Impairing Traffic Safety from Changes in the Safety Band

Introduction of Interference from Unlicensed Users

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7. Author(s)

James A. Arnold, Office of the Assistant Secretary for Technology and Research (OST-R)

Alan Chachich, Walton Fehr, Leisa Moniz, Tom Schaffnit, Suzanne Sloan and Eric Wallischeck, Office of the Assistant Secretary for Technology and Research (OST-R)/Volpe National Transportation Systems Center

Volker Fessmann, Federal Highway Administration/Turner-Fairbank Highway Research Center

Robert Kreeb, National Highway Traffic Safety Administration

Michael Markowski, Army Research Laboratory

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1200 New Jersey Ave., S.E.
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U.S. Department of Transportation
55 Broadway
Cambridge, MA 02142

U.S. Department of Transportation
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101

U.S. Army Research Lab
6007 Combat Drive, RDRL-SLE-W
Aberdeen, MD 21005

National Telecommunication and Information Administration
325 Broadway
Boulder, CO 80305

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16. Abstract:

The exponential growth in smart and connected devices is accompanied by an increased demand for spectrum, which ultimately is a finite resource. Government, academia, and industry are currently working on advances both to evolve to optimal use of spectrum with current configurations as well as to consider revolutionary changes in the way that spectrum is accessed and used.

This white paper explores an industry proposal for re-channelization and use of the 5.850-5.925 GHz band, currently allocated for transportation safety and system efficiency purposes (the “Safety Band”). This allocation advances the ability for surface transportation operations to perform “cooperatively” with surrounding vehicles, infrastructure, and other roadside systems in a manner similar to aviation. Also similar to aviation, communications in this band are dedicated in a manner that, currently, assures no interference from other devices. Dedicated spectrum is a key element in aviation’s impressive safety record.

The rechannelization proposal represents a significant change to the current band plan endorsed by the FCC. This prospective approach will move three (3) of most heavily used transportation Vehicle-to-Everything (V2X) safety channels—the Basic Safety Message Broadcast Channel (172), the Safety Band’s Control Channel (178), and the Safety Band’s High-Power Vehicle-to-Infrastructure (V2I) Public Safety Channel (184)—to the upper 30 MHz of the Safety Band. This change is proposed as one (1) potential mitigation for sharing the Safety Band with Unlicensed National Information Infrastructure (U-NII).

This white paper presents a structured, technical analysis of re-channelization, as proposed in the FCC docket by U-NII vendors as of 2017, and identifies the issues associated with this particular mitigation based on current rules. As of mid-2019, other band plan approaches are also under study that involves introducing U-NII detect-and-vacate capabilities without restructuring (or rechannelizing) the band plan; as well as introduction of unlicensed cellular based on band plan changes Analysis of these other approaches will be reported on separately as their respective tests conclude. The analysis of the rechannelization approach concludes that there will be a significant, negative degradation of transportation safety communications and the ability to support the range of vehicle-to-vehicle (V2V), V2I, and public safety functions as currently defined. This effect is due to the self-interference and adjacent channel interference experienced when moving the three channels next to each other in the upper band without any isolation from the U-NII transmissions. In this new configuration, re-channelization will significantly affect the ability to transmit and receive the broadcast basic safety messages (BSMs) and other similar messages such as emergency vehicle messages or signal phase and timing (SPaT) information. Additionally, re-channelization will also affect the transmission and receipt of other critical safety information passed to users through the service channels that are managed by the control channel.

In a manner similar to aviation, life-critical safety applications have little tolerance for interference that could result in crashes. The effects of rechannelization will bring this type of interference to surface transportation connected vehicle applications; will pose significant challenges to both current deployments as and development of vehicle safety applications; and may preclude deployment of safety services entirely.

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Table of Contents

List of Tables iv

List of Figures v

1 Background 1

2 Status of the DSRC Technology 4

3 Thesis Statement and Approach 5

3.1 Thesis Statement 5
3.2 Analysis Approach 5

4 The DSRC Service Channel Plan and Description 6

4.1 High Level Concept 6
4.2 Channel 172 8
4.3 Channel 178 9
4.4 Channel 184 9
4.5 Moderate Power Service Channels—174, 176 9
4.6 Low Power Service Channels—180, 182 9
4.7 20 MHz Channels—175, 181 10

5 Factors Influencing Operations in a 10 MHz Channel 11

5.1 Transmitter Mask 11
5.2 Factors Influencing Receiver Capability 14
5.3 Adjacent and Non-Adjacent Channel Rejection 18
5.4 Summary 19

6 Channel Loading/Duty Cycle of the BSM Broadcast, Control, and High-Powered V2I Channels 20

6.1 BSM Broadcast Channel 20
6.2 Control Channel (CCH) 21
6.3 High-Power Vehicle to Infrastructure Channel (HPV2I) 21
6.4 Summary 22

7 Interference Analysis 23

7.1 Types of Interference 23
7.2 Proposed Re-channelization 24
7.3 Interference vs. Range 25
7.4 Clear Channel Assessment Transmission Suppression 29

7.5 Real World Scenario 29
7.6 Packet Collision 35
7.7 Interference Range 37
7.8 Summary 45
8 Conclusion 46
9 Further Work 47
Appendix A: Glossary of Terms A-1
Appendix B: List of Acronyms B-1
Appendix C: Modeling C-1

List of Tables

Table 1. Channel with Corresponding Power and Transmitter Class 13
Table 2. Modulation vs. Received Signal Thresholds 16
Table 3. Adjacent and Non-Adjacent Channel Rejection Receiver Performance Thresholds ... 19
Table 4. Length of Basic Safety Message (BSM) in Microseconds 21
Table 5. Channel Loading, High-Power V2I (HPV2I) 22
Table 6. Channel Occupancy 22
Table 7. Options for Placing BSM, CCH, and HPV2I Channels in Upper 30 MHz of the DSRC Service Band 24
Table 8. Interference Range Based on Minimum Received Signal Level 29
Table 9. Assumptions and Operational Descriptions of Deployed DSRC 31
Table 10. Range and Power Levels for DSRC CCH Transmission at Roadway Intersections 32
Table 11. S/J Ratio for DSRC traffic and AWGN 36
Table 12. Comparison of Signal to Jamming Ratio for On-Channel, Adjacent Channel, and Next Adjacent Channel for 90 percent Packet Completion Rate 42

List of Figures

Figure 1. The DSRC Service Channel Plan and Power Levels for OBU and RSU 6
Figure 2. Transmitter Masks by Transmitter Class 12
Figure 3. DSRC Service Channel Plan Showing Allowable Power into Other DSRC Channels .. 14
Figure 4. PER vs. RSS Scatter Plot, Supplier 1 17
Figure 5. PER vs. RSS Scatter Plot, Supplier 2 18
Figure 6. Comparison of Existing, Proposed, and Suggested DSRC and U-NII Channels 25
Figure 7. Interference from BSM Broadcast Channel 172 on Nearby Channels 27
Figure 8. Interference from CCH Channel 178 on Nearby Channels 27
Figure 9. Interference from High-Power V2I Channel 184 to Nearby Channels 28
Figure 10. Interference Range from CCA for Six Options in Upper DSRC Service Band Placement 29
Figure 11. Typical Location of RSUs along the 1st and 2nd Avenue Corridor, New York City ... 30
Figure 12. Traffic Pattern at Intersection of 2nd Avenue and 14th Street, New York City 34
Figure 13. Laboratory Configuration to Determine Packet Collisions for DSRC in Adjacent and Non-Adjacent Channels 35
Figure 14. Signal to Jamming Ratio for Recorded DSRC traffic and AWGN versus Packet Completion Ratio 36
Figure 15. Received Interference Power at DSRC Receiver from CCH 37
Figure 16. Receiver Sensitivity for All Seven DSRC Channels 39
Figure 17. Received Interference Power vs. Distance of Class C DSRC Transmitter 40
Figure 18. Comparison of Jamming Signal from AWGN and Recorded DSRC on Packet Completion Rate 41
Figure 19. Received Interference Power vs. Distance with Measured Data 42
Figure 20. 44.8 dBm DSRC CCH into First Adjacent BSM Channel at 20 dBm 43
Figure 21. 40.0 dBm DSRC HPV2I into Adjacent BSM Channel at 20 dBm 44
Figure 22. 44.8 dBm DSRC CCH into Third Adjacent BSM Channel at 20 dBm 45

Summary: The proposal to place the three most heavily used V2X safety channels—the Basic Safety Message Broadcast Channel (172), the Safety Band's Control Channel (178), and the High-Power Vehicle-to-Infrastructure (V2I) Public Safety Channel (184)—in the upper 30 MHz of the Safety Band has been proposed as one mitigation for sharing the Safety Band with Unlicensed National Information Infrastructure (U-NII) applications (i.e., Wi-Fi).

This paper explores the problems with that proposal and concludes that there will be a significant, negative effect on the existing operations and the ability to support the range of vehicle-to-vehicle (V2V), V2I, and public safety functions as currently defined. Rechannelization will significantly affect the ability to transmit and receive basic safety messages and other similar messages such as emergency vehicle messages and signal phase and timing information. Rechannelization will also affect the transmission and receipt of other critical safety information passed to users through the service channels that are managed by the control channel.

The negative effect is expected to pose significant challenges to both current deployments and further development of vehicle safety applications, and may preclude deployment of safety services entirely.

1 Background

The U.S. Department of Transportation (U.S. DOT) has been working with State, regional, tribal, and local transportation agencies; transportation associations; automobile manufacturers; device suppliers; and standards development organizations (SDOs) to facilitate the development of a communication service that would support the safety goals of the Department and the Nation. This collaboration has culminated in the development and deployment of IEEE 802.11 based vehicle-to-everything (V2X) services.

Telecommunications technology has evolved over the last several years and offers new approaches to meeting the Department's safety goals. These new technologies will be subject to the same level of rigorous testing and analysis that have been conducted with the original IEEE 802.11 communications (known widely as dedicated short-range communications or DSRC) to prove that they provide at least the same level of technical capability. The analysis in this report only examines DSRC since that was the only technology available to test in 2017. In the future, the Department plans to test and analyze the performance of new technologies.

The V2X communication system addressed in this report, DSRC, is an Institute of Electrical and Electronics Engineers (IEEE) 802.11-based (Wi-Fi) technology designed for use as part of Intelligent Transportation Systems (ITS). While standard Wi-Fi works well in stationary or slow-moving environments, DSRC is uniquely configured to enable continuous, high-speed, trusted, and authenticatable data exchange among moving vehicles and between vehicles and roadway infrastructure or mobile devices, to support safety-critical and transportation-related applications in a highly dynamic operating environment. Current V2X configuration standards, discussed below, are capable of supporting communications between vehicles traveling at relative velocities up to and exceeding 160 mph.

DSRC, as used within this document, refers not only to the basic ability to communicate, but the ecosystem that has developed to support those communications, including privacy and security. All levels of the ecosystem are expected to be impacted if the communication services of V2X are interrupted.

DSRC standards were developed through the IEEE Standards Association process and encompass two families of standards: IEEE 802.11p, which establishes the Physical (PHY) and Media Access Control (MAC) layers; and, the IEEE 1609.x suite of standards that address the upper layers and security. Additionally, the Society of Automotive Engineers (SAE) J2945/1 standard establishes specific technical parameters for V2V communications whose exchanges require no network infrastructure. The DSRC ecosystem allows for trusted and secure communications between vehicles, vehicles and infrastructure, and any other elements of the transportation system (or V2X).

Work on developing these technical standards was initiated by ASTM International (formerly the American Society for Testing and Materials) in 1999, and subsequently transferred to IEEE in 2004. With the incorporation of amendment “p” into IEEE 802.11-2012[1] (the fourth revision of the base standard), the IEEE 802.11p Task Group completed work to develop and test the technology,[2] ensuring it was sufficiently robust to meet the needs of the high-speed surface transportation environment.

The term “DSRC Service” was coined by the FCC to represent the allocation within Title 47 of the U.S. Code. In this report, we use the acronym to describe the communications as well as the

[1] IEEE 802.11-2016 was published December 14, 2016 and is available from IEEE. This update includes work through Task Group AH. This update did not change information relative to Task Group P.
[2] IEEE 802.11p Task Group is no longer active, having completed their work. The IEEE has archived their meeting information (presentations, notes, reports, etc.), which is available (as of July 26, 2019) at https://mentor.ieee.org/802.11/documents?is_dcn=dcn%2c%20title%2c%20author%20or%20affiliation&is_group=000p. The archives contain the results of testing by various organizations.

specialized requirements for secure, privacy-protected, low latency, wireless mobile data communication exchanges in both a broadcast and point-to-point operation. These requirements also allow DSRC to coexist and function in a band of the spectrum with existing primary users including satellite uplinks and Department of Defense radars. Additionally, as a V2I link, DSRC can offer transportation network-level assessments in real time to improve traffic flow and reduce crashes.[3] For additional background on DSRC and its benefits for transportation, please see *The 2015 Report to Congress, Status of the Dedicated Short-Range Communications Technology and Applications*.[4]

It is important to note that the decision to apply IEEE 802.11 for transportation safety use was the result of a comprehensive, deliberative analysis. Developers in the transportation sector were looking for a mature technology with a solid production base in order to leapfrog the development process and ensure the technology could be economically deployed once the necessary standards were complete. In addition, the IEEE 1609 standards addressing the upper layers and security are now complete and fielding of V2V, V2I and V2X has begun. Significant financial investments in IEEE 802.11-based technology have been made by transportation owners, operators, and industry.

The introduction of DSRC has also required long-standing institutional processes to change. Vehicle manufacturers have shifted production-line designs to incorporate the new technologies and security organizations have created a uniquely-tailored communications security solution for a highly-mobile environment. Transportation infrastructure owners and operators are investing in new application development for safety and system efficiency as well as changing internal operations in anticipation of the significant new "big data" that will be generated by DSRC.[5]

[3] FHWA-HRT-11-040, Crash Data Analyses for Vehicle-to-Infrastructure Communications for Safety Applications: https://www.fhwa.dot.gov/publications/research/connectedvehicles/11040/11040.pdf.
[4] U.S. Department of Transportation, "Status of the Dedicated Short-Range Communications Technology and Applications Report to Congress", July 2015, http://www.its.dot.gov/research_archives/connected_vehicle/pdf/dsrcreportcongress_final_23nov2015.pdf.
[5] A deployment map of DSRC-based V2V, V2I and V2X operations and planned installations can be found at: https://www.transportation.gov/research-technology.

2 Status of the DSRC Technology

As of mid-2017, no other packet-based wireless technology had demonstrated the proven capability to provide all of the critical attributes of DSRC needed to support trusted, cooperative communications in support of safety-related connected vehicle technologies. The DSRC technology has been tested with the safety applications in both controlled settings and in real-world naturalistic environments with hundreds of equipment vehicles as well as portable devices to emulate some of the critical “edge-cases” for cooperative ITS.

V2X communications are important to the Nation because they can provide real-time crash-avoidance alerts and warnings. V2X communications offer a significant opportunity to achieve a transformation in transportation safety, with the potential to address 83 percent of light-vehicle crashes involving unimpaired drivers.[6] They may also form a basis for introducing automated transportation into the current transportation environments.

[6] “Status of the Dedicated Short-Range Communications Technology and Applications, Report to Congress”, July 2015, p. 24.

3 Thesis Statement and Approach

3.1 Thesis Statement

This paper assesses whether rechannelization as a spectrum-sharing approach is feasible or whether and what types of impact it might have on DSRC communications and the associated safety applications that depend on it. If there is a negative effect, then proposals to reassign all V2V, V2I, and public safety related communications from their current frequencies to the top three channels of the existing band may pose significant challenges to both current deployments as well as further development of vehicle safety applications. Rechannelization may even preclude deployment of V2X safety services entirely.

3.2 Analysis Approach

For the analysis approach, this white paper begins with a technical description of what DSRC is and how safety applications use the spectrum (section 4). This paper also describes the existing transmitter masks, and considers adjacent and non-adjacent channel rejection (section 5), examines the impact of channel loading (section 6), and examines the different types of interference that may occur (section 7).

The argument against moving all the safety applications to the top three channels is based on three fundamental characteristics of any telecommunication service:

- Transmission mask (or spectral mask) of the device, which provides the ability to limit interference by containing the energy within the channel;
- Adjacent and non-adjacent channel rejection in the device receivers, which filters out what is outside of its “receive” channel; and,
- Data loading/duty cycle, which establishes a theoretical upper limit for any channel that is based on how many transmitters can be active in a local area and the amount of desired data throughput.

The analysis concludes with an evaluation of the re-channelization concept and whether this concept provides a practical alternative for spectrum sharing with DSRC, given the safety applications that will depend on it (section 8). Appendix C provides a detailed example of some of the analysis behind these conclusions.

4 The DSRC Service Channel Plan and Description

4.1 High Level Concept

The channel structure in the DSRC Service (also referred to as the "Safety Band") reflects the requirement to support the diverse needs of surface transportation communications associated with safety, system efficiency and mobility, and environmental impact (see Figure 1). Note that the band plan is designed with different power levels assigned to each channel, a Control Channel (CCH), and multiple service channels. Each channel has their own requirements for minimal latency, channel availability, and location, and time-specific information transfer between vehicles and between vehicles and infrastructure that reflect how applications are designed to access and use this spectrum.

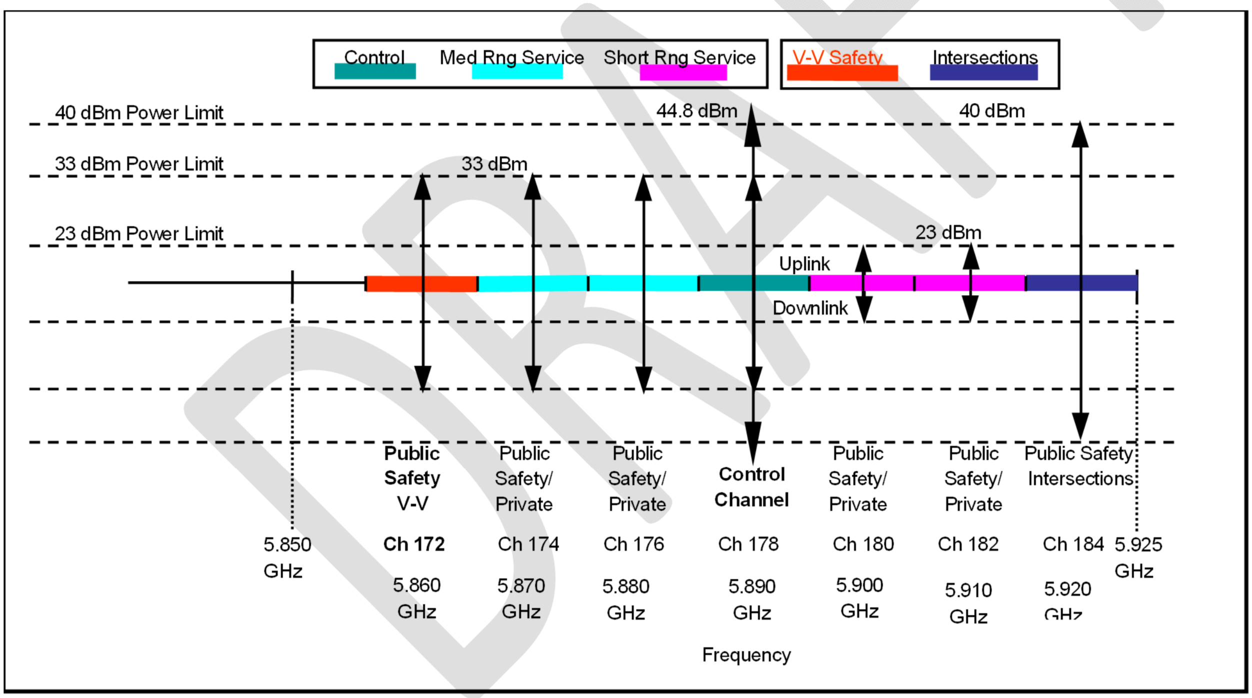

Image from FCC Report and Order as presented in U.S. DOT Report to Congress on the Status of DSRC (2015)

Figure 1. The DSRC Service Channel Plan and Power Levels for OBU and RSU

Early development and technology assessments focused on applications and how these applications could be implemented, focusing in part on how to use the available spectrum to its maximum effectiveness. The two primary approaches explored were: (1) assigning specific applications to specific channels; or (2) using a control channel (CCH) to more dynamically assign applications. As more and more applications were conceived, it became clear that the CCH concept was best able to accommodate the majority of applications now and in the future, as well as to optimize use of the available Safety Band spectrum.

Early application testing by the Crash Avoidance Metrics Partnership (CAMP) in a cooperative agreement with the National Highway Traffic Safety Administration (NHTSA) determined that broadcast safety information requires a specific channel without use of the CCH.[7] Thus, channel 172, designated by the Federal Communications Commission (FCC) for "public safety applications involving safety of life and property", will primarily broadcast the basic safety message (BSM) which predominantly supports V2V safety applications and critical V2I safety applications.[8] Channel 172 will also be used to broadcast: Signal Phase and Timing (SPaT) messages; MAP (an intersection geometry message); GNSS location correction messages (a subset of Radio Technical Commission for Maritime (RTCM) messages); and, the Traveler Information Message (TIM)/Basic Infrastructure Message (BIM), particularly at intersections.[9]

Similarly, transportation's public safety need for a longer range channel was emphasized by signal pre-emption requirements. Thus, the higher-powered V2I (HPV2I) channel was designed at the upper end of the Safety Band at Channel 184. This longer-range (up to 1000 meters) channel also supports other applications, e.g., emergency vehicles that seek to alert other vehicles and the infrastructure to their approach.[10]

Service channels separate the three (3) most highly used safety channels (172, 178, and 184), reducing the potential for adjacent channel interference while still enabling access to the service channels when the potential for interference is negligible. The ability to use all of the channels adjacent to each other is in contrast to how current-day 802.11 Wi-Fi is structured. For instance, in the 2.4 GHz band, eleven (11) channels are allocated for Wi-Fi transmissions with three of them—one channel located at each end of the band and one in the middle—predominantly in use. This band plan allows for Wi-Fi transmissions to transmit without adjacent channel interference. In an attempt to optimize use of unlicensed spectrum, IEEE is working on 802.11ax to attempt to gain greater use of this band.

As the DSRC stakeholder community requirements for utilizing all of the channels in the Safety Band began to coalesce in the late 1990s, the analyses and test results led to the channel plan adopted by the FCC in 2004. The aspects that were examined were presented in various papers over several years and merged into a single report in 2004.[11] Among the factors that went into

[7] WT Docket No. 01-90; ET Docket No. 85-95, Notification of *Ex Parte* Meetings, https://ecfsapi.fcc.gov/file/6518331690.pdf.
[8] FCC 03-324, Report and Order, paragraph 34, https://apps.fcc.gov/edocs_public/attachmatch/FCC-03-324A1.pdf.
[9] Note that "MAP" is identified only as an acronym. For the purposes of this paper it is important to understand there are multiple messages associated with crash-imminent safety to be broadcast on this channel but their specific meaning is not important. The specific types of messages are described in detail in SAE J2945/0.
[10] "Longer-range" is still considered short-range with a parameter of about 1000 meters.
[11] DSRC Band Plan Rationale, 2004, Jason Liu, TechnoCom.

the Safety Band's band plan developments were: receiver performance; multipath, co-channel, and adjacent channel interference; and, service and control channel capacity.

One of the unique approaches used in DSRC is a broadcast mode. Most packet-based networks require some form of two-way communication between transmitting stations or points: Station A transmits a packet, Station B receives it, and then Station B transmits an acknowledgement to Station A that the packet was received. Since DSRC is characterized as a point-to-multipoint system, using the packet acknowledgement approach could add significant message delays. Instead, experts developed a configuration that does not require an acknowledgment for some applications; thus, information is passed very quickly. This non-acknowledgment approach is of critical importance when developing safety applications for the DSRC.

Further, to ensure the information is delivered to surrounding vehicles, the channel must be very reliable and the application must assume a level of reliability and authentication capability for the data reception. Early efforts identified other users in the band and worked to quantify these other users so an understanding of the channel reliability could be developed.[12] In essence, the channel reliability is built into the applications and any added degradation to the channel will negatively impact the safety applications.

It is important to note that DSRC functions not only in this broadcast mode but also, for some applications, in a peer-to-peer mode. The peer-to-peer mode may support both long messages as well as multi-message exchanges (likely a TCP-IP based secure session) for basic operations such as security certificate refresh or software or data updates.

While never explicitly stated, the goal for DSRC is to support a host of safety applications that have somewhat different requirements but always focus on location- and time-critical transfer of information. Looking more broadly, DSRC also provides for authentication of messages so recipients are aware of the trustworthiness of information while still protecting the anonymity of users. Overall, the Safety Band's band plan reflects the requirements for minimal latency, channel availability, and location- and time-specific information transfer among vehicles and between vehicles and the infrastructure to support this highly dynamic and dense vehicle environment. The following sections offer more detail on the use of the specific channels.

4.2 Channel 172

Channel 172 has been designated primarily for high-availability of the BSM broadcast that supports low-latency (tolerating only the delay caused by radio frequency (RF) propagation) public safety applications such as collision avoidance. Based on testing, Channel 172 is not

[12] Measured Occupancy of 5850-5925 MHz and Adjacent 5-GHz Spectrum in the United States, NTIA Report 00-373, https://www.its.bldrdoc.gov/publications/download/00-373_ocr.pdf.

subject to control by the CCH (channel 178), but operates independently, allowing for broadcast of the BSM ten times per second. While the primary exchange of data is a broadcast of the vehicles' BSM, other critical data may be transferred as well; for instance, from the roadside infrastructure, and from the SPaT message.[13]

4.3 Channel 178

Channel 178 is designated the control channel (CCH). Typically used in roadside units (RSUs), it "advertises" services or applications available on service channels, directing onboard units (OBUs) to service channels where application data can be exchanged.

4.4 Channel 184

Channel 184 has been designated exclusively for high-power, high-availability, long-range public safety DSRC applications such as emergency vehicle warnings and signal preemption.

4.5 Moderate Power Service Channels—174, 176

Other than applications to increase work zone safety, many of the applications that will use these channels have not yet been well defined. Work zone injuries and deaths are tracked through the National Work Zone Safety Information Clearinghouse. In 2017, the latest year where data is available, there were 799 deaths and 37,000 injuries.[14] Work zone boundaries and lane configurations are dynamic, often changing between daily peak and non-peak travel times, and from weekday to weekend. Providing updates to vehicles about speed restrictions, lane information, or exit details can improve safety for the traveling public and personnel in the work zone, while also increasing traffic throughput. Additional applications are expected to come later for these channels. For example, in 2015, U.S. DOT announced the Connected Vehicle Pilot winners—New York City, Wyoming, and Tampa, Florida.[15] These deployments are using these and other service channels for many vehicle-to-infrastructure (V2I) safety applications that they are implementing.

4.6 Low Power Service Channels—180, 182

These lower-powered service channels are well-suited for very short range communications, and applications to take advantage of these characteristics are in development. For example, passenger cars or trucks can use these channels to exchange information to maintain spacing,

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[13] Alliance of Automobile Manufacturers presentation to the FCC, March 21, 2006, https://ecfsapi.fcc.gov/file/6518331690.pdf.

[14] National Work Zone Safety Information Clearinghouse, "National Estimates of Total and Injury Work Zone Crashes", https://www.workzonesafety.org/crash-information/work-zone-injuries-injury-property-damage-crashes/.

[15] More information on these deployments can be found at http://www.its.dot.gov/pilots/cv_pubs.htm.

allow vehicles to enter or exit platoons or groups, or safely execute more complex maneuvers and eliminate any potential conflicts. Alternatively, these channels can be used to communicate with the infrastructure while within range of an RSU. As noted above, these service channels are expected to see use during the deployment of the Connected Vehicle Pilots deployments.

4.7 20 MHz Channels—175, 181

In developing the Safety band plan, the FCC allowed for potential use of wider, 20 MHz channels. However, analysis showed that 10 MHz channels are most effective in a high-speed, highly mobile environment. Issues with broader channels operating in the mobile environment of surface transportation include increased multipath susceptibility, and reduced range with similar power to 10 MHz channels. Some of these issues were highlighted in a presentation to the IEEE Tiger Team in 2014.[16] As a result, the 20 MHz channel concept and supporting device configurations have not seen much development or testing to date, but may be available for use with additional developments that address these constraints.

[16] Arnold, Jim. “DSRC Band Plan Rationale”, Presentation to IEEE 802.11 Regulatory Subcommittee, October 3, 2015, https://mentor.ieee.org/802.11/dcn/14/11-14-1335-01-0reg-dsrc-band-plan-rationale.

5 Factors Influencing Operations in a 10 MHz Channel

5.1 Transmitter Mask

As noted in Table 1, channels in the Safety Band use several power levels. These correspond to different transmitter classes (A, B, C, D) and to different power levels, requiring different transmitter masks. Sound spectrum management requires users to use only the power necessary to accomplish the communication task. Thus, the multiple masks allow users the flexibility to select the needed power but still ensure that power into adjacent channels is limited by the transmitter mask.[17] Figure 2 illustrates the different transmitter masks that support each class.

As seen in Figure 2, for DSRC, the dBr is dB *relative* to the power allowed for the specific class of transmitter. For example, the Class C transmitter is allowed up to 33 dBm of power at the output of the transmitter. In this scenario the, 0 dBr is referenced to the 33 dBm of the allowed Effective Isotropic Radiated Power (EIRP) for the transmitter.[18]

As noted above, the power for the transmitter mask is at the output of the transmitter and does not necessarily correspond to the power associated with a specific channel. Table 1 lists channels and the corresponding transmitter masks based on existing work supporting the SAE J2945 set of standards.[19]

[17] Note that Class A transmitters are not used in the Safety Band.

[18] EIRP is defined by the Institute of Electrical and Electronics Engineers (IEEE) as the amount of power radiated from a theoretical point source.

[19] SAE J2945 development consists of a /0, /1, /2. /4, and /9 with more under consideration. As noted, SAE J2945/1 applies to channel Vehicle to Vehicle communications (currently planned for Channel 172) and utilizes a Class C transmitter mask.

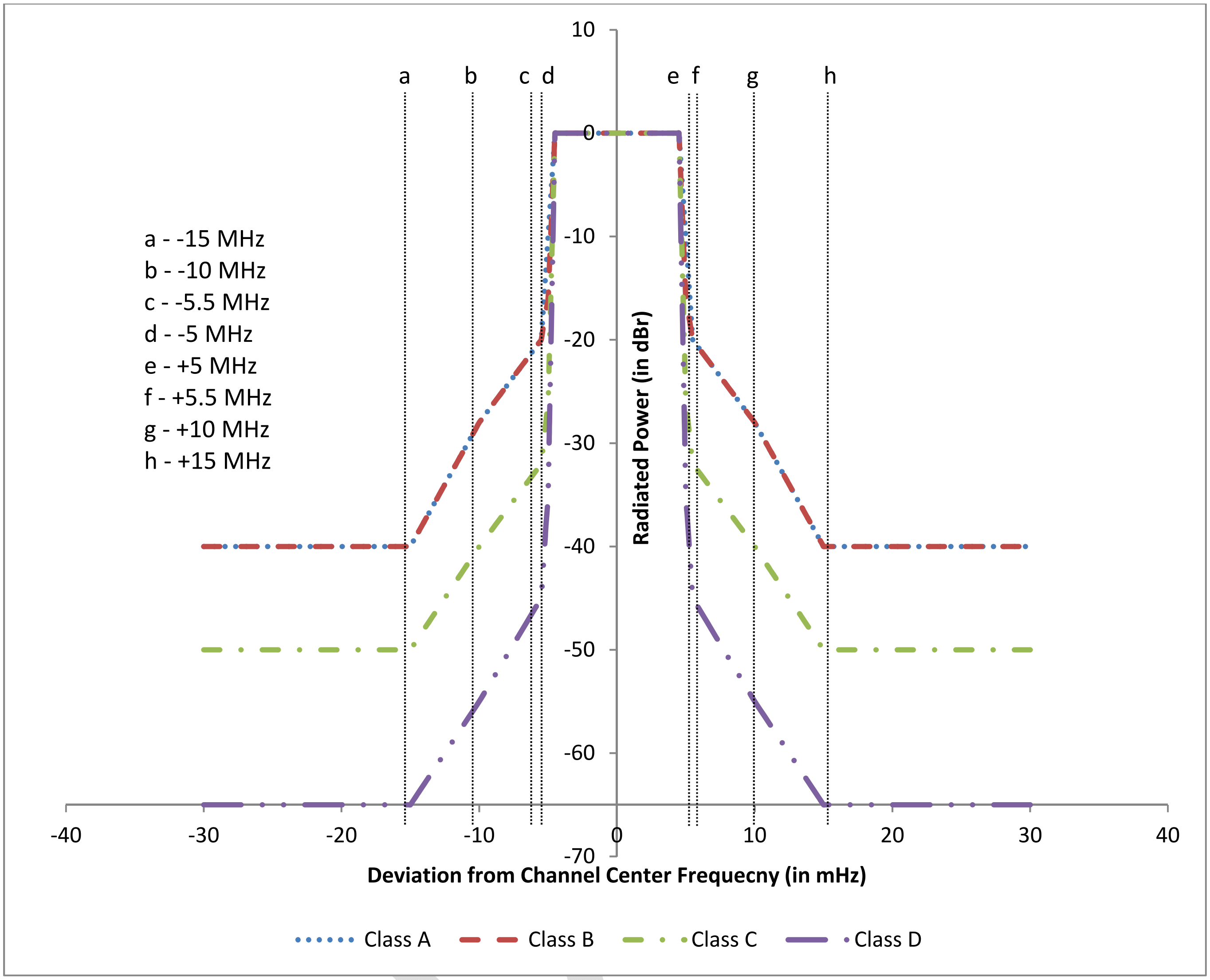

Image from U.S. DOT

Figure 2. Transmitter Masks by Transmitter Class[20]

[20] Class A and Class B transmitter masks appear to overlap in the figure but the initial slopes are slightly different.

Table 1. Channel with Corresponding Power and Transmitter Class

Channel	Power	Transmitter Class
172	33.0 dBm	Class C
174	33.0 dBm	Class C
176	33.0 dBm	Class C
178	44.8 dBm	Class D
180	23.0 dBm	Class B
182	23.0 dBm	Class B
184	40.0 dBm	Class D

As the transmitter mask diagram in Figure 2 illustrates, there is not a sharp cutoff of power at the edge of the channel; some energy will extend outside the intended transmit channel. Figure 3 illustrates the channel structure and allowable power levels for all seven DSRC channels. Given their proximity, there will be some overlap of each channel into the adjacent (ADJ) and non-adjacent (nADJ) channels. This overlap is reflected in the Safety Band's band plan design and is accommodated in the application designs.

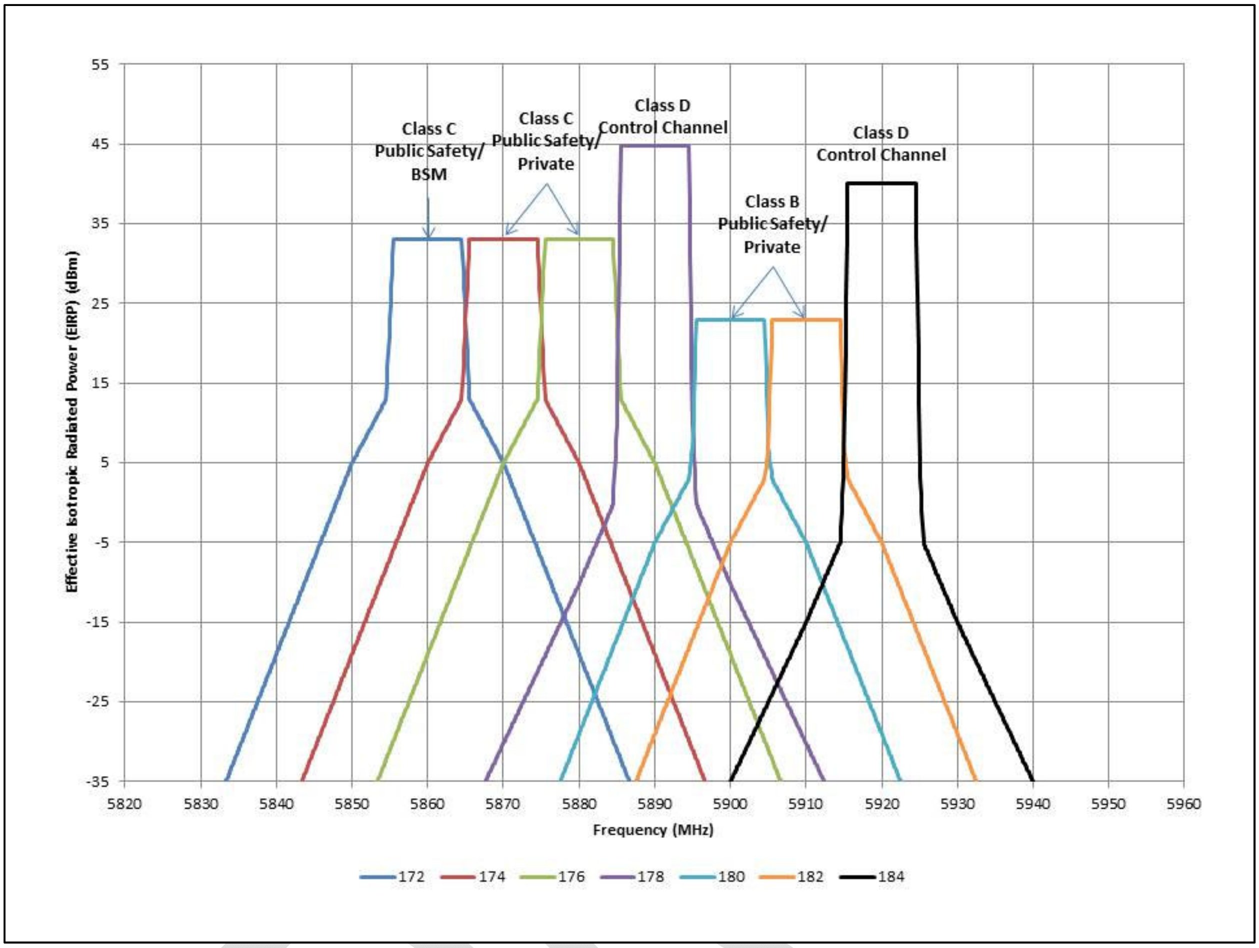

Image from U.S. DOT

Figure 3. DSRC Service Channel Plan Showing Allowable Power into Other DSRC Channels

5.2 Factors Influencing Receiver Capability

There are several factors that impact the ability of a receiver to process information coming over the airwaves. These include but are not limited to data rate, modulation, receiver bandwidth, receiver sensitivity, background noise level, and emissions from adjacent or non-adjacent channels. The significance of these factors is described in the following sections.

5.2.1 Data Rate

Data rate refers to how fast information is sent over the channel. The faster the data is sent, the more difficult it is to decode. A good analogy is a 30-second television advertisement that intelligibly describes a product for 25 seconds, but ends with an unintelligible, 5-second legal disclaimer recited at breakneck speed. In order to understand the high “data rate” of the legal clause, the listener must pay close attention and eliminate distractions.

Something similar happens with data on a communication channel. Receivers listen to the channel and detect minor changes and fluctuations (the modulations) in the signal. These changes represent the encoded data. As the data rate increases, the changes come more rapidly and are more difficult to discern. Thus, higher data rates need more significant signal changes to be detected or they can only be detected at shorter ranges. Similarly, as data rates increase, error rates also increase; think again of the television advertisement example.

For communication systems, including DSRC, higher data rates are achieved through more complex modulation schemes and more encoding, as described in the next section. At present, to ensure a reliable communications channel, 6 Mb/s has been specified in SAE J2945/1 and corresponds to Quadrature Phase Shift Keying (QPSK) with 1/2 rate encoding. This was chosen in order to optimize all the factors associated with DSRC.

5.2.2 Modulation

Modulation refers to varying the amplitude, frequency, or phase of a fixed carrier with the information that needs to be transmitted. The IEEE 802.11-2012 standard supports several different modulation schemes.[21] A simple modulation technique is Binary Phase Shift Keying (BPSK) with 1/2 rate encoding, while a more complex scheme is 64 Quadrature Amplitude Modulation (QAM) with a 3/4 rate encoding. Understanding the different modulation schemes is not important; but, what is important is that as the *modulation* complexity increases to carry more data, it becomes more difficult to *demodulate* the incoming information.

Table 2 compares each modulation technique with receiver sensitivity and data rate. Transmitter power is kept constant in order to highlight the reduced receiver sensitivity. As the modulation becomes more complex, the receiver needs a larger signal-to-noise ratio to demodulate the data. This is indicated by the reduction in receiver sensitivity as the modulation becomes more complex. In other words, as the data rate and modulation complexity increases, the range at which a receiver can decode the signal decreases. Table 2 illustrates the progression of simple to complex (BPSK to 64 QAM) and the corresponding slow to fast data rate (3 Mb/s to 27 Mb/s). The yellow highlighted row identifies the modulation used for BSMs using DSRC. This choice is a trade-off between range and data rate. Other techniques are likely to use different modulations that are tailored to their specific operational characteristics.

[21] See page 1590 of IEEE 802.11–2012.

Table 2. Modulation vs. Received Signal Thresholds

Modulation and Code Rate	Sensitivity (dBm)	Data Rate (Mb/s)
BPSK 1/2	-95	3.0
BPSK 3/4	-94	4.5
QPSK 1/2	-92	6.0
QPSK 3/4	-90	9.0
16 QAM 1/2	-87	12.0
16 QAM 3/4	-83	18.0
64 QAM 2/3	-79	24.0
64 QAM 3/4	-78	27.0

5.2.3 Receiver Sensitivity

Receiver sensitivity is a function of bandwidth and the noise figure of the receiver. (Any time electronic components are added to an electrical circuit, noise is also added—this is known as the “noise figure”.) There is also a constant background noise in any environment. In the quietest spectrum, this would equate to a noise floor of about -174 dBm/Hz. A detailed component design can reduce the overall noise, but it cannot be fully eliminated.

The DSRC Service channel plan works with a 10 MHz channel bandwidth that will have, assuming a perfect receiver, a theoretical noise floor of about -104 dBm for any of the 10 MHz channels.[22] During the IEEE Tiger Team deliberations, Toyota and DENSO presented information that, to date, best represents the reality of DSRC receivers with a sensitivity of better than -90 dBm in a relatively quiet environment.[23] This is one of several design criteria established in SAE J2945/1.[24]

In addition to minimum receiver sensitivity, maximum transmit power and modulation parameters work together as operational parameters that ensure vehicles within a 300 meter range will be able to communicate with one another (i.e., can “hear each other”) and to the infrastructure (V2V and V2I) when broadcasting the BSMs.[25] This ability to “hear each other” is a critical capability that allows for “cooperative” applications—which is different from simply being connected.

[22] Absolute noise floor for a 10 MHz channel is -174 dBm/Hz*10^7 Hz=-174 dBm/Hz+70 dB Hz = -104 dBm.
[23] DSRC PER versus RSS Profiles, IEEE 802.11-1260r0.
[24] SAE J2945, Table 21.
[25] Note that SAE J2945/1 applies to channel 172 only. Thus, the description provided here applies to vehicle to vehicle communications. Vehicle to Infrastructure communications will have different criteria.

The results of Toyota's and DENSO's tests are reproduced in Figures 4 and Figure 5, and are fundamental to understanding the channel use. The plots describe packet error rate (PER) versus received signal strength (RSS) and clearly show that error increases at RSS below -90 dBm with a modulation of QPSK 1/2 rate encoding. Notably, these results align with the standards: IEEE 802.11-2012 specifies a packet error rate (PER) of 10 percent (which is reached at -92dBm), and SAE J2945/1 specifies a receiver sensitivity of better than -92dBm for QPSK 1/2 modulation.[26,27]

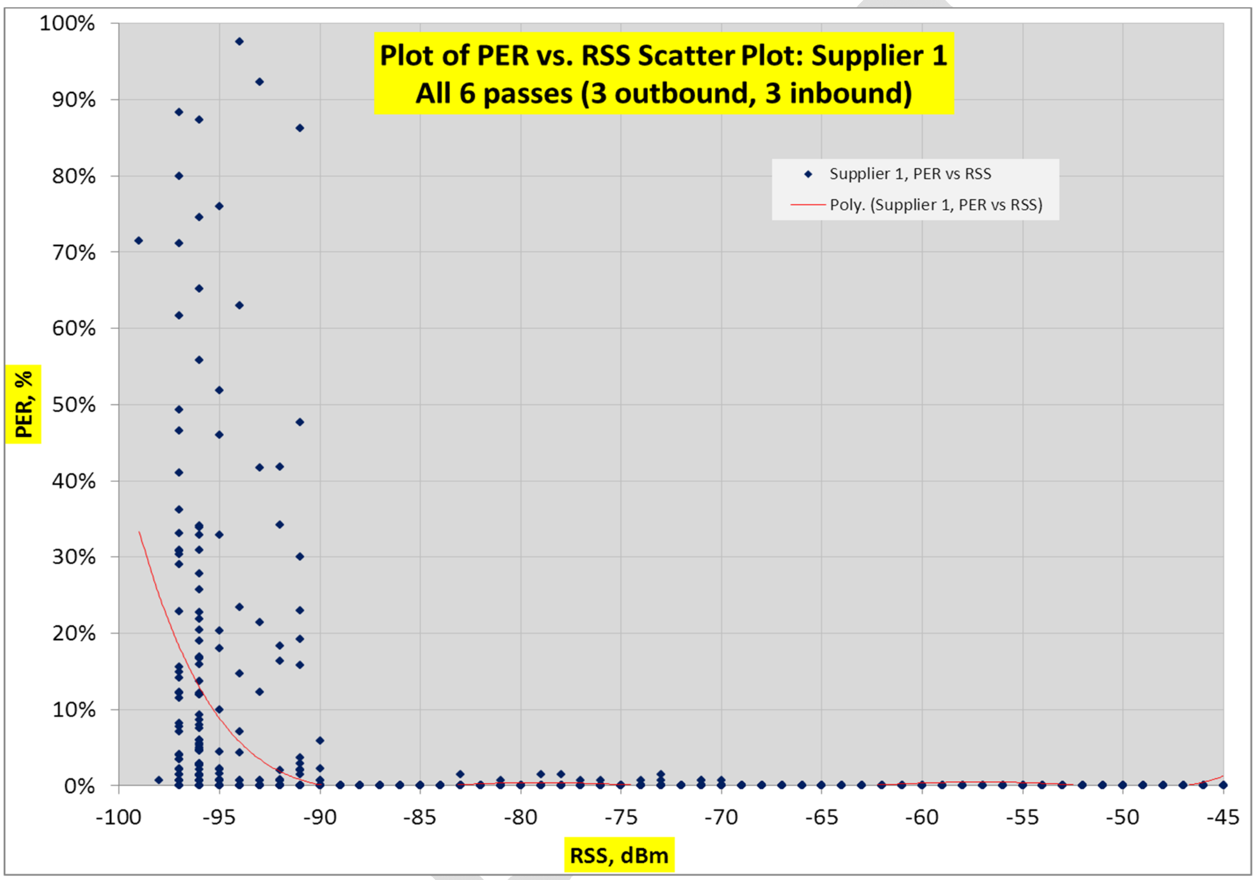

Image from Crash Avoidance Metrics Partnership (CAMP) IEEE Tiger Team presentation (2014)

Figure 4. PER vs. RSS Scatter Plot, Supplier 1

[26] SAE J2945, Table 21.

[27] It should be noted that at least one DSRC device manufacturer is considering the use of DSRC as radar to enhance operation for users when non-DSRC equipped vehicles are nearby. While not as rich in cooperative data, the technique can provide usable information for some collision avoidance applications. Reflected energy is a function of the size and reflectivity of the object doing the reflecting. A reasonable assessment of use as a radar indicates that the receivers are more sensitive, but there is little other than anecdotal data to go on as of this writing.

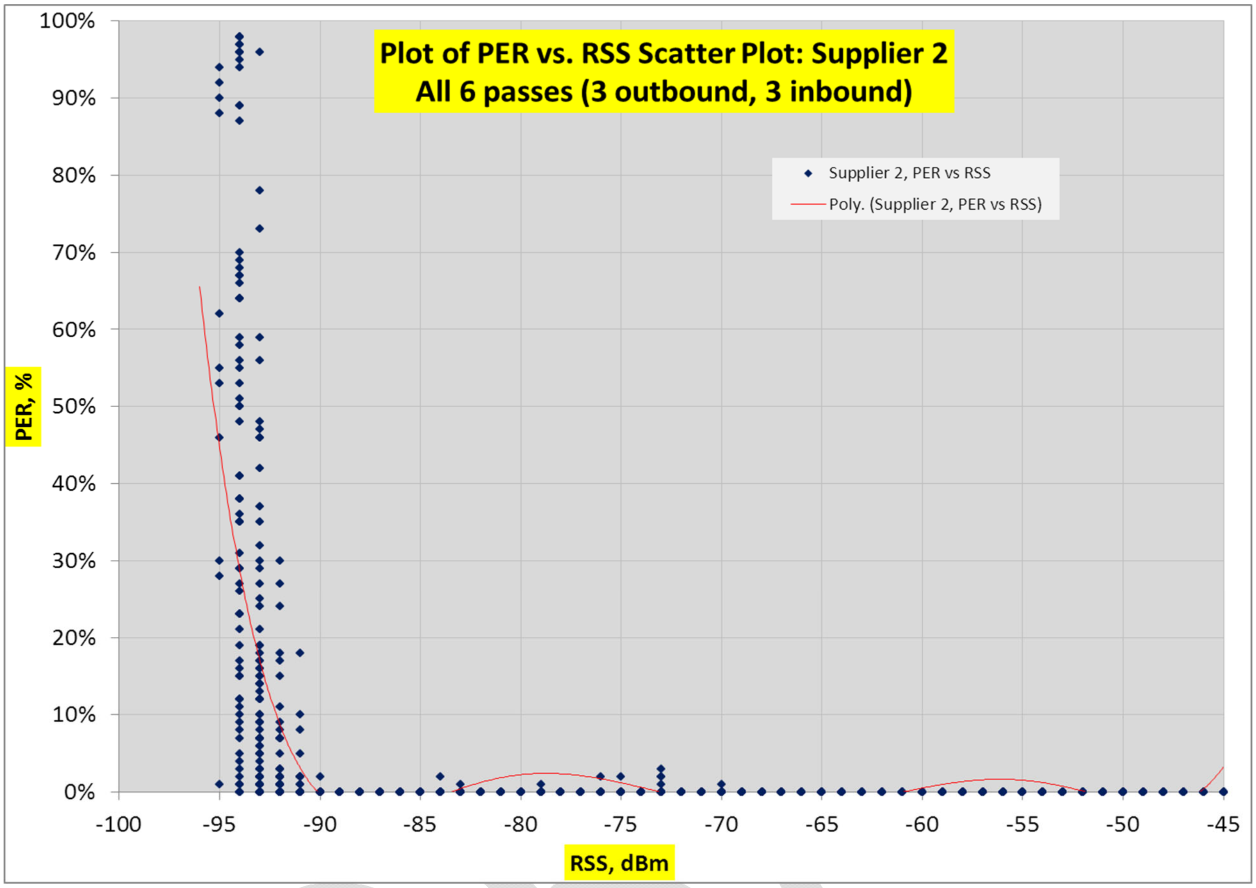

Image from Crash Avoidance Metrics Partnership (CAMP) IEEE Tiger Team presentation (2014)

Figure 5. PER vs. RSS Scatter Plot, Supplier 2

5.3 Adjacent and Non-Adjacent Channel Rejection

In Section 3 of this paper, the phrase “adjacent channel rejection” (ACR) was introduced. An understanding of receiver performance is necessary to understand the impact of ACR. Radio receivers accept input (RF energy) over a range of frequencies. In the case of DSRC, the “pass band”—the frequency band over which the DSRC radio is interested in receiving—is 5850-5925 MHz. Most receivers are general purpose and are capable of detecting frequencies over a much broader range. Therefore, to limit the impact of extraneous RF energy, a DSRC receiver is fitted with “band pass filters” that attenuate unwanted frequencies.

Review of the DSRC receiver data sheets and conversations with manufacturers’ show that the band pass filters associated with DSRC units are very broad, allowing frequencies from 5700 MHz up to 6000 MHz to enter the receiver. Depending on receiver design, this frequency range can either be shifted to a much lower frequency (down converted) that is easier to work with or digitized so that a computer does the filtering. A receiver may employ either or both methods.

In either case, individual channels are filtered and then demodulated. This filtering is where the ACR is important. Simply described, energy in the adjacent channel is suppressed or rejected so that it does not impact the channel of interest. This suppression is ACR. Non-adjacent channel rejection is similar, but describes rejection of the immediate non-adjacent channel (nACR) and those channels further out. These rejection values are described in IEEE 802.11-2012 and are shown in Table 3.

Table 3. Adjacent and Non-Adjacent Channel Rejection Receiver Performance Thresholds

Modulation	Adjacent Channel Rejection (ACR) (dB)	Non-Adjacent Channel Rejection (nACR) (dB)
BPSK 1/2	28	42
BPSK 3/4	27	41
QPSK 1/2	25	39
QPSK 3/4	23	37
16 QAM 1/2	20	34
16 QAM 3/4	16	30
64 QAM 2/3	12	26
64 QAM 3/4	11	25

5.4 Summary

This section described the 10 MHz DSRC channels, identified the typical modulation schemes, and discussed the data rates. Additionally, receiver sensitivity and adjacent and non-adjacent channel rejection was introduced. As noted earlier, DSRC is based on the IEEE 802.11 standard that is also used for Wi-Fi implementation, but which is enhanced to operate in the highly dynamic surface transportation environment. With these enhancements, IEEE 802.11 offers great flexibility and low cost, but various tradeoffs must be considered. Among these is self-interference from adjacent channel use.

6 Channel Loading/Duty Cycle of the BSM Broadcast, Control, and High-Powered V2I Channels

As noted above, the three channels that have been suggested to be moved adjacent to each other include the BSM broadcast, the Control, and the High-Power V2I (HPV2I) channels. Section 6 seeks to calculate the potential duty cycle for these channels.[28]

6.1 BSM Broadcast Channel

The BSM broadcast channel is used to broadcast safety messages between moving vehicles at very high speeds. Although the channel also broadcasts SPaT, MAP data (intersection geometry), and several other safety messages from infrastructure and other travel platforms (e.g. bicycles), these applications are projected to represent less than 5 percent of data traffic. Consequently, for the purpose of this paper and calculations of duty cycle, it is assumed that the channel only carries BSM data.[29]

Estimates of BSM length from the Leesburg data set[30] indicate an average length of 315 octets (with digest) to 380 octets (with full security certificates).[31] Full certificate messages represented approximately 1 in 5 messages sent (20 percent). Table 4 provides the rough calculation for how long it takes to transmit a single BSM at 6 Mbps. The window to transmit BSMs is 100 milliseconds. Thus, if the length of a BSM is 437 microseconds then a 100 millisecond window will allow 229 BSMs to be transmitted (100 milliseconds divided by 437 microseconds = 228.8). This is an estimate of the number of BSMs the channel can support before congestion mitigation begins.[32]

Given the 300-meter range of a BSM, this translates to a potential density of 229 vehicles within a 300 meter radius before any sort of congestion mitigation techniques are used, as described in SAE J2945/1. This density, as well as higher densities, can be found in many urban settings and even a few rural areas at rush hour or during special events. Based on this calculation, we can assume that the BSM broadcast channel will be heavily used in many locations, having close

[28] Duty cycle is the percent of time a repetitive process is active, in this case, transmitting within the channel.
[29] It is expected that some 95 percent of the BSM broadcast channel will be occupied by BSM data.
[30] The files in this data environment were produced using the Vehicle Awareness Device (VAD) installed on one test vehicle over a two-month period. This data environment consists of data collected on 143 trips taken during the period from October 18, 2012 through December 19, 2012. Activities included numerous repetitive trips by one individual in and around Leesburg, Virginia and one long road trip from Ann Arbor, Michigan to Leesburg, Virginia by way of eastern Indiana. More information can be found at: https://catalog.data.gov/dataset/intelligent-transportation-systems-research-data-exchange-vehicle-data-from-leesburg-va-ve-dbcef.
[31] An octet is an 8-bit byte.
[32] "Congestion mitigation" is defined in SAE J2945.

to a 100 percent duty cycle for the channel. To be clear, in the context used here, duty cycle refers to the amount of time the channel is in use as opposed to the more typical meaning of individual transmit duration for a given transmitter.

Table 4. Length of Basic Safety Message (BSM) in Microseconds

Message Type	BSM Bits	Data Rate (Mbps)	Length of BSM (µsec)	Percentage (%)
Digest	315 octets * 8 bits = 2520 bits	6	464 Note 1	80
Certificate	408 octets * 8 bits = 3264 bits	6	592 Note 1	20
Combined			490 Note 2	

Note 1: The length of the BSM in µsec includes overhead inserted by the MAC layer of 33-65 octets but does not include interframe spacing and other information.

Note 2: The combined weighted average length of a BSM is 80 percent of 464 µsec plus 20 percent of 592 µsec, or 490 µsec.

6.2 Control Channel (CCH)

The CCH is established to be the arbitrator for the service channels. As originally conceived, each roadside unit (RSU) will broadcast service announcements 10 times a second; these service announcements tell OBUs what services are available in the service channels from that RSU. The more services available, the longer the CCH message will be. Since all devices are required to listen on the CCH at the beginning of every CCH transmission (the beginning of every 100 msec time interval), there can be assumed to be a quiet time on the other channels (with the exceptions of the BSM broadcast and HPV2I public safety channels). Estimates suggest the length of a single CCH service announcement is approximately 1 msec. With multiple service announcements, one source identified this as up to 40 msec.[33] It is not clear at this point how many services will be advertised on the control channel, but that number is likely to grow over time as the system and its uses evolve. Thus, for this analysis, a maximum 40 percent duty cycle is estimated.

6.3 High-Power Vehicle to Infrastructure Channel (HPV2I)

The HPV2I channel will be used to broadcast emergency vehicle (EV) warnings, EV signal pre-emption, EV routing, and incident responder pre-arrival guidance. These types of messages and the corresponding message sizes are estimates based on current development efforts. While additional public safety messages are expected in this channel, ongoing research will need to be completed prior

[33] Li Y. (2012). An Overview of the DSRC/WAVE Technology. In: Zhang X., Qiao D. (eds) Quality, Reliability, Security and Robustness in Heterogeneous Networks. QShine 2010. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, vol 74. Springer, Berlin, Heidelberg.

to estimating their impact on channel occupancy. Table 5 shows the calculation used to determine loading on the HPV2I channel.

Table 5. Channel Loading, High-Power V2I (HPV2I)

Message	Size Note A			Interframe Packet Spacing (µsec) Note B	Total Message Length (µsec)	Transmission Interval	Average % of 100 msec occupied
	Octets	Bits	µsec				
Emergency Vehicle Approach Warning	936	7488	1296	260	1556	1 / sec	0.156%
Emergency Vehicle Pre-emption	1316	10528	1800	260	2060	2 / sec	0.412%
Emergency Vehicle Routing	1752	14016	2384	260	2644	5 / sec	1.322%
Mayday Relay	1192	9536	1640	260	1900	5 / sec	0.950%
Incident Pre-Arrival Guidance	1752	14016	2384	260	2644	10 / sec	2.644%
Percentage of time High-Power V2I channel is occupied							5.484%

Note A: Message sizes based on input from industry and deployers.

Note B: See SAE J2945/1 for further definition on Arbitration Inter-Frame Space Number (AIFSN) and interframe packet spacing parameters.

6.4 Summary

Based on this analysis, Table 6 summarizes the channel loading developed in Section 6:

Table 6. Channel Occupancy

Channel	Percentage of time in use
BSM Broadcast Channel	100.0 percent
Control Channel	40.0 percent
High Power V2I Channel	5.4 percent

7 Interference Analysis

7.1 Types of Interference

The U.S. DOT is concerned with three types of radio interference that can disrupt DSRC communications:

- First: The increase in ambient noise level due to unlicensed devices transmitting in or near the DSRC Service band.
- Second: The Clear Channel Assessment (CCA) mechanism causes a radio to suppress and not send its message when it detects energy from another source already on the channel. Put differently, a transceiver listens to the channel and if it detects activity on that channel (whether a legitimate message or interference from another channel), it will not transmit until it detects a clear channel. As a result, messages are not received because they are *suppressed*, or prevented from being transmitted in the first place.
- Third: When two or more message packets from different sources are received simultaneously, the receiver may accurately interpret only one, or likely none, of the incoming message packets. As a result of this "packet collision", the messages are not received and considered lost.

The U.S. DOT considers that a secondary or unlicensed user that prevents a primary user from transmitting due to transmission suppression is interfering with the primary user's ability to communicate, which is a violation of the FCC Part 15 rules for secondary or unlicensed users.

Under the present analysis, the first interference type—an increase in the ambient noise—is beyond the scope of this paper and will not be discussed further. This analysis focuses on:

- The variation in options for re-channelization (Section 7.2).
- Calculations for interference that the three DSRC channels will have on each other based on a device's signal strength and physical distance (Section 7.3).
- Calculations for ranges at which energy from one channel will cause suppression of a transmitting radio's message (Section 7.4).
- Calculations applied in a real-world example to understand the implications (Section 7.5).
- Laboratory measurements to establish the minimum signal level at which a DSRC receiver will receive BSM data from a DSRC transmitter; and then measurements at which the signal interference causes an excessive Packet Error Rate (Section 7.6).
- Calculations on the signal levels and their impact on the physical distances a transmitter and receiver need to be in order to be heard (Section 7.7).

7.2 Proposed Re-channelization

Several organizations within the Unlicensed National Information Infrastructure (U-NII) industry have suggested that the DSRC community move the traffic on channels 172 (broadcast BSM Channel), 178 (CCH), and 184 (High-Power V2I channel) adjacent to each other in the upper portion of the DSRC Service band. This concept puts the three channels next to each other as channels 180, 182, and 184.

The use of the remaining 40 MHz of spectrum in the lower portion of the DSRC Service band is unclear, but it appears that the U-NII industry suggests creating two 20 MHz channels out of the four 10 MHz channels that would remain in the lower portion of the DSRC Service band. These newly created 20 MHz channels would allow for DSRC traffic, but would be expected to share the channels with U-NII traffic. The proponents of this approach have not specified the form of this sharing and no specific channel reassignments have been proposed. Table 7 reflects the possible channel configurations for BSM broadcast, CCH and HPV2I. Figure 10 illustrates the results of each configuration.

Table 7. Options for Placing BSM, CCH, and HPV2I Channels in Upper 30 MHz of the DSRC Service Band

Option	Channel 180	Channel 182	Channel 184
	5895-5905 MHz	5905-5915 MHz	5915-5925 MHz
1	BSM broadcast	CCH	High-power V2I
2	BSM broadcast	High-power V2I	CCH
3	CCH	High-power V2I	BSM broadcast
4	CCH	BSM broadcast	High-power V2I
5	High-power V2I	CCH	BSM broadcast
6	High-power V2I	BSM broadcast	CCH

Figure 6 illustrates the current and proposed channel assignments for both the DSRC Service and U-NII-3 and proposed U-NII-4 bands in the vicinity of the 5900 MHz frequency.

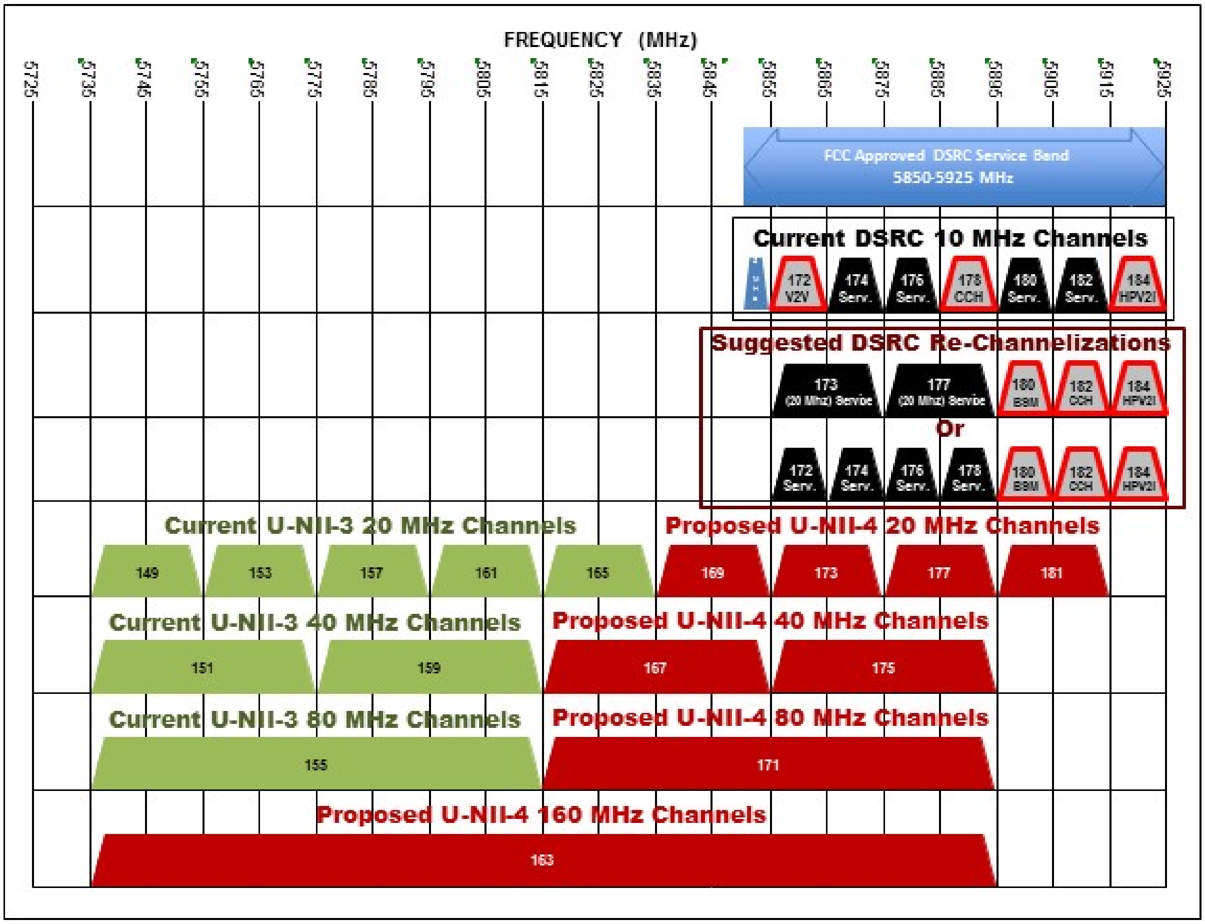

Image from U.S. DOT

Figure 6. Comparison of Existing, Proposed, and Suggested DSRC and U-NII Channels

7.3 Interference vs. Range

As noted previously, DSRC receiver sensitivity is typically better than -90 dBm.[34] The first analysis is to look at the interference that each channel's transmissions will have on the adjacent and next adjacent channels. The Undisturbed Field Model (UFM) is used to generate the propagation loss versus separation distance.[35] Figures 7 to 9 on the following pages illustrate:

[34] SAE J2945 identifies a receiver minimum sensitivity of -92 dBm.

[35] N. DeMinco, "Propagation Loss Prediction Considerations for Close-in Distances and Low-Antenna Height Applications", NTIA Report TR-07-449, July 2007.

- The transmission power of the BSM channel and its effects on the CCH and HPV2I in order to identify the distance at which the BSM broadcast channel will interfere with the adjacent channel (CCH) and the next adjacent channel (HPV2I);
- The CCH transmissions and effects on the BSM channel and HPV2I; and,
- The HPV2I and its effects on the CCH and BSM channels.

The UFM uses the following parameters in the analysis:[36]

- Height of the Interference Source - h_i = 1.5m[37]
- Height of the transmitting antenna for the DSRC device - h_t=1.5m
- Height of the receiving antenna for the DSRC device - h_r=1.5m
- BSM broadcast channel transmitter EIRP level of 33 dBm
- CCH transmitter EIRP level of 44.8 dBm
- HPV2I Channel transmitter EIRP level of 40 dBm
- S/I of 14 dB
- Channel bandwidth 10 MHz using typical DSRC receiver characteristics defined in IEEE 802.11-2012; notably the enhanced ACR and nACR identified in Table 3
- Transmitter masks associated with Class C and D transmitters
- QPSK ½ encoding modulation for a 6 Mbps transmission

While the UFM provides the final data for plotting, there are a number of other factors that go into it, such as transmit and receive antennas and frequency dependent rejection, etc. Appendix C provides details on how this model is used.

Figure 7 provides curves that illustrate the distance at which the BSM broadcast channel will interfere with the adjacent channel (red dotted curve) and the next adjacent channel (black dash-dot curve). Similar curves are provided in Figures 8 and 9.

[36] While the Undisturbed Field Model generated the figure, other models were used as input. For example, a frequency dependent rejection (FDR) model was used to compute the rejection due to off tuning the interference source with respect to the victim receiver. System parameters as well as S/I and S/N also play a factor in the total computation.

[37] In this model, 1.5 meters was used as height of the interference source. This is the typical height of the vehicle antenna. While infrastructure based systems will almost certainly be located higher, this height provides a best case scenario.

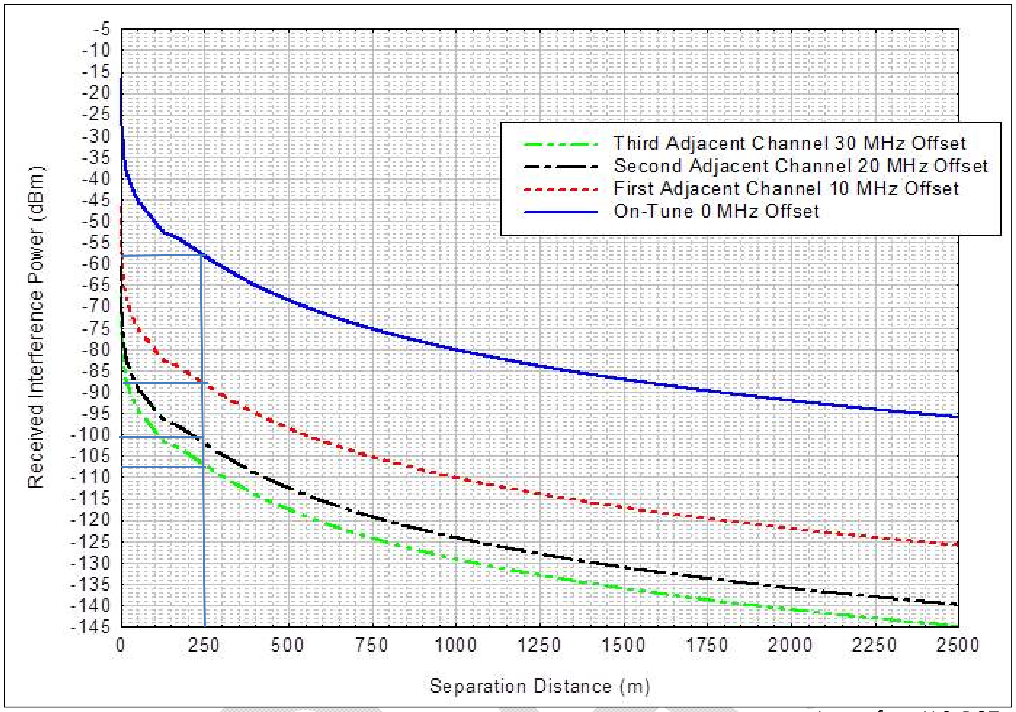

Image from U.S. DOT

Figure 7. Interference from BSM Broadcast Channel 172 on Nearby Channels

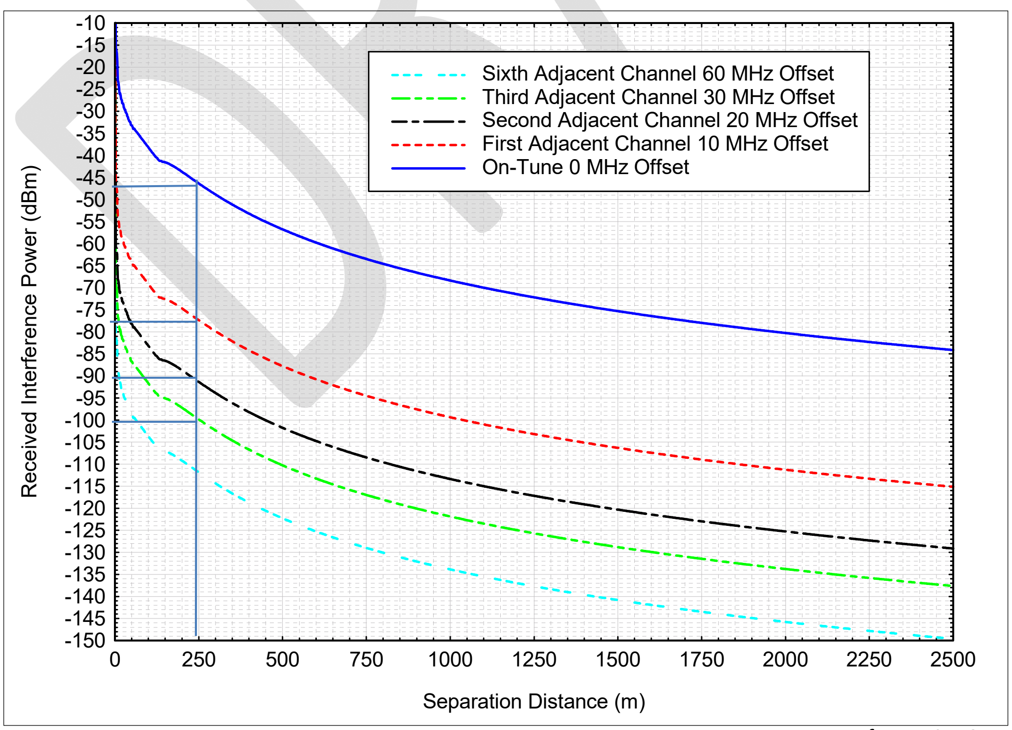

Image from U.S. DOT

Figure 8. Interference from CCH Channel 178 on Nearby Channels

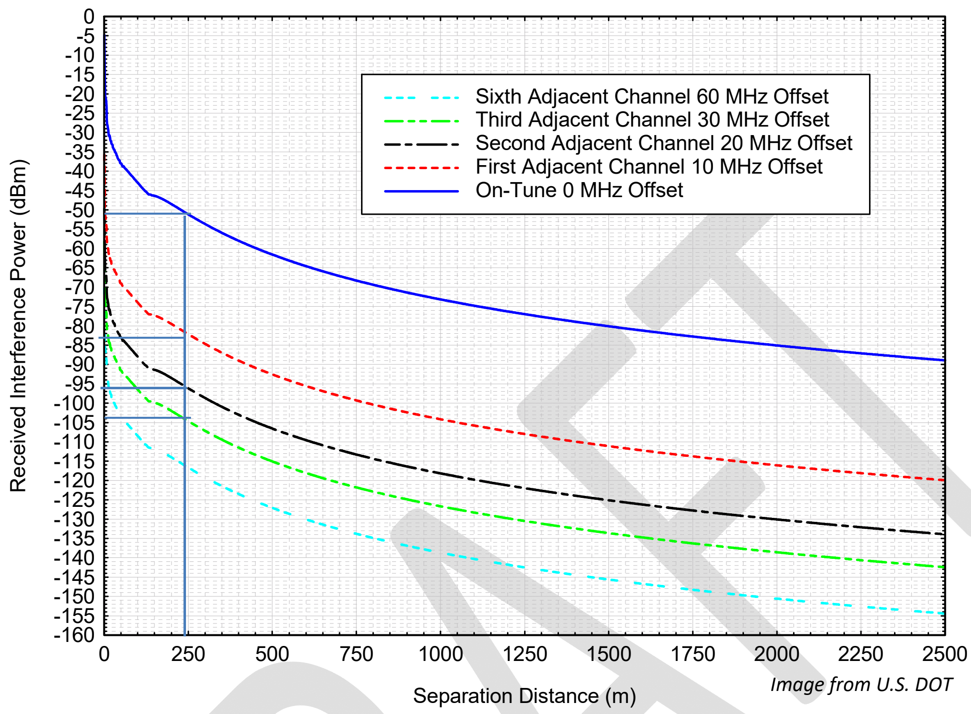

Figure 9. Interference from High-Power V2I Channel 184 to Nearby Channels

Interpreting these curves provides an interference range for each of the channels; see Table 8. An example will help illustrate how to interpret these plots. Using Figure 7, the signal level seen by the first adjacent channel from the BSM channel at 250 meters would be about -88 dBm. Looking at Figure 8, the first adjacent channel would see -77 dBm at 250 meters.[38] For Figure 9, the signal level would be -82 dBm at 250 meters for the first adjacent channel. Note that the Clear Channel Assessment (CCA) on the device will identify any noise that is 20 dB above the noise floor and instruct the device not to transmit. If the noise floor is -92dBm, the values in Table 8 identifies the distances at which devices have to be separated from each other in order to transmit. Note that some of the distances are greater than the 300 m for which the V2V and V2I applications are configured. The next section provides additional detail on CCA and how it works.

[38] Note that in Figures 8 and 9, an additional curve is provided for the sixth adjacent channel. This was added after the appendix was developed and adds some perspective on self-interference for DSRC when operating on the HPVI channel and the BSM channel simultaneously.

Table 8. Interference Range Based on Minimum Received Signal Level (For receiver sensitivity of -95 dBm.)

Channel	BSM broadcast	CCH	V2I
Adjacent	400 m	750 m	600 m
2nd Adjacent	100 m	325 m	225 m

7.4 Clear Channel Assessment Transmission Suppression

Table 8 provides the ranges at which energy from one channel can be seen at a receiver in the adjacent or non-adjacent channel, assuming -95 dBm sensitivity. In this case, this range is where the CCA mechanism causes the radio to suppress and not send a message because it detects energy or a carrier from another source already on the channel and considers the channel in use. How these ranges compare under the six possible re-channelization options is depicted in Figure 10.

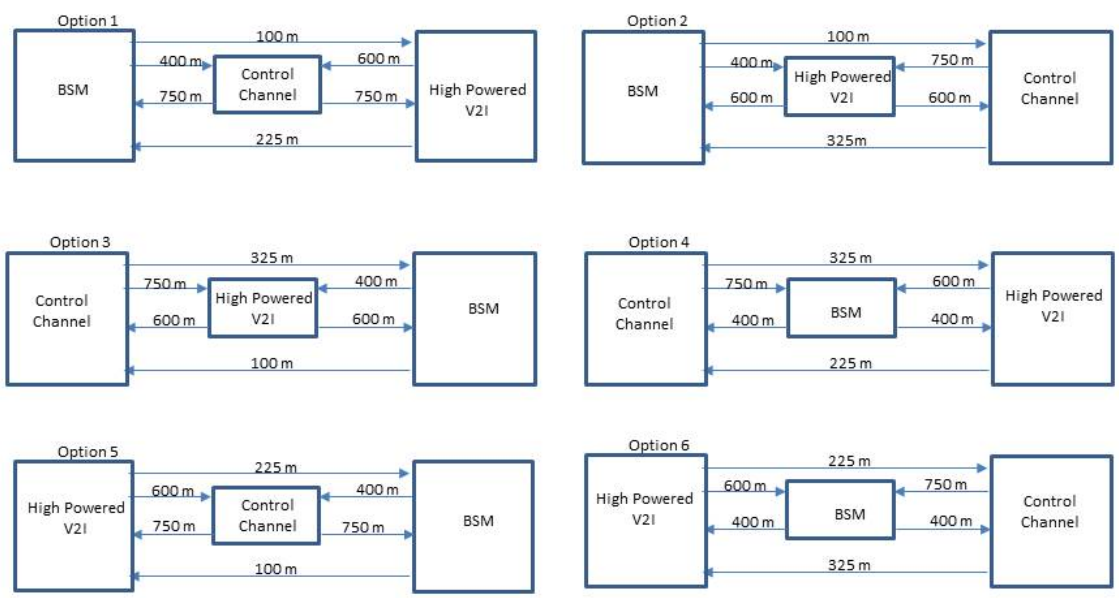

Image from U.S. DOT

Figure 10. Interference Range from CCA for Six Options in Upper DSRC Service Band Placement

7.5 Real World Scenario

A real world example may assist in illustrating the complexities of fielding DSRC deployments as well as understanding the potential for self-interference. The New York City Department of

Transportation (NYCDOT) was recently awarded a Connected Vehicle Pilot Deployment contract by the U.S. DOT.[39] In April 2016, NYCDOT released the Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations (ConOps).[40]

Within its ConOps, NYCDOT describes the use of numerous safety applications as well as their intent to deploy approximately 300 roadside units (RSUs) in strategic areas in the city. One such area is in Manhattan along 1st and 2nd Avenues. Figure 11 shows a typical location of four RSUs installed in the 1st and 2nd Avenue corridors in the vicinity of 14th and 15th Streets.

Images from U.S. DOT and New York City CV Pilot Site Concept of Operations

Figure 11. Typical Location of RSUs along the 1st and 2nd Avenue Corridor, New York City

7.5.1 Area Description

Both 1st and 2nd Avenues are one-way thoroughfares, traveling in opposite directions. They are each four lanes wide with designated turn lanes, crosswalks, and street side parking. 14th Street is a two-way street with two lanes in each direction and street side parking on both sides. 15th Street is a one-way street with two lanes running westbound, as well as street side parking on both sides.

The intersections along the two avenues are roughly 300 feet (91 meters) apart while the distance along the streets between 1st and 2nd Avenues is roughly 800 feet (243 meters). Deployment scenarios are left to the local jurisdiction (in this case, NYCDOT), since there are various ways to achieve a deployment to create the appropriate communication zones. For this

[39] New York City was one of three pilot sites selected by U.S. DOT; the others were Tampa, FL and the I-80 corridor in Wyoming. For more information on the Connected Vehicle Pilot Deployment Program, see the ITS Joint Program Office website at http://www.its.dot.gov/pilots/

[40] Connected Vehicle Pilot Deployment Program Phase 1, Concept of Operations, https://rosap.ntl.bts.gov/view/dot/30881.

white paper, a simple deployment is used to examine power levels and illustrate a simple adjacent channel interference scenario.

7.5.2 Assumptions and Reality

As done previously, several assumptions are made in order to simplify the analysis. These assumptions are detailed in table 9 along with a narrative description of how DSRC is to be implemented.

Table 9. Assumptions and Operational Descriptions of Deployed DSRC

Operational Implementation	Assumption / Reason
The CCH uses CCA as do all DSRC Channels	The CCH does not use CCA / Simplifies the analysis
While EIRP may be limited, it is expected that RSUs will have overlapping coverage.	EIRP will be limited so RSU does not provide coverage beyond next intersection / Dealing with a single intersection is difficult, overlapping intersections will require a more in depth analysis and could be done with additional time and resources.
There are two radios within the vehicle and two within the roadside. One is always tuned to the BSM broadcast channel while the other is tuned to the CCH or a service channel at any given time.	
The HPV2I is not used full time since the radios must tune to the control channel for some period of time to listen for service announcements. The period for which they must listen to the control channel is 40 milliseconds	
OBUs use CCA	
Vehicles can operate bumper-to-bumper and will vary in size	Vehicles occupy an average of 20 linear feet (6 meters) of roadway. This offers a typical vehicle spacing commonly used in analysis.
RSUs may use directional antennas that limit reception to vehicles approaching the intersection or moving away from the intersection. Specific implementation will be dependent on requirements for the specific intersection.	RSUs will only receive signals from approaching vehicles only / Simplifies the analysis

7.5.3 Channel Power Levels

7.5.3.1 Control Channel - CCH

The RSU CCH is authorized to transmit at 44.8 dBm; however, efficient spectrum management would dictate use of a lower transmission power sufficient to ensure reliable data exchange within a defined communication zone. In the case of the DSRC control channel used by the RSU, the intent is to provide information from the RSU to the DSRC OBU in the vicinity of each intersection. Along 1st Avenue and between 14th and 15th streets, the range of the RSU should be limited to the distance between the intersections or 300 feet/91 m, per DOT assumptions.

Using a very simple free space path loss, this would indicate that power out should be some 49 dB below the +44.8 dBm allowed for an S/I of 0 dB. Noting that the measured data identified a 13.6 dB S/I requirement (see Figure 16 and Table 11), this would lead to a power out of 9.4 dBm. This can be achieved either by reducing the power in the RSU transmitter or attenuating the transmitted power. Along 14th or 15th Streets between 1st and 2nd Avenues, the range should be greater—something on the order of 800 feet/243 meters—indicating a power of 13.6 dBm.[41] Table 10 provides this information in a tabular format.

Table 10. Range and Power Levels for DSRC CCH Transmission at Roadway Intersections

Intersection	Range	Power
1st Avenue and 14th Street along 1st Avenue	300 feet/91 m	9.4 dBm
1st Avenue and 14th Street along 14th Street	800 feet/243 m	13.6 dBm
1st Avenue and 15th Street along 1st Avenue	300 feet/91 m	9.4 dBm
1st Avenue and 15th Street along 15th Street	800 feet/243 m	13.6 dBm
2nd Avenue and 14th Street along 2nd Avenue	300 feet/91 m	9.4 dBm
2nd Avenue and 14th Street along 14th Street	800 feet/243 m	13.6 dBm
2nd Avenue and 15th Street along 2nd Avenue	300 feet/91 m	9.4 dBm
2nd Avenue and 15th Street along 15th Street	800 feet/243 m	13.6 dBm

7.5.3.2 BSM Broadcast Channel

Per SAE J2945/1, the power needed to support the BSM broadcast on channel 172 is 20 dBm for OBUs and RSUs. OBUs will transition across the communication zone of the RSUs. A vehicle will occupy roughly 20 linear feet of roadway (based on our assumptions). Each RSU must be capable of handling the radio traffic of approximately 220 vehicles approaching the intersection

[41] Free space path loss is calculated using 20 log ((4*pi*distance*f(MHz)/speed of light (m))^2). Adding attenuation until the signal at the range selected is below the receiver sensitivity defines the range. Free space loss was used here for simplicity. A better estimate of the actual loss could come from a 2 ray model or even the UFM.

of an avenue and a street. For this example, we will use the intersection of 2nd Avenue and 14th Street (RSU 1 from Figure 11):[42]

- For vehicles traveling on 2nd Avenue
  - 4 lanes (southbound)
  - 15 vehicles per lane (approaching from 15th Street)
  - **60 vehicles total**
- For vehicles traveling on 14th Street
  - 4 lanes (2 westbound, 2 eastbound)
  - 40 vehicles per lane (approaching from 1st Avenue and 3rd Avenue, respectively)
  - **160 vehicles total**
- **Total at Intersection: 220 vehicles**

This scenario, illustrated in Figure 12, provides an estimated 220 vehicles approaching the subject intersection during peak travel times (e.g., evening rush hour).

[42] This scenario ignores transmissions from traffic that is traveling away from the intersection.

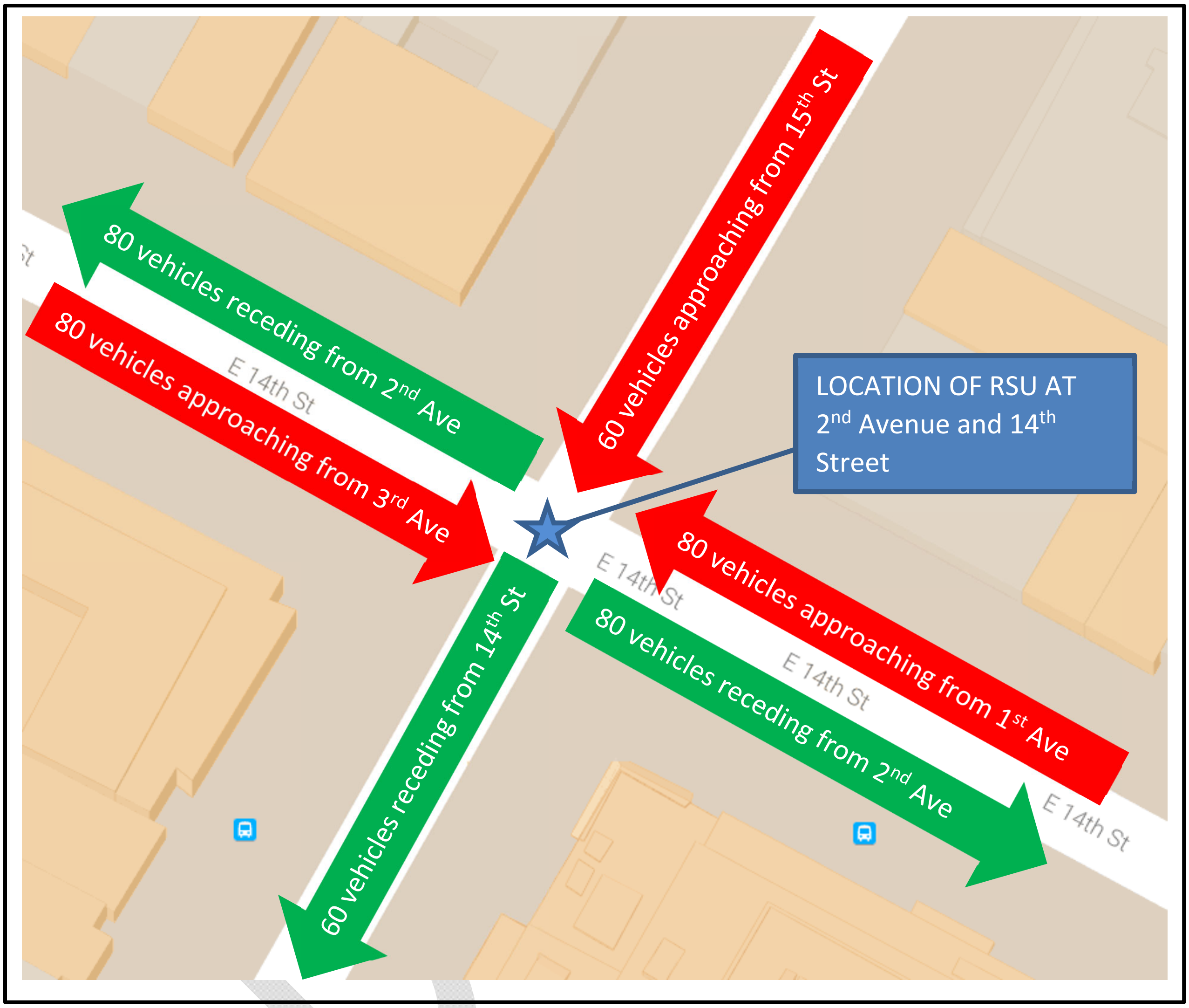

Image from U.S. DOT

Figure 12. Traffic Pattern at Intersection of 2nd Avenue and 14th Street, New York City

7.5.3.3 HPV2I

The power transmitted by an OBU of an emergency vehicle, using the HPV2I channel, may be as high as +40 dBm. As with non-emergency vehicles using the BSM broadcast channel, these OBUs will transition through the CCH communication zone. For this simplistic scenario, the assumption is that only one of the 220 vehicles approaching the intersection is an emergency vehicle transmitting on the HPV2I channel.[43]

[43] Emergency vehicles respond to over 30 million calls annually. In addition to aiding response time, the emergency vehicle applications offer significant safety benefits. In responding to an incident, the fatality rates for emergency medical services is 10 fold higher than it is for heavy trucks; see https://trid.trb.org/view.aspx?id=848882).

7.6 Packet Collision

As noted previously, packet collisions occur when two or more packets enter the receiver at approximately the same time. In this particular case, the concern is that a transmission from an adjacent channel will have sufficient energy to make it impossible to demodulate the desired packet due to packet collision. The plots depicted in Figures 7, 8, and 9, while theoretical, provide a sound basis for framing the analysis.

In order to address these issues from a more concrete standpoint, laboratory measurements were made at the Army Research Laboratory in Aberdeen, MD. A DSRC link was established in a laboratory setting to measure the impact of adjacent and non-adjacent channels on the desired channel. The equipment configuration is shown in Figure 13.

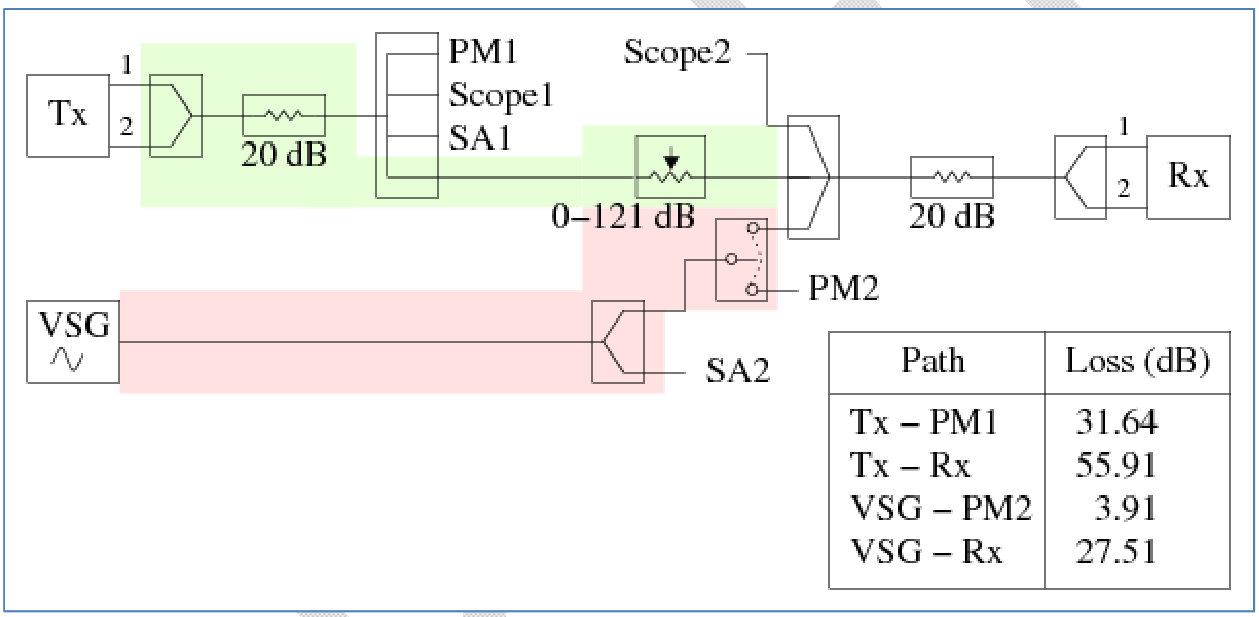

Image from U.S. Army Research Laboratory

Figure 13. Laboratory Configuration to Determine Packet Collisions for DSRC in Adjacent and Non-Adjacent Channels[44]

The process used to determine one point on a free space loss curve was to establish the minimum signal level at which the DSRC receiver (Rx) was receiving BSM data from the DSRC transmitter (Tx), then increase the DSRC transmit power by 20 dB to ensure there was a solid

[44] The acronyms in Figure 13 are: Tx – DSRC Transmitter, PM1 – Power Meter 1, Rx – DSRC Receiver, VSG – Vector Signal Generator, PM2 – Power Meter 2, SA1 – Spectrum Analyzer 1, SA2 – Spectrum Analyzer 2. dB losses noted in the box indicate the attenuation between the two points on the diagram. For example, Tx-PM1 has 31.64 dB of loss between the output of the transmitter and the point denoted by PM1. Finally, DSRC units have two separate radios; this is why there is a port 1 and a port 2 on each of the transmitters and receivers.

link established. The vector signal generator (VSG) was programmed to continuously broadcast either additive white Gaussian noise (AWGN) or a recorded DSRC BSM data. Power out of the VSG was increased until a 0 percent packet completion rate (PCR) was measured. This created the PCR curves from 0 to 100 percent PCR for both AWGN and recorded DSRC BSM (see figure 14 and table 11). The S/J depicted in Figure 14 is the ratio, in dB, of the desired signal to the jamming or interference signal. Since IEEE 802.11 compliant radios use PER instead of PCR, it is important to note that PCR is the opposite of PER. Thus, a 10 percent PER is the same as a 90 percent PCR.

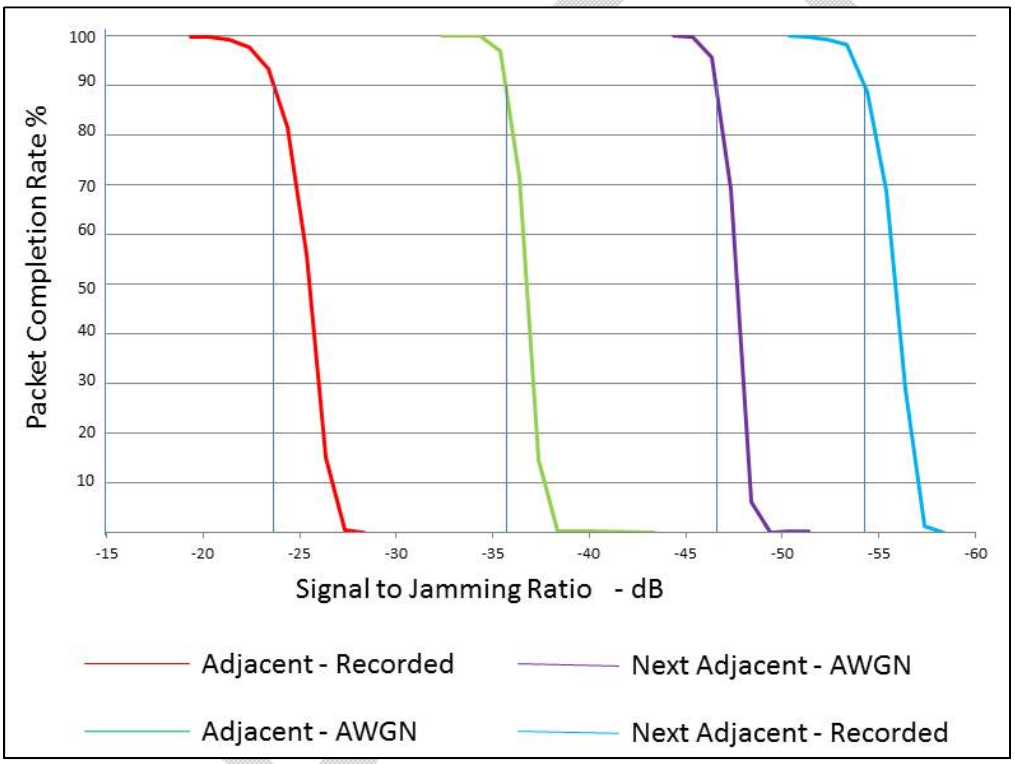

Image from U.S. DOT and U.S. Army Research Laboratory

Figure 14. Signal to Jamming Ratio for Recorded DSRC traffic and AWGN versus Packet Completion Ratio

Table 11. S/J Ratio for DSRC traffic and AWGN

Interfering Channel	S/J (dB) - Recorded	S/J - AWGN
Adjacent	-23.5 dB	-35.5 dB
Next Adjacent	-57.0 dB	-53.5 dB

7.7 Interference Range

7.7.1 Clear Channel Assessment (CCA)

As described previously, the CCA mechanism uses energy detection (ED) to determine if a channel is busy. The power at which the CCA ED suppresses transmissions is 20 dB above the receiver minimum sensitivity of -92 dBm.[45] Some receivers are more sensitive than others so this value can be different for different receivers. In this example, the receiver sensitivity from IEEE802.11-2012 is used. Thus, -92dBm + 20 dB = -72dBm at the CCA ED threshold. Figure 15 expands the first 500 meters of figure 7. The 20 dB threshold can be simulated by moving the curves in figure 15 down 20 dB. The first adjacent channel would detect the CCH at approximately 160 meters (524 feet) from the intersection. For a second adjacent channel, CCA interference would be detected at about 20 meters (65 feet).

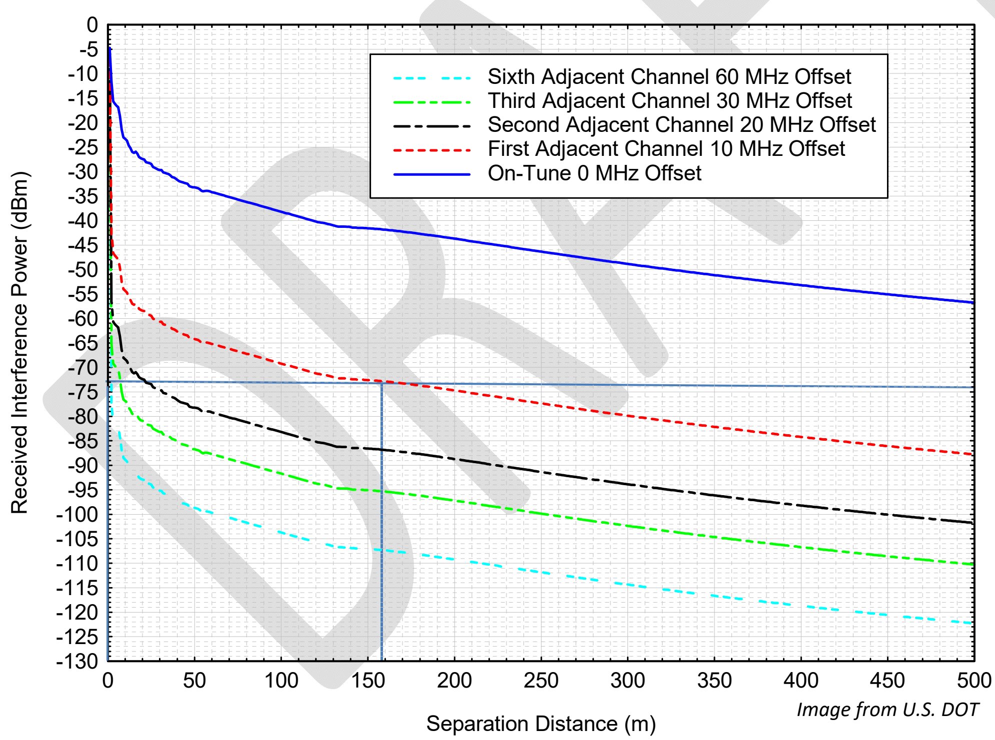

Figure 15. Received Interference Power at DSRC Receiver from CCH

[45] The energy detection threshold is set in IEEE 802.11-2012 (see 16.4.8.5) and depends on a number of factors. In discussions with the DSRC device manufacturers, they have set the CCA-ED level to be 20 dB above the minimum received signal level.

Note that the CCH broadcast has been set at 40 milliseconds. If the CCH is adjacent to both the BSM broadcast and HPV2I channels, then CCA ED will suppress transmissions at significant range for those 40 milliseconds.

This analysis next looks at the number of vehicles and BSM broadcasts. The BSM average length is 437 microseconds; with an interframe spacing for channel access of 260 microseconds, each BSM transmission will require a total period of 697 microseconds. Assuming each of the 220 vehicles in our scenario transmits its BSM serially,[46] without overlapping of messages, this represents channel traffic of 153 milliseconds.[47] This is a congested channel–too many BSMs to transmit in the 100-millisecond window. This will cause the congestion mitigation function to be enabled and reduce the overall load on the channel to 100 percent from just over 153 percent.[48] Clearly, this is a fully loaded channel and will likely be heavily loaded at other than peak travel times given the density of traffic in this urban setting.

For the HPV2I channel, we will assume one transmission every 100 milliseconds for signal pre-emption at a length of 3544 microseconds or 3.5 milliseconds. Since the HPV2I channel does not have a dedicated radio as the BSM channel does, it will only be allowed to transmit when it is not listening for the service announcements from the CCH. Thus, the HPV2I channel will be available to transmit for some 60 milliseconds of the 100 milliseconds (100 millisecond window less the 40-millisecond length of the CCH announcement leaves 60 milliseconds open) window. Further simulation and analysis is needed to evaluate the impact on safety for this scenario if additional safety messages are broadcast or additional emergency vehicles are present.

General conclusions can be drawn from this analysis. As noted above, the CCH will cause the CCA ED to suppress all transmissions for some distance from the intersection, depending on whether it is the first or second adjacent channel. Thus, even with the CCH and BSM channels not immediately adjacent, the vehicles that are near, entering, or leaving the intersection at peak travel times will not consistently be able to broadcast BSMs. If the simplifying assumptions presented in table 10 (e.g., limit transmit power in range) are removed, it becomes even less likely that any level of consistent and reliable BSM transmission will occur due to adjacent channel interference. This would have a direct impact on safety. Additionally, if the CCH is authorized to transmit without using a CCA mechanism, for at least 40 milliseconds, no BSMs will be available at or near this intersection, regardless of whether the channels are immediately next to each other or separated by one channel.

[46] A serial broadcast of BSMs is assumed based on the CCA mechanisms available within the IEEE 802.11-2012 standard. Each radio listens before it transmits and, if something is received, it implements a random delay before again determining if a channel I available. This randomness creates a roughly serial string of BSM transmissions.
[47] 220 vehicles X 1 BSM per vehicle X 697 microseconds per BSM = 153,340 microseconds (153 milliseconds).
[48] The Congestion Mitigation algorithm is explained in SAE J2945/1.

It is for these reasons that the existing band plan and channel spacing was established, in order to reduce or eliminate the impact of adjacent or non-adjacent RF interference.[49]

7.7.2 Packet Collision

The process used to identify when packet collision caused interference occurs was described in section 6.3. Figure 16 shows the receiver sensitivity for all seven channels and they are very similar. Furthermore, figure 16 also depicts that the minimum receiver sensitivity for these receivers was better than -95 dBm for a 10 percent PER.

7.7.3 Predicted Interference Levels

Using the test configuration depicted in figure 13, the receivers of a commercially available DSRC radio were analyzed and the performance of each was found to be similar. This is shown in figure 16.

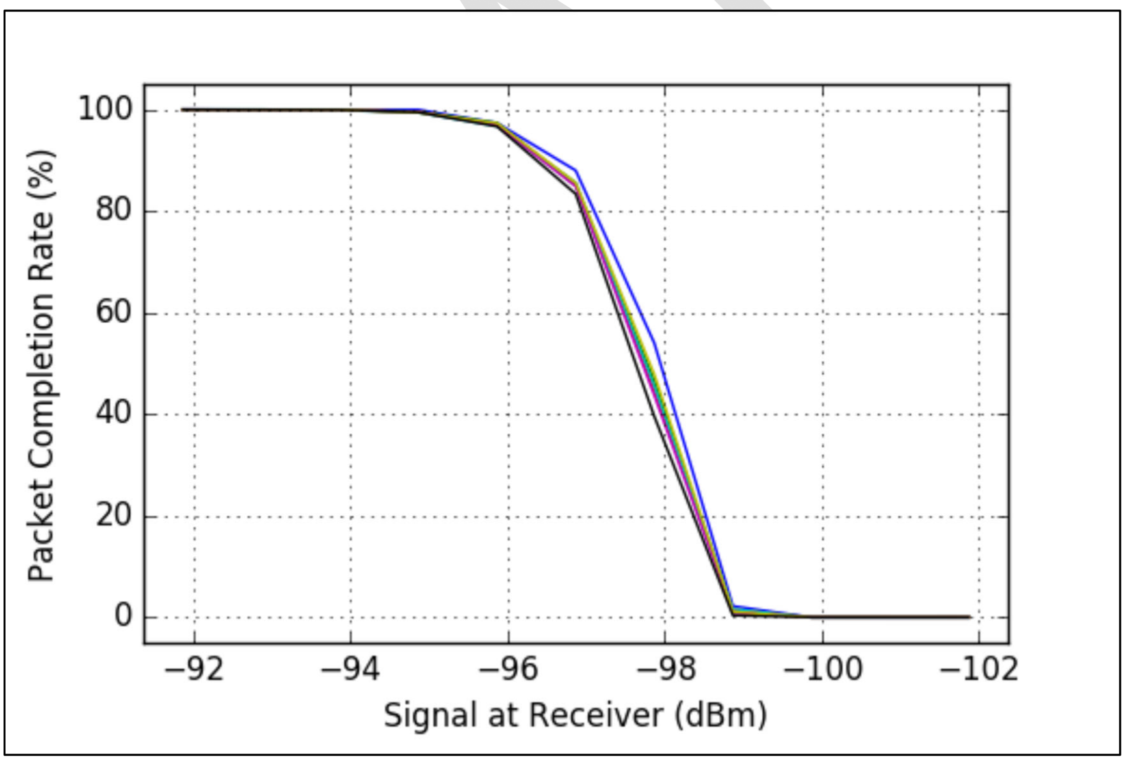

Image from U.S. DOT

Figure 16. Receiver Sensitivity for All Seven DSRC Channels

[49] Note that the assumptions are made to simplify the analysis. Reality is far more complex and would likely show more significant interference. The intent is to illustrate the impacts of adjacent channel issues, not fully describe DSRC.

Using this data and the receiver performance characteristics from IEEE 802.11-2012, the received interference from the first and second adjacent channels can be calculated. The plot in figure 17 shows the theoretical desired signal, and the power that must arrive at the receiver from the interfering source in the (first) adjacent channel and the next (second) adjacent channel in order to cause packet loss in the desired channel. Note that this also includes frequency dependent rejection of these adjacent channels.

To be clear, the energy in the next (second) adjacent channel would need to be at or above -25 dBm to interfere with the desired signal at 200 meters. Similarly, the energy in the (first) adjacent channel would need to be at or above -40 dBm to interfere with the desired signal at 200 meters. This is, as noted, theoretical. While the models used to generate this plot have proven successful many times, data was sought to further support this assertion.

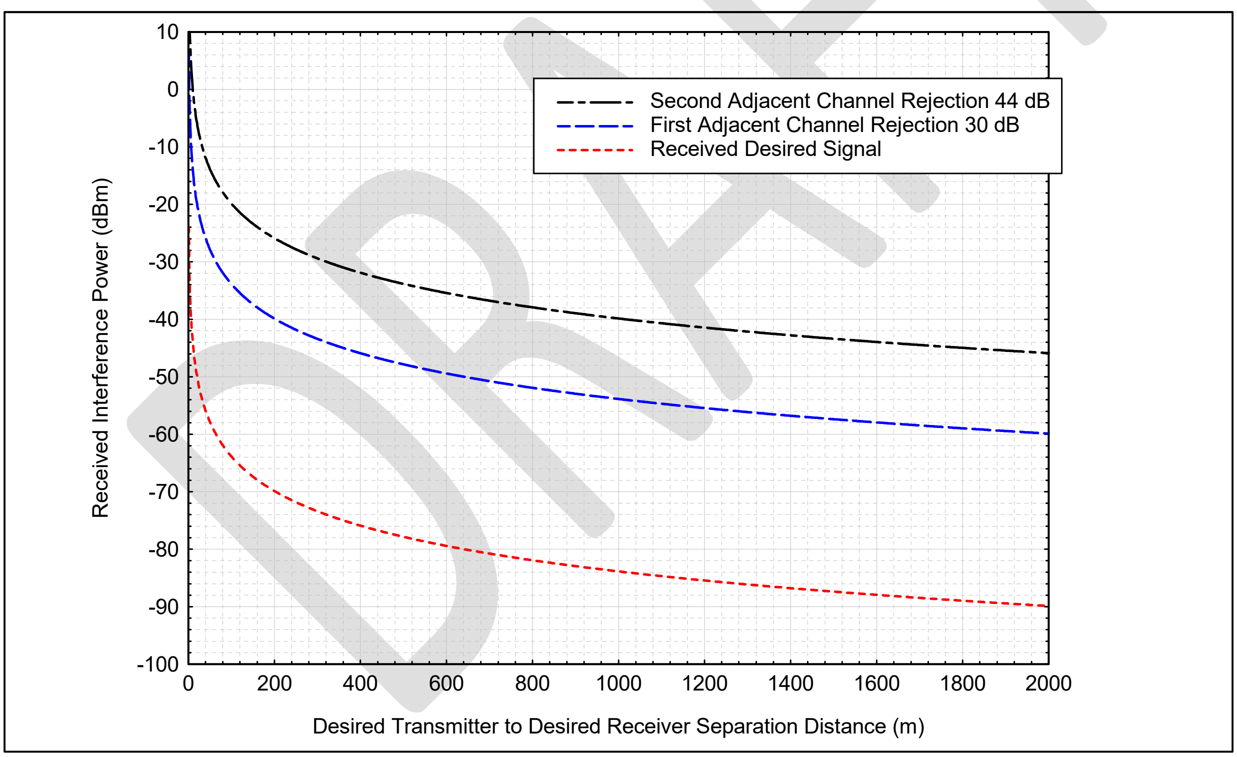

Image from U.S. DOT

Figure 17. Received Interference Power vs. Distance of Class C DSRC Transmitter

7.7.3.1 AWGN and Recorded Playback

Two methods of generating in-channel and adjacent-channel interference were used: (1) Additive White Gaussian Noise (AWGN) and (2) recorded DSRC BSM broadcasts.[50] Figure 18 compares real world data in the two evaluations using DSRC receivers, and shows that the impact due to interference from recorded DSRC traffic had a more significant impact than the AWGN. For the AWGN, the desired signal must be approximately 7.6 dB stronger than the AWGN signal to be demodulated and the data extracted, while for the recorded DSRC traffic, the desired signal must be approximately 13.6 dB stronger than the recorded signal to be demodulated and the data extracted. Table 12 shows signal to jamming values for several channel comparisons.

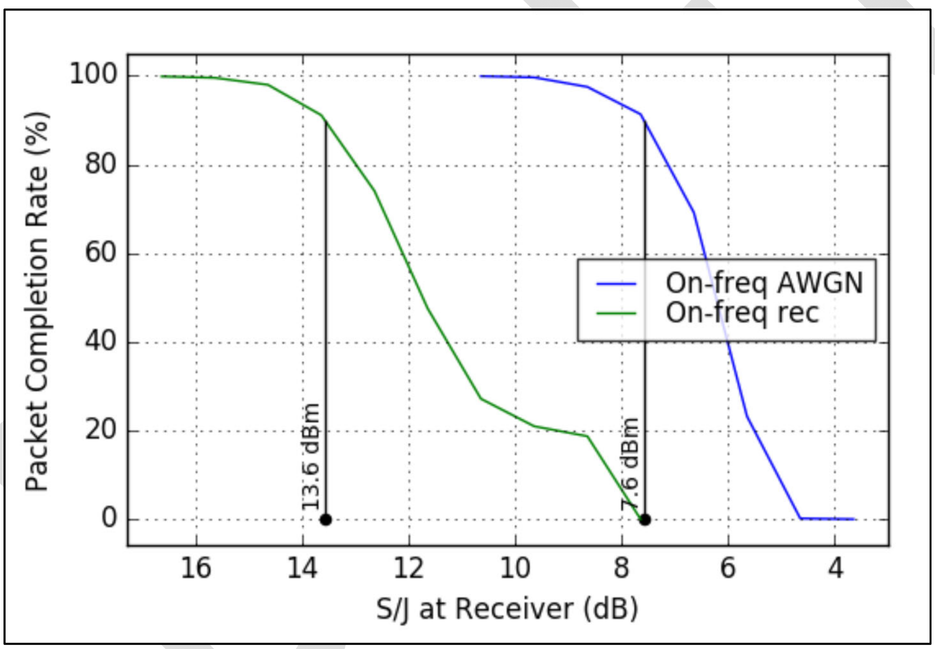

Image from U.S.DOT

Figure 18. Comparison of Jamming Signal from AWGN and Recorded DSRC on Packet Completion Rate

[50] DSRC BSM broadcasts were recorded using a signal analyzer and regenerated using a signal generator that was able to retransmit a single DSRC broadcast in a loop, creating a simulated fill DSRC BSM channel.

Table 12. Comparison of Signal to Jamming Ratio for On-Channel, Adjacent Channel, and Next Adjacent Channel for 90 percent Packet Completion Rate

Interference Channel	S/J	
	AWGN	Recording
On-Channel	7.6 dB	13.6 dB
Adjacent Channel	-35.5 dB	-23.5 dB
Next Adjacent Channel (+1)	-53.5dB	-57 dB

Using this measured data, a plot similar to figure 15 was created and is shown in Figure 19. A DSRC receiver is co-located with a DSRC transmitter on the adjacent channel (10 MHz offset) or another DSRC transmitter on the next adjacent channel (20 MHz offset). This figure represents the existing isolation between a desired signal and energy from the adjacent (+10 MHz) or next adjacent (+20 MHz) channels. The distance on the x-axis represents the distance between a DSRC receiver and the transmitting data source it is trying to demodulate.

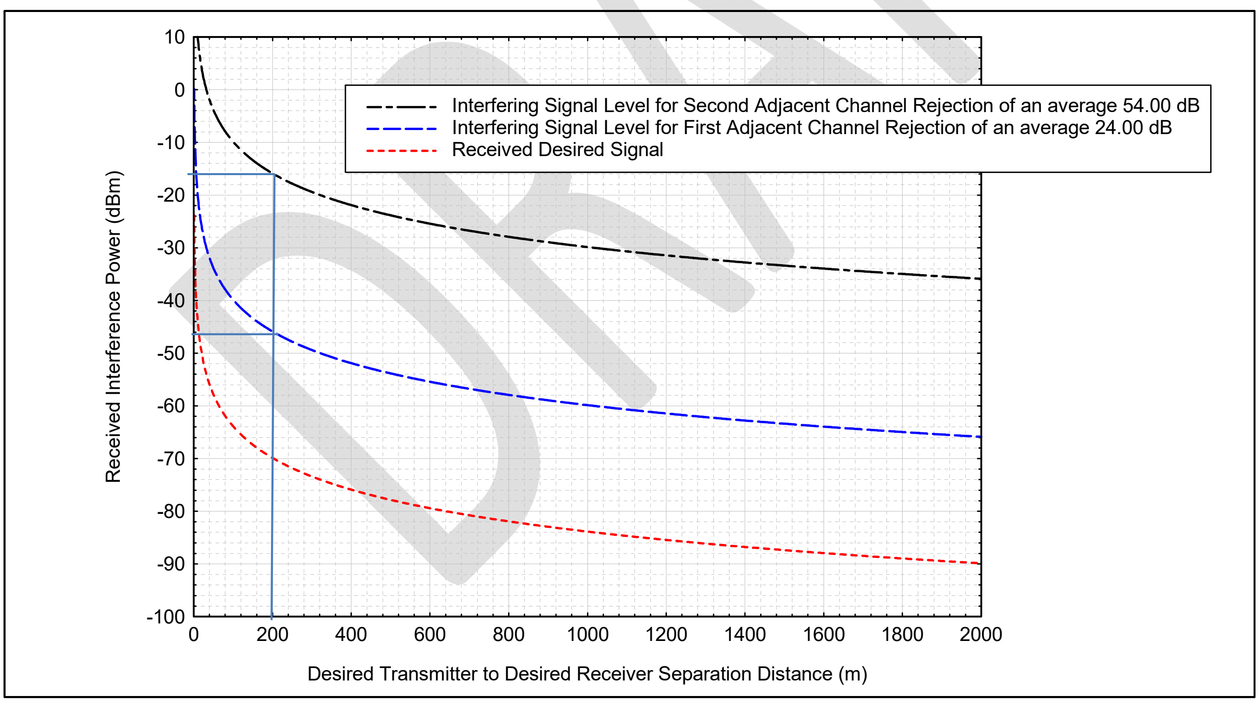

Image from U.S. DOT

Figure 19. Received Interference Power vs. Distance with Measured Data

If the distance between the DSRC receiver and its associated transmitter were 200 meters, the energy needed in the next adjacent channel (+10 MHz) will need to be above-48 dBm to interfere. The following section provides further narrative details involving a real world scenario.

7.7.3.2 Impact to Real World Scenario Example

Recalling the scenario based on the NYC CV Pilot Concept of Operations, it is difficult to visualize on a static paper the impact of this level of interference. The RSUs are stationary but OBUs are constantly moving in and out of range, and the distance between OBUs is highly dynamic as well. Figures 20 and 21 attempt to illustrate the impact of this dynamic environment.

In figure 20, for example, the interference from the RSU transmitting on the control channel will depend on the distance to the BSM broadcast channel receiver and its distance to the BSM broadcast channel transmitter. In this case, if the CCH transmitter is 100 meters from the BSM broadcast receiver, that receiver will not be able to process packets from a BSM broadcast transmitter that is more than 30 meters from it (see red lines on Figure 20). As the BSM broadcast receiver moves closer to the CCH transmitter, the interference will increase to the point that vehicles within a few meters will be unable to process packets. This is significant when it is understood that RSUs are located at intersections and that is where a significant number of crashes occur. Figure 20 provides an illustration of similar impacts from the HPV2I channel.

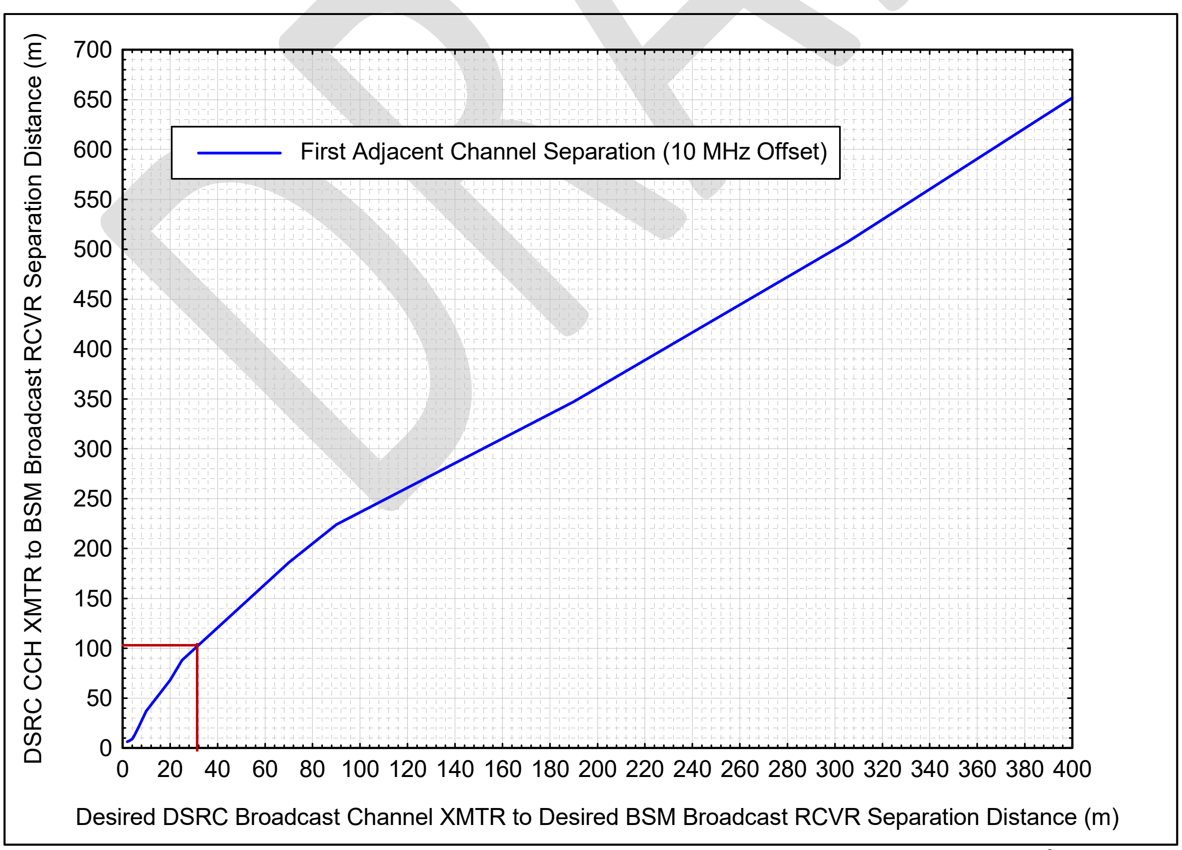

Image from U.S. DOT

Figure 20. 44.8 dBm DSRC CCH into First Adjacent BSM Channel at 20 dBm

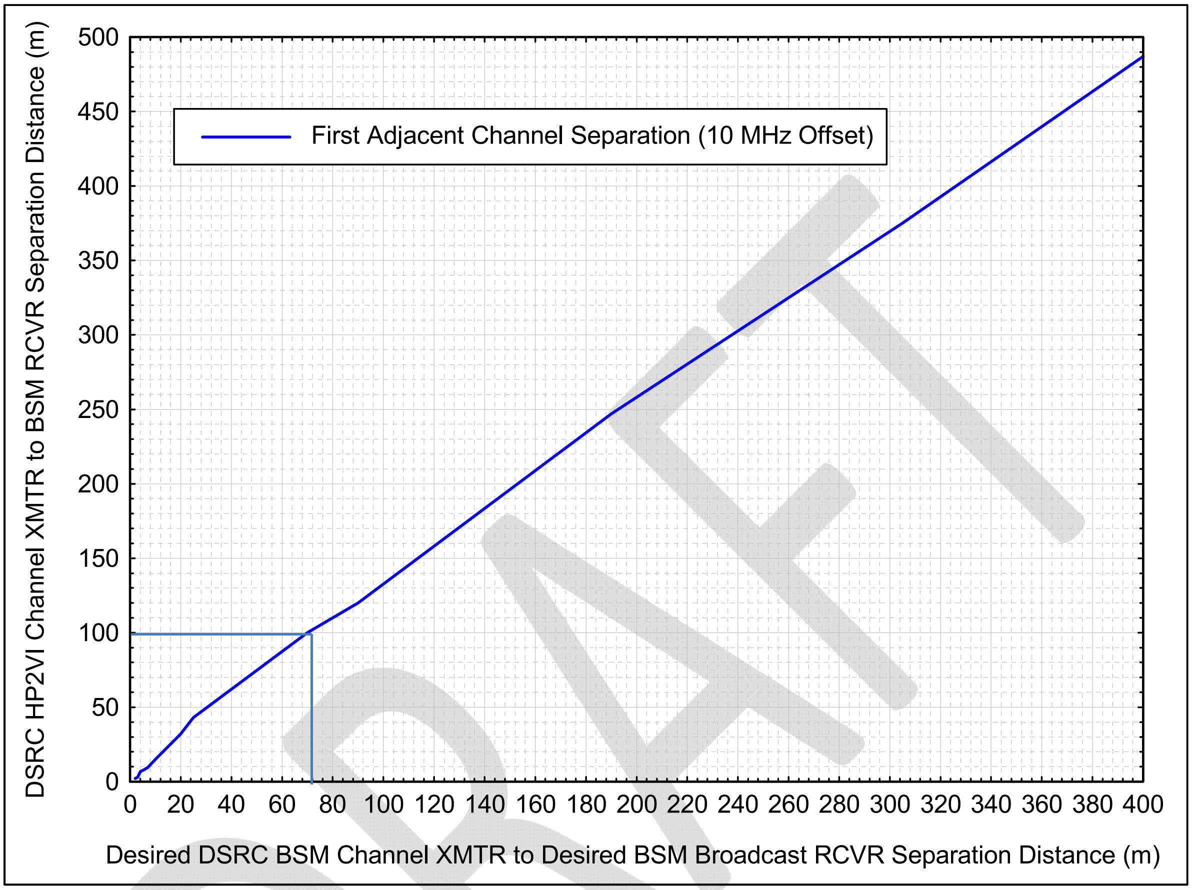

Image from U.S. DOT

Figure 21. 40.0 dBm DSRC HPV2I into Adjacent BSM Channel at 20 dBm

A basic question that can now be asked is: How is this different than the current implementation where there is a 30 MHz offset between the BSM channel and the CCH? Figure 22 illustrates this well. As a comparison, a DSRC BSM receiver that is 100 meters away from an RSU on the control channel will not be able to receive BSMs from devices more than 390 meters distant as compared to the 30 meters when the two channels are adjacent. As a point of reference, a vehicle traveling at 65 miles per hour will cover 29 meters in one second.

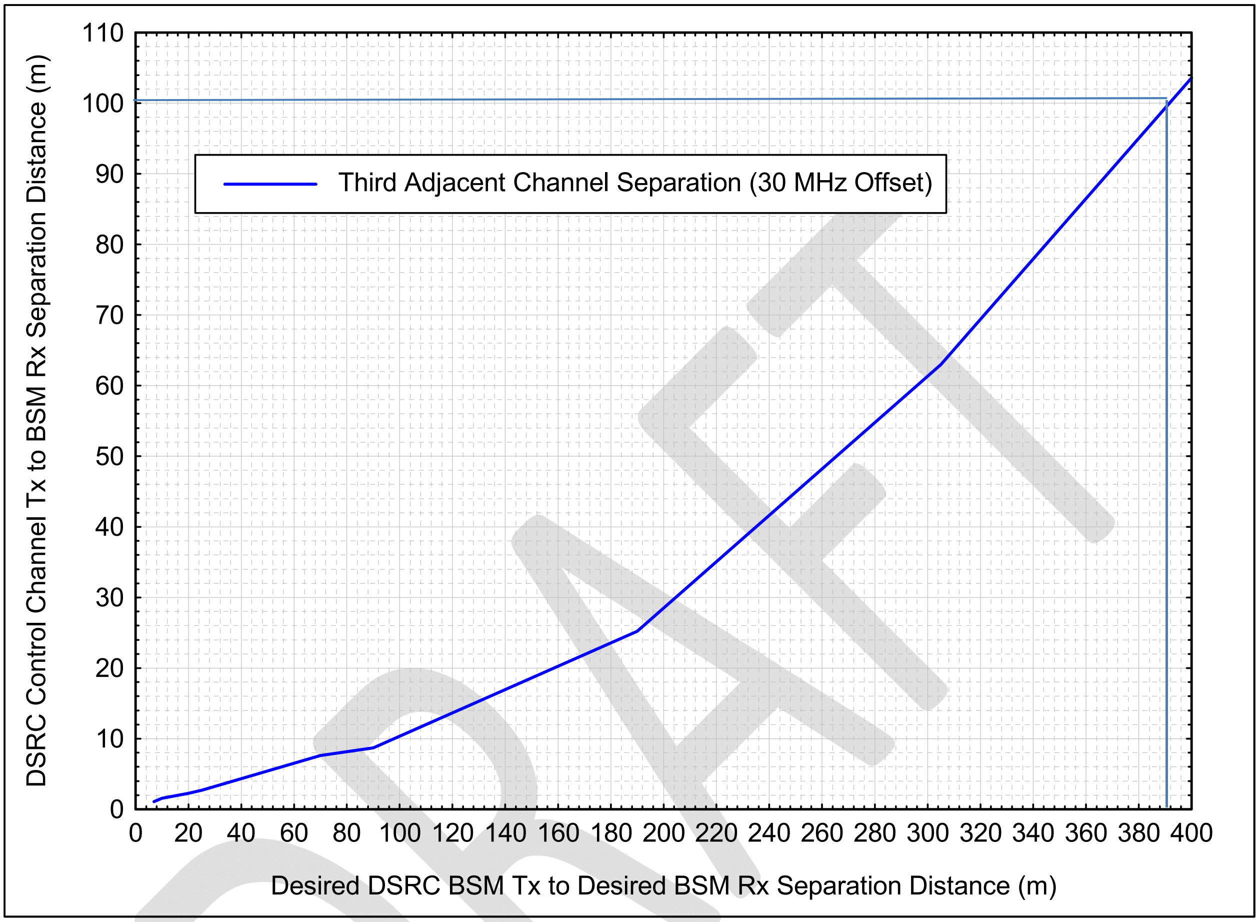

Image from U.S. DOT

Figure 22. 44.8 dBm DSRC CCH into Third Adjacent BSM Channel at 20 dBm

7.8 Summary

Within this section, options for re-channelization was analyzed; signal levels and interference levels were established for DSRC radios based on measured data and modeling; and a real word scenario based on a current deployment program was used to identify impacts to deployments. When all the factors are considered, including the adjacent and next adjacent channel interference, the interference range is sufficient to undermine any benefits to V2V and V2I safety.

8 Conclusion

The conclusions presented in the paragraph below are based on a variety of DSRC channel-use assumptions drawn from accepted standards (e.g. IEEE 802.11-2012) identified within the body of this paper. These assumptions include, but are not limited to transmit power levels, adjacent and non-adjacent channel rejection, message sizes, and message frequency.

The potential for adjacent and non-adjacent channel interference if the BSM, CCH, and HPV2I channels are placed in the upper 30 MHz of the DSRC Service band is significant. It is important to note that there are three types of interference: (1) ambient noise due to licensed and unlicensed devices operating in adjacent frequency bands, (2) packet collision, and (3) message suppression. The latter is due to the impact of the CCA mechanism on channel access, which prevents RSUs and OBUs from transmitting BSM or other data when the transmitter detects existing RF energy in the band, suggesting the band is occupied. Self-interference based on adjacent and non-adjacent channel rejection is also significant and will cause severe degradation beyond 400 meters. An increase in the background noise has been identified but was not explored in this paper.

This analysis and its findings substantiate U.S. DOT concerns that re-channelization will have a significant negative operational impact on DSRC communications and the safety functions it is intended to support.

9 Further Work

The key focus of the U.S. DOT is "to ensure our nation has the safest, most efficient and modern transportation system in the world; that improves the quality of life for all American people and communities, from rural to urban, and increases the productivity and competitiveness of American workers and businesses".[51] However, nearly 40,000 individuals in the U.S. die each year on our Nation's highways while many more are injured. Our transportation system needs new and innovative approaches to addressing these problems. Development of V2X technologies offers the Nation an opportunity to significantly reduce these deaths and injuries; and studies have shown this reduction to be real.

The impetus for this report was to examine whether re-channelization could pose a risk to surface transportation safety, since any new technology or approach that increases fatalities, injuries, or property damage cannot and should not be supported. Originally conceived and written in 2017, this report was intended to address one potential approach to spectrum sharing—the opening up of the Safety Band to unlicensed devices.

In addition to looking at the effects of sharing in the Safety Band, which have been demonstrated to be negative, another consequence that can result from re-channelization is the financial impact to infrastructure owners and operator (IOOs) agencies that are already using the Safety Band, as well as to travelers who would lose access to the V2V, V2I, and other safety applications during any transition time. These other impacts that derive from any change to the Safety Band are now under investigation with the introduction of other new approaches. As of mid-2019, several new or modified approaches to communications in the Safety Band include:

- A new version of the IEEE 802.11 standard with amendment bd,
- 3GPP Release 14 of Long Term Evolution (LTE) Cellular V2X (with updates in Releases 15 and 16), and
- 5G New Radio (3GPP Release 17), the next generation of cellular technology.

Each of these approaches is being examined in detail to help ensure that transportation safety remains a high priority and that any new technologies or innovations improve safety by reducing deaths and injuries.

[51] The Mission of the U.S. Department of Transportation, U.S. DOT website, https://www.transportation.gov/briefing-room/safetyfirst/us-department-transportation.

Appendix A: Glossary of Terms

TERM	DEFINITION
Arbitration Inter-Frame Spacing Number (AIFSN)	AIFSN is the specified offset a radio transmitter will back-off when it encounters information on a given channel before trying to transmit again.
attenuate	Reduce the strength of a signal with little or no distortion.
dB, dBm, dBr	Decibel, decibel-milliwatts (abbreviation for the power ratio in decibels of the measured power referenced to 1 milliwatt), decibel-relative (logarithmic scale relative to a set value – in our case 0).
Effective Isotropic Radiated Power (EIRP)	EIRP is the amount of power radiated from a theoretical point source.
free space path loss (FSPL)	FSPL is the loss of signal strength along a non-obstructed line-of-sight path.
modulate/ demodulate	Encoding information within a signal is modulation; retrieving the information is demodulation.
noise figure	A measure of signal degradation.
octet	An 8 bit byte.
packet error rate	Percentage of packets that are not successfully transmitted and received in a packet-based system.
packet-based	A method of data transmission in which data is broken into small blocks that are transmitted over their different channels and are reassembled into their original order at their destination.
transmission mask	A transmission, or transmitter, mask, reduces adjacent channel interference by attenuating signals outside the desired bandwidth.

Appendix B: List of Acronyms

Term	Definition
µsec	micro-seconds
ACR	Adjacent Channel Rejection
adj	Adjacent
AIFSN	Arbitration Inter-Frame Spacing Number
ASTM	ASTM International (formerly American Society for Testing and Materials)
AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partnership
CCA	Clear Channel Assessment
CCH	Control Channel
ConOps	Concept of Operations
dB	Decibel
dBm	Decibels relative to a milliwatts
dBr	Decibels relative
DSRC	Dedicated Short Range Communication
ED	Energy Detect
EIRP	Effective Isotropic Radiated Power
EV	Emergency Vehicle
FCC	Federal Communications Commission
FDR	Frequency Dependent Rejection
FHWA	Federal Highway Administration
GHz	Gigahertz
HPV2I	High Power Vehicle-to-Infrastructure
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
m	meters
MAC	Media Access Control layer
MAP	Message name in J2735. The message conveys the relevant road geometry.
Mb/s	Megabits per second
MHz	Megahertz
mph	Miles Per Hour

Term	Definition
nADJ	next or non-adjacent
NHTSA	National Highway Traffic Safety Administration
NTIA	National Telecommunications and Information Administration
NYCDOT	New York City Department of Transportation
OBU	On-Board Unit
OST-R	Office of the Assistant Secretary for Technology and Research
PER	Packet Error Rate
PHY	Physical layer
PM	Power Meter
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RCVR	Receiver
RSS	Received Signal Strength
RSU	Road Side Unit
Rx	receiver
S/J	Signal-to-Jamming
SA	Spectrum Analyzer
SAE	Society of Automotive Engineers
SPaT	Signal Phase and Timing
TBD	To Be Determined
TFHRC	Turner-Fairbank Highway Research Center
Tx	Transmitter
U-NII	Unlicensed National Information Infrastructure
U.S. DOT	U.S. Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VSG	Vector Signal Generator
XMTR	Transmitter

Appendix C: Modeling

1 Introduction

The objective of this appendix is to present the analysis procedure used in the main body of the report. This analysis is an example that looks at the impact of the HPV2I transmissions on the BSM channel with 60 MHz of separation. This example is based on parameters that were available for both the DSRC High Power V2I Channel as an interference source and the DSRC BSM Receiver. The DSRC device parameters were extracted from the IEEE 802.11-2012 Standard.

Certain parameters such as distance and signal levels cover a large dynamic range. The separation distances for DSRC High Power V2I Channel transmitter to DSRC BSM receiver as well as DSRC BSM transmitter to DSRC BSM receiver can cover distances of 2 meters to 2000 meters. This creates a situation in which the received signal level from a transmitter will be between -93 dBm to levels as high as -14 dBm, depending on range. As better approximations to the parameters are determined for these DSRC systems to values closer to actual values, there will still be a large dynamic range for the operating ranges, since the distance and signal ranges will be similar to the original analysis, but the protection distances and frequency offsets will change for the modified set of parameters.

2 Discussion

The outline of the analysis procedure is as follows:

a) Device parameters for the DSRC High Power V2I Channel and BSM equipment were first gathered from all available sources.

b) DSRC High Power V2I Channel transmitter emission spectra were obtained from IEEE Standard 802.11-2012.

c) The receiver selectivity for a good DSRC receiver design was selected from a combination of the available standards and principles of good receiver design. This would allow performing an analysis that would give the best approximation to the value of Frequency Dependent Rejection (FDR) available.

d) Computations of the FDR available versus frequency offset between a DSRC High Power V2I Channel transmitter and a DSRC BSM receiver were computed from parameters obtained from available standards. FDR available is the amount of rejection between a transmitter and receiver that can be obtained by off-tuning the transmitter and receiver frequencies. This FDR will be referred to as "FDR available" in this discussion.

e) Received power versus transmitter-to-receiver separation distance is then computed for both the interference signal of the DSRC High Power V2I Channel transmitter and the desired signal of the DSRC BSM broadcast transmitter. The DSRC High Power V2I Channel signal is considered the interference signal into the desired DSRC BSM broadcast receiver. The DSRC BSM broadcast transmitter signal is considered the desired signal into the DSRC BSM broadcast receiver.

f) "FDR required" is computed differently than the "FDR available" which is computed from the available standards, as described in (d) above. Instead, the FDR required versus distance is computed using the received interference power from the High Power V2I Channel transmitter and combining it with the interference-to-noise ratio and the noise level.

g) By combining the results of the FDR available versus frequency offset computations with the FDR required versus interference source to desired receiver separation distance computations, a frequency offset versus separation distance is obtained.

h) The results of (e) above for received power versus separation distance for the two transmitters is then used to plot: (1) the interference of the DSRC High Power V2I Channel transmitter to the DSRC BSM receiver separation distance; and (2) the desired DSRC BSM broadcast transmitter to the DSRC BSM receiver separation distance, while maintaining a fixed signal-to-interference ratio.

i) The final results are presented in two formats:

    1. As a frequency offset between the DSRC High Power V2I Channel transmitter and DSRC BSM receiver frequencies versus the DSRC High Power V2I Channel transmitter to DSRC BSM receiver separation distance. This computation was obtained by combining the FDR available results with the FDR required computations.
    2. As plots of interfering DSRC High Power V2I Channel to DSRC BSM receiver separation distance as a function of desired DSRC BSM transmitter to DSRC BSM receiver separation distance.

2.1 Device Parameters of the DSRC High Power V2I Channel Interference Source

This discussion will explain the analysis procedure and show by example how the effects of interference are determined on the DSRC High Power V2I channel to the DSRC BSM channel for the adjacent channel case. The following parameters were used to characterize the DSRC devices for this analysis, but new updated information could change these parameters (i.e., improved receiver design). The interfering transmitter of Figure C-1a for this analysis was the

DSRC High Power V2I Channel and the emission spectra were obtained from IEEE Standard 802.11-2012 for a Class D transmitter. Figure C-1b shows the emission spectra for a Class C BSM transmitter for comparison to the Class D transmitter of Figure C-1a. In Figure C-1b, HPV2I Class D emission spectra are much tighter than that of Class C emission spectra which has more out-of-band emissions). The EIRP of this DSRC High Power V2I Channel is 40.0 dBm. An omni-directional antenna is assumed to be 1.5 m above ground for the DSRC High Power V2I Channel, which is best case for minimum interference to DSRC BSM. A worst case of more interference would result if the antenna height were increased to 5.0 m. For this analysis only the effects of the DSRC High Power V2I Channel 178 emissions on the DSRC BSM receiver were considered. The antenna gain for the DSRC High Power V2I Channel is taken into account in the EIRP of 40.0 dBm.

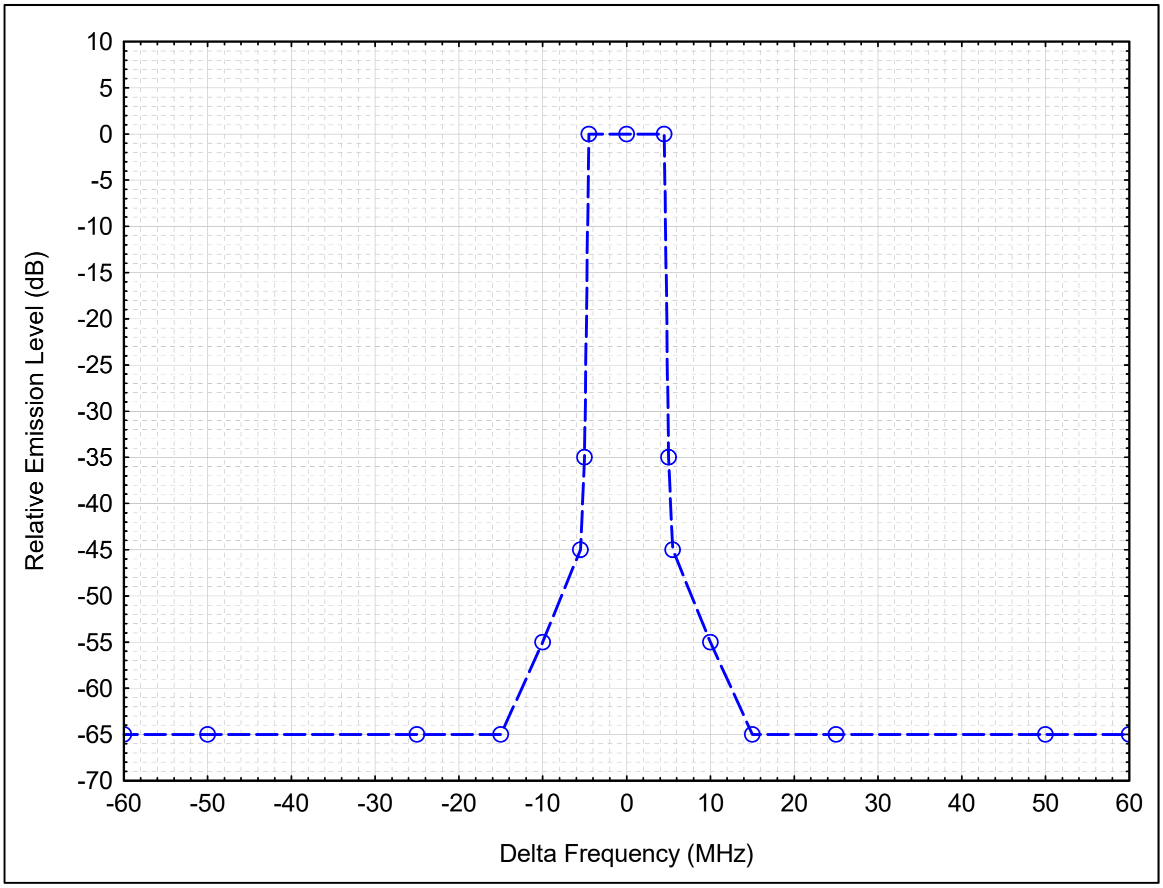

Image from U.S. DOT

Figure C-1a. DSRC High Power V2I Channel Class D Transmitter Emission Spectrum

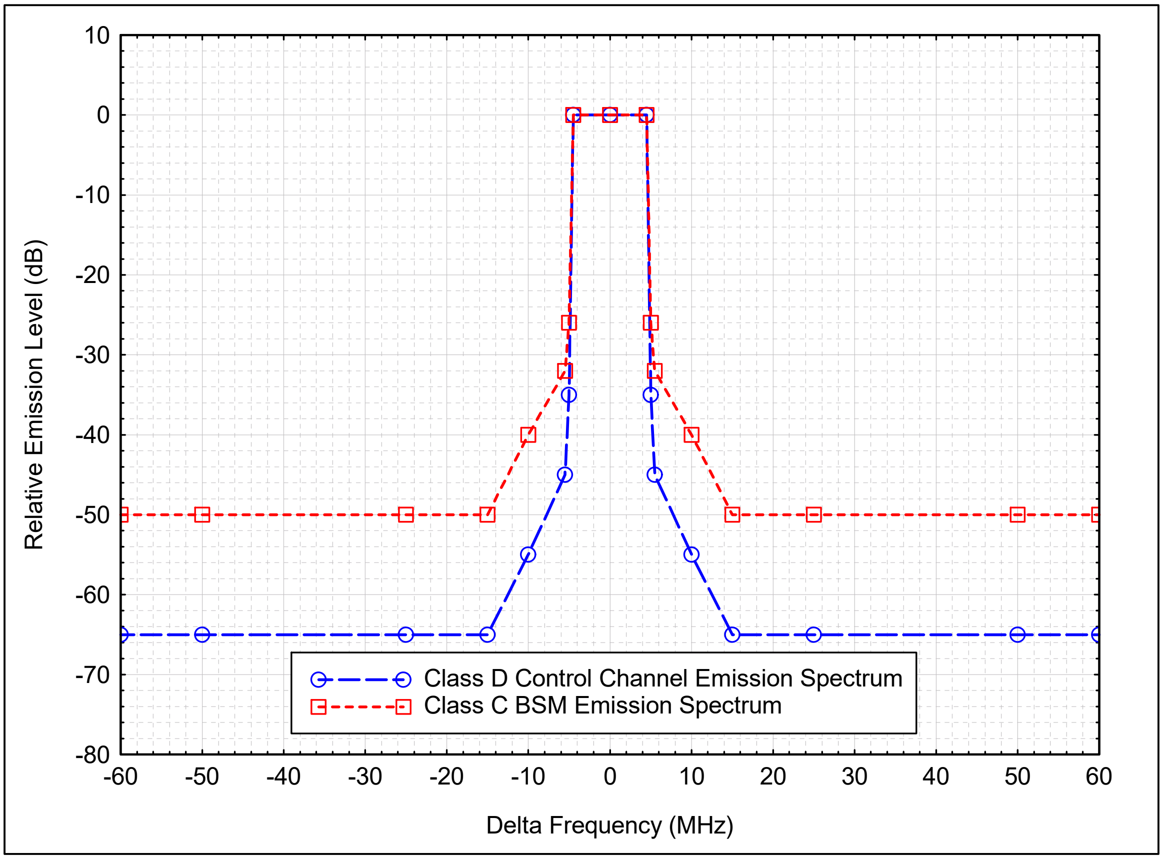

Image from U.S. DOT

Figure C-1b. Comparison of DSRC Class D High Power V2I Channel to Class C BSM Channel Emission Spectra

2.2 Device Parameters of the DSRC BSM Transmitter and Receiver

The IEEE Standard 802.11-2012 was first examined to determine the selectivity characteristic of the DSRC BSM receiver. Since the DSRC receiver selectivity in that standard was not adequate to reject interference in a preliminary analysis, a typical "good" receiver design was developed for the DSRC receiver using the 802.11-2012 Standard as a starting point. The result is illustrated in Figure C-2. Using representative good receiver design practices to make these modifications results in a more representative manner for how devices are implemented. It is expected that DSRC devices will have better selectivity than that in the 802.11-2012 Standard and be more like the good receiver design presented in this discussion.

Figure C-2 is the receiver selectivity used in this analysis. Figure C-3 is a comparison of the selectivity of Figure C-2 to that of the selectivity in IEEE Standard 802.11-2012.

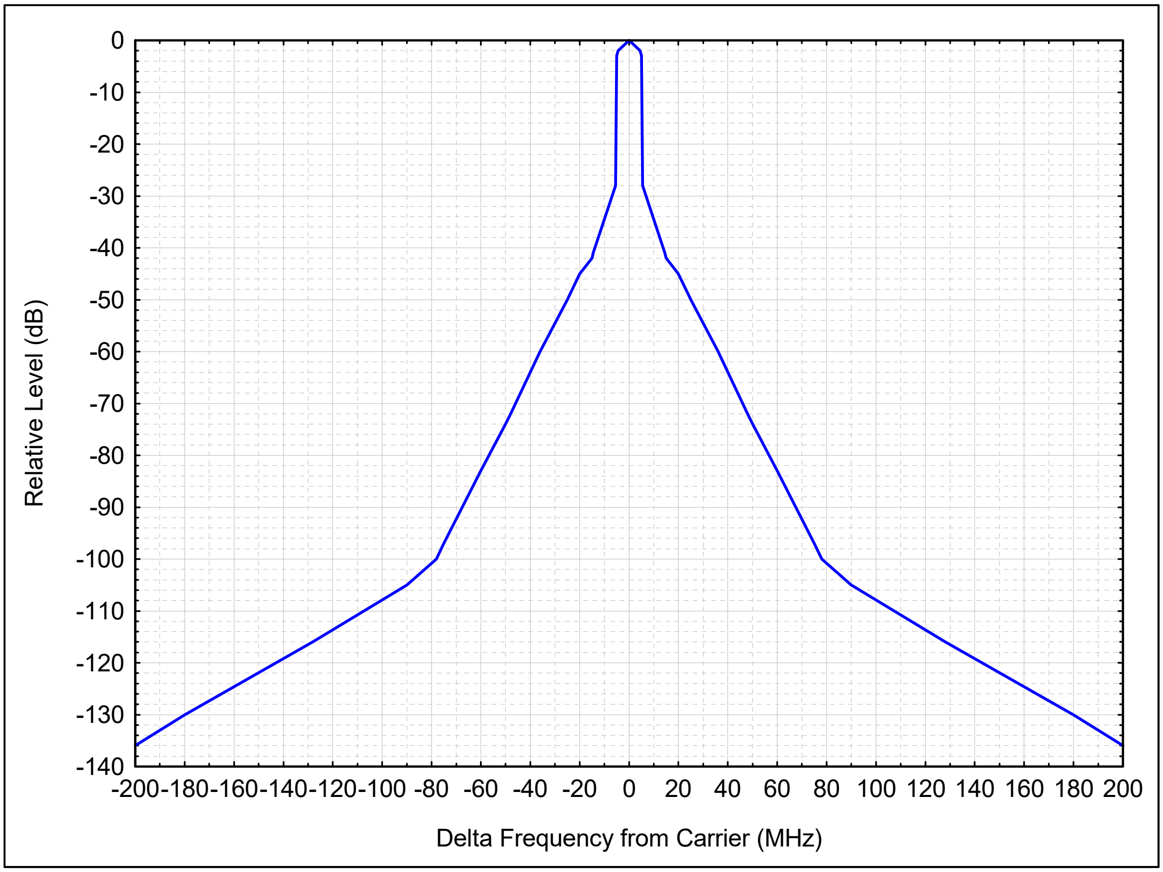

Image from U.S. DOT

Figure C-2. DSRC BSM Channel Receiver Selectivity Used in FDR Available Analysis

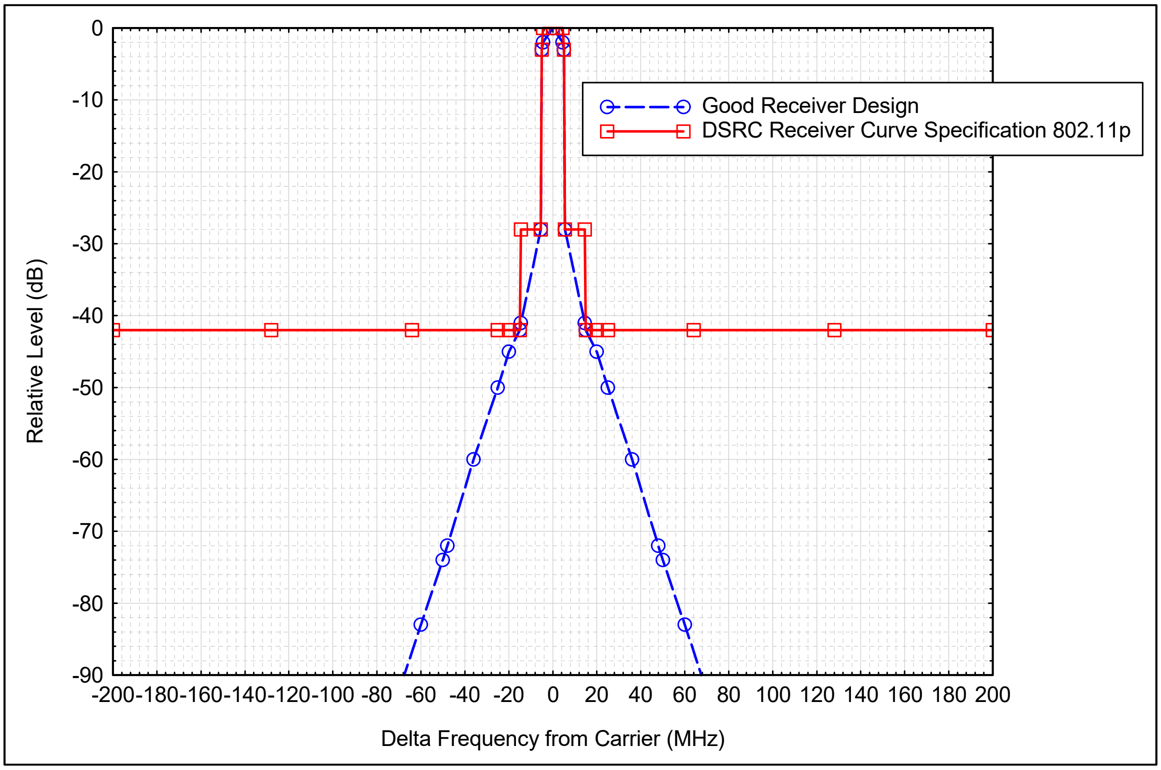

Image from U.S. DOT

Figure C-3. DSRC BSM Channel IEEE802.11-2012 Receiver Specification Comparison to the Receiver Selectivity Used in the FDR Available Analysis

The maximum EIRP for the BSM Channel 172 is set to 20 dBm by SAE J2945/1. The frequency of operation is in the 5855 to 5865 MHz band with a 10 MHz bandwidth at Channel 172. The DSRC BSM transmitter power was used for computation of the desired DSRC BSM signal into the DSRC BSM receiver as a function of distance and antenna height. This is presented in Figure C-4.

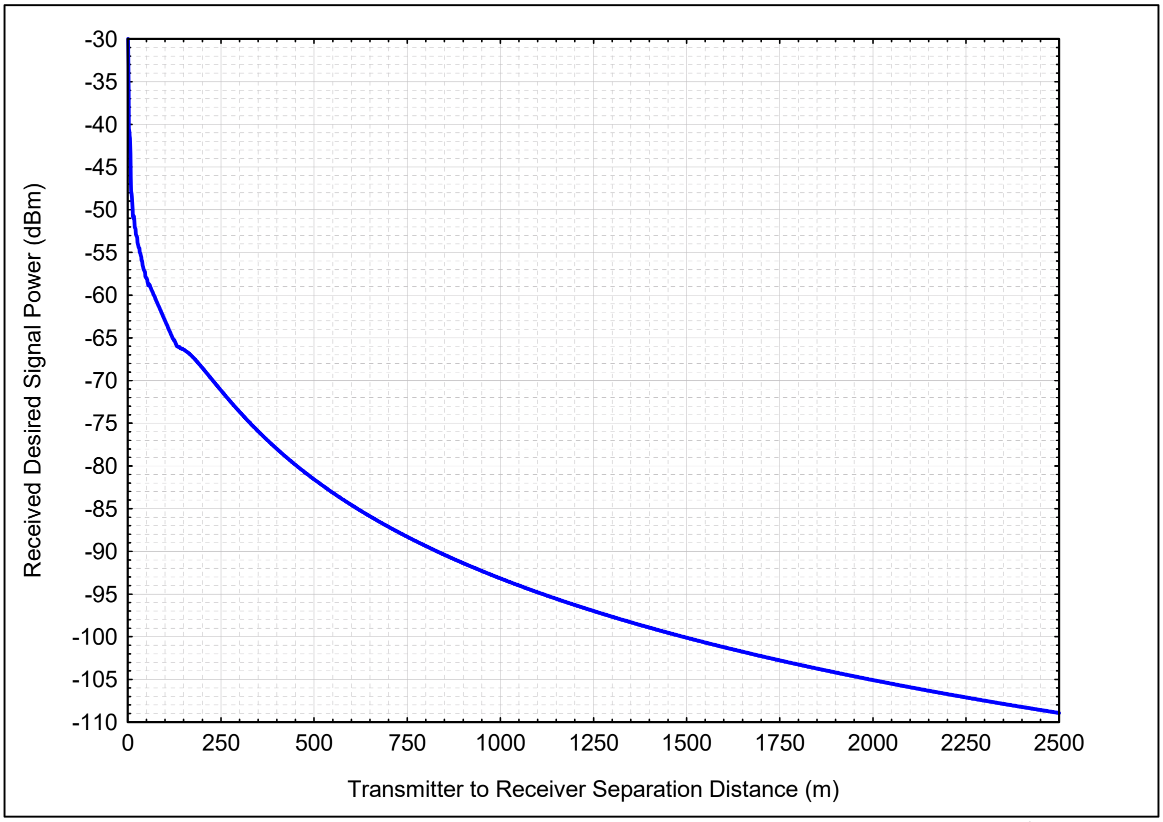

Image from U.S. DOT

Figure C-4. Desired BSM Receiver Signal Power from DSRC BSM Transmitter at 20 dBm versus Separation Distance

The antenna height for the DSRC BSM unit is 1.5 m for the transmitter and receiver locations. The worst case (lowest desired BSM received signal level) that will occur at a DSRC BSM transmitter antenna height of 1.5 m was used in this preliminary analysis and represents communication between two vehicles.

The antenna gain was assumed to be 0 dBi omni-directional in azimuth for the receiver antenna. This antenna gain was used for the DSRC BSM receiver and represents a worst case situation. The 6 dBi antenna gain for the BSM transmitter is taken into account in the maximum EIRP of 20 dBm.

The receiver sensitivity was derived from measured data in document IEEE 802.11-13/1360r0 (Tiger Team document[52]) and the result was S = -93 dBm. The DSRC receiver noise level, N(dB)

[52] DSRC Packet Error Rate versus Packet Profiles at: https://mentor.ieee.org/802.11/documents?is_dcn=1360&is_year=2013, Last accessed07/26/2019.

in a 10 MHz bandwidth BW(Hz) was computed assuming a state-of-the-art 6 dB noise figure, NF(dB) as follows:

N (dBm) = -174 dBm/Hz + 10 log BW(Hz) + NF(dB)

= -174 dBm/Hz + 10 log 10E6 + 6 dB

= -174 dBm/Hz + 70 dBHz + 6 dB = -98 dBm

S (dBm) = S/N (dB) + N (dBm) = 5 dB + (-98 dBm) = -93 dBm

The S/N = 5 dB is derived from the DSRC receiver sensitivity of -93 dBm and the noise level of N = -98 dBm. The S/N = 5 dB and S/I = 14 dB are verified by independent measurements performed by Denso International America Inc.

If S/I = 14 dB, then the DSRC HPV2I interference level I= S – S/I = -93 dBm -14 dB = -107 dBm.

The resulting interference-to-noise ratio,

I/N (dB) = I (dBm) – N (dBm) = -107 dBm – (-98 dBm) = -9 dB at minimum sensitivity.

This scenario represents the DSRC units operating at a minimum sensitivity level, but this is not realistic in actual operation because the separation distance to attain a -93 dBm signal level is a large separation distance.

Figure C-4 is a plot for DSRC BSM received signal power (20 dBm) versus DSRC BSM transmitter to DSRC BSM receiver separation distances. The -93 dBm signal level is attained at a long distance of 1000 meters. The DSRC transmitter to receiver distance separation is much shorter than this for normal operation. This curve was generated with the ITS Undisturbed-Field Model (UFM). An example of a more practical separation distance of 210 meters occurs at a received power of -69 dBm.

2.3 Computations for Establishing Protection Distances and Electromagnetic Compatibility

Determination of the electromagnetic compatibility, and hence spectrum sharing capability, requires not only the frequency dependent rejection available as a result of off-tuning the DSRC High Power V2I Channel interference source frequency from the DSRC BSM receiver frequency, but also determines the frequency dependent rejection required as a function of DSRC High Power V2I Channel interference source to DSRC BSM receiver separation distance.

A combination of the FDR required and the FDR available provides a determination of a frequency offset required versus this interference source to victim receiver separation distance. The combining of the FDR required with the FDR available is a correlation process of the two FDRs, which is performed in a MATLAB program. The resulting distance is a protection distance for specific frequency offsets. This analysis can be used to make trade-offs between protection distances and frequency offset.

An additional analysis included in this discussion plots the required DSRC High Power V2I Channel interference source to DSRC BSM receiver separation distance to avoid interference versus the DSRC BSM transmitter to DSRC BSM receiver separation distance. This analysis takes into account the desired DSRC BSM transmitter to DSRC BSM received signal level as a function of separation distance in addition to the interference power versus the interference DSRC High Power V2I Channel to desired DSRC BSM receiver separation distance.

2.4 Frequency Dependent Rejection Available

The Frequency Dependent Rejection (FDR) available between the DSRC High Power V2I Channel was computed by using the emission spectra of a DSRC High Power V2I Channel Class D transmitter from IEEE 802.11-2012 in Figure C-1a, and the DSRC BSM receiver selectivity for a good receiver design shown in Figure C-2. It was computed from the interferer emission characteristic and the receiver selectivity curves cited previously using the FDR computer program contained within the MSAM model. Figure C-5 is the FDR available as a function of frequency offset between these DSRC High Power V2I Channel and DSRC BSM device frequencies. Figure C-5 illustrates that 65.5 dB maximum of frequency dependent rejection is available, but at a minimum of 55 MHz offset. The FDR available doesn't get above 40 dB until a 15 MHz frequency offset. A 20 MHz offset provides approximately 45 dB of FDR, and finally a 10 MHz offset provides 30 dB of FDR. Other case values of available frequency dependent rejection can be read from Figure C-5.

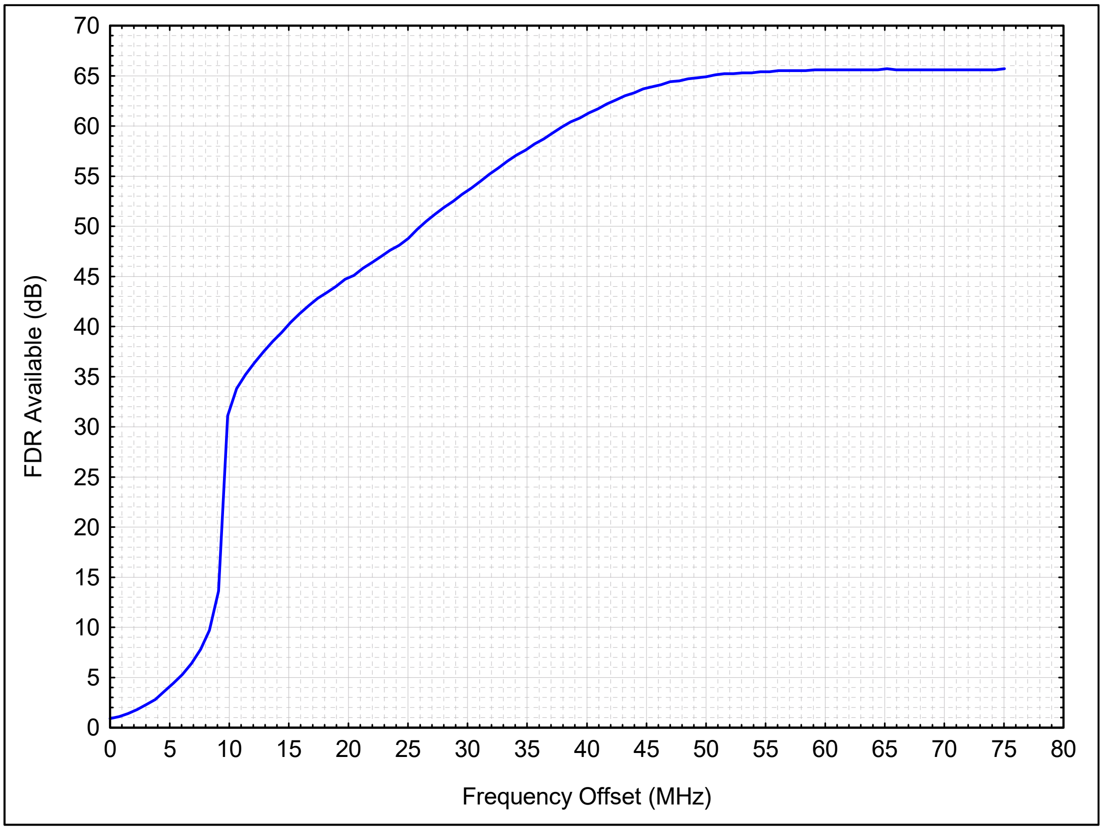

Image from U.S. DOT

Figure C-5. Frequency Dependent Rejection Available versus Frequency Offset for DSRC High Power V2I Channel Transmitter to DSRC BSM Receiver

Many other transmitter/receiver combinations were computed using the 802.11-2012 Standards. Computations of FDR using the actual DSRC emissions and selectivity characteristics from the standards resulted in poor rejection results for reasonable frequency offsets. The FDR in Figure C-5 best represents a practical combination DSRC transmitter to DSRC receiver for a reasonable prediction of required frequency offset versus available FDR based on current available parameter information. A measurement of actual emission characteristics for a DSRC transmitter may provide a better emission for the High Power V2I transmitter and result in a more accurate analysis. Computations of FDR available for other combinations of DSRC interference source to DSRC receiver models are available upon request.

2.5 Computations of Received Interference DSRC High Power V2I Channel Signal into the DSRC BSM Receiver

The received interference level from the DSRC High Power V2I Channel signal source to the DSRC BSM receiver was computed as a function of the separation distance between them. Figures C-6a and C-6b are plots of this DSRC High Power V2I Channel interference power into the desired DSRC BSM receiver as a function of separation distance for a DSRC High Power V2I Channel interference source with EIRP = 40.0 dBm at a DSRC High Power V2I Channel antenna height of 1.5 m and a DSRC receiver antenna height of 1.5 m.

Note in Figure C-6a that at a separation distance of 1900 meters the received interference is at a level of I= -84 dBm. Figure C-6b is an expanded distance axis plot of Figure C-6a to display the short to intermediate distance regions with better resolution.

The received interference powers into a DSRC BSM receiver for both on-tune and off-tune conditions are shown in Figures C-6c (distances of 0 to 2500 meters) and C-6d (distances of 0 to 500 meters). This is for a High Power V2I Channel 40.0 dBm source.

Notice that for the frequency offsets of 20 MHz (second adjacent channel) or more, some additional rejection is available. This is due to the FDR available characteristic of this DSRC High Power V2I Channel transmitter to DSRC BSM receiver combination of Figure C-5.

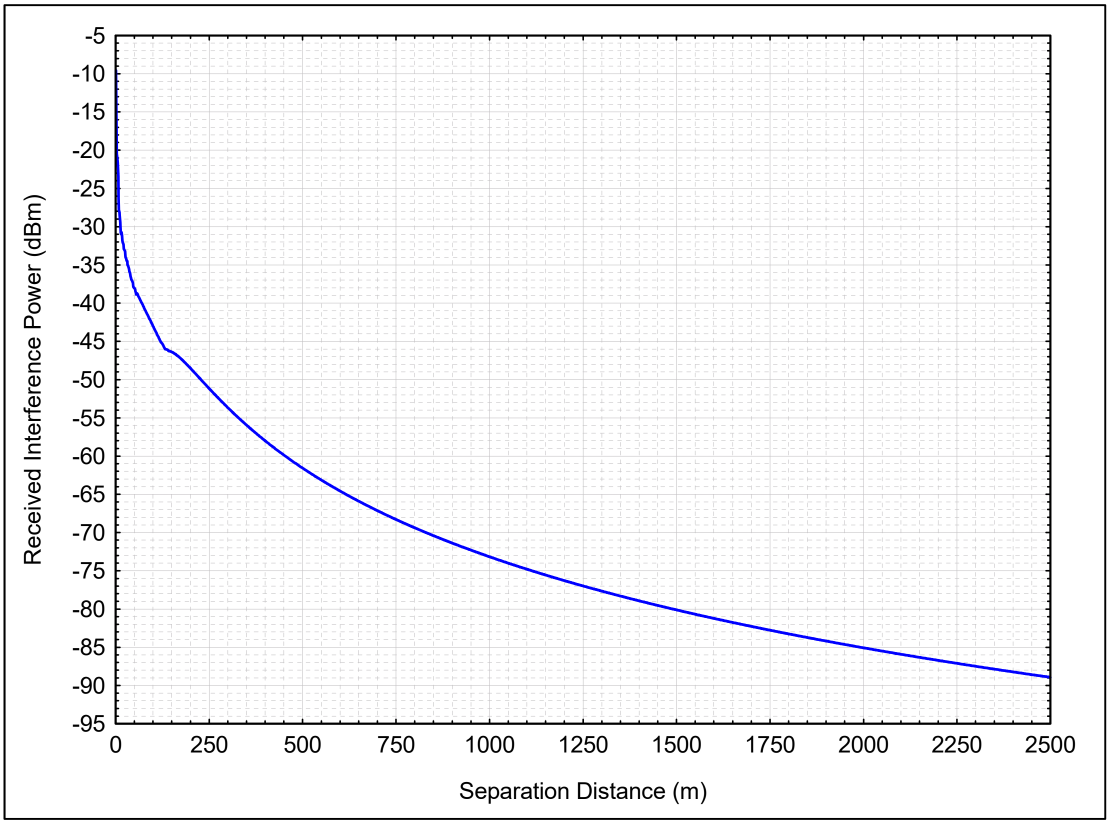

Image from U.S. DOT

Figure C-6a. Received Interference Power at DSRC BSM Receiver from DSRC High Power V2I Channel at 40.0 dBm versus Separation Distance for Long Distances

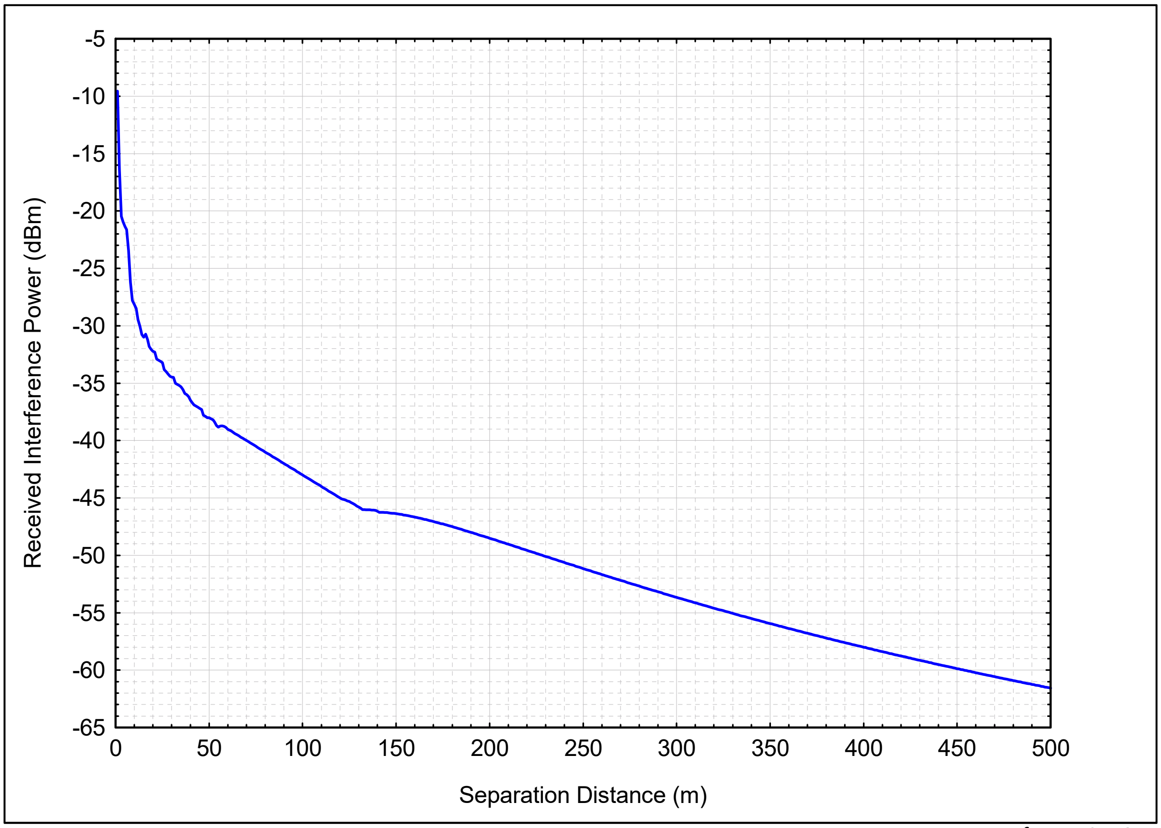

Image from U.S. DOT

Figure C-6b. Received Interference Power at DSRC BSM Receiver from DSRC High Power V2I Channel at 40.0 dBm versus Separation Distance for Short Distances

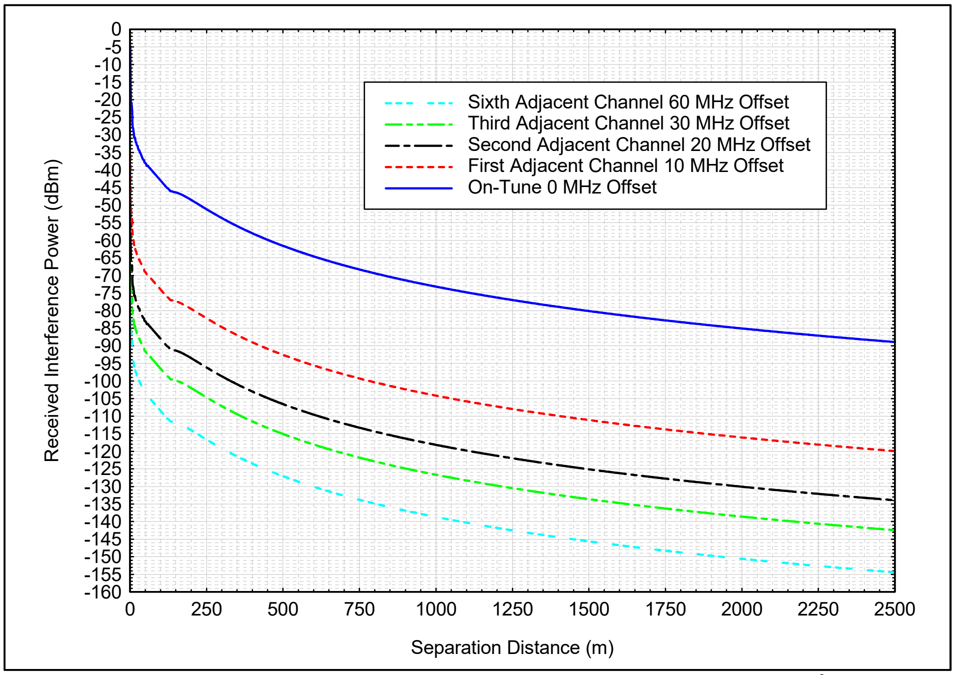

Image from U.S. DOT

Figure C-6c. Received Interference Power at DSRC BSM Receiver from DSRC High Power V2I Channel at 40.0 dBm versus Separation Distance for Long Distances for the On-tune and Off-tune Cases

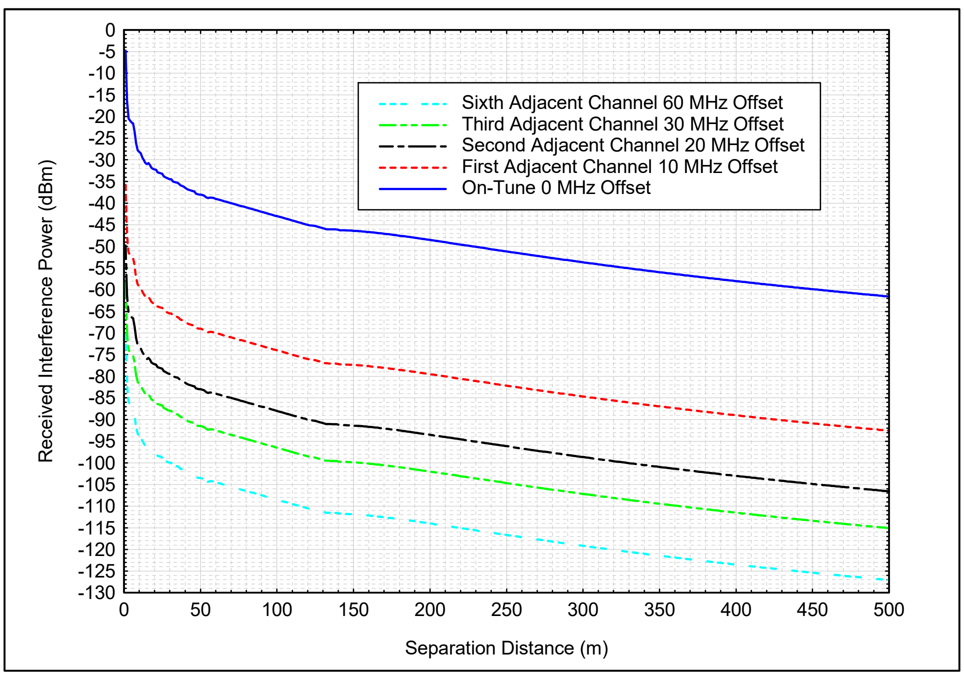

Image from U.S. DOT

Figure C-6d. Received Interference Power at DSRC BSM Receiver from DSRC High Power V2I Channel at 40.0 dBm versus Separation Distance for Short Distances for the On-tune and Off-tune Cases

2.6 Frequency Dependent Rejection Required

The frequency dependent rejection required starts with a computation of the received interference power level P_r(dBm) versus DSRC High Power V2I Channel source to BSM DSRC receiver separation distance. The received interference level for a transmitter power P_t(dBm), antenna gains G_t(dBi) + G_r(dBi), and propagation loss L_p(dB) is given by:

$$P_r(\text{dBm}) = P_t(\text{dBm}) + G_t(\text{dBi}) + G_r(\text{dBi}) - L_p(\text{dB}).$$

The received interference power at a DSRC BSM receiver from a DSRC High Power V2I Channel at P_t = 40.0 dBm versus distance was shown in Figures C-6a and C-6b for a distance range of 0 to 2500 meters and 0 to 500 meters for the on-tune case, respectively. Figures C-6c and C-6d show the same on-tune curves with the addition of the off-tune cases of the first (10 MHz), second (20 MHz), third (30 MHz), and sixth (60 MHz) adjacent channel cases.

The FDR required to bring the received interference signal level P_r(dBm) down to a level such that the interference-to-noise ratio, I/N(dB) and the noise level, N(dBm) requirements are met is given by:

$$FDR_{req}(\text{dB}) = P_r(\text{dBm}) - [N(\text{dBm}) + I/N(\text{dB})] = P_r(\text{dBm}) - [\,-98 + (-9)]$$

$$FDR_{req}(\text{dB}) = P_r(\text{dBm}) + 107 \text{ dB}$$

The FDR required versus DSRC High Power V2I Channel interference source to DSRC BSM receiver separation distance is computed from the received interference power versus distance using the above equations.

2.7 Computations of the Received Desired DSRC BSM Channel signal into the DSRC BSM Receiver

Figures C-7a (separation distance 0 to 2500 meters) and C-7b (separation distance 0 to 500 meters) are the plots of received desired power (EIRP = 20.0 dBm source) versus desired DSRC BSM transmitter to DSRC BSM receiver separation distance. These plots are for on-tune received power. Notice the minimum sensitivity of -93 dBm is attained at a separation distance of 1000 meters.

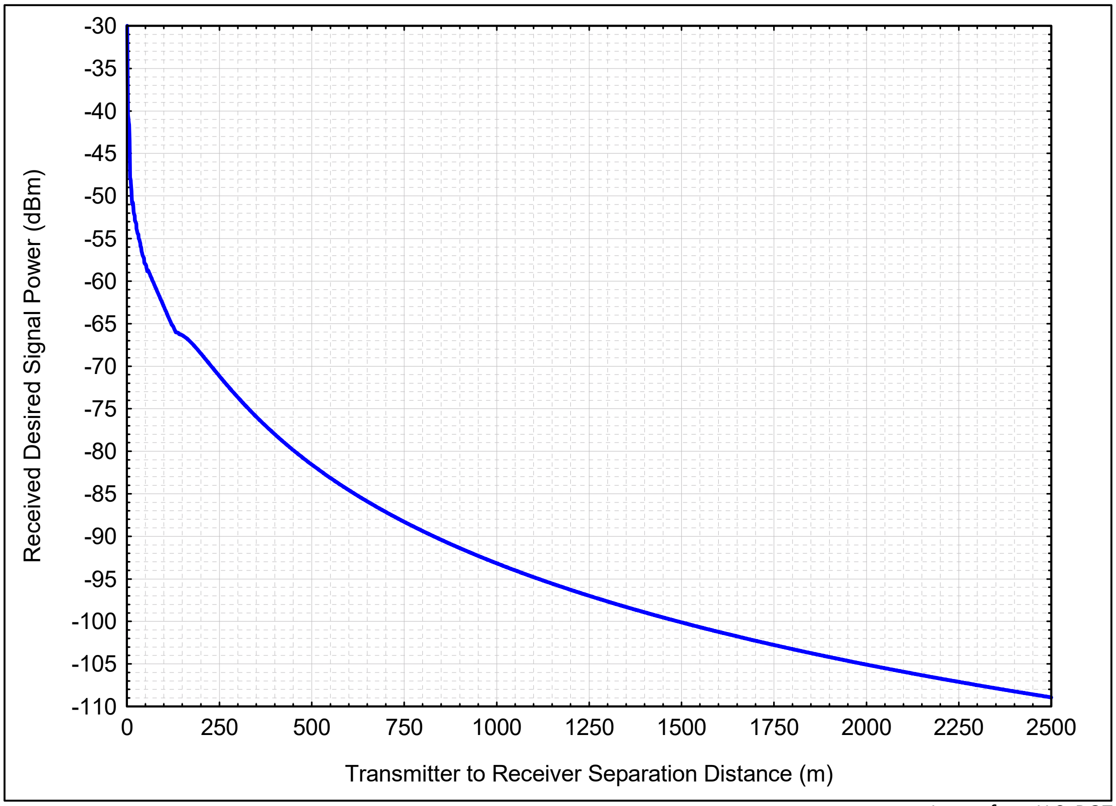

Image from U.S. DOT

Figure C-7a. Received Desired Signal Power at DSRC BSM Receiver from DSRC BSM Transmitter at 20 dBm versus Distance for Long Distances

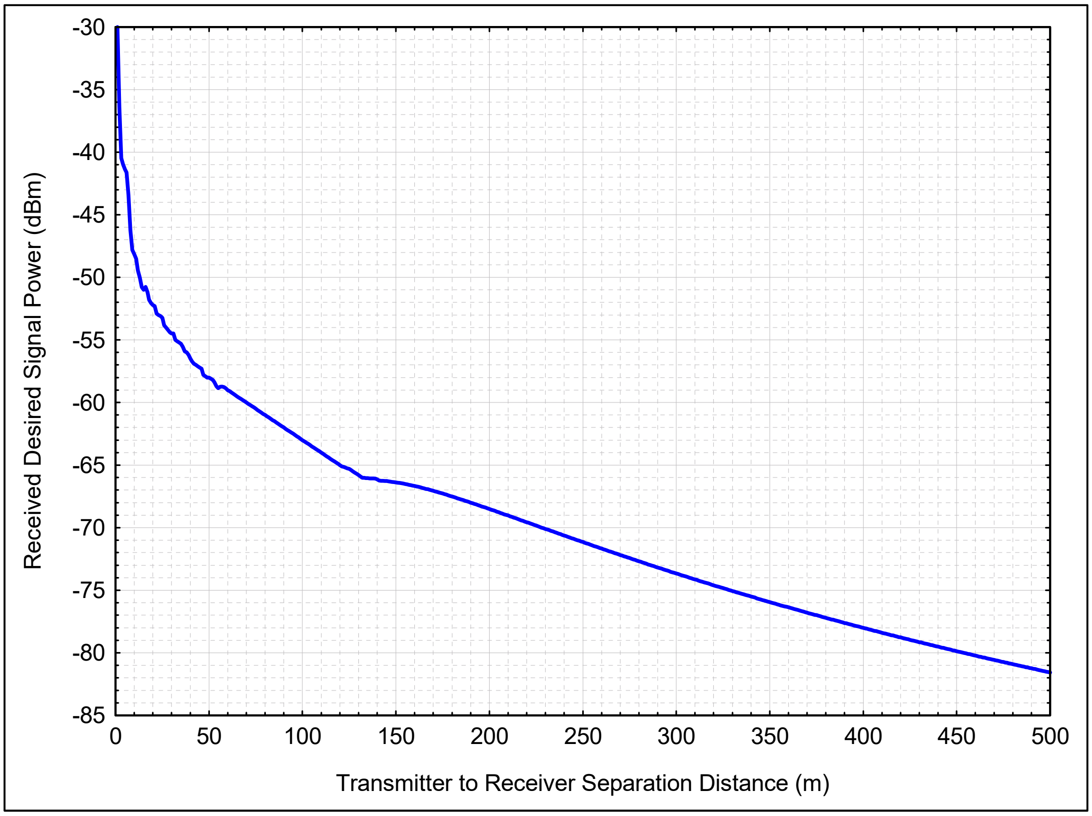

Image from U.S. DOT

Figure C-7b. Received Desired Signal Power at DSRC BSM Receiver from DSRC BSM Transmitter at 20 dBm versus Distance for Short Distances

3 The Effect of Stronger Desired Signal Levels on Achieving Electromagnetic Compatibility

During normal operation of the DSRC transmitter to DSRC receiver link, the separation distances between them are generally less than 2000 meters. Figures C-7a and C-7b shown previously are plots of the desired received signal level between DSRC units. An EIRP of 20.0 dBm was assumed for the transmitted signal level, which includes the transmitter antenna gain. The antenna heights are both 1.5 meters above ground level. The receiver antenna gain is assumed to be 0 dBi for a worst case situation. To attain a signal level of -93 dBm occurs at a distance of 1000 meters (Figure C-7a), so it is feasible that the DSRC receiver sees a large signal for most of its operation in the typical scenarios. Figure C-7b shows that at a practical operating distance of 210 meters the desired received BSM signal level is -69 dBm. With a stronger desired signal level the interference level can be higher and still maintain a good signal-to-interference ratio, S/I (dB).

4 The Frequency Dependent Rejection Required Computation

The FDR required to reduce the interference signal level down to a level needed to attain compatibility is then computed as a function of distance from the received interference level versus distance, the signal-to-interference level, the interference-to-noise level, and the noise level using the equations from section 11.2.2.

An example of this is shown in Figure C-8 for a High Power V2I Channel antenna height of 1.5 meters and a DSRC receiver antenna height of 1.5 meters, where the signal-to-noise ratio is 5 dB and the signal-to-interference ratio is 14 dB. Figure C-8 is the case with the minimum detectable signal of -93 dBm and an interference level of -107 dBm. This is a worst case situation, since the FDR required at a DSRC High Power V2I Channel interference source to DSRC receiver separation distance of 1000 meters is about 34 dB from Figure C-8.

Figure C-5 requires a 10.5 MHz offset to attain 34 dB of FDR available attenuation. This is attainable if the received signal level is at a more practical level of -69 dBm for a desired DSRC transmitter to DSRC Receiver separation of 210 meters. Figure C-9 shows that for a DSRC High Power V2I Channel interference source to DSRC BSM receiver distance of 200 meters the FDR required from Figure C-9 is about 35 dB. Figure C-5 indicates that a frequency offset of 11 MHz is necessary to attain 35 dB of FDR available.

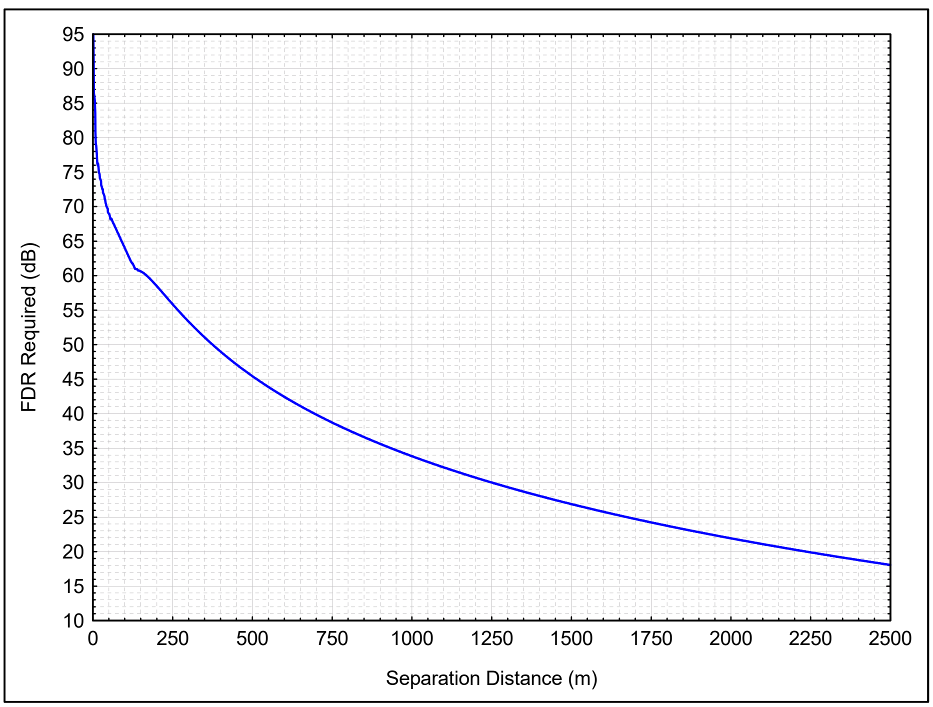

Image from U.S. DOT

Figure C-8. FDR Required between DSRC BSM Receiver and DSRC High Power V2I Channel Interference at 40.0 dBm versus Distance for Minimum Sensitivity Case at -93 dBm

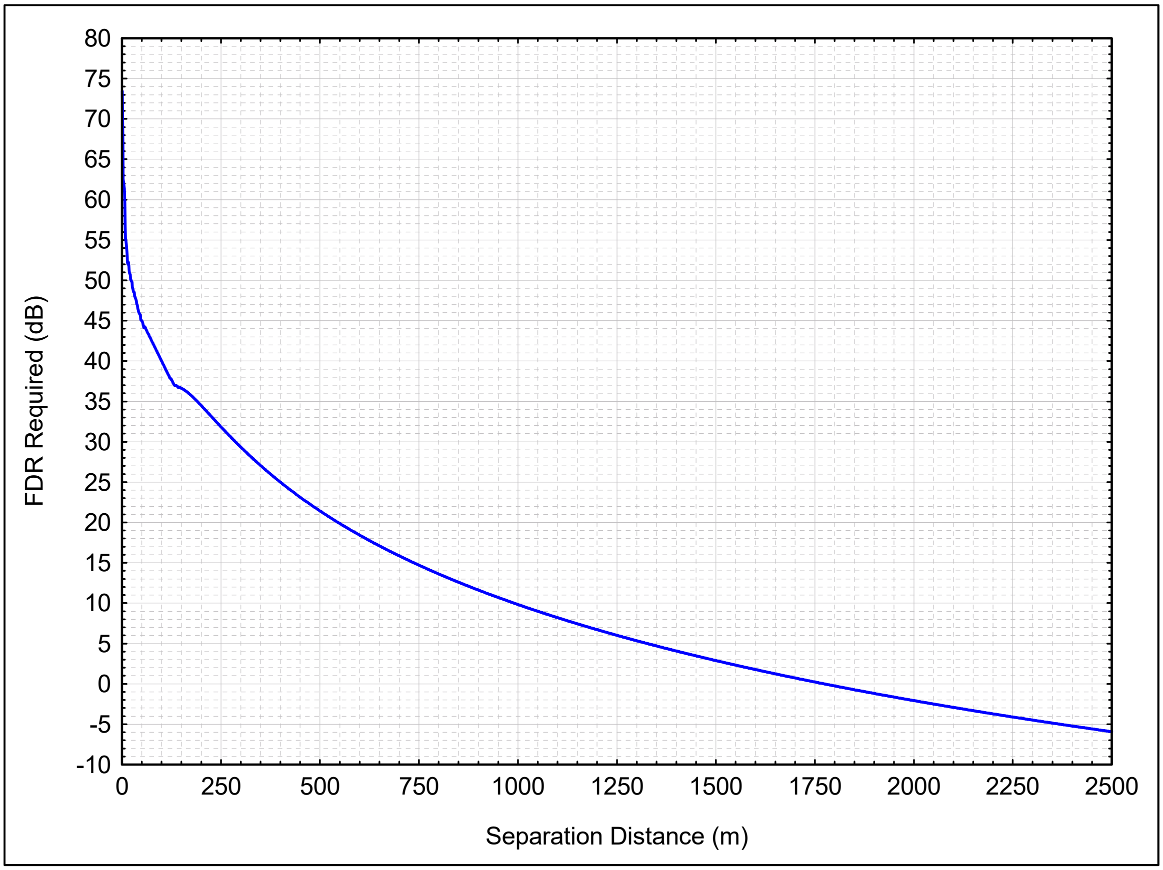

Image from U.S. DOT

Figure C-9. FDR Required between DSRC BSM Receiver and DSRC High Power V2I Channel Interference at 40.0 dBm versus Distance for a Larger Signal Case at -69 dBm

5 Computation of Frequency Offset versus DSRC HPV2I Transmitter to DSRC BSM Receiver Separation Distance

Figures C-10a and C-10b are plots of the frequency offset as a function of High Power V2I Channel transmitter to DSRC BSM receiver distance for a High Power V2I Channel antenna height of 1.5 meters and a DSRC receiver antenna height of 1.5 meters. Figure C-10a is for the case of minimum desired signal level of -93 dBm for a DSRC BSM transmitter to DSRC BSM receiver separation distance of 1000 meters. Figure C-10b is for the desired signal level of -69 dBm and a DSRC transmitter to DSRC receiver separation distance of 210 meters.

Figures C-10a and C-10b are a result of the combination of the calculations of Figures C-8 and C-9 (frequency dependent rejection required versus distance) with those of Figure C-5 (frequency dependent rejection available versus frequency offset). Figure C-10a indicates that the High Power V2I Channel interference source needs to be at a separation distance from the DSRC BSM receiver greater than or equal to 900 meters for a frequency offset of 15 MHz. This is for the condition of a minimum desired signal level of -93 dBm. The plot is almost vertical for shorter distances due to the shape of attenuation characteristic of Figure C-5 for Frequency Dependent Rejection (FDR) available, which is a result of the transmitter emission characteristic of the interference source of Figure C-1a.

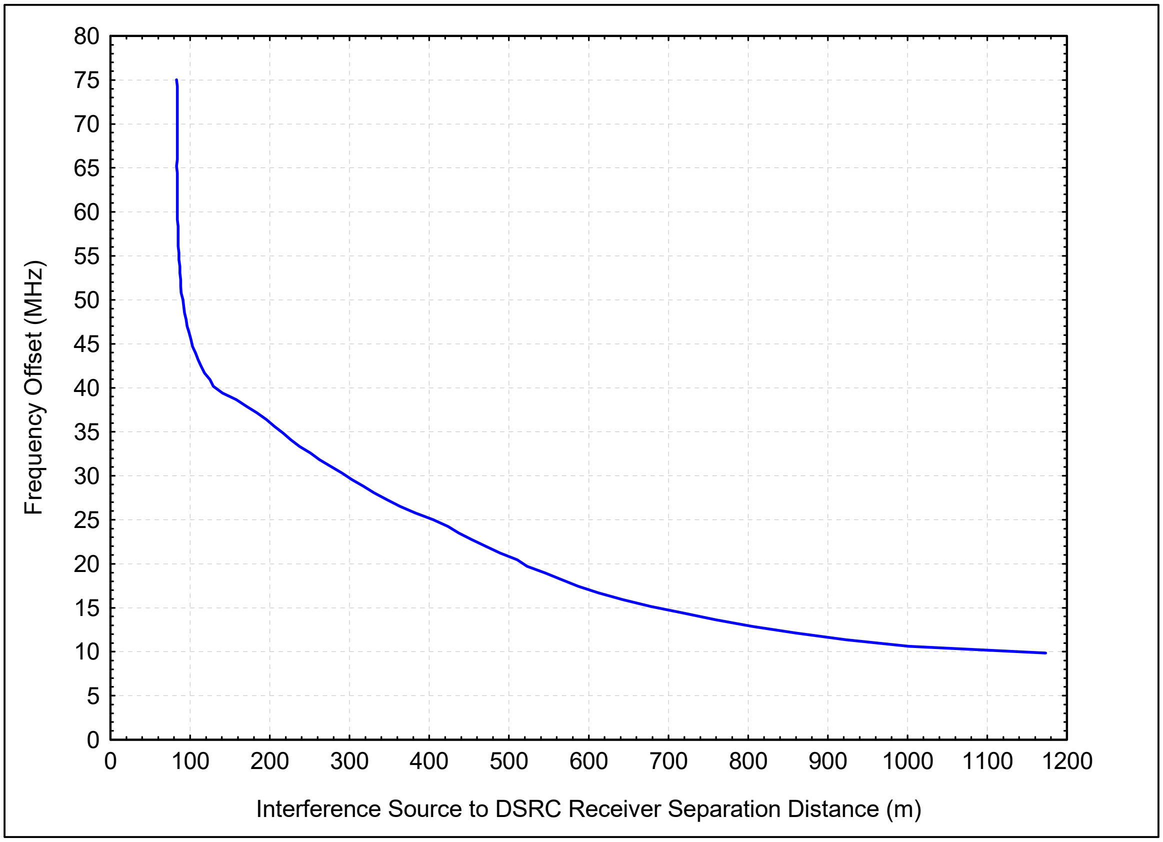

Image from U.S. DOT

Figure C-10a. Frequency Offset versus Separation Distance for DSRC High Power V2I Channel Interference into a DSRC BSM Receiver for Minimum Sensitivity at -93 dBm

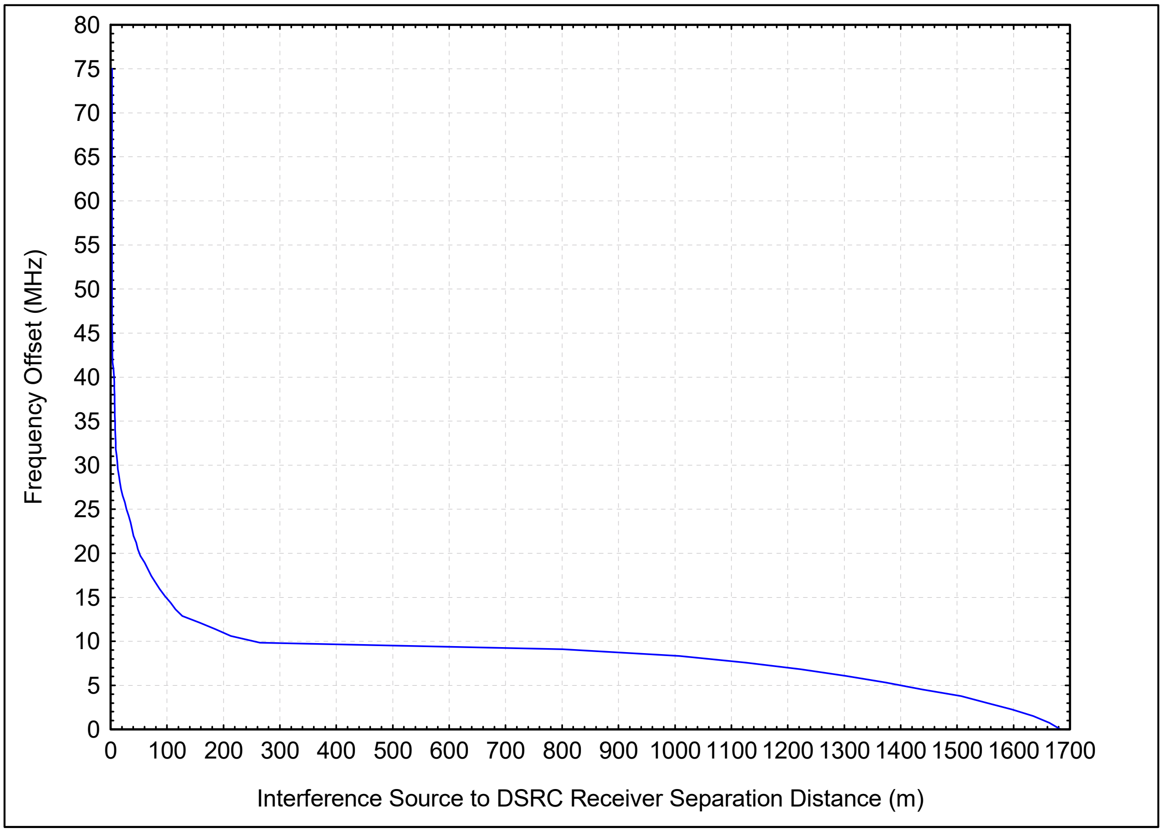

Image from U.S. DOT

Figure C-10b. Frequency Offset versus Separation Distance for DSRC High Power V2I Channel Interference into a DSRC BSM Receiver for a Larger Signal Case at -69 dBm

A more practical example would be that from Figure C-10b for a DSRC High Power V2I Channel interference source to victim DSRC BSM receiver separation distance of 100 meters for a frequency offset of 15 MHz. The desired DSRC BSM received signal level is at -69 dBm. Other values of required separation distance for different frequency offsets can be obtained from Figures C-10a and C-10b.

6 Distance versus Distance plots

Figures C-11a through C-11e are plots of the 40.0 dBm DSRC High Power V2I Channel 178 interference source to DSRC BSM Broadcast Channel 172 receiver separation distance versus the 20.0 dBm Channel 172 desired DSRC BSM transmitter to desired DSRC BSM receiver distance. These plots show the required separation distances of the interference source from the receiver as a function of the desired transmitter to desired receiver separation distance for different frequency offsets.

Figures C-11a (0 to 1100 meters desired separation distance on the x-axis) and C11b (0 to 40 meters desired separation distance on the x-axis) contain the on-tune case as well as the off-tune 10 MHz, 20 MHz, 30 MHz, and 60 MHz cases. Figures C-11c and C-11d are similar to Figures C-11a and C-11b, except that the on-tune case has been eliminated to provide more resolution in the y-axis (DSRC High Power V2I Channel interference source to desired DSRC BSM receiver).

Figure C-11e is the case for the 60 MHz frequency offset (sixth adjacent channel). Notice that the plots for the 20 MHz (second adjacent channel) and 30 MHz (third adjacent channel) frequency offset cases are different than that of the 60 MHz case (sixth adjacent channel offset).

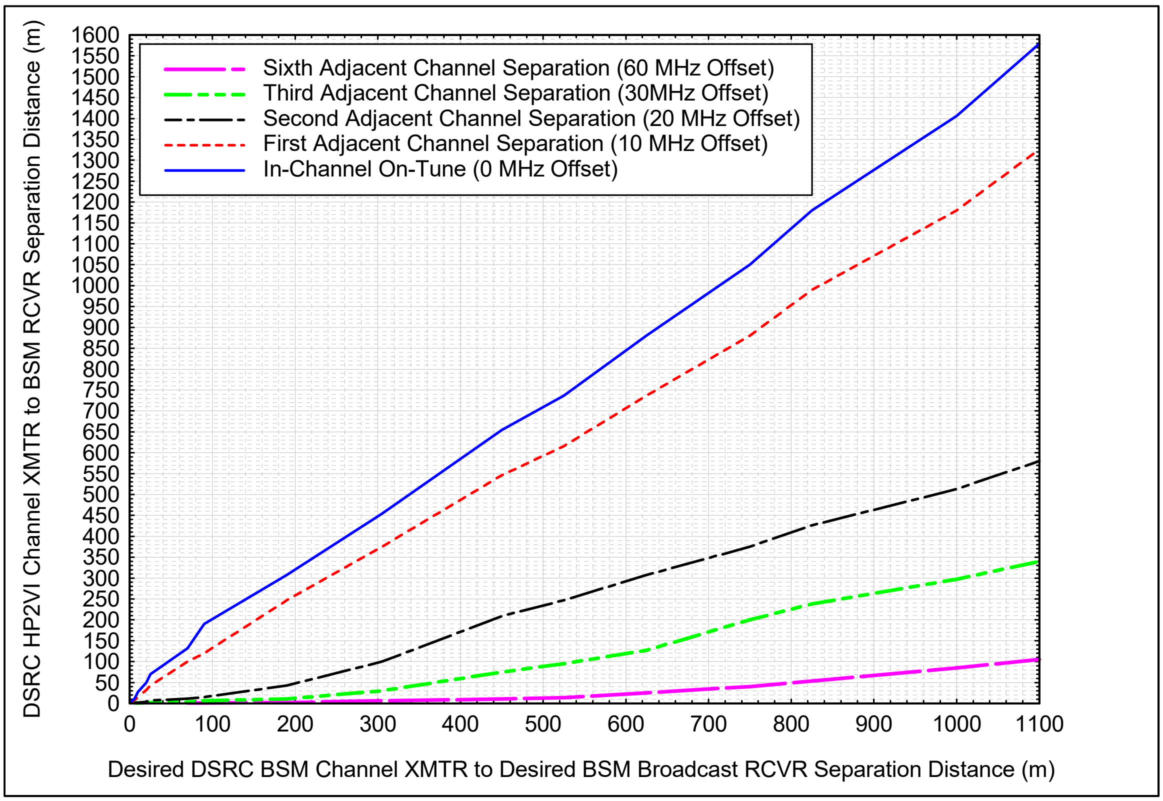

Image from U.S. DOT

Figure C-11a. 40.0 dBm DSRC High Power V2I (Channel 184) Interference Source to DSRC BSM Broadcast Channel 172 Separation Distance versus 20.0 dBm (Channel 172) Desired DSRC BSM XMTR to Desired DSRC BSM RCVR with On-Tune Case for Long Distances

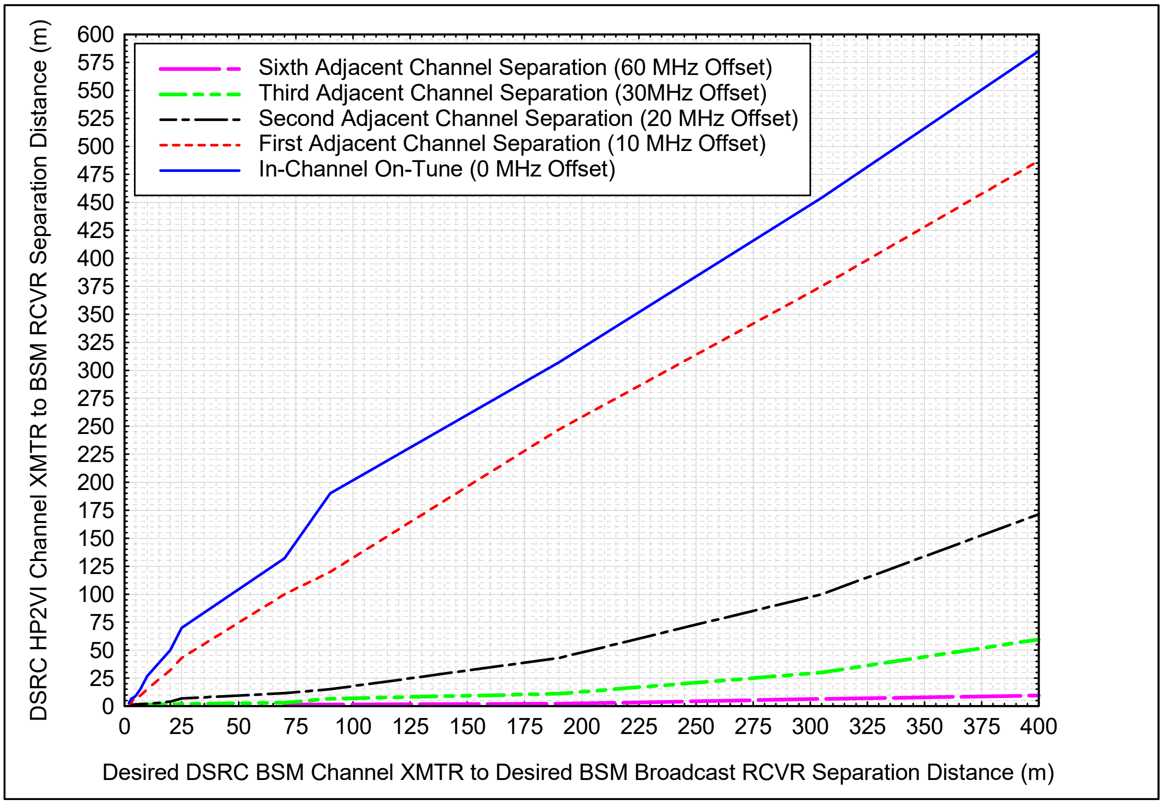

Image from U.S. DOT

Figure C-11b. 40.0 dBm DSRC High Power V2I (Channel 184) Interference Source to DSRC BSM Broadcast Channel 172 Separation Distance versus 20.0 dBm (Channel 172) Desired DSRC BSM XMTR to Desired DSRC BSM RCVR with On-Tune Case for Short Distances

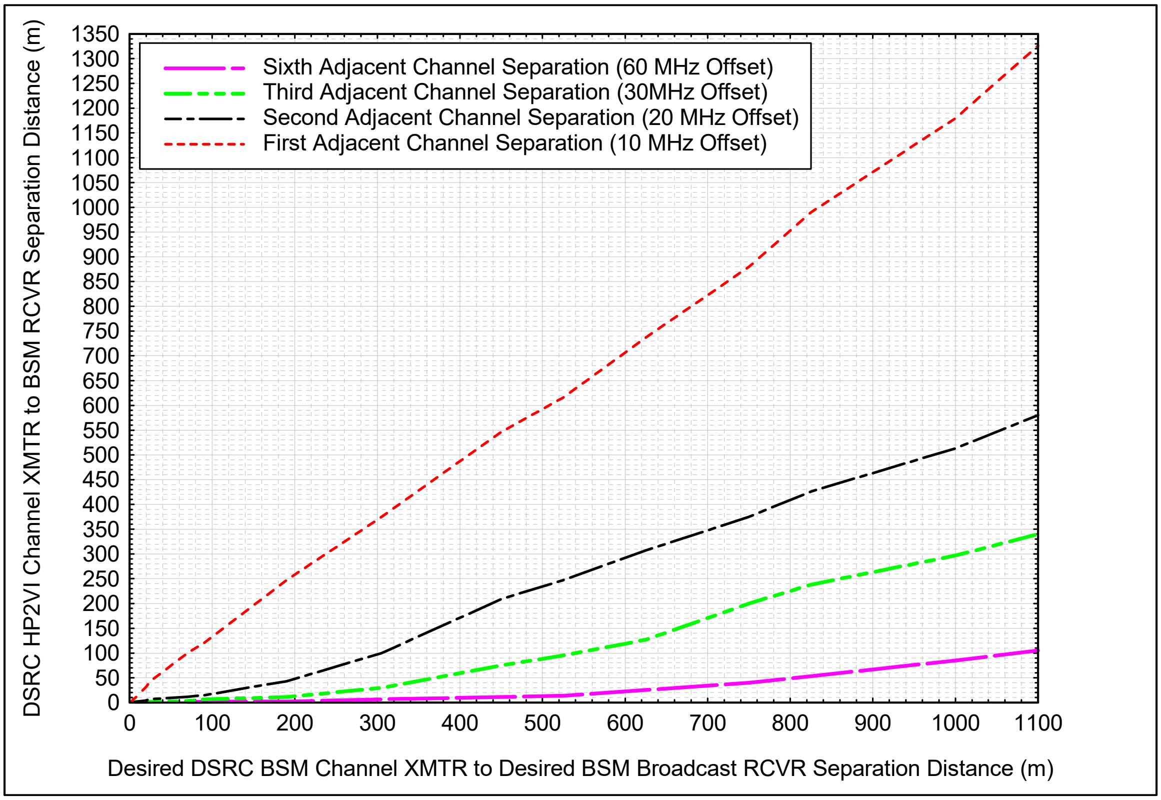

Image from U.S. DOT

Figure C-11c. 40.0 dBm DSRC High Power V2I (Channel 184) Interference Source to DSRC BSM Broadcast Channel 172 Separation Distance versus 20.0 dBm (Channel 172) Desired DSRC BSM XMTR to Desired DSRC BSM RCVR with Only Adjacent Channel Cases for Long Distances

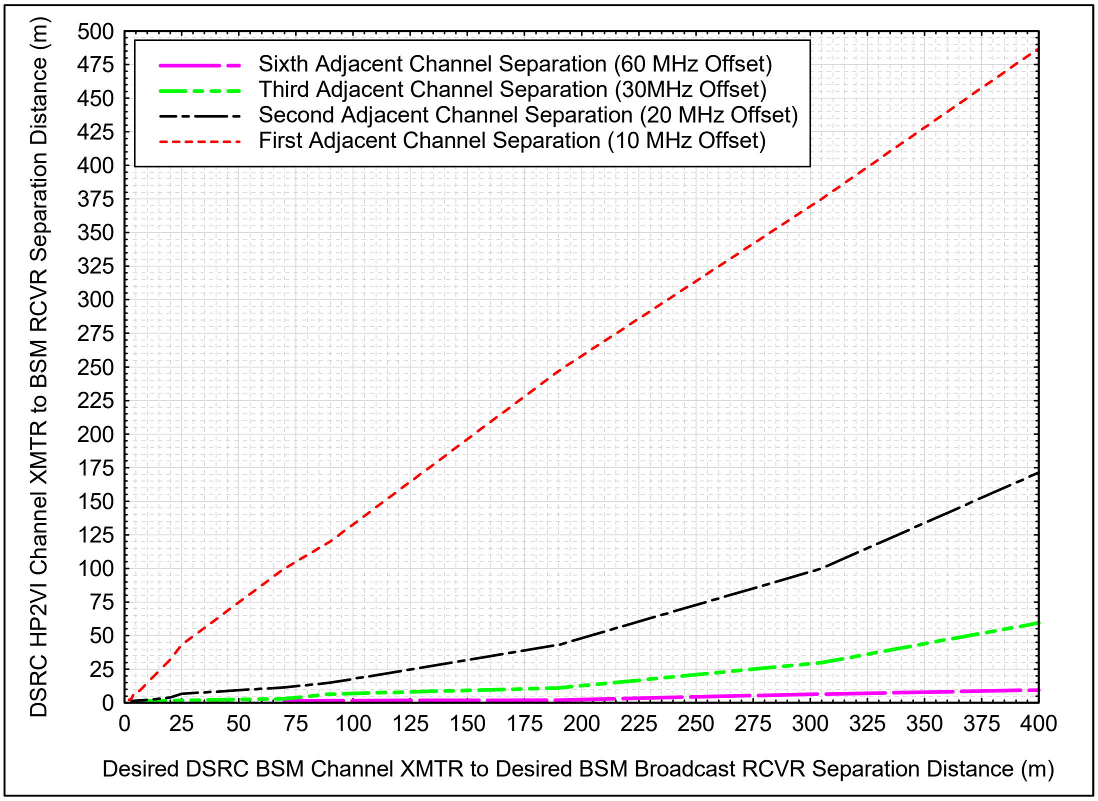

Image from U.S. DOT

Figure C-11d. 40.0 dBm DSRC High Power V2I (Channel 184) Interference Source to DSRC BSM Broadcast Channel 172 Separation Distance versus 20.0 dBm (Channel 172) Desired DSRC BSM XMTR to Desired DSRC BSM RCVR with Only Adjacent Channel Cases for Short Distances

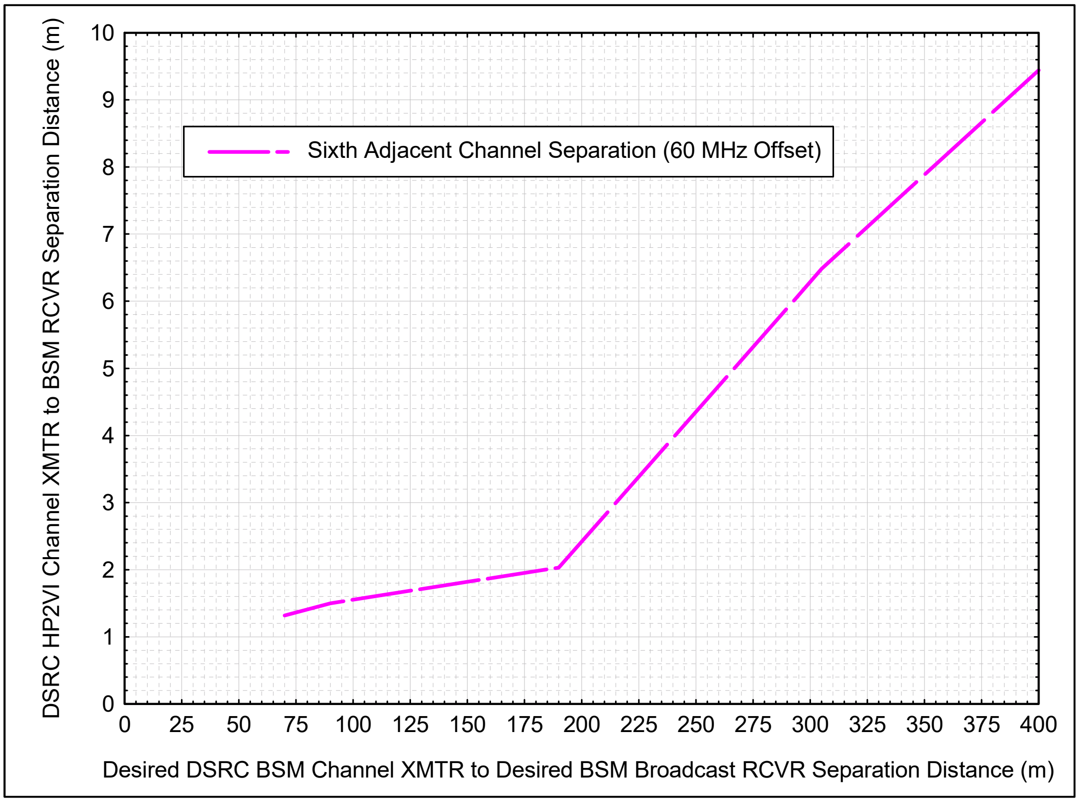

Image from U.S. DOT

Figure C-11e. 40.0 dBm DSRC High Power V2I (Channel 184) Interference Source to DSRC BSM Broadcast Channel 172 Separation Distance versus 20.0 dBm (Channel 172) Desired DSRC BSM XMTR to Desired DSRC BSM RCVR with Sixth Adjacent Channel Case for Short Distances

These plots are obtained by using the received power versus distance computations for both the DSRC High Power V2I Channel interference source and the DSRC BSM Channel transmitter plots of Figures C-6a and C-6b and Figures C-7a and C-7b, respectively.

Notice that additional rejection/attenuation for frequency offsets greater than the third adjacent channel (30 MHz) there is a significant advantage for frequency offsets greater than 30 MHz. This is a result for the emission spectra of the DSRC High Power V2I Channel for Class D as specified in IEEE Standard 802.11-2012 and shown in Figure C-1. This could be improved by using an actual measurement of a DSRC High Power V2I Channel emission, which may provide a tighter emission spectrum with less spillover to the adjacent channels. A measurement of the out-of-band emission spectra may reveal a significant slope outside of the plus and minus 15 MHz frequency offset instead of the horizontal lines as indicated in Figures C-1a and C-1b.

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