Figure 81: Receiver Behind the Truck Along I-880

17.2 Data Analysis

Figure 82 and Figure 83 show the PER and RSSI curves for the freeway shadowing tests. These results are for the following power levels: 5 dBm, 10 dBm, 20 dBm, and 33 dBm. The data rate in each test was 3 Mbps.

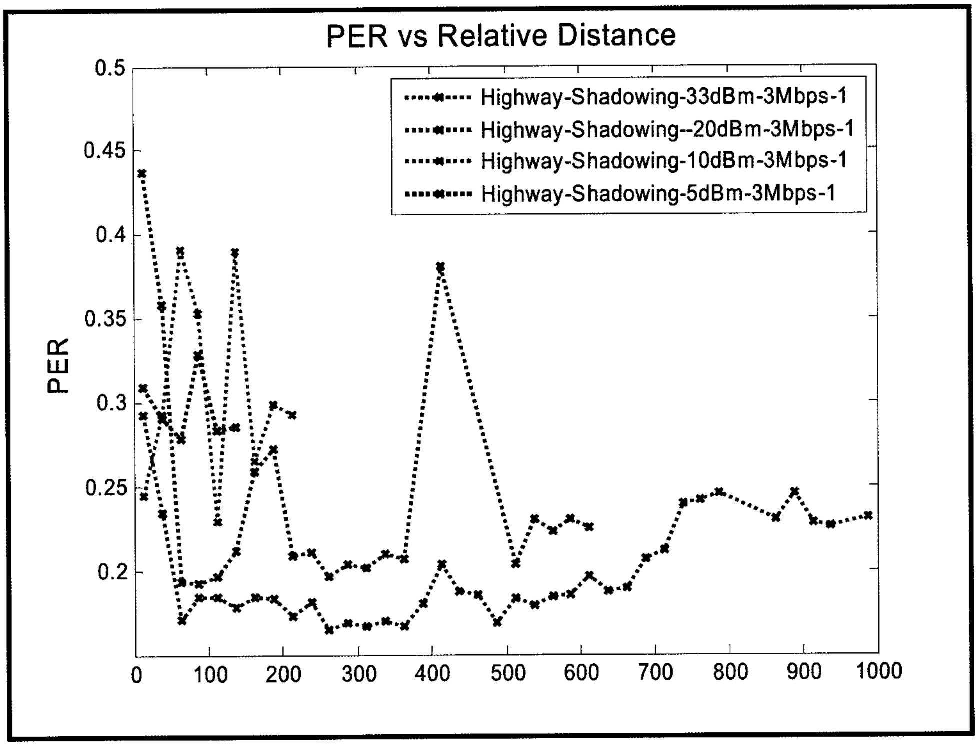


Figure 82: Comparison of PER versus Distance Curves for Various Power Levels in a Freeway-Shadowing Scenario when Transmitter is Set to 3 Mbps

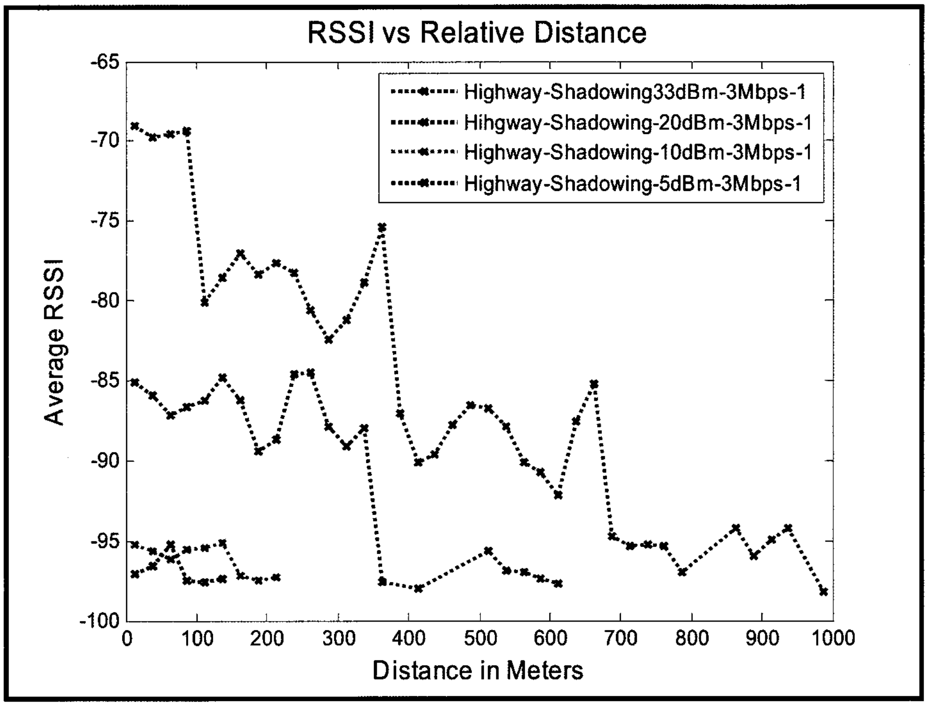


Figure 83: Comparison of RSSI versus Distance Curves for Various Power Levels in a Freeway-Shadowing Scenario when Transmitter is Set to 3 Mbps

Figure 84 and Figure 85 show the effect of different data rates (3 Mbps and 6 Mbps) at different transmit powers (20 dBm and 33 dBm). Performance differences are not significant.

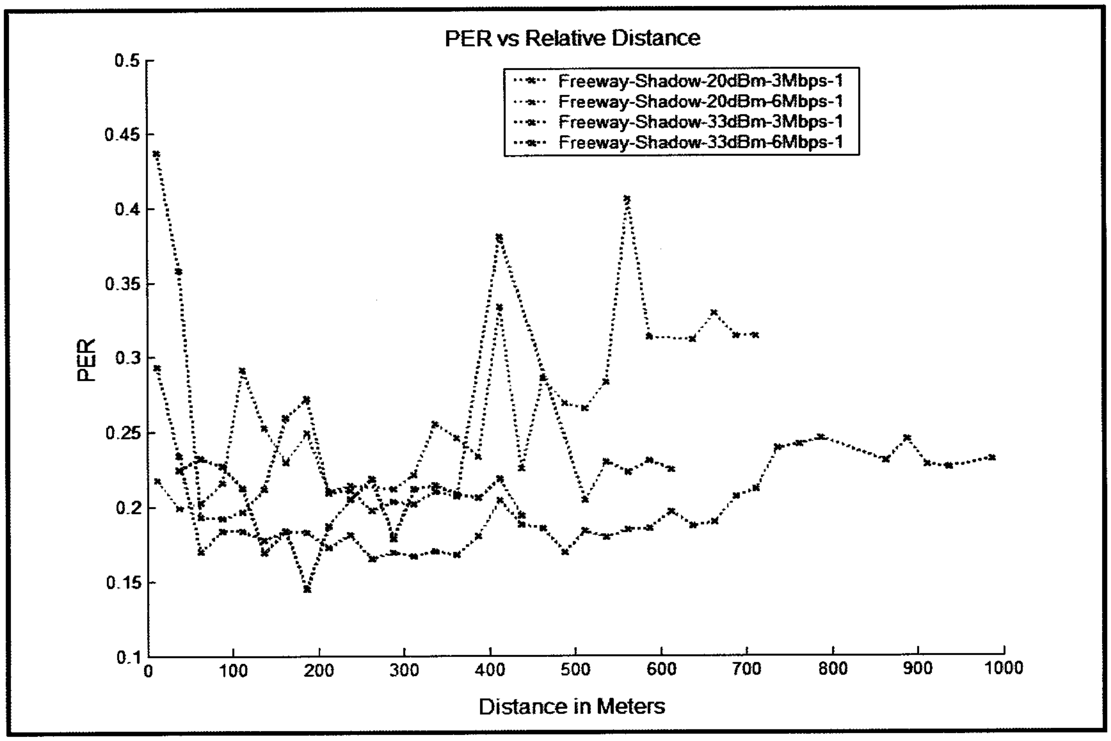


Figure 84: Comparison of PER Curves in a Freeway-Shadowing Scenario Test for 33 dBm and 20 dBm at 3 Mbps and 6 Mbps

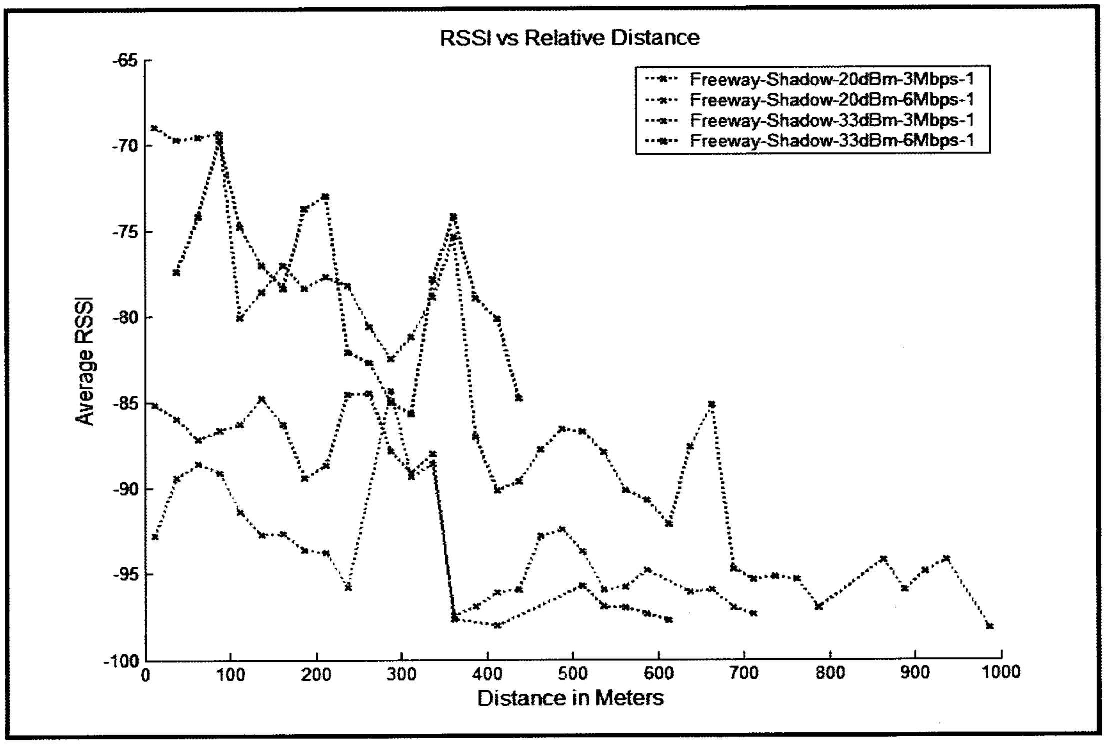


Figure 85: Comparison of RSSI Curves in a Freeway-Shadowing Scenario Test for 33 dBm and 20 dBm at 3 Mbps and 6 Mbps

17.3 Observations for Freeway–Shadowing Scenario Test

1. 33 dBm transmissions offer a PER of about 10 percent for up to 500 meters
2. 20 dBm transmissions offer a PER of about 20 percent for up to 400 meters
3. 5 dBm and 10 dBm transmission cannot support reliable DSRC communications in a Shadowing environment. At these power levels the PER never drops below 20 percent.
4. Regardless of transmit power, when the V2V distance approaches zero the PER increases.. The higher PER at close distances can be attributed to the fact that the truck more completely blocks the receiver from the transmitter. A similar phenomenon was observed in the Baseline Shadowing tests at 5 dBm and 10 dBm (see Section 6).

18 Rural-Highway-Shadowing Scenario Test

The Rural-Highway-Shadowing Scenario test was conducted along Highway 156 in Hollister, California. In this test, the transmitter, truck, and receiver remained in the same lane. The receiver maintained a safe driving distance behind the truck; while the transmitter varied its speed to achieve a good spread of V2V distances. This test was conducted for the various test cases outlined in Table 14.

Table 14: Test Cases for the Rural-Highway-Shadowing Scenario

TX Power / Data Rate	10dBm	20dBm	26dBm	33dBm
3Mbps	Test 1	Test 3	Test 5	Test 7
6Mbps	Test 2	Test 4	Test 6	Test 8

18.1 Location Overview

The propagation environment was similar to that of the rural highway environment described in Section 16 except for the addition of the truck to serve as a NLOS obstruction between the vehicles. The road is fairly representative of a rural highway with open fields and occasional trees, houses, or farms on either side of the road. Figure 86 shows the propagation environment on Highway 156. Note that in comparison with the Freeway Shadowing environment discussed in Section 17, the rural highway generally had lower vehicle density, and thus less vehicle-related multipath.

Figure 86: Driving Down Highway 156

18.2 Data Analysis

Figure 87 shows the PER measured in the Rural-Highway-Shadowing Scenario tests at 3 Mbps for various transmission power levels.

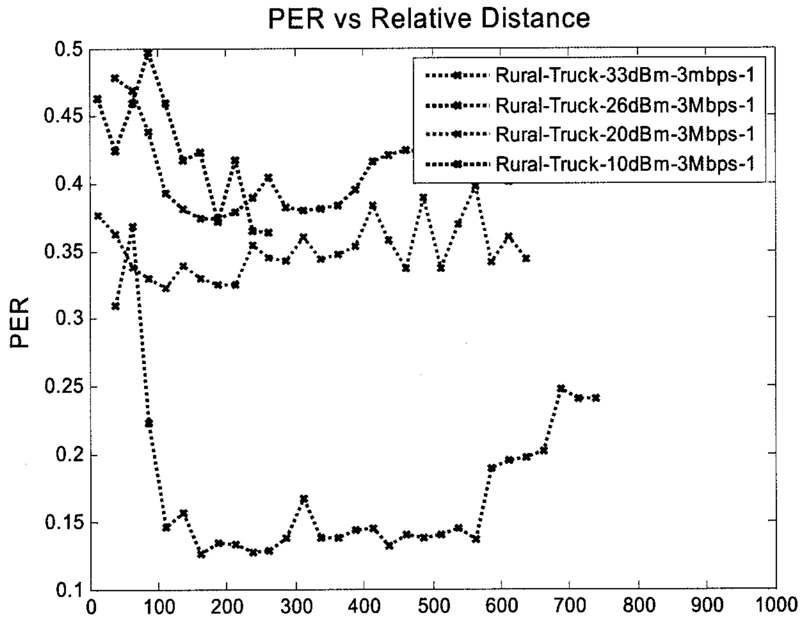


Figure 87: Comparison of PER versus Distance Curves for Various Power Levels in a Rural Highway Shadowing Scenario when Transmitter is Set to 3 Mbps

Figure 88 and Figure 89 show the effect of different data rates (3 Mbps and 6 Mbps) for a 33 dBm transmission. There appears to be little difference in performance.

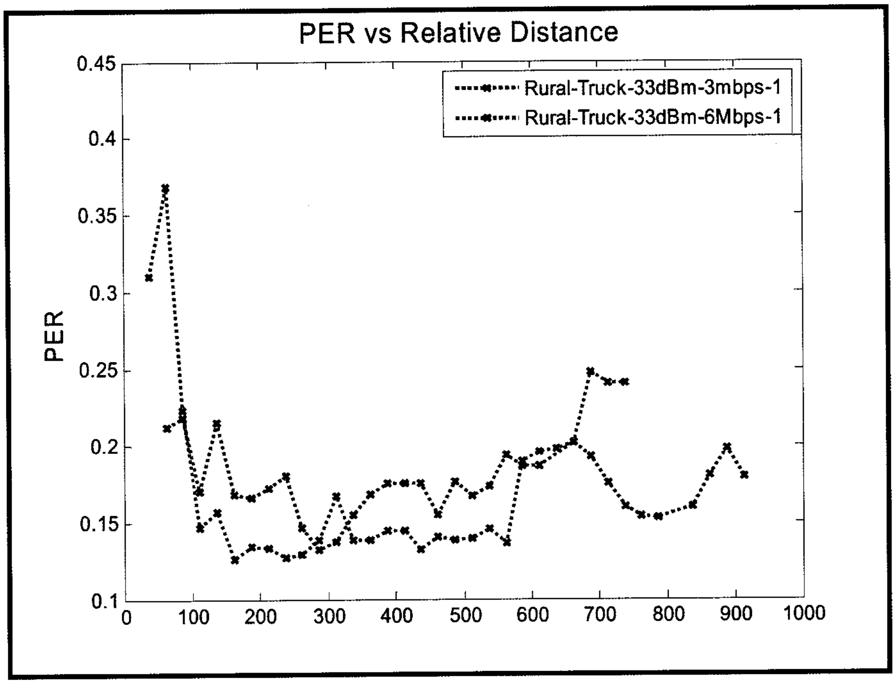


Figure 88: Comparison of PER versus Distance Curves for a Rural-Highway-Shadowing Scenario when Transmitting at 33 dBm and Different Data Rates

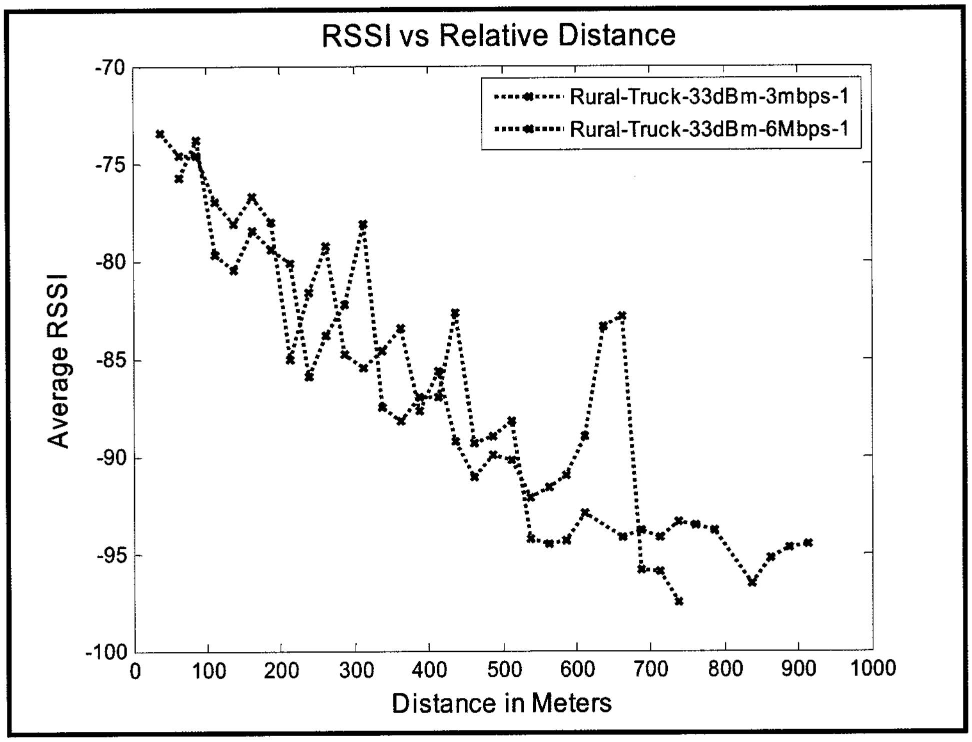


Figure 89: Comparison of RSSI versus Distance Curves for a Rural-Highway-Shadowing Scenario when Transmitting at 33 dBm and Different Data Rates

18.3 Observations for Rural-Highway-Shadowing Scenario

1. 33 dBm transmissions offer a PER of about 15 percent or less between 100 and 600 meters
2. Transmissions at or below 20 dBm maintain a PER above 30 percent at all distances
3. Regardless of transmit power, when the V2V distance approaches zero the PER increases or remains high. This phenomenon was also observed in other shadowing scenarios.

19 Arterial–Road-Shadowing Scenario-Test

The Arterial-Road-Shadowing Scenario tests were conducted along El Camino Real in the vicinity of Mountain View in Palo Alto, California. In these tests, the transmitter, truck, and receiver remained in the same lane. The receiver maintained a safe driving distance behind the truck while the transmitter varied its speed achieve a good spread of V2V distances. This test was conducted for the various cases shown in Table 15.

Table 15: Test Cases for the Arterial-Road-Shadowing Scenario Test

Data Rate \ TX Power	5dBm	10dBm	15dBm	20dBm	26dBm	33dBm
3Mbps	Test 1	Test 4	Test 7	Test 10	Test 13	Test 16
6Mbps	Test 2	Test 5	Test 8	Test 11	Test 14	Test 17
12Mpbs	Test 3	Test 6	Test 9	Test 12	Test 15	Test 18

19.1 Location Overview

El Camino Real is a fairly busy arterial with a moderate- to high-level of traffic any time of day. The road is lined with trees, strip malls, and apartment complexes along the sides. In some places there are trees in a narrow median. There are several major intersections per mile, in addition to smaller intersections. The road is 6- to 8-lanes wide in most places. Figure 90 shows a typical view along El Camino.

Figure 90: Driving North Along El Camino Real

19.2 Data Analysis

Figure 91 and Figure 92 show PER and RSSI versus distance at 3 Mbps and for three transmit power levels: 10 dBm, 20 dBm, and 33 dBm.

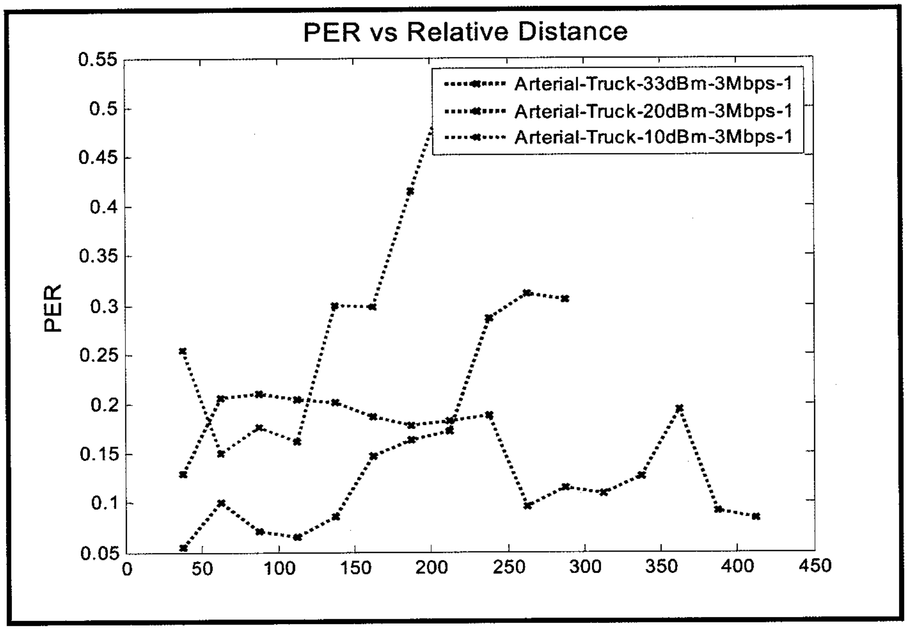


Figure 91: Comparison of PER versus Distance Curves for Various Power Levels in an Arterial-Road-Shadowing Scenario when Transmitter is Set to 3 Mbps

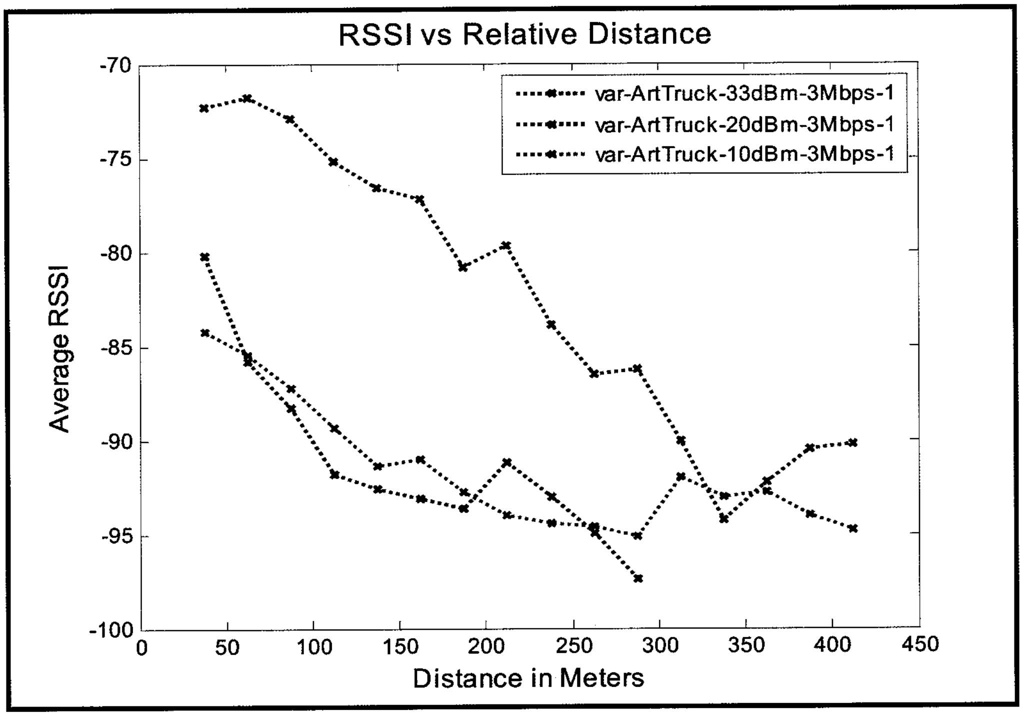


Figure 92: Comparison of RSSI versus Distance Curves for Various Power Levels in an Arterial-Road- Shadowing Scenario when Transmitter is Set to 3 Mbps

19.3 Observations for Arterial-Road-Shadowing Scenario

The following observations can be drawn with regard to communication performance in Arterial Shadowing environments:

1. This appears to be a relatively challenging communication setting, with even 33 dBm transmission unable to achieve a consistently low PER at any distance. Similar results were observed in other shadowing tests.
2. The effective transmission range increases with transmit power as expected, with low-power (10 dBm) performance falling off quickly after about 100 meters, nominal-power (20 dBm) performance remaining relatively good until about 150 to 200 meters, and high-power (33 dBm) performance consistently between 10 and 20 percent PER over the 450 meter distance range tested

20 Expressway-Shadowing Scenario Test

The Expressway-Shadowing Scenario tests were conducted along Central Expressway between Palo Alto and Santa Clara, California. As in the other shadowing tests, the transmitter, truck, and receiver remained on the same lane. The receiver maintained a safe driving distance behind the truck while the transmitter varied its speed to achieve a good spread of V2V distances. This test was conducted for the various test cases outlined in Table 16. Higher powers were not included in the tests due to time constraints with the rented truck.

Table 16: Test Cases for the Expressway-Shadowing Scenario Test

TX Power / Data Rate	5dBm	10dBm	15dBm
3Mbps	Test 1	Test 3	Test 5
6Mbps	Test 2	Test 4	Test 6

20.1 Location Overview

The Central Expressway allows for higher traffic speed (40-50 mph) than the El Camino arterial discussed in Section 19 but lower speed than a freeway or highway. The road is 4- to 6-lanes wide in most places. In some places it has a median and in others it does not. Intersections are less frequent than on El Camino. It runs through suburban sections of towns and has a propagation environment similar to the locations where the suburban tests were conducted. Figure 93 shows a typical view along the Central Expressway.

Figure 93: Driving East on Central Expressway

20.2 Data Analysis

Figure 94 and Figure 95 show PER and RSSI curves for the 5 dBm, 10dBm, and 15 dBm test cases.

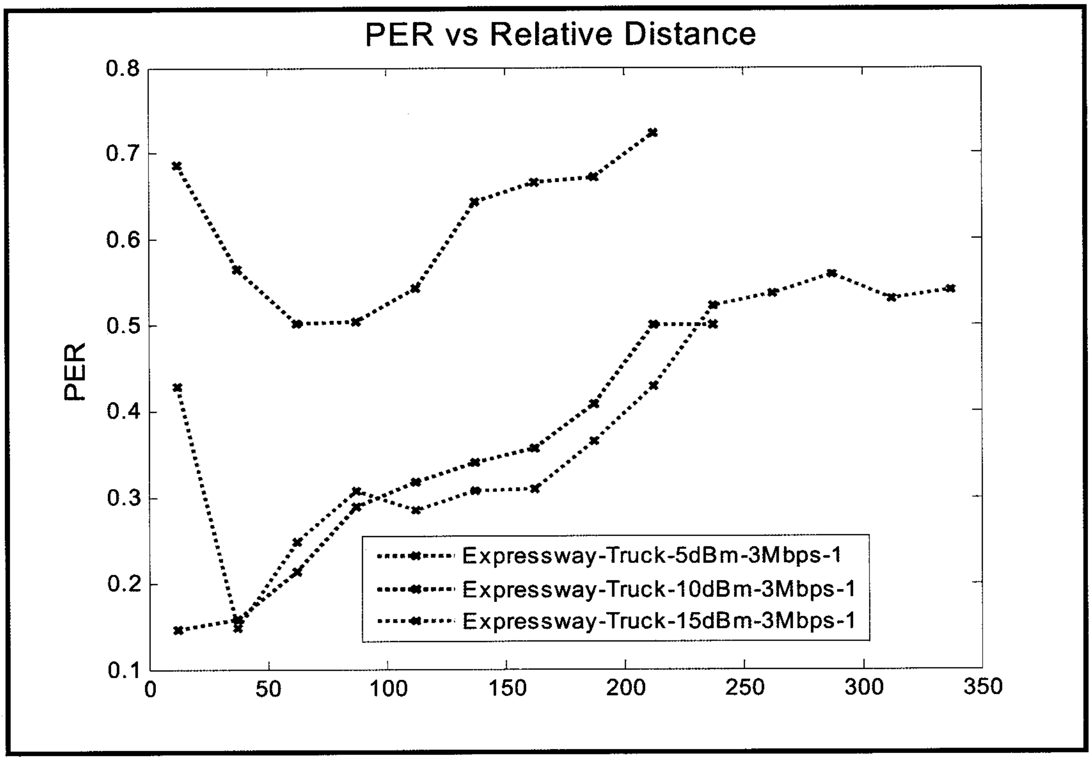


Figure 94: Comparison of PER versus Distance Curves for Various Power Levels in an Expressway-Shadowing Scenario when Transmitter is Set to 3 Mbps

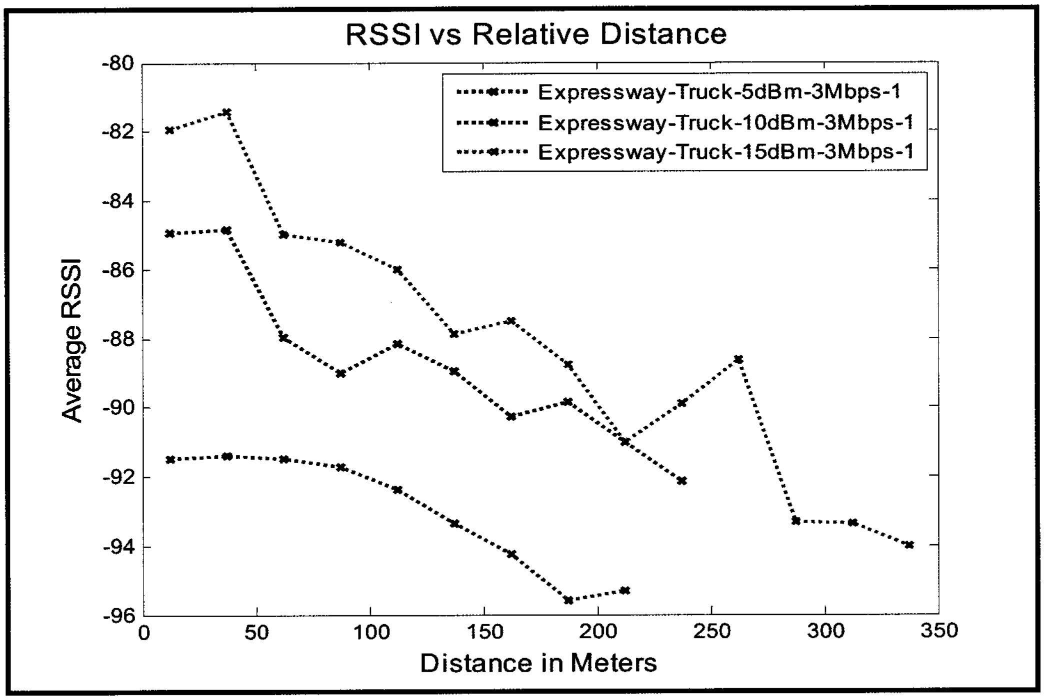


Figure 95: Comparison of RSSI versus Distance Curves for Various Power Levels in an Expressway-Shadowing Scenario when Transmitter is Set to 3 Mbps

20.3 Observations for Expressway–Shadowing Scenario

The following observations can be drawn with regard to communication performance in the Expressway Shadowing tests:

1. Time constraints limited the tests only to lower power levels
2. Use of lower powers (< 20 dBm) offers limited communication range in these NLOS conditions. All three power levels (5 dBm, 10 dBm and 15 dBm) had PERs of greater than 20 percent for V2V separation of greater than 20 meters.

21 Power Test Conclusions

Power tests were conducted in 16 environments. These scenarios were motivated by the VSC-A safety applications. The primary performance metrics were related to lower-layer behavior: PER and RSSI. As such, they give some indication of application layer performance but not a definitive answer. In scenarios where the indications flowing from these tests are not sufficiently precise, additional application-level testing may be warranted.

As expected, higher power consistently (though not universally) translated to better performance (e.g., lower PER at a given distance and/or larger achievable communication range). In the case of the intersection scenarios, there is reason to believe that the additional range provided by higher powers (i.e., above 20 dBm) may sufficiently improve application performance to be warranted. For example, in the Urban–Closed-

Intersection Scenario, Figure 26 shows that a 33 dBm transmission 100 meters from the intersection can be received reliably within about 35 meters of the intersection on the perpendicular street; whereas a 20 dBm transmission cannot be received with less than 20 percent PER even when the receiver is at the stop line of the intersection.

The scenarios that utilized a truck to create shadowing between the transmitter and receiver indicated a similar potential application advantage to using high-power transmission. For example, Figure 87 shows that in the Rural-Highway-Shadowing Scenario test when the transmit power was 33 dBm, a receiver was able to maintain fairly reliable connectivity (PER < 15 percent) up to distances on the order of 500 meters. On the other hand, for lower-transmit powers, the receiver could not achieve a PER less than about 30 percent at any distance.

The tests for which the transmitter and receiver were able to maintain Line-of-Sight indicate that higher powers may not be necessary for good application performance. For example, Figure 73 shows that in a Freeway-LOS test the link range was on the order of 250 to 300 meters even at 5 or 10 dBm.

While PER is an important performance metric, there are others that may be of interest as well. For example, statistics of the inter-message delay at a receiver (assuming a given message broadcast rate) can provide information related to application-level latencies. The power test data logs have been subjected to a limited amount of burst error analysis and are available for additional analysis.

The VSC-A team made use of an external power amplifier to produce high-power transmissions. If high power capability is desired in deployed DSRC safety systems, it would be advantageous for the power amplifier function to be built in.

22 Observations of Reduced Range in Some Baseline LOS Tests

The team noticed that after a certain point on the afternoon of the first day of testing, the ranges observed were lower than expected. For example, tests at 26 dBm and 33 dBm achieved lower range than 20 dBm tests conducted earlier in the day. A repetition of the 20 dBm test case showed a reduced range as well. The team was unable to identify a change in the environment that would explain the reduced range. Potential explanations include an equipment malfunction[4], movement of ships in the channel, and a fog that appeared off the bay; but the cause could have been something else as well. The 20 dBm and 33 dBm LOS tests were repeated on the second day of tests, and the range achieved was consistent with observations from the morning of the first day and were higher than on the afternoon of the first day. The 26 dBm LOS test was not repeated on the second day due to time constraints. The PER plots in Figure 9 use runs that correspond to expected ranges, with the exception of the 26 dBm plot. The observed inconsistency can be seen in Figure 96, which shows the RSSI for seven 20 dBm baseline LOS tests. Six of the tests occurred either early on day 1 or on day 2. These exhibit the expected range, and the RSSI plots of these six runs are highly correlated. The seventh plot (labeled

[4] Note that the equipment was checked for consistency of transmit output power level, and no inconsistencies were observed.

LOS-20 dBm-3 Mbps-Day1-3 p.m.) is from a run late on the first day and exhibits the reduced range observed at that time. Similarly, Figure 97 illustrates the reduced range observed on the first day for the 33 dBm Baseline LOS tests. This figure shows the results of five tests. The two plots labeled "Day 1" have reduced range compared to the three plots labeled "Day 2."

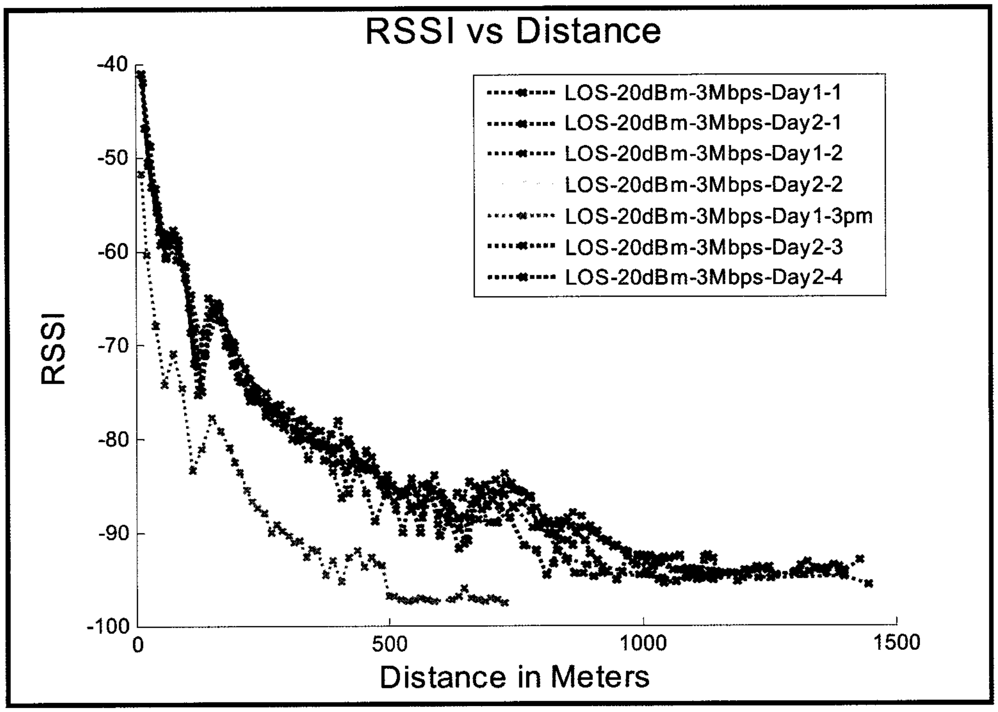


Figure 96: RSSI versus Distance at 20 dBm and 3 Mbps for the Baseline-LOS-Scenario Test

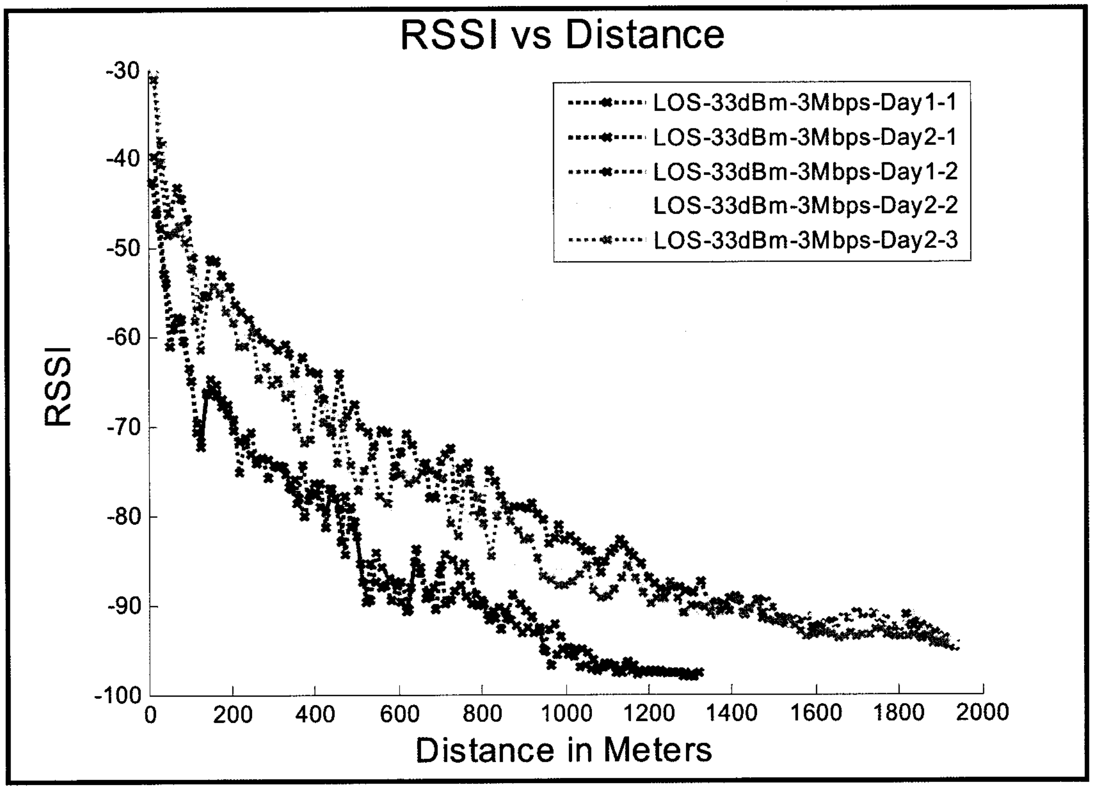


Figure 97: RSSI versus Distance for 33 dBm and 3 Mbps in Baseline LOS

VSC-A Final Report: Appendix D-2

Multi-Channel Operations

List of Acronyms

BSM	Basic Safety Message
CAMP	Crash Avoidance Metrics Partnership
CCI	Cross-Channel Interference
DSRC	Dedicated Short Range Communications
FCC	Federal Communications Commission
I-V or I2V	Infrastructure-to-Vehicle
MAC	Medium Access Control
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturers
RSE	Road Side Equipment
SPaT	Signal Phase and Timing
USDOT	United States Department of Transportation
UTC	Universal Coordinated Time
V2V or V-V	Vehicle-To-Vehicle
WAVE	Wireless Access in Vehicular Environments
WG	Working Group
WSM	WAVE Short Message

Table of Contents

List of Figures

List of Tables

1 Introduction

This appendix reports on research results obtained under the VSC-A Project: Channel 172 Usage / Multi-Channel Operations. The goal of this research is to determine the potential best ways to use the Dedicated Short Range Communication (DSRC) spectrum in the U.S. for vehicle-to-vehicle (V2V) safety communication. A complete answer would require consideration of both technical and non-technical factors; the latter include business, market penetration, and regulatory issues. The research conducted under the VSC-A Project only explored the technical dimensions of the question, while recognizing the existence of the non-technical factors. Two documents informed the organization of the work: the Trial-Use IEEE 1609.4 Standard on Multi-Channel Operation [2] and the U.S. Federal Communications Commission (FCC) designation of DSRC Channel 172 "exclusively for V2V safety communications for accident avoidance and mitigation, and safety of life and property applications [4]." These are discussed as part of the background material in the next section. The research was conducted in two phases, and there is a section devoted to each below. The most promising approaches are summarized in Section 5. Section 6 reports on a proposal that the VSC-A team made to the IEEE 1609 Working Group (WG) regarding additional header bits to support multi-channel operation. The final section of the appendix provides a brief conclusion.

2 Background

V2V safety is enabled by the frequent exchange of vehicle state information in the form of Basic Safety Messages (BSMs), which are defined in the SAE J2735 Message Set Dictionary Standard [3]. This work was motivated by the existence of two nascent, potentially competing concepts of how to use the DSRC spectrum for BSM exchange between neighboring vehicles. The first flows from the IEEE 1609.4 Multi-Channel Operation Trial-Use Standard, which provides a means for all interested devices to rendezvous on one channel in a certain interval of time for the exchange of critical data. Under this concept, BSMs would be among the critical data exchanged on that channel in that interval. The other concept is related to an FCC designation of a different DSRC channel for use in safety communication. The two documents are not explicitly in conflict, but to many people they imply inconsistent safety communication models.

2.1 The Trial-Use 1609.4 Standard

The FCC has allocated 75 MHz of spectrum in the 5.9 GHz band for DSRC. This is divided into seven non-overlapping 10 MHz channels, plus a 5 MHz guard band, as shown in Table 1.

The Trial-Use 1609.4 Standard defines a time division mechanism for a device to operate on both the control channel (CCH) and one or more service channels (SCHs). The mechanism assumes each device is synchronized to Coordinated Universal Time (UTC). Time is divided into sync intervals which are further sub-divided into a CCH interval and a SCH interval. There are guard intervals at the start of each CCH and SCH interval as well. See Figure 1. The nominal sync interval is 100 ms, which corresponds to the default BSM interval for V2V safety communications. The default division within a sync interval is 50 ms for the CCH interval and 50 ms for the SCH interval.

Table 1: FCC Allocation of DSRC Spectrum

Channel No.	Frequency Range (MHz)	Channel Use	Notes
170	5850-5855	Reserved	Guard band
172	5855-5865	Service Channel	Special FCC designation for V2V safety and other safety
174	5865-5875	Service Channel	
176	5875-5885	Service Channel	
178	5885-5895	Control Channel	
180	5895-5905	Service Channel	
182	5905-5915	Service Channel	
184	5915-5925	Service Channel	Special FCC designation for longer distance public safety

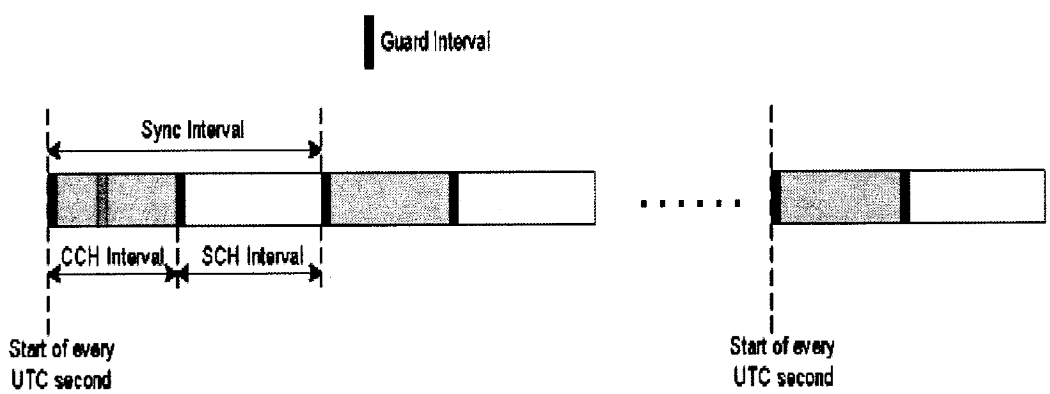


Figure 1: Time Division in the Trial-Use 1609.4 Standard

The combination of the CCH spectrum and the CCH time interval constitute a "rendezvous" capability. Without need of any other coordination, devices know that certain types of information exchanges will occur in this band and interval. These include the broadcast of service advertisements and other control packets.

V2V safety applications can use this rendezvous capability as well. According to this approach, vehicles interested in V2V safety send and receive BSMs on the CCH during the CCH interval. This V2V safety communication model is not required by IEEE 1609.4, or any other standard, but is taken as the default approach for the purposes of this research. The goal of the research is to investigate alternative approaches for V2V safety communication and compare them with each other and with the default approach.

The default approach has several advantages and disadvantages. One of the main advantages is that it allows a single-radio vehicle to participate in V2V safety by exchanging BSMs with its neighbors and also to avail itself of DSRC services that are offered during SCH intervals (e.g., by Road Side Equipment (RSE)). This capability is especially attractive as part of an initial DSRC deployment strategy to boost market penetration. One of the main disadvantages is that safety messages are effectively limited to the CCH interval, and thus channel congestion is a significant concern. At high channel loads, the probability that two or more packets "collide" due to overlapping transmissions can become significant.

Determining channel capacity via analysis is quite complex due to the Medium Access Control (MAC) protocol used in DSRC. However, a back-of-the-envelope calculation shows why 1609.4 time division causes a concern for V2V safety. If a DSRC channel supports 6 Mbps, this is equivalent to 2000 messages/second[5] for 3000 bit messages (the approximate size of an average BSM). At 10 messages/second/vehicle, this is equivalent to 200 vehicles in a given transmission region. With BSMs confined to the CCH interval, the capacity is cut to about 45 percent due to the guard interval and the need to complete packet transmissions before the start of the SCH interval. In this simple example, that is equivalent to 90 vehicles in a region. It is not difficult to construct realistic traffic scenarios in which a capacity of 90 vehicles in a transmission region represents a significant constraint.

While Trial-Use 1609.4 allows single-radio devices to access both the CCH and the SCHs, it also allows for multi-radio devices. It is worth considering what the addition of a second optional radio can do for a system that wishes to participate in V2V safety and also access other DSRC services. Two models have been discussed by the VSC-A team and are described below.

In the first model, Radio #1 remains tuned to the CCH all the time, and Radio #2 is available for tuning to a SCH at any time. In the second model, Radio #1 performs just as a single-radio system would, tuning to the CCH in the CCH interval and perhaps tuning to a SCH in the SCH interval to access services. In this model, Radio #2 can tune to any channel at any time.

In the first dual-radio model, Radio #1 is not very useful during the SCH interval since the CCH is not expected to carry critical information outside of the CCH interval. Therefore, the second model provides an advantage over the first in that the vehicle can access two SCHs at one time, and thus more services.

[5] We use 100% channel utilization in this simple example, but in reality the inefficiencies of the MAC protocol reduce maximum effective utilization well below that level.

With regard to the narrower question of safety communication performance, however, neither dual-radio model improves significantly on the single-radio system. BSM broadcasts are still limited to the CCH during the CCH interval, because dual-radio and single-radio systems will, in general, co-exist. The CCH interval constitutes the primary limitation on safety communication performance. It is possible for a dual-radio system to tune both radios to the CCH during the CCH interval and, therefore, have two chances to receive each BSM from another vehicle. However, dual receivers will do little to overcome collision-based packet loss.

The conclusion, then, is that under the default approach single-radio and dual-radio systems will have similar safety communication performance. Furthermore, among the dual-radio models, the model in which both radios are available to tune to an SCH during the SCH interval has advantages over the model in which one radio remains tuned to the CCH all the time.

2.2 FCC Designation of DSRC Channel 172

The FCC has designated DSRC Channel 172 "exclusively for V2V safety communication for accident avoidance and mitigation, and safety of life and property applications" [4]. This designation limits what can be sent on channel 172, but does not require that any particular safety communication be carried out on that channel. In that sense, it is not in conflict with the default approach described above in which BSMs are sent on the CCH. One goal of this subtask is to explore alternative safety communication approaches that make more use of Channel 172.

The FCC language quoted above is quite general and is subject to some interpretation. Since it is clear that the designation includes the exchange of BSMs between vehicles, it is not critical to analyze the various interpretations to which the language can be subjected, but these do have some implications for the assessment of approaches that will be considered below.

3 Phase I Alternative Approaches

The default approach described in the previous section has advantages and disadvantages. The goal of the research under this subtask is to investigate alternatives and assess their merits relative to each other and to the default approach.

3.1 Phase I Constraints

The team carried out its research in two phases. In the first phase the approaches were subject to the following constraints:

- No additional over-the-air (OTA) protocol information is available beyond what is available in the Trial-Use 1609 standards and the IEEE 802.11 header
- Each vehicle attempts to hear all V2V safety messages, i.e. there are commonly understood times and channels during which all vehicles will be listening for safety messages. Of course, the unreliability of the IEEE 802.11 protocol does not ensure that any given broadcast will be correctly received.

- A single-radio is sufficient to fully participate in safety communication; a second radio is optional

3.2 Phase I Taxonomy of Scenarios Studied

The team developed a set of eleven approaches, including the default approach, and classified each according to how many radios are used, which channel is used for safety communication, and other factors. Figure 2 shows this classification. The two-character codes are used as shorthand labels for each approach.

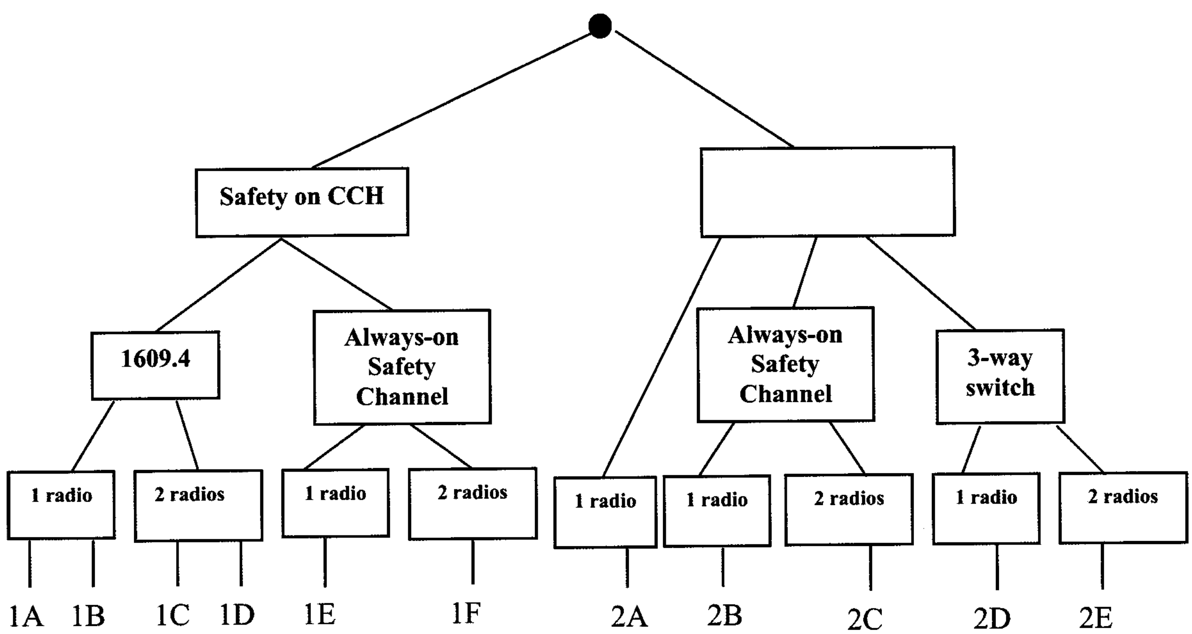


Figure 2: Taxonomy of Phase I Multi-Channel Scenarios

Note that some scenarios separate safety and control messages by using Channel 172 as the safety channel, while others continue to use the CCH for the safety channel. Also, some of the scenarios consider an "always-on" safety channel, meaning that a sender can expect a safety message to be heard no matter when it is sent, while others use time division.

Scenario 1B represents the single-radio default approach described in Section 2.1. It sends and receives BSMs on the CCH during the CCH interval, and it may switch to a SCH to take advantage of a general DSRC service during the SCH interval. Though BSMs are exchanged on the CCH, a default approach implementation might use Channel 172 for some other type of safety exchange, referred to here as a "session-oriented safety service." Such a service, which would be advertised in a control message on the CCH, is beyond the scope of the VSC-A Project.

The two dual-radio models consistent with the default approach, discussed in Section 2.1 above, are labeled 1C and 1D, respectively, in Figure 2. Scenario 1C keeps one radio tuned to the CCH all the time and was shown to be less attractive than Scenario 1D, which can access services on two SCHs simultaneously during the SCH interval. So, Scenarios 1B and 1D can co-exist and interoperate and are, thus, considered a single deployment approach.

3.3 Channel Usage Map and Time Usage Map for Default Approach

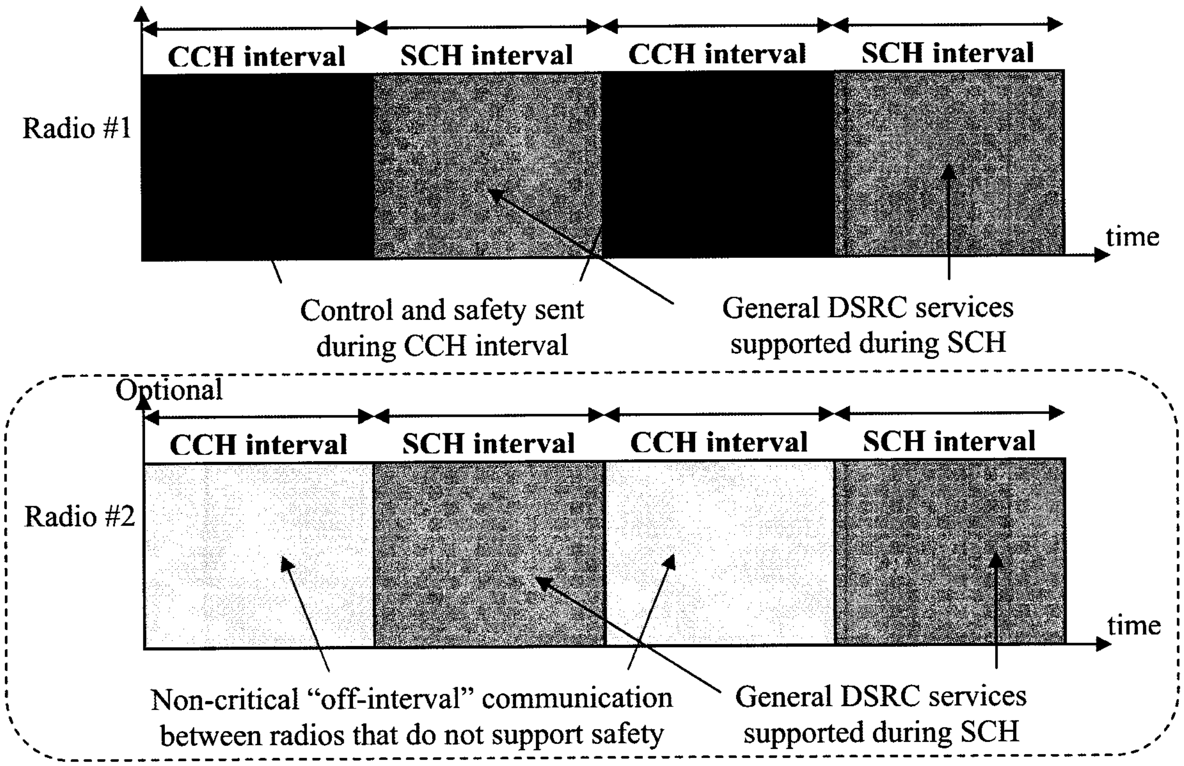
The team used a graphical tool to concisely represent the scenarios under consideration. The tool consists of two drawings, a Channel Usage Map and a Time Usage Map. The Channel Usage Map uses colors and shading to indicate how each of the seven DSRC channels is used in that scenario. The Time Usage Map shows how each radio segregates its functions in time. The Channel Usage Map and Time Usage Map for the combination of Scenarios 1B and 1D are shown in Figure 3 and Figure 4.

The Channel Usage Map shows a blend of red and blue in the CCH, which supports both safety and control data exchanges. Channel 172 is colored red because it supports session-oriented safety services. The other SCHs are green indicating they support general DSRC services.

The Time Usage Map for Radio #1 alternates between the CCH during the CCH interval and an SCH during the SCH interval. Since the SCH could be Channel 172, a more accurate shading would be a blend of green and red in those boxes, but since session-oriented safety is beyond the scope of the VSC-A Project, that level of detail in these diagrams has been omitted. Optional Radio #2 is shown switching to an SCH during the SCH interval just like Radio #1 and, therefore, Figure 4 shows graphically the capability of Scenario 1D to support two SCH accesses simultaneously. During the CCH interval, Radio #2 could do a variety of things, including tuning to the CCH or to an SCH. If it is tuned to the CCH, it is largely redundant with Radio #1, and, in particular, it must be careful not to add to channel congestion by transmitting. If it tunes to an SCH, it will communicate with other devices that have dual-radios and/or are not participating in V2V safety. Since single-radio vehicles will not be able to participate in these exchanges, they are labeled "non-critical" exchanges. And since they take place on an SCH during the CCH interval, they are labeled "off-interval" exchanges. Scenario 1B is represented in these figures with the omission of optional Radio #2 in Figure 4.

Ch 172	Ch 174	Ch 176	Ch 178	Ch 180	Ch 182	Ch 184
	General DSRC messages	General DSRC messages	Control messages and Safety messages	General DSRC messages	General DSRC messages	General DSRC messages

Figure 3: Channel Usage Map – Scenarios 1B+1D



The color shading legend is as follows:
Red indicates safety — Green indicates general services
Blue indicates control — Gray indicates "non-critical" communication

Figure 4: Time Usage Maps – Scenarios 1B+1D

3.4 An Alternative Approach that uses Channel 172 for an Always-On Safety Channel

Compared to the default approach, the most attractive Phase I alternative is represented by the combination of Scenarios 2B and 2C in Figure 2. The Channel and Time Usage Maps for these scenarios are illustrated in Figure 5 and Figure 6.

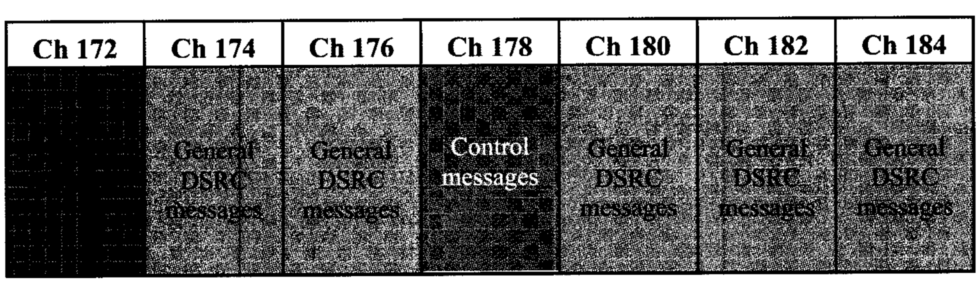


Figure 5: Channel Usage Map – Scenarios 2B+2C

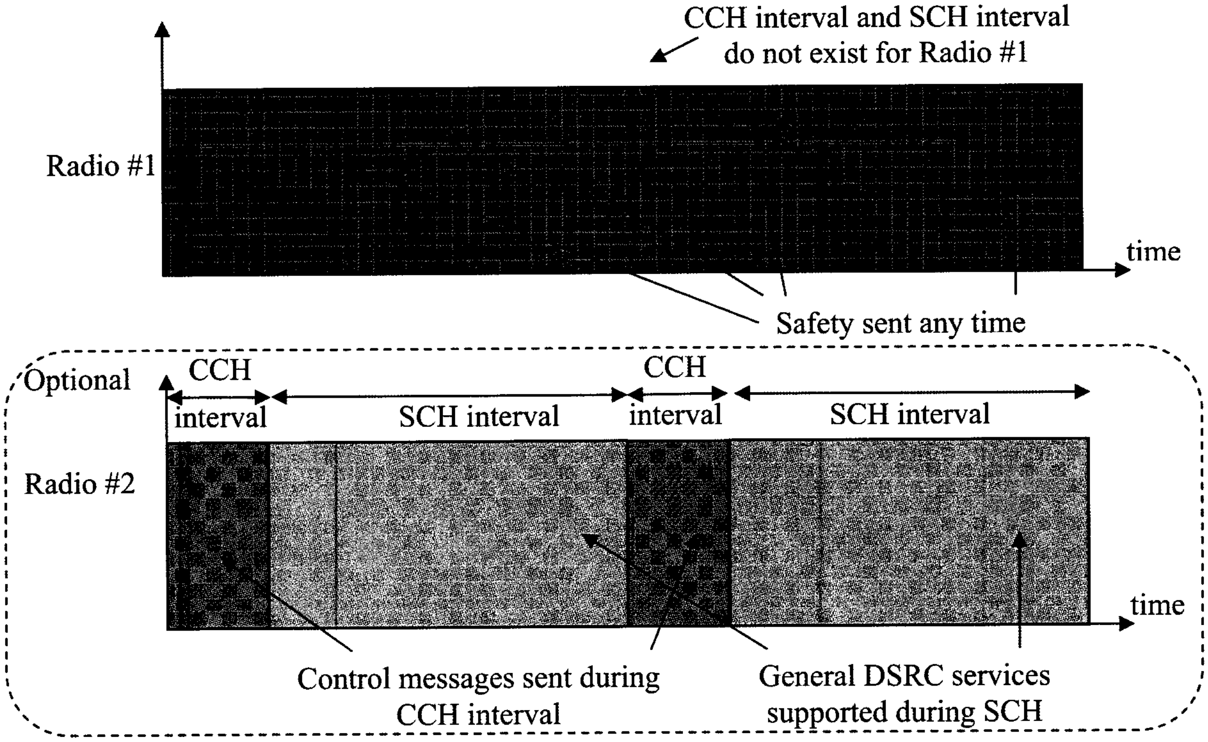


Figure 6: Time Usage Maps – Scenarios 2B+2C

In Scenarios 2B and 2C, safety communication is moved entirely to Channel 172. So, in Figure 5, the CCH is no longer a red/blue blend as in Figure 3, but rather it is solid blue. Channel 172 is now labeled simply "safety messages," since it supports all safety communication not just that of a session-oriented nature. Scenario 2B has a single-radio, Radio #1, which tunes to Channel 172 at all times. It does not concern itself with the CCH or SCH interval. Scenario 2C includes an optional Radio #2, which monitors the CCH during the CCH interval, and could switch to an SCH to access a service if it wished during the SCH interval. Radio #2 follows more traditional 1609.4 channel switching but does not participate in safety communication since that is all handled by Radio #1. Scenarios 2B and 2C can co-exist and interoperate and are considered a single deployment approach. Note that with BSMs removed from the CCH, the team observed that the optimal division between the CCH interval and SCH interval might now favor the SCH interval. This observation is illustrated in Figure 6, though the particular division shown should not be interpreted as optimal.

The biggest advantage of the 2B+2C approach, compared to the default approach, is that BSM communication takes place on an always-on safety channel, which has more than twice the capacity of the CCH interval.

The biggest disadvantage of the 2B+2C approach is that a single-radio implementation that wants to support V2V safety can do nothing else outside of Channel 172. It does not monitor the CCH for control messages, and it cannot switch to another SCH to access general DSRC services. One consequence of this is that the question of what falls within the FCC designation for Channel 172 becomes very important because single-radio vehicles will not hear anything transmitted outside of Channel 172. For example, in some prototype efforts for intersection collision avoidance applications using infrastructure-to-vehicle (I2V) communication, Signal Phase and Timing (SPaT) messages and intersection geographic description messages have been sent on other channels. These would need to be moved to Channel 172 if a single-radio vehicle is to be able to support those I2V safety applications.

3.5 Cross-Channel Interference Effect

Another point of comparison among multi-channel approaches is their susceptibility to cross-channel interference (CCI). CCI is the energy in a target channel that results from a transmission in another channel. There are standards that limit this energy, but it cannot be eliminated entirely. CCI, like other forms of noise, can reduce the reception probability for a packet. In this section, the effect that CCI can have on reception probability of a BSM under various multi-channel approaches is discussed.

Field tests were performed with prototype DSRC radios to study how CCI affects packet reception probability [5]. Two important factors are:

- The spectral distance between the channel on which the BSM is transmitted and the channel on which the interfering signal is transmitted. The effect is much more prevalent when the interferer is in the adjacent channel (e.g., Channel 174 in the case of a BSM transmission on Channel 172), than when the interferer is two or more channels away.
- The ratio of the BSM transmitter-to-receiver distance to the interferer-to-receiver distance. When that ratio is at least 10:1, the CCI affect on packet reception was found to be much more significant.

As an example and considering a receiver on Channel 172 using the 2B+2C approach, if an interfering transmitter is 10 meters away and using Channel 174 at the same time that a vehicle 100 or more meters away is sending a BSM on Channel 172, the probability of correctly receiving the BSM is expected to be significantly reduced. On the other hand, if the interfering transmission is not on Channel 174, or if the ratio of distances becomes less than 10:1, the probability of correctly receiving the BSM is expected to be similar to the case where there is no CCI. The ratio threshold of 10:1 should be considered a rough rule of thumb for a continuously varying effect, not a given.

The time division inherent in IEEE 1609.4 might be expected to make CCH receptions immune to a CCI effect. However, IEEE 1609.4 does not prohibit SCH transmissions during the CCH interval. Indeed, the version of the IEEE 1609.4 Standard published in 2010 defines explicit protocol enhancements to announce a service that will be available on a SCH during the CCH interval. If such a service is offered on either of the channels adjacent to the CCH, Channel 176 or Channel 180, there could be a significant CCI effect on BSM receptions on the CCH.

To some extent, all of the approaches considered, including the default approach, are subject to some degree of CCI. Without specifying detailed use cases, it is difficult to compare the impact that CCI has on BSM receptions in different multi-channel approaches. While CCI is not a prominent factor in the research reported in this document, it should be considered in more definitive assessment.

3.6 Other Phase I Scenarios

The other scenarios investigated as Part of Phase I were found to be less attractive than the 2B+2C combination. These are described briefly below for completeness.

Scenario 1A: This was included as an incremental approach leading to Scenario 1B and need not be discussed further.

Scenarios 1E and 1F: These expanded safety communication on the CCH to occupy the entire sync period with no concern for CCH or SCH intervals. Scenario 1E uses a single radio, Radio #1, which is tuned to the CCH all the time. Scenario 1F adds an optional Radio #2, which is capable of switching to any of the channels to access DSRC services. This pair of scenarios has some similarities to the 2B+2C combination, namely an always-on safety channel that a single-radio system never leaves, and the consequent inability of a single-radio system to access general DSRC services like the default approach can. Compared to 2B+2C, the combination of 1E+1F has an advantage in that the single-radio in 1E can hear control messages in addition to safety messages. In the future, there may be control messages of importance to such a radio. A disadvantage of this is that safety messages compete for channel access with control messages, and thus suffer higher collision rates than in the 2B+2C Approach where the safety channel is not shared with control. Another difference for the 1E+1F combination is that it does not use Channel 172.

Scenario 2A: This is a single-radio approach in which the radio alternates between the CCH during the CCH interval and Channel 172 during the SCH interval. It exchanges all BSMs on the latter channel. An advantage is that the single-radio has access to both safety and control messages. However, it has a big disadvantage compared to the 2B+2C approach because it does not use Channel 172 in an always-on manner. By perpetuating the time division on Channel 172, it suffers the same congestion weakness as the default approach. On the other hand, the single-radio implementing Scenario 2A cannot access both safety and general DSRC services as it can in Scenario 1B.

Scenarios 2D and 2E: This is the final pair of scenarios. They not create an always-on safety channel and instead add a third time division to each sync period. In addition to a CCH Interval and an SCH Interval, the 2D+2E combination creates a Safety Interval. During the Safety Interval, all devices wishing to participate in V2V safety tune to Channel 172 and exchange BSMs. This approach not only perpetuates the channel capacity problems of the default approach, it actually magnifies them with the third time division. Any capacity allocated to one interval is explicitly unavailable for the other two types of communication. This approach was not investigated further by the team.

3.7 Phase I Conclusion

The conclusion of the Phase I part of the research is that among the scenarios considered the 2B+2C combination offers the best alternative to the default approach. Each of these approaches has advantages and disadvantages, some of which are documented in Table 2 below. Single-radio versions of both approaches were implemented in the VSC-A test bed prototype.

More specifically, the VSC-A team recognized that the single-radio, 1609.4 channel switching approach, Scenario 1B, has the aforementioned advantages of supporting both safety and general services with one radio, which is good for DSRC market penetration. The team also recognized that the dual-radio Scenario 2C represents an attractive model at higher penetration levels where congestion will likely be a concern because it supports safety with the capacity of an always-on safety channel in addition to supporting general services as well.

For a scenario whereby initial deployments would follow channel switching as in Scenario 1B and later deployments would utilize an always-on Channel 172 as in Scenario 2C, the Section 3.1 constraints create a dilemma in which there is no clear migration strategy which would allow early deployment radios to communicate with later deployment radios.

This migration dilemma led the team to initiate Phase II of the study.

4 Phase II Alternative Approaches

In Phase II of the multi-channel operation research, the constraint against introducing new OTA protocol information is relaxed. The goal of this phase is to identify one or more approaches that allow co-existence between implementations that can only send and receive BSMs according to the default approach (i.e., on the CCH during the CCH interval) and implementations that can utilize an always-on safety channel. Such a co-existence approach would facilitate a migration from the former type of implementation to the latter over time.

In each co-existence approach identified in this phase, there is a single always-on channel. For simplicity, a vehicle that cannot take advantage of this always-on channel and is constrained to exchange BSMs on the CCH during the CCH interval is referred to as a "default vehicle." A vehicle that can take advantage of the always-on channel is referred to as a "non-default vehicle." The co-existence approaches studied in Phase II require two things:

- A non-default vehicle must be capable of exchanging BSMs with a default vehicle on the CCH during the CCH interval (i.e., of adapting its communication to accommodate the default vehicle)
- A non-default vehicle must be capable of determining when it has one or more default vehicles within its transmission range

The technical innovation that enables an approach to meet the second requirement is the addition of an OTA bit (or bits) in the safety message, the state of which identifies the sender's type (default or non-default). The concept behind the Phase II research is illustrated in Figure 7 and Figure 8.

In Figure 7, each vehicle includes a header bit in its BSM broadcast. Default vehicles set the bit to 1, and non-default vehicles set the bit to 0 (the polarity could just as easily be reversed). The figure shows the transmission region of a given target vehicle in the intersection and shows one default vehicle within that region. The target vehicle detects the presence of its default vehicle neighbor via the header bit. When it knows it has a default vehicle neighbor, it sends its BSMs on the CCH during the CCH interval so that the default vehicle can hear them.

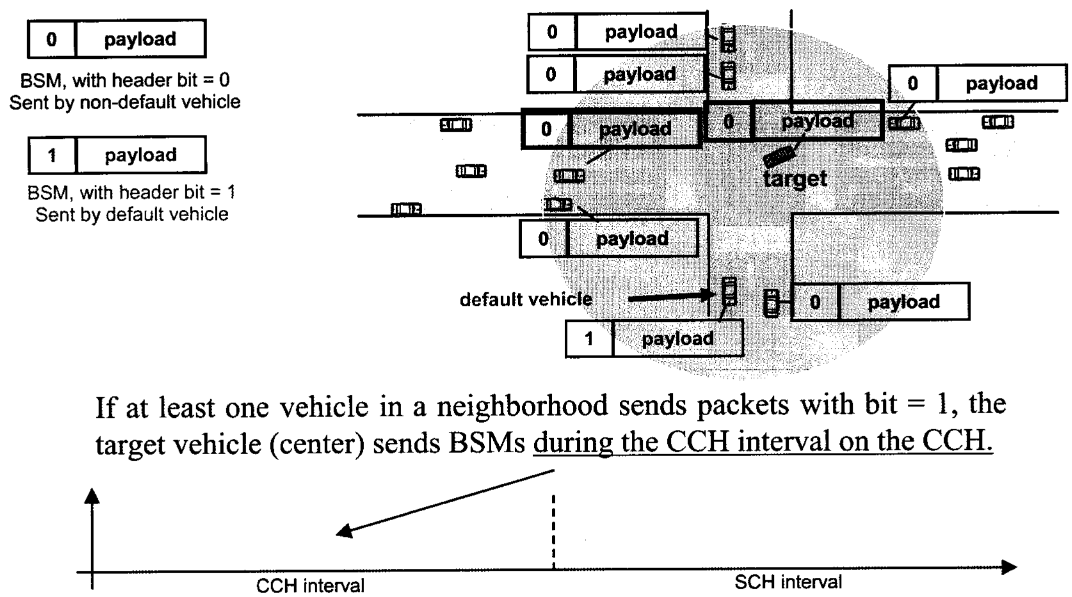


Figure 7: Default Vehicle in the Neighborhood

Figure 8 shows the same intersection scenario, but this time the transmission region around the target vehicle has only non-default vehicles. When the target vehicle determines that all of its neighbors are non-default vehicles, it transmits its BSMs on the always-on safety channel at any time.

Every non-default vehicle must monitor the CCH during every CCH interval to detect the presence of a default neighbor. However, it need only adjust its BSM transmissions when a default neighbor is present. A default vehicle must set the header bit correctly, but does not need to monitor the header bits in received BSMs. Its BSM transmission and reception behavior does not change as a function of the types of vehicles in its neighborhood.

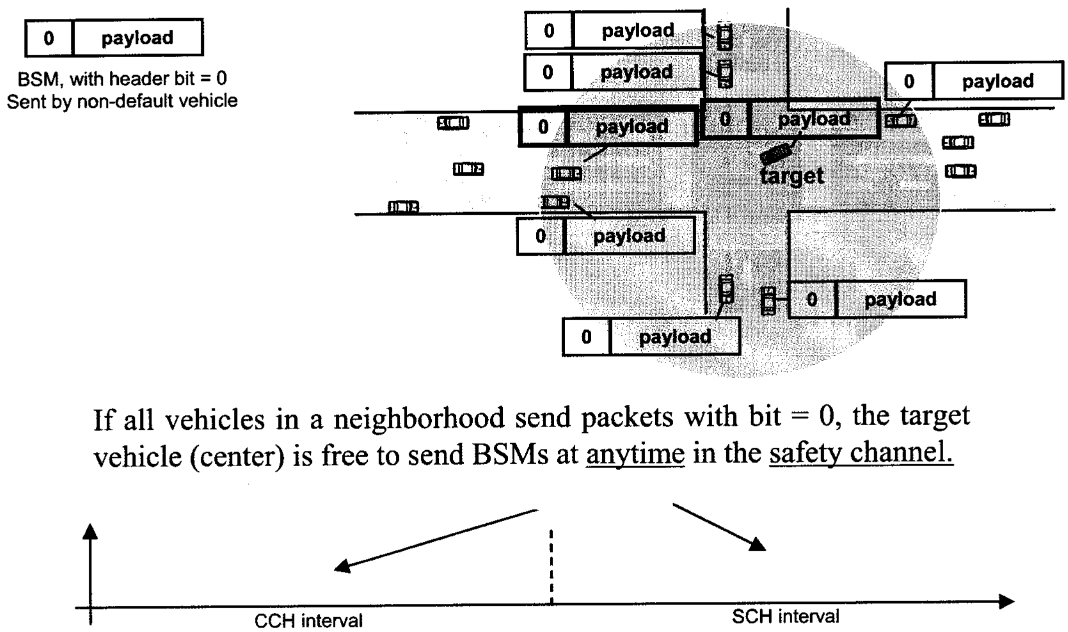


Figure 8: No Default Vehicles in the Neighborhood

These figures illustrate the basic paradigm of the co-existence approaches investigated in Phase II of the research. Specific approaches are documented below. There are a number of implementation issues associated with these types of approaches (e.g., if a non-default vehicle has detected a neighboring default vehicle but then misses an expected BSM from that vehicle, how does it manage the transition back to the no-default-vehicle-neighbors state?) These are beyond the scope of the research conducted in this project.

The team investigated a number of co-existence approaches. Of these, two were judged to be feasible and preferable to the others. The next two subsections present details of each of these approaches.

4.1 Capability/Channel 172 Approach

In this approach, the always-on safety channel is Channel 172. The approach uses one new header bit to communicate vehicle type. This bit is referred to as a "capability bit," because it conveys the capability of the vehicle in terms of whether it has one radio or more than one radio. This approach is characterized by the following behaviors:

Single-Radio Vehicle:

- A single-radio vehicle sends and receives BSMs on the CCH during the CCH interval. This radio is available to switch to a SCH during the SCH interval if desired. In other words, it follows the default approach.
- It sets the header bit in its outgoing BSMs to indicate it is a single-radio vehicle

Multiple-Radio Vehicle:

- A multi-radio vehicle keeps one radio tuned to Channel 172 all the time. The vehicle sends and receives BSMs on Channel 172 at any time, without regard to time division within the sync period.
- A second radio is tuned to the CCH during the CCH interval to listen for BSMs and control messages. This radio may switch to an SCH during the SCH interval. In other words, it follows the default approach.
- If the header bit of a BSM received on the CCH indicates its sender is a single-radio vehicle, the multi-radio vehicle also begins sending its BSMs on the CCH during the CCH interval. It sends each BSM twice, once with each radio. When it sends a BSM on the CCH, it sets the header bit to indicate it is a multi-radio vehicle.
- If the multi-radio vehicle determines that it has no single-radio neighbors, it ceases sending its BSMs on the CCH during the CCH interval to avoid unnecessary loading on the CCH

Performance:

In this approach, multi-radio vehicles are able to communicate with each other on the always-on safety channel (Channel 172). So, the performance of a link between two such vehicles is that associated with an undivided channel (and of course dependent on vehicle density, transmit power, distance, and the multi-path environment, among other factors). For example, the performance between multi-radio vehicles under the Capability/Channel 172 approach should be similar to that between vehicles in the 2B+2C approach of Phase I.

By comparison, a single-radio vehicle communicates with other vehicles on the CCH during the limited CCH interval. The performance of communication to or from a single-radio vehicle should be similar to that between two vehicles in the default approach.

4.2 Intention/CCH Approach

In this approach the always-on safety channel is the CCH (i.e., the CCH is used by both default vehicles and non-default vehicles). Some BSMs are limited to the CCH interval and some are sent at any time on the CCH. BSMs are not sent on Channel 172. Like the Capability/Channel 172 approach, the Intention/CCH approach uses one new header bit to communicate vehicle type. This bit is referred to as an "intention bit," because it conveys the sender's intention to switch away from the CCH during the SCH interval. In this approach the team distinguished between three types of vehicles:

- A single-radio vehicle that intends to switch away from the CCH in the next SCH interval (call this a "switching" vehicle)
- A single-radio vehicle that intends to remain tuned to the CCH in the next SCH interval (call this a "non-switching" vehicle)
- A multi-radio vehicle

This approach is characterized by the following behaviors:

<u>Single-Radio Switching Vehicle:</u>

- A single-radio switching vehicle sends and receives BSMs on the CCH during the CCH interval
- It sets the header bit to indicate it intends to switch away from the CCH during the next SCH interval

<u>Single-radio Non-switching Vehicle:</u>

- A single-radio non-switching vehicle keeps its radio tuned to the CCH throughout the current sync period
- It sets the header bit to indicate it does not intend to switch away from the CCH during the next SCH interval
- If it detects a switching vehicle among its neighbors, it sends its BSM during the CCH interval. Otherwise it chooses any time during the sync period to send its BSM.

<u>Multiple-Radio Vehicle:</u>

- The behavior of the first radio of a multi-radio vehicle is identical to that of a single-radio, non-switching vehicle above
- The second radio can be used as desired, for example, to access a service on an SCH during the SCH interval. It is similar to the second radio in the Phase I Scenario 1D. It has essentially no impact on safety communication.

Performance:

Note that in the Intention/CCH approach the classification of a single-radio vehicle can be dynamic. It may be a switching vehicle in one sync period and a non-switching vehicle in another. This raises a minor timing issue with regard to setting the Intention Bit. For example, if a non-switching vehicle sends a BSM early in a sync period and then receives a service advertisement and decides to leave the CCH to access the service on the next SCH interval, it cannot indicate this change in state until it sends its next BSM in the following sync period. This can lead to additional latency before the single-radio vehicle hears BSMs from some of its neighbors.

From a congestion perspective, the performance of the Intention/CCH approach should be considered for two cases: i) within a neighborhood consisting only of non-switching vehicles, and ii) within a neighborhood with at least one switching vehicle.

Where all vehicles are non-switching, the communication performance is that of an always-on channel. In other words, it is similar to the performance of the 2B+2C approach from the Phase I study, and similar to the performance of the Capability/Channel 172 approach in a neighborhood consisting only of multi-radio vehicles. In the Intention/CCH case, there could be a slight degradation due to the fact that the safety channel is also the CCH, and thus carries control messages in addition to BSMs.

Where there is at least one switching vehicle, all the BSMs are constrained to be sent during the CCH interval. These BSM transmissions are, thus, subject to the higher channel load associated with that constraint. The communication performance between any pair of vehicles in that neighborhood is affected and will be similar to the performance of the default approach. Note that this is true even between non-switching vehicles. The fact that performance between non-switching vehicles is constrained in the neighborhood of a switching vehicle contrasts with the performance of the Capability/Channel 172 approach in the neighborhood of a single-radio vehicle. In the Capability/Channel 172 case, communication between multi-radio vehicles is not constrained by the CCH interval, and the performance between those vehicles is much better than the default approach. This point of comparison can be interpreted as an advantage for the Capability/Channel 172 approach over the Intention/CCH approach. On the other hand, the Intention/CCH approach has the following advantage over the Capability/Channel 172 approach: all single-radio vehicles create a region of constrained performance in the Capability/Channel 172 approach, whereas only those single-radio vehicles that are currently switching create such a region in the Intention/CCH approach. Thus, an assessment of the Intention/CCH approach requires estimating how frequently a vehicle will switch away from the CCH.

Note that the VSC-A team considers the Capability/Channel 172 approach and the Intention/CCH approach to be mutually exclusive. No attempt has been made to consider interoperation between the two.

5 Summary of Research Results

This research assessed the default approach (Section 2.1) and developed three potential alternatives: the "all safety on Channel 172 approach" (Section 3.4), the Capability/Channel 172 approach (Section 4.1), and the Intention/CCH approach (Section 4.2). The major advantages and disadvantages of each of these four approaches are summarized in Table 2.

Table 2: Summary of Multi-Channel Approaches

Approach	Safety Band(s)	Advantages	Disadvantages
Default	CCH during CCH interval	Single-radio vehicle supports safety and non-safety services	Congestion due to CCH interval capacity limit
All Safety on Channel 172	Channel 172	Always-on safety channel for all BSMs Possible optimization of CCH/SCH interval ratio	Single-radio vehicle cannot support both safety and non-safety

Approach	Safety Band(s)	Advantages	Disadvantages
Capability/ Channel 172	Channel 172, and CCH during CCH interval	Safety and non-safety for single-radio vehicles Multi-radio vehicles have access to always-on safety channel	Requires new header bit Uses 1.5 channels for safety
Intention/CCH	CCH, during both intervals	Safety and non-safety for single-radio vehicles Non-switching vehicles have access to always-on safety channel; only a switching vehicle triggers CCH interval limitation (dynamic)	Requires new header bit Presence of switching vehicle limits performance for all neighbors, even between non-switching vehicles

6 Proposal for the Header Bits in the Next Version of IEEE 1609.3

In the event that the default approach for V2V safety communication is chosen for initial deployment, it is possible that the automotive industry will eventually adopt an alternative to this approach. A vehicle deployed after such a decision could be designed to conform to the new approach. A vehicle deployed before such a decision may or may not be able to conform. The VSC-A team recognized that it would be advisable to "future proof" the standards now, to the extent possible, to maximize the chance that a vehicle deployed prior to an eventual multi-channel decision would be able to conform to it.

The IEEE 1609.3 Standard [1] defines the Wireless Access in Vehicular Environments (WAVE) Short Message (WSM), which is the Network Layer packet in which BSMs will be carried. As reported above, two of the alternative approaches researched require the addition of a new header bit. A logical place to allocate such bits is in the WSM header. The IEEE 1609.3 Standard is currently being revised with an expected publication date in 2010. At the October 2009 IEEE 1609 meeting, the VSC-A team proposed [6] that 2 bits be allocated in the WSM header to allow the sender to advertise its multi-channel capability and intention. This proposal was accepted by the IEEE 1609 WG, subject to editing, for inclusion in the draft 1609.3 Standard. One modification is that instead of using WSM header bits, the requested bits will be placed in a new WSM sub-layer header, which will only appear in a WSM that carries a safety message. The WSM sub layer is defined in IEEE 1609.3 draft.

The capability bit and intention bit concepts were developed with the idea that one or the other, but not both, would be provided in the packet header. But the October 2009

VSC-A proposal covered both cases, and the most efficient way to do that was with a pair of bits that collectively provide the information necessary for either the Capability/Channel 172 approach or the Intention/CCH approach. Neither of these bits can be identified precisely as a capability bit or an intention bit. The specific 2-bit proposal from VSC-A is shown in Table 3.

Table 3: VSC-A Proposal to IEEE 1609 for Header Bits

Bit Values	Meaning
00	Sender requires others' safety messages to be sent on the CCH during the CCH interval.
01	Sender requires others' safety messages to be sent on the CCH, but has no time interval constraint.
10	Sender is capable of receiving others' safety messages on a designated Safety Channel that is distinct from the CCH (in the U.S. this is Channel 172).
11	Sender is not capable of processing received safety messages (all other categories above implicitly assume sender can process safety messages).

Bit Values 00 and 01 provide the information necessary to enable the Intention/CCH approach. Under this approach, the 10 value would not normally be used, and vehicles deployed after a decision to follow this approach would not send value 10. A non-switching vehicle receiving the 10 value would treat the sender as a switching vehicle, and they could exchange BSMs on the CCH during the CCH interval.

Bit Values 00 and 10 provide the information necessary to enable the capability/Channel 172 approach. Under this approach, the 01 value would not normally be used. A multi radio vehicle receiving the 01 value would treat the sender as a single-radio vehicle, and they could exchange BSMs on the CCH during the CCH interval.

Bit Value 11 is useful so that a transmit-only safety device (e.g., an aftermarket device using the BSM to provide limited location and speed information) does not trigger an unnecessary transmission behavior in a more capable vehicle.

7 Conclusion

The VSC-A team assessed the default approach for safety communication under IEEE 1609 and researched alternatives. The research was conducted in two phases. Phase I identified one alternative in which all safety communication is carried out on DSRC Channel 172. Phase II identified two additional alternatives, each of which employ a new header bit and provide a migration path, should it be needed, between deployments that conform to the default approach and deployments that can take advantage of an always-on safety channel. One of these approaches uses both channel 172, as an always-on safety channel, and the CCH, during the CCH interval. The other approach expands use of the CCH to an always-on mode for vehicles that can keep one radio tuned to that channel. Table 2 summarizes the advantages and disadvantages of the default approach and the three alternative approaches. The VSC-A team worked with the IEEE 1609 WG to define two header bits in the 1609 packet to support the two Phase II alternative approaches.

8 References

[1] IEEE Vehicular Technology Society, *"IEEE Trial-Use Standard for Wireless Access in Vehicular Environments – Networking Services,"* IEEE Std. P1609.3™-2007, April 2007.

[2] IEEE Vehicular Technology Society, *"IEEE Trial-Use Standard for Wireless Access in Vehicular Environments – Multi-channel Operation,"* IEEE Std. P1609.4™-2006, November 2006.

[3] SAE International™, *"SAE J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary,"* DSRC Committee, November 2009.

[4] Federal Communications Commission, *"Amendment of the Commission's Rules Regarding Dedicated Short-Range Communication Services in the 5.850-f.925 GHz band (5.9 GHz band),"* FCC Memorandum Opinion and Order, FCC 06-110, adopted July 20, 2006, released July 26, 2006, WG Docket no. 01-90.

[5] Rai, V., Bai, F., Kenney, J., and Laberteaux, K., *"Cross-Channel Interference Test Results: A report from the VSC-A Project,"* IEEE 802.11 11-07-2311-00-000p, July 2007.

[6] CAMP VSC2 Consortium, *"Proposal to define WSMP bits to support Multi-Channel Operation for Safety,"* IEEE 1609 WG, Oct. 20, 2009.

VSC-A Final Report: Appendix E-1

Relative Positioning Software Performance Analysis

List of Acronyms

CAMP	Crash Avoidance Metrics Partnership
CICAS-V	Cooperative Intersection Collision Avoidance System for Violations
DSRC	Dedicated Short Range Communications
GPS	Global Positioning System
GUI	Graphical User Interface
HV	Host Vehicle
ITS	Intelligent Transportation Systems
LOS	Line-of-Sight
NHTSA	National Highway Traffic Safety Administration
OTA	Over-the-Air
RMS	Root Mean Square
RTK	Real-Time Kinematic
RV	Remote Vehicle
SDH	Sensor Data Handler
SP	Single Point
SW	Software
USDOT	United States Department of Transportation
VSC2	Vehicle Safety Communications 2 (consortium)
VSC-A	Vehicle Safety Communications – Applications
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WAAS	Wide Area Augmentation System
WAVE	Wireless Access in Vehicular Environments
WGS84	World Geodetic System 84
WMH	Wireless Message Handler
WRM	WAVE Radio Module

Table of Contents

List of Figures

1 Background and Objectives

Relative positioning is a critical system component of the Vehicle Safety Communications – Applications (VSC-A) test bed. Based on preliminary studies, team experience, and industry expert input, the test bed is designed to use Global Positioning System (GPS) Real-Time Kinematic (RTK) positioning for relative positioning of vehicles. The objective of this report was to investigate certain performance characteristics of the VSC-A RTK software (SW). This SW is a commercial, off-the-shelf SW product from a leading GPS system. This report summarizes a series of evaluation tests conducted by the VSC-A team and an analysis of its accuracy and solution availability characteristics. The performance of VSC-A RTK SW is also compared against that of alternative methods of relative positioning.

This section outlines the background information relating to vehicle positioning modes, absolute versus relative positioning accuracy, and basic information about the RTK method. Objectives of this report are discussed in this section.

1.1 Absolute and Relative Positioning Accuracy

Positioning accuracy can be split into two components as absolute accuracy and relative accuracy. Absolute accuracy is expressed with respect to a global frame (typically World Geodetic System 84 (WGS84) when GPS is used) and becomes a critical requirement when the vehicle position needs to be determined with respect to, for instance, individual lanes on a roadway. Achievable absolute accuracy of a positioning system is dependent on the technologies used in positioning. Three vehicle positioning technologies were used in the work given in this report and these are identified as Positioning Modes. For the purpose of this report, the three Vehicle Positioning Modes used were:

1. GPS: Standalone GPS without any augmentation or correction sources
2. WAAS: Wide Area Augmentation System (WAAS) enabled GPS
3. RTK: Positioning conducted using GPS RTK relative to a fixed base (vehicle-to-infrastructure (V2I) case) or a moving vehicle (moving base, vehicle-to-vehicle (V2V) case). Essentially this involves estimating a precise baseline between two entities using raw GPS. More information on this mode can be found in Misra and Enge (2006) [1].

Expected accuracy of these modes differ, and a general comparison is given in Figure 1. Figure 1 shows a vehicle (A) traveling in the left-most lane of a three-lane road, and its actual position is indicated as A_{ACTUAL}. Centered at the actual position of vehicle A are three error ellipses corresponding to typical accuracies achievable with using GPS, WAAS, and RTK Positioning Modes. Using GPS L1 only, typical values for these modes are 5, 2, and better than 1 m correspondingly [1]. Hence, for the scenario shown, the actual position estimate coming out of a GPS receiver could be anywhere within the error ellipse for a given mode. For instance, a receiver in GPS mode could report A_{GPS} as the vehicle location instead of reporting A_{ACTUAL} due to positioning mode dependent errors.

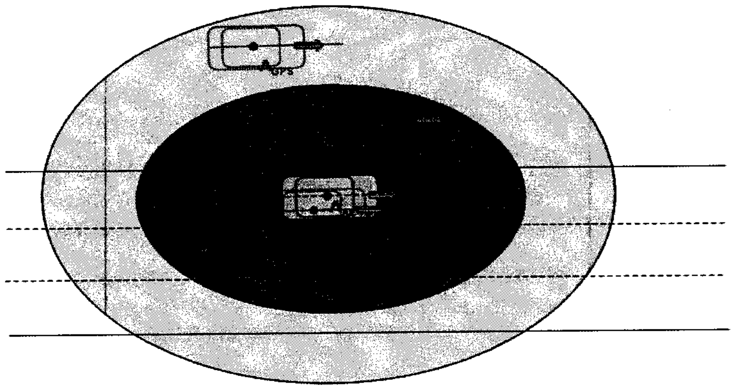


Figure 1: Typical Accuracy Bounds Depending on Positioning Mode

Relative positioning accuracy refers to the accuracy of a relative solution, for instance, the along and across distances between two vehicles. Extending the Figure 1 illustration to two vehicles, if two vehicles are traveling in adjacent lanes as shown in Figure 2, there is a high likelihood of both vehicles experiencing almost the same absolute error given the following assumptions are true:

1. Using the same Positioning Mode (i.e., GPS, WAAS, or RTK)
2. Sky visibility is identical
3. Receiver/antenna characteristics including positioning algorithms are identical

Given that the above are true, both vehicles A and B in Figure 2 most likely will have almost identical 2D absolute errors. The illustration shows errors in excess of 3 m as shown by the error vector between the actual position of vehicle A (A) and the WAAS augmented reported position of it (A_{WAAS}). If individual vehicle GPS receiver reported positions (A_{WAAS} and B_{WAAS}) are used to derive the relative position of one vehicle with respect to the other, the relative errors that are almost negligible due to the fact that common errors cancel each other.

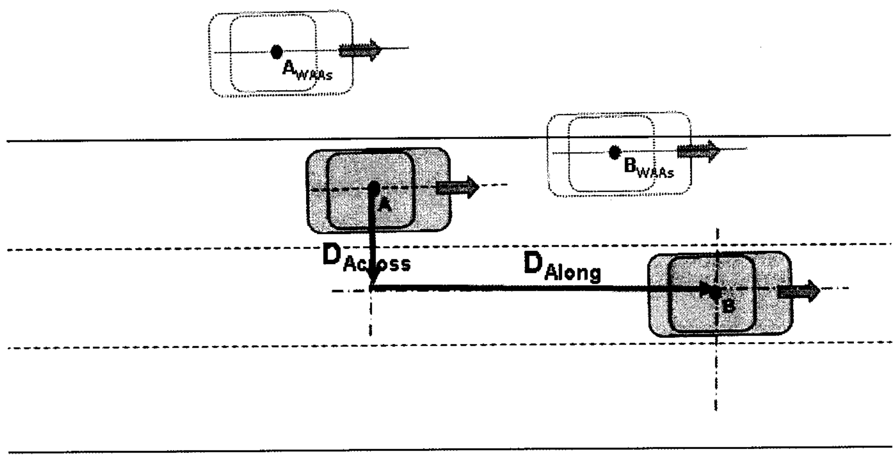


Figure 2: Between Vehicle Distance

It is noted that if the positioning mode of one of the vehicles change, for instance vehicle A changed from WAAS to GPS, the absolute positioning error associated with vehicle A may change as the probable positioning mode dependent error increases. Thus a relative position derived using reported position may abruptly change as indicated later in the analysis.

It is important to note that in the RTK method, the GPS raw measurements are the key variables shared between vehicles and that these do not change due to positioning modes of individual vehicles. The errors/biases in GPS raw measurements made by vehicles in a particular region (i.e., typically within a radius of several tens of km under normal ionospheric activity) are almost identical and, therefore, are nearly eliminated in relative positioning. It is noted that in RTK mode, the accuracy concept should be applied in the relative sense only. For instance, the RTK method error becomes an error in a vector, whereas it is a function of accuracies of two receivers if the relative positioning is done using the positions reported by them.

The primary objective of the tests given in this report is to investigate the relative positioning accuracy of the VSC-A system. The emphasis was to verify that the system performance meets the VSC-A specification of *Which Lane* or better relative positioning accuracy and is *Which Road* level absolute positioning accuracy. It is noted that the tests described in this report specifically looked for situations where assumptions given in this section are violated in normal day-to-day driving.

1.2 VSC-A RTK Software-Based Relative Positioning vs. Alternative Methods

The VSC-A system design provides Over-the-Air (OTA) data for implementing two basic relative positioning approaches. These two approaches are evaluated as alternatives in this report.

Firstly, since vehicle position and other kinematic information with respect to a global frame is shared using OTA messaging (i.e., latitude, longitude, and heading), straightforward latitude longitude differencing can be used to determine the relative position of a vehicle with respect to any other. This method is identified as the Single Point (SP) method of relative positioning in the rest of the report.

The second approach involves using the well-established GPS RTK techniques using the VSC-A RTK SW. This method is identified as the RTK or VSC-A RTK SW method of relative positioning in the rest of the report. More information on RTK can be found in [1].

1.3 Impact of GPS Outages

GPS is a line-of-sight (LOS) system and, therefore, sky visibility obstructions can deteriorate the performance of GPS. In extreme cases, reduced signal availability may totally disable the functionality of a GPS device. More information on performance characteristics of GPS can be found in [1] and other literature.

The analysis presented in this report particularly looks at the availability of the VSC-A RTK SW solution and its accuracy in short GPS outages (i.e., under a few seconds). Also investigated is the time taken for VSC-A RTK SW to start generating solutions after a short complete GPS outage. It is noted that the current implementation of VSC-A relative positioning system is designed specifically for open sky operation and that VSC-A future enhancements are expected to add-in the no-GPS positioning capability in latter stages of the project.

2 Test Setup, Scenarios and Objectives

2.1 Test Objectives

The objective of these tests was to confirm that the VSC-A relative positioning method and the selected SW is capable of providing *Which Lane* level relative positioning capability under operating conditions defined for the VSC-A implementations. Only the positioning system components were used for these tests as shown in Figure 3.

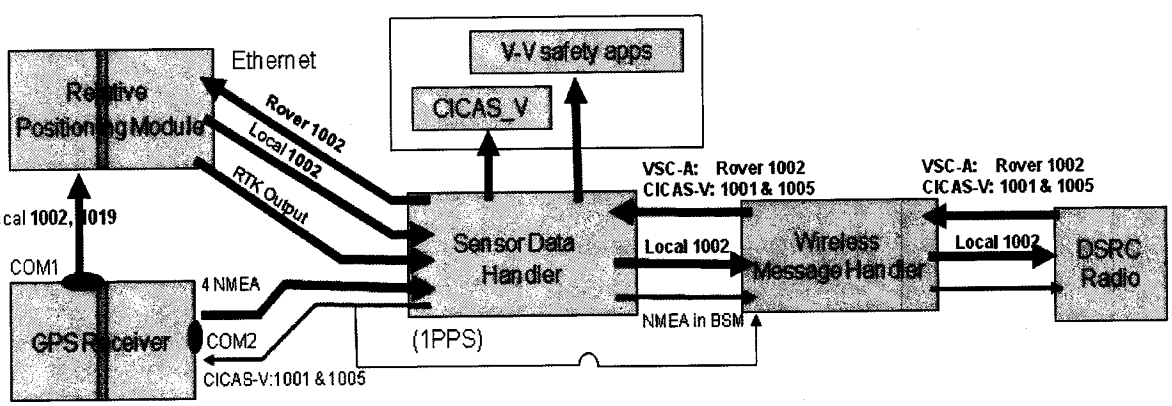


Figure 3: VSC-A Test Bed – Positioning Components