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Performance of DSRC during Safety Pilot Model Deployment

Scott E. Bogard, Shan Bao, and David LeBlanc
University of Michigan - Ann Arbor

Jun Li, Shaobo Qiu, and Bin Liu
FAW Group Corporation - China

ABSTRACT

This paper provides an analysis of how communication performance between vehicles using Dedicated Short-range Communication (DSRC) devices varies by antenna mounting, vehicle relative positions and orientations, and between receiving devices. DSRC is a wireless technology developed especially for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. A frequency band near 5.9 GHz has been set aside in the US and other countries for exploring safety and other uses for road vehicles. DSRC devices installed onboard vehicles broadcast their location using global navigation space systems (GNSS), speed, heading, and other information. This can be used to study communication performance in many scenarios including: car-following situations, rear-end crash avoidance, oncoming traffic situations, left turn advisory, head-on crash avoidance and do-not-pass warnings. Message Capture Fraction and Packet Loss Duration highlight how these measures change with distance and orientation of the vehicles. Data used in this study address four years of real-world use with over 2500 vehicles, with antennas primarily in an aftermarket-style installation.

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INTRODUCTION

This analysis uses data from an ongoing deployment of prototype DSRC systems that spans four years of continuous operation. This deployment began with the Safety Pilot Model Deployment (SPMD), the largest naturalistic study of V2V and V2I wireless technology to date. Sponsored by the US Department of Transportation (USDOT), the SPMD involved fielding over 2800 DSRC devices -- provided by several industry entities – including vehicle-based onboard units (OBU) devices and 29 sets of roadside units (RSU). Data was collected for over 1.5 years starting in August 2012. The test itself was led by University of Michigan Transportation Research Institute (UMTRI) with several partners. The devices exchanged wireless messages with each other and infrastructure units. The objectives of SPMD addressed demonstration and evaluation of real-world performance of DSRC, including data collection to support USDOT safety benefits analyses for a set of driving safety applications; operation of an early security system; exposure of V2X applications to the driving public with subjective data collected from many drivers; and the creation of data archives to support further development. The SPMD ended in spring 2013, but operation continued, supported in part by a three year USDOT project called Ann Arbor Connected Vehicle Test Environment (AACVTE), as well as support from the University of Michigan's Mobility Transformation Center. The results reported in this paper use data from this entire period of data collection, as well as data from another study that compared roof-mounted and interior-mounted DSRC antenna performance.

As of October, 2016 the total distance travelled for both SPMD and AACVTE is 41.8 million miles in 6.4 million trips (ignition-on to off). Total driving time accumulated during this period was 1.48 million hours. The bulk of the data collected during the study is at 10 Hz and includes measures of time, GPS location and heading, speed, acceleration, yaw-rate, brake pedal status and vehicle length and width. These data are stored in a set of relational databases. The principal time-series table contains 53.4 billion records.

This paper focuses on V2V performance. Prior studies of DSRC V2V communication performance have established important insights for understanding how this communication can support safety applications. This includes awareness that packet loss occurs, and is an important consideration for applications dependent on DSRC ([3], [4]). The influences on packet loss, and the duration of those losses have been studied in most cases with roof-mounted antennas and with limited numbers of vehicles. In this paper, the data set is large, incorporating billions of messages collected over years. The receiving units have DSRC antennas inside the vehicle, and most but not all transmitting device antennas are also inside. A limited experiment where the antenna is moved from inside to a roof-mounted locatin is included. Thus this study has hallmarks of a possible "aftermarket" installation. We note that these units are not OEM installed and are of a 2012 vintage, but the basic performance influences of the 5.9 GHz wavelength are thought to be useful for current developments.

PROTOTYPE SYSTEMS

Vehicle Platforms and Device Pedigree

During the SPMD and AACVTE studies, the DSRC equipment was installed on heavy- and medium-duty trucks, transit and school buses, passenger and delivery vehicles, motorcycles, bicycles and Segway PTs. In total, 3,518 vehicles have participated in the project. The vast majority of these vehicles (approx. 3,300) were passenger cars, sport utility vehicles and large vans. Transit and school buses constitute the next largest population of about 120 vehicles; 65 were medium-duty trucks; and 25 heavy trucks (class 7 and 8). Eight motorcycles participated in the study.

The OBUs were installed in three distinct levels or pedigree. The most common OBU was a Vehicle Awareness Device (VAD). Vehicles with these units performed a 'broadcast' only function. They served as remote vehicles broadcasting the Basic Safety Message (BSM) for the safety and convenience applications running on other equipped vehicles. During these studies, there were approximately 3,076 distinct VAD deployed with a peak deployment of approximately 2500 units at one time. In addition to broadcasting a BSM, VAD also logged all broadcasted messages. The next OBU was called the After-market Safety Device (ASD). These units processed both sent and received BSM, for safety applications and used an audible interface to warn the driver of potential conflicts with other equipped vehicles. There were approximately 375 ASD vehicles deployed during the study. The third and most integrated devices were called Integrated Safety Devices (ISD), these devices were developed and installed by a consortium of automakers under the Crash Avoidance Metrics Partnership (CAMP), with support from USDOT. The 67 ISD vehicles were equipped with an advanced Human-Machine Interface (HMI) with both visual and audible alerts in potential conflicts with other equipped vehicles. The ISD pedigree were modeled after a production system designed and integrated into the vehicle instrumentation cluster. Installation on heavy-trucks and transit vehicles followed a similar three level pedigree structure.

DSRC devices (aka "radios") from three suppliers were used in this analysis. In addition to the logging capability of the OBU, all of which recorded transmitted messages, a subset of ASD and all ISD vehicles were up-fit with an independent Data Acquisition System (DAS). These units recorded measures of time; GPS location, heading, quality; speed, acceleration; yaw-rate; brake and cruise control status; forward object detection; lane tracking; Inform and imminent warnings; remote vehicle BSM and classification; and forward, cabin, rear-left, rear-right video along with triggered audio during a warning. For this study both the DAS recorded archives from ASDs (and not OEM ISDs) and the Sent (or broadcast) BSM data archives from all units was used. Note: this analysis does not address OEM-style installations (ISD) as receiving units, and OEM-style installations are only a small fraction of transmitting units.

The safety applications deployed in these studies included:

1. FCW—Forward Collision Warning
2. EEBL—Electronic Emergency Brake Light
3. CSW—Curve Speed Warning
4. IMA—Intersection Movement Assist
5. BSW—Blind Spot Warning

Note: Radio suppliers and device pedigree determined the list of safety applications deployed on any given vehicle. Safety applications common to all vehicles included CSW, FCW, and EEBL.

DSRC and GPS Antenna Location

Most vehicles in SPMD were privately owned and could not be permanently modified by the Test Conductor. This constraint had a large impact on mounting locations of both DSRC and GPS antennas for ASD and VAD units. In general most VAD and ASD sedan vehicles used a Hirschmann Sharkfin antenna mounted on the rear package shelf inside the vehicle. For larger passenger vehicles, vans and SUVs, a MobileMark glass mounted antenna was placed on the driver's side rear window near the tailgate. The GPS antenna was mounted on the trunk lid or on the roof near the tailgate of larger vehicles. Figures 1, 2, and 3 below show typical antenna mounting locations used in SPMD. DSRC wavelengths do not travel well through solid objects and so use of interior-mounted DSRC antennas can suffer in performance.

Fig. 1. Package Shelf DSRC Location

Fig. 2. Window DSRC Location

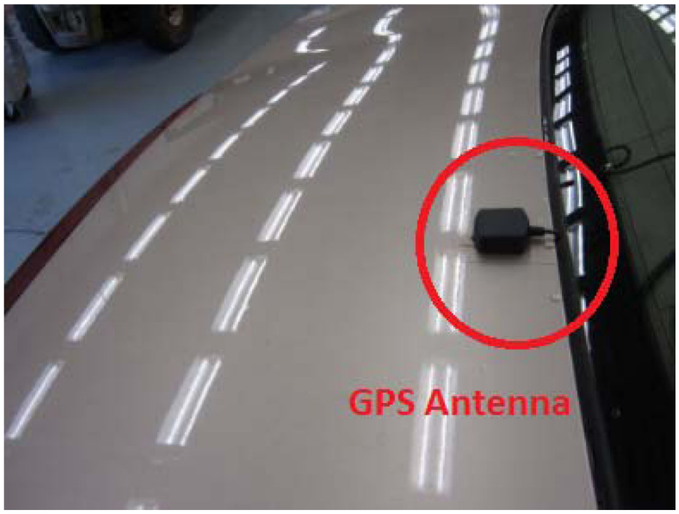

Fig. 3. Trunk Lid GPS Location

ANALYSIS METHODOLOGY AND MEASURES OF COMMUNICATION PERFORMANCE

Methodology

For this analysis, data from 105 passenger vehicles that were equipped with UMTRI data acquisition systems (DAS) and DSRC platforms (ASD) from two suppliers (called Radios 1 and 2 in the figures) were used. These vehicles were chosen because they were passenger vehicles with similar installations in terms of antenna location and type. The remote vehicles used in this analysis are any of the over 2800 vehicles in SPMD (predominately passenger vehicles) broadcasting the BSM during the periods that the host vehicles were driven.

The primary data filtering for this analysis identifies messages that were sent from remote vehicles near the host vehicles, as well as messages received by the 105 ASD vehicles. These data were aggregated as a function of the location and orientation of the remote vehicles, relative to the receiving host vehicle. The methodology used to calculate the performance measures is outlined below:

1. Using received BSMs from remote vehicles (RV) (uniquely identified in every BSM) logged by the DAS on-board the host vehicle (HV), to create a set of interaction events for all HV trips, which are time periods during which the host vehicle is receiving messages from the RV.
2. For each HV trip containing at least one BSM from an RV, search the Sent BSM database and identify all messages from the RV (regardless of location) between the start and end time of the HV trip.
3. At every time step (0.1 s), find the remote vehicle BSMs that were broadcast at that same time (temporal alignment of data) and calculate the geographical distance between the host and remote vehicle using GPS coordinates. If the straight-line distance is less than 1000 m save the RV BSM to a permanent table.
4. Flag all RV messages that match the list of received messages recorded by the HV. Figure 4 shows an example of this method. The map shows an instant in time when host vehicle 15101 was surrounded by eight remote vehicles (within 1000 m).
5. Calculate the East and North vectors of the remote vehicle location, using derived gain values specific to the area to convert latitude and longitude coordinates (degrees) to a relative East/North distance (m).
6. Perform a coordinate transformation rotating the relative locations of all remote vehicle vectors to a vehicle-fixed X/Y coordinate system, with X as the host longitudinal axis and Y pointing to the left (ISO coordinate system). This transformation is shown in the boxes below the map in Figure 4.

Measures of DSRC Performance

Two performance measures are discussed. They are defined as:

- Message Capture Fraction (MCF): is the total number of messages logged by the HV divided by all the RV messages sent and is shown as a function of the distance between the HV and RV.
- Packet Loss Duration (PLD): is the amount of time between subsequent messages received by the HV. Nominally messages are being broadcast in 0.1 s intervals and if all broadcast messages are received then the loss duration is 0 s. A packet loss duration of 0.4 s indicates that three sequential messages were not seen by the HV indicating that the time-gap between received messages was 0.4 s.

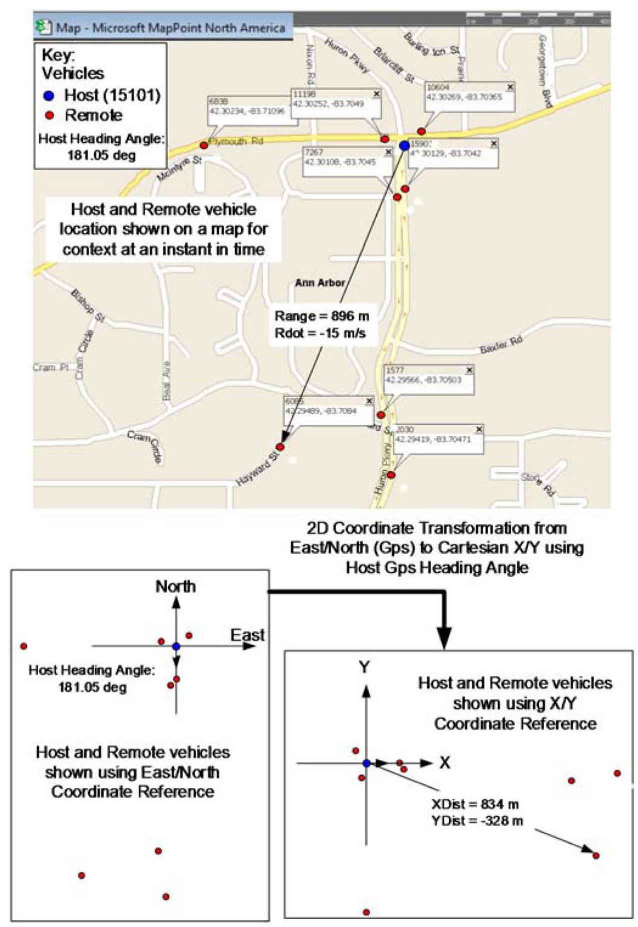

Fig 4. Example showing process for calculating the Cartesian distance from the host to remote vehicles for the BSM communication analysis.

In many DSRC safety applications, these measures of performance are important and inter-dependent. A message capture fraction of 0.5 with a packet loss duration of 0.2 s (HV received every-other message) is different than a capture fraction of 0.5 with a packet loss of 0.6 s. Applications like Forward Collision Warning and Do Not Pass Warning can involve large relative speeds (range-rate) values between host and remote vehicle making a packet loss duration of 0.6 s significant in terms of the conflict severity not to mention the computational instabilities and assumptions that must be used to estimate the vehicle kinematics while waiting for an updated estimate from DSRC.

RESULTS

Overall MDF result for one radio supplier is shown as a contour plot in Figure 5. The x-axis is the longitudinal distance between the host and remove vehicle. This presentation assumes the host vehicle is located at an (x, y) location of (0, 0) m with a heading in the positive x-direction. The y-axis is the lateral distance between the host and remote vehicle. For this presentation, the relative speed and direction of the remote vehicle is not considered. That is, a remote vehicle located at (-100, 0) would be 100 m behind the host vehicle but could be heading in the same, opposite or orthogonal direction compared to the host vehicle. The contours of the figure show the average MCF as function of longitudinal and lateral distance for one radio supplier during SPMD.

The figure shows that performance is better longitudinally compared to laterally by an approximate factor of about 1.6. The reasons for this difference are probably due to: a) directional component in the design of the DSRC antenna and b) reduced line-of-sight in lateral direction compared to the longitudinal direction due to road side objects like trees, buildings and signs.

The outer-most contour is a MCF of 0.1. At this range an average of only 1 in 10 messages were received by the host vehicle. A MCF of 0.1 ranges from over ±200 m longitudinally to ±125 m laterally. A MCF of 0.5 ranges from over ±75 m longitudinally to ±50 m laterally. Note that a receiving radio's performance depends in part on the transmitting radios. This analysis does find a difference in performance based on the receiving radio supplier, but the mechanisms for this are not identified and should not be taken as a definitive finding that one units is better than the other.

Figure 6 shows the same performance measure for radio suppler 2. Similar to Figure 5, the performance is better in longitudinal direction compared to the lateral direction. These data suggest that the performance of radio 2 compared to radio 1 is limited to closer distances for the same MCF. A MCF of 0.1 ranges from over ±150 m longitudinally to ±75 m laterally. A MCF of 0.5 ranges from over ±50 m longitudinally to ±40 m laterally.

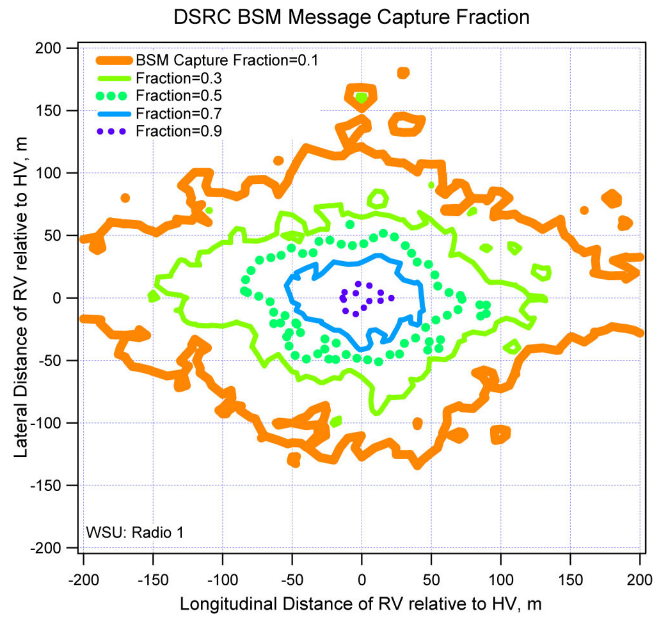

Fig 5. Message Capture Fraction for Radio 1

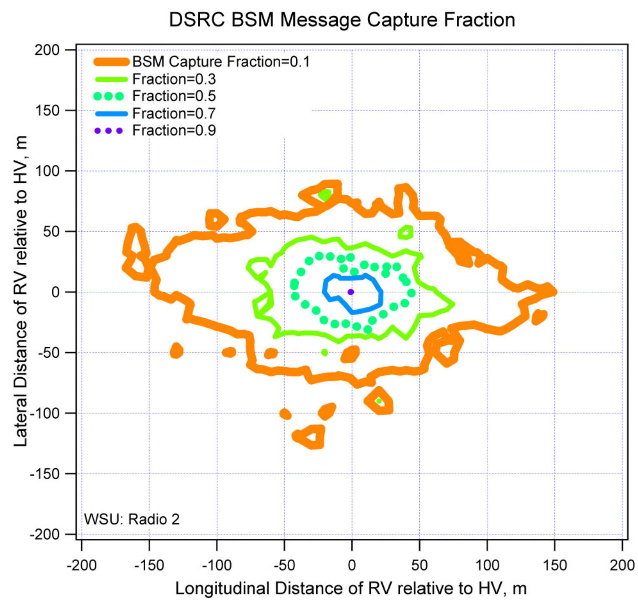

Fig 6. Message Capture Fraction for Radio 2

The next plots focus on scenarios in which the broadcasting RV and the receiving HV are likely on the same roadway, traveling in the same direction or in opposite directions. Figures 7 and 8 shows the message capture fraction for Radios 1 and 2 as a function of relative direction of travel between the host and remote vehicles. The x-axis is longitudinal distance of the remote vehicle relative to the host. The value at the center of the axis is zero. Positive distance values are to the right on the figure and reflect the case when the remote vehicle is forward of the host vehicle. Negative distance values are the left of the figure and represent times when the remote vehicle is behind the host. The data shown in the figure only includes remote vehicles that are within -20 to 20 m laterally relative to the host. These data represent a rectangle 40 m wide and 400 m long with the host vehicle at the center, pointed in the positive longitudinal direction.

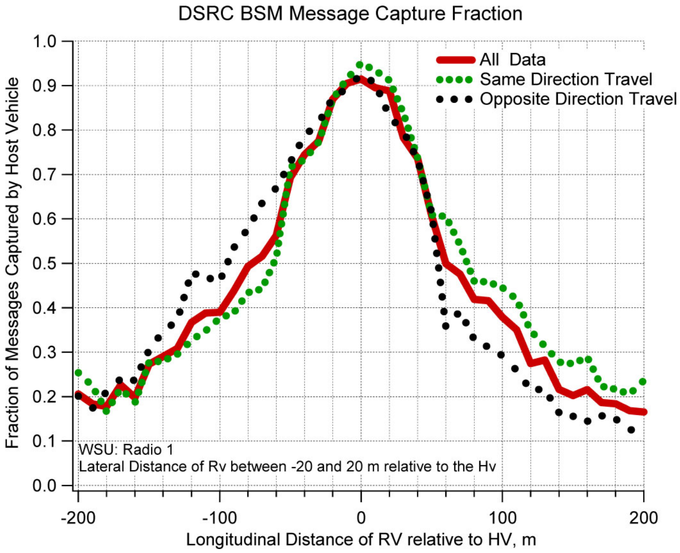

Fig 7. Message Capture Fraction as a function of relative heading for Radio 1

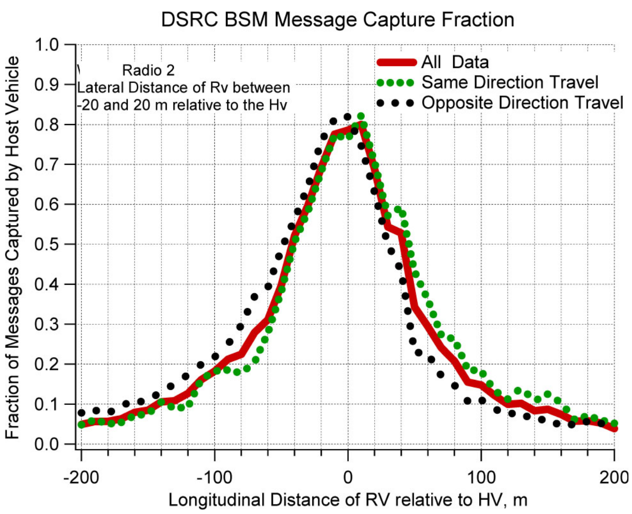

Fig 8. Message Capture Fraction as a function of relative heading for Radio 2

The vertical axis on the figure is the fraction of messages captured by the host vehicle. The MCF ranges from 0 to 1. The MCF is the number of messages received by the host divided by the total number of messages broadcast by the remote vehicle while in the defined geographical area.

The solid line in both plots represents the BSM capture fraction of all data regardless of remote vehicle travel direction (or heading relative to the host). For both radio types, this distribution has a similar bell-curve shape with a peak value of approximately 0.85 at 0 m relative distance longitudinally. This means approximately 85% of messages sent by remote vehicles at very short ranges are received by the host vehicle. The fraction decreases as the distance to the remote vehicle increases, with a slightly higher message capture fraction for remote vehicles behind the host vehicle. Radio 1 shows a message capture fraction of 0.2 (1 in 5 messages are received) at a 200 m relative position of the remote vehicle. The performance of Radio 1 compared to 2 is better in terms of received messages performance which is illustrated by the wider distribution (hence higher capture fraction as a function of relative distance) shown in the upper plot. Conversely, Radio 2 shows a narrower distribution and lower capture fraction at all relative longitudinal distances compared to Radio 1. Note that the Radio 1 and 2 difference addresses the receiving units. Both radio types are receiving broadcasts from devices provided by the suppliers of Radios 1 and 2, as well as a third supplier. Almost all broadcasting radios are from either the third supplier or the supplier of Radio 1

Also shown in Figure 7 and 8 is the cumulative influence of remote vehicle travel direction relative to the host. The closely spaced dotted line represents same direction travel, while the less dense dotted line is opposite direction travel of the remote vehicle. Conceptually, same direction travel simply means both the host and remote vehicle have similar heading angles. There was no constraint on the relative speed of the two vehicles and both closing and separating behavior is captured in the figure. Opposite direction travel means the relative heading of the host and remote vehicle are approximately 180 deg. apart. As in the case of same direction travel, there was no constraint on relative speed. The performance of both Radio 1 and 2 does change with relative heading. Both distributions show higher capture rates for same direction travel when the remote vehicle is ahead of the host vehicle (positive relative longitudinal distance). Also, both Radio 1 and 2 show a lower capture rate for same direction travel when the remote vehicle is behind the host. For opposing direction travel radio capture fraction is the converse of same direction travel. Than is, performance increases when the remote vehicle is behind the host and decreases when the remote vehicle is ahead of the host.

The reason for this performance difference is not clear from the figure. Judging from the general characteristics of the dominant vehicles (passenger vehicles) and the DSRC antenna installation used in SPMD, the difference could be due antenna placement. In most installation, the DSRC receiving and broadcasting antenna was mounted on the package shelf inside the car behind the rear seats. Since DSRC performance is negatively influenced by 'line-of-sight' disturbance, the best performance would come from opposite direction travel with the remote vehicle to the rear of the host (negative relative longitudinal distance) since the DSRC signal only needs to pass through the rear glass of both vehicles. Conversely, the poorest performance would be opposite direction with the remote vehicle ahead of the host, in this case the DSRC signal must pass through the cabin and front glass of both vehicles.

Similar observations can be made about same direction travel. Performance appears to be more symmetric regardless of the remote vehicle position with slightly less performance when the remote vehicle is behind the host. The reason for this difference probably depends less on the antenna position between the two vehicles since in either configuration (remote behind or ahead of host), the DSRC signal must pass through the cabin of one vehicle and the rear glass window of the other.

Figures 9 and 10 address Packet Loss Duration for Radio 1 and 2, respectively. Similar to earlier figures, the x-axis shows the relative distance between the host and remote vehicles. The y-axis shows a normalized distribution of the capture fraction and packet loss duration. The capture fraction, as defined before is simply the ratio of received messages by the host divided by the total number of messages broadcast by the RV at a given distance. Note: in both figures the lateral distance between the HV and RV is constrained to ±20 m. The PLD is divided into four categories, namely: a single dropped message (PLD = 0.2 s); two or three consecutively dropped messages (PLD between 0.3 and 0.4s); four to 10 dropped messages (PLD between 0.5 and 1.1s) and more than 10 dropped messages (PLD > 1.1s). In the figure, the PLD message count for each category is then divided by the total number of messages broadcast by the RV to show the relative fraction of each PLD category as function of distance from the HV.

One important observation from these figures is that even at a small relative distance there is PLD of more than 1.1s. This occurred about 5 percent for Radio 1 and 15 percent of the time for Radio 2. At distances between 20 and 50 m (an important range for FCW) the PLD gap of more than 1.1s increases to 25 and 45 percent for Radio 1 and 2, respectively. These durations of packet loss suggest strongly that closed loop control based only on DSRC is unlikely to be successful. DSRC, however, can be useful in supporting closed loop control that is based primarily on a more persistence sensor, such as radar; in this case, fusing DSRC data may provide valuable information to enhance performance due to its wide angular coverage and 'look-around' capabilities.

Consistent with earlier results, these figures show a difference in performance between Radio 1 and 2. Radio 2 (Figure 10) shows a lower MCF and hence greater fraction of PLD for all longitudinal distances. Furthermore, the figure shows a much faster rate of decline in MCF as distance increases compared to Radio 1.

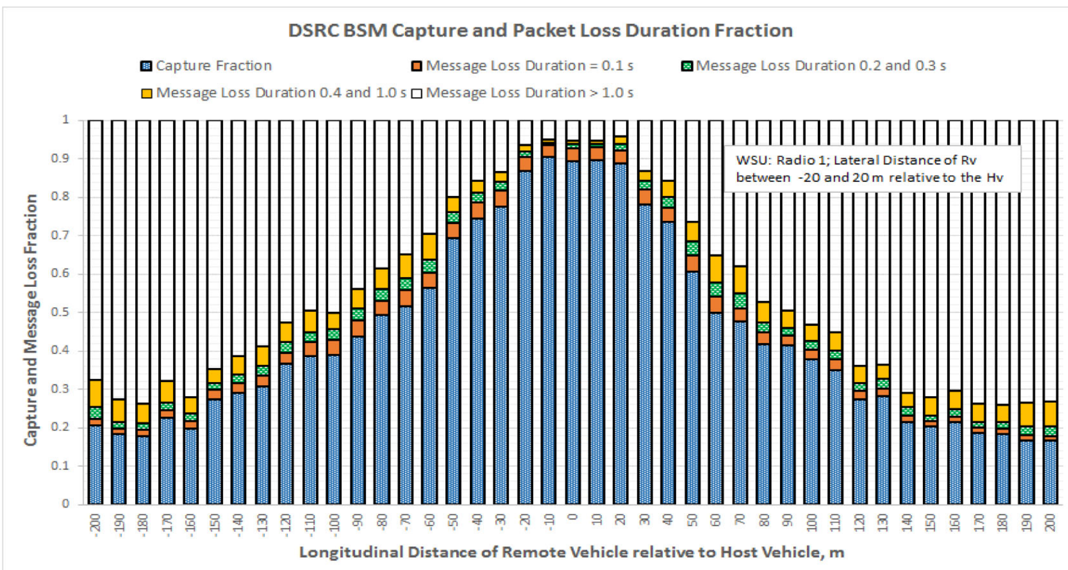

Fig. 9. Packet Loss Duration for Radio 1

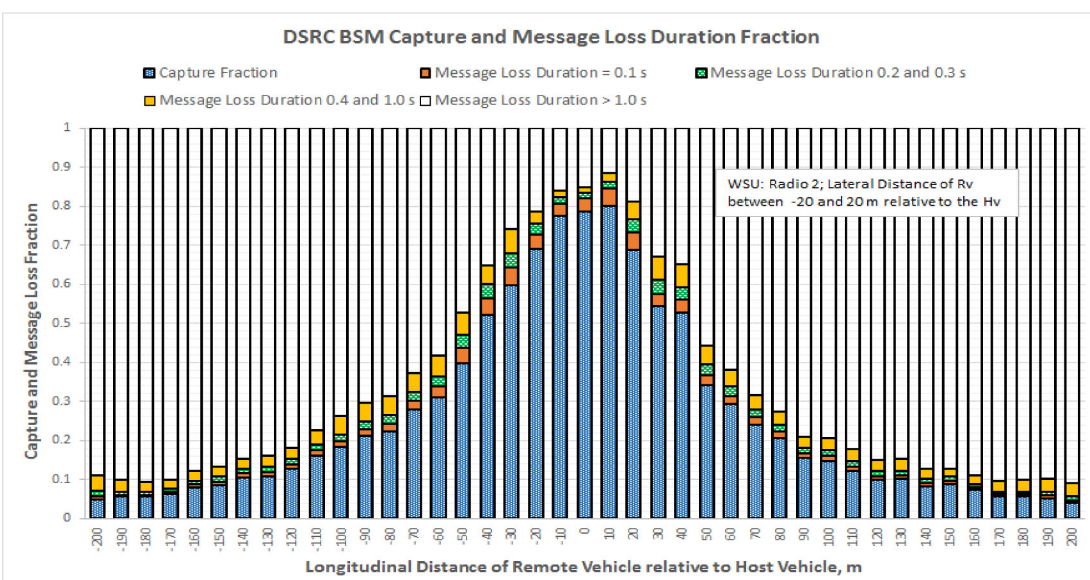

Fig. 10. Packet Loss Duration for Radio 2

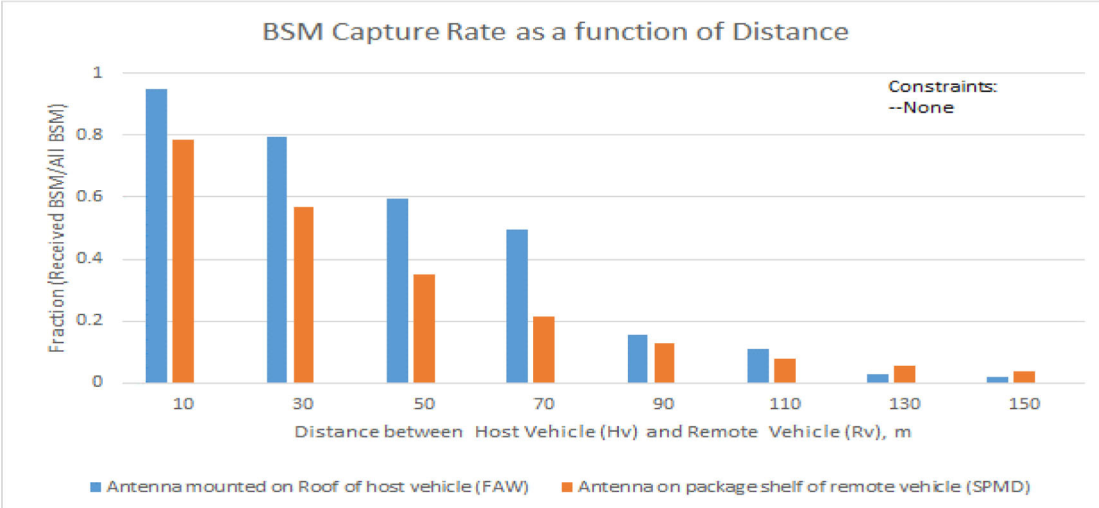

Fig. 12. BSM Capture Rate as function of Distance for SPMD (package shelf DSRC) and Roof Mounted DSRC Antenna

Antenna Roof Location

In addition to findings based on results from the large vehicle set, limited testing was done using a Hongqi H7 vehicle on loan from FAW Group Corporation, a Chinese OEM headquartered in Changchun, Jilin, China. For these tests, UMTRI installed a data logger and a DSRC OBU similar to the light vehicle ASDs in SPMD/ AACVTE. However, a special mount was formed that allowed a DSRC antenna (Hirschmann Sharkfin) to be mounted on the roof of the vehicle with a 360 degree view of the horizon, or on the interior package shelf. The antenna in its roof-mounted location is in Figure 11.

Fig. 11. Roof Mount DSRC Antenna

The vehicle was then driven for 2800 km in the SPMD area to interact with other DSRC equipped vehicles. Data from the vehicle were then downloaded and analyzed in a similar manner to the approach above. Initial findings from these tests are shown in Figure 12. The figure shows a marked increase in the MCF for distances between 10 and 110 m when mounted exterior and above the roofline. These results show only data where the FAW (HV) was behind the RV. The improvement ranges from a factor of 1.21 at 10 m to 2.32 at 70 m. Although, the roof mounted antenna performance appears to make substantial difference in performance more testing is necessary, since data collected on the FAW vehicle was limited compared to the millions of miles logged by the SPMD vehicles. However it is consistent and perhaps supports findings from the earlier analyses.

CONCLUSION

This paper addresses V2V communication performance using DSRC in a realistic environment in Ann Arbor, Michigan, with over 2500 vehicles, across a period of years. Messages sent by all vehicles, and messages received by 105 specially instrumented vehicles, were compared to compute performance measures as a function of relative locations and relative orientations of the vehicles, as well as looking at influences of an interior DSRC antenna location. Message Capture Fraction and Packet Loss Duration performance measures are shown to illustrate how the distance between vehicles changes these measures. Even at modest ranges, the packet drop rate and the duration of message losses seems to indicate that closed-loop control based only on DSRC is unlikely unless performance improves. The paper also illustrates performance differences as function of intra-vehicle directionality which might be important depending on the safety applications being developed. Preliminary results show a marked increase in communication performance for a roof-mounted DSRC antenna opposed to an interior package shelf location. For the after-market installation this is an important consideration given that a roof-mounted antenna may not be practical. Finally, the equipment used in these studies is considered first generation DSRC and like all technology improvements will increase both the positional accuracy of the technology and its ability to communicate with other devices at longer distances. The antenna locations were similar to potential aftermarket installations and are not directly indicative of OEM-style installations on vehicle roofs.

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