testing for DSRC and Wi-Fi coexistence [11]. While such *sense and vacate* mechanisms are expected to protect DSRC transmissions, the resulting Wi-Fi throughput makes the band unusable for Wi-Fi devices even at moderate vehicular densities. Since the purpose of allowing spectrum sharing between ITS band devices and Wi-Fi is to cater to the ever-growing demand for unlicensed spectrum, such coexistence mechanisms defeat the purpose of opening up additional bands.

In order to consider the performance of Wi-Fi, different coexistence mechanisms have been proposed, which rely on theoretical models [12], simulation studies [13] and experimental evaluations [14] and provide varying degrees of interference mitigation to DSRC devices while maximizing the Wi-Fi throughput. In addition, ETSI has proposed a range of coexistence mechanisms [6], which, depending on the degree of protection desired for DSRC devices, can strike a balance between Wi-Fi performance and interference mitigation to DSRC devices. In contrast, however, the issue of interference from Wi-Fi devices operating in the adjacent bands has received limited attention in the literature.

In the context of coexistence between C-V2X and Wi-Fi, this issue has only been briefly discussed in [1]. To the best of our knowledge, the question of how well existing coexistence mechanisms fare for C-V2X and Wi-Fi coexistence is unanswered in today's literature. On the other hand, Wi-Fi induced adjacent channel interference to DSRC and C-V2X devices has been experimentally studied in [15]. Specifically, it has been shown that in the presence of a Wi-Fi Access Point (AP) operating in the U-NII-3 band, the performance of both DSRC and C-V2X, drops significantly. However, experiments in [15] only evaluate the impact of interference due to Wi-Fi transmissions in the U-NII-3 band. The impact of Wi-Fi transmitters operating in the U-NII-4 and U-NII-5 bands, which have a smaller frequency separation from ITS channels is unexplored in the literature.

III. Background

A. DSRC Channels

In the US, the 5.9 GHz band is divided into seven 10 MHz channels, each of which can be used for vehicular safety applications. These channels, ranging from ch. 172 to 178, are shown in Fig. 2. Note that even though the same seven channels are reserved for vehicular applications in Europe, not all seven channels are used in all countries. Interested readers can refer to [16] for details on ITS channels in Europe.

B. Mechanisms for Co-channel Coexistence

1) Tiger Team Proposals: In the US, the *DSRC Coexistence Tiger Team* was formed in 2013 to study mechanisms by which Wi-Fi devices could operate in the 5.9 GHz band without causing harmful interference to DSRC users operating in the band. The Tiger Team published their final report [5] on mechanisms for DSRC–Wi-Fi coexistence in March 2015. The report described two key proposals.

The first proposal [17], which we refer to as the *sense and vacate* proposal, recommends that Wi-Fi devices operating in the ITS band must be capable of detecting 10 MHz DSRC preambles as *valid* Wi-Fi frames, thereby causing the Wi-Fi transmitters to use the carrier sensing threshold (-85 dBm/10 MHz) to declare the channel busy in the presence of DSRC transmitters. Furthermore, if a Wi-Fi device detects a DSRC frame, it must cease transmissions on all seven ITS channels for an interval of 10 seconds. Following this idle time, the Wi-Fi transmitter can operate on the ITS channels as long as DSRC signals are not detected.

The second proposal [18], which is referred to as the *re-channelization* proposal, recommends re-farming of the ITS band. According to [18], all vehicular *safety* applications should be moved to the upper three ITS channels, i.e., channels 180, 182 and 184 (see Fig. 2), while the lower four ITS channels should be used for vehicular non-safety applications. Wi-Fi devices can then be allowed to operate in and share the spectrum with DSRC users in the lower four ITS channels. If this proposal is to be adopted, because Wi-Fi devices coexist only with vehicular non-safety applications, less conservative coexistence mechanisms (i.e., mechanisms that allow for a higher probability of Wi-Fi transmissions) can be adopted.

In the final Tiger Team report, a consensus was not arrived at either of the two coexistence mechanisms. Consequently, both the aforementioned proposals are under consideration in the US for DSRC–Wi-Fi coexistence.

2) ETSI Proposals: In Europe, following recommendations from the Wi-Fi industry, two coexistence mechanisms, viz. Detect and Mitigate (DAM) and Detect and Vacate (DAV), have been standardized by the ETSI [6]. The two proposals offer a varying degree of flexibility to Wi-Fi devices operating in the ITS band depending on the required interference mitigation at the DSRC devices. Both proposals, i.e., DAM and DAV, require Wi-Fi transmitters to sense 10 MHz DSRC preambles as valid Wi-Fi frames.

Detect and Mitigate: In Wi-Fi devices post 802.11n, Enhanced Distributed Channel Access (EDCA) parameters control the probability with which Wi-Fi transmitters access the channel. EDCA divides packets generated by various applications into four access categories—voice (VO), video (VI), best effort (BE) and background (BK). Each access category has an associated priority, with VO having the highest and BK the lowest priority. This is reflected in the channel access parameters, i.e., minimum and maximum contention windows and arbitration inter-frame spacing (AIFS). Larger the values of these parameters for a traffic type, smaller is the priority of channel access for that category.

In DAM, if a DSRC frame is detected during Wi-Fi carrier sensing, Wi-Fi transmitters can continue to operate on the ITS channels, but with larger EDCA parameters. Two versions of DAM have been standardized by ETSI—the *reduced DAM* and *absolute DAM*. The EDCA parameters (i.e., minimum and maximum contention window and AIFS number, or AIFSN) for reduced and absolute DAM along with default EDCA parameters are shown in Table I. If a DSRC frame is detected, the Wi-Fi transmitter must use the DAM (reduced or absolute) parameters for a period of 2 seconds, after which the Wi-Fi device can resume the use of default EDCA parameters. If, however, another DSRC signal is detected during this 2 second interval, the 2 second timer is reset. Depending on the level of interference mitigation required, the reduced DAM (low interference mitigation) or the absolute DAM (high interference mitigation) can be used by Wi-Fi devices.

Detect and Vacate: In scenarios where the interference protection offered by DAM is insufficient, ETSI proposes the use of DAV, which is similar in principle to the Tiger Team's sense and vacate proposal but with additional measures for preventing the hidden node problem. A Wi-Fi device using the DAV mechanism, when using one of the ITS channel for the first time, must sense the channel using carrier sensing to detect the presence of DSRC transmitters in its vicinity. If no DSRC transmissions are detected, the Wi-Fi transmitter must send a *probe frame* to detect the presence of *hidden* DSRC terminals. The maximum duration of this probe frame must be 250 μsec. If the reception of the probe frame is acknowledged, then the Wi-Fi device can operate on the ITS channel with an AIFS of 300 μsec and a maximum packet duration of 6 msec. If, however, the probe frame is not acknowledged, or if a DSRC frame is detected during the Wi-Fi device's operation, the Wi-Fi device must vacate all ITS channels for an interval of 10 seconds (similar to Tiger Team re-channelization proposal). Following this silent period, the Wi-Fi device must repeat the above procedure before attempting to access the channel.

C. Wi-Fi in Adjacent Bands

1) Wi-Fi Spectral Mask: When a Wi-Fi device transmits, it radiates some of its power in the adjacent bands in addition to transmitting on the intended channel. This behavior of Wi-Fi transmitters is dictated by the *spectral mask* of Wi-Fi, which is determined by regulatory agencies. The default spectral mask (class A mask [19]) for the U-NII bands is shown in Fig. 1. For different bandwidth configurations, the points A, B, C and D in Fig. 1 correspond to different frequency points around the center frequency as shown in Table II.

In the US, as per FCC regulations, the spectral mask shown in Fig. 1 represents the maximum power that can be radiated outside the desired band. Commercial devices typically radiate within these power limits, i.e. the actual spectral mask of most

Access Category	CWmin Default	CWmax Default	AIFSN Default	TXOP Default	CWmin Reduced DAM	CWmax Reduced DAM	AIFSN Reduced DAM	TXOP Reduced DAM	CWmin Absolute DAM	CWmax Absolute DAM	AIFSN Absolute DAM	TXOP Absolute DAM
BK	15	1023	7	0	31	2047	49	2.528ms	31	2047	2065	2.258ms
BE	15	1023	3	0	31	2047	43	2.528ms	31	2047	2059	2.258ms
VI	7	15	2	3.008ms	15	31	31	3.000ms	15	31	1029	3.008ms
VO	3	7	2	1.504ms	7	15	11	2.080ms	7	15	515	1.504ms

TABLE I: EDCA parameters for default Wi-Fi, reduced DAM and absolute DAM

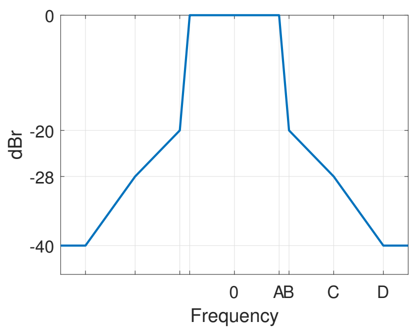


Fig. 1: The default (class A) spectral mask for Wi-Fi

TABLE II: Frequency offsets A, B, C and D for the class A mask

Bandwidth	A (0 dBr)	B (-20 dBr)	C (-28 dBr)	D (-40 dBr)
20 MHz	9 MHz	11 MHz	20 MHz	30 MHz
40 MHz	19 MHz	21 MHz	40 MHz	60 MHz
80 MHz	39 MHz	41 MHz	80 MHz	120 MHz
160 MHz	79 MHz	81 MHz	160 MHz	240 MHz

devices lie within the maximum permissible mask shown in Fig. 1. OOBE characteristics are governed by the device cost; low-cost devices tend to possess low-quality radio frequency (RF) filters, radiating more power outside the desired channel. On the other hand, high-end Wi-Fi devices have superior RF filters, thereby radiating less power in the adjacent channels. Since a wide variety of devices are available commercially, we assume the worst case spectral mask, i.e. *we assume that Wi-Fi devices transmit with the spectral mask shown in Fig. 1.*

2) Wi-Fi Channels: The granularity of Wi-Fi channels in the 5 GHz bands is 20 MHz. There are no overlapping 20 MHz channels in the 5 GHz bands, unlike the 2.4 GHz bands. The center frequency, f_c, of each channel is decided by the channel number, c, as $f_c = 5000 + 5 \times \text{c}$. The set of Wi-Fi channels in the U-NII-3, U-NII-4 and U-NII-5 bands is shown in Fig. 2.

Assuming that Wi-Fi devices radiate negligible power beyond point D in Fig. 1, only a few Wi-Fi channels shown in Fig. 2 can interfere with C-V2X receivers operating in the ITS band. For example, a Wi-Fi device operating in channel 165 ($f_c = 5825$ MHz) radiates almost all of its power in the $5795 - 5855$ MHz band, which does not cause interference to any of the ITS channels. However, a Wi-Fi device operating in channel 155 ($f_c = 5775$ MHz) radiates most of its power in the $5735 - 5805$ MHz band with undesired emissions in the $5655 - 5735$ MHz and $5805 - 5895$ bands. These undesired emissions can potentially interfere with C-V2X devices receiving packets in ch. 172, 174, 176 or 178. In Fig. 2, the shaded channels are those that can interfere with ongoing C-V2X operations on one of the seven ITS channels.

Note that if U-NII-4 devices are permitted to operate as per the re-channelization proposal, C-V2X safety applications will be confined to ch. 180, 182 and 184. As a result, adjacent band Wi-Fi transmissions will interfere with C-V2X operations only if C-V2X devices use one of these channels. In this case, a Wi-Fi device operating in ch. 173 will not leak any of its power on to ch. 180, 182 or 184. Furthermore, under this proposal, the use of ch. 181 for Wi-Fi operations will be prohibited. Consequently, ch. 173 and 181 do not cause any adjacent channel interference to the C-V2X system even though they may cause interference in co-channel operating scenarios.

D. C-V2X Resource Reservation Algorithm

3GPP Release 14 defines C-V2X operations for two scenarios, (i) when vehicles are within eNodeB coverage, (ii) when vehicles operate outside eNodeB coverage. Direct vehicular communications in these two scenarios are referred to as sidelink modes 3 and 4, respectively. In sidelink mode 3, the serving eNodeB handles radio resource management, i.e. assignment of resources to individual vehicles. On the other hand, if vehicles are outside eNodeB coverage, vehicles use sidelink mode 4, whereby they must *reserve* resources for transmissions in a distributed fashion. In the context of C-V2X, 3GPP Release 14 defines a resource as a collection of LTE Resource Blocks in which the entire packet to transmit can fit. To harmonize spectrum access across vehicles, 3GPP Release 14 has standardized an algorithm for resource reservation in sidelink mode 4 [3]. This algorithm is semi-persistent in nature, i.e. when a vehicle picks a resource for its transmissions, it selects a resource not only for the immediately following transmission but also for a number of subsequent transmissions.

The resource reservation algorithm comprises of a *selection window*—the time duration in the future within which the next packet must be sent, and a *sensing window*—the time duration in the past for which the channel is sensed. A vehicle using the resource reservation algorithm creates a *pool* of resources in which it can transmit its next packet. This pool initially comprises of all resources in the selection window. Resources in the pool are then filtered out to select the best possible resource as follows: (A) if a C-V2X packet from a nearby vehicle is correctly decoded, the sensing vehicle can determine the resource on which the next transmission from that vehicle will occur, and consequently avoid transmitting on such a resource. (B) However, if the transmitting vehicle is too far, or if two C-V2X packets collide, the receiver might be unable

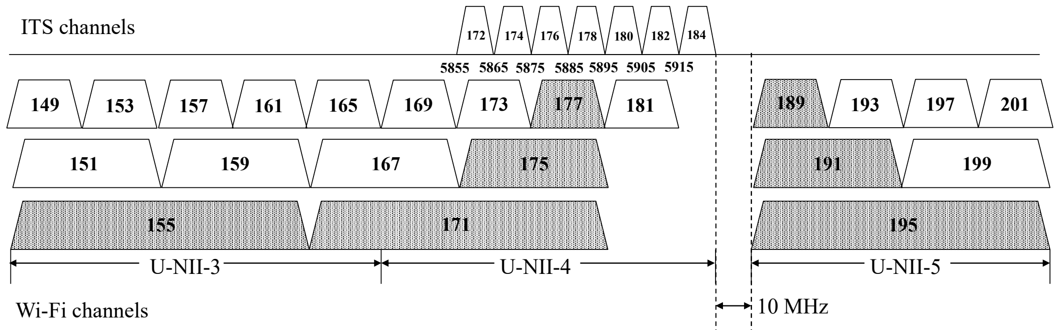


Fig. 2: ITS channels and U-NII Wi-Fi channels. The shaded channels indicate those adjacent channels that can interfere with ongoing C-V2X operations.

to decode the packet(s). To account for such cases, sensing vehicles filter out resources in the selection window based on the energy content of resources in the sensing window. For detailed discussions and analysis on the mode 4 resource reservation algorithm, we refer interested readers to [20], [21].

IV. Simulation Setup

In order to perform our simulation study, we implement the C-V2X mode 4 algorithm in network simulator 3 (ns-3). We extended support for sidelink mode 4 over the simulator developed in [22], where the authors extend the ns-3 simulator to support sidelink modes 1 and 2. Our simulator conforms to all 3GPP Release 14 specifications for sidelink mode 4 as per [3], [23], [24]. To simulate interference from Wi-Fi transmissions in the adjacent bands, we implement the spectral mask for Wi-Fi for different bandwidths as discussed in Sec. III-C1. Furthermore, for all coexistence mechanisms described in Sec. III-B, we assume that the same mechanisms apply if the incumbent ITS technology is C-V2X. For example, in all co-channel coexistence proposals, the Wi-Fi transmitters can detect C-V2X transmissions and use a carrier sensing threshold of -85 dBm/10 MHz.

We consider the *urban* scenario defined in [25] to perform our simulation study. The importance of this scenario stems from the fact that most roadside Wi-Fi deployments can be observed in urban areas, while at the same time, these areas are prone to high vehicular densities. Thus, among the various scenarios in which C-V2X and Wi-Fi users operate in each others' vicinity, the urban scenario is the most likely.

The simulation setup consists of a Manhattan grid layout shown in Fig. 3, where each block size is 250×433 m as recommended in [25]. Vehicles are dropped using Poisson distribution, with the inter-vehicle distance computed from the average vehicle velocity (the inter-vehicle distance is equal to the distance traveled by a vehicle in 2.5 seconds [25]). The total number of vehicles simulated is 600. Four Wi-Fi networks are simulated along the roads as indicated in Fig. 3. The number of Wi-Fi clients associated to the AP in each network is ten, and these clients are distributed uniformly around the AP in a circle of radius 10 m. To understand the worst-case impact of Wi-Fi transmissions on C-V2X performance, we

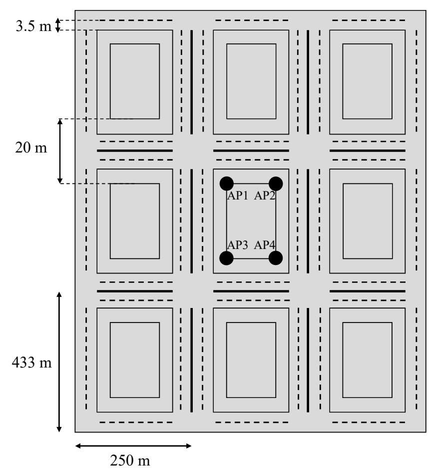


Fig. 3: The Manhattan grid layout and location of Wi-Fi APs

assume saturated traffic at all Wi-Fi devices of traffic class BE ($\sim$ 90% duty cycle). The performance metric chosen in our study is the packet delivery ratio (PDR), which is the ratio of the number of packets received at a C-V2X receiver from a given transmitter to the number of packets transmitted by that transmitter. Each simulation run lasts for an interval of 20 sec., where Wi-Fi devices begin to transmit at t=1 sec. and C-V2X devices transmit from t=2 sec. to t=17 sec. All simulation parameters used in this paper are outlined in Table III. These simulation parameters and the performance metric, i.e. PDR, are widely used in other works such as in [20]. Unless explicitly stated otherwise, the Wi-Fi power is set to 30 dBm. For all simulation results presented in Sec. V, the performance of C-V2X is averaged over C-V2X receivers located in the intersection region next to the four Wi-Fi APs shown in Fig. 3.

TABLE III: Simulation Parameters

Param.	**Value**	**Param.**	**Value**
Avg. Velocity	60 kmph	Inter-vehicle dist.	41.67 m
Propagation Loss	WINNER+ B1	C-V2X Tx. power	23 dBm
C-V2X periodicity	10 Hz	C-V2X bandwidth	10 MHz
C-V2X pkt. size	190, 300 bytes	Wi-Fi PHY rate	24 Mbps
Wi-Fi pkt. size	1024 bytes	Wi-Fi traffic	Saturated

V. Simulation Results

A. Co-channel Coexistence

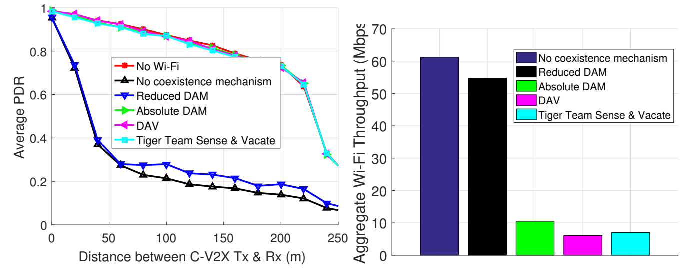
In this sub-section, we take a look at the performance of C-V2X sidelink mode 4 when Wi-Fi devices share the spectrum using coexistence mechanisms described in Sec. III-B.

Fig. 4a shows the average PDR observed across all C-V2X receivers located in the four intersection regions as a function of the distance between that receiver and a C-V2X transmitter. As a baseline for comparison, we show the performance of C-V2X sidelink mode 4 in the *no Wi-Fi* scenario, i.e., scenarios where C-V2X devices are free from any external interference. In such scenarios, any losses in C-V2X performance are due to propagation effects and packet collisions resulting from the use of the C-V2X resource reservation algorithm.

We begin by observing that unhindered transmissions from Wi-Fi devices operating in the same channel (i.e., with no coexistence mechanism) significantly bring down the PDR of C-V2X receivers. In fact, the average 90 % reliability range is reduced merely to 20 meters! It must be noted that for urban scenarios, the 3GPP sets a PDR requirement of 90 % for transmitter-receiver distances up to 120 m [26]. In the absence of co-channel Wi-Fi transmitters, the observed PDR at this transmitter-receiver distance is 85 %. However, this is reduced to only about 20 % in the presence of Wi-Fi transmissions. It is, thus, clear that if C-V2X and Wi-Fi devices are to share the spectrum, effective coexistence mechanisms that mitigate interference at C-V2X receivers are needed.

In light of the aforementioned discussions, Fig. 4a indicates that the reduced DAM mechanism is completely ineffective in preventing interference at C-V2X receivers. In fact, the average PDR observed at a C-V2X receiver is only marginally better than the case where Wi-Fi devices use no coexistence mechanism. The reduced DAM mechanism fails at interference mitigation because it was designed for DSRC–Wi-Fi coexistence bearing the similarities between the MAC protocols of DSRC and Wi-Fi. Because DSRC and Wi-Fi both use Carrier Sense Multiple Access for channel access, by moderately increasing the contention parameters of Wi-Fi transmitters (as is the case in reduced DAM, see Table I), the probability of Wi-Fi channel access can be substantially lowered. However, C-V2X uses a considerably different MAC protocol from Wi-Fi. C-V2X transmitters sense and reserve the spectrum and once reserved, C-V2X devices transmit on the reserved resource without any further sensing. As a result, even if Wi-Fi devices are already transmitting on the channel, C-V2X devices proceed with their transmissions, thereby potentially causing interference at C-V2X receivers. Furthermore, the choice of contention parameters for reduced DAM as shown in Table I results in AIFS of 0.4 msec[1], which is smaller than a C-V2X sub-frame duration (1 msec). As a result, if no C-V2X device within the sensing range of the Wi-Fi transmitter transmits in a given sub-frame, the Wi-Fi device will get access to the channel in that sub-frame. Since reduced DAM

[1] AIFS = 16 μsec + (AIFSN $\times$ 9) μsec.



(a) Impact on C-V2X performance (b) Wi-Fi throughput

Fig. 4: Evaluation of co-channel coexistence mechanisms

allows a maximum transmit opportunity of 2.5 msec, C-V2X transmissions in the next two sub-frames are at risk from Wi-Fi interference. Thus, for every single idle C-V2X sub-frame, the next two sub-frames are at risk from Wi-Fi-induced interference. This manifests itself in the ineffectiveness of reduced DAM in mitigating interference at C-V2X receivers.

On the other hand, Fig. 4a shows that when Wi-Fi devices use one of the other three coexistence mechanisms, the C-V2X performance is practically unaffected. This is expected with the ETSI DAV and Tiger Team's sense and vacate mechanisms since Wi-Fi devices vacate the spectrum as soon as C-V2X activity is detected. In this work, we assume 100 % probability of detection of C-V2X signals at the Wi-Fi transmitter (as long as the Wi-Fi device is not in the transmit state). Consequently, Wi-Fi devices cease transmissions as soon as C-V2X transmissions are detected, thereby resulting in negligible Wi-Fi-induced performance loss to the C-V2X system.

A more interesting behavior is observed when Wi-Fi devices use the absolute DAM mechanism for coexistence. Since we simulate BE traffic at Wi-Fi devices, Wi-Fi transmitters use AIFSN of 2065, which translates to AIFS of 18.5 msec (i.e., 18.5 sub-frames). Even in modest vehicular traffic conditions, the probability that there are no C-V2X transmissions in 18 consecutive sub-frames is very small. As a result, while a Wi-Fi device continues to defer channel access for 18.5 milliseconds (after a C-V2X transmission is first detected), it is likely to detect at least one C-V2X transmission during this interval and consequently continue to use the extended contention parameters. Furthermore, every time a C-V2X transmission is detected, the AIFS countdown is reset and as soon as the C-V2X transmission ends, the Wi-Fi device must wait for an additional AIFS duration (i.e., additional 18.5 sub-frames) before resuming its back-off countdown. As a result, Wi-Fi devices continue to defer channel access to C-V2X devices as long as the C-V2X traffic density is sufficient enough that there is at least one C-V2X transmission (within the Wi-Fi device's sensing range) in every 18 consecutive sub-frames. Thus, even though the absolute DAM mechanism is fundamentally similar to the reduced DAM mechanism and was originally designed by leveraging the similarities in MAC protocols of DSRC and Wi-Fi, the same mechanism also effectively mitigates interference to C-V2X users.

While interference mitigation at the C-V2X receivers is an absolute necessity, it is also essential to look at the Wi-Fi performance resulting from the use of the above coexistence mechanisms. The eventual goal of allowing Wi-Fi access in the ITS band is to provide additional unlicensed bands so that emerging bandwidth-intensive applications can be effectively supported. Fig. 4b shows the aggregate Wi-Fi throughput as a result of using the different coexistence mechanisms. Clearly, all mechanisms that provide a sufficient degree of protection to the C-V2X system do so at the cost of complete loss in Wi-Fi throughput. Note that the small Wi-Fi throughput observed in these cases is due to Wi-Fi transmissions in intervals before and after the C-V2X devices are turned on (i.e., t=1 sec to t=2 sec for all mechanisms and t=19 sec to t=20 sec for the absolute DAM). Thus, *even though conservative schemes such as the absolute DAM, DAV or the Tiger Team's sense & vacate can achieve interference mitigation, these mechanisms render the channel unusable for any meaningful Wi-Fi applications.*

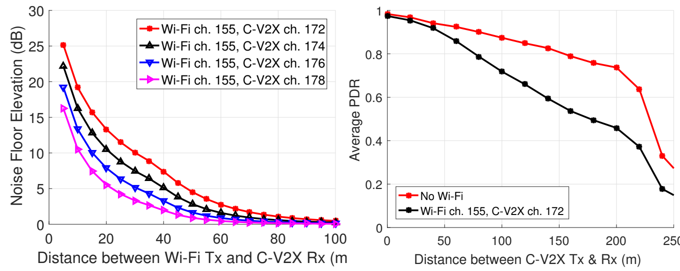
B. Adjacent Channel Interference

Interference from Wi-Fi device(s) operating in the adjacent band can affect C-V2X performance in two ways. First, OOBE from Wi-Fi transmitters can raise the noise floor of a C-V2X receiver, which will result in lowering of the Signal-to-Interference-plus-Noise Ratio (SINR) of the received C-V2X packet. This can result in the loss of a C-V2X packet, which could have been received successfully if not for the adjacent band Wi-Fi device. Second, adjacent channel Wi-Fi transmissions will increase the energy content of resources within the sensing window, which can lead to selection of a non-ideal resource from the selection window (see Sec. III-D). The resulting C-V2X system level performance will drop due to the combined effect of the two aforementioned factors. We investigate this performance drop in this sub-section.

1) Interference from U-NII-3 Wi-Fi: We first look at the impact of adjacent channel interference resulting from Wi-Fi operations in the U-NII-3 band. What distinguishes this scenario from Wi-Fi's (proposed) operations in the U-NII-4 and U-NII-5 bands is that in the US and many other countries, Wi-Fi operations in the U-NII-3 band are already present, whereas those in the U-NII-4/5 band are still under consideration. Consequently, C-V2X devices operating in one of the channels affected by Wi-Fi transmissions in the U-NII-3 band are already set to suffer from Wi-Fi-induced interference.

It must be noted that the only U-NII-3 channel that can cause interference at a C-V2X receiver is channel 155[2], OOBE from which stretches up to 5.895 MHz, potentially interfering with C-V2X operations in ch. 172, 174, 176 and 178. Fig. 5a shows the elevation in the noise floor observed at a C-V2X receiver as a function of its distance from the Wi-Fi transmitter. This is computed as the difference between the noise floor at the C-V2X receiver when the Wi-Fi device in the adjacent channel transmits and when there is no Wi-Fi device in the adjacent channel (both in the absence of C-V2X transmissions). It is seen that for a C-V2X receiver operating

[2]For all other U-NII-3 channels, all ITS channels fall beyond point D in Fig. 1. We ignore the impact of such Wi-Fi channels on C-V2X performance.



(a) Noise floor elevation (b) System performance

Fig. 5: Impact of U-NII-3 adjacent channel interference on C-V2X performance

on ch. 172 and located very close to the Wi-Fi transmitter (< 10 m), its noise floor can be elevated by as much as 25 dB! As the frequency separation between the Wi-Fi and C-V2X operating channel increases (i.e., from ch. 172 through 178), Wi-Fi transmissions begin to have a smaller impact on the C-V2X receivers' noise floor. Nevertheless, as long as the Wi-Fi transmitter operates close to the C-V2X receivers, the C-V2X performance remains susceptible to Wi-Fi interference.

Fig. 5b shows the impact of the aforementioned elevated noise floor on the system level performance of C-V2X operating in ch. 172, where the impact of Wi-Fi devices operating in ch. 155 is the largest. For short distances between the C-V2X transmitter and receiver, the received signal strength is usually large enough to overcome the negative effects of the elevated noise floor. However, as the distance between the C-V2X transmitter and receiver increases, the interference power due to adjacent channel Wi-Fi operations becomes significant compared to the desired C-V2X signal power, thereby resulting in a large fraction of C-V2X packets being dropped at the C-V2X receiver. In the simulated scenario, the 90 % reliability range (i.e., the C-V2X transmitter-receiver distance up to which the PDR is greater than 90 %) is reduced to nearly half (from ~ 80 m to ~ 45 m)!

2) Interference from U-NII-4 and U-NII-5 Wi-Fi: Next, we look at the impact of transmissions from Wi-Fi devices operating in those bands that are yet to finalized for unlicensed use. Since Wi-Fi operations in these channels are yet to be standardized, results presented in this section can be used to make an informed decision on future channelizations of the U-NII-4 and U-NII-5 bands. In terms of Wi-Fi U-NII-4 channels, we first note that if the re-channelization mechanism is permitted by regulations, all ITS safety applications will be moved to channels 180, 182 and 184, allowing Wi-Fi devices to operate in the newly opened up U-NII-4 channels shown in Fig. 2. As a result, the only C-V2X channels affected by U-NII-4 Wi-Fi transmissions are 180, 182 and 184. On the other hand, there is a 10 MHz guard band between channel 184 and the lower edge of the U-NII-5 band. Depending on the channel bandwidth of the U-NII-5 channels, these channels can affect some or all of the seven ITS channels.

Fig. 6 shows the elevation in the noise floor for different Wi-Fi and C-V2X channel configurations. In each case, the Wi-Fi transmitter is located 10 m away from the C-V2X receiver.

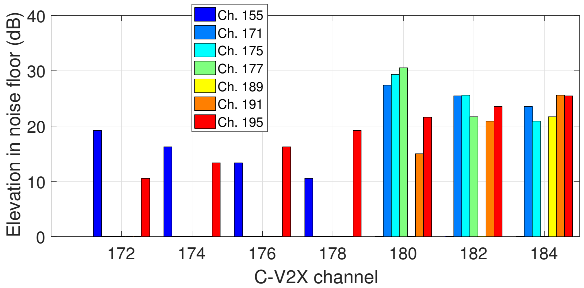


Fig. 6: Elevation in the noise floor for C-V2X receiver

As shown in Fig. 5a, for a C-V2X receiver operating on ch. 172, a Wi-Fi transmitter located 10 m away and operating on ch. 155 raises the noise floor by 20 dB. What is interesting to note is that C-V2X ch. 172, even though being the lowermost of all ITS channels, is affected by Wi-Fi transmissions in ch. 195, which is the first 80 MHz channel in the U-NII-5 band! Like ch. 172, ch. 174, 176 and 178 are only affected by Wi-Fi operations in ch. 155 and 195 due to their large bandwidths.

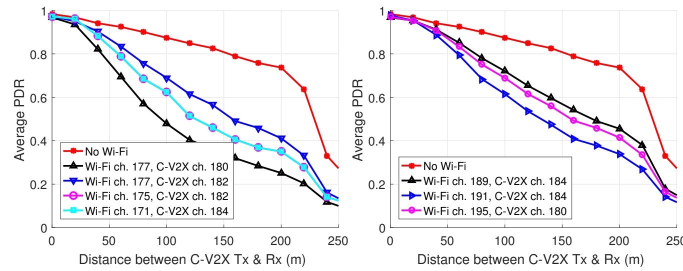
On the other hand, C-V2X ch. 180 through 184 are impacted differently by different Wi-Fi channels depending on the Wi-Fi channel width and the frequency separation between the Wi-Fi and C-V2X channels. The C-V2X ch. 180 is affected heavily by Wi-Fi transmissions on ch. 171, 175 and 177, with ch. 177 creating the largest interference on ch. 180 among all Wi-Fi and C-V2X channel configurations. When we look at the impact on ch. 182, on the other hand, Wi-Fi ch. 171 and 175 create larger interference than ch. 177. This highlights an important fact that OOBE resulting from Wi-Fi operations on a 20 MHz channel create the maximum interference at the immediately adjacent channel (e.g., Wi-Fi ch. 177 and C-V2X ch. 180). This can be explained by the fact that when a Wi-Fi device doubles its bandwidth, the power per sub-carrier is reduced by 3 dB for the same total radiated power. Consequently, the narrowest channel configuration, i.e. 20 MHz, is likely to leak the maximum power on to the immediately adjacent channel. However, interference due to wider Wi-Fi channels (such as ch. 171 or 175) span a larger number of ITS channels and consequently, have a larger impact on far-away ITS channels. Similarly, the Wi-Fi ch. 191 and 195 in the U-NII-5 band have a larger impact on C-V2X ch. 184 than the Wi-Fi ch. 189 (due to the 10 MHz guard band).

Important observations from Fig. 6 are summarized in Table IV, which shows the set of Wi-Fi channels that interfere with different ITS channels and the Wi-Fi channel that results in the largest interference at each of the seven ITS channels.

The impact of adjacent channel interference from Wi-Fi devices operating in the U-NII-4 and U-NII-5 bands on the system-level performance of C-V2X is shown in Fig. 7. Note that the reduction in the PDR of the C-V2X system at a given distance in the presence of Wi-Fi is directly related to the elevation in the noise floor observed at the C-V2X receiver as shown in Fig. 6. Thus, the C-V2X system performance drops the most when C-V2X and Wi-Fi operate in ch. 180 and ch.

C-V2X channel	**Wi-Fi channels impacting C-V2X performance**	**Maximum impact channel**
172	155, 195	155
174	155, 195	155
176	155, 195	195
178	155, 195	195
180	171, 175, 177, 191, 195	177
182	171, 175, 177, 189, 191, 195	175
184	171, 175, 177, 189, 191, 195	191

TABLE IV: Summary of the impact of adjacent channel Wi-Fi interference



(a) U-NII-4 (b) U-NII-5

Fig. 7: Impact of U-NII-4 and U-NII-5 adjacent channel interference on C-V2X performance

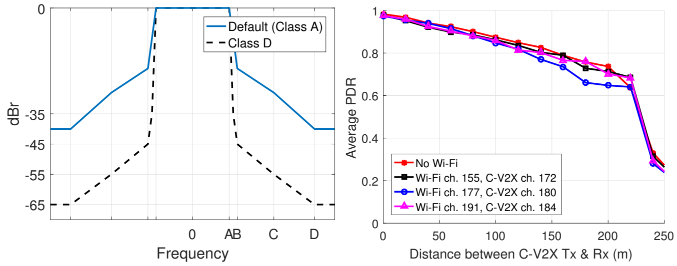
177, respectively for the U-NII-4 band scenario (see Fig. 7a). On the other hand, the impact of U-NII-5 transmissions is maximum when C-V2X and Wi-Fi operate in ch. 184 and ch. 191, respectively (see Fig. 7b).

C. *Interference Mitigation*

In what follows, we describe two ways by which adjacent channel interference from Wi-Fi devices can be minimized.

Tighter Masks: By controlling OOBE from Wi-Fi transmitters operating in the U-NII bands, less power can be radiated into channels reserved for ITS applications. The tighter the spectral mask, the lower will be the impact of Wi-Fi transmissions on C-V2X performance. The *Class D* spectral mask [19] (see Fig. 8a) has the most stringent OOBE requirements among all Wi-Fi spectral masks, leaking the least power into adjacent channels. Fig. 8b shows that in the presence of a Wi-Fi network operating on any of the adjacent channels and using the class D mask, the interference at a C-V2X receiver largely alleviated. In fact, when Wi-Fi and C-V2X devices operate in channels 177 and 180, respectively, which is the case of maximum adjacent channel interference (see Fig. 6), the 90% PDR range is reduced by only 5 meters.

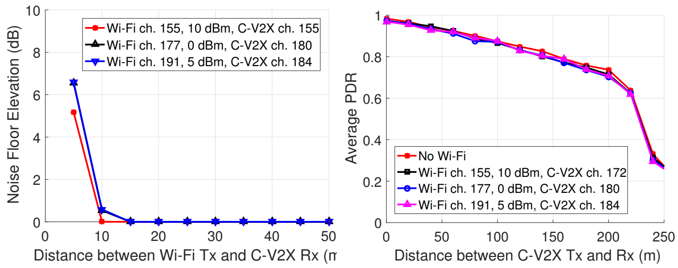
Reduced Wi-Fi Transmission Power/Indoor Operations: The disadvantage of using tighter spectral masks is that to use such masks, high-quality RF filters need to be used, which leads to an increase in the cost of Wi-Fi devices. Such an increase in the cost can be prohibitive to provisioning Wi-Fi services as is reported in [27]. A simpler alternative to tighter spectral masks is to reduce the maximum permissible transmission power of Wi-Fi devices in channels that can potentially interfere with C-V2X operations. Fig. 9a shows that the elevation in the noise floor due to adjacent channel Wi-Fi transmissions can be reduced to zero by reducing the Wi-



(a) Class D spectral mask

(b) Impact on C-V2X system performance

Fig. 8: Impact of Class D mask on C-V2X performance



(a) Elevation in C-V2X receiver noise floor

(b) Impact on system level performance

Fig. 9: Impact of Wi-Fi power on C-V2X performance

Fi transmission power (U-NII-3, U-NII-4 and U-NII-5 power levels of 10 dBm, 0 dBm and 5 dBm, respectively) beyond a distance of 10 m between the Wi-Fi transmitter and the C-V2X receiver. Fig. 9b shows that the resulting loss in the performance of C-V2X is negligible. Further, by restricting the usage of such Wi-Fi devices to indoor environments, a separation of 10 m between Wi-Fi devices and C-V2X receivers can be achieved. Additionally, the confinement of Wi-Fi to indoor environments provides additional protection to C-V2X devices due to attenuation from walls ($\sim$ 10 dB), windows ($\sim$ 6 dB) and doors ($\sim$ 6 dB) [28].

While reducing the power of Wi-Fi devices to $0-10$ dBm may reduce the interference to C-V2X devices, the lower Wi-Fi transmission power will substantially reduce the signal strength at Wi-Fi receivers, thereby resulting in lower SINR of received Wi-Fi packets. Consequently, Wi-Fi devices may be unable to use higher order modulation and coding schemes (MCS) that are enabled by the latest Wi-Fi technologies, such as 256-QAM in 802.11ac. Furthermore, for the same MCS, the reduction in power from 30 dBm to $0-10$ dBm can reduce the transmission range in indoor environments by nearly a factor of 8 [29]. Therefore, *a reduction in Wi-Fi power to mitigate interference to C-V2X may reduce the lucrativeness of those Wi-Fi channels that are adjacent to C-V2X channels.* Eventually, it is up to the regional regulators as to which alternative to select (i.e., tighter masks or lower transmit power). However, from the discussions in this section, it is clear that without employing such mechanisms, the only other option to sufficiently protect C-V2X devices in the vicinity is to prohibit Wi-Fi operations in all those channels that are adjacent to the ITS band. If the latter is the case, the Wi-Fi community will have to let go of three 80 MHz channels (ch. 155, 171 & 195), two 40 MHz channels (ch. 175 & 191) and two 20 MHz channels (ch. 177 & 189)!

VI. Summary & Discussions

A. Co-channel Coexistence

Results presented in Sec. V-A indicate that existing coexistence mechanisms fall into two categories. On one hand, a technique such as the reduced DAM fails at mitigating Wi-Fi-induced interference at C-V2X receivers owing to the mechanism's reliance on DSRC and Wi-Fi MAC protocol similarities. On the other hand, the DAV and Tiger Team's sense & vacate mechanisms use a conservative approach, whereby Wi-Fi devices must completely cease transmissions in the ITS band for a large interval of time. Consequently, as long as the ITS technology signal is reliably detected, mechanisms such as DAV and sense & vacate are agnostic to the choice of the incumbent ITS technology.

The absolute DAM mechanism is a notable exception to the above discussion. Even though this mechanism was developed for DSRC–Wi-Fi coexistence, the choice of very large contention parameters minimizes the impact of Wi-Fi on the C-V2X system performance. A common link, however, between the absolute DAM, DAV and sense & vacate is that these mechanisms practically result in no utilization of the ITS band by Wi-Fi devices. It is, thus, clear that existing coexistence mechanisms are not effective at enabling *harmonious* and meaningful coexistence between C-V2X and Wi-Fi devices. Unsurprisingly, this is an expected conclusion because these mechanisms were originally designed for DSRC–Wi-Fi coexistence. An effective C-V2X–Wi-Fi coexistence mechanism is one that lets Wi-Fi devices utilize time-gaps between C-V2X transmissions, thereby optimizing Wi-Fi performance while ensuring that C-V2X system performance remains unaffected. Whether such a mechanism can be developed with reasonable implementation complexity remains an interesting research problem, which we will investigate in our future work. Nevertheless, it can be concluded that unless novel coexistence mechanisms, which are tailored to the specifics of C-V2X and Wi-Fi MAC protocols, are developed, *Wi-Fi and C-V2X devices cannot meaningfully coexist in the same spectrum.*

B. Adjacent Channel Interference

We first note that because U-NII-3 Wi-Fi devices are already deployed, not much can be done about interference resulting from such devices. At best, it must be ensured that the use of channel 155 must be avoided in all scenarios where the Wi-Fi AP or clients can come in the proximity of vehicles.

At the time of writing this paper, U-NII-4 Wi-Fi operations are not permitted in the US but are under considerations. To ensure that such adjacent channel U-NII-4 transmissions do not affect C-V2X performance, proactive measures must be taken. For example, if channel 180 is selected for C-V2X safety applications, Wi-Fi devices must strictly avoid using all adjacent channels. On the other hand, if channel 182 or 184 is chosen for C-V2X safety applications, the use of ch. 171 and

175 must be restricted, whereas ch. 177 may be permitted at lower transmission powers. Furthermore, based on our findings in Sec. V-C, if permitted, it is best to confine U-NII-4 devices within indoor environments.

Interference from Wi-Fi users in the U-NII-5 band is of grave concern in the US considering that the 5G Automotive Association (5GAA) is considering C-V2X operations in ch. 182 and 184 [30]. The current 6 GHz FCC NPRM [7] only considers the impact of co-channel Wi-Fi transmissions on the incumbent technologies in the U-NII-5 band. As a preliminary approach, the use of geo-location databases to ascertain the absence of incumbent users is considered. If the channel is found to be idle after querying the database, Wi-Fi devices are free to transmit, even in outdoor environments. However, outdoor U-NII-5 installments can place Wi-Fi transmitters in close proximity of C-V2X receivers. From our discussions in Sec. V-B2, it is evident that in such cases, the C-V2X system performance can be significantly degraded. It is, therefore, critical that all stakeholders must consider the impact of allowing Wi-Fi operations in the U-NII-5 band on C-V2X system performance. Regulations must either restrict (i.e., impose tighter masks or lower transmit powers) or prohibit the use of ch. 189, 191 and 195 in all deployment scenarios where Wi-Fi and C-V2X can operate in close proximity.

VII. Conclusions

In this paper, we perform a comprehensive simulation study on the impact of Wi-Fi transmissions in and around the 5.9 GHz ITS band on the system-wide performance of C-V2X sidelink mode 4. Our work, being the first of its kind, is driven by an objective to help inform the regulatory process in its decision to allow Wi-Fi operations in co-channel scenarios with C-V2X (i.e., in the U-NII-4 band) and in adjacent channel scenarios (i.e., in the U-NII-4 and U-NII-5 bands). Our evaluation of existing co-channel coexistence mechanisms, which were originally developed for DSRC–Wi-Fi coexistence, unsurprisingly leads to a conclusion that these mechanisms are not suitable for C-V2X–Wi-Fi coexistence. This calls for design of novel mechanisms that enable harmonious and meaningful C-V2X–Wi-Fi coexistence. Furthermore, our simulation study indicates that the C-V2X system performance is also at risk from Wi-Fi operations in the adjacent bands. While not much can be done regarding interference from existing Wi-Fi devices in the U-NII-3 band, we highlight the need for regulators to take into consideration the impact of U-NII-4 and U-NII-5 band Wi-Fi transmitters on the C-V2X performance.

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