

Vehicle Safety Communications - Applications: Multiple On-Board Equipment Testing

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ABSTRACT

The United States Department of Transportation (USDOT) and the Crash Avoidance Metrics Partnership-Vehicle Safety Communications 2 (CAMP-VSC2) Consortium (Ford, General Motors, Honda, Mercedes-Benz, and Toyota) initiated, in December 2006, a three-year collaborative effort in the area of wireless-based safety applications under the Vehicle Safety Communications-Applications (VSC-A) Project. The VSC-A Project developed and tested Vehicle-to-Vehicle (V2V) communications-based safety systems to determine if Dedicated Short Range Communications (DSRC) at 5.9 GHz, in combination with vehicle positioning, would improve upon autonomous vehicle-based safety

systems and/or enable new communications-based safety applications.

A crucial element required for potential deployment of V2V safety systems is the understanding of how DSRC will perform as larger numbers of DSRC radios are added to the system and ensuring that the communication channel can support a large number of vehicles in potentially congested traffic conditions. This is referred to as system scalability. In the VSC-A Project, a preliminary, multiple On-Board Equipment (OBE) testing effort was undertaken utilizing up to sixty DSRC radios which had the following objectives:

1. Analyze how well the communication channel operates, primarily in terms of Packet Error Rate (PER) and the Inter-

Packet Gap (IPG) distribution, in a variety of channel configurations and transmit characteristics.

2. Gain experience in the set-up and execution of a large-scale DSRC test effort and in the areas of tools development, software tools, efficient logistics, setup, procedures, and analysis to ensure the end results are correct, meaningful, and repeatable.

The multiple OBE scalability testing conducted and the results obtained are described in this paper. Based on the results it is clear that using a dedicated, full-time, safety channel to transmit V2V safety messages provides superior performance over any of the other channel configuration methods employing IEEE 1609.4 channel switching when considering the PER and IPG metrics.

INTRODUCTION

The United States Department of Transportation (USDOT) and the Crash Avoidance Metrics Partnership-Vehicle Safety Communications 2 (CAMP-VSC2) Consortium (Ford, General Motors, Honda, Mercedes-Benz, and Toyota) initiated, in December 2006, a three-year collaborative effort in the area of wireless-based safety applications under the Vehicle Safety Communications-Applications (VSC-A) Project. One of the main achievements of the project is the implementation, testing, verification, and standardization of a safety message that supports all of the VSC-A safety applications. The result is the Basic Safety Message (BSM) as defined in the SAE J2735 Message Set Dictionary standard [1]. This message set is crucial in that it provides the foundation for the required Vehicle-to-Vehicle (V2V) safety system interoperability between automotive manufacturers.

Understanding how Dedicated Short Range Communications (DSRC) will perform as larger numbers of DSRC radios are added to the system (i.e., system scalability) is crucial for deployment of V2V safety systems. Following the successful completion of VSC-A Project objective testing activities [5], a preliminary multiple On-Board Equipment (OBE) scalability testing effort was undertaken utilizing up to 60 DSRC radios.

The primary objectives of the testing were to:

1. Gather the necessary data in order to analyze how well the communication channel operates, primarily in terms of Packet Error Rate (PER) and the Inter-Packet Gap (IPG) distribution, in a variety of channel configurations and transmit characteristics as well as a varying total number of radios
2. Gain experience in the set-up and execution of a large scale DSRC test effort and in the areas of tools development, software (SW) tools, efficient logistics, setup, procedures, and analysis to ensure the end results are correct and repeatable

Secondary goals and achievements confirmed that the operation of the VSC-A system, including the core and safety application modules, was not adversely affected during each of the scaling increments. Some of the scalability tests included on-board security, based on IEEE 1609.2 Elliptic Curve Digital Signature Algorithm (ECDSA) [2] and Verify-on-Demand (VoD) [4].

The OBE implementation [5] was enhanced to enable the emulation of two OBEs via dual-radio functionality. Self-contained DSRC enclosures (pods) were developed as a cost-effective approach for increasing the number of radios in the scalability test to the maximum achievable level of sixty units. In addition, to aid in ensuring testing was efficient, repeatable, and correct, a 2.4GHz Wi-Fi™ wireless mesh network, which enabled communication with each of the OBEs from a single point, along with scripts for command and control of the OBEs, was developed. Finally, the Over-the-Air (OTA) data was supplemented with a few additional data elements to ensure, in real-time, the ability to verify that the proper configuration was being used by all the radios during each test run.

Four channel configurations were defined for this testing. Three of the channel configurations utilized IEEE 1609.4 [3] channel switching and two of its variants. The fourth one utilized full-time access to Channel 172 (the safety channel).

The rest of this paper describes the multiple-OBE testing activities and provides an analysis of the results obtained based on the testing.

Note: Throughout this paper the term Host Vehicle (HV) refers to the OBE that was the focal point for the data collection and subsequent analysis for a particular test and the term Remote Vehicle (RV) refers to any other OBE, participating in the test, whose data was being collected by the HV. Each test had multiple HVs to allow the data from the test to be analyzed from multiple test setup perspectives, however, the data presented on any individual chart is from the perspective of a single HV.

DSRC POD DEVELOPMENT

In preparation for the multiple-OBE testing, the following activities were undertaken:

1. The OBE implementation, which supports dual-radio operation, was enhanced to enable the OBE to emulate two separate OBEs via the dual radios.
2. A second OBE was integrated into the vehicle system test bed in such a way that full duplication of the system test bed hardware (HW) was not required by splitting Global Positioning System (GPS) and vehicle Controller Area Network (CAN) inputs. In combination with activity 1 above, this effectively brought the total number of radios per vehicle to four.

3. Self-contained DSRC pods running a GPS-only mode were developed to increase the total number of potential communication nodes to 60.

Due to the limited number of OBEs that could be adequately installed in the vehicles and with the aid of the dual-radio functionality, the DSRC pod development was a critical and cost-effective means of increasing the number of radios to the desired level for the scalability testing efforts. The design of the pods allowed for them to be deployed in a stationary configuration via a tripod mount or in a mobile configuration via magnetic mount to the roof of a vehicle. The magnetic mounting capability, while not critical for the preliminary scalability testing effort, will potentially be more valuable in future scalability testing efforts. It allows the increase of the number of mobile DSRC-capable vehicles without having to fully equip vehicles and, thus, minimize costs. [Figure 1](#) and [Figure 2](#) below detail some of the internal and external design aspects of the DSRC pods which include:

- Internal Top Level: Steel Plate for mounting DSRC antenna, GPS antenna / receiver, and Wi-Fi antenna(s)
- Internal Middle Level: Holds OBE, 2.4GHz Wi-Fi Wireless Router, and optional equipment via side panel mounting
- Internal Bottom Level: Holds 12 Amp hour NiMH battery and steel box for internal component connection to external equipment
- External Enclosure: Made of material that is transparent to radio frequencies in the 5.9 GHz DSRC frequency band
- External Base Plate: Steel box for external equipment connection to internal components, magnetic mounts for attaching to the roof of a vehicle, 5/8 - 11 tripod mounting point

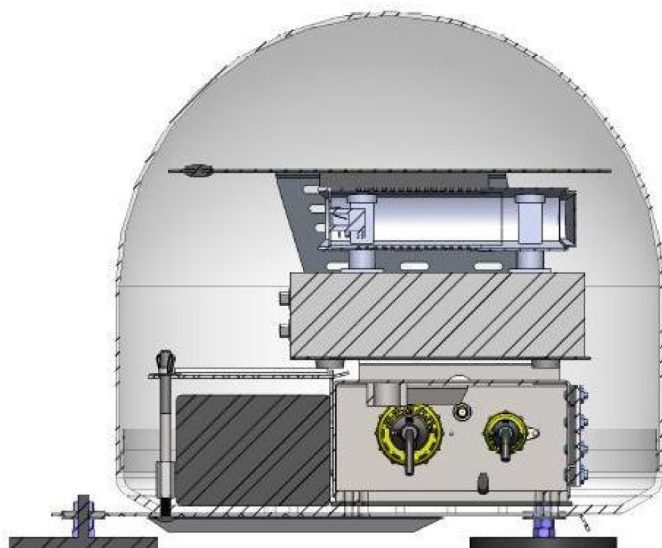


Figure 1. DSRC Pod Internal Structure Diagram

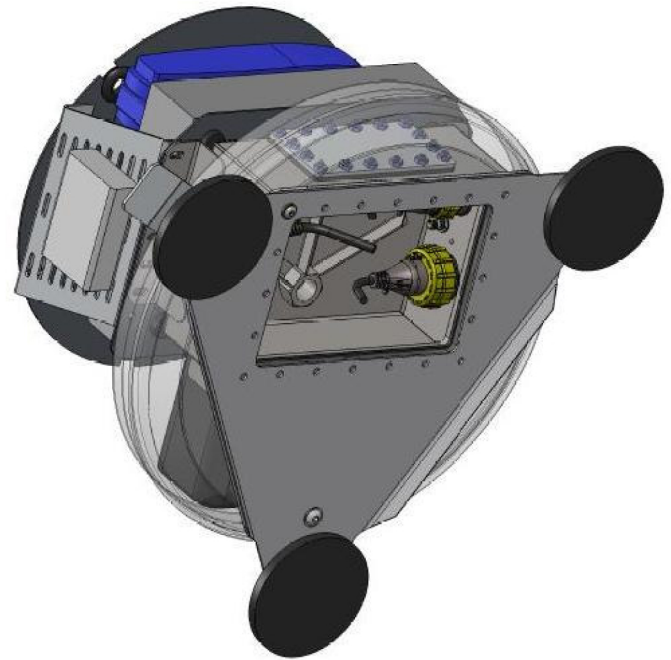


Figure 2. DSRC Pod Base Plate Diagram

TEST COMMAND, CONTROL, AND CONFIRMATION

Early in the project, a smaller scale, project testing effort exposed the difficulties in manually configuring and controlling multiple OBEs and ensuring the testing was correct, repeatable, and efficient. Therefore, the team made sure the preparation process included a number of steps to address these difficulties:

1. The use of a 2.4GHz Wi-Fi wireless network which enabled communication with each of the OBEs from a single point
2. The development of scripts for command and control of the OBEs via the 2.4GHz Wi-Fi wireless network
3. The addition of the applicable test number to the corresponding OTA message to ensure that early on in the field testing each OBE in the network was running the proper test configuration

WIRELESS NETWORK

A 2.4GHz Wi-Fi wireless router was installed and connected to the OBE(s) in each of the vehicles and pods. The routers were configured to utilize a light-weight mesh network protocol. Individual nodes use this topology information to compute the best path to a destination using and minimum number of relays or "hops." This provided a single central point for command and control of the entire system over a large area (see [Figure 14](#) and [Figure 15](#) in [Appendix B](#) for the vehicle and pod deployment configurations used during the

testing) without requiring use of high power communications equipment.

SCRIPT DEVELOPMENT

With the 2.4GHz Wi-Fi wireless network in place, a set of scripts were developed to take advantage of the single central point of command and control that the network offered. For each test the scripts allowed for pushing the required configuration files to each of the OBEs, starting up each of the OBEs at the same time, and shutting down each of the OBEs at the same time at the end of the test. The scripts were also used to confirm that each test data log was appropriately captured on the OBEs upon completion of the test. The scripts, in combination with the network, allowed for confidence in test repeatability, efficient test execution, and flexibility in adding and/or modifying tests without requiring manual access to each OBE.

TEST NUMBER IDENTIFICATION

To confirm that the same test was being run on each of the OBEs for each test, the startup scripts provided a unique test number to the OBE at startup. This test number was then appended to all OTA transmissions from the OBE. A special Engineering Graphical User Interface (EGUI) screen was developed to display the test number of the test the HV was running as well as highlight in red any of the RVs whose test number did not match that of the HV.

CHANNEL AND TEST CONFIGURATIONS

Four different channel configurations were identified along with seven tests exhibiting different transmit characteristics in order to determine how the channel behaved for each of the tested channel configuration/transmit characteristic combinations. This was one of the primary goals of the testing.

CHANNEL CONFIGURATIONS

Testing by the VSC-A team showed that, even with smaller numbers of radios, utilization of the IEEE 1609.4 channel switching mode without any changes leads to an increase in the observed PER due to “synchronized collisions.” This is caused by the application layer being unaware of the start point and end point of the Control Channel (CCH) and/or the Service Channel (SCH) interval (defined by IEEE 1609.4). This increases the likelihood of the application layer attempting to transmit a message in a channel interval other than the intended one. If this occurs, the Media Access Control (MAC) layer will hold on to the message and transmit it at the beginning of the appropriate channel interval. Even with the back-off mechanism defined in IEEE 802.11, if enough radios are present in the system, the

likelihood of having synchronized collisions increases. [Table 1](#) below lists the channel configurations which were tested.

Table 1. Channel Configurations for Scalability Testing

Channel Configuration #	Channel Configuration Description
C1	IEEE 1609.4 channel switching mode
C2	Channel 172 dedicated safety channel (i.e., no channel switching)
C3	IEEE 1609.4 channel switching mode with messages submitted for transmission at a random time during each control channel interval
C4	IEEE 1609.4 channel switching mode with messages submitted for transmission via a time-shifting algorithm in an attempt to evenly space transmissions out during the intended channel

Configuration 1 (C1) was included in the scalability testing to confirm the synchronized collision issue as well as to serve as a baseline for the test results from the other channel configurations. Configurations 3 and 4 (C3 and C4) are countermeasures which were developed in an attempt to address the synchronized collision issue and in turn decrease the PER encountered when employing IEEE 1609.4 channel switching. Finally, Configuration 2 (C2) does not employ channel switching which provided full-time access to the channel essentially removing the artificial boundaries created by the CCH and SCH intervals as well as the need for the transmission guard interval at these boundaries. This more than doubles the bandwidth for transmission which decreases the likelihood of two radios transmitting at the same time, and, thus, was expected to decrease the PER observed over any of the other channel configurations tested.

TEST CONFIGURATIONS

Like the channel configurations, a baseline test configuration was defined. This configuration was tested for all four channel configurations in combination with all four DSRC radio scaling increments (24, 36, 48, and 60 radios). Some of the primary configuration settings for the baseline test configuration included:

- Stationary vehicles
- Transmit timer re-randomized every 30 seconds (not applicable for C3)
- Safety applications disabled
- Security disabled

- 222 bytes of extra padding added to OTA messages (total packet size 378 bytes)
- 10 Hz message transmit rate
- 6 Mbps data transmit rate

Note that the 222 bytes of extra padding was included to account for the security overhead that would have been present had security been enabled and a certificate attached to each message.

The baseline test configuration was the primary configuration used for analyzing channel behavior for each of the four channel configurations listed in [Table 1](#). Seven additional tests were defined and were run on a sub-set of the channel configurations and scaling increments. These tests varied one or more of the baseline test configuration settings in order to analyze what effect these settings had on the channel configurations when compared to the results of the baseline test configuration. [Table 2](#) in [Appendix A](#) provides a list of all the tests run along with the channel configurations and radio scaling increments that were tested for each test configuration. This paper provides the detailed analysis for the baseline stationary tests (Test # 1 in [Table 2](#)) and baseline moving tests (Test #2 in [Table 2](#)). For the other tests a brief discussion of the results is provided in the 'Summary/Conclusions' section of this paper.

SAMPLE STATIONARY SCALABILITY TEST RESULTS

For the stationary test data analysis, gathering the necessary data in order to analyze the PER and the IPG distribution was of primary interest. Testing the baseline test configuration (Test # 1 in [Table 2](#)), in combination with each of the DSRC radio scaling increments for each of the four channel configurations listed in [Table 1](#) above, was the initial focus of the testing activities. The results of this testing are presented in this section along with a brief discussion on some of the other non-baseline stationary test results.

Note that for any given radio scaling increment the number of expected receive signals for data analysis was two less than the number of transmit signals. This was due to the primary radio on an OBE not receiving its own transmit signal as well as the primary radio on an OBE filtering out the signals it received from its secondary radio. The filtering of the second radio was done in order to simplify the dual radio implementation.

TEST POD & VEHICLE DEPLOYMENT

As previously mentioned, each OBE was able to emulate two separate OBEs via the dual radio functionality supported by the OBE. There were eleven pods, each with one OBE, providing for 22 radios. In addition, there were 10 vehicles, 9 of which had 2 OBEs and 1 that had a single OBE which

added an additional 38 radios for a grand total of 60 radios and thus 60 emulated OBEs.

The stationary pod/vehicle layout consisted of a center cluster of 4 pods and 5 vehicles with the remaining pods and vehicles placed at varying distances up to 275 m from the center cluster. [Figure 14](#) in [Appendix B](#) provides a diagram identifying the location of each of the pods and vehicles used in the stationary tests.

The layout of the pods and vehicles was such that the center cluster OBEs were in communication range of all the other OBEs, whereas the OBEs furthest from the center cluster were not within communication range of one another. It should be noted that the primary radio on the OBE supported ~19-20 dBm output power, whereas the secondary radio supported ~14.5-16 dBm output power. It was the output power of the secondary radio that influenced selecting 275 m as the maximum range from the center cluster.

As previously mentioned, four DSRC radio scaling increments were tested consisting of 24, 36, 48, and 60 transmitting radios. In general the lower scaling increments included pods and vehicles closer to the center cluster while the ones that were further away were included as the scaling increments increased.

Note that due to the multi-tasking nature of the OBE, at the application layer, the OBE was not capable of providing both a non-emulated OBE packet and an emulated OBE packet to the radio HW of the OBE at precisely the same time. However, due to each of the OBE radios operating independently of one another, once the packets were obtained by the radio HW, the physical (PHY) characteristics of the channel take over. Thus, while it was unlikely that the 2 radios on the same OBE would provide contention with each other, it was expected that the 2 radios would be equally likely to provide contention with other remote OBEs in the test. Therefore, even though emulated OBEs were used in these tests via the dual-radio functionality of the OBE, the test results are expected to be closely representative to those obtained had non-emulated OBEs been used instead.

PACKET ERROR RATE TEST RESULTS

[Figure 3](#), [Figure 4](#), [Figure 5](#) below show the results of PER analysis from the perspective of vehicle V2 as the HV which was part of the center cluster (see [Figure 14](#) in [Appendix B](#)). C1 (1609.4-Timer Based), C3 (1609.4-Random Control Channel Interval Transmit), and C2 (Dedicated Safety Channel 172) results are shown for the 60 radio scaling increment tests only; however, the trends for all scaling increments were similar to the ones presented. The results from C4 (1609.4-Time Shifter) were very similar to C3; thus only the C3 results are presented.