CONNECTED VEHICLE/INFRASTRUCTURE UNIVERSITY TRANSPORTATION CENTER (CVI-UTC)

Connected Motorcycle System Performance

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Disclaimer

Connected Vehicle/Infrastructure UTC

The mission statement of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) is to conduct research that will advance surface transportation through the application of innovative research and using connected-vehicle and infrastructure technologies to improve safety, state of good repair, economic competitiveness, livable communities, and environmental sustainability.

The goals of the Connected Vehicle/Infrastructure University Transportation Center (CVI-UTC) are:

- Increased understanding and awareness of transportation issues
- Improved body of knowledge
- Improved processes, techniques and skills in addressing transportation issues
- Enlarged pool of trained transportation professionals
- Greater adoption of new technology

Abstract

This project characterized the performance of Connected Vehicle Systems (CVS) on motorcycles based on two key components: global positioning and wireless communication systems. Considering that Global Positioning System (GPS) and 5.9 GHz Dedicated Short-Range Communications (DSRC) may be affected by motorcycle rider occlusion, antenna mounting configurations were investigated. In order to assess the performance of these systems, the Virginia Tech Transportation Institute's (VTTI) Data Acquisition System (DAS) was utilized to record key GPS and DSRC variables from the vehicle's CVS Vehicle Awareness Device (VAD). In this project, a total of four vehicles were used where one motorcycle had a forward mounted antenna, another motorcycle had a rear mounted antenna, and two automobiles had center-mounted antennas. These instrumented vehicles were then subject to several static and dynamic test scenarios on closed test track and public roadways to characterize performance against each other. Further, these test scenarios took into account motorcycle rider occlusion, relative ranges, and diverse topographical roadway environments.

From the results, both rider occlusion and approach ranges were shown to have an impact on communications performance. In situations where the antenna on the motorcycle had direct line-of-sight with another vehicle's antenna, a noticeable increase in performance can be seen in comparison to situations where the line of sight is occluded. Further, the forward-mounted antenna configuration provided a wider span of communication ranges in open-sky. In comparison, the rear-mounted antenna configuration experienced a narrower communication range. In terms of position performance, environments where objects occluded the sky, such as deep urban and mountain regions, relatively degraded performance when compared to open sky environments were observed.

Acknowledgements

The principal investigators would like to thank the Connected Vehicle/Infrastructure – University Transportation Center for funding this project. Dedicated data collection and analysis for a high-risk population serves this group as well as the transportation community as a whole. In particular, the support and skill set provided by the Center for Technology Development at the Virginia Tech Transportation Institute proved instrumental in integration of the motorcycles and vehicles used by this project. Further, Alexandria Noble went above and beyond by taking the lead in execution of experimental tasks and assisting in data analysis efforts. The principal investigators would also like to thank Melissa Hulse, Miao Song, Arnab Gupta, Leslie Harwood, Shane McLaughlin and Zac Doerzaph for assisting in the various phases of this study. It should be noted that this document should be considered a technical report and is not peer-reviewed or archival for the purposes of publication.

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Background

Motorcycle riders have much to gain with the widespread adoption of connected vehicle systems (CVS) and the safety applications enabled by this technology. One in every seven fatalities on our nation's roads is a motorcycle rider, even though they report substantially lower annual vehicle miles traveled. Fatal motorcycle crash rates have been increasing in recent years, rising from 7% to 13% of all traffic fatalities over a 10-year period [1]. Based on the United States Department of Transportation (U.S. DOT) National Highway Traffic Safety Administration's (NHTSA's) decision to move forward with vehicle-to-vehicle (V2V) communication for light vehicles, a research need exists to further characterize how CVS can be leveraged to support this at-risk population on our nation's roadways.

Research performed during the Safety Pilot Model Deployment (SPMD) by the Crash Avoidance Metrics Partnership (CAMP), Virginia Tech Transportation Institute (VTTI), and various U.S. DOT research entities indicated that Dedicated Short-Range Communications (DSRC)-based safety systems proved feasible. These systems may address a substantially large percentage of crash types across various vehicle types, and, in particular, motorcycles.

It was shown during preparatory research investigating the introduction of motorcycles in the SPMD environment that the location of key CVS components is critical. For example, differences in DSRC signal ranges and packet error rate were found as a function of antenna location [2]. In an effort to characterize these differences, this project used the two key components of CVS, DSRC and GPS to measure their effectiveness for motorcycles. Considering that GPS and DSRC antenna receive and transmit propagation patterns which will likely be occluded, or blocked, by the motorcycle rider, two different antenna mounting configurations (i.e., forward and behind the rider) were analyzed.

Figure 1 and Figure 2 illustrate how the location of an antenna may impact exposure to wireless signals. Further, depending on the location of the antenna, the motorcycle rider may physically block and absorb wireless signals resulting in lower signal levels when receiving or transmitting. This attenuation of signals may affect performance and, therefore, the overall reliability of CVS. For these configurations, positioning and wireless performance were tested in various static and dynamic experiments that take into account motorcycle rider occlusion, relative ranges, and diverse topographical roadway environments. Additionally, Global Navigation Satellite Service (GNSS) tracking contends with different patterns of occlusion (Figure 2).

Figure 1. Illustration of DSRC propagation occlusion on a motorcycle with a forward mounted antenna.

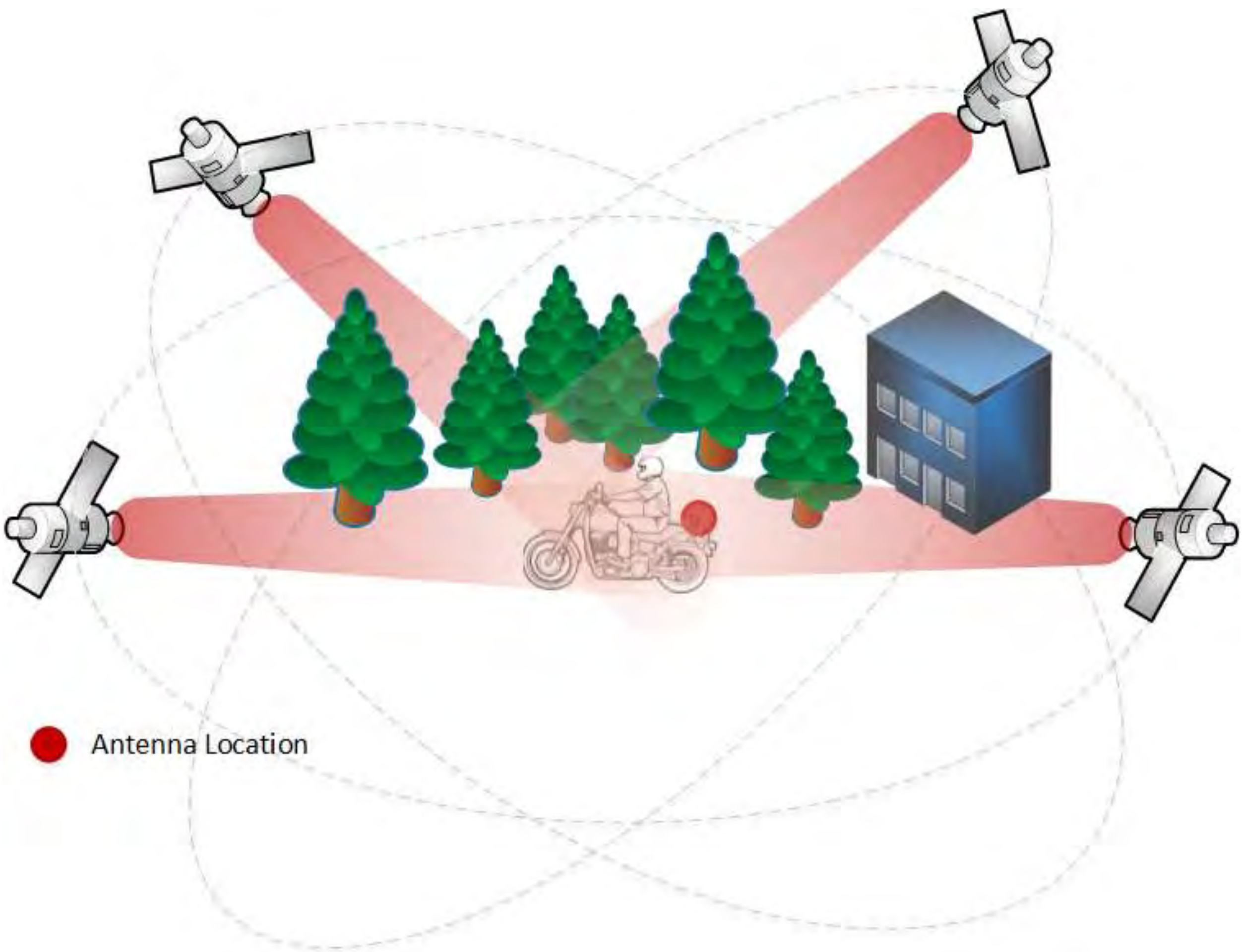


Figure 2. Illustration of GNSS propagation occlusion.

Objectives

This research project focuses on characterizing the positioning and communications performance of CVS for motorcycles. Investigating the antenna placement on a motorcycle undergoing test scenarios took into account motorcycle rider occlusion, relative ranges, and diverse topographical roadway environments. The relevant data were collected and analyzed to characterize the effects of antenna mounting location. The experiment was designed to be comparable with the system performance tests performed by VTTI in cooperation with the CAMP Vehicle Safety Consortium 3 (VSC3) during the Safety Pilot Driver Acceptance Clinics Performance Drives (DAC) project [3]. Lastly, based on the analyzed results, a summary of key observations and recommendations has been provided.

Method

In an effort to understand the overall performance of CVS for motorcycles, an extensive study involving instrumentation of vehicles and collection of data in various configurations was undertaken. Test configurations were developed to focus on specific performance metrics. The collected data per experimental test scenario were then analyzed for communications and positioning performance measures of interest.

The following sections provide detailed descriptions regarding performance measures, performance considerations, study vehicles and instrumentation, test environments, and experimental test plan scenarios.

Performance Measures

The primary communications performance measures, which deal specifically with the DSRC link between vehicles, were the received signal strength indicator (RSSI) and the packet error rate (PER) as defined below. Each of these metrics was analyzed from the perspective of the receiving vehicles. Such metrics are typically affected by obstacles (e.g., motorcycle riders, vehicles braking in formation, buildings, trees), bad signal-to-noise ratio due to distance, and signal interference due to collisions with other over the air (OTA) messages [3].

- The RSSI is a power measurement for each message received OTA from a transmitting vehicle. Each vehicle was set to transmit at a fixed power level of 15 dBm (decibel milliwatts) (equivalent to 31.6 mW [milliwatts]). The closer the RSSI measure is to 15 dBm, the stronger the signal.

- The PER is the ratio of packets that were not received versus the total number of packets expected to be received from a transmitting vehicle (Equation 1). In the case of BSMs, packets are required to be transmitted 10 times per second. For this study, the PER is assessed every second where we expect 10 packets to be received. Generally, the lower the PER, the stronger the signal.

EQUATION 1 - PACKET ERROR RATE

$$PER = \frac{Packets\ Received - Packets\ Expected}{Packets\ Expected}$$

Position performance measured the link between the GPS satellites in orbit and the vehicle on the roadway. The primary metrics analyzed in this study included satellites available, satellites used and horizontal dilution of precision (HDOP); circular error probability (CEP) was assessed for the static test only.

- Satellites Available, or the number of satellites seen by the GPS receiver.
- Satellites Used, or the number of satellites actually used by the GPS receiver in deriving the location solution. Generally the more satellites used in deriving the location solution, the better the accuracy.
- HDOP is a GPS-receiver-derived measure of the geometric quality of the GPS satellite configuration in the sky. HDOP is a factor in determining the relative accuracy of a horizontal position. The smaller the dilution of precision (DOP) number, the better the geometry [4].
- CEP is the radius of the smallest circle, centered at the true position point, which encompasses 50% of the measurement [5]; this assessment was only relevant for the static test scenario.

Such metrics are typically affected by the ability of the receiver to "see" the satellites in orbit. Therefore, any obstructions blocking view of the sky (e.g., motorcycle riders, mountains, buildings) may impact performance.

Performance Considerations

Assessment of the performance measures requires consideration of factors involving the instrumentation and testing environment. As mentioned, any obstruction between the antenna and the source of wireless transmission (GPS satellites or DSRC-instrumented vehicles) may impact overall operational performance. Obstructions can involve combinations of the motorcycle riders themselves, vehicles, buildings, trees, overpasses, roadway elevation grades, and roadway curvatures, to name a few. With that in mind, methods to identify and quantify these effects were taken into account for this study. Further, the specific scenarios (as defined in the Experimental Test Scenarios section) were developed to collect data in the presence of such obstructions.

The primary consideration in this study was the antenna mounting location on the motorcycle. As Figure 1 and Figure 2 show, the motorcycle rider may be seated within the path of the wireless signals, causing attenuation of the signal power. Two motorcycles were utilized, both cruiser style motorcycles of similar size. On the Front Antenna motorcycle, the antenna was mounted in front of the rider; on the Rear Antenna motorcycle, the antenna was mounted behind the rider. The Study Vehicles and Instrumentation section will provide details regarding the configurations of both the cars and motorcycle vehicle types. It should be noted that throughout the report, the term vehicle is used to encompass motorcycles as well as four-wheel cars.

The relative vehicle-to-vehicle ranges proved particularly important. As the distance between the DSRC-equipped vehicles increased, the overall received power was expected to decrease due to several attenuation factors in the channel. Conversely, the closer the vehicles were to each other, the overall received power was expected to increase. Utilizing the collected position data from the host vehicles (HVs) GPS, as well as the received Basic Safety Message (BSM) position information from the remote vehicle (RV), relative distances were calculated. Unfortunately, it was not within the scope of this project to include an accurate independent source of range measurement (e.g. Radar, Lidar). Thus, in instances where the GPS position accuracy was diminished, the corresponding performance metrics relating to distance bins may contain some associated error. In general, this error is expected to be small relative to the distance between antennas. Further, vehicle awareness devices (VAD) cease to report a position solution when accuracy drops below the given specification as defined in the Study Vehicles and Instrumentation section.

Environment played an important part as well. The environment in which the vehicles were operating are exposed to various occlusion angles, which may have blocked partial view of the sky, as described in Table 1 [3]. By leveraging roadway environment map databases and terrain data, the collected GPS locations of vehicles were flagged by environment. By breaking up the data and analyzing environments separately, the influence of each environment on CVS performance was assessed.

Table 1. Roadway Environments

Environment	Road Description	Environment Occlusion Angle	Typical Speed Limits
Deep Urban	City centers lined by multi-story buildings	High; 20° to 40°, occasionally 80°	25 mph frequent starts and stops
Major Urban Thruway	Roads lined by 3- to 4-story buildings	20°	41 to 64 mph
Major Rural Thruway	Only occasional 3- to 4-story buildings, otherwise open sky	0° to 20°	41 to 64 mph
Major Roads	Other major roads	5° to 20°	31 to 40 mph
Local Roads	Neighborhood streets, commonly lined with trees	5° to 10°, worse with trees	25 mph, frequent stops and turns
Interstate/Freeway	Divided highway with at least two lanes in each direction	0° to 5°	65 to 75 mph
Mountains	Tree covered and mountainous	5° to 20°, worse with trees	25 to 75 mph

Study Vehicles and Instrumentation

A total of four vehicles, consisting of two motorcycles and two automobiles, were used in the CVS performance assessment for motorcycles. Each vehicle was instrumented with a data acquisition system (DAS), which collected synchronized data from forward radar, inertial measurement unit (IMU), vehicle CAN, networks, and various video views throughout the testing scenarios. Additionally, the DAS collected data from a VAD that allowed for wireless communication between instrumented vehicles and infrastructure. The overall data collected from the sensors allowed for evaluation of system performance. Figure 3 depicts a generalized overview of the vehicle builds and component layout.

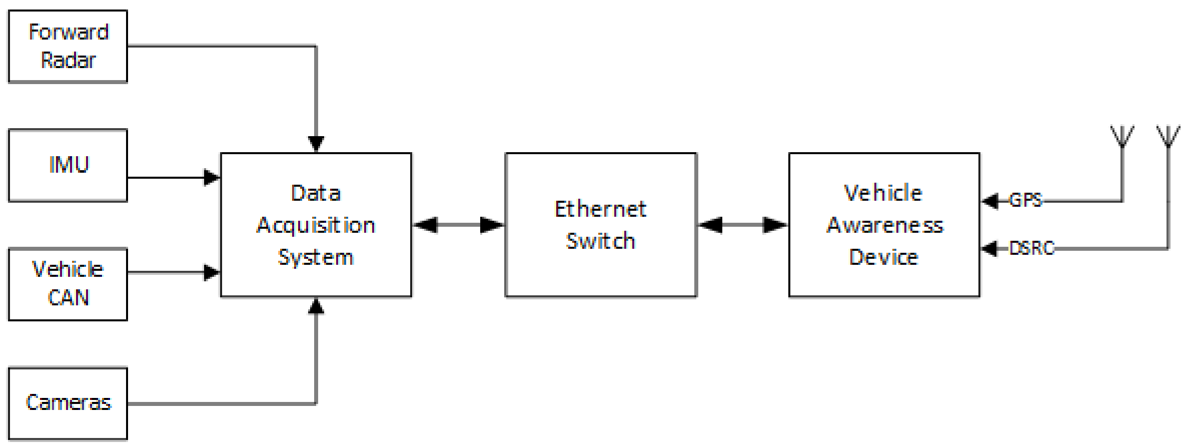


Figure 3. Test vehicle equipment diagram.

The primary device of interest in this study was the Savari MobiWAVE VAD (Table 2). This device utilizes an embedded GPS receiver to populate specific data elements in a standardized SAE 2735 DSRC BSM as shown in Table 3. The VAD then utilizes the DSRC radio to transmit BSMs wirelessly at a rate of 10 Hz while also receiving BSMs from RVs via a Hirschman Shark fin Combined DSRC/GPS antenna (Figure 4). In addition to the received and transmitted BSMs, detailed DSRC and GPS performance data elements are transmitted to the DAS from the VAD. Selected BSM data elements and DSRC/GPS performance variables serve as the primary source to measure overall performance of the CVS as defined in Table 4.

Figure 4. Hirschman Shark fin Combined DSRC/GPS antenna.

Table 2. OBE Technical Specifications [6]

Device	Power	Wireless	GPS	Port	Antenna	Storage
Vehicle Awareness Device (VAD)	12VDC USCAR connector	1 25dbm DSRC/Wi-Fi 5.15-5.9GHz, 10, 20 MHz channels, 802.11a	+/- 2m Position Accuracy, 50% CEP	1 Ethernet 1 RS-232 2 USB 2 FAKRA	Multiband Wi-Fi / DSRC / GPS	Up to 512MB internal, USB external

Table 3. Basic Safety Message Data Elements [7]

Basic Safety Message		
Dynamic Content		**Static Content**
DSRC Message ID	Positional Accuracy	Vehicle Width
Message Count	Heading	Vehicle Length
Temporary ID	Transmission and Speed	Vehicle Height
Dsecond	Steering Wheel Angle	Vehicle Type
Latitude	Acceleration Set (Four Way)	
Longitude	Brake System Status	
Elevation	Event Flag	

Table 4. Collected Performance Variables

Variables of Interest	Performance Focus	Use Case Definition
Latitude	Communication & Position	Vehicle geographic latitude used for location mapping and calculating relative distances between vehicles.
Longitude	Communication & Position	Vehicle geographic longitude used for location mapping and in calculating relative distances between vehicles.
Heading	Communication & Position	Vehicle geographic heading used for location mapping and in calculating relative distances between vehicles.
Message Count	Communication	Message number that increments by 1 per each message transmitted by a motorcycle (i.e. 0, 1, 2, 3, 4, … , 127). Value is used to determine the PER of a transmitting motorcycle as received by a car.
RSSI	Communication	Power level measurement for each OTA message received by a car from a transmitting motorcycle.
HDOP	Position	Geometric quality of GPS satellite configuration as seen by the GPS receiver on a motorcycle.
Satellites Used	Position	Number of satellites used in determining a location solution as seen by the GPS receiver on a motorcycle.
Satellites Available	Position	Number of satellites available for use in determining a location solution as seen by the GPS receiver on a motorcycle.
Space Vehicle Number	Position	Unique serial number assigned to each GPS satellite used in determining location solution. Information is used to associate which satellites were used by each motorcycle

The four vehicles utilized in this study are shown below and summarized in Figure 5 and Table 5. In an effort to simplify test configurations, as well as to accommodate vehicle usage across CVI-UTC projects, two fixed antenna configurations were chosen for all experimental scenarios. As mentioned previously, one motorcycle had the antenna placed in the front, forward of the rider. The other had the antenna place rearward, behind the rider.

Figure 5. Study vehicles (antenna installations identified with red circles).

Table 5. Study Vehicles

Vehicle Type	Sedan	Motorcycle (Black)	Motorcycle (Blue)	SUV
Antenna Location	Center	Front	Rear	Center

The location of the antennas offer several Radio Frequency (RF) peculiarities due to the maneuvers that are necessary in operation of a motorcycle. Provided in Figure 6 and Figure 7 are diagrams detailing the location of the mounted antenna, driver occluded wireless communication paths, and axes of rotation on motorcycles. In both cases, as is noted in the forward cross-section diagram below, motorcycle maneuvering involves leaning into turns which directs the beam of RF energy into different vectors such as the sky or roadway. In the side view, the motorcycle rider will occluded the antenna from receiving and transmitting wireless energy depending on mounting location. Specific to the forward antenna overhead view, the mounting location is on the handlebar of the motorcycle and will focus the RF energy towards the direction of travel.

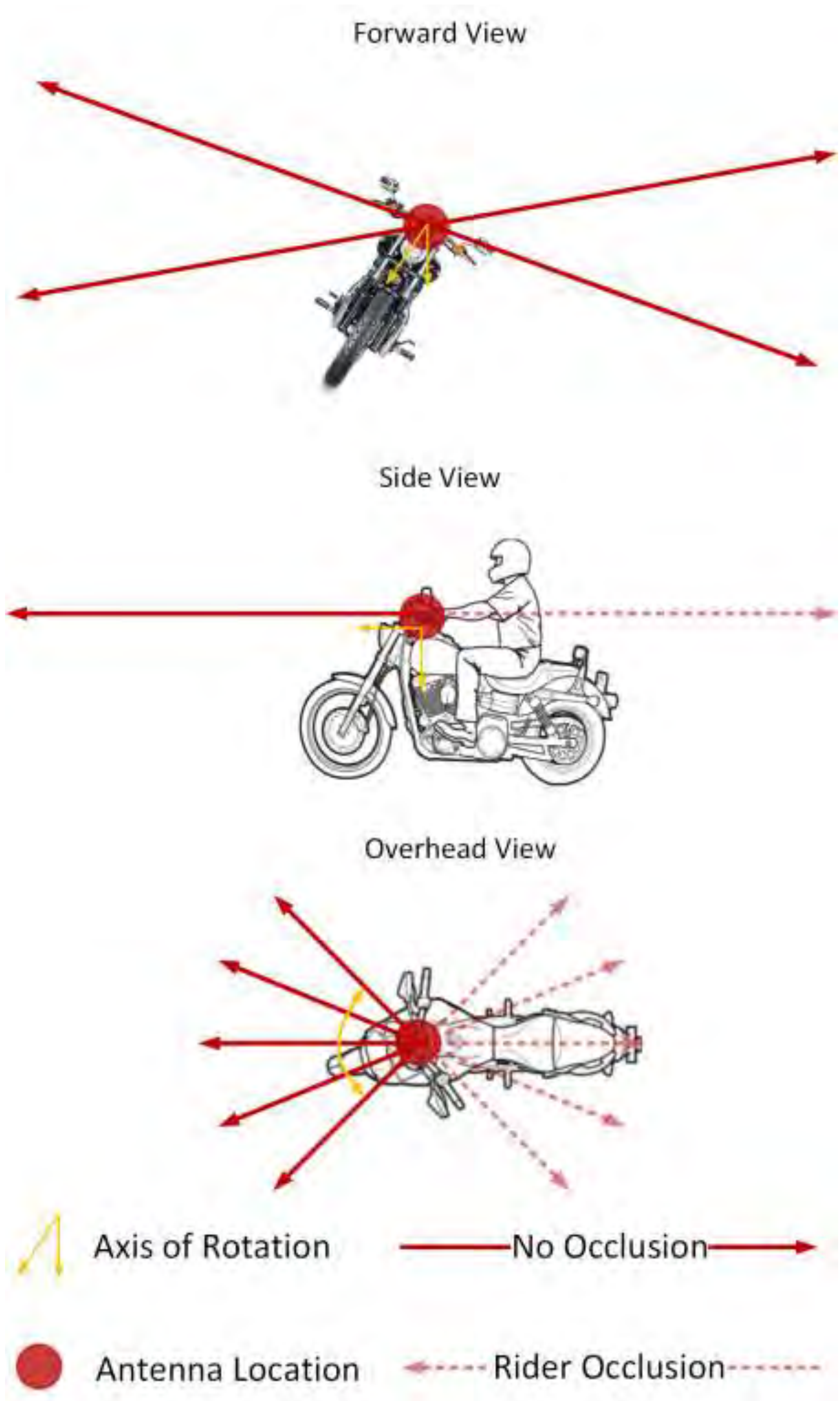


Figure 6. Forward antenna.

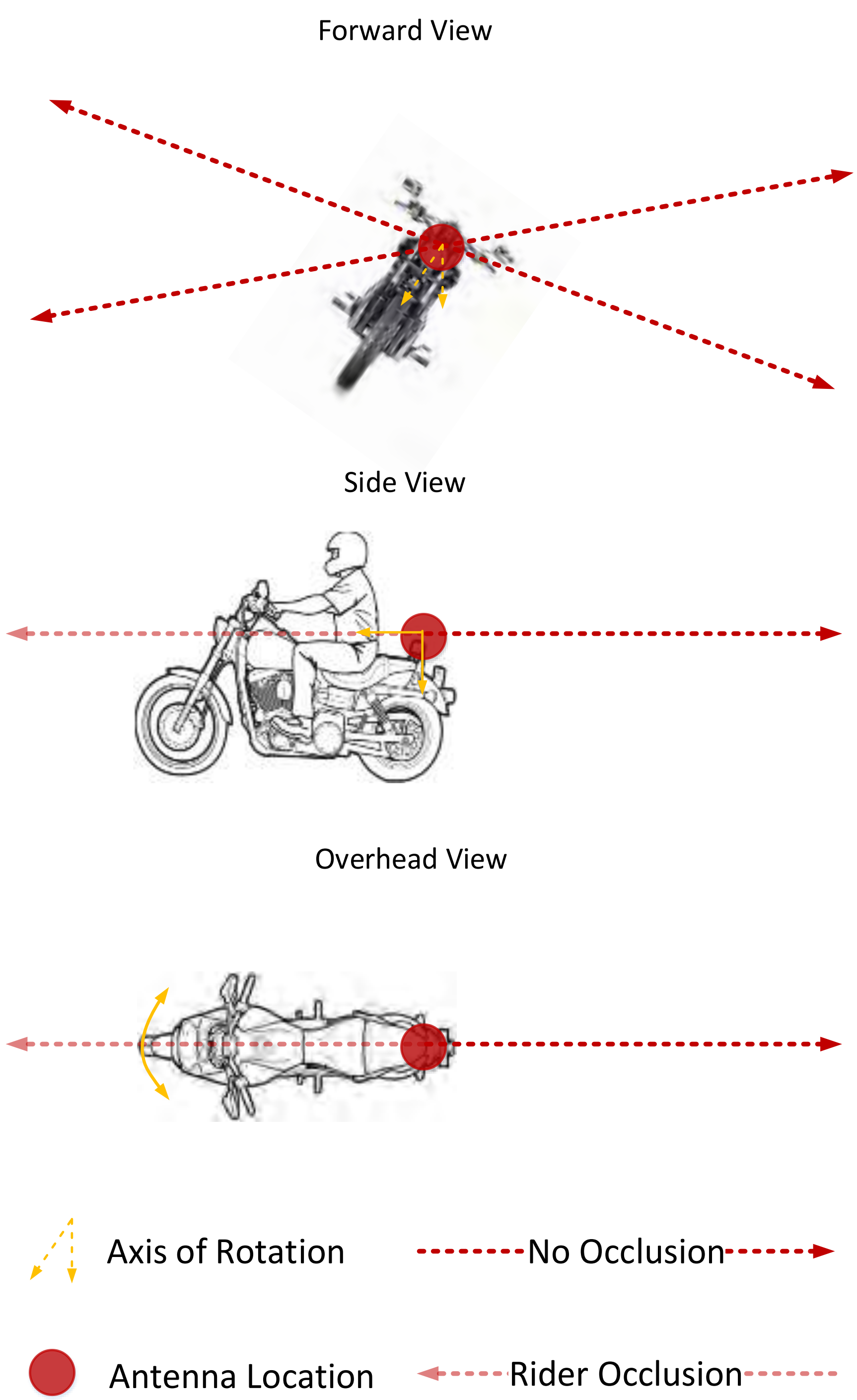


Figure 7. Rear Antenna.

Testing Locations

The following section describes the two primary testing locations used to evaluate CVS performance. In each of these locations, specific experimental test scenarios were executed. Provided in Table 6 is a matrix of the corresponding testing location and experimental test scenarios.

Table 6. Testing Locations and Experimental Test Scenarios Matrix

Experimental Test Scenario	Virginia's Smart Road	New River Valley
Static Dwell	X	
Dynamic Range	X	
Platoon	X	X

The Virginia Smart Road

The Virginia Smart Road was used as the primary testing location for this performance study. The Smart Road is a 2.2-mile, two-lane roadway built to highway specifications located in Blacksburg, Virginia. This closed test-track allows for researchers to conduct experiments in a safe and uninterrupted environment. Additionally, the Smart Road allows for assessments of CVS performance measures in varied environment occlusion angle situations.

Figure 8 provides a general overview of the layout of the Smart Road test facility. Figure 9 through Figure 12 highlight the different environmental and topographic conditions at the test track. In particular Figure 9 shows an example of an open-sky environment, while Figure 10 shows a mountainous valley region where view of the sky is limited. Other pertinent characteristics illustrated are the horizontal and vertical roadway curvatures that may impact communications or positioning performance due to occlusion by the roadway itself. As Figure 11 depicts, horizontal curvature influences the lean angle of a motorcycle and, therefore, the antenna's view, as one side is essentially transmitting into the road. Figure 12 depicts the vertical curvature or elevation change of the roadway. Depending upon the elevation delta of the RV relative to the transmitting HV, the antenna's range may also be occluded by the roadway itself.

Figure 8. Virginia's Smart Road.

Figure 9. Smart Road – open sky.

Figure 10. Smart Road – mountain valley occlusion.

Figure 11. Smart Road – horizontal roadway curvature.

Figure 12. Smart Road – vertical roadway curvature.

New River Valley

The second phase of the study involved real-world testing on an approximately 95 mile predefined route in Virginia's New River Valley (Figure 13). This route includes roadways consisting of the environments experienced by the vehicles in the DAC as defined by Table 1

[3]. These roadways provided unique characteristics where overpasses, vegetation, and buildings are blocking the view of the sky (Figure 14).

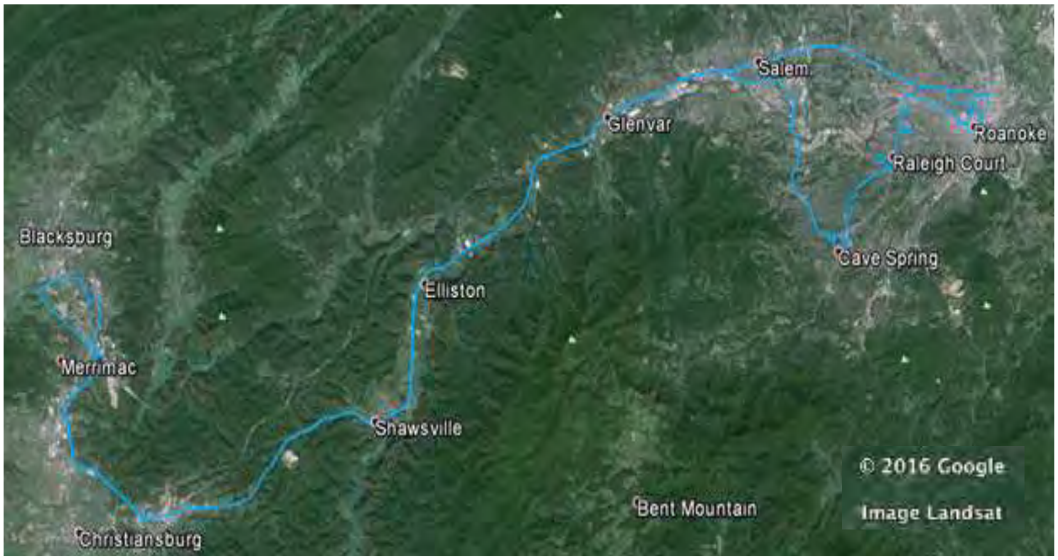


Figure 13. New River Valley route.

Figure 14. New River Valley route – sky occlusion.

Experimental Test Scenarios

Static Dwell Testing

The following test allowed for a baseline assessment of position performance of the test vehicle equipment. Collecting data for an extended period in a static state permitted analysis to focus on the impacts of rider occlusion in various test configurations that involved different environments and test vehicle formations. Figure 15 depicts the two static testing environments, open sky and mountain/valley on the Virginia Smart Road. Figure 16 defines the two vehicle test formations, adjacent-lane and single lane. The formations were selected to represent motorcycle-to-automobile roadway interactions. Table 7 lists all the test scenario combinations for which data have been collected.

Open Sky Location | Mountain/Valley Location

Figure 15. Static dwell test environments.

Adjacent lane Formation | Single lane Formation

Figure 16. Static dwell test formations on the Virginia Smart Road.

Table 7. Static Dwell Configurations

Environment	Rider Occlusion	Formation
Open Sky	Yes	Single lane
Open Sky	No	Single lane
Open Sky	Yes	Adjacent
Open Sky	No	Adjacent
Mountain/Valley	Yes	Single lane
Mountain/Valley	No	Single lane
Mountain/Valley	Yes	Adjacent
Mountain/Valley	No	Adjacent

The standard positioning performance measures, HDOP and satellites used, were assessed, and, considering the static nature of the test setup, positioning performance analysis of the CEP was also performed. To account for the change in the GPS constellation, these tests were executed all on the same day and within minutes of each configuration; thereby maintaining a constant GPS constellation.

Dynamic Range Testing

The test depicted below involved two motorcycles approaching and leaving a static vehicle at extended ranges on the Smart Road for multiple revolutions. This test allowed for assessment of the communications performance between each individual motorcycle (with different antenna locations) and the static vehicle depicted in Figure 17. The two locations used on the Smart Road included environmental features such as open sky and mountain/valley terrain. Figure 18 depicts the routes the motorcycles traversed in blue, while the static vehicle location is marked in red. The focus of this test was to collect data to understand the impacts of range and environment on communications performance; specifically, PER and RSSI were assessed.

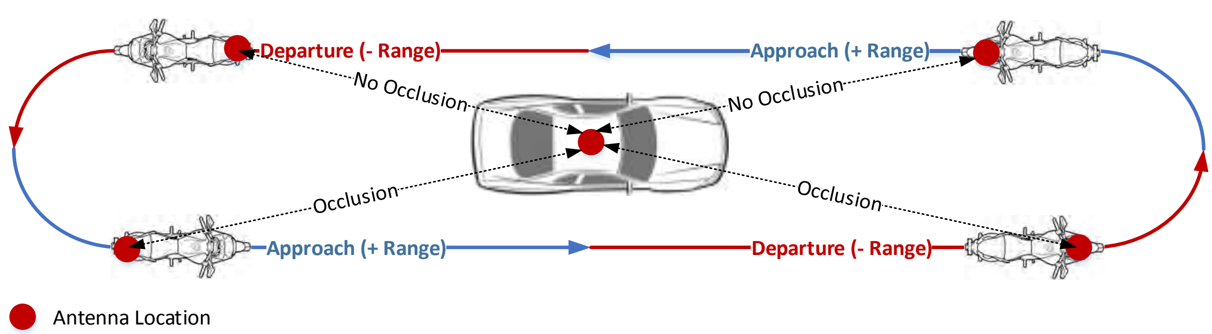


Figure 17. Dynamic ranging scenario.

Open Sky Mountain/Valley

Figure 18. Dynamic range test locations (red dot signifies static vehicle location, blue points signify motorcycle route).

Dynamic Platoon

This testing scenario involved all four vehicles traversing the closed Smart Road test track as well as some public roads in the New River Valley. The vehicles navigated these roadways in a same-lane formation, at varying speeds, while attempting to maintain a safe following distance of approximately two seconds headway from each other. Additionally, during testing in the New River Valley, steps were taken to minimize breaking out of the formation.

Breaking formation generally occurred in two situations: (1) where vehicles not involved in the test came in between test vehicles in the formation; and (2) when all the test vehicles were not in a single-file, single-lane formation [3]. The platoon allowed for assessment of the communications performance between vehicles, while also evaluating the influence of antenna placement and rider occlusion (as depicted in Figure 19). The configuration of vehicles and motorcycles maximized the exposure of Front and back antenna locations on the motorcycles communicating with the automobiles. For this study, two platoon configurations (listed in Table 8) were utilized.

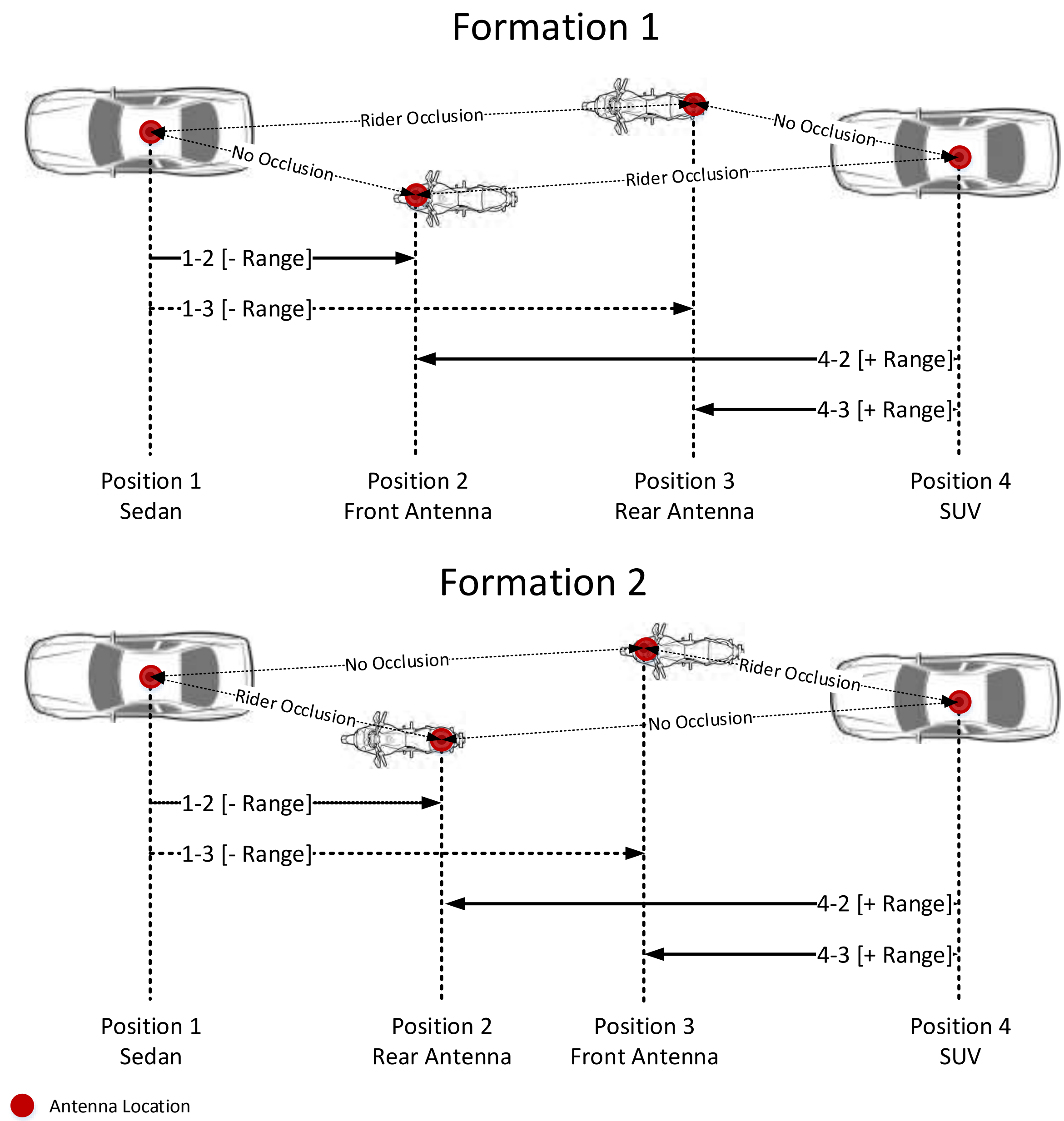


Figure 19. Hypothesized antenna occlusion in platoon.

Table 8. Dynamic Platoon Configuration

Platoon Test Location	Formation	Position 1	Position 2	Position 3	Position 4
Smart Road	1	Sedan	Front Antenna	Rear Antenna	SUV
Smart Road	2	Sedan	Rear Antenna	Front Antenna	SUV
New River Valley	1	Sedan	Front Antenna	Rear Antenna	SUV

The New River Valley route expanded on the fixed environments experienced on the Smart Road by traversing the roadway environments defined in Table 1. These environments were chosen so that the collected data could be used to compare to the performance data collected and analyzed under the DAC project. Further, the route selected was planned to match, as closely as possible, the overall percent allocation of environments experienced during the DAC project (as displayed in Table 9) [3].

Table 9. DAC Environment Percentage [3]

CATEGORY	TIME (%)
Deep Urban	3.76%
Major Rural Thruway	26.63%
Major Urban Thruway	15.23%
Major Road	17.31%
Local Road	12.15%
Interstate/Freeway	15.28%
Mountains	9.65%
Grand Total	**100.00%**

Similar to the other experimental tests, the communications performance measures of interest used were PER and RSSI. The position performance measures of interest were HDOP and satellites used.

Results

Static Testing

Position Performance

This test focused specifically on the effects of rider occlusion on position-based performance measures. The static dwell testing involved arranging vehicles in the two formations, with or without a rider, in both a mountainous and an open-sky environment. Details regarding the test configuration are provided in Static Dwell Testing section.

Provided in Figure 20 - Figure 22 are the box plot results detailing the position performance metric split between the various environmental (open sky, mountain/valley), rider occlusion (rider, no rider) and formation configurations (lane, adjacent).

The central red mark is the median, the edges of the blue box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a red plus. The right hand y-axis provides the count of samples in the bin detailed on the left hand y-axis.

Provided in Figure 23 - Figure 25 are plots examining the position performance differences between forward and Rear Antenna motorcycles across the various test configurations. Along the y-axis is the mean of the performance metric per all of the samples along the test configuration bins defined on the x-axis.

From the plots the overall HDOP metric between Front and Rear Antenna stands out. The Front Antenna across all configurations is approximately off by a factor of one. Interestingly, the GPS receivers typically saw and used the same number of satellites. In the cases where there are differences in the number of satellites used as depicted in Figure 24, Open-No-Lane and Valley-Yes-Adjacent configurations, the corresponding mean HDOP delta values also varied. In the Open-No-Lane case, the Front Antenna used one less satellite and the HDOP value increased. In the Valley-Yes-Adjacent case, the Rear Antenna used one less satellite and the HDOP value increased. This trend is expected as one less satellite used in the solution generally degrades the geometric quality.

To investigate this further, identification of the actual satellites used in deriving the solution was explored. Provided in Figure 26 is a distribution of the unique satellites used during the test. It was assumed that there was a specific satellite that may be affecting the HDOP value of the Front Antenna, from the results this does not appear to be the case. As the plot shows, the two antennas generally used the same satellites in deriving its position. Additionally, there appears to be no other significant difference between the two antennas locations as the presence of the rider nor the formation seem to impact performance. Only in the mountain/valley case, both used fewer satellites than in the open sky, as expected due to the occlusion of the sky blocking out view of other satellites. These observations suggest that there may be a bias in the Front Antenna reported HDOP values.

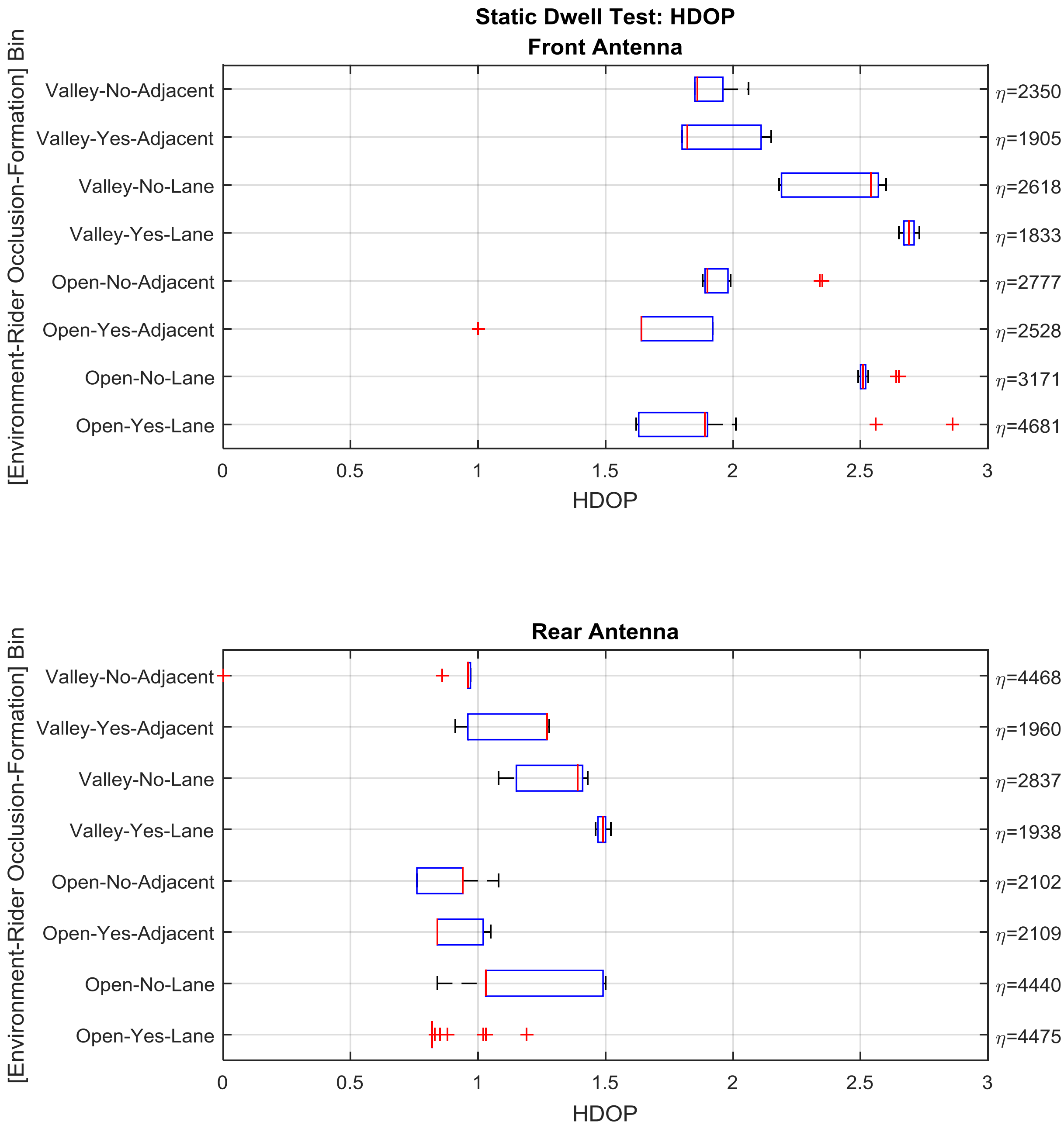


Figure 20. Static dwell test – HDOP.

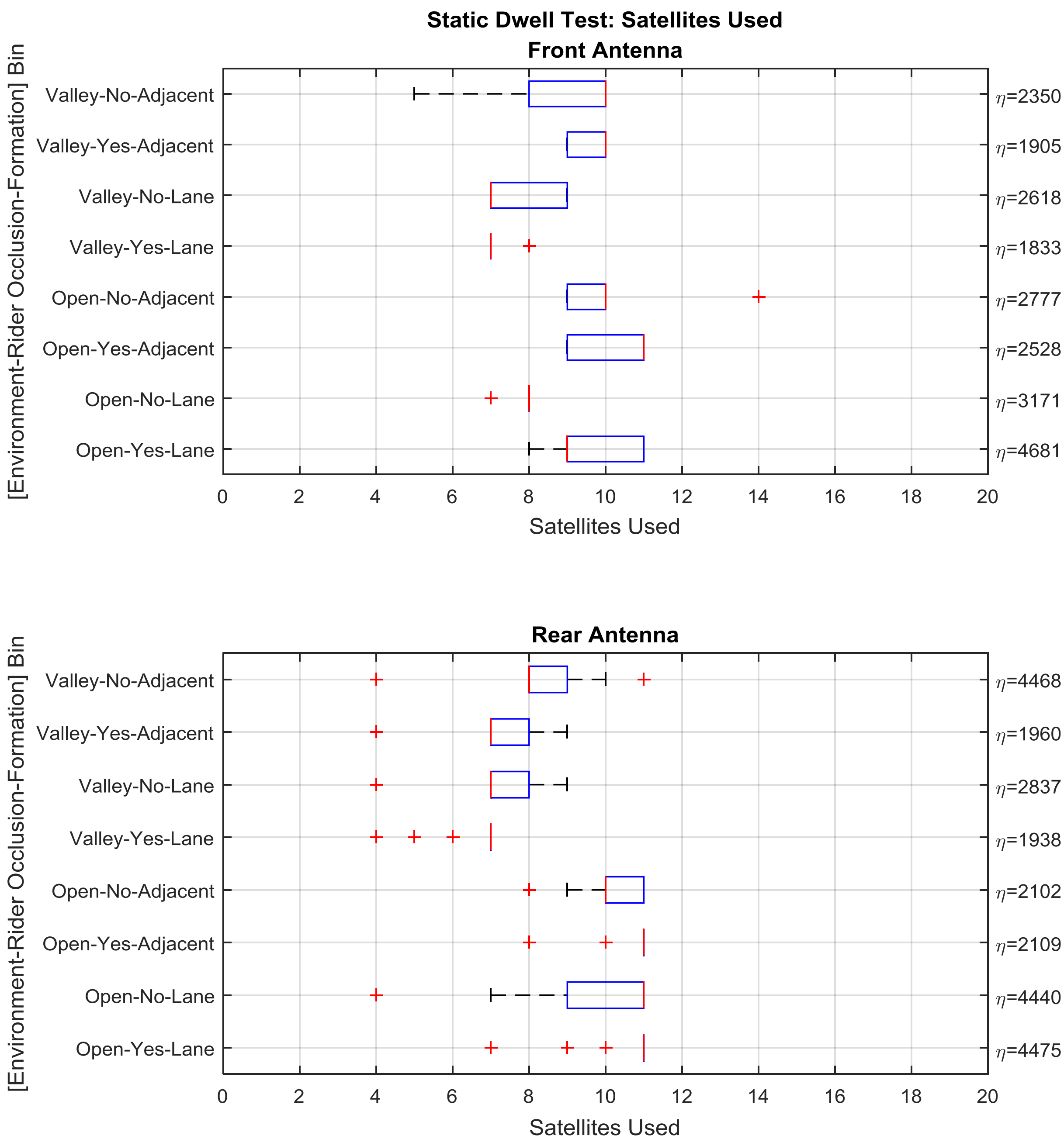


Figure 21. Static dwell test – Satellites used.

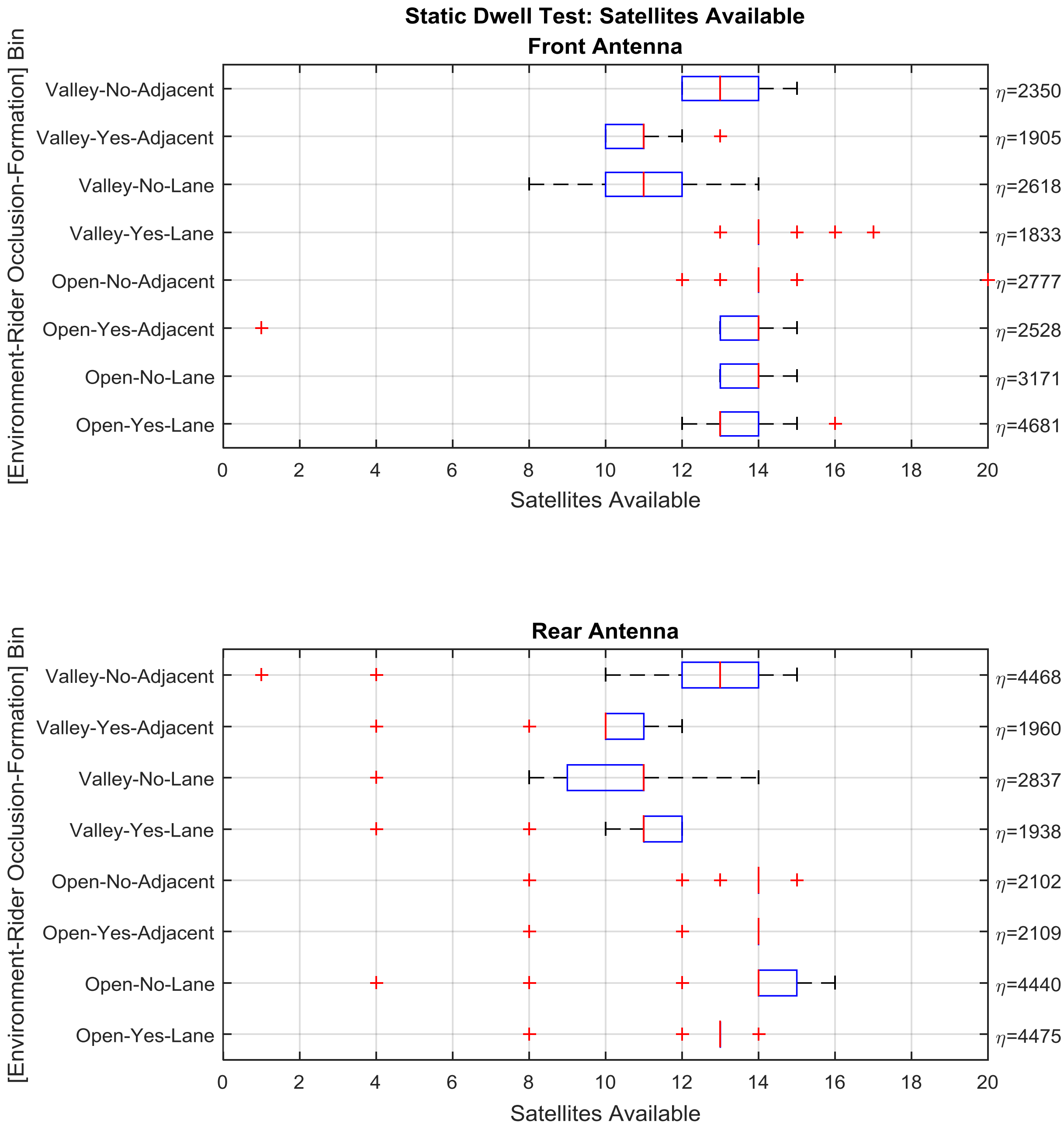


Figure 22. Static dwell test – Satellites available.

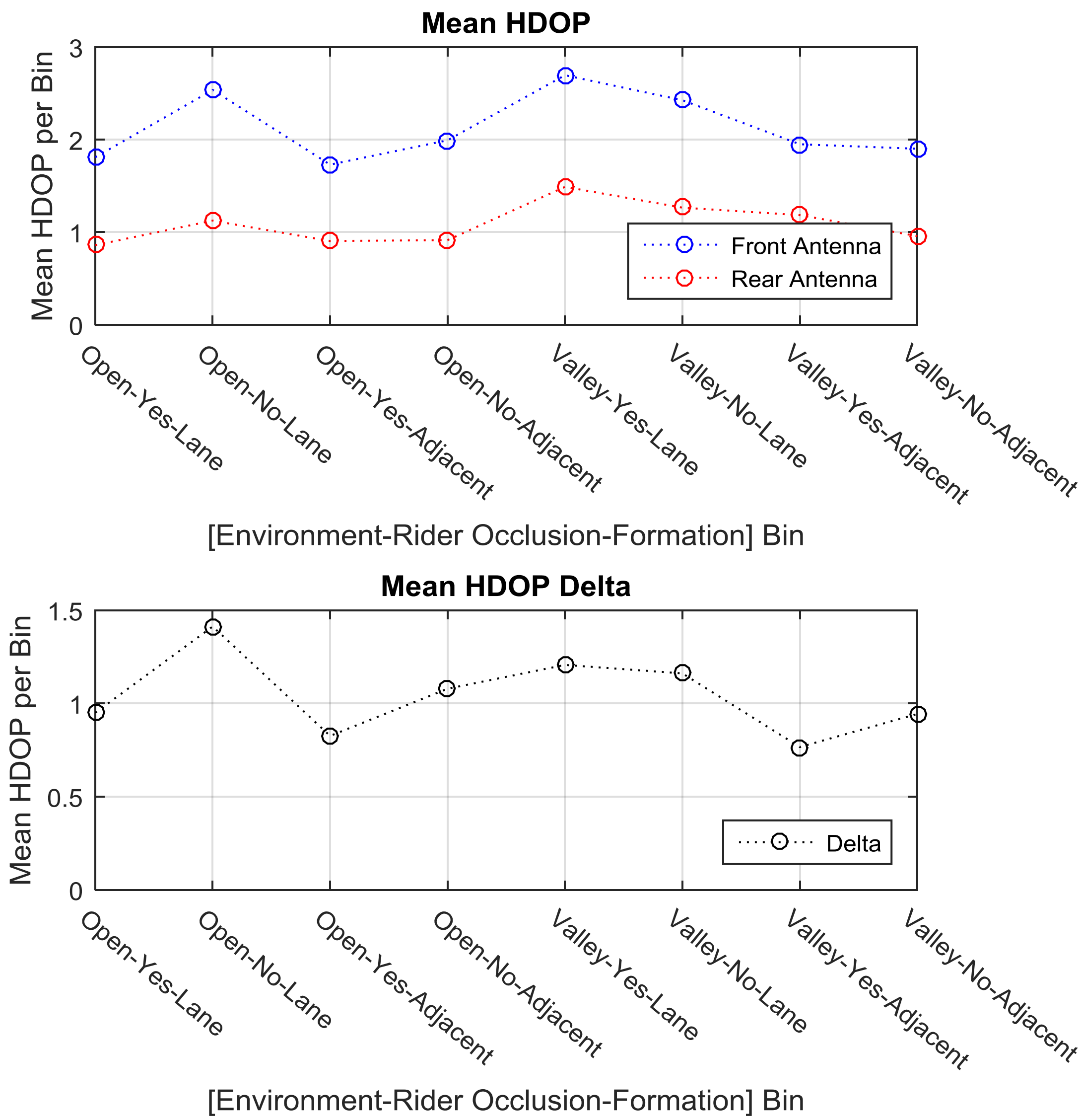


Figure 23. Static dwell test comparison – HDOP.

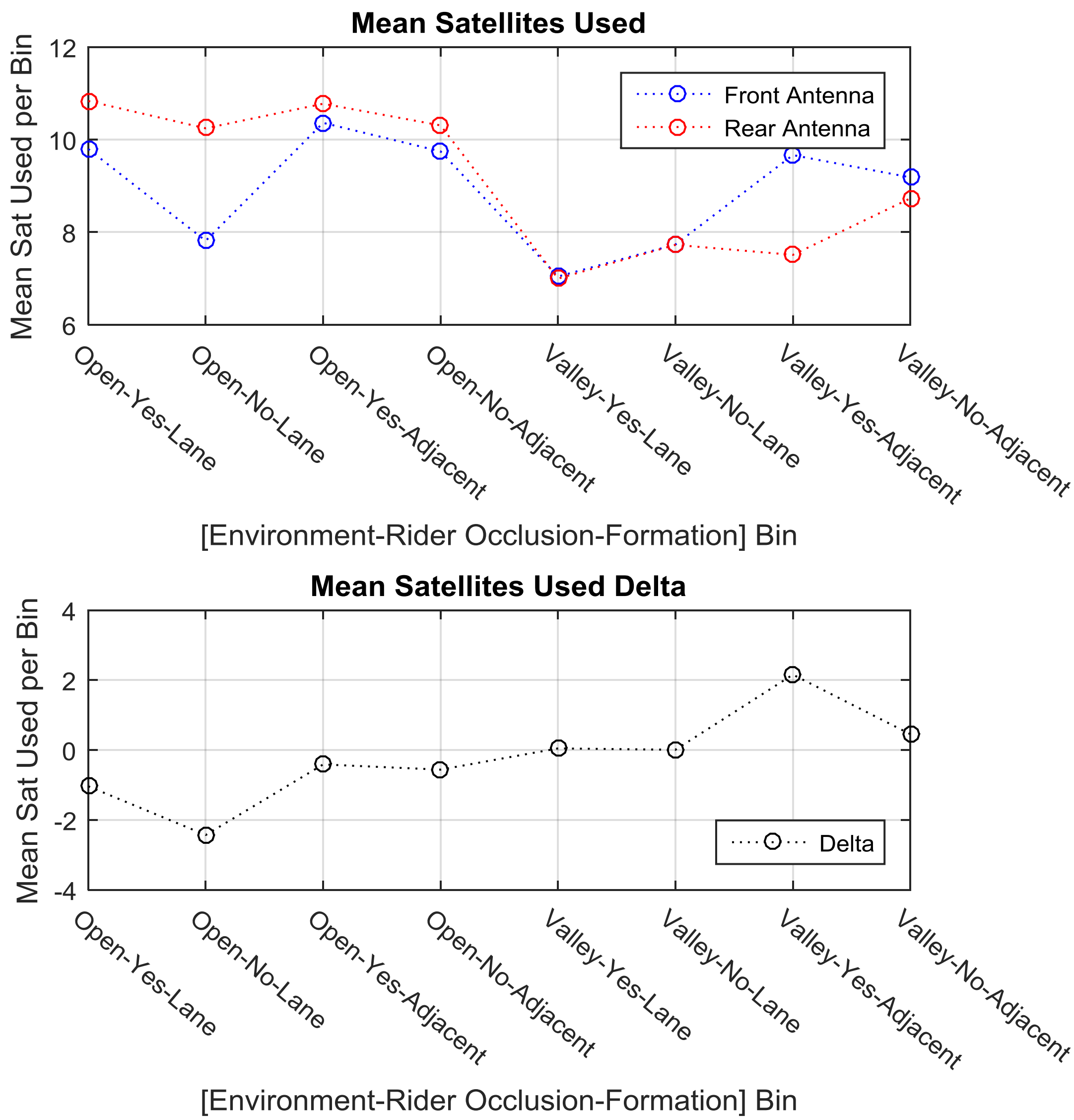


Figure 24. Static dwell test comparison – Satellites used.

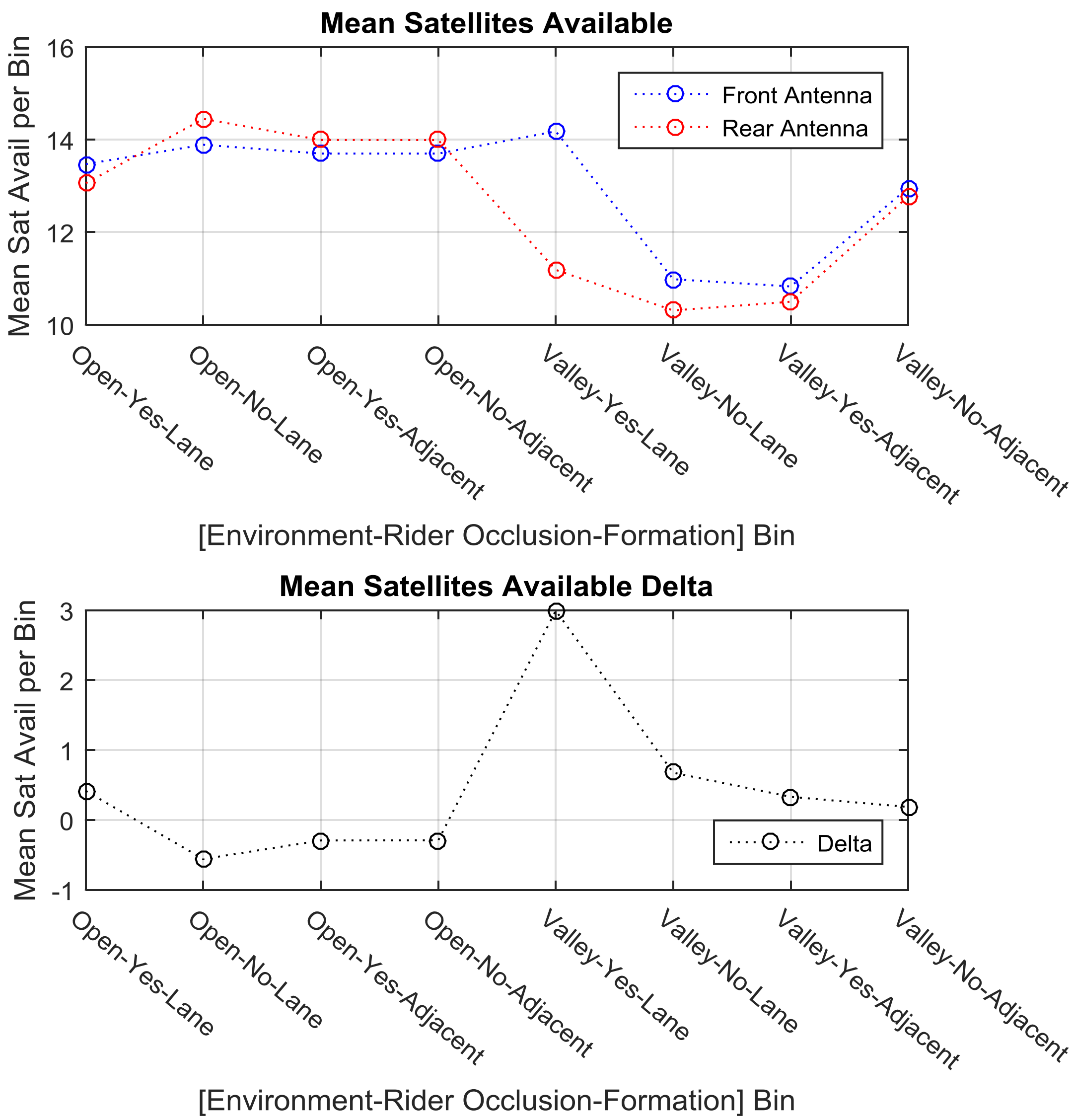


Figure 25. Static dwell test comparison – Satellites available.

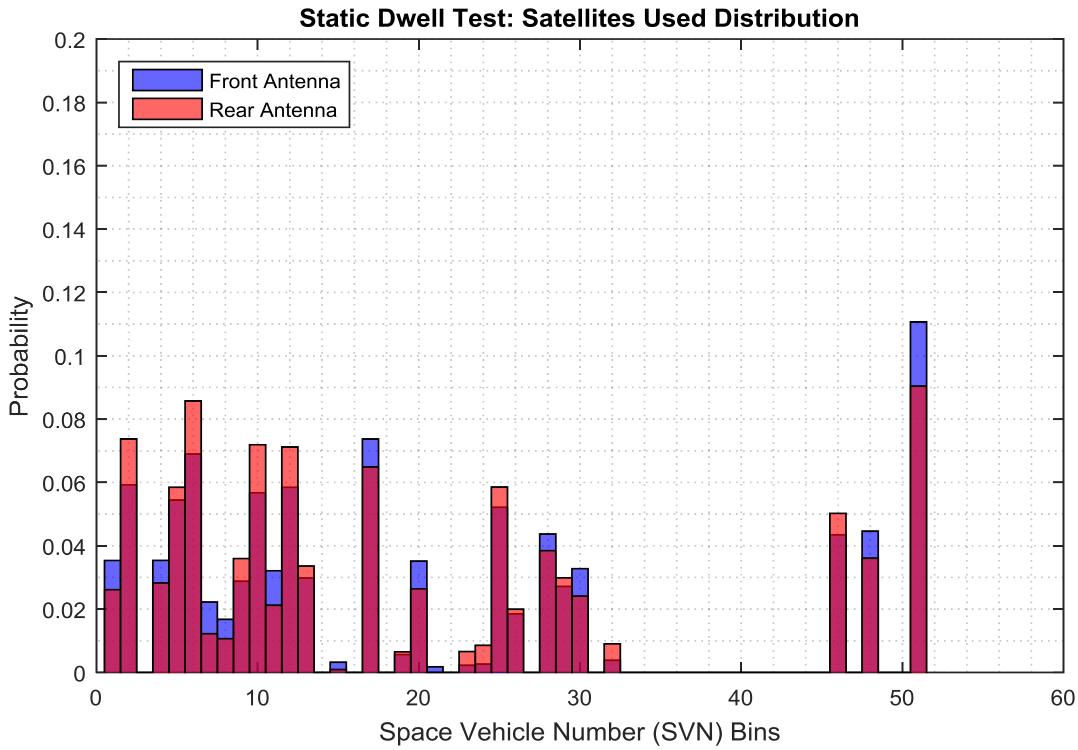


Figure 26. Static dwell test – Space vehicles used distribution.

Dynamic Ranging

Communication Performance

This test focused specifically on communications measures as a function of range and environments. As described in the Dynamic Range Testing section, a motorcycle essentially circled around a static vehicle in various locations on the Smart Road. During this revolution around the static vehicle, approaches and departures were identified. The reason for this identification was to understand the effects of antenna location and rider occlusion. For example, in the case with the rear-mounted antenna, the approach to the static vehicle was expected to show poorer performance than the departure because the signal was being occluded by the rider. Conversely, an approach by the motorcycle with the forward-mounted antenna was expected to show better performance because the signal was not being occluded by the rider.

Figure 27 and Figure 28 provides maps detailing the route of the motorcycles and environment. The green line indicates the path of the motorcycles along the various environments looping around a static vehicle marked by the pink square. Approach (Blue) and Departure (Red) dots signify locations along the path where the static vehicle received a BSM from the motorcycles. As was depicted in Figure 17 in the Dynamic Range Testing section, approach signifies the motorcycle heading towards the static vehicle, while Departure signifies the motorcycle heading away from the static vehicle.

Provided in Figure 29 and Figure 30 are the box plot results detailing the communication performance metric split between the various approach and departure range bins. Approach ranges are positive, while Departure ranges are negative.

The central red mark is the median, the edges of the blue box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a red plus. The right hand y-axis provides the count of samples in the bin detailed on the left hand y-axis.

Figure 31 examines the communication performance differences between forward and Rear Antenna motorcycles across the various environments. Along the y-axis is the mean of the performance metric per all of the samples along the range bins defined on the x-axis.

Based on the results from the figures, Table 10 summarizes the various antenna positions, locations and max/min communication ranges between the motorcycles and static vehicle. In cases where there is no occlusion, Rear Antenna-Negative Ranges and Forward Antenna-Positive Ranges, the peak ranges were typically wider than on the occluded side.

One interesting observation from the collected data is the increase in communication performance in the mountain/valley environment. Within this region, a wider span of approach and departure ranges also exist. It is likely that the reason for this increased performance is that the mountainsides reflected the wireless signals back, as opposed to an open-sky condition, where signals keep propagating out and away from the receiving vehicle.

Table 10. Dynamic Ranging Communication Performance Comparison

Antenna	Environment	Behind Range	Ahead Range	Peak Effective Range	PER < 1 Behind Range	PER < 1 Ahead Range	PER < 1 Effective Range
Front	Open	-300	300	600	-50	200	250
Front	Valley	-350	350	700	-150	150	300
Rear	Open	-300	100	400	-100	50	150
Rear	Valley	-400	300	700	-300	50	350

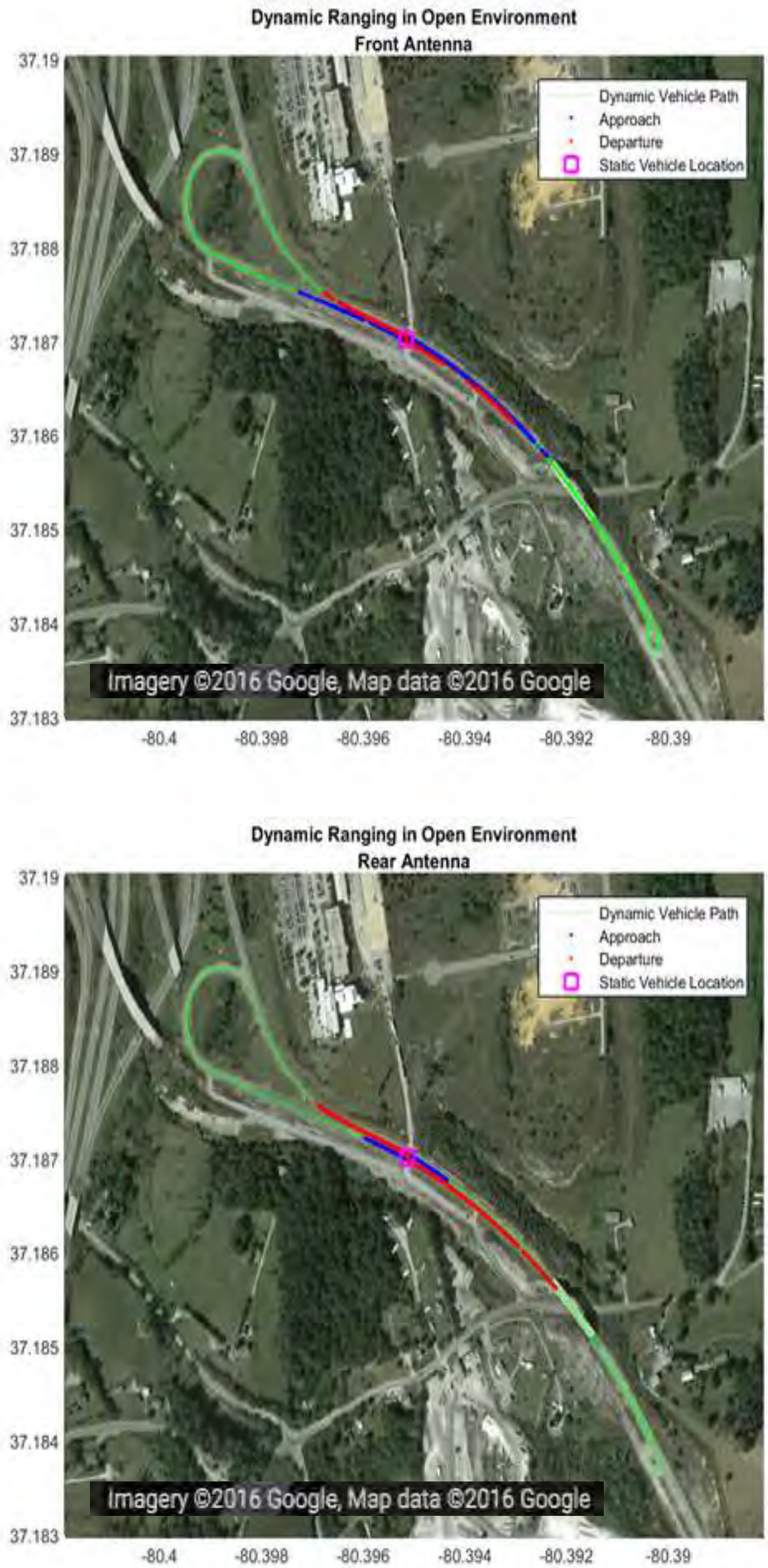
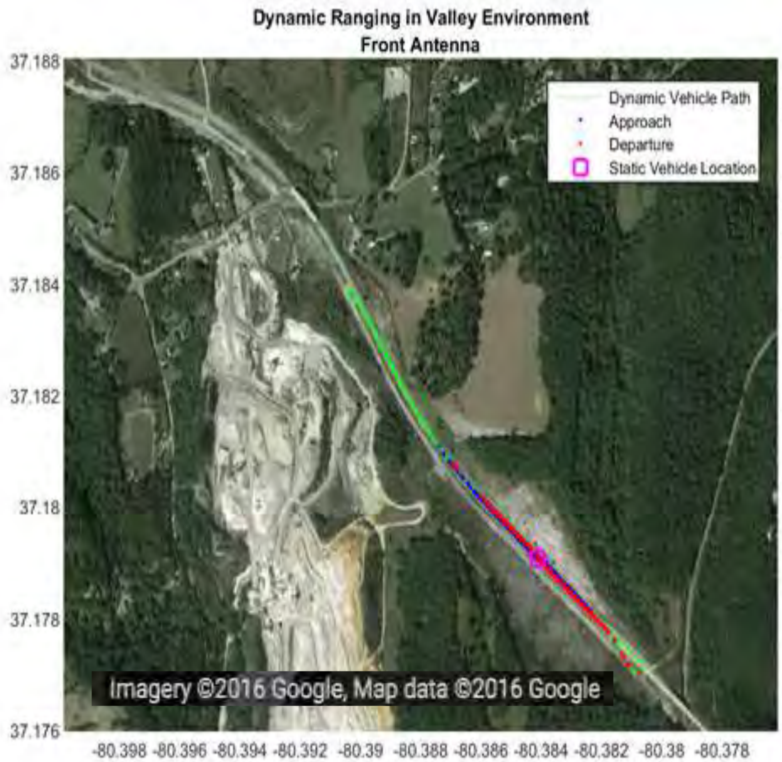


Figure 27. Dynamic ranging maps – Open environment.



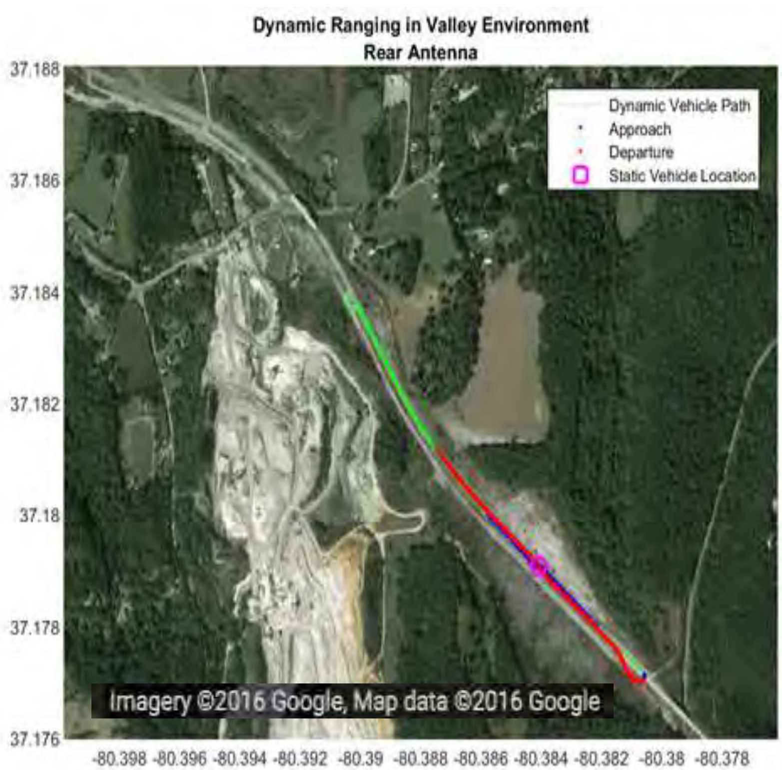


Figure 28. Dynamic ranging maps – Valley environment.

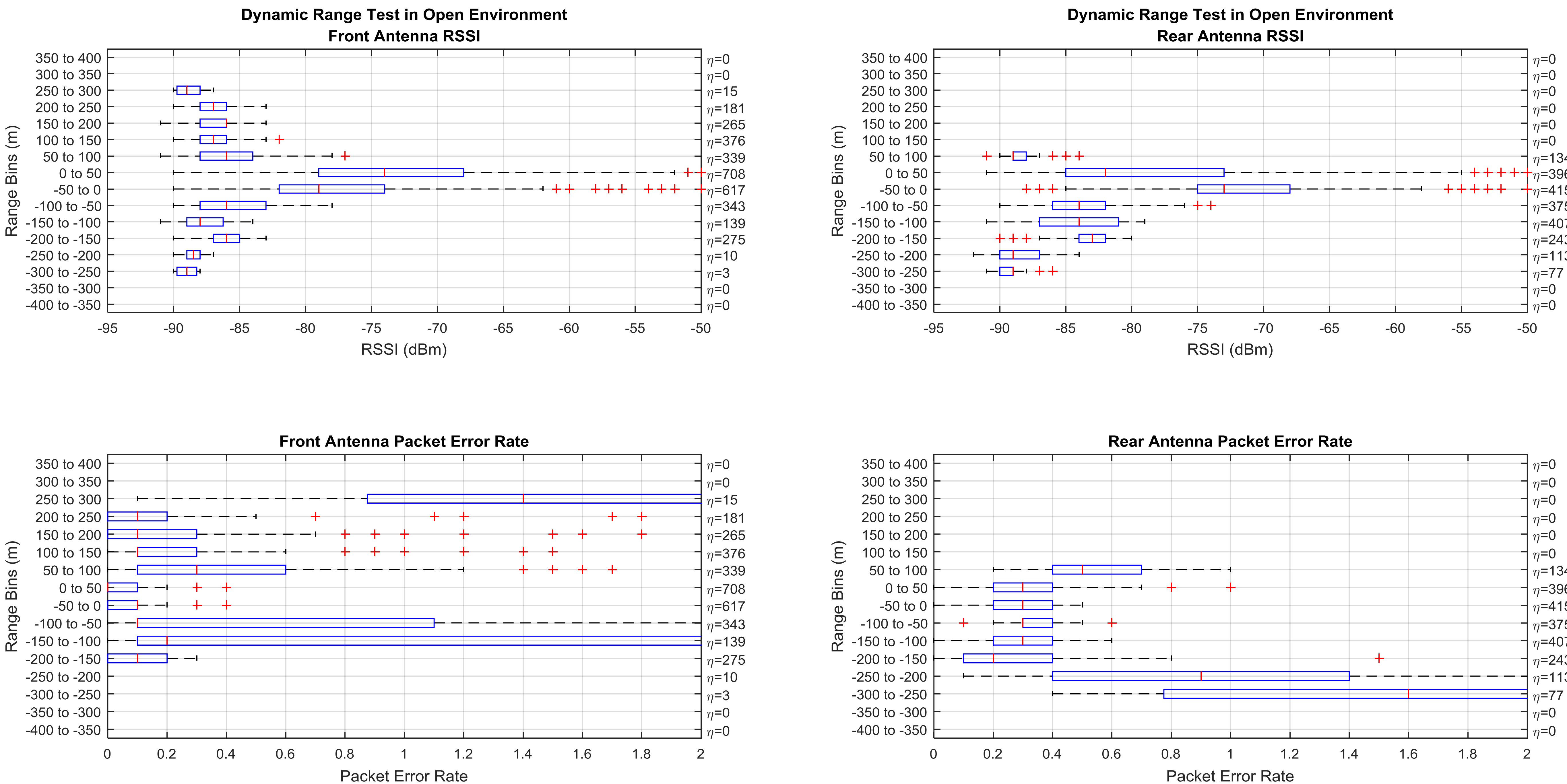


Figure 29. Dynamic ranging communication performance – Open environment.

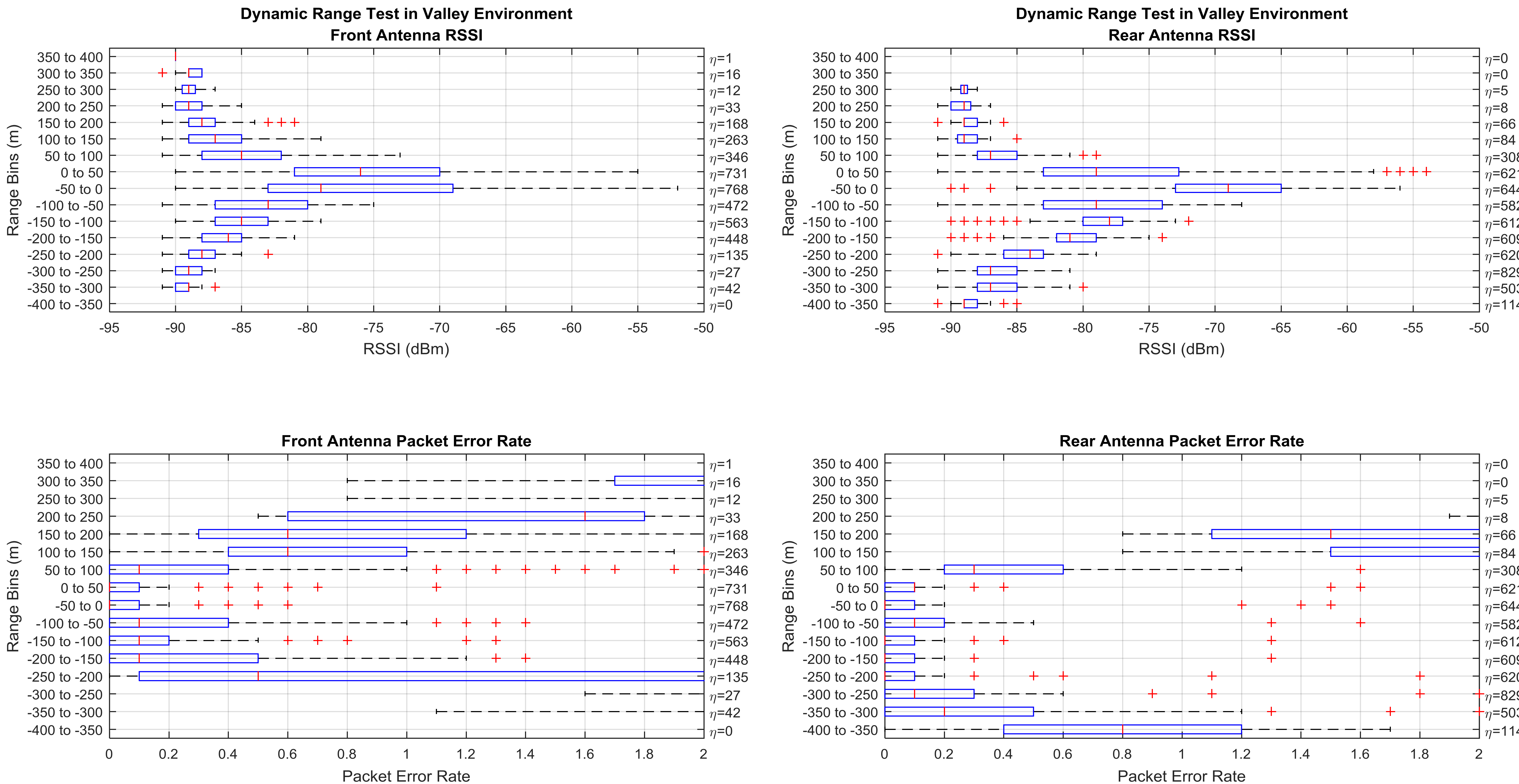


Figure 30. Dynamic ranging communication performance – Valley environment.

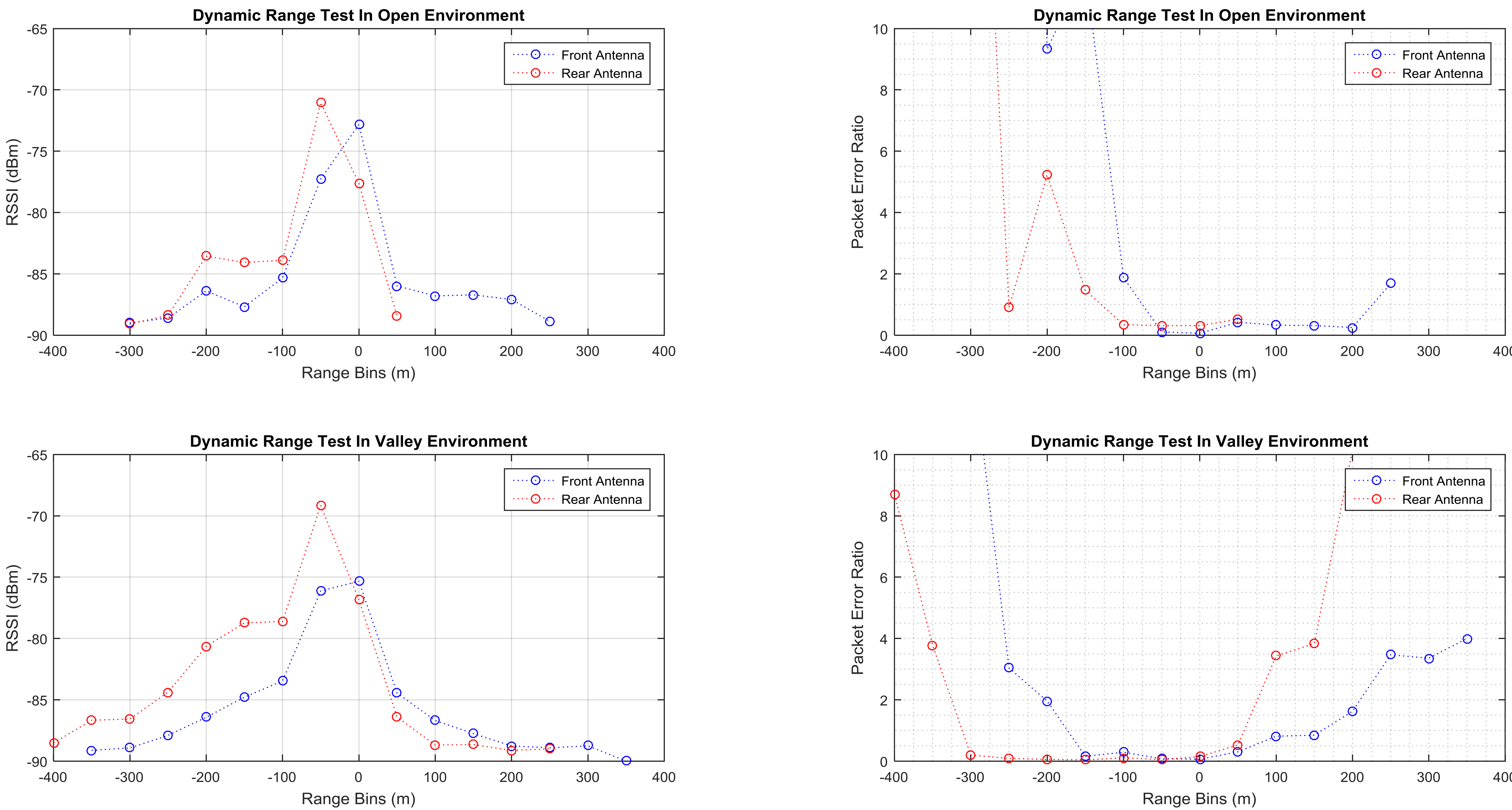


Figure 31. Dynamic ranging communication performance - Antenna comparison.

Dynamic Platoon – Smart Road

This test scenario, Dynamic Platoon, involved four vehicles traveling in a single-lane formation up and down the Smart Road at fixed speeds of 35, 45, and 55 mph. During this test, positioning and communications performance measures were analyzed. For ease of presentation, the various speed configuration tests were consolidated for all performance measures. This decision was made because the results for each speed did not vary significantly.

Positioning Performance

This test focused specifically on position performance measures experienced throughout the entire platooned drive on the Smart Road. As described in the Dynamic Platoon section, a group of vehicles were configured in a single lane formation and traversed the entire Smart Road. The Virginia Smart Road section describes the various environments encountered. As mentioned, the test plan called for various fixed speeds and formations. For ease of presentation, these results were all combined as the results did not vary significantly for position performance.

Provided in Figure 32 are the box plot results detailing the position performance metrics and motorcycle antenna location. The central red mark is the median, the edges of the blue box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a red plus. The right hand y-axis provides the count of samples in the bin detailed on the left hand y-axis.

Figure 33 provides maps detailing the route of the motorcycle and position performance metric outliers. The green points indicates the path of travel the motorcycle took along the Smart Road. The Front Antenna (Blue dot) and Rear Antenna (Red Circle) signify locations along the path of travel where the performance metric is considered a statistically poor performing outlier. The map plotted outliers consist of the bottom 1% experienced per motorcycle antenna location. Other percentages ranging from 2-10% were investigated, but the number of markers produced maps where insights could not be easily inferred.

As was seen in the static dwell tests, the HDOP values of the Front Antenna, in comparison to the Rear Antenna in the dynamic platoon test, is also off by a factor of one. Similarly, the two antennas used and saw the same number of satellites. Although similar in average, the Front Antenna had more variation in the number of satellites used during the tests. This variation trended towards fewer satellites used, indicating that the Front Antenna often dropped use of satellites.

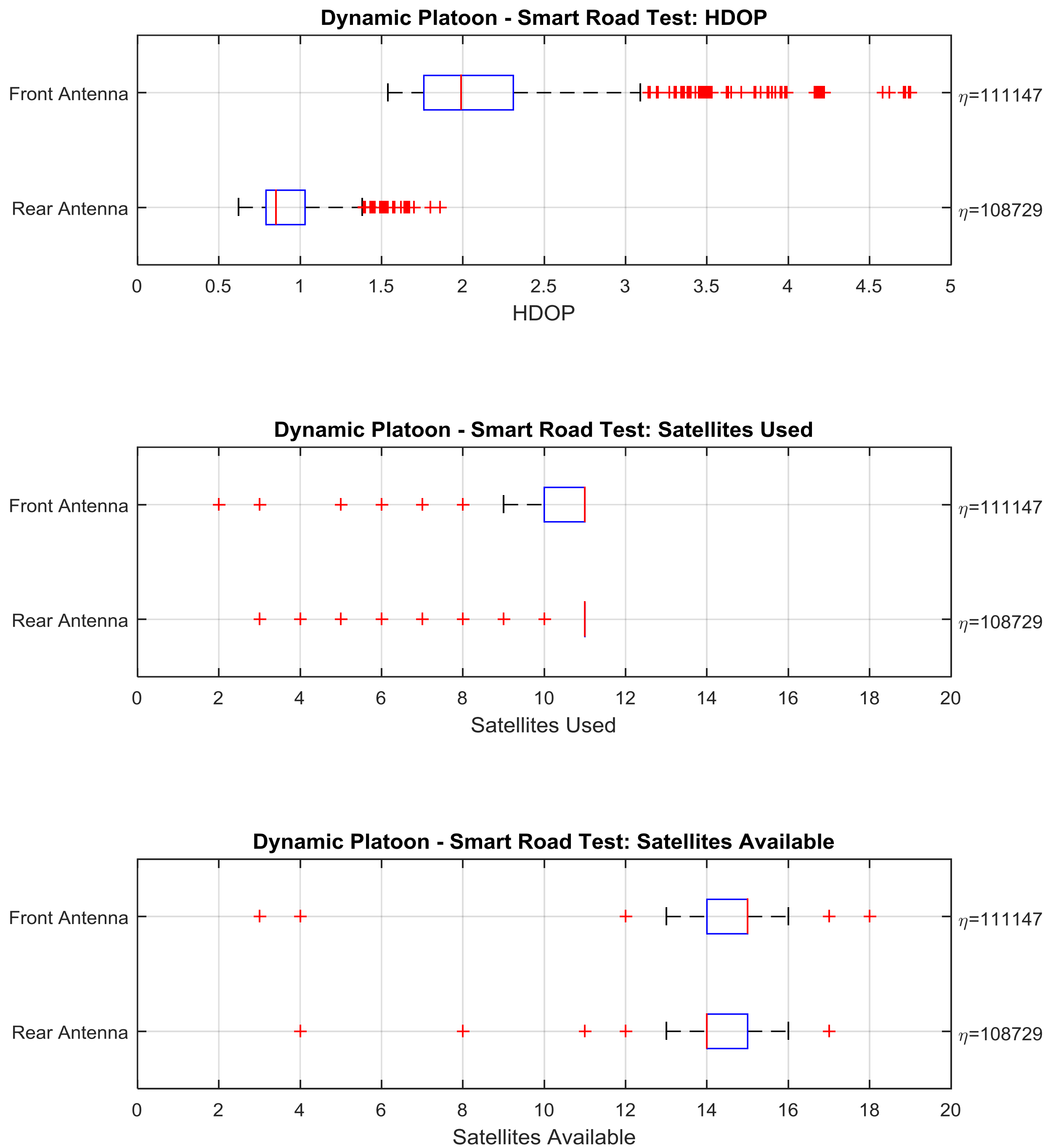


Figure 32. Dynamic platoon in Smart Road – Position performance antenna comparison box plot.

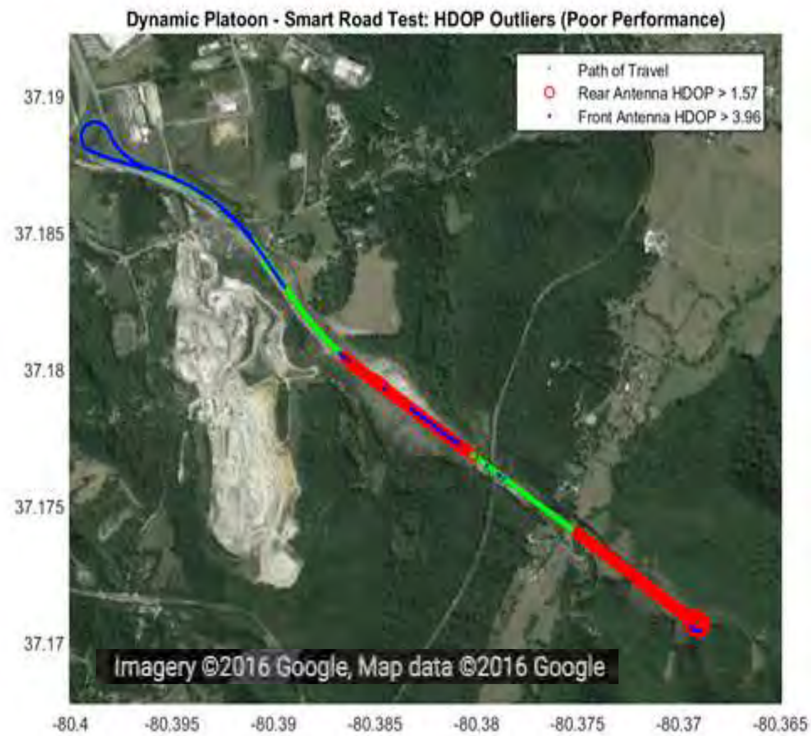


Figure 33. Dynamic platoon in Smart Road – Position performance antenna comparison map.

As depicted in the maps, several regions of the Smart Road exhibited relatively poor position performance based on the antenna location. In the mountain/valley region (center of map), both Front and Rear Antennas experienced poor HDOP measurements. This was expected due to the GPS constellation being occluded by the mountain. Figure 34 are the forward motorcycle views of the roadway environment in the mountain/valley region.

Figure 34. Dynamic platoon in Smart Road – Valley views.

In the South East region of the map, the Rear Antenna appeared to have difficulty with the roadway environment. As Figure 35 depicts, valley conditions as well as lean angles may have an influence on position performance.

Figure 35. Dynamic platoon in Smart Road – South East views.

In the North West region of the map, the Front Antenna appeared to have difficulty with the roadway environment. As the map and Figure 36 depicts, motorcycle maneuvering needed to traverse the roadway curvature may have an influence on position performance for the front mounted antenna.

Figure 36. Dynamic platoon in Smart Road – North West views.

Communications Performance

This test focused specifically on communications measures experienced throughout the entire platooned drive on the Smart Road. As described in the Dynamic Platoon section, a group of vehicles were configured in a single lane formation and traversed the entire Smart Road. The Virginia Smart Road section describes the various environments encountered. As mentioned, the test plan called for various fixed speeds. For ease of presentation, these results were all combined as the results did not vary significantly for position performance.

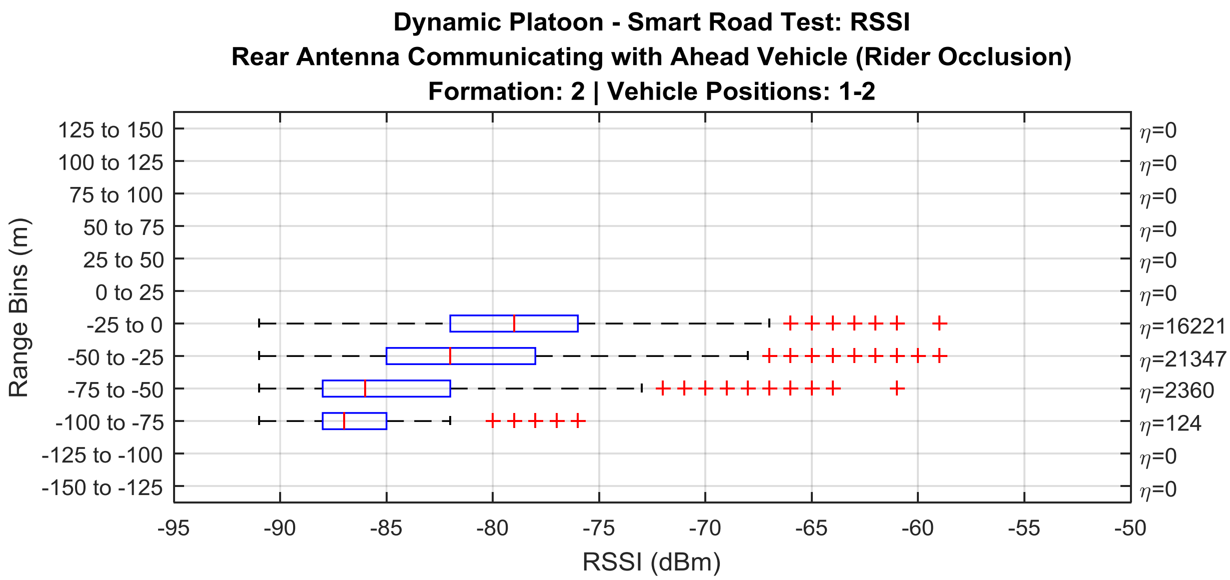
Vehicle position was of importance to understand the effects of antenna location and rider occlusion. For example, in the case with the rear-mounted antenna, the communication with the ahead vehicle (Sedan) was expected to show poorer performance than the rear vehicle (SUV) because the signal was being occluded by the rider. Conversely, the motorcycle with the forward-mounted antenna was expected to show better performance communicating with the ahead vehicle (Sedan) because the signal was not being occluded by the rider.

Provided in Figure 37 is a selection of box plot results detailing the communication performance metrics per antenna location as was illustrated in Formation 1 and Formation 2 in Figure 19. The central red mark is the median, the edges of the blue box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a red plus. The right hand y-axis provides the count of samples in the bin detailed on the left hand y-axis. The complete collection of plots can be found in the Appendix B – Dynamic Platoon – Smart Road Test.

It should be noted that range is not the test here, rather a point of reference. The primary objective behind this test is to measure communication performance in typical driving headway distances encountered in real world situations. Further, for this platoon test, vehicles traveled in a single-lane formation, with most communication range distributions samples between 0 and 50 m for proximate vehicles (i.e., Positions 1-2, 4-3) and between 25 and 75 m for the distal vehicle (i.e., Positions 1-3, 4-2). In regards to relative range on all plots, ranges that are negative, the motorcycle is behind; in positive ranges, the motorcycle is ahead. Typically, in instances where the sedan is the HV, the motorcycle ranges are negative since they are behind in the formation. When the SUV is the HV, the motorcycle ranges are positive since they are ahead in formation.

Figure 38 and Figure 39 examines the communication performance differences between occluded and non-occluded motorcycle configurations across the various formations. Along the y-axis is the mean of the performance metric per all of the samples along the range bins defined on the x-axis.

From the comparison plots, in cases where the Lead vehicle (Sedan) is communicating with the motorcycles behind, there isn't a significant difference between rear occluded antenna and front non-occluded antenna communications. In cases where the Rear vehicle (SUV) is communicating with the motorcycles ahead there is a significant difference between occluded and non-occluded communications. The non-occluded behind mounted antenna shows an improvement of ~10 dBm and ~10% PER.



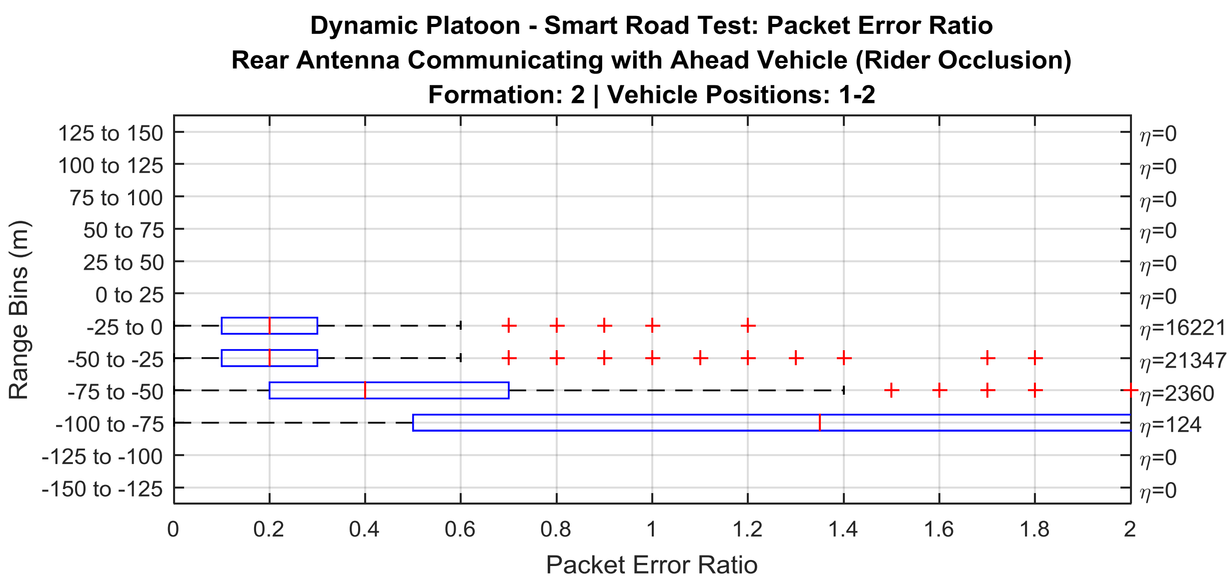


Figure 37. Dynamic platoon in Smart Road – Communication (selected plots).

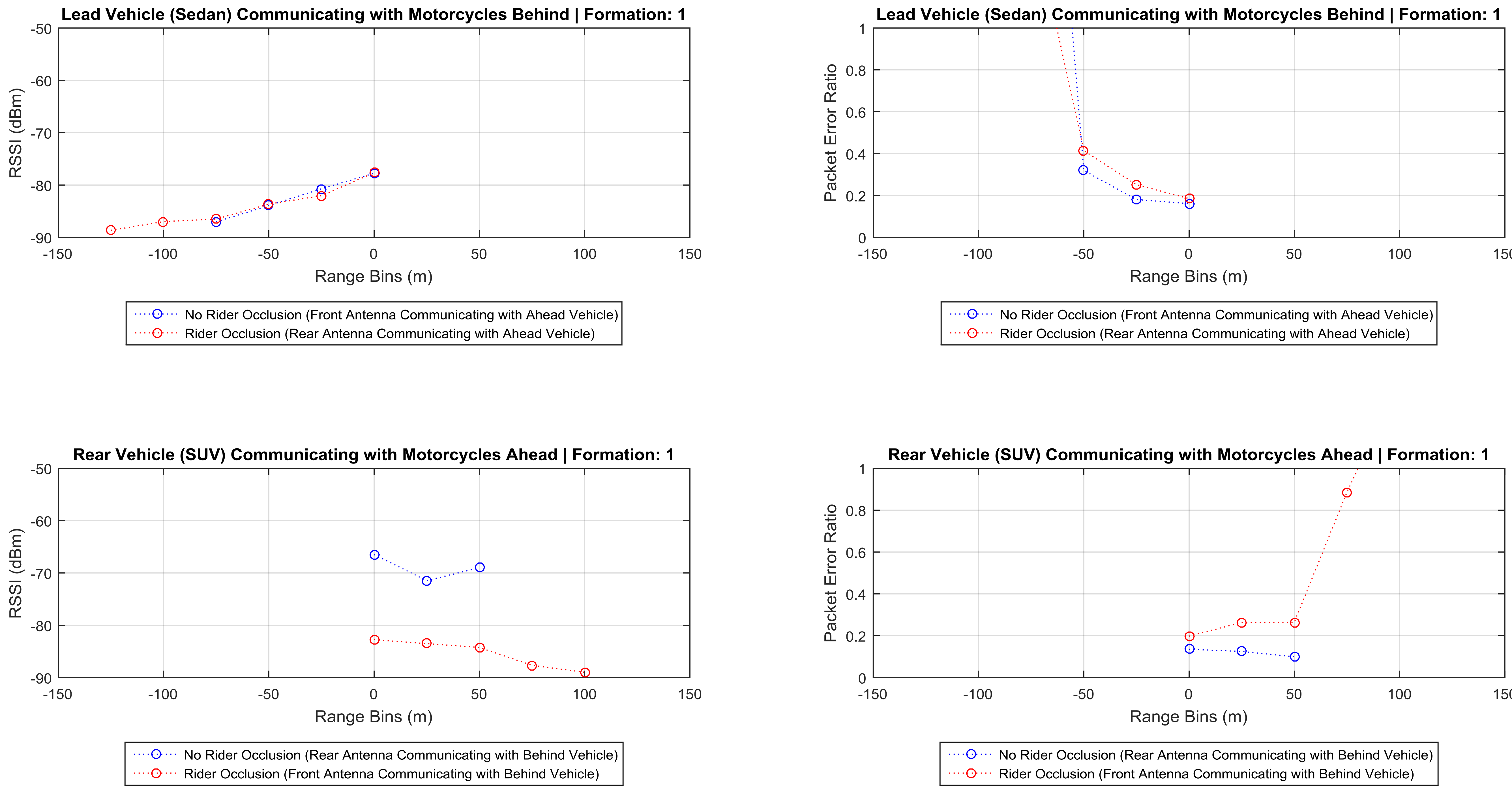


Figure 38. Dynamic platoon in Smart Road communication performance comparison formation 1.

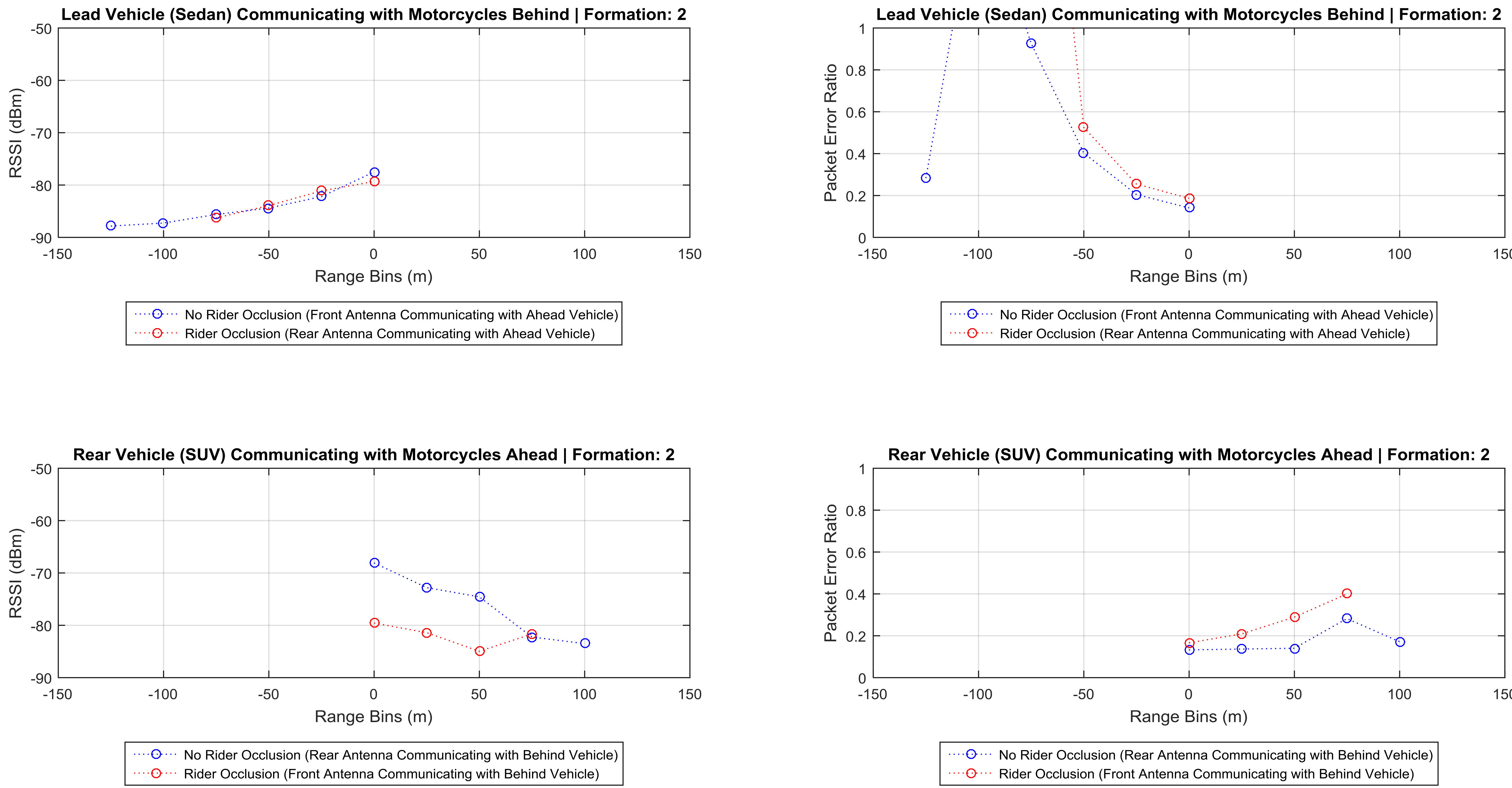


Figure 39. Dynamic platoon in Smart Road communication performance comparison formation 2.

Dynamic Platoon – New River Valley

This test scenario (as described in detail in Experimental Test Scenarios), Dynamic Platoon, consisted of four vehicles riding in a single-lane formation (Formation 1) on a predefined route in the New River Valley. These routes involved traversing various roadway environments so that data could be collected for measurement of positioning and communications performance in diverse locations. Table 11 depicts the distribution of data collected in each environment during the single NRV performance assessment drive and compares it to the DAC sample.

Additionally, the platoon tests performed on portions of the Smart Road represent, to a certain extent, environments like an interstate/freeway.

Table 11. Roadway Environment Breakdown

Environment	Collected Sample %	DAC Sample %	% Diff
Deep Urban	2.12%	3.16%	-1.04%
Major Urban Thruway	13.08%	24.68%	-11.60%
Major Rural Thruway	15.42%	15.19%	0.23%
Major Roads	36.89%	23.42%	13.47%
Local Roads	26.64%	11.39%	15.25%
Interstate/Freeway	0.01%	15.19%	-15.18%
Mountains	5.84%	6.96%	-1.12%

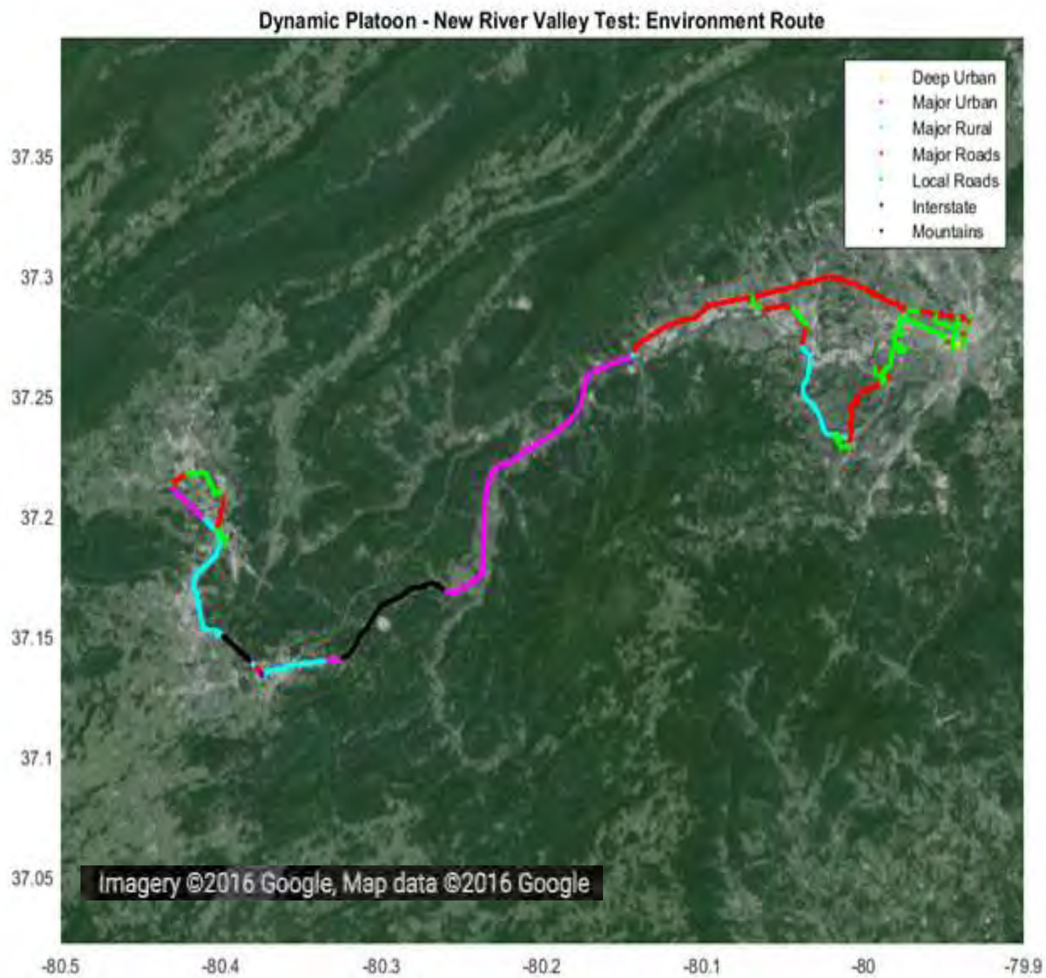


Figure 40. New River Valley route environments.

Positioning Performance

This test focused specifically on position performance measures experienced throughout the entire platooned drive on public roads in the New River Valley as described in the Dynamic Platoon section. Further, the New River Valley section describes the various environments encountered on this route

Provided in Figure 41 - Figure 43 are the box plot results detailing the position performance metrics versus environment per motorcycle antenna location. The central red mark is the median, the edges of the blue box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a red plus. The right hand y-axis provides the count of samples in the bin detailed on the left hand y-axis.

Figure 44 provides maps detailing the route of the motorcycle and position performance metric outliers. The green points indicates the path of travel the motorcycle took along the Smart Road. The Front Antenna (Blue dot) and Rear Antenna (Red Circle) signify locations along the path of travel where the performance metric is considered a statistically poor performing outlier. The map plotted outliers consist of the bottom 5% experienced per motorcycle antenna location.

As was seen in the static dwell and Smart Road platoon tests, the HDOP values of the Front Antenna, in comparison to the Rear Antenna in the dynamic platoon test, is also off by a factor of one. In addition, significant variation is seen from the Front Antenna.

As depicted in the maps, traversing several regions of the New River Valley exhibited relatively poor position performance based on the antenna location. In the South West region of the map, a string of Rear Antenna red circles are in the Mountains environment (Figure 45). As expected, due to sky occlusion fewer satellites will be used in deriving a location solution.

In the North East region, the environments with poor position are Local Roads and Deep Urban. As the Figure 46 maps indicate sky occlusion either from tree foliage, tall buildings, overpasses, underpasses or bridges associate with relatively lower GPS performance.

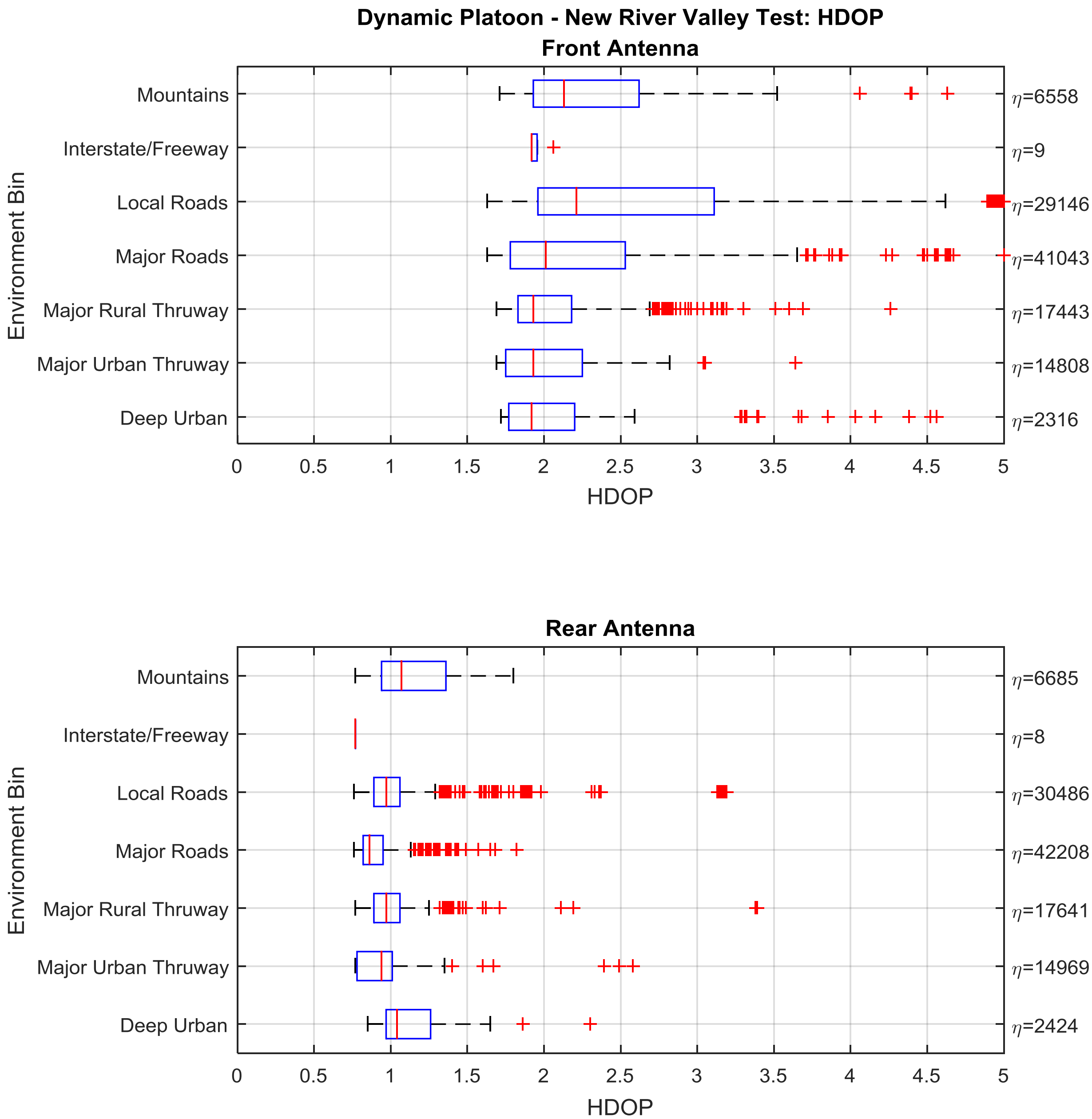
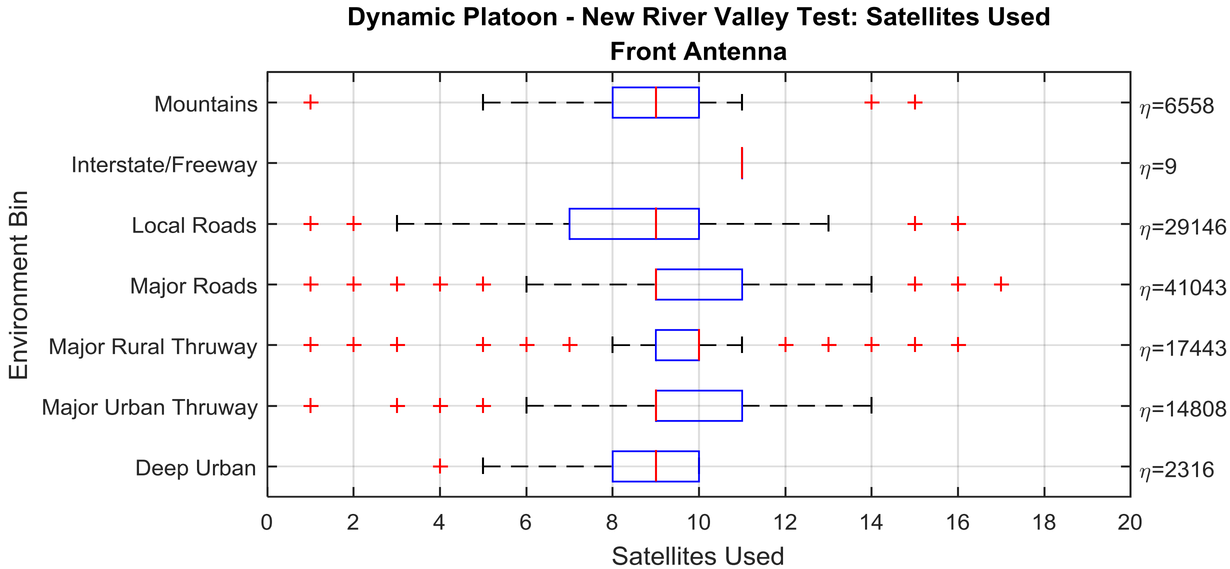


Figure 41. New River Valley Position performance – HDOP.



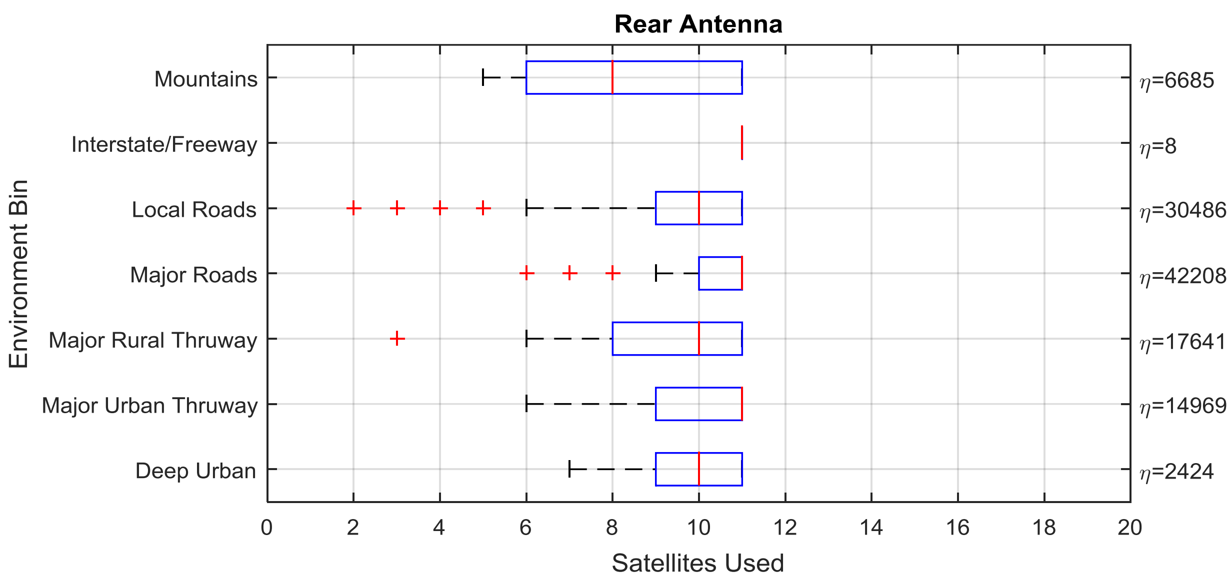


Figure 42. New River Valley Position performance – Satellites used.

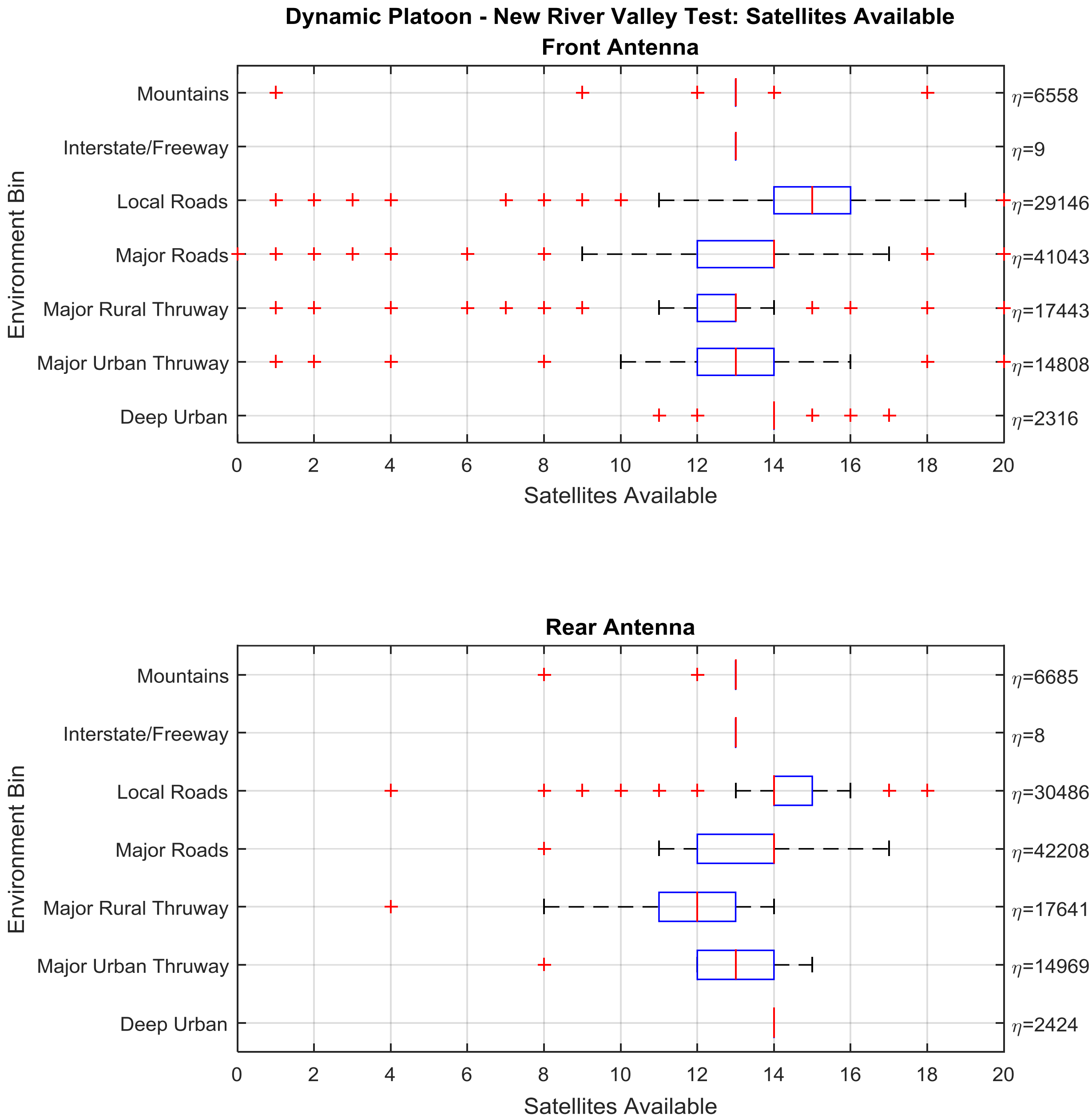


Figure 43. New River Valley Position performance – Satellites available.

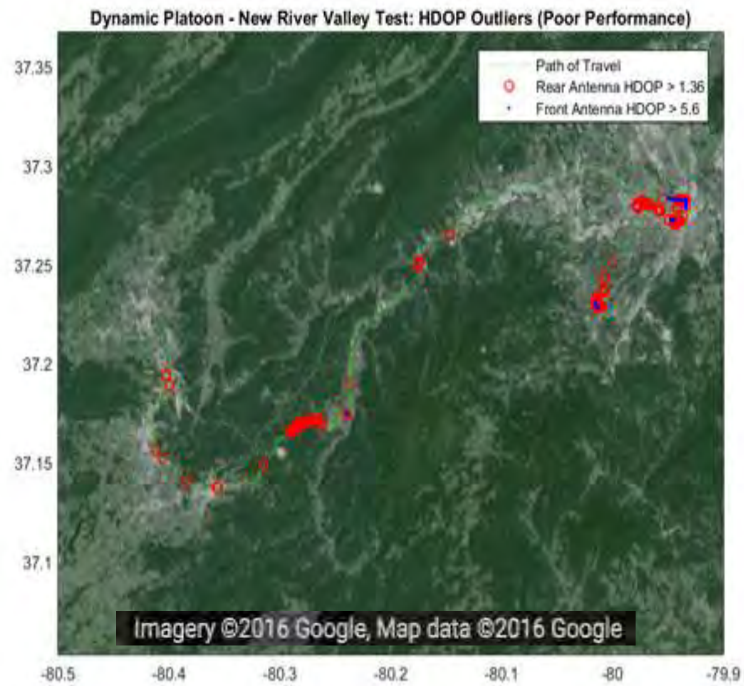


Figure 44. New River Valley Position poor performance map.

Figure 45. New River Valley Position poor performance map – South West.

Figure 46. New River Valley Position poor performance – North East.

Communications Performance

This test focused specifically on communication performance measures experienced throughout the entire platooned drive on public roads in the New River Valley as described in the Dynamic Platoon section. Further, the New River Valley section describes the various environments encountered on this route

Vehicle position was of importance to understand the effects of antenna location and rider occlusion. For example, in the case with the rear-mounted antenna, the ahead vehicle (Sedan) was expected to show poorer performance than the rear vehicle (SUV) because the signal was being occluded by the rider. Conversely, the motorcycle with the forward-mounted antenna was expected to show better performance communicating with the ahead vehicle (Sedan) because the signal was not being occluded by the rider.

Provided in Figure 47 is a selection of box plot results detailing the communication performance metrics per antenna location as was illustrated in Formation 1 in Figure 19. The central red mark is the median, the edges of the blue box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually as a red plus. The right hand y-axis provides the count of samples in the bin detailed on the left hand y-axis. The complete collection of plots can be found in the Appendix C – Dynamic Platoon – New River Valley.

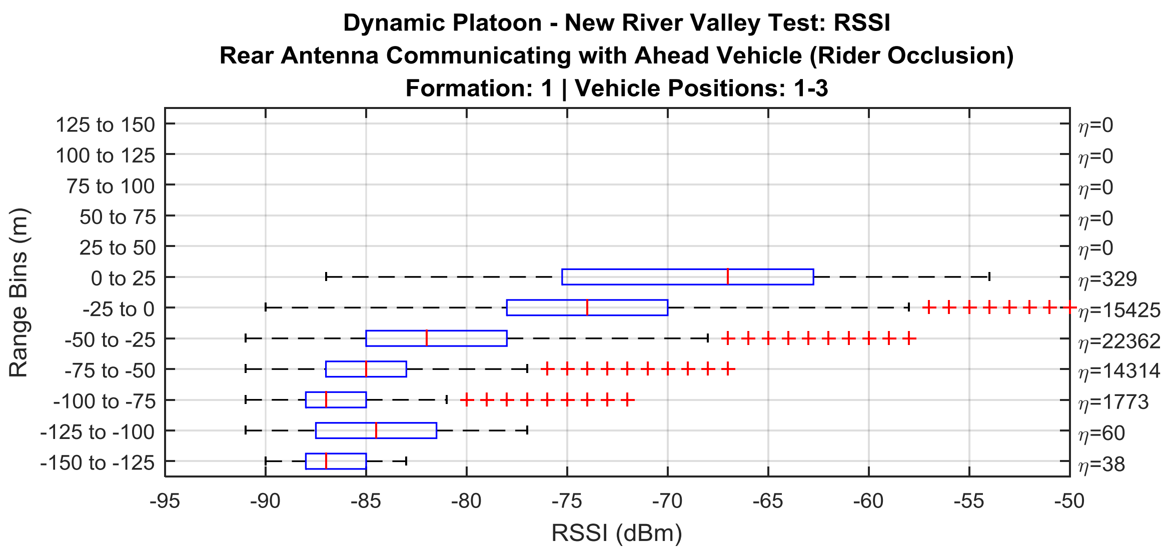
It should be noted that range is not the test here, rather a point of reference. The primary objective behind this test is to measure communication performance in typical headway distances encountered in real world situations. Further, for this platoon test, vehicles traveled in a single-lane formation, with most communication range distributions samples between 0 and 50 m for proximate vehicles (i.e., Positions 1-2, 4-3) and between 25 and 75 m for the distal vehicle (i.e., Positions 1-3, 4-2). In regards to relative range on all plots, ranges that are negative, the motorcycle is behind; in positive ranges, the motorcycle is ahead. Typically, in instances where the sedan is the HV, the motorcycle ranges are negative since they are behind in the formation. When the SUV is the HV, the motorcycle ranges are positive since they are ahead in formation.

Figure 48 is a three dimensional (3d) plot relating the communication performance metric to relative vehicle to vehicle range bins and environments. The entire collection across performance metrics and vehicle configurations are provided in the Appendix C – Dynamic Platoon – New River Valley.

To interpret the plot, the top of the bars represent the average RSSI/PER experienced at the corresponding Range Bin and Environment. Below the 3d plot are the cross sections relating the average RSSI/PER vs Range or RSSI/PER vs Environment.

Figure 49 examines the communication performance differences between occluded and non-occluded motorcycle configurations across the various formations. Along the y-axis is the mean of the performance metric per all of the samples along the range bins defined on the x-axis.

From the comparison plots, in cases where the Lead vehicle (Sedan) is communicating with the motorcycles behind, there isn't a significant difference between rear occluded antenna and front non-occluded antenna communications. In cases where the Rear vehicle (SUV) is communicating with the motorcycles ahead there is a significant difference between occluded. Additionally, it should be noted that these plots contain all the data for the entire trip and are not separated by environment.



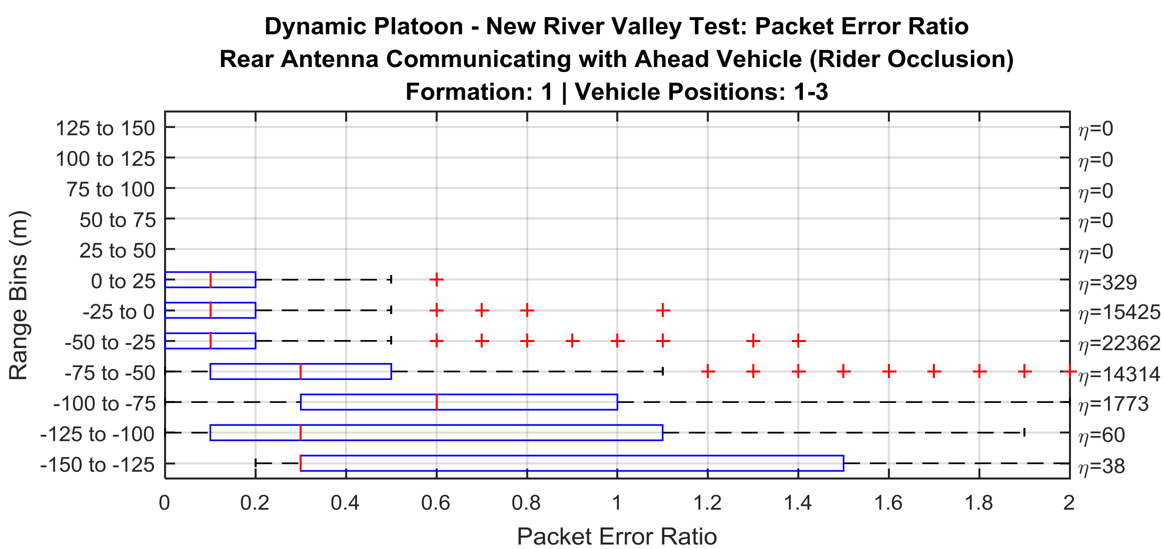


Figure 47. Dynamic platoon in New River Valley – Communication (example).

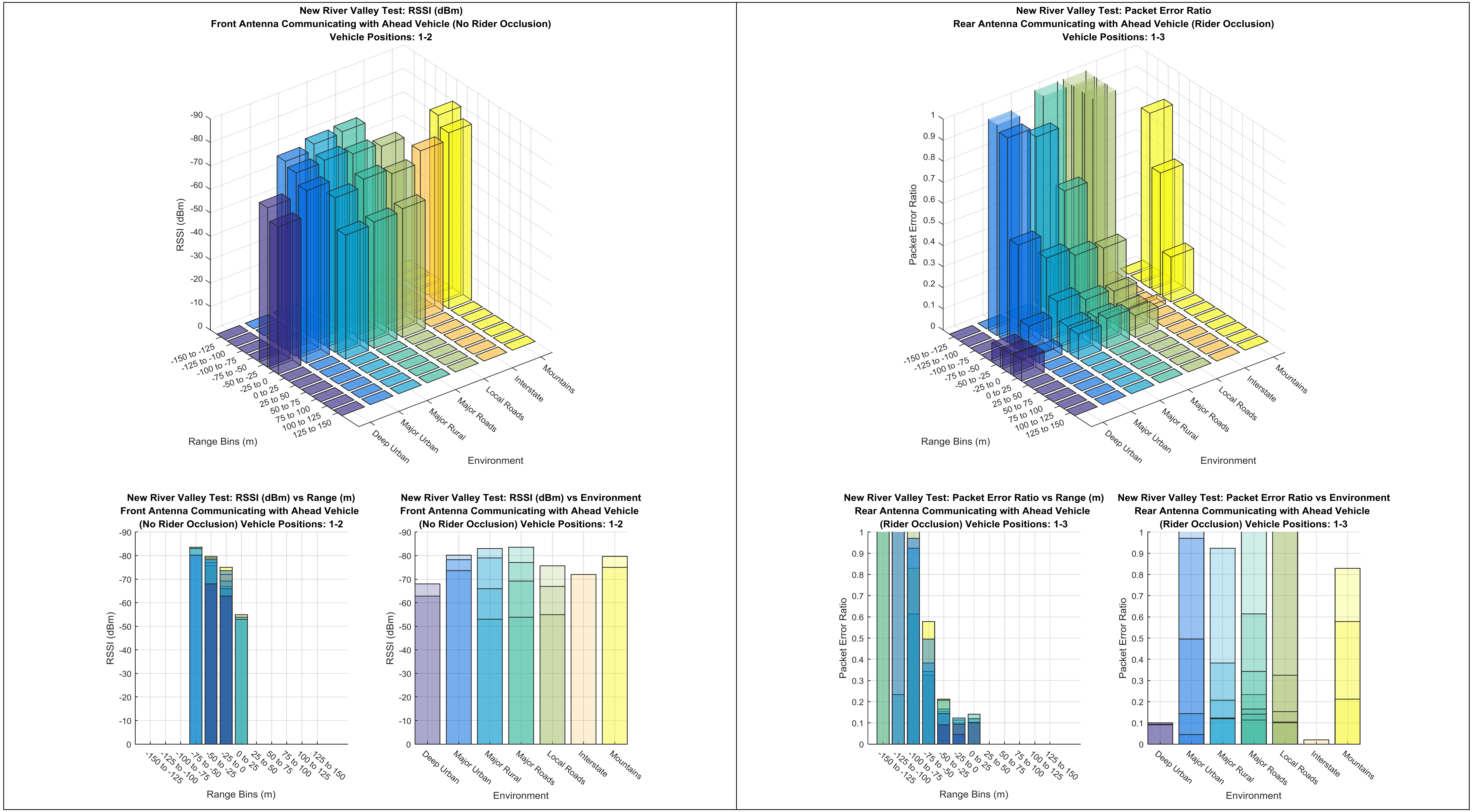


Figure 48. Dynamic platoon in New River Valley communication performance measure vs range bin vs environment 3d plot (example).

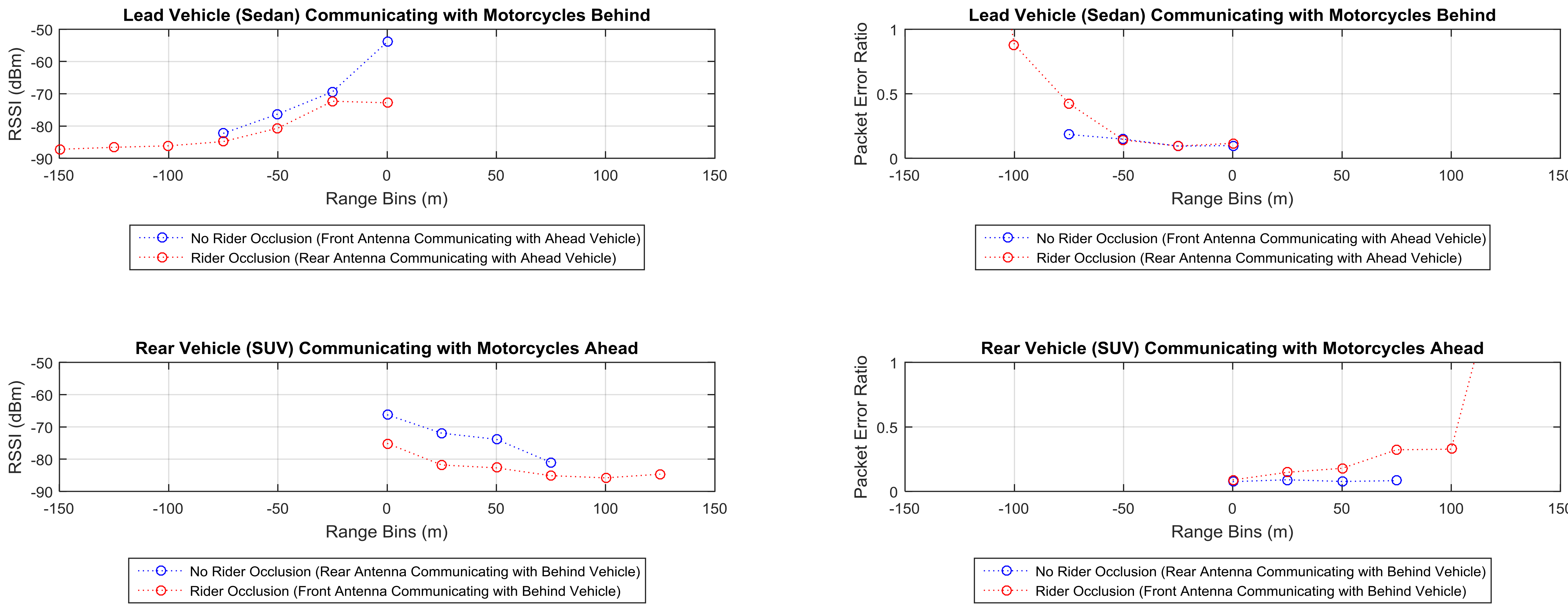


Figure 49. Dynamic platoon in New River Valley communication performance comparison.

Conclusions

Static Dwell Test

As reported in the Static Testing results section, the HDOP metric between Front and Rear Antenna stands out. The Front Antenna across all configurations is approximately off by a factor of one while the GPS receivers typically saw and used the same number of satellites. Identification of the actual satellites used in deriving the solution was explored and showed that the two antennas generally used the same satellites in deriving its position. Further, the presence of the rider nor the formation appear to negatively impact position performance. Only in the mountain/valley case, both used fewer satellites than in the open sky, as expected due to the occlusion of the sky blocking out view of other satellites.

Dynamic Ranging

As reported in the Dynamic Ranging results section, for both antenna locations, an increase in communication performance experienced in the mountain/valley region was observed. Table 12 takes the max/min ranges as reported in Table 10 and then takes the range differential between the valley and open sky environments for the given antenna location (e.g. Front Antenna mountain/valley min range – open min range). It is likely that the reason for this increased performance is that the mountainsides reflected the wireless signals back, as opposed to an open-sky condition, where signals keep propagating out and away from the receiving vehicle. From these results, the rear mounted antenna saw significant communication performance gains in valley environments.

Table 12. Dynamic Ranging Environment Comparison

Antenna Location	Smart Road Environment	Behind Range Diff	Ahead Range Diff	Peak Effective Range Diff	PER < 1 Behind Range Diff	PER < 1 Ahead Range Diff	PER < 1 Effective Range Diff
Front	Open	50	50	100	100	-50	50
	Valley						
Rear	Open	100	200	300	200	0	200
	Valley						

In order to compare between the two antenna locations, Table 13 takes the max/min ranges as reported in Table 10 and then takes the range differentials between Front and Rear Antenna locations for the given environment (e.g. open environment min Rear Antenna range – min Front Antenna range). As the results indicate, the Front Antenna has better communication performance than the Rear Antenna with the exception of cases where the Rear Antenna is communicating with the behind vehicle. In this configuration, the communication path is not occluded by the rider.

In general, the range results indicate that the communication path that is not occluded by the rider will have better communication performance than the occluded path. Further, the Front Antenna ranges are evenly distributed between occluded and non-occluded communications versus the Rear Antenna.

Table 13. Dynamic Ranging Antenna Location Comparison

<table>
<tr><th>Antenna Location</th><th>Smart Road Environment</th><th>Behind Range Diff</th><th>Ahead Range Diff</th><th>Peak Effective Range Diff</th><th>PER < 1 Behind Range Diff</th><th>PER < 1 Ahead Range Diff</th><th>PER < 1 Effective Range Diff</th></tr>
<tr><td>Front</td><td rowspan="2">Open</td><td rowspan="2">0</td><td rowspan="2">-200</td><td rowspan="2">-200</td><td rowspan="2">50</td><td rowspan="2">-150</td><td rowspan="2">-100</td></tr>
<tr><td>Rear</td></tr>
<tr><td>Front</td><td rowspan="2">Valley</td><td rowspan="2">50</td><td rowspan="2">-50</td><td rowspan="2">0</td><td rowspan="2">150</td><td rowspan="2">-100</td><td rowspan="2">50</td></tr>
<tr><td>Rear</td></tr>
</table>

Dynamic Platoon

As reported in the Dynamic Platoon – Smart Road section, similar to the static dwell tests, the HDOP values of the Front Antenna, in comparison to the Rear Antenna is also off by a factor of one. Further, the two antennas on average, used and saw the same number of satellites. Although similar in average, the Front Antenna had more variation in the number of satellites used during the tests. This variation trended towards fewer satellites used, indicating that the Front Antenna often dropped use of satellites. During this test, the motorcycles were exposed to various environments such as open sky and valley locations. In the valley case, both antennas had relatively poor position performance as the GPS constellation was occluded by the environment. In certain regions of the Smart Road, the roadway curvature required the motorcycle to maneuver in a manner that produced lean angles; in such regions the Front and Rear Antenna differed in position performance.

From the communication performance perspective, it should be noted that range is not the metric, rather a point of reference. The primary objective behind this test is to measure communication performance in typical headway distances encountered in real world situations. For this platoon test, vehicles traveled in a single-lane formation, with most communication range distributions samples between 0 and 50 m for proximate vehicles (i.e., Positions 1-2, 4-3) and between 25 and 75 m for the distal vehicle (i.e., Positions 1-3, 4-2).

In both the Dynamic Platoon – Smart Road & Dynamic Platoon – New River Valley tests where the Lead vehicle (Sedan) is communicating with the motorcycles behind, there isn't a significant difference between rear occluded antenna and front non-occluded antenna communications at close ranges. In cases where the Rear vehicle (SUV) is communicating with the motorcycles ahead there is a significant difference between occluded and non-occluded communications. The non-occluded rear mounted antenna shows an improvement of ~10 dBm and ~10% PER.

Overall Position Performance

An interesting observation is that the front mounted antenna had significantly worse HDOP measures than the rear mounted antenna. This observation appeared in all other positioning-based analysis. For both antenna positions, the VADs were installed in an enclosure mounted at the rear of the motorcycles; in the case of the motorcycle with the front mounted antenna, the cables to reach the antenna had to traverse the body of the motorcycle, while the motorcycle with the rear mounted antenna had a less complex cable run. Introduction of potential sources of electromagnetic interference (EMI) or attenuation may include overall length, electrical noise, and/or cable routing. Assessment of this could involve measuring the attenuation of the cables for the specific frequency ranges of GPS bands.

Overall however, in environments where there are objects (e.g. buildings, trees) occluding the view of the open-sky, position performance degrades. These effects of raw positioning performance data ultimately have implications for crash avoidance applications of CVS. Considering that GPS elements are packaged into BSMs, poor positions may impact reliability of such systems as lane level accuracy is needed for certain crash warnings [2].

In comparison to results from position performance metrics measured during the DAC, Table 14 provides the average number of satellites used for various GPS receivers across all of the different environments traversed. The HA0, HA1, HA2, HA3 receivers are considered to be survey-grade and the receivers A1 and A2 are automotive-grade [3]. Further the A1 receiver and the GPS receiver used in the VAD for this study are from the same manufacturer. As the results indicate, the average number of satellites used for light vehicles during the DAC is comparable to the motorcycle configurations used in this study.

Table 14. Satellites Used Study Results Comparison: DAC Vehicles [3] versus Motorcycle Antenna Locations

Receiver / Environment	HA0	HA1	HA2	HA3	A1	A2	Front Antenna	Rear Antenna
All Environments	7.37	7.47	7.44	7.33	10.68	8.81	9.10	9.91
Deep Urban	4.76	4.79	5.18	3.83	9.81	7.75	8.72	9.74
Interstate/Freeway	7.81	7.79	8.46	9.14	10.85	8.79	11.00	11.00
Local Road	7.47	7.54	7.06	7.47	11.00	8.77	8.40	9.62
Major Road	7.85	7.89	6.77	7.81	10.92	9.30	9.28	10.49
Major Rural Thruway	7.55	7.75	8.37	7.42	10.92	9.00	9.62	9.61
Major Urban Thruway	7.66	7.74	7.82	7.72	10.63	8.74	9.53	9.81
Mountains	5.85	6.20	6.12	-	9.41	7.64	8.86	8.64

Communications

Across the various tests, it became quite apparent that both rider presence and ranges between vehicles impact communications performance. In situations where the motorcycle has direct line of sight with the vehicle, a noticeable increase in performance can be seen.

As mentioned in the results, the mountain environment may have allowed for the wireless signals to reflect back into the roadway, increasing overall range, as opposed to leaking out and away from a receiver. Although the performance reported was greater in environments that can reflect signals, this characteristic will be limited to locations along a few roadways.

Having a wider overall communication range allows for earlier detection of motorcycles in crash avoidance applications. Depending on the specific crash avoidance application, however, such distances may have different effects depending on direction. For example, if a vehicle and a motorcycle approach each other head on, having a longer communication range in the ahead direction will improve performance.

Based on the results of the dynamic platoon tests on the Smart Road and in the New River Valley, communications performance was quite good. Since the platoons gravitated towards ranges of 0 to 75 m in traffic, testing the upper limits of DSRC ranges was not performed. However, for such ranges, relatively close-proximity crash avoidance alert warnings (such as blind spot warnings or forward collision warnings) will work effectively.

Communication performance between light vehicles and motorcycles results from the DAC were referenced for comparison. From these results, the motorcycles measures are generally equivalent depending on the configuration. In cases where there is driver occlusion, performance generally drops below the DAC vehicle results, while in cases where there is no driver occlusion, performance is generally above the DAC vehicle results. At 10Hz, a PER of no more than 30% indicates that the average effective rate would be 7Hz, which is over the 5Hz at which safety applications have been successfully tested [3]. The effective average PER at the distances were the vehicles spent most of their time was below 10%, similar to the DAC vehicle results.

Recommendations

The results has shown that motorcycles, regardless of antenna placement, are comparable to light vehicles in terms of position and communication performance. However, in cases where a rider is occluding the wireless communication path, performance penalties exist. What hasn't been investigated, is the impact of a passenger in occluded communication paths. Overall however, the results from this study indicate that CVS safety applications can be implemented on motorcycles with one rider. In order to address communication performance risks associated with occluded communication paths, implementation of antenna diversity (i.e. both Front and Rear Antennas) or a new antenna location (i.e. rider helmet) should be investigated.

The next steps needed to mature CVS technologies on motorcycles is to investigate the implementation of crash avoidance applications. Considering that the research performed under this project only focused on the applied systems communications and positioning measures, neither crash avoidance algorithms nor application level target classification assessments were performed. When integrating crash avoidance algorithms, considerations regarding the kinematics of a motorcycle need to be considered. Specifically, due to centripetal forces, a lean angle is formed as a rider traverses roadway curvature. Factors involving the velocity, radius of curvature, and gravitational forces influence the lean angle experienced by the motorcycle. Since the motorcycle will be at an angle, so will the view of the antenna. Future work could be performed to understand this unique effect.

References

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[3] F. Ahmed-Zaid, H. Krishnan, V. Vladimerou, S. Brovold, A. Cunningham, R. Goudy, T. Khatchatrian, M. Maile, E. McGlohon, M. Naserian, N. Probert, J. Scally, J. Stinnett, V. Vijaya Kumar, S. VanSickle, Z. Doerzaph and R. Viray, "Vehicle-to-Vehicle Safety System and Vehicle Build for Safety Pilot (V2V-SP) Final Report, Volume 2 of 2, Performance Testing," NHTSA, U.S. Department of Transportation, 2014.

[4] ESRI, "HDOP," 06 2015. [Online]. Available: http://support.esri.com/en/knowledgebase/GISDictionary/term/HDOP.

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[7] SAE International, "SAE J2735 Surface Vehicle Standard - Dedicated Short Range Communication (DSRC) Message Set Dictionary," SAE International, 2009.

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Appendix/Appendices

Appendix A – Static Dwell Test

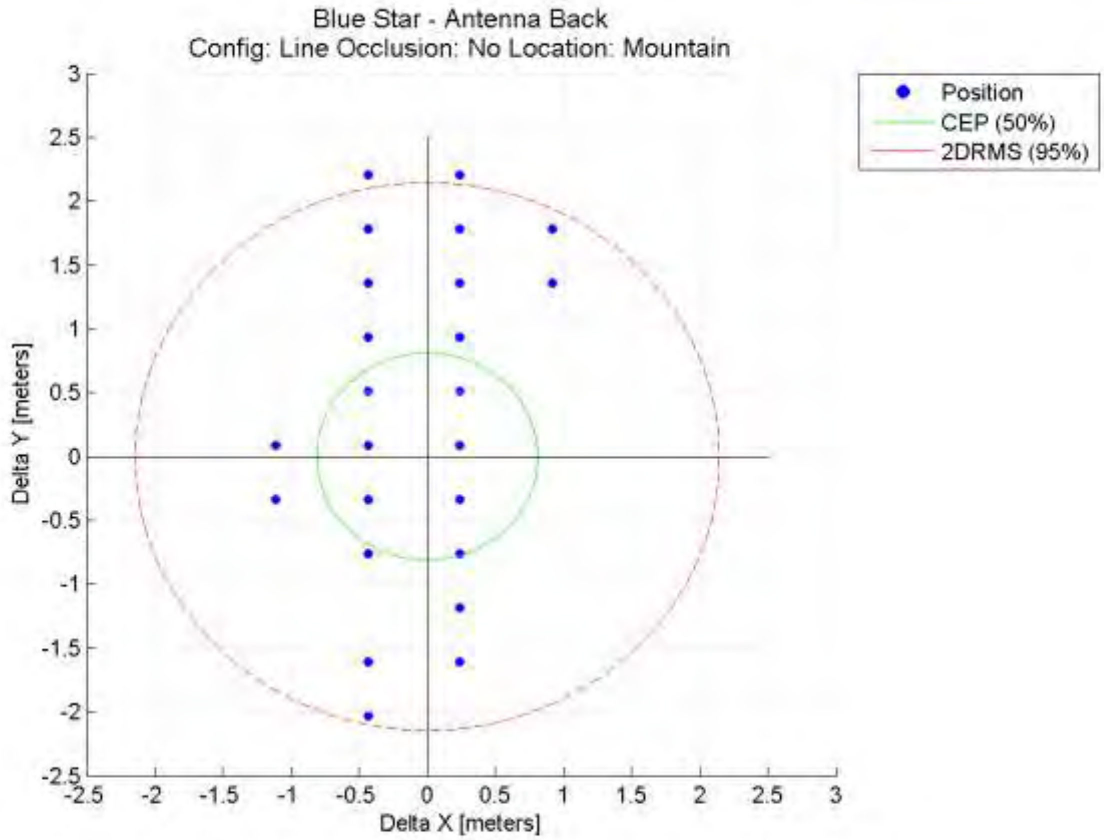
Position Performance

Measure	Antenna Location	Location	Rider Occlusion	Formation	CEP	Distance Root Mean Squared (DRMS)	Duration
CEP	Rear	Open	No	Single-lane	0.54	1.38	4.93
CEP	Rear	Open	Yes	Single-lane	0.45	1.08	4.40
CEP	Front	Open	No	Single-lane	0.46	1.12	5.17
CEP	Front	Open	Yes	Single-lane	0.58	1.45	4.95

Measure	Antenna Location	Location	Rider Occlusion	Formation	CEP	DRMS	Duration
CEP	Rear	Open	No	Adjacent	0.64	1.56	3.83
CEP	Rear	Open	Yes	Adjacent	0.50	1.21	3.86
CEP	Front	Open	No	Adjacent	0.70	1.72	4.85
CEP	Front	Open	Yes	Adjacent	0.35	0.85	4.63

Measure	Antenna Location	Location	Rider Occlusion	Formation	CEP	DRMS	Duration
CEP	Rear	Mountain	No	Single-lane	0.81	2.14	4.29
CEP	Rear	Mountain	Yes	Single-lane	1.04	2.61	3.49
CEP	Front	Mountain	No	Single-lane	1.16	2.93	4.76
CEP	Front	Mountain	Yes	Single-lane	0.72	1.82	3.39

Measure	Antenna Location	Location	Rider Occlusion	Formation	CEP	DRMS	Duration
CEP	Rear	Mountain	No	Adjacent	0.52	1.26	3.83
CEP	Rear	Mountain	Yes	Adjacent	0.55	1.32	3.57
CEP	Front	Mountain	No	Adjacent	1.07	2.67	4.34
CEP	Front	Mountain	Yes	Adjacent	1.15	2.77	3.51


Blue Star - Antenna Back
Config: Line Occlusion: No Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
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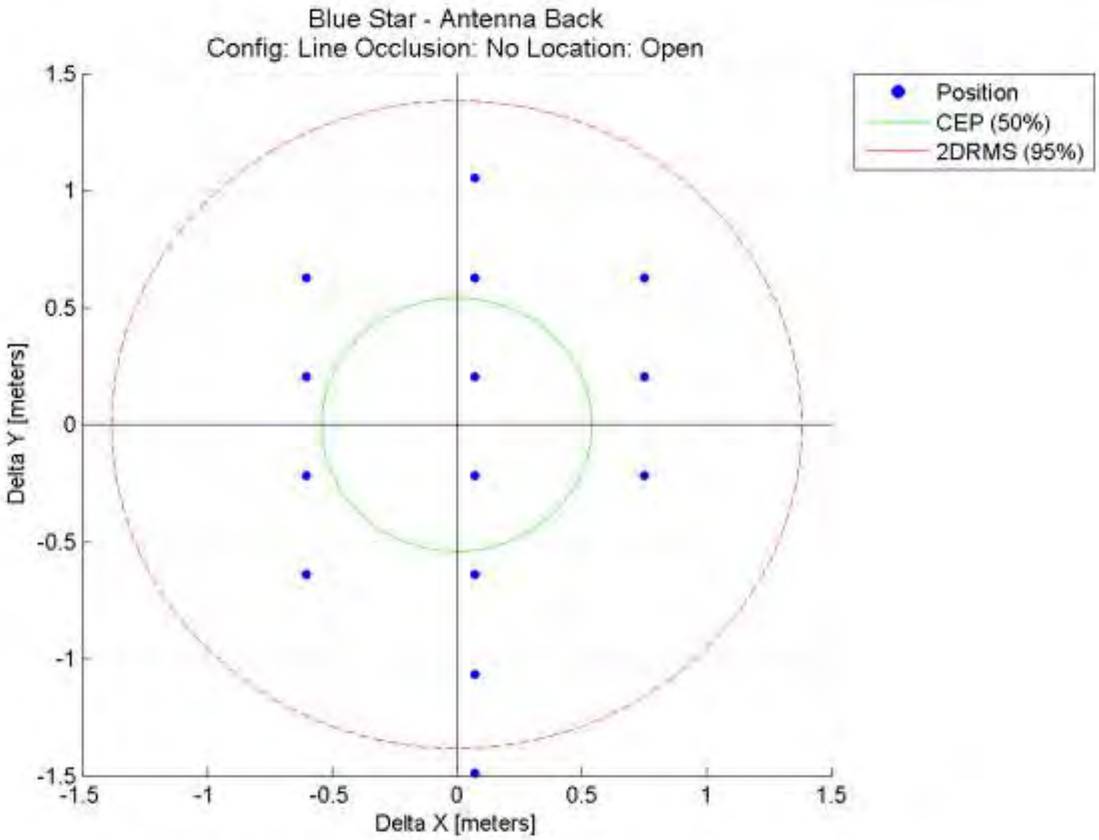
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5


Blue Star - Antenna Back
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Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
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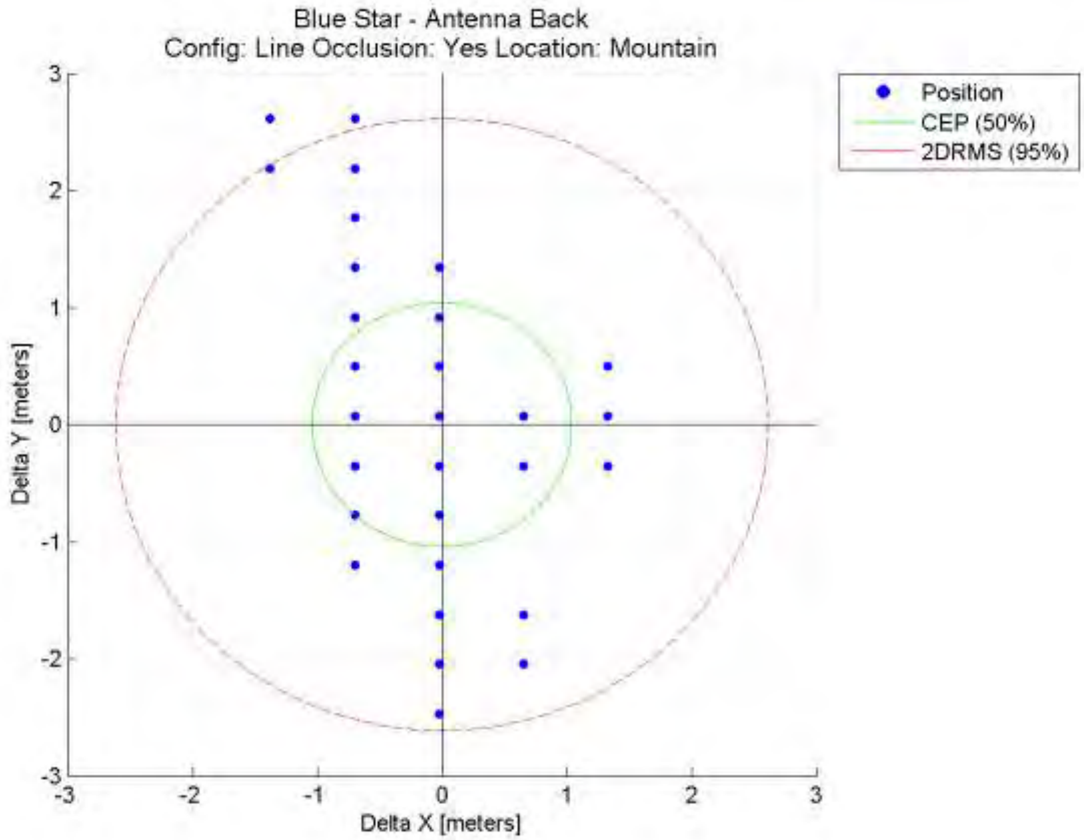
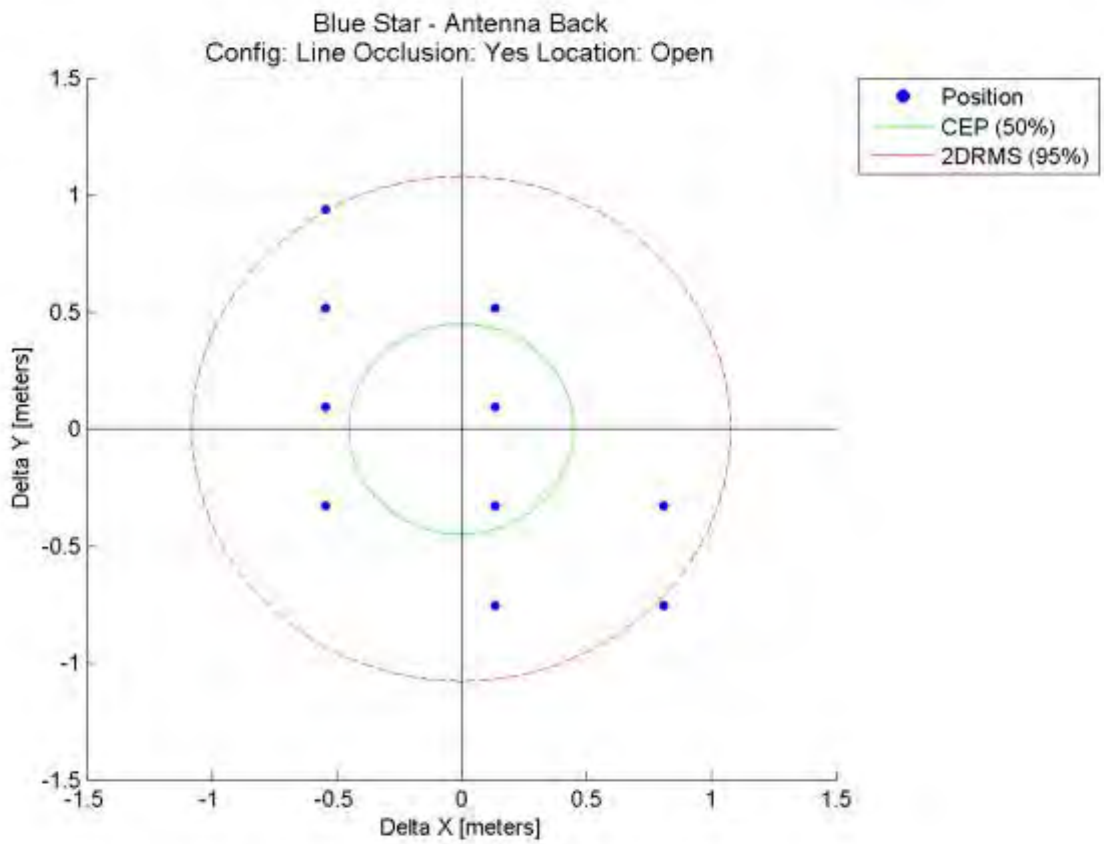
1
0.5
0
-0.5
-1
-1.5



Blue Star - Antenna Back
Config: Line Occlusion: Yes Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
3
2
1
0
-1
-2
-3


Blue Star - Antenna Back
Config: Line Occlusion: Yes Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
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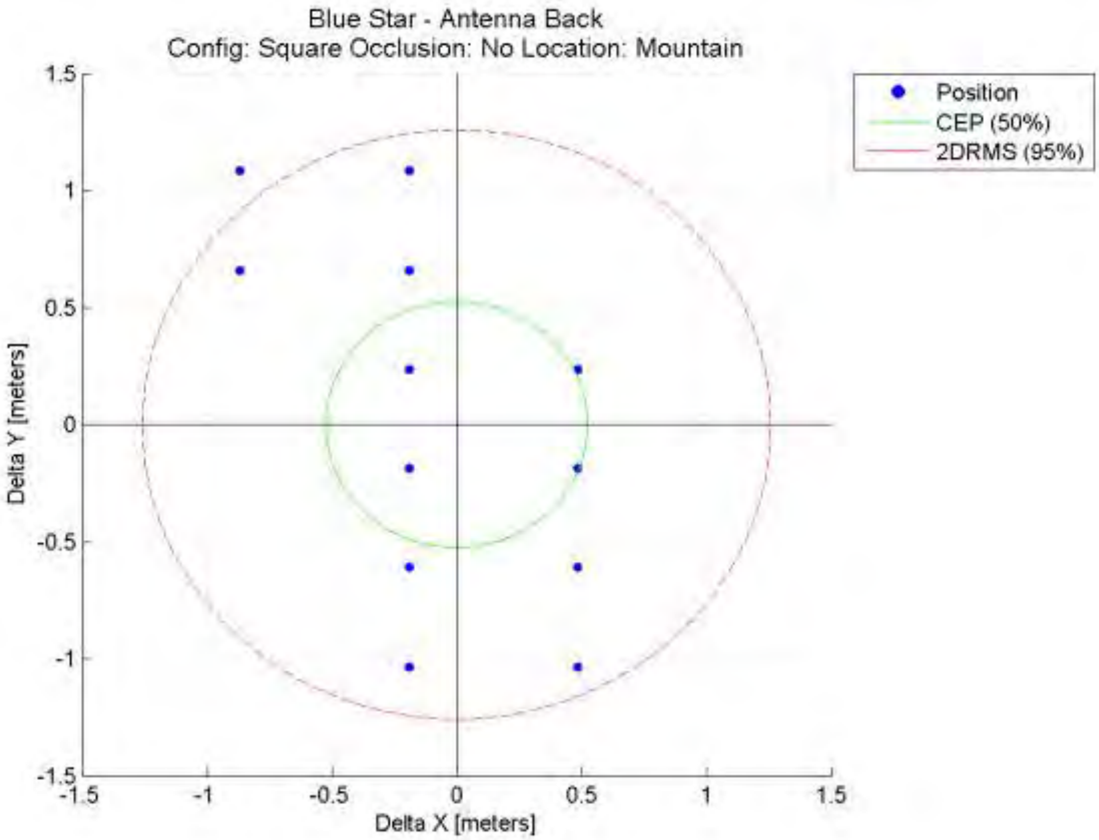
1
0.5
0
-0.5
-1
-1.5



Blue Star - Antenna Back
Config: Square Occlusion: No Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
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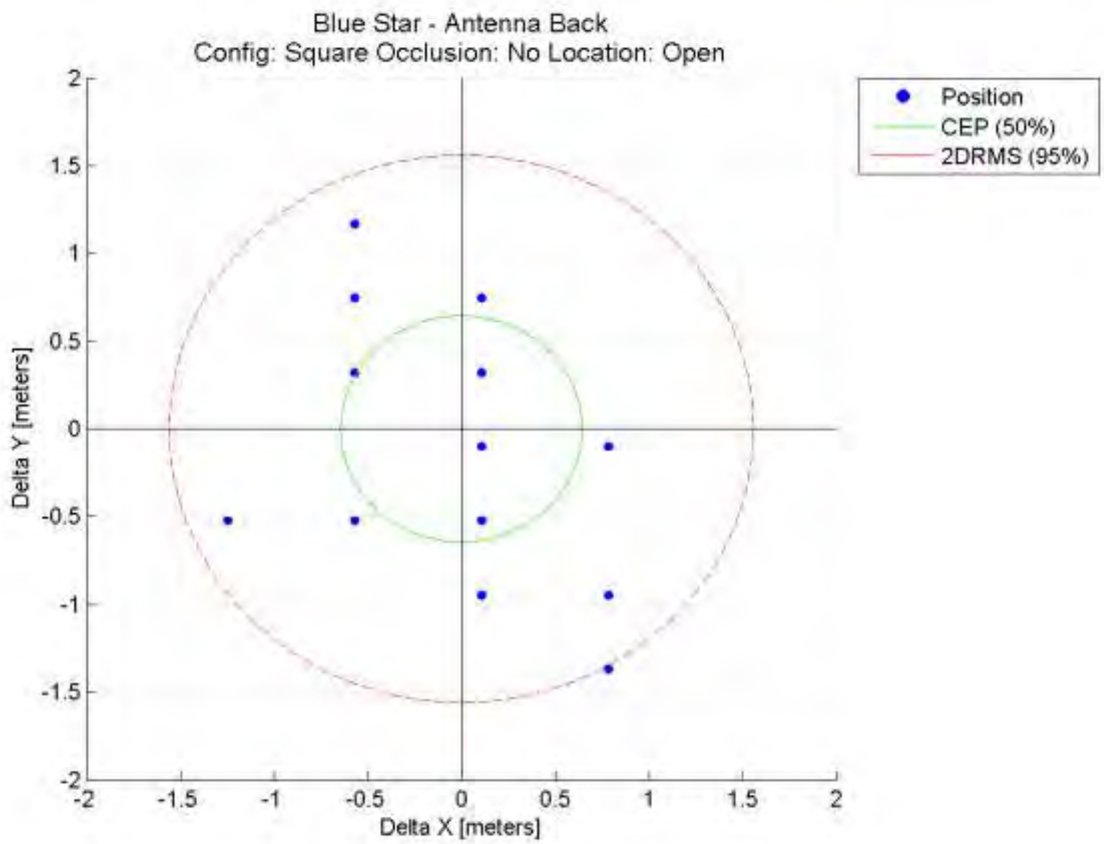
1
0.5
0
-0.5
-1
-1.5


Blue Star - Antenna Back
Config: Square Occlusion: No Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
2
1.5
1
0.5
0
-0.5
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-1.5
-2
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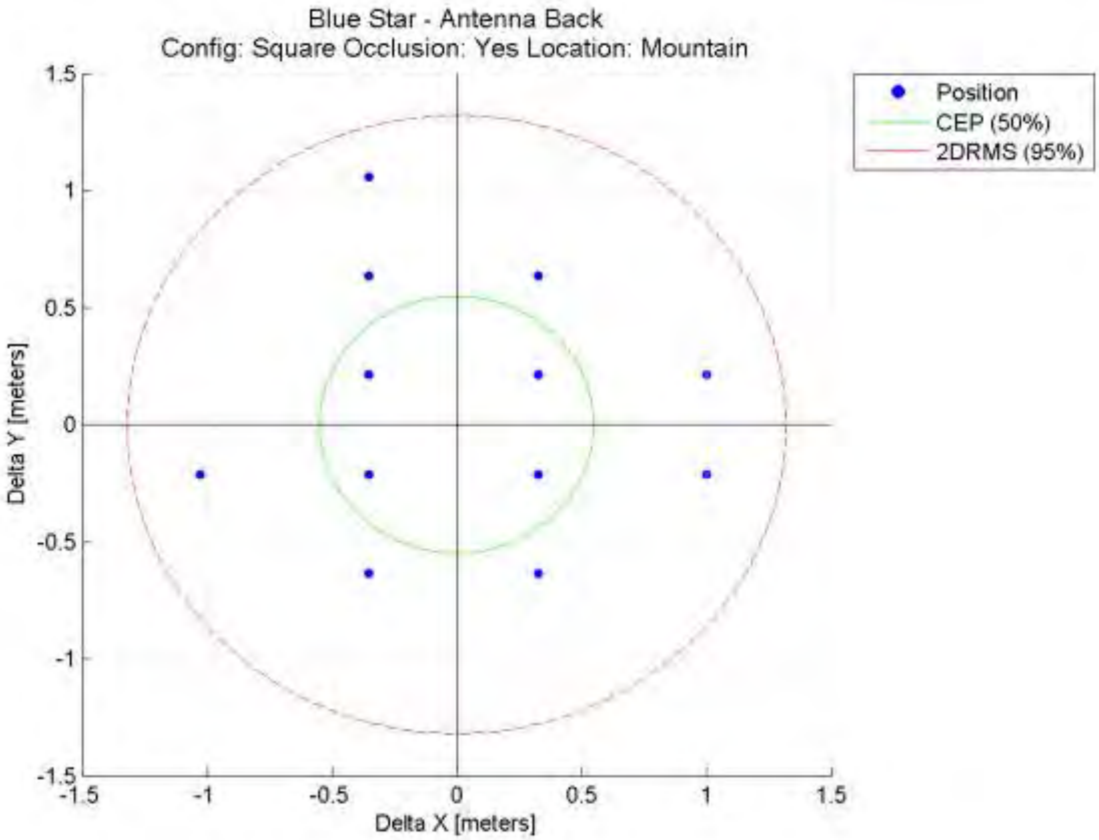
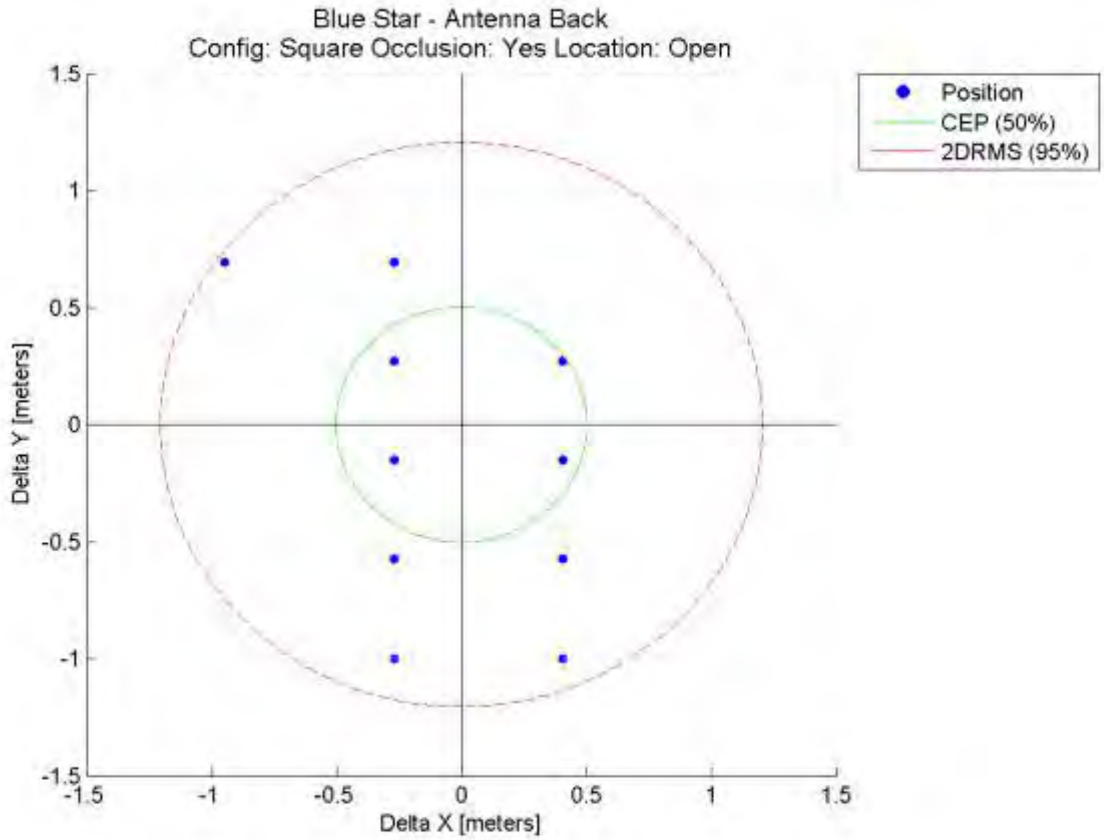
-1.5
-1
-0.5
0
0.5
1
1.5
2



Blue Star - Antenna Back
Config: Square Occlusion: Yes Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
1.5
1
0.5
0
-0.5
-1
-1.5


Blue Star - Antenna Back
Config: Square Occlusion: Yes Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
1.5
1
0.5
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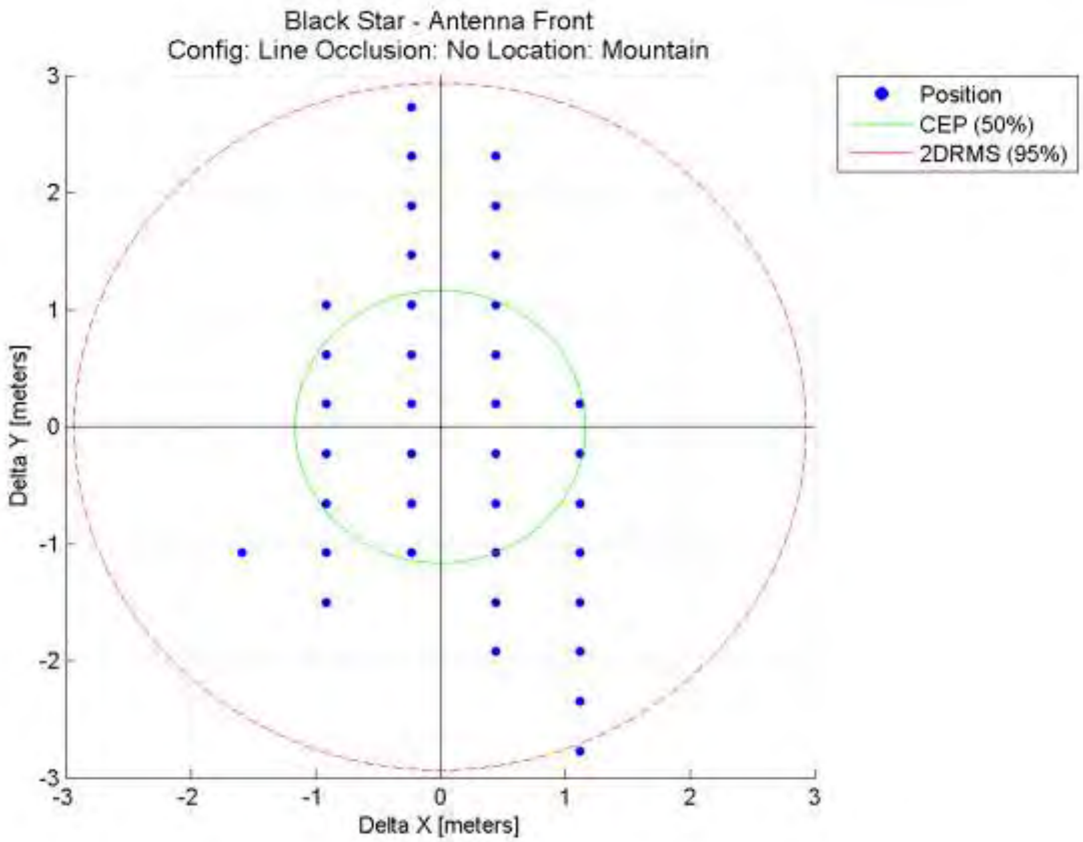
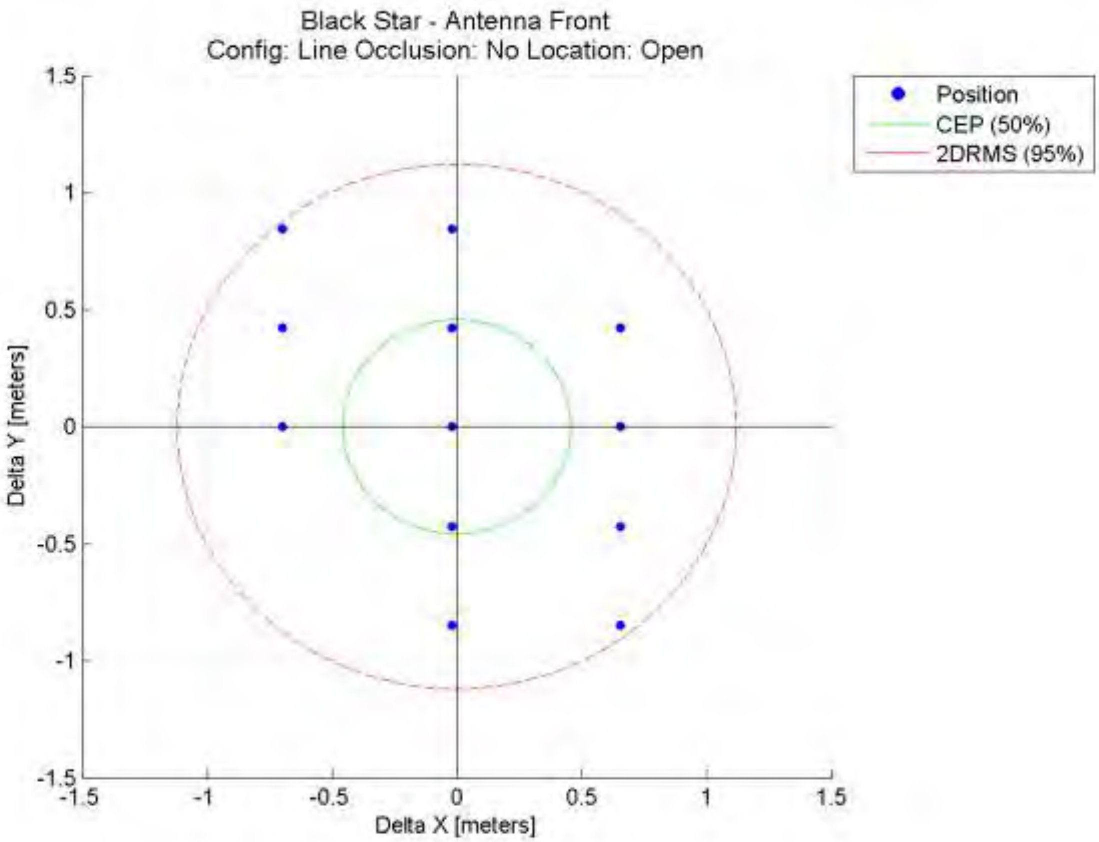
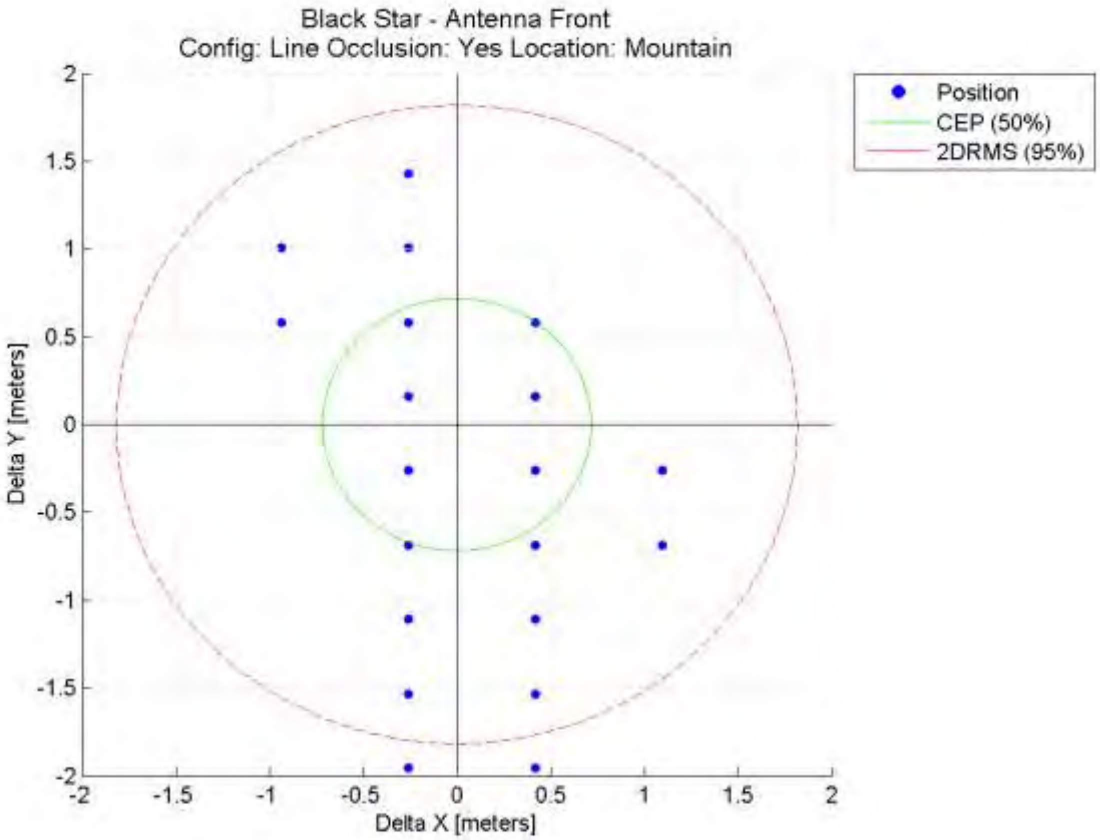
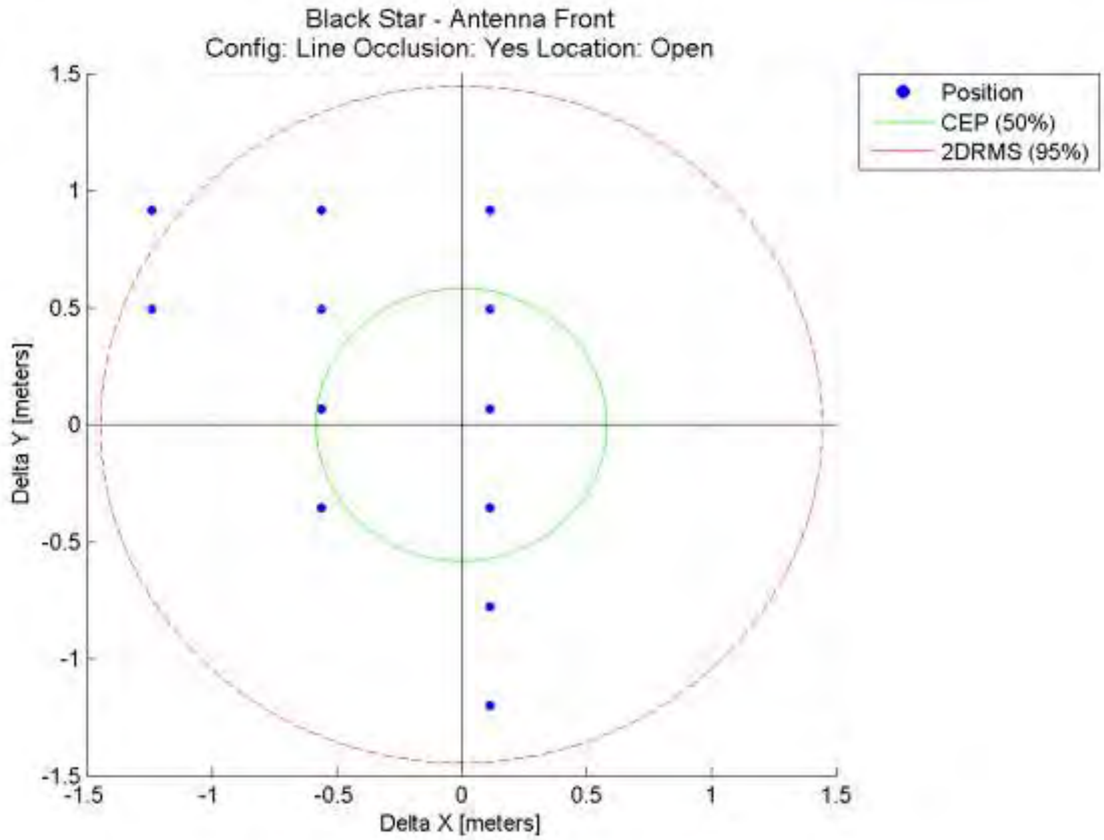
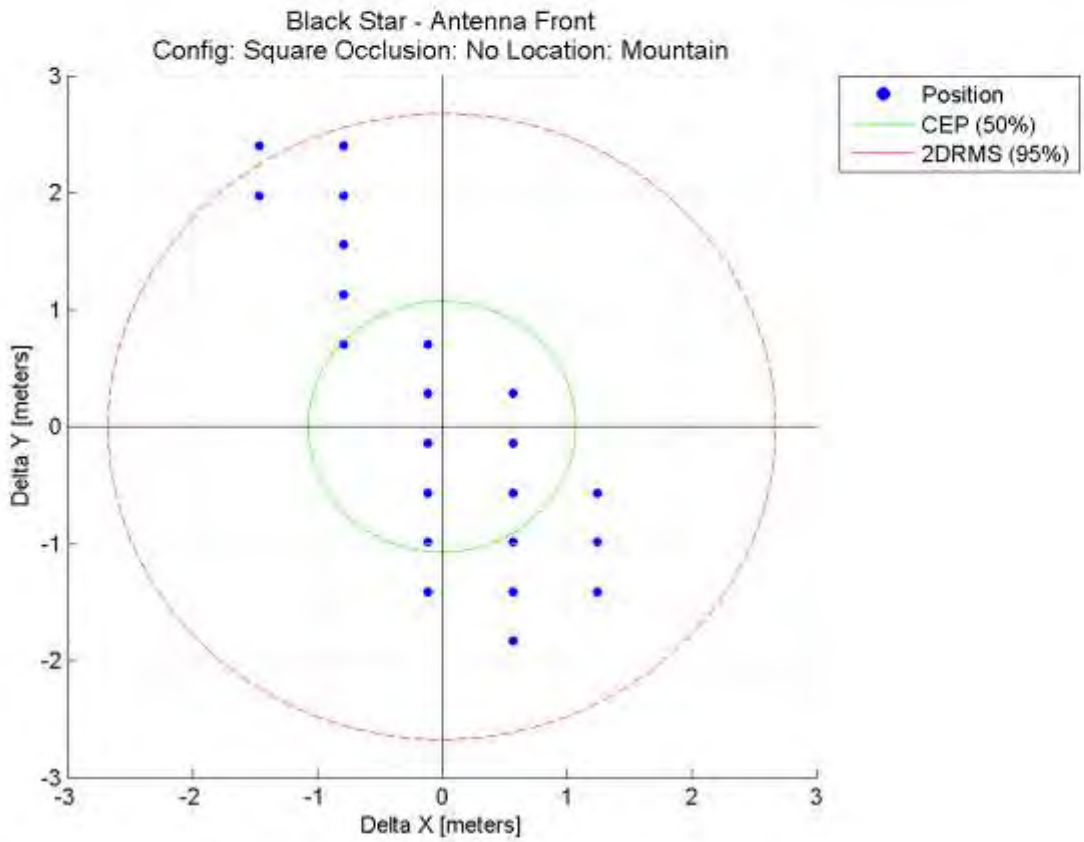
-0.5
-1
-1.5
-1.5
-1
-0.5
0
0.5
1
1.5

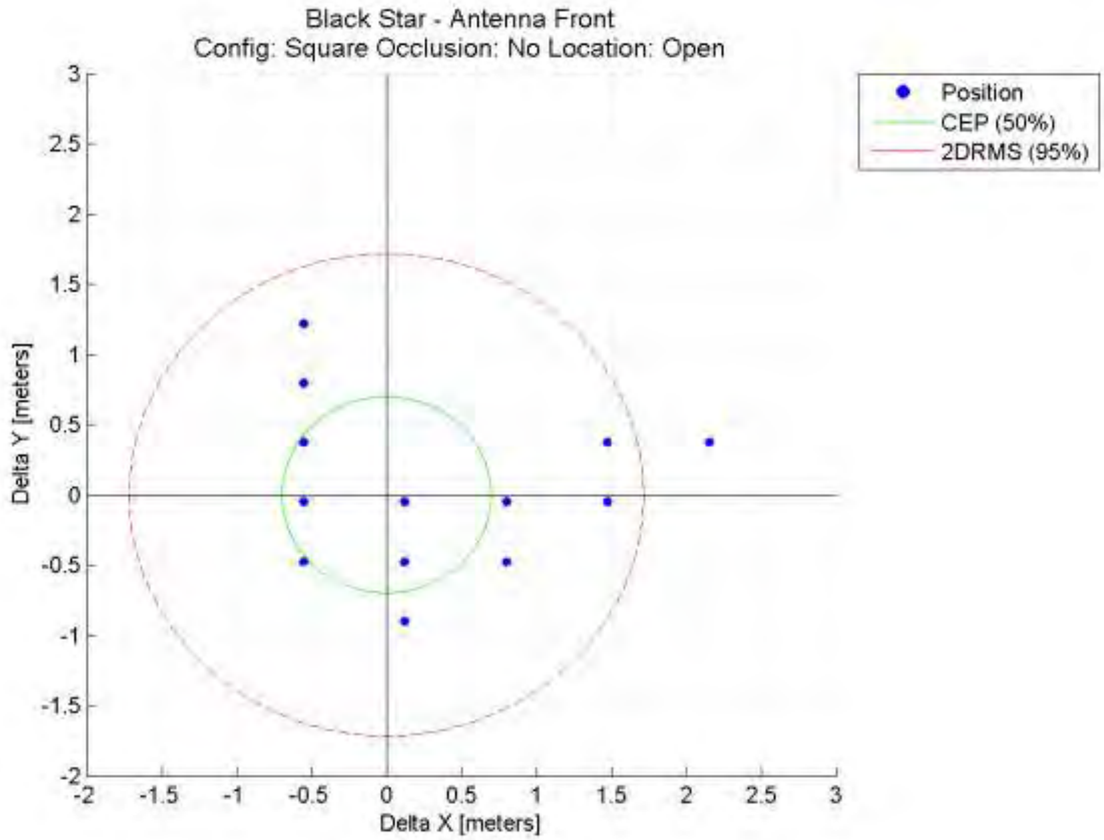

Black Star - Antenna Front
Config: Line Occlusion: No Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
3
2
1
0
-1
-2
-3


Black Star - Antenna Front
Config: Line Occlusion: No Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
1.5
1
0.5
0
-0.5
-1
-1.5


Black Star - Antenna Front
Config: Line Occlusion: Yes Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2


Black Star - Antenna Front
Config: Line Occlusion: Yes Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
1.5
1
0.5
0
-0.5
-1
-1.5


Black Star - Antenna Front
Config: Square Occlusion: No Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
3
2
1
0
-1
-2
-3


Black Star - Antenna Front
Config: Square Occlusion: No Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
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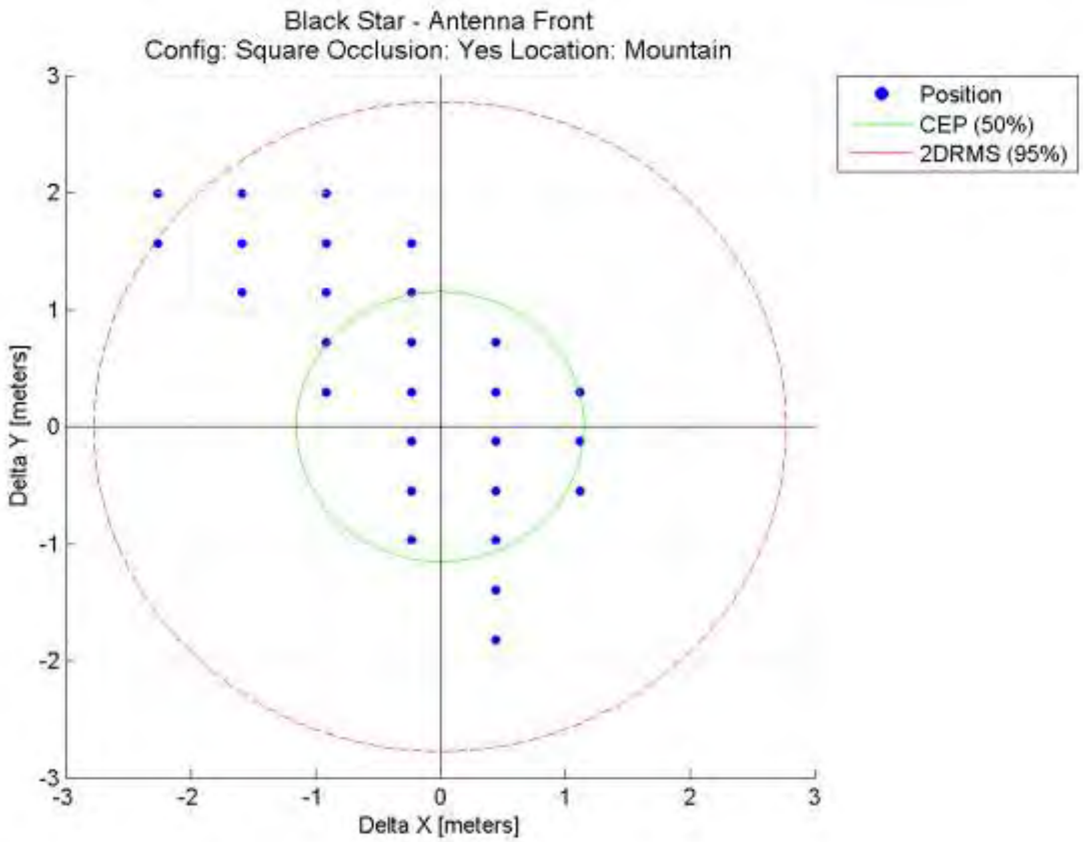
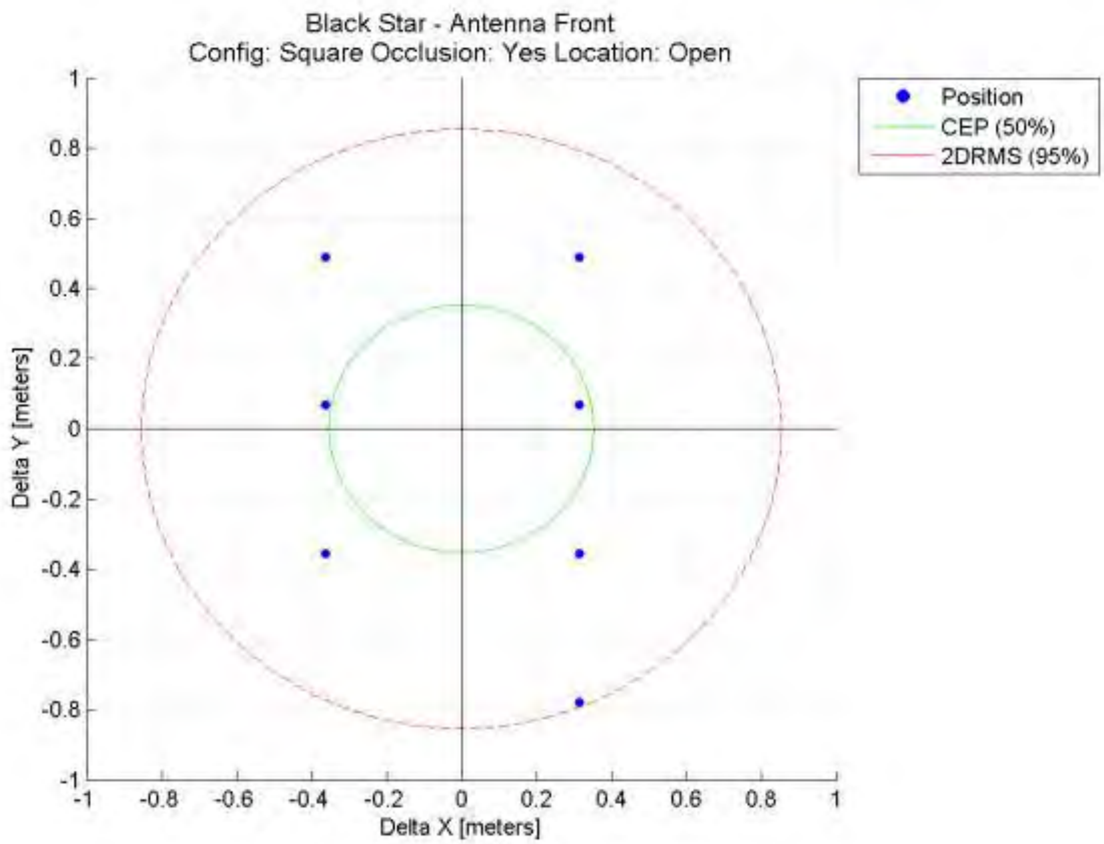
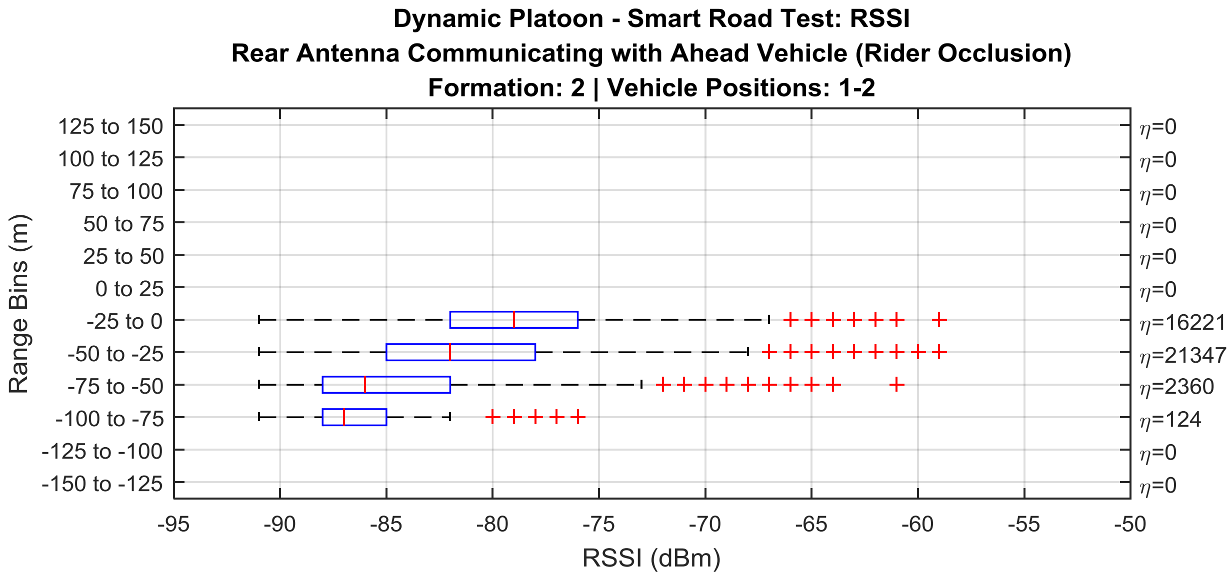
-1
-0.5
0
0.5
1
1.5
2
2.5
3


Black Star - Antenna Front
Config: Square Occlusion: Yes Location: Mountain
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
3
2
1
0
-1
-2
-3
-3
-2
-1
0
1
2
3


Black Star - Antenna Front
Config: Square Occlusion: Yes Location: Open
Position
CEP (50%)
2DRMS (95%)
Delta Y [meters]
Delta X [meters]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

Appendix B – Dynamic Platoon – Smart Road Test

Communication Plots


Dynamic Platoon - Smart Road Test: RSSI
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Formation: 2 | Vehicle Positions: 1-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
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η=16221
η=21347
η=2360
η=124
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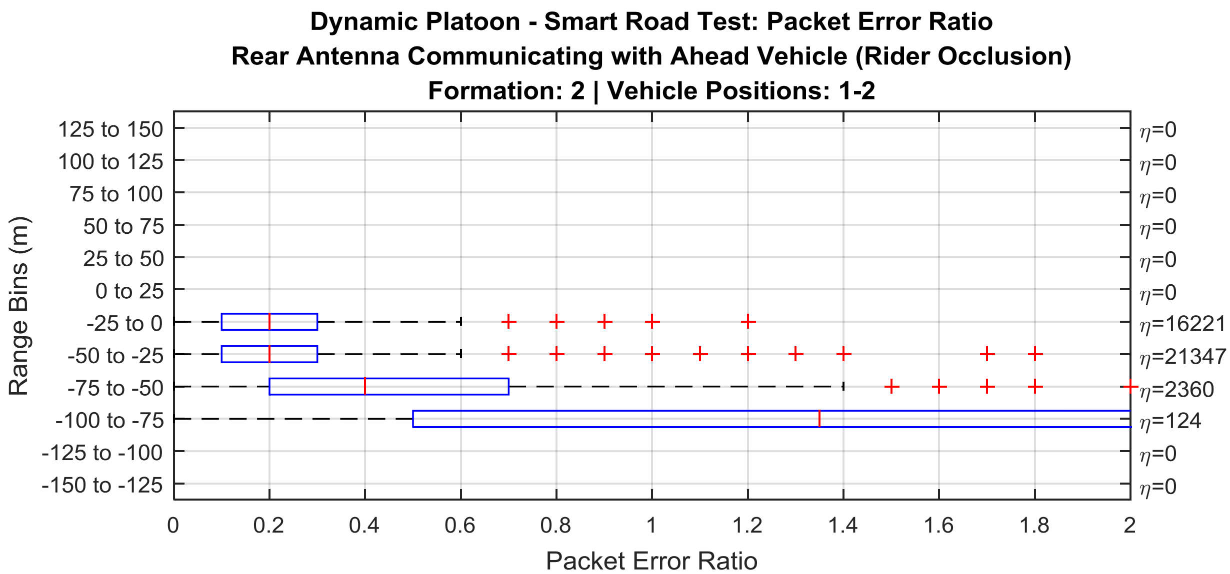
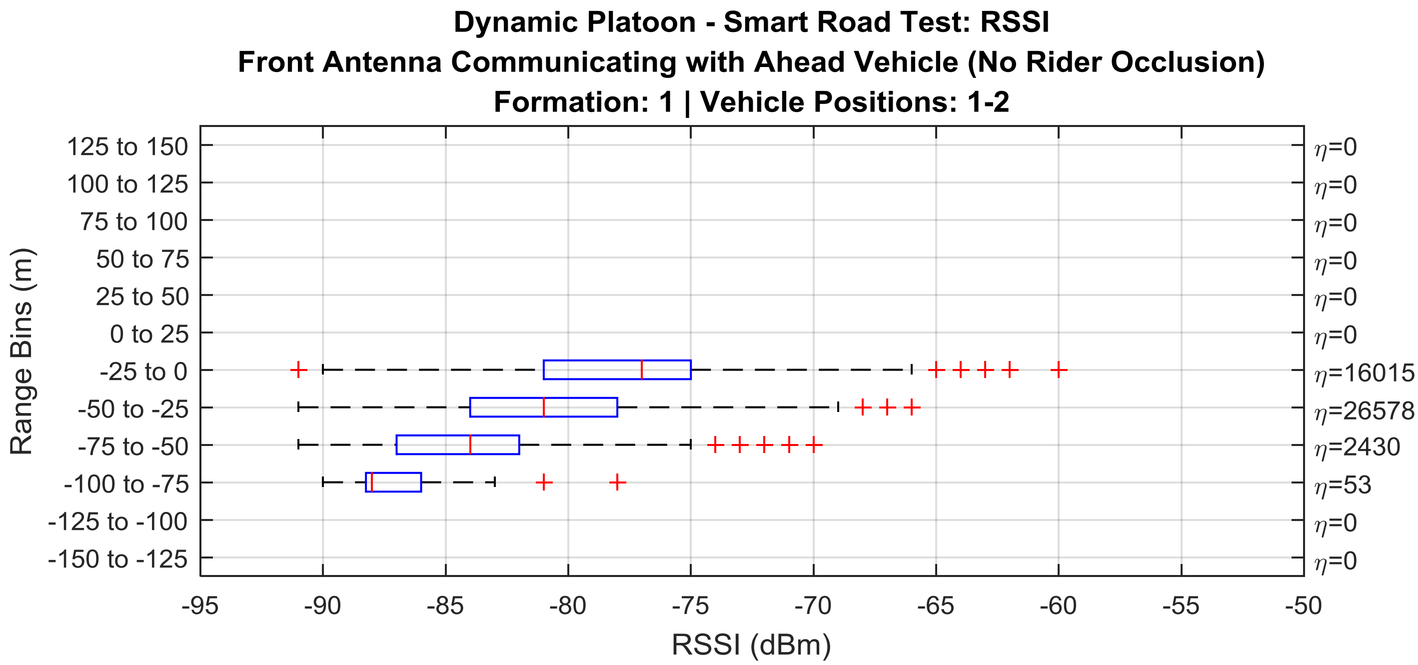
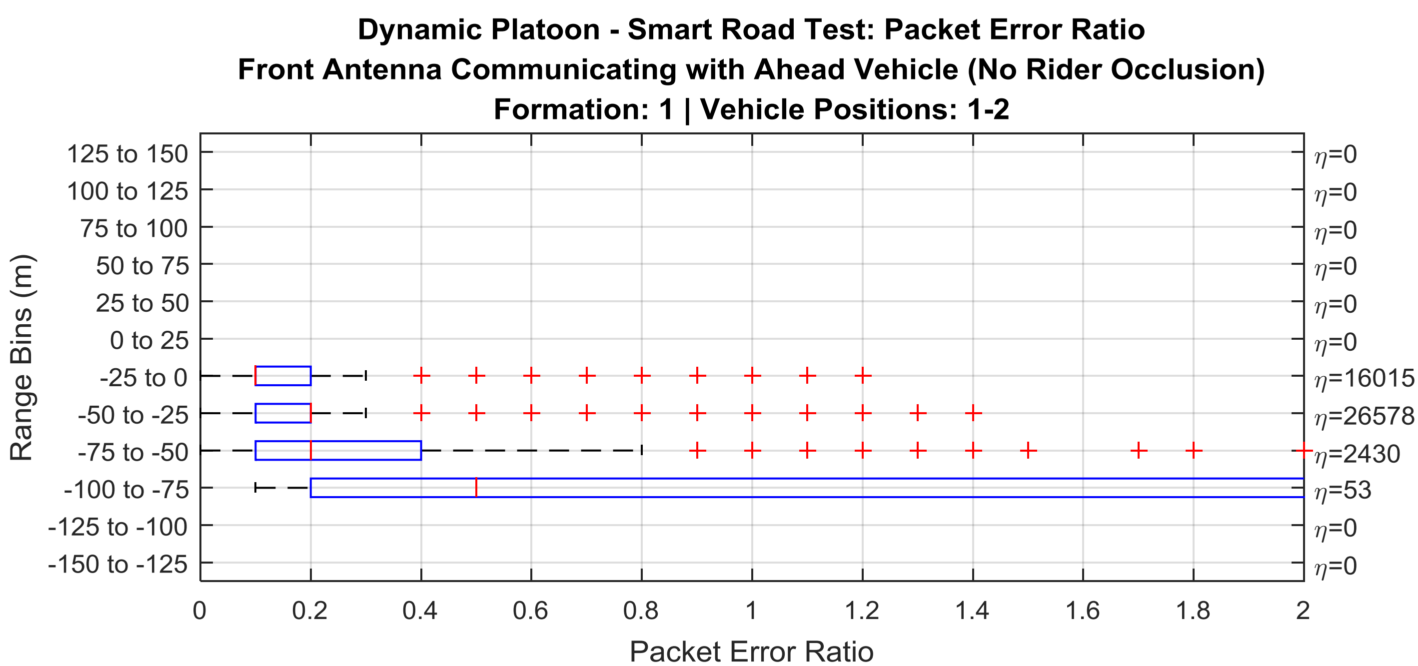
-60
-55
-50
RSSI (dBm)


Dynamic Platoon - Smart Road Test: Packet Error Ratio
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Formation: 2 | Vehicle Positions: 1-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=0
η=16221
η=21347
η=2360
η=124
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio



Dynamic Platoon - Smart Road Test: RSSI
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=0
η=16015
η=26578
η=2430
η=53
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)



Dynamic Platoon - Smart Road Test: Packet Error Ratio
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=0
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η=26578
η=2430
η=53
η=0
η=0
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0.4
0.6
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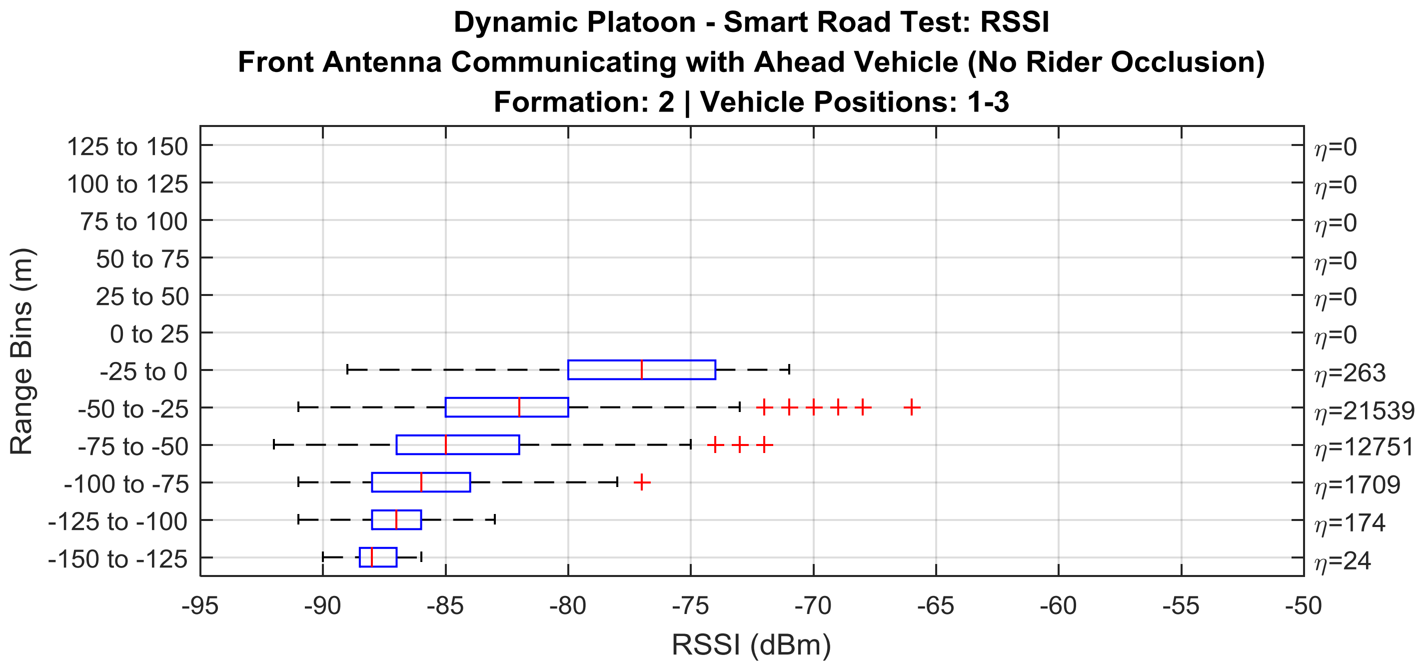
1.2
1.4
1.6
1.8
2
Packet Error Ratio


Dynamic Platoon - Smart Road Test: RSSI
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Formation: 2 | Vehicle Positions: 1-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
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η=0
η=0
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η=21539
η=12751
η=1709
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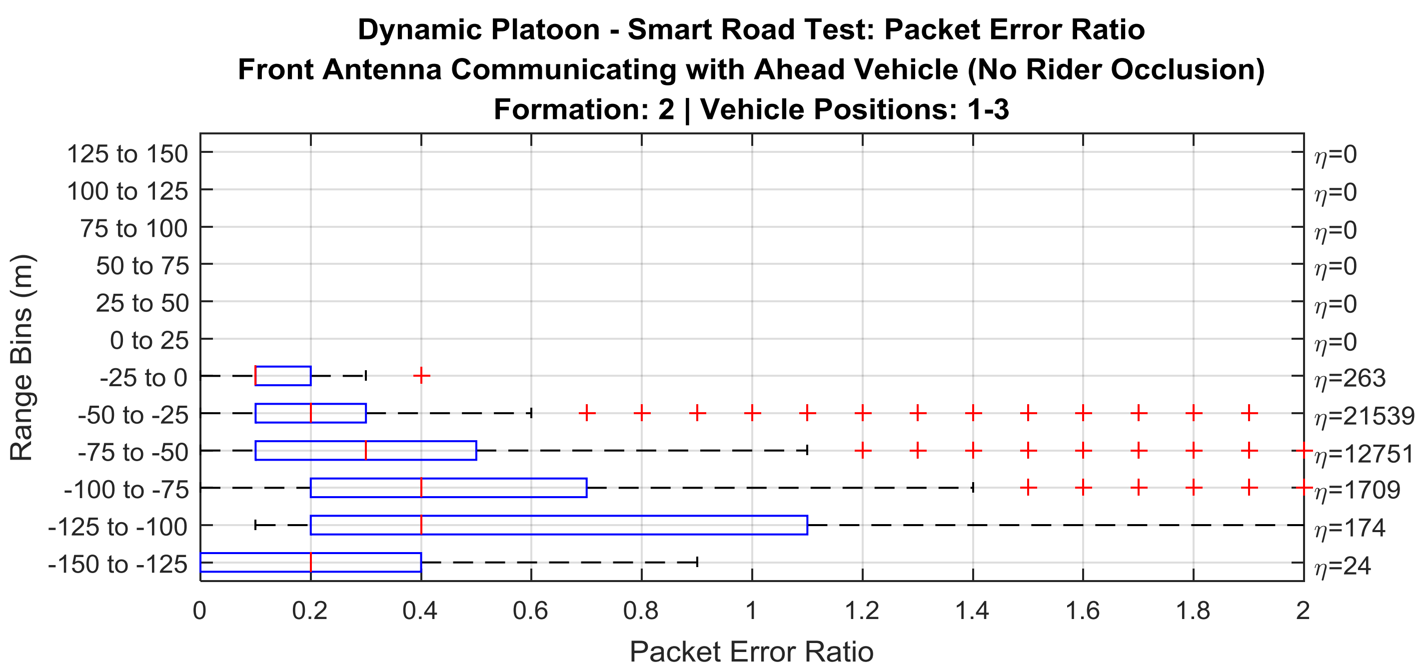
-75
-70
-65
-60
-55
-50
RSSI (dBm)


Dynamic Platoon - Smart Road Test: Packet Error Ratio
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Formation: 2 | Vehicle Positions: 1-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=0
η=263
η=21539
η=12751
η=1709
η=174
η=24
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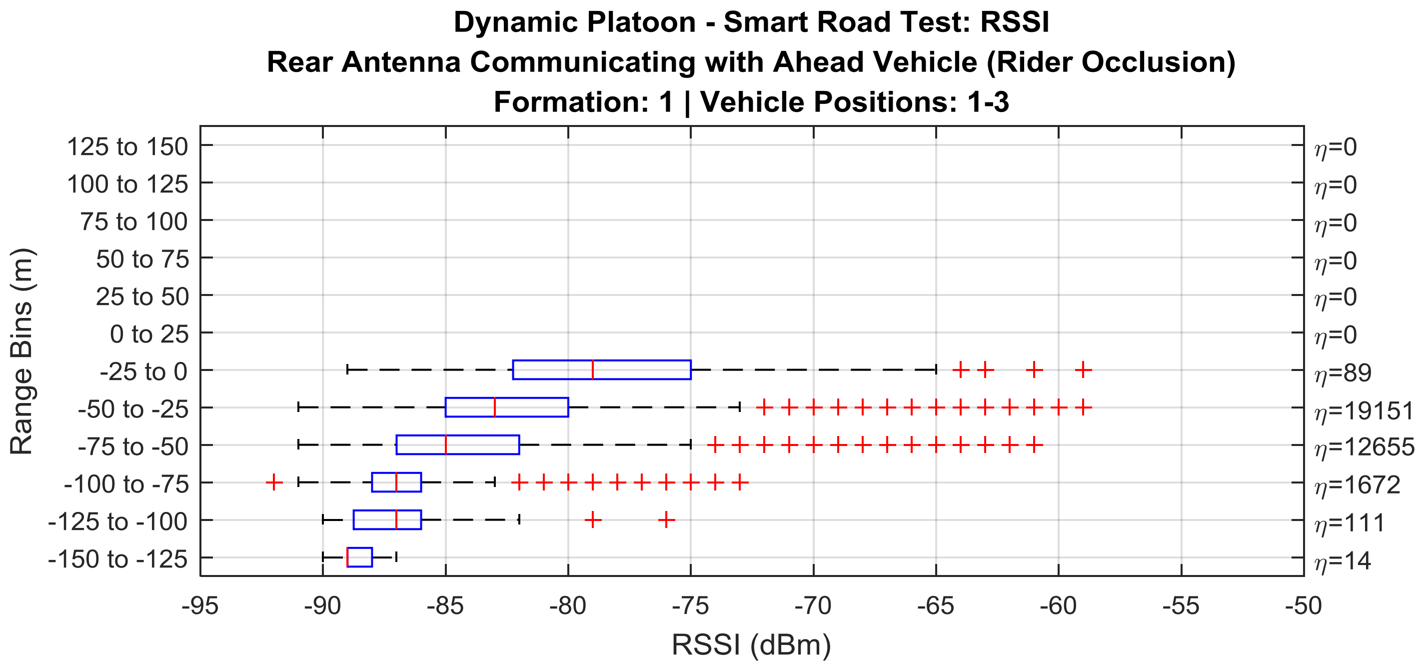
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio


Dynamic Platoon - Smart Road Test: RSSI
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
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η=0
η=0
η=0
η=0
η=0
η=89
η=19151
η=12655
η=1672
η=111
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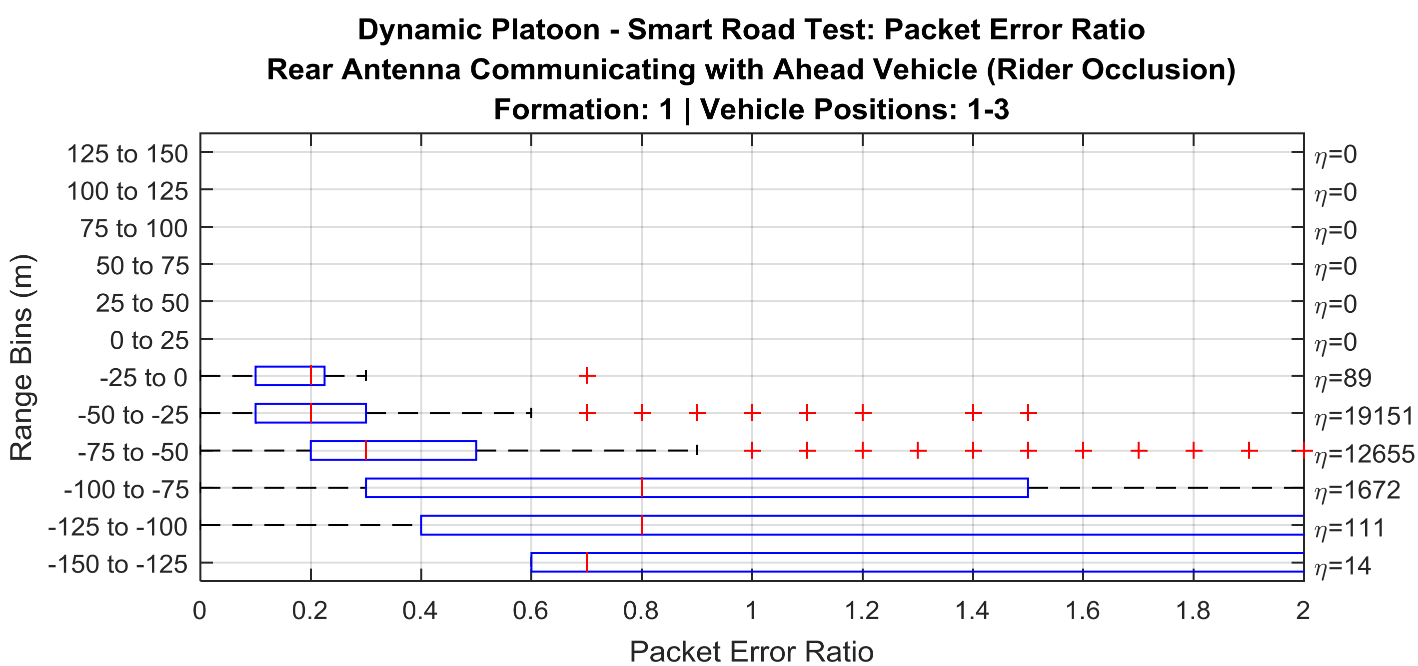
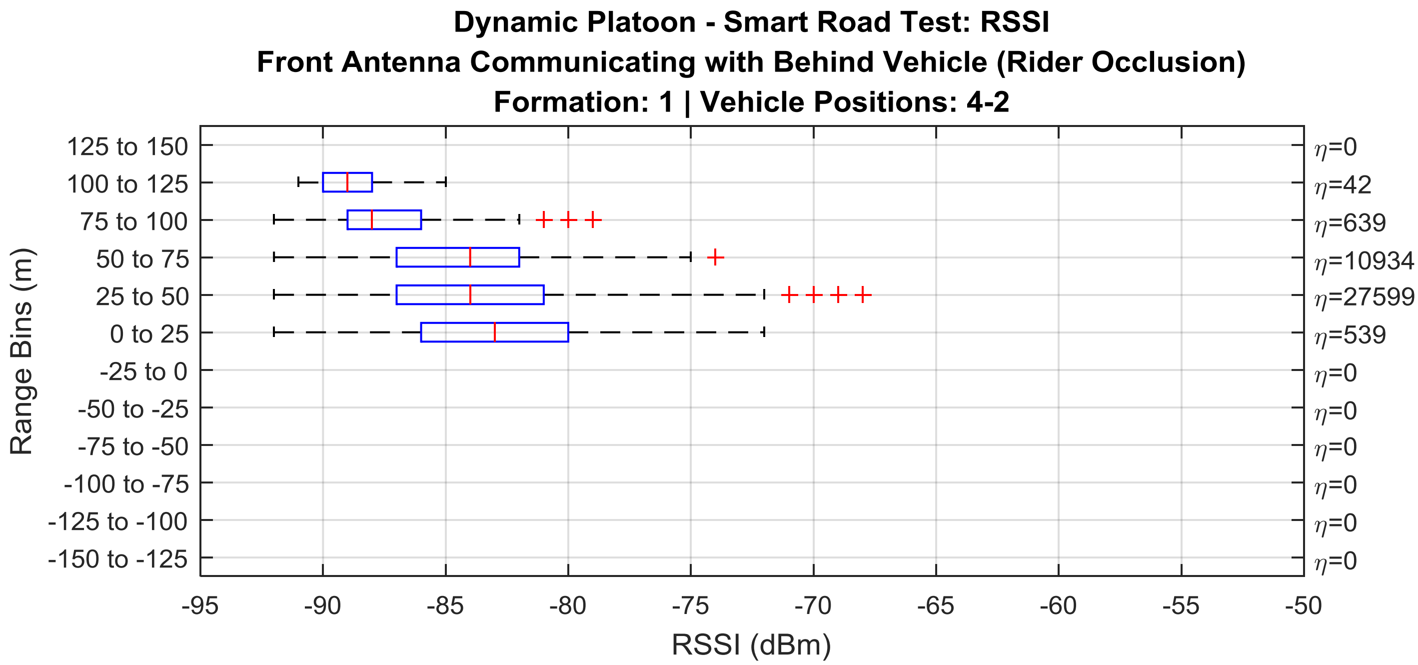
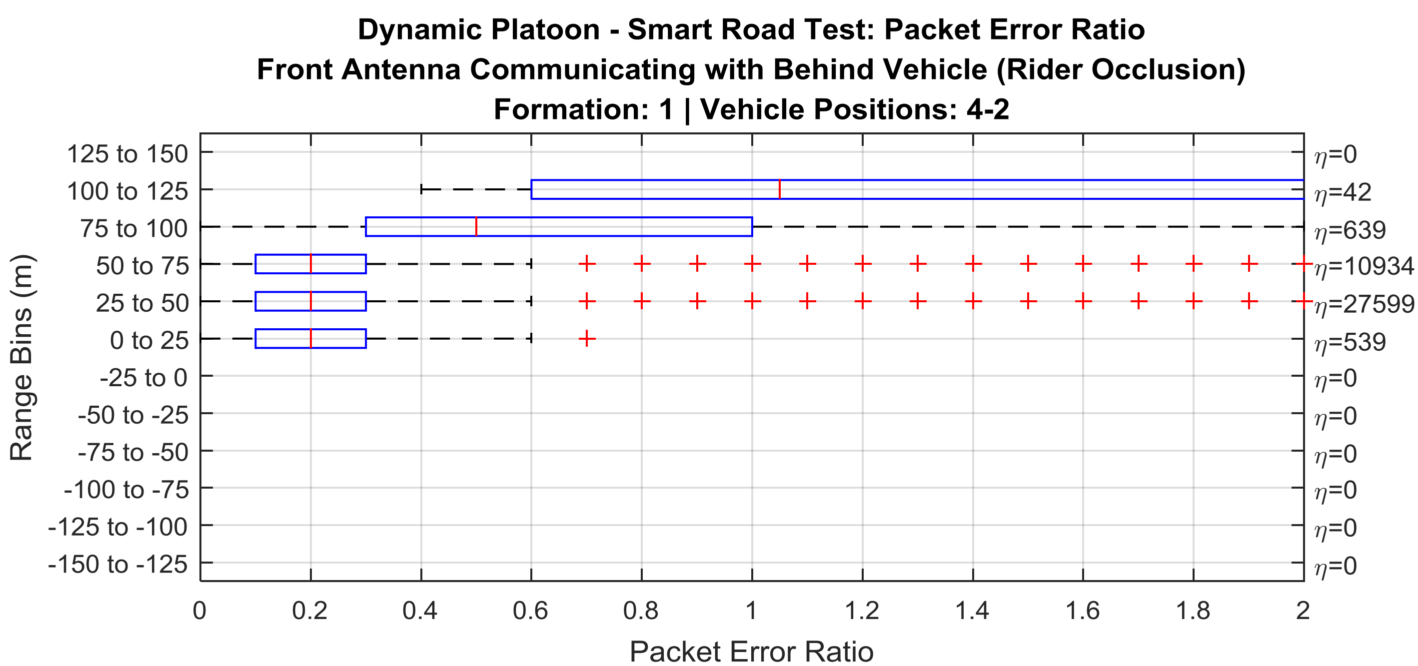
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)

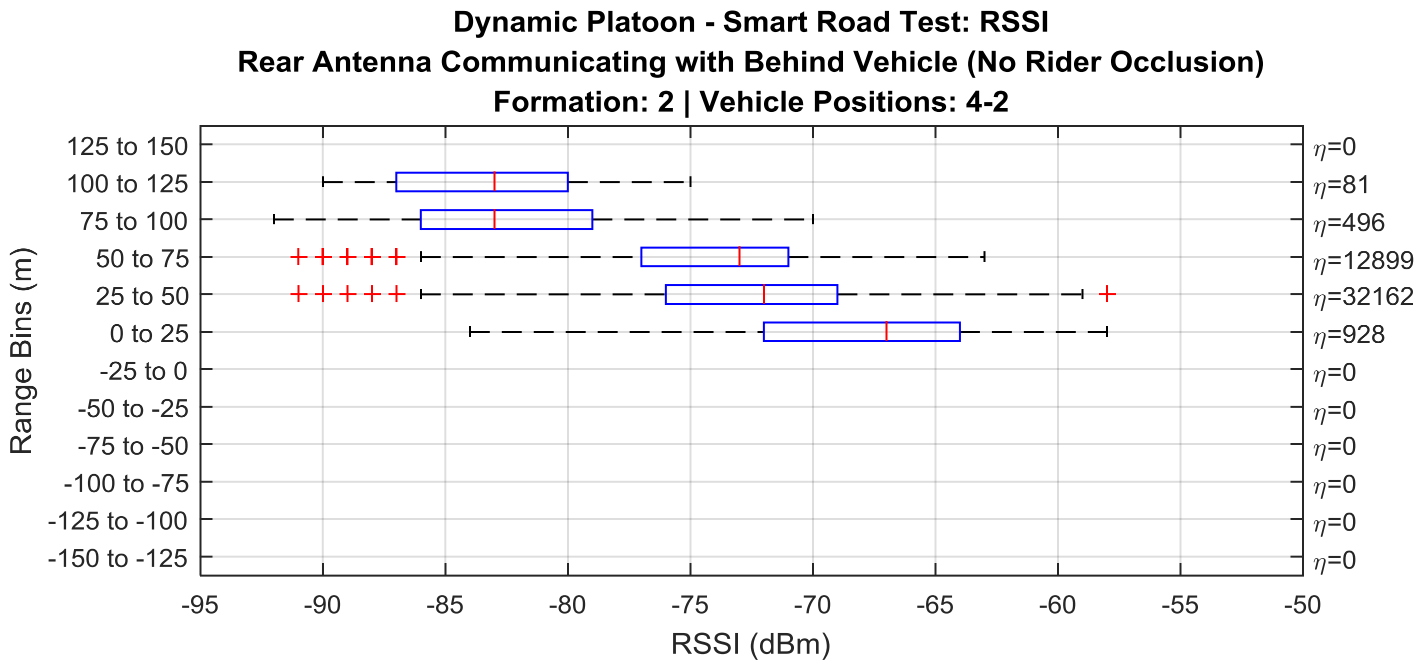

Dynamic Platoon - Smart Road Test: Packet Error Ratio
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=0
η=89
η=19151
η=12655
η=1672
η=111
η=14
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio

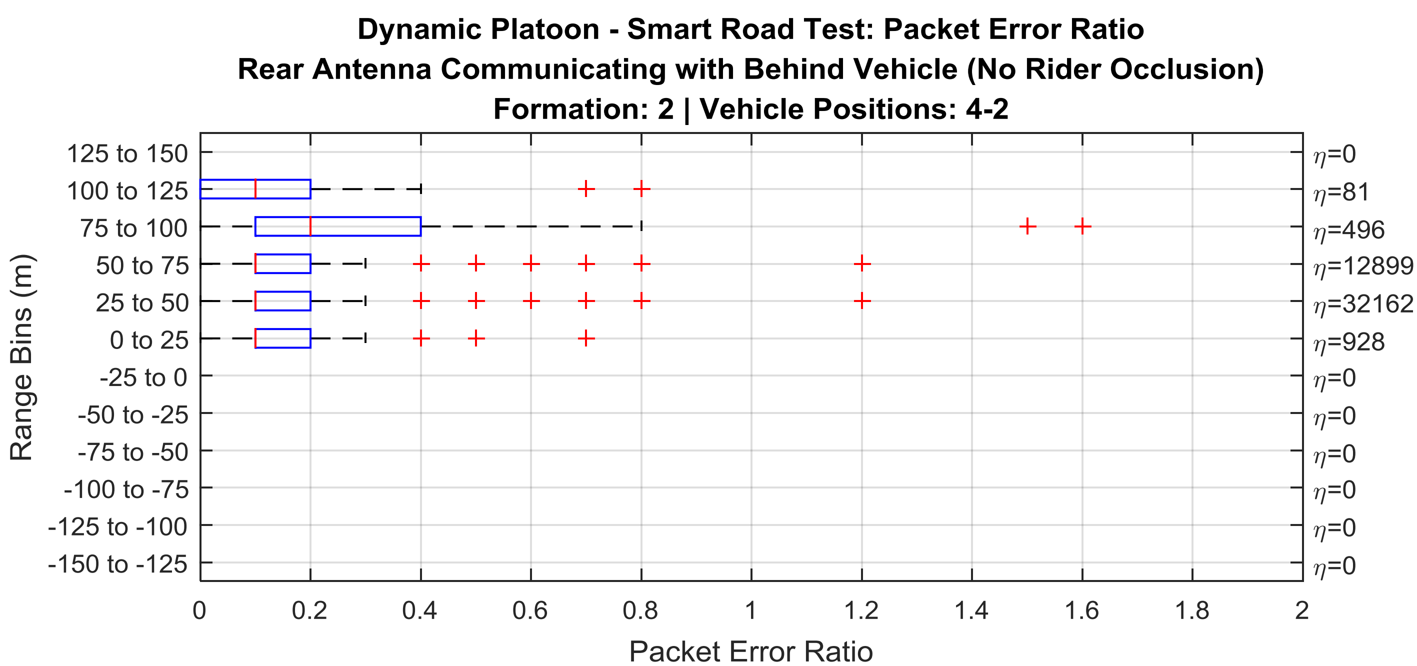


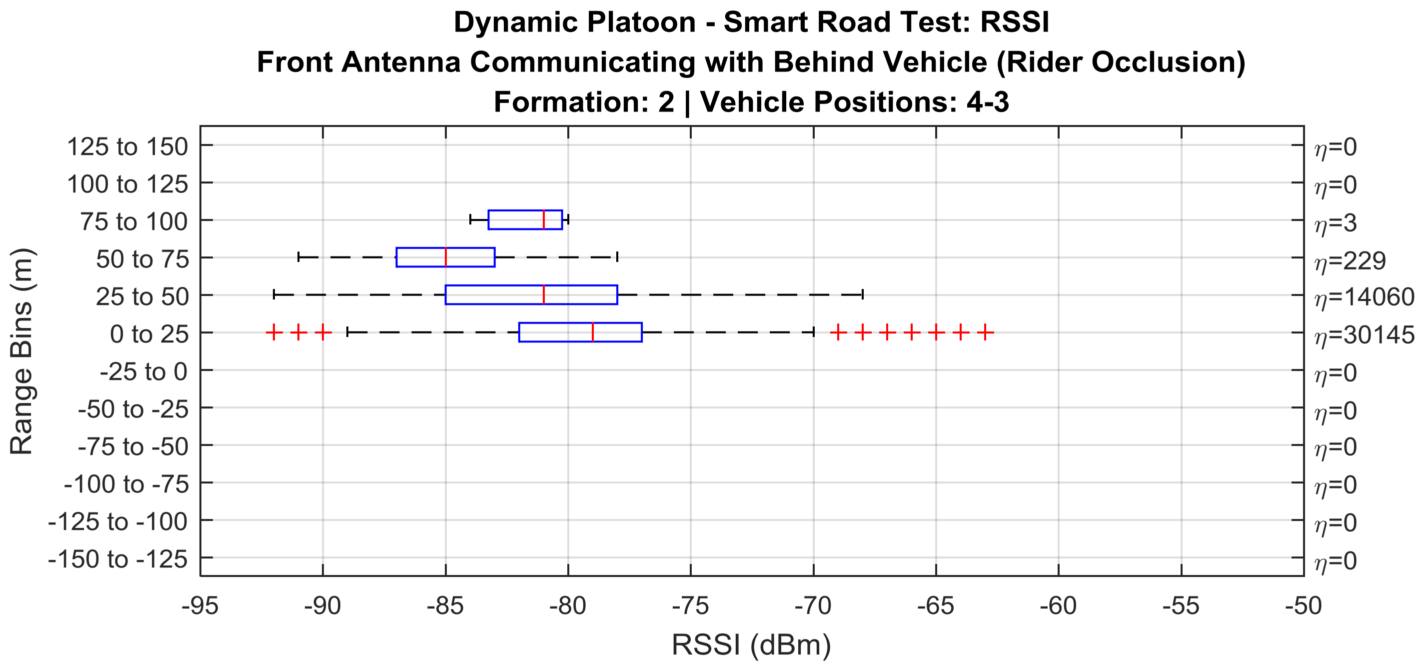
Dynamic Platoon - Smart Road Test: RSSI
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=42
η=639
η=10934
η=27599
η=539
η=0
η=0
η=0
η=0
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)



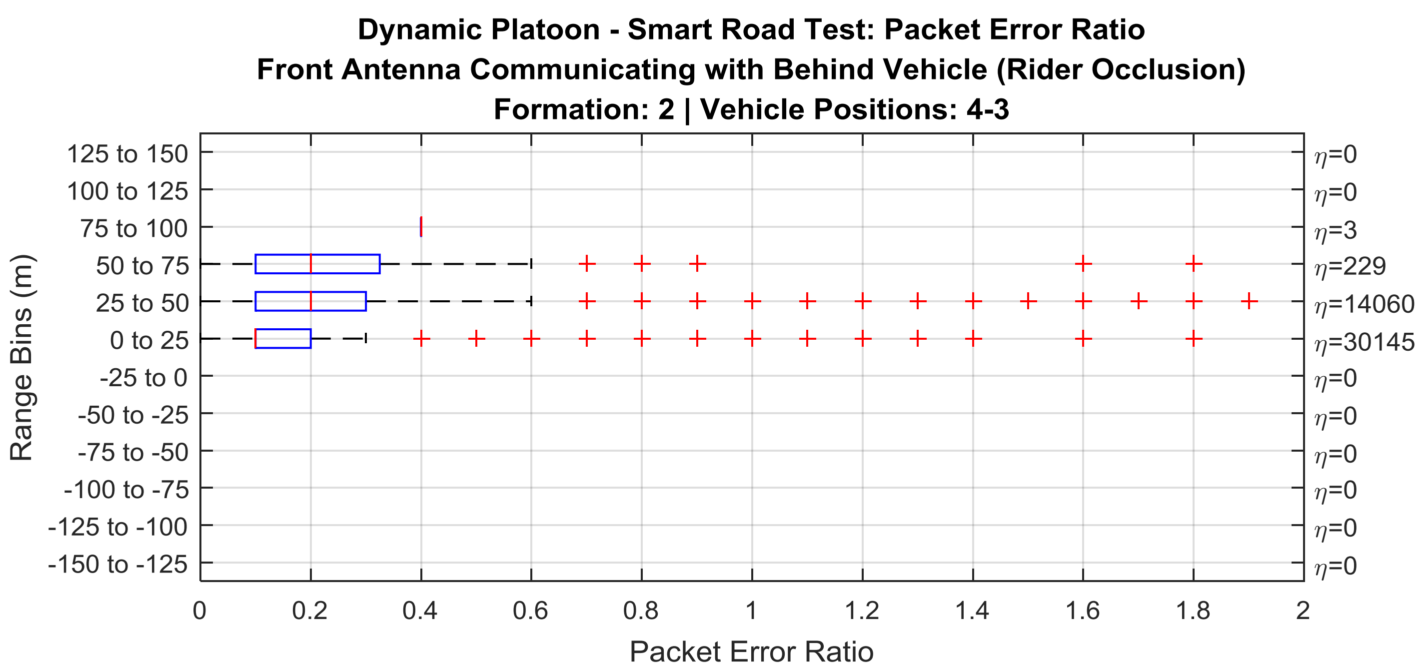
Dynamic Platoon - Smart Road Test: Packet Error Ratio
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=42
η=639
η=10934
η=27599
η=539
η=0
η=0
η=0
η=0
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio


Dynamic Platoon - Smart Road Test: RSSI
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Formation: 2 | Vehicle Positions: 4-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=81
η=496
η=12899
η=32162
η=928
η=0
η=0
η=0
η=0
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)

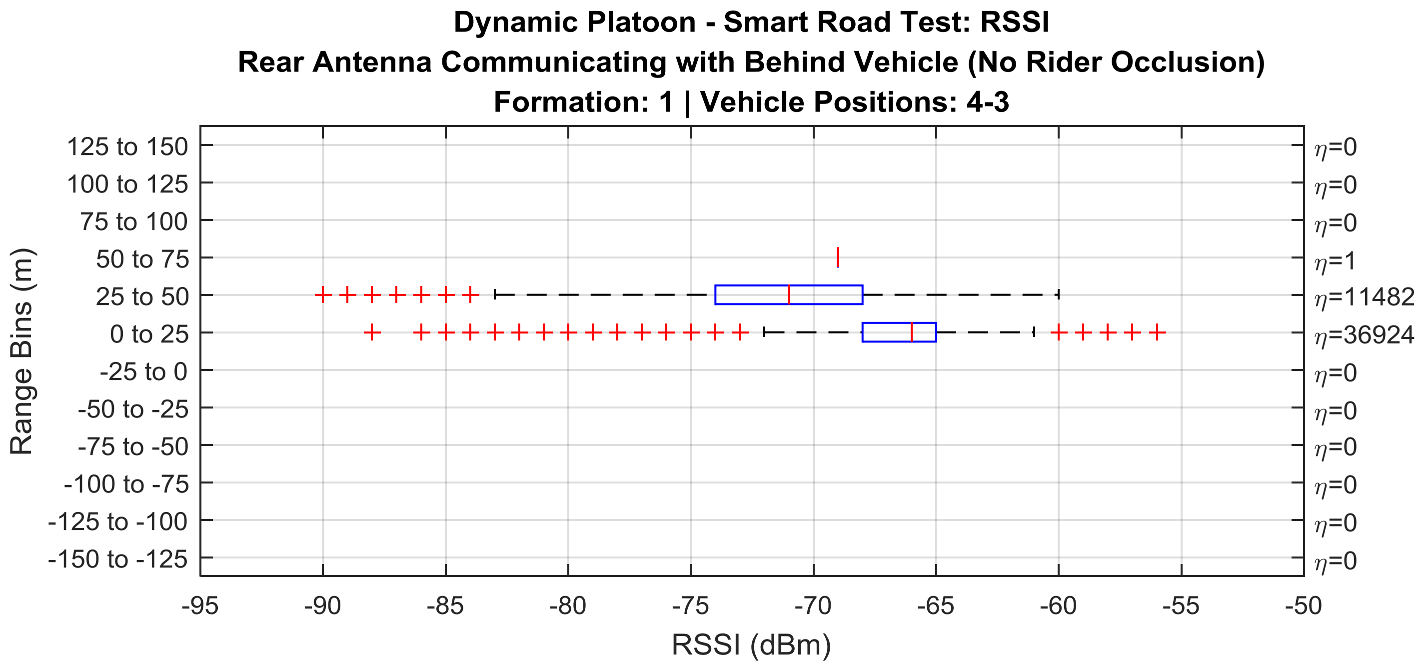

Dynamic Platoon - Smart Road Test: Packet Error Ratio
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Formation: 2 | Vehicle Positions: 4-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=81
η=496
η=12899
η=32162
η=928
η=0
η=0
η=0
η=0
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio

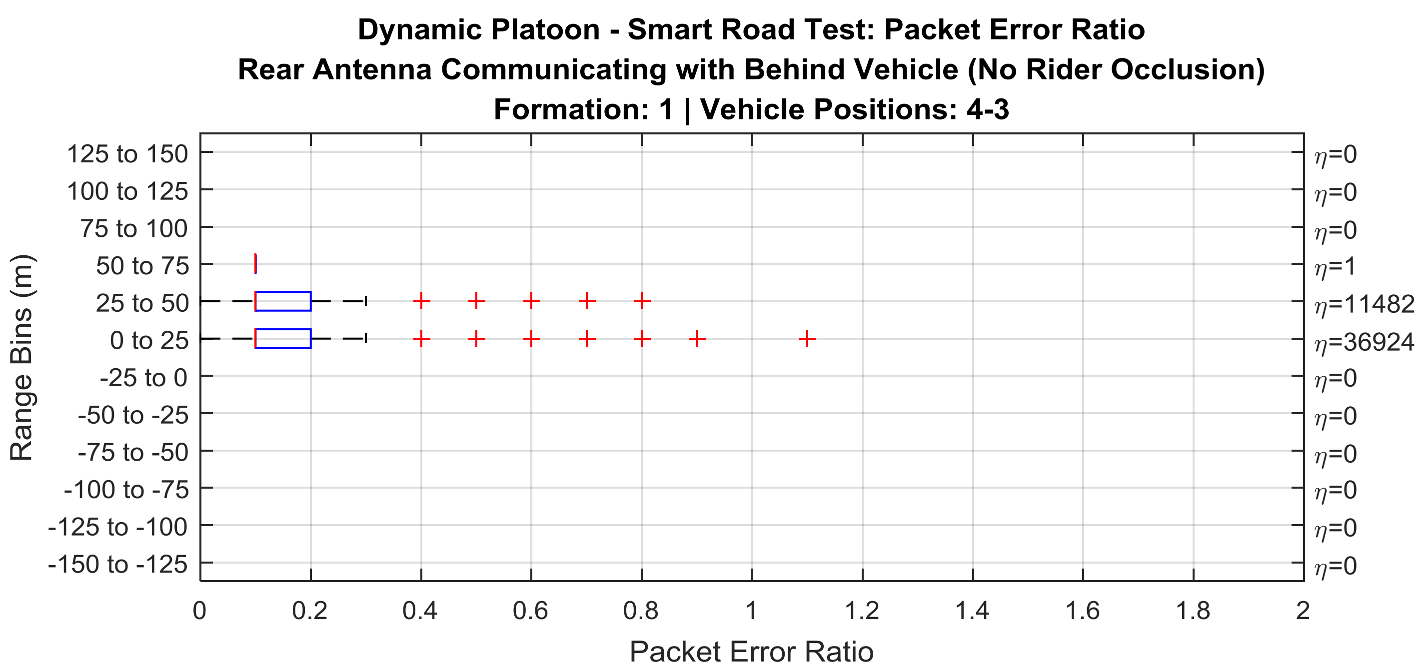


Dynamic Platoon - Smart Road Test: RSSI
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Formation: 2 | Vehicle Positions: 4-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=3
η=229
η=14060
η=30145
η=0
η=0
η=0
η=0
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)



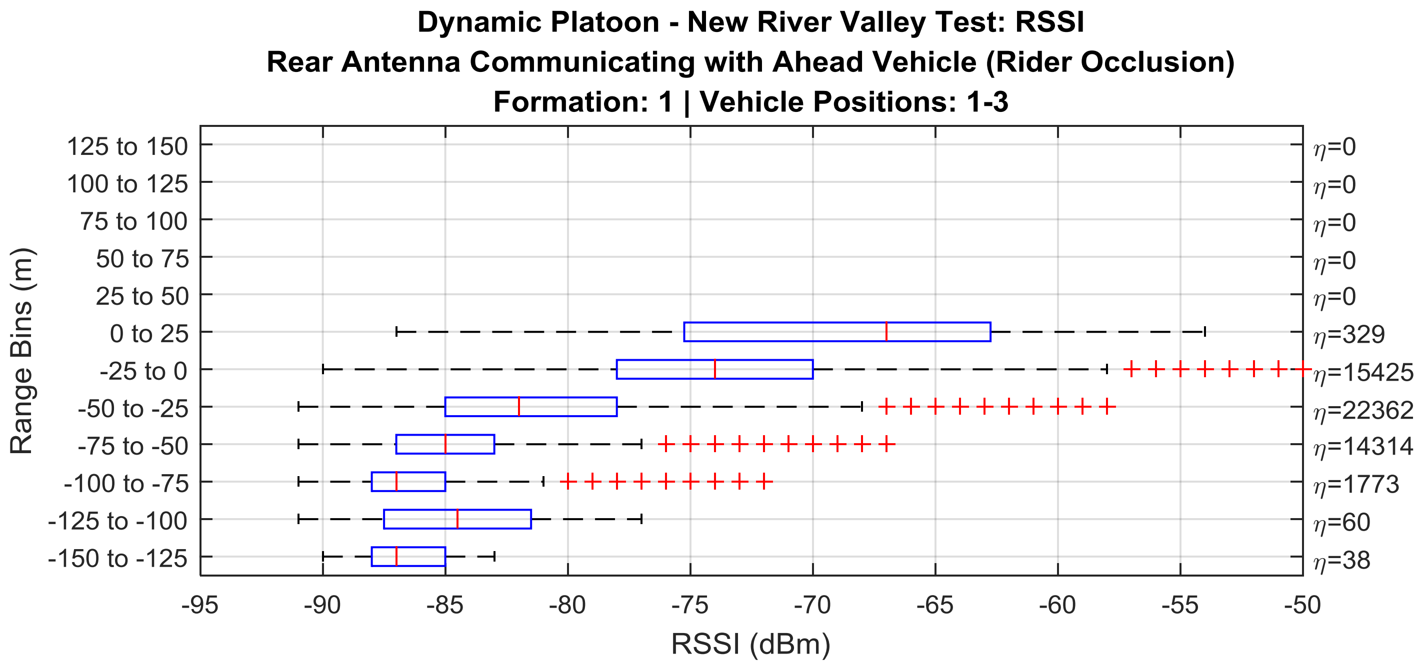
Dynamic Platoon - Smart Road Test: Packet Error Ratio
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Formation: 2 | Vehicle Positions: 4-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=3
η=229
η=14060
η=30145
η=0
η=0
η=0
η=0
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio

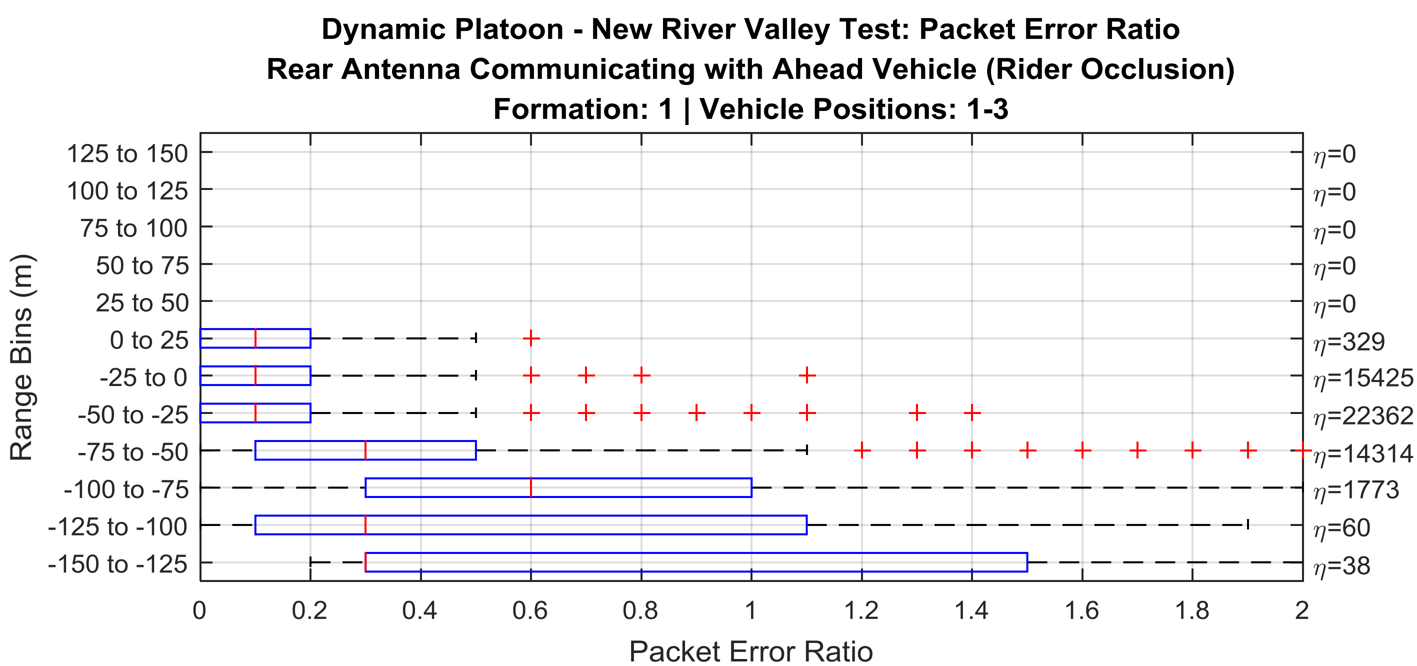

Dynamic Platoon - Smart Road Test: RSSI
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=1
η=11482
η=36924
η=0
η=0
η=0
η=0
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)

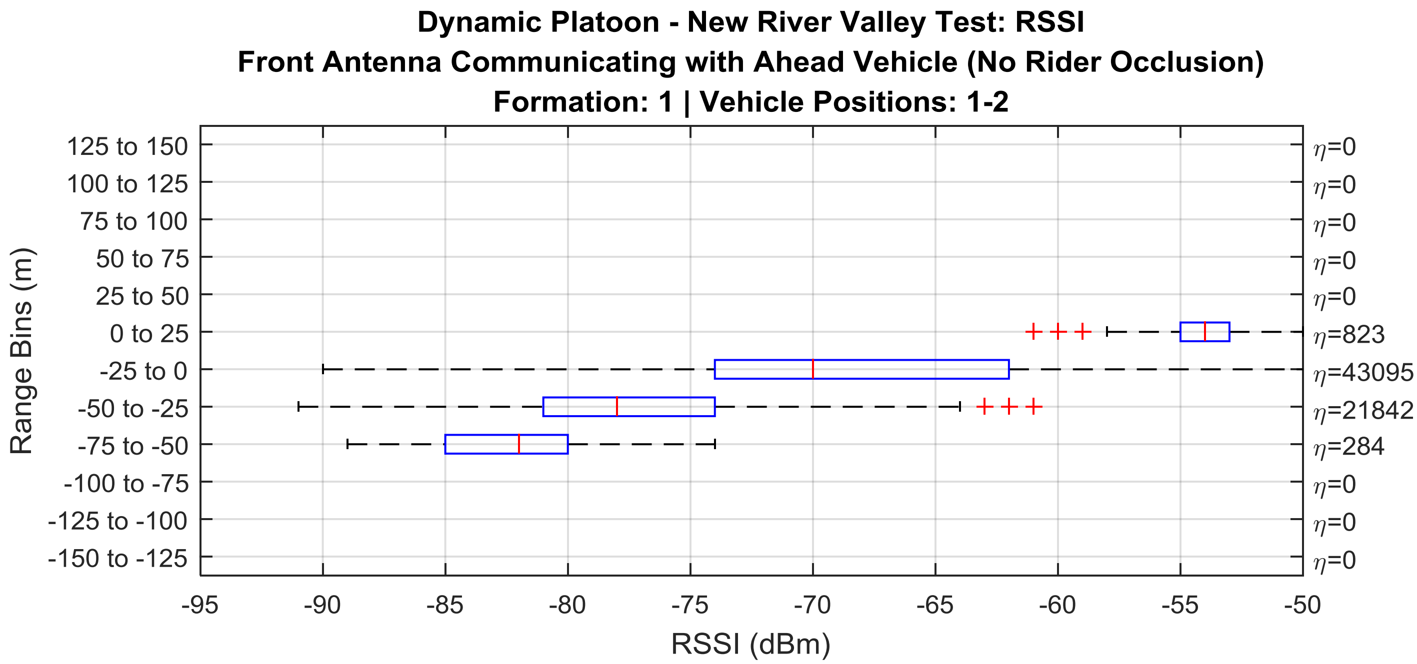

Dynamic Platoon - Smart Road Test: Packet Error Ratio
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=1
η=11482
η=36924
η=0
η=0
η=0
η=0
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio

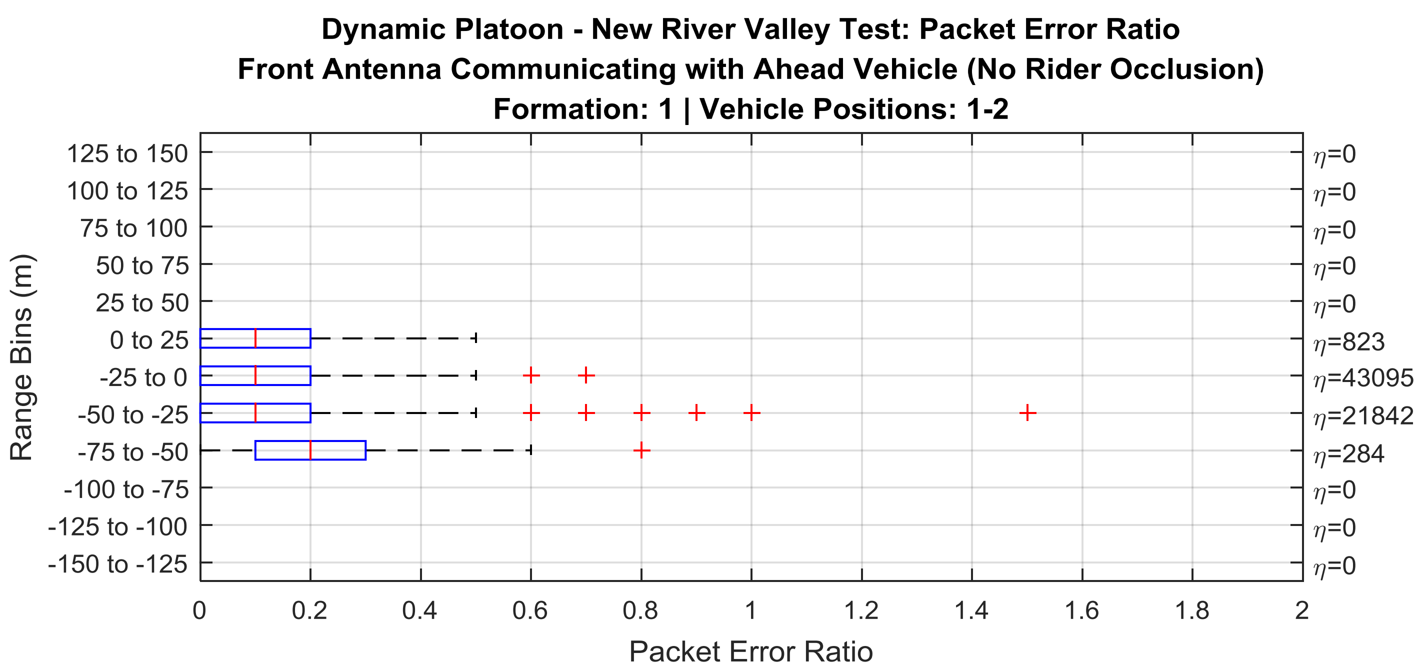
Appendix C – Dynamic Platoon – New River Valley

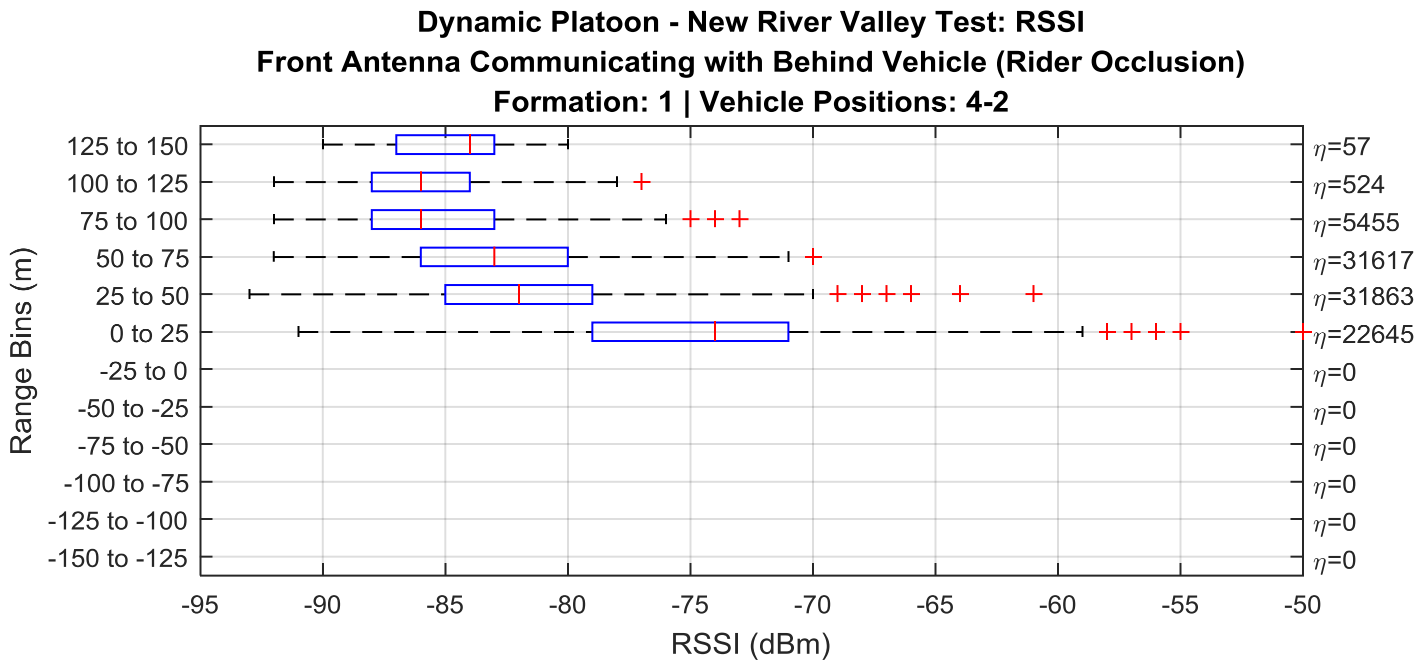
Communication Plots


Dynamic Platoon - New River Valley Test: RSSI
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=329
η=15425
η=22362
η=14314
η=1773
η=60
η=38
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)

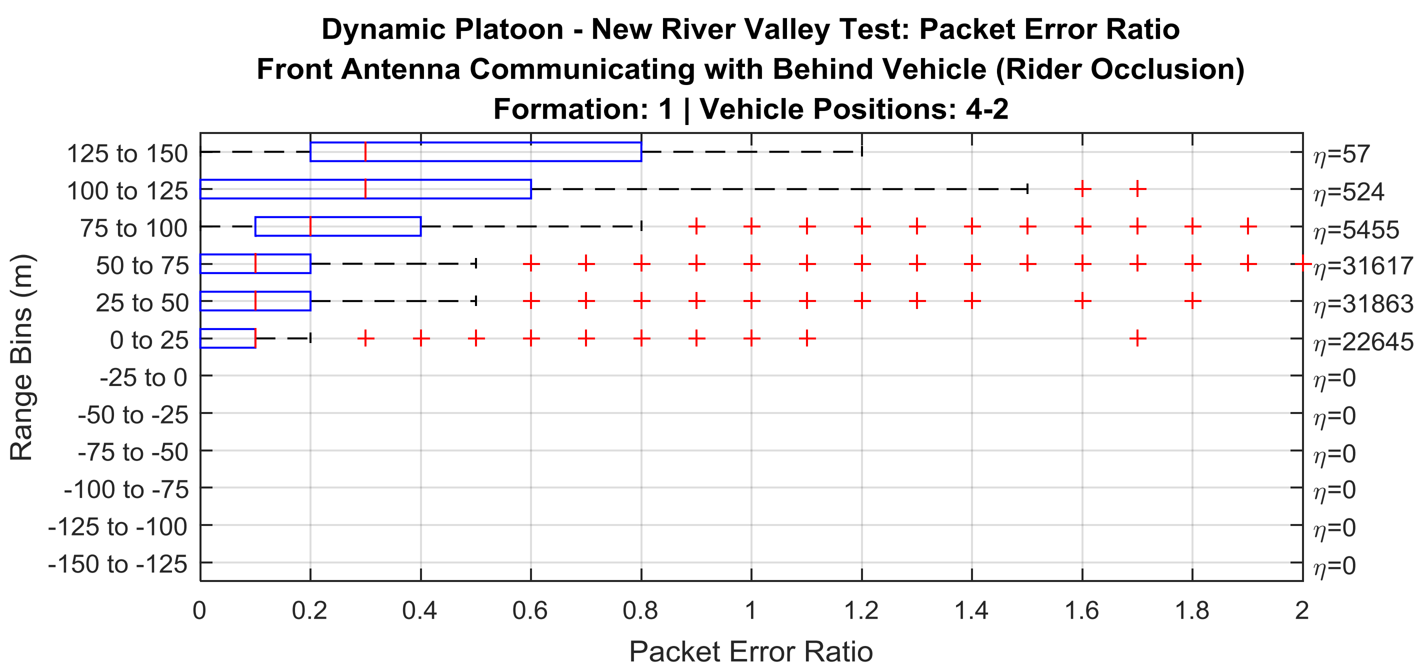

Dynamic Platoon - New River Valley Test: Packet Error Ratio
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-3
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=329
η=15425
η=22362
η=14314
η=1773
η=60
η=38
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio


Dynamic Platoon - New River Valley Test: RSSI
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=823
η=43095
η=21842
η=284
η=0
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)

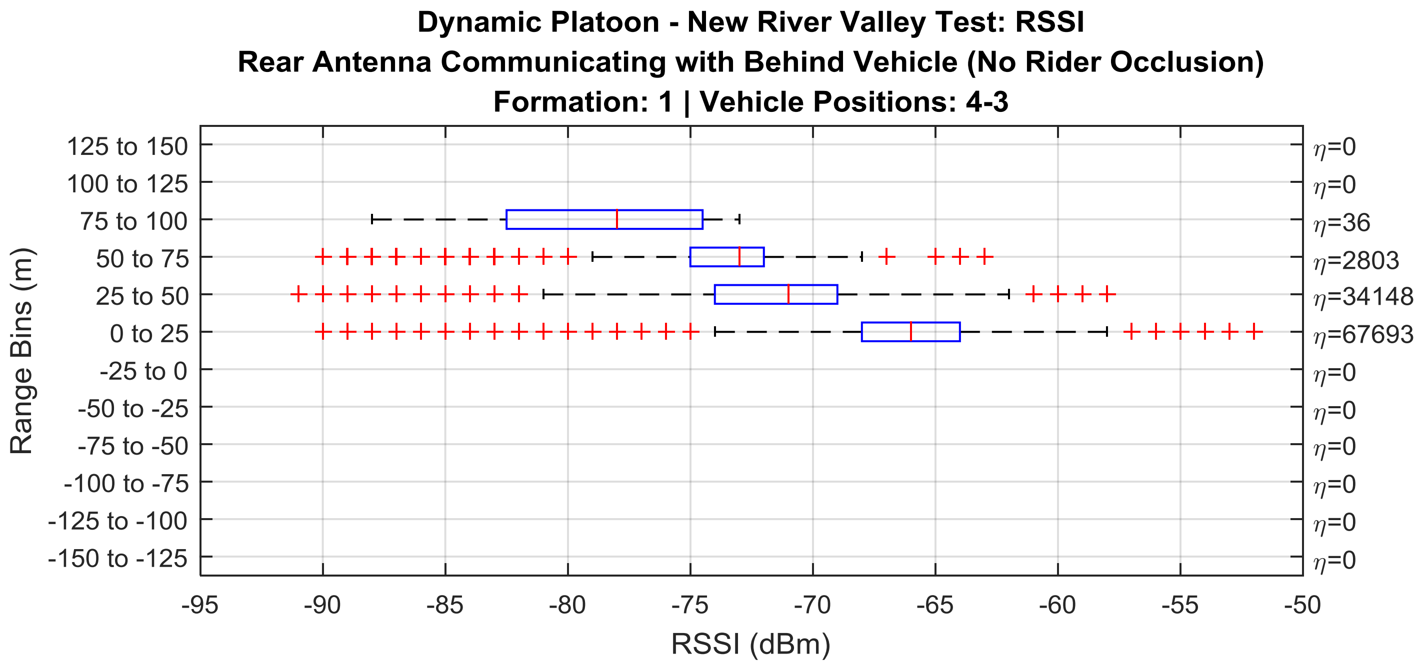

Dynamic Platoon - New River Valley Test: Packet Error Ratio
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 1-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=0
η=0
η=0
η=0
η=0
η=823
η=43095
η=21842
η=284
η=0
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio

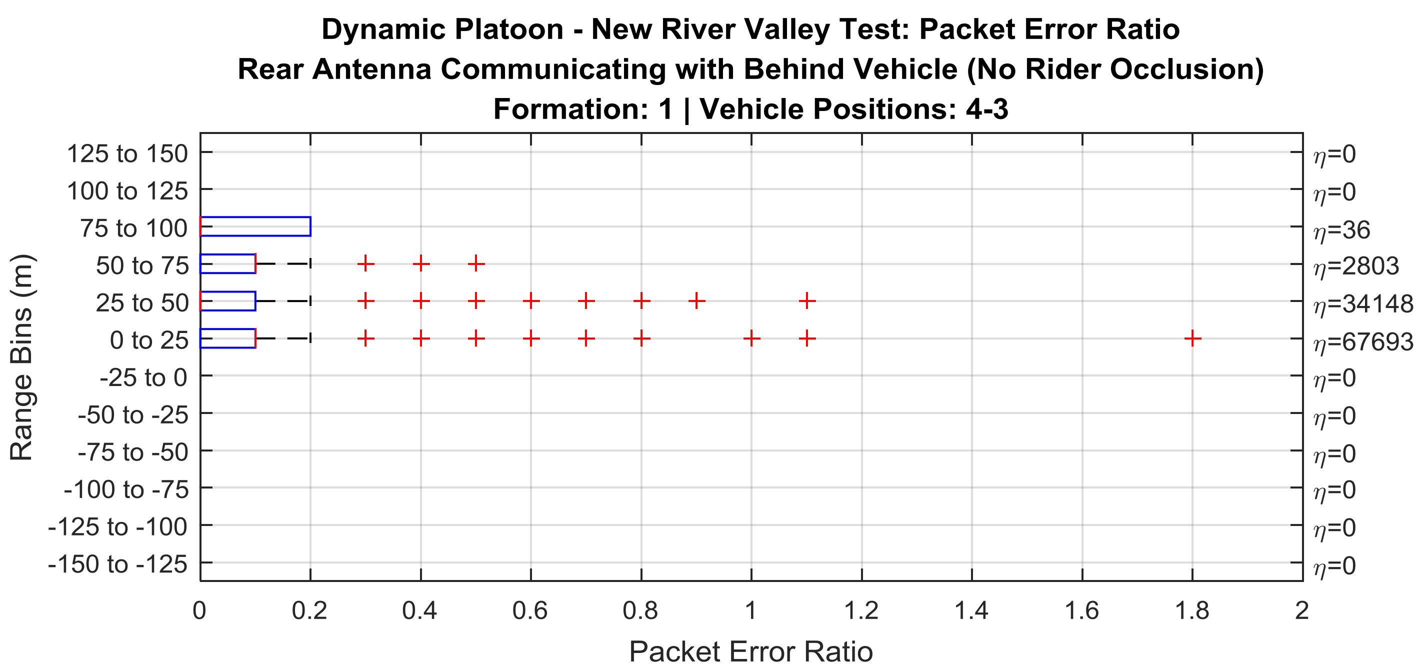


Dynamic Platoon - New River Valley Test: RSSI
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=57
η=524
η=5455
η=31617
η=31863
η=22645
η=0
η=0
η=0
η=0
η=0
η=0
-95 -90 -85 -80 -75 -70 -65 -60 -55 -50
RSSI (dBm)

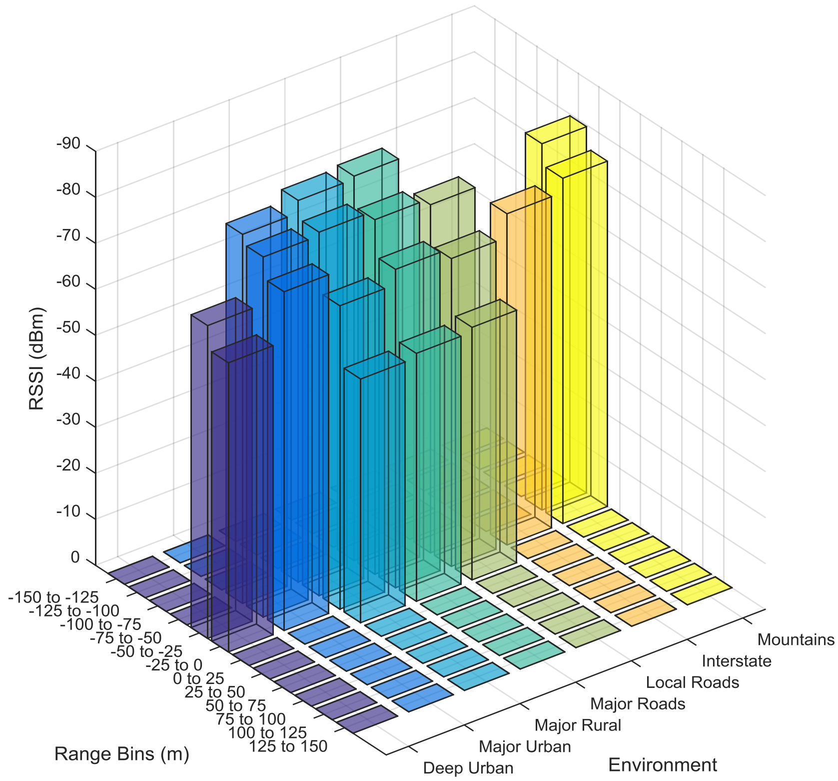


Dynamic Platoon - New River Valley Test: Packet Error Ratio
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-2
Range Bins (m)
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
η=57
η=524
η=5455
η=31617
η=31863
η=22645
η=0
η=0
η=0
η=0
η=0
η=0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Packet Error Ratio

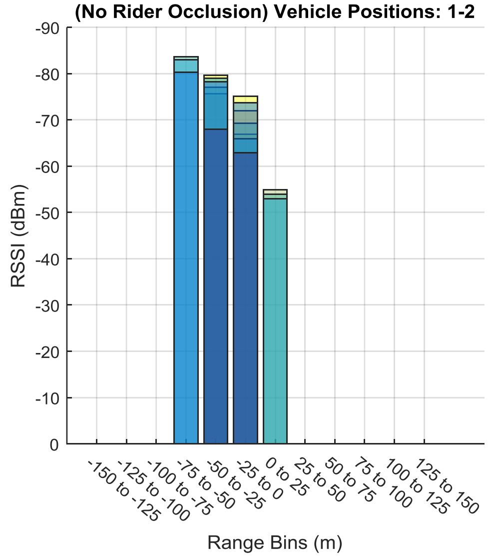

Dynamic Platoon - New River Valley Test: RSSI
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-3
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
Range Bins (m)
η=0
η=0
η=36
η=2803
η=34148
η=67693
η=0
η=0
η=0
η=0
η=0
η=0
-95
-90
-85
-80
-75
-70
-65
-60
-55
-50
RSSI (dBm)


Dynamic Platoon - New River Valley Test: Packet Error Ratio
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Formation: 1 | Vehicle Positions: 4-3
125 to 150
100 to 125
75 to 100
50 to 75
25 to 50
0 to 25
-25 to 0
-50 to -25
-75 to -50
-100 to -75
-125 to -100
-150 to -125
Range Bins (m)
η=0
η=0
η=36
η=2803
η=34148
η=67693
η=0
η=0
η=0
η=0
η=0
η=0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Packet Error Ratio

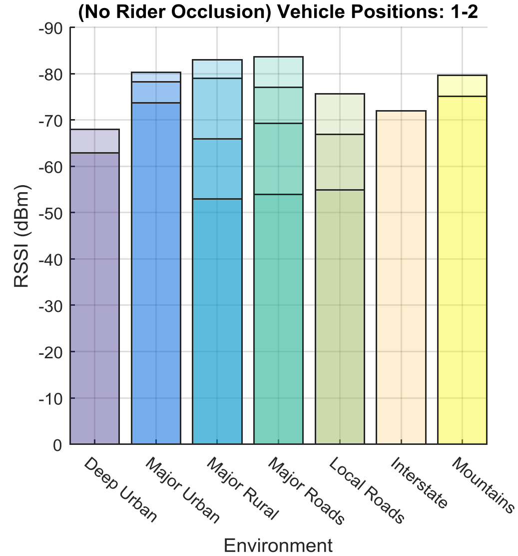
New River Valley Test: RSSI (dBm)
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Vehicle Positions: 1-2

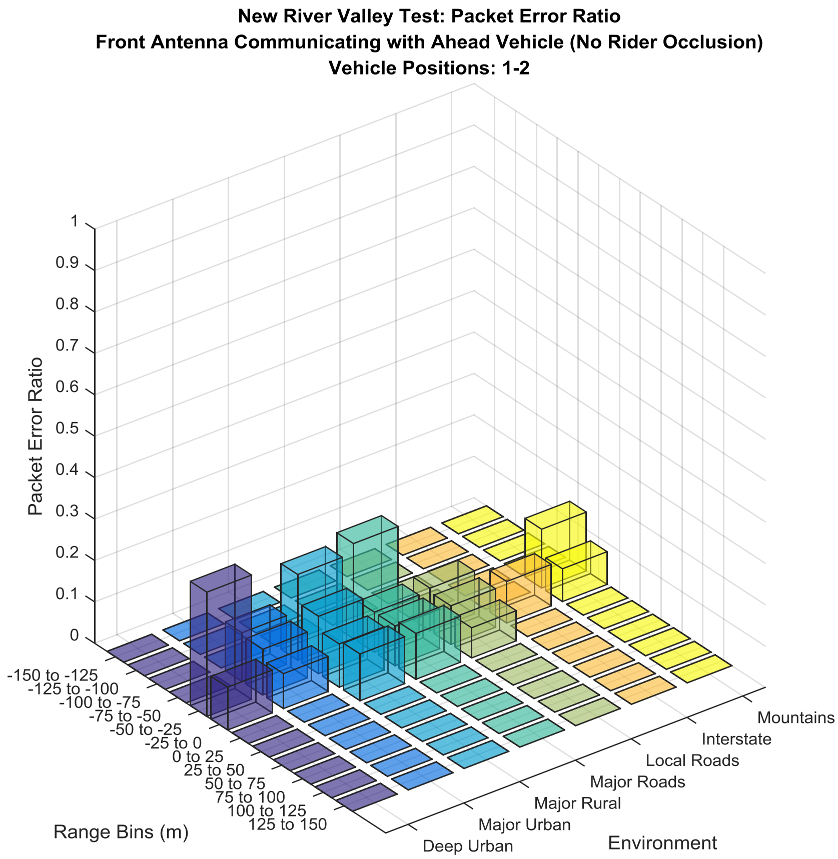


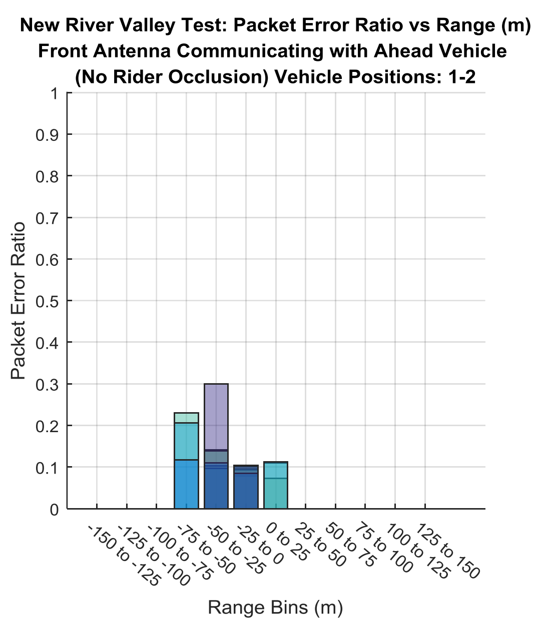
New River Valley Test: RSSI (dBm) vs Range (m)
Front Antenna Communicating with Ahead Vehicle
(No Rider Occlusion) Vehicle Positions: 1-2

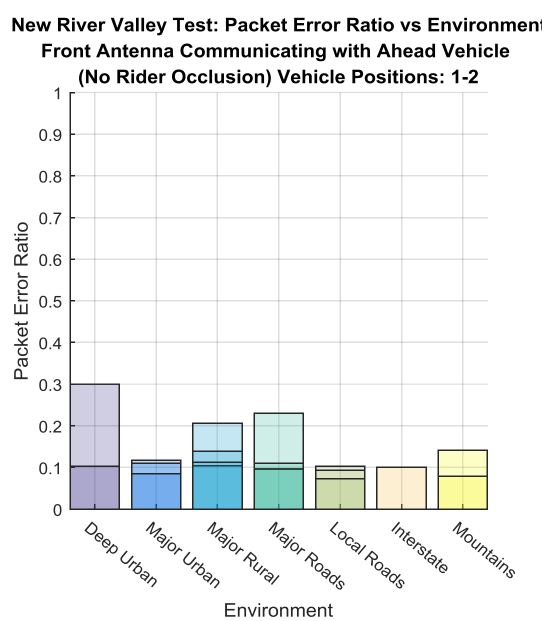


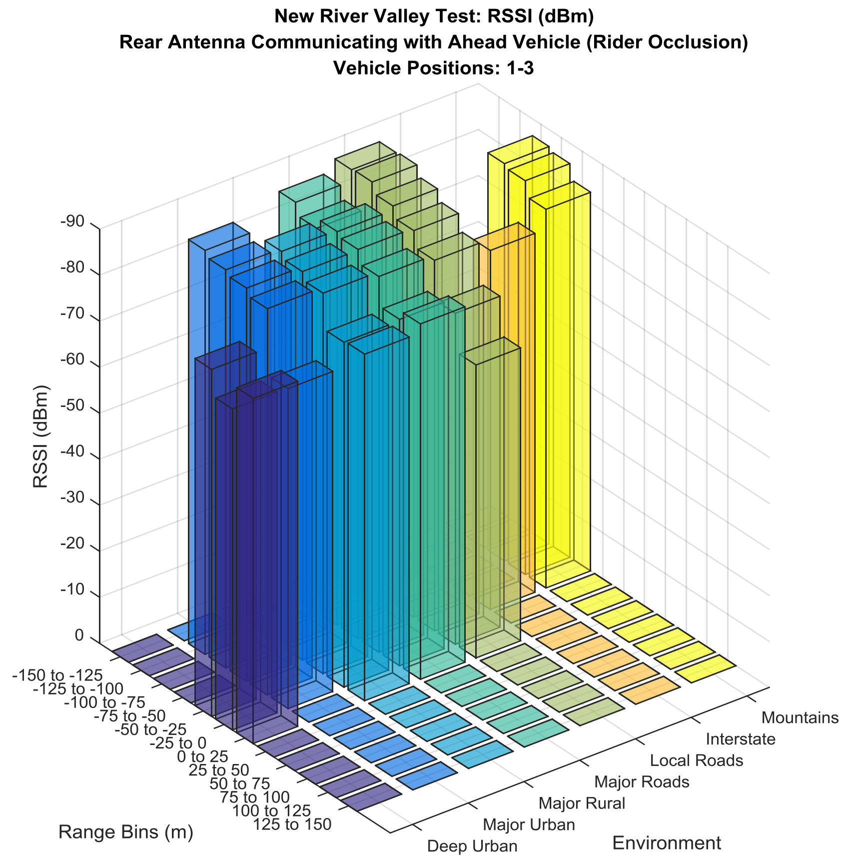
New River Valley Test: RSSI (dBm) vs Environment
Front Antenna Communicating with Ahead Vehicle
(No Rider Occlusion) Vehicle Positions: 1-2

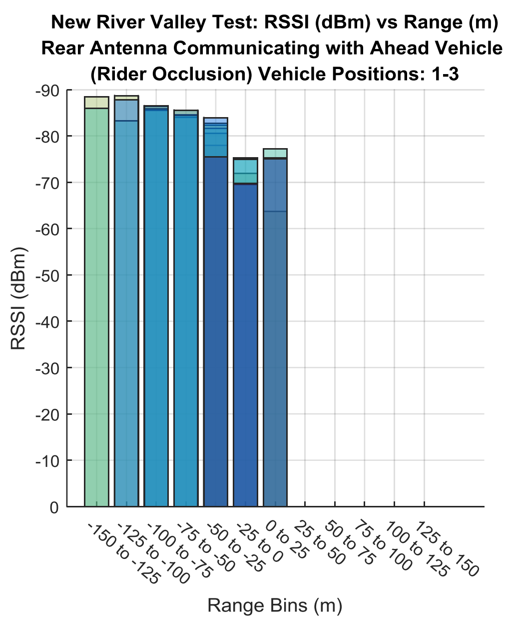


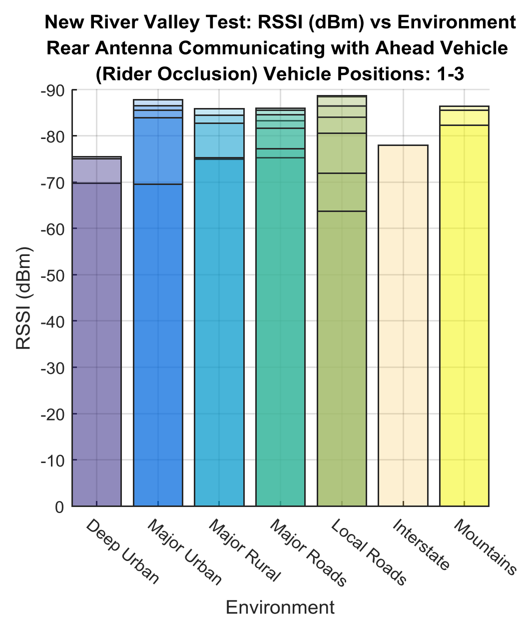

New River Valley Test: Packet Error Ratio
Front Antenna Communicating with Ahead Vehicle (No Rider Occlusion)
Vehicle Positions: 1-2
Packet Error Ratio
Range Bins (m)
Environment
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains


New River Valley Test: Packet Error Ratio vs Range (m)
Front Antenna Communicating with Ahead Vehicle
(No Rider Occlusion) Vehicle Positions: 1-2
Packet Error Ratio
Range Bins (m)

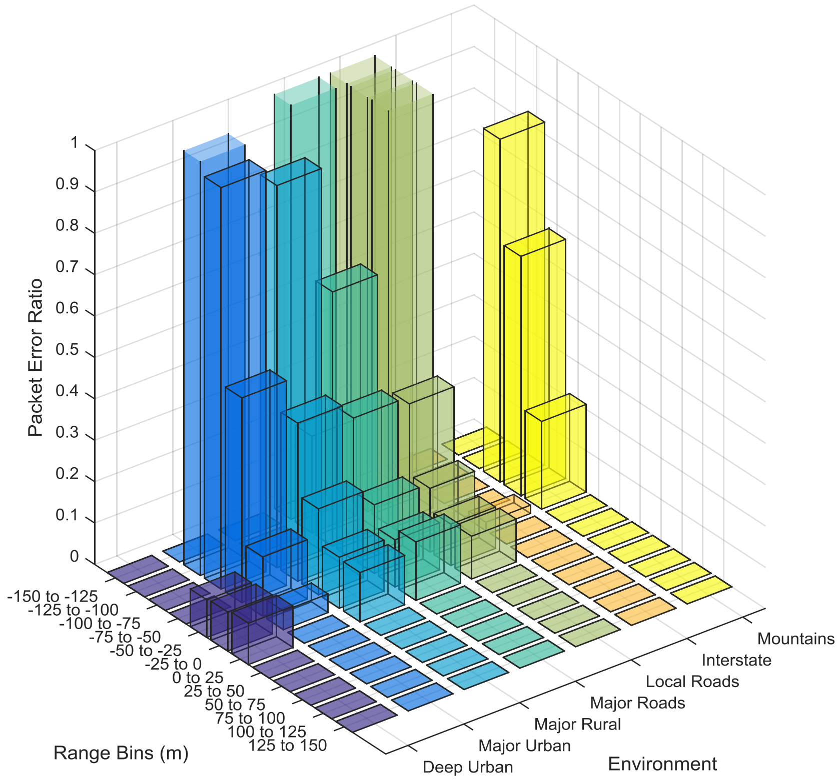

New River Valley Test: Packet Error Ratio vs Environment
Front Antenna Communicating with Ahead Vehicle
(No Rider Occlusion) Vehicle Positions: 1-2
Packet Error Ratio
Environment
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains


New River Valley Test: RSSI (dBm)
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Vehicle Positions: 1-3
RSSI (dBm)
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
-150 to -125
-125 to -100
-100 to -75
-75 to -50
-50 to -25
-25 to 0
0 to 25
25 to 50
50 to 75
75 to 100
100 to 125
125 to 150
Range Bins (m)
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains
Environment

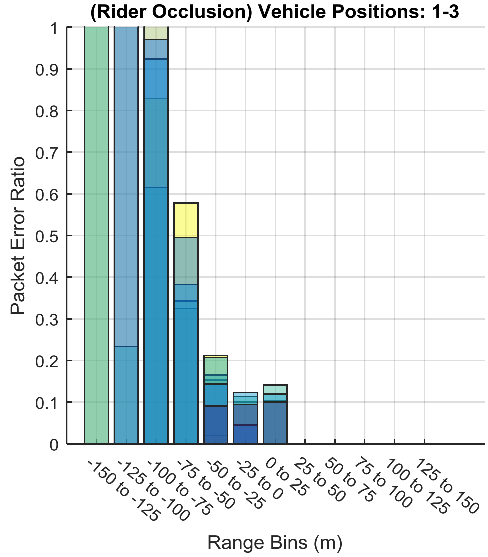

New River Valley Test: RSSI (dBm) vs Range (m)
Rear Antenna Communicating with Ahead Vehicle
(Rider Occlusion) Vehicle Positions: 1-3
RSSI (dBm)
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
-150 to -125
-125 to -100
-100 to -75
-75 to -50
-50 to -25
-25 to 0
0 to 25
25 to 50
50 to 75
75 to 100
100 to 125
125 to 150
Range Bins (m)


New River Valley Test: RSSI (dBm) vs Environment
Rear Antenna Communicating with Ahead Vehicle
(Rider Occlusion) Vehicle Positions: 1-3
RSSI (dBm)
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains
Environment

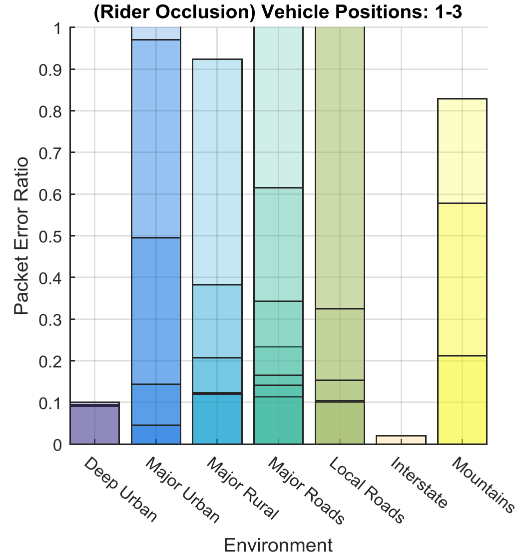
New River Valley Test: Packet Error Ratio
Rear Antenna Communicating with Ahead Vehicle (Rider Occlusion)
Vehicle Positions: 1-3

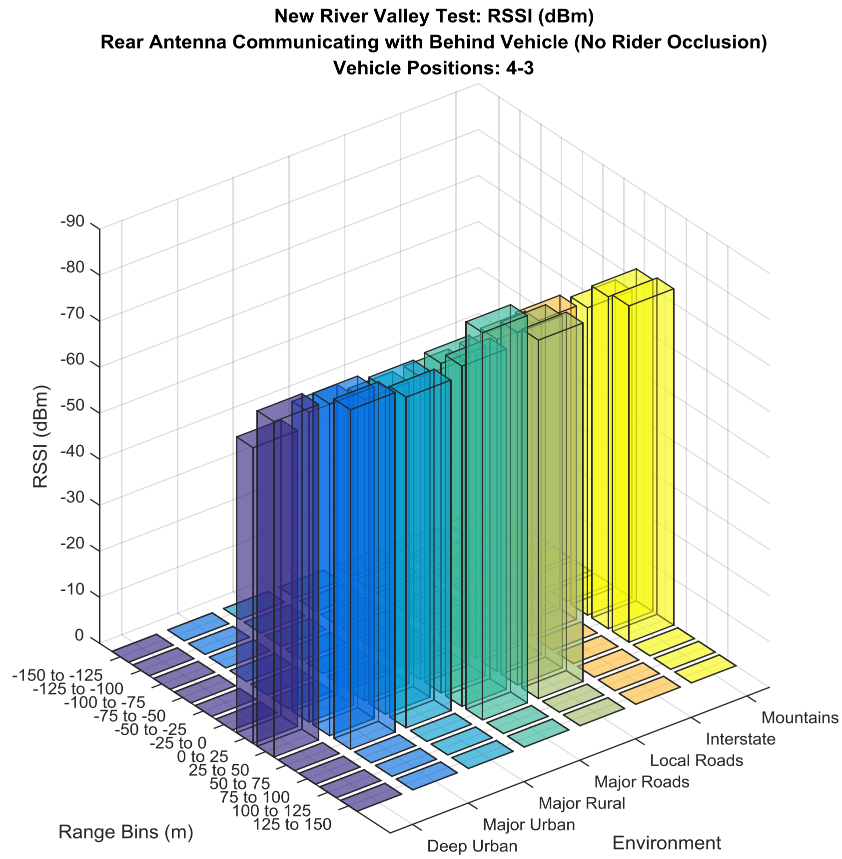


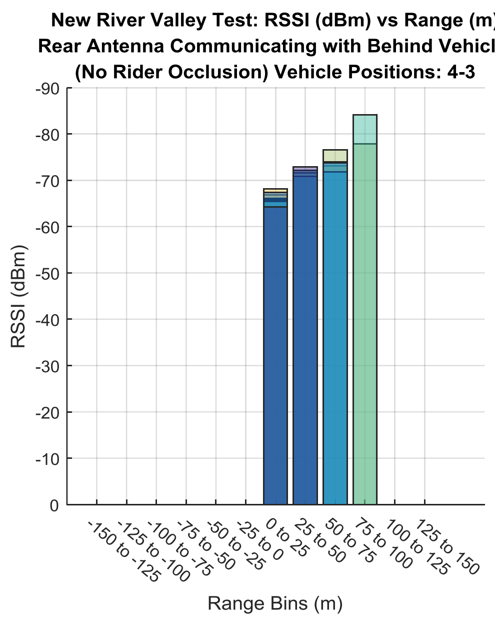
New River Valley Test: Packet Error Ratio vs Range (m)
Rear Antenna Communicating with Ahead Vehicle
(Rider Occlusion) Vehicle Positions: 1-3

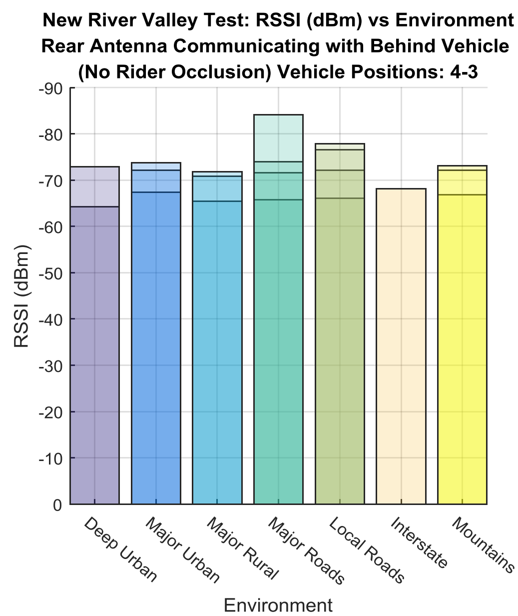


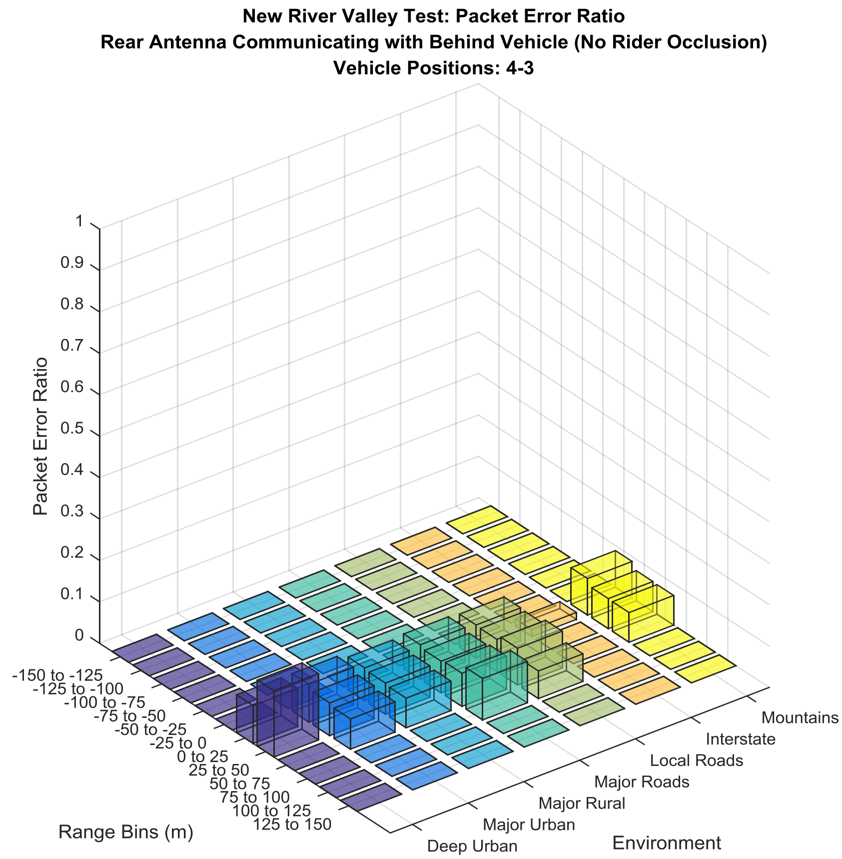
New River Valley Test: Packet Error Ratio vs Environment
Rear Antenna Communicating with Ahead Vehicle
(Rider Occlusion) Vehicle Positions: 1-3

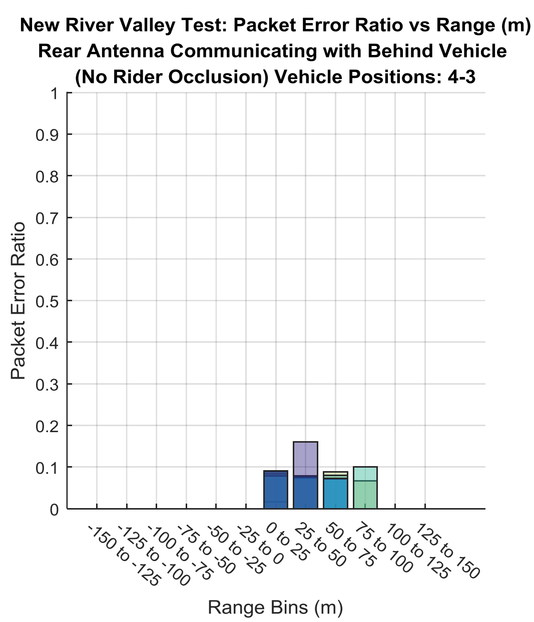


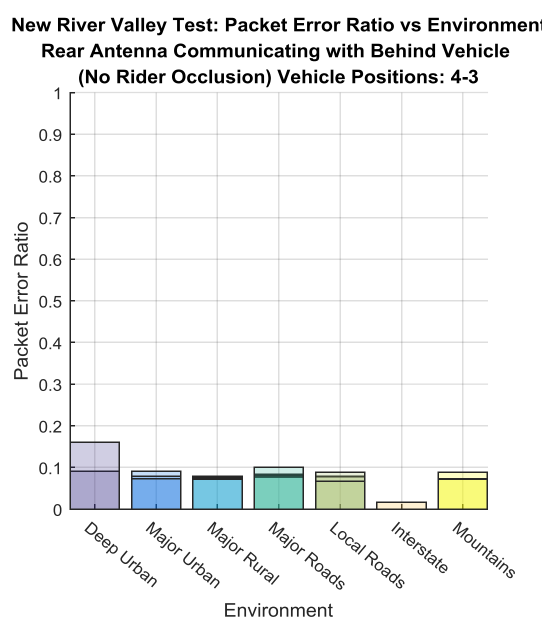

New River Valley Test: RSSI (dBm)
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Vehicle Positions: 4-3
RSSI (dBm)
Range Bins (m)
Environment
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains


New River Valley Test: RSSI (dBm) vs Range (m)
Rear Antenna Communicating with Behind Vehicle
(No Rider Occlusion) Vehicle Positions: 4-3
RSSI (dBm)
Range Bins (m)


New River Valley Test: RSSI (dBm) vs Environment
Rear Antenna Communicating with Behind Vehicle
(No Rider Occlusion) Vehicle Positions: 4-3
RSSI (dBm)
Environment
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains


New River Valley Test: Packet Error Ratio
Rear Antenna Communicating with Behind Vehicle (No Rider Occlusion)
Vehicle Positions: 4-3
Packet Error Ratio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-150 to -125
-125 to -100
-100 to -75
-75 to -50
-50 to -25
-25 to 0
0 to 25
25 to 50
50 to 75
75 to 100
100 to 125
125 to 150
Range Bins (m)
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
Mountains
Environment


New River Valley Test: Packet Error Ratio vs Range (m)
Rear Antenna Communicating with Behind Vehicle
(No Rider Occlusion) Vehicle Positions: 4-3
Packet Error Ratio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-150 to -125
-125 to -100
-100 to -75
-75 to -50
-50 to -25
-25 to 0
0 to 25
25 to 50
50 to 75
75 to 100
100 to 125
125 to 150
Range Bins (m)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0.2
0.1
0
Deep Urban
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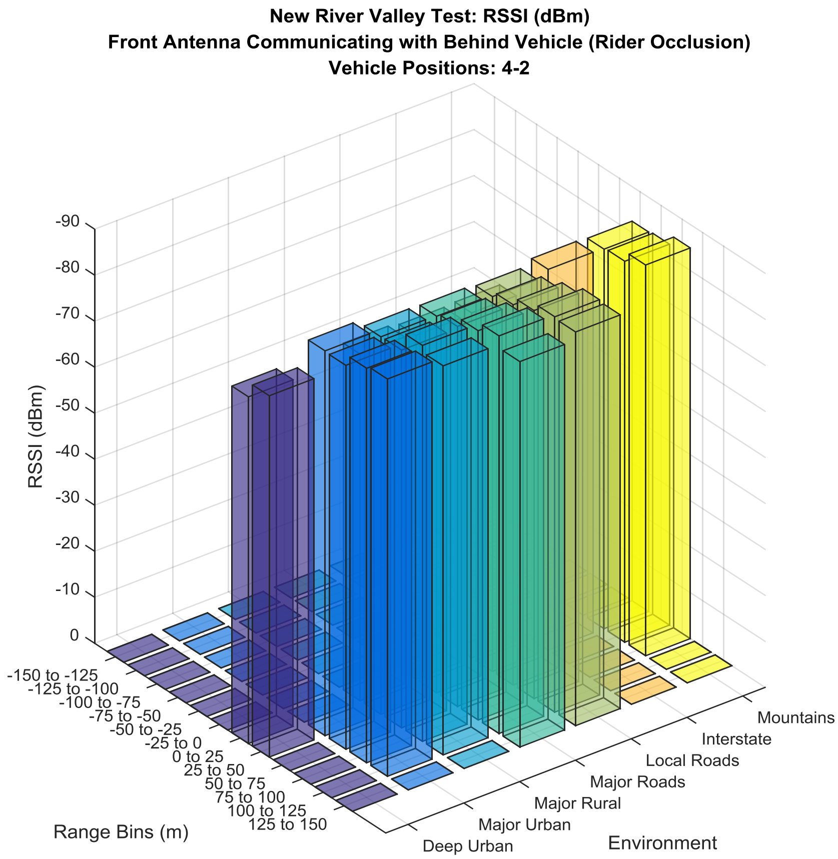
New River Valley Test: RSSI (dBm)
Front Antenna Communicating with Behind Vehicle (Rider Occlusion)
Vehicle Positions: 4-2
RSSI (dBm)
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
-150 to -125
-125 to -100
-100 to -75
-75 to -50
-50 to -25
-25 to 0
0 to 25
25 to 50
50 to 75
75 to 100
100 to 125
125 to 150
Range Bins (m)
Deep Urban
Major Urban
Major Rural
Major Roads
Local Roads
Interstate
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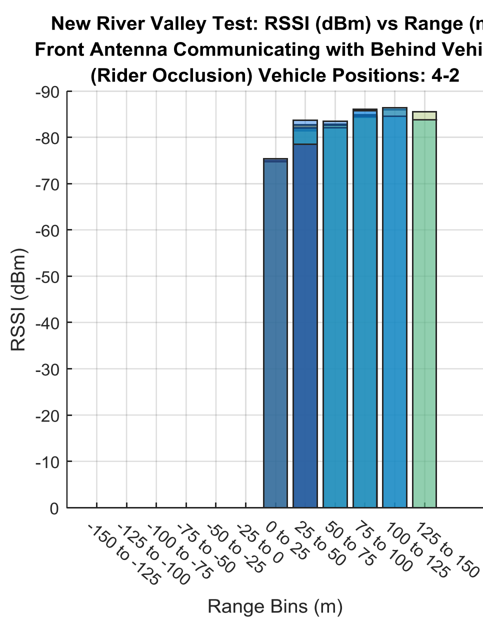
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RSSI (dBm)
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0
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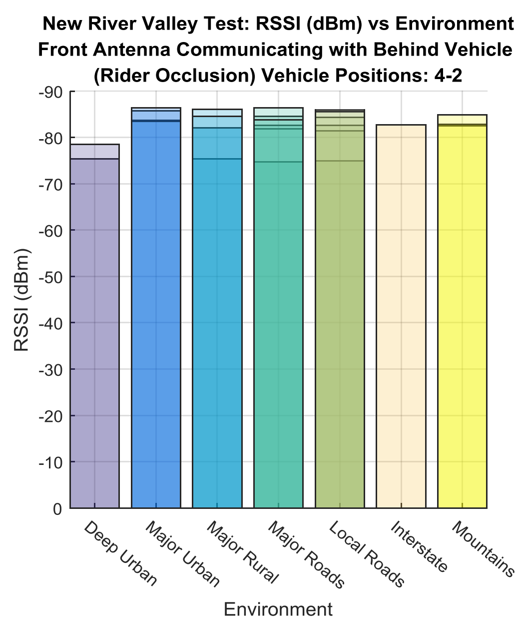
-125 to -100
-100 to -75
-75 to -50
-50 to -25
-25 to 0
0 to 25
25 to 50
50 to 75
75 to 100
100 to 125
125 to 150
Range Bins (m)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RSSI (dBm)
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-80
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-50
-40
-30
-20
-10
0
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Major Urban
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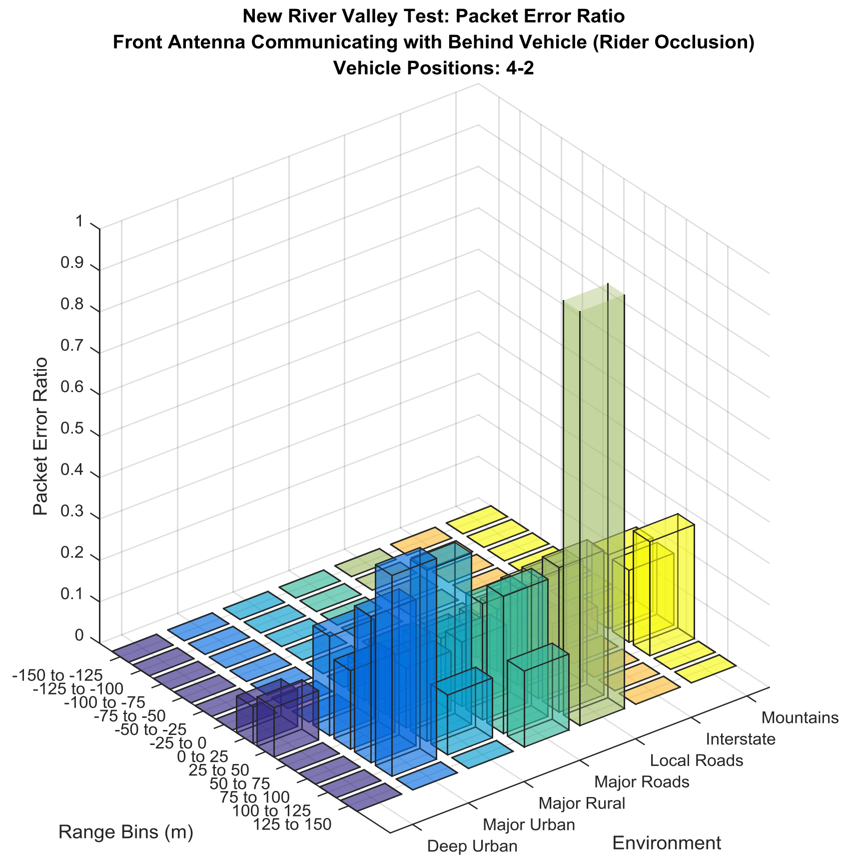
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75 to 100
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125 to 150
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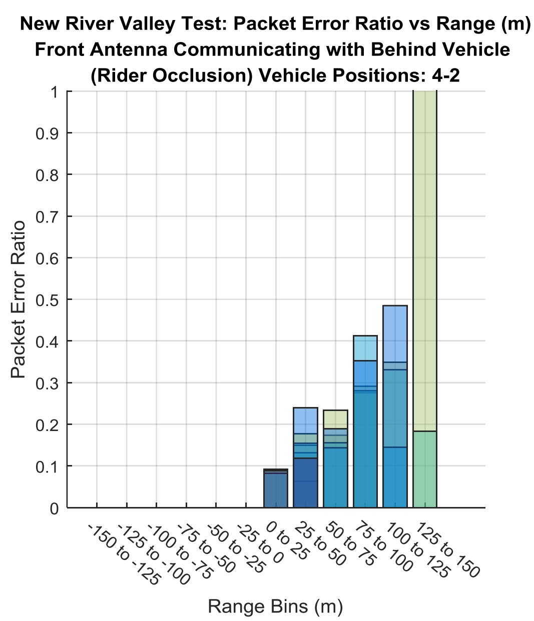
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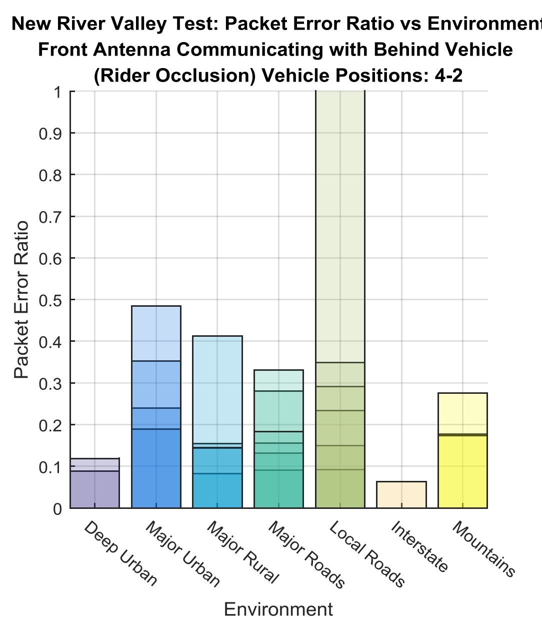
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