Repeatability of Vehicular Measurements on Public Roadways

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ABSTRACT

Connected vehicle applications promise to transform traffic management and safety. Evaluating the performance of vehicular communication systems in real-world settings benefits from detailed propagation models. Developing such models can be challenging due to the dynamic nature of the vehicular environment. This paper presents an experimental methodology to control and monitor key experimental factors and to efficiently conduct real-world measurements. We tested the Dedicated Short Range Communication (DSRC) technology at 5.9 GHz in a week-long experiment involving 10 vehicles on a major highway under one of the most dense traffic conditions in the United States. We study the repeatability of such measurements for different experiment durations, which may help place earlier propagation studies into context. The experiments show that, with orchestrated vehicle movement in a 2 km section of highway, the pathloss exponent estimation is repeatable within a tolerance of ±0.1 in 11 minutes of measurements for extremely light traffic and in 48 minutes for moderate to heavy traffic.

1 INTRODUCTION

Vehicle-to-Vehicle (V2V) communications can support vehicle safety, for example, when no direct Line-Of-Sight (LOSight) to a hazard exists, or it can improve traffic flow, for example, through cooperative merge applications. Assessing the performance of V2V communications depends on a precise knowledge of wireless propagation effects in real-world environments. Propagation effects are a key factor to determine the range at which messages can be received, the timeliness of received messages, and the effect of transmitter density on interference and system performance. Overall, propagation models are often the primary factor affecting the accuracy of simulation studies [7].

Conducting field tests to capture precise propagation models is challenging due to the dynamic nature of real-world road environments. Vehicular communications are affected by signal reflections, attenuation, and interference from many different outdoor sources which change rapidly over time as cars move: nearby structures, vegetation, parked vehicles, traffic density and surrounding vehicles. It has been shown that this highly dynamic nature translates into very weak spatial and temporal correlation [3], thus rendering field test planning, execution and posterior modeling of propagation effects a very challenging task. Such field tests also require considerable coordination among all elements involved, namely the vehicles, drivers, test planners and test operators.

Many efforts have measured propagation data and fitted propagation models, like Nakagami fading or lognormal shadowing, for the Dedicated-Short Range Communications (DSRC) vehicular channel targeting real-world driving environments arriving at different sets of results [4–6, 8, 9, 12, 15]. Solid V2V communication assessment in simulation tools depends on the accuracy of such models. While accuracy is a qualitative concept, repeatability may be expressed quantitatively in terms of the dispersion of the results. Repeatability can be defined as the closeness of agreement between results of successive measurements. According to the National Institute of Standards and Technology (NIST) guidelines [16], repeatability can be established with experiment repetition over a short period of time under the same measurement procedure, observer, measurement instrument, conditions and location. To the best of our knowledge, the prior work used limited control and monitoring of the parameters involved in the signal propagation which was measured under different locations and conditions, thus raising questions about the repeatability of such results.

In this paper, we study the repeatability of V2V propagation measurements on public roadways. We also describe the methodology and execution of a week-long 10 car V2V communications field test on 2 km of a 16-lane highway, that offers one of the highest levels of vehicle density in the United States, and at a busy urban intersection in Orange County, CA, which was conducted to develop calibrated simulation models for these environments. The work was led by the Crash Avoidance Metrics Partners LLC (CAMP LLC) Vehicle Safety Communications 6 (VSC6) Consortium, in partnership with the United States Department of Transportation (USDOT), as part of the V2V safety communications scalability research activity of the CAMP VSC6 Vehicle-to-Vehicle Communications Research (V2V-CR) Project. The testbed was developed exclusively for internal CAMP experiments. The Team that planned and executed the field test consisted of the CAMP VSC6 Consortium, Rutgers University, and the University of Central Florida. The field testing

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used an incremental approach where the Team developed the final test methodology based on the experience from earlier smaller scale tests. In particular, the early small scale tests, with 6 vehicles, provided insight into the necessity for exercising a precise control and monitoring of factors affecting the signal propagation for the posterior testing phases. Specifically, we target the generation of repeatable test results by accounting for factors such as signal interference effects caused by the test cars, the antenna setup, the test environment and the observed traffic. The collection of this data should support the creation of realistic and accurate reference simulation models for the DSRC channel. The results highlight the need for extensive data collection even under similar traffic conditions. We found that the propagation model estimation, and more specifically the pathloss exponent, is repeatable with a tolerance of ± 0.1 for extremely light and moderate to heavy traffic.

2 RELATED WORK

During the last decade there have been multiple research efforts focused on modeling the V2V channel. While a variety of propagation models have been studied in the characterization of the channel, the parameter estimation was usually done based on empirical values obtained in field tests. The data was collected using either channel sounding techniques or readily available DSRC radios logging the Received Signal Strength Indication (RSSI) values. The channel sounding experiments were conducted using two vehicles, i.e. one transmitter and one receiver, as seen in [8, 9, 12]. On the other hand, experiments where RSSI readings were obtained directly from DSRC compliant radios employed fleets of two vehicles [4, 15], three vehicles [6] and four vehicles [5]. As can be seen, the number of vehicles utilized in the measurements is considerably reduced. In such settings, the overall results might not average the effect of singular communication events within a defined scenario, thus possibly creating a biased statistical representation of the propagation characteristics in the predominant stochastic simulation models.

In addition, and to the best of our knowledge, existing field tests on public roads do not consider orchestrated moving patterns for large testing fleets. In [9] the authors covered two large areas but tested them only for a day with only two vehicles that drove at each driver's prerogative. Similarly, in [2] one transmitter and one receiver equipped with DSRC radios covered over 1100 km in 12.5 hours. The long routes traversed by the cars are subject to significant differences in the environment configuration. This might indicate that the estimated models might not have converged in the provided length of measurements. Furthermore, in [10] the authors estimate sets of propagation model parameters for different traffic conditions, e.g. highway under light and heavy traffic. However, the tests were performed at different sites. This could potentially introduce a bias in the results as the composition of the chosen experiment sites may cause interference that could be improperly attributed to the traffic density. In this project, we focused on two regions of interest by repeatedly driving the same orchestrated moving patterns on the same road segments under extremely light traffic and regular traffic conditions.

Moreover, in the existing literature the propagation model parameter estimation is performed considering an imprecise classification

Figure 1: Satellite view and region of interest within the freeway I-405 (Google Maps, 2017) [11].

of the tested scenarios. For example, the overall traffic condition, if considered, was classified visually and subjectively by the experiment operators [14] or using the low resolution Annual Average Daily Traffic (AADT) metrics [10, 12]. In reality, the traffic condition changes very rapidly and may be different within the same tested region; therefore, its quantification requires objective and higher resolution metrics. Additionally, the antenna radiation pattern, which in final deployment is expected to be omnidirectional, can be distorted due to presence of other artifacts on the roof of the test vehicles. To the best of our knowledge, separate characterization of the antenna setup prior to testing on public roads has not been performed in the related work.

3 EXPERIMENT CONTEXT AND INFRASTRUCTURE

The field tests are part of a larger effort to design and evaluate a congestion control protocol that can maintain a desired level of DSRC communication performance under extremely dense traffic conditions, where transmissions from surrounding vehicles contribute to high channel loads and potentially interfere with each other. Evaluating such protocol benefits from propagation data and calibrated simulation models for realistic, busy highway environments.

Experiment Sites. To satisfy this goal, the team selected 2 km of a 16-lane flat, straight highway segment of the I-405 CA freeway in Seal Beach, which offers one of the densest traffic volumes in the country with 393,000 vehicles per day [13]. Fig. 1 shows this highway with the region of interest (ROI) marked by the red box (our analysis considers collected data only when both transmitter and receiver are in this region). The flat, straight, multi-lane segment increases the potential for interference from other nearby cars, thus producing a highly congested scenario and a better stress test for the technology. The Team also selected a nearby major intersection for testing. In this paper, we present a preliminary analysis of the highway data only and future work will focus on analyzing the collected intersection propagation data.

Vehicles and Equipment. The testbed consisted of ten sedan cars and two SUVs equipped with a DSRC On-Board Equipment (OBE) unit containing a DSRC implementation capable of transmitting and receiving Basic Safety Messages (BSMs). Due to the required coordination between vehicles, the tests were executed by drivers with advanced professional driving backgrounds. Table 1 lists the vehicle models and roof heights. Vehicle brands and models were determined by availability at the rental car provider, with preference for vehicles with a clear roof (no roof rails or large antennas) to not obstruct propagation from our DSRC antenna. The Team further equipped each car with a GPS tracking system reporting the car's real-time location via Ultra High frequency (UHF) to a Command and Control Center (CnC). In order to be able to estimate the traffic condition and, more particularly, the presence and number of obstacles between the cars at a given time, they were all equipped with a front-facing dashboard camera. The camera recorded video, time, speed, and the GPS location of the vehicle. Ensuring the recording of videos from all cars at the time when the experiments took place was essential; to this end, a remote camera control application was developed. Furthermore, the Team equipped the vehicles with a cellphone dialed into a conference call to receive instructions from the CnC.

Table 1: Description of experimental vehicles

Brand & Model	Type	Height
Volkswagen Passat (×3)	Sedan	148.59 cm
Mitsubishi Lancer	Sedan	148.08 cm
Nissan Altima	Sedan	147.07 cm
Nissan Sentra	Sedan	149.60 cm
Kia Optima (×3)	Sedan	146.56 cm
Ford Fusion SE	Sedan	147.57 cm
Kia Sorento (×2)	SUV	168.40 cm

The On-Board Equipment consisted of the DSRC device, a GPS device, and a logging system that recorded measurements. It also provided WiFi-based remote control access for configuring the parameters of the DSRC communication and for activating or deactivating transmissions or logging. The DSRC, GPS, and WiFi radios were connected to a shark-fin antenna that was mounted in the center of the car roof. The real-time position tracking system for the CnC required an additional GPS and a UHF antenna, which were laterally offset from the DSRC antenna to minimize any potential effect on the front or rear signal propagation that is of primary interest. Fig. 2 shows the final placement of all antennas on the roof of the vehicles. All other equipment was placed in the trunk of the vehicles.

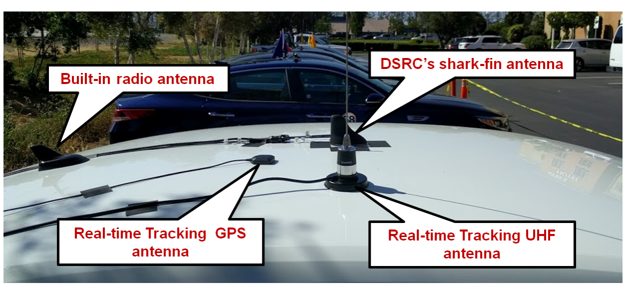


Figure 2: Antenna setup on roof of test vehicles.

The Team developed a logging system that collected information at transmission and reception of packets. The packets are BSMs, DSRC's beacon messages, which are broadcasted periodically by all vehicles to inform others of the vehicle's position, speed and other vehicle data. Each node therefore both transmits and receives BSMs. At transmission time, the node's logged information comprised: latitude, longitude, speed, heading, transmission power, packet size and sequence number. Similarly, at reception of a packet we logged: sender ID, RSSI in dBm, positional information of the receiver (obtained from GPS), packet size and sequence number. Furthermore, the vehicles logged their GPS position every 100 ms.

Key experiment parameters and their values are listed in Table 2. To increase the number of propagation measurement samples obtained, particularly during high-speed highway driving, the OBEs were configured to transmit at a higher message transmission rate of 20 Hz, compared to production DSRC system that are expected to transmit at a rate of 10 Hz or below (determined by the channel congestion control algorithm). The analysis will focus on signal strength readings from these experiments, which we do not expect to be significantly affected by higher transmission rates since the chance of collisions is low with 10 cars along the highway region and intersection. Also, the transmitter parameters were kept constant during all the experiments as we do not expect them to have an impact on signal propagation, which is our key variable of interest. Furthermore, for the repeatability analysis, the experimental tools and measuring instruments remain the same throughout the tests.

Table 2: Experiment Parameters

Parameter	Value
DSRC Message Rate	20 Hz
Packet Size	∼ 135 Bytes
Transmit Power	20 dBm
DSRC Channel	172 (5855-5865 MHz)
Position Update Interval	100 ms

3.1 Characterization Experiments

This set of experiments validates and characterizes the wireless DSRC communication system installation in each vehicle. The objective of characterization is to validate that far-field RSSIs are consistent at various angles around a vehicle for the same range, similar to what can be expected from production DSRC antenna installations. To minimize multi-path signal interference effects on these measurements, the experiments used an open space location with a minimum number of reflectors and scatterers, such as buildings, cars, trees or pedestrians. The Team chose a decommissioned airfield runway where a 1,000 m × 80 m flat open environment was available for the experiments. The staging area was placed in the field at least 75 meters from the experiment setting. Also, during the experiments, all operators remained within the staging area or inside the test vehicles to avoid affecting the measured signals.

Antenna Pattern Experiment. In this test, a reference vehicle drove one loop on a circular path of radius $r = 25$ ft at approximately 1 mph while another vehicle remained static at the center of the circle. Note that r was the approximate distance between the two antennas. The test was repeated with all 12 vehicles in the center. This test allows examining the radiated signal power from the center vehicle as well as the reception pattern in all directions. The test reveals, for example, whether artifacts from the car roof have a significant effect on received power.

Figure 3a shows the position of the cars during the tests. Figure 3b illustrates an example of the RSSI at the circling car for the different angles of transmission. As expected, it shows a shape

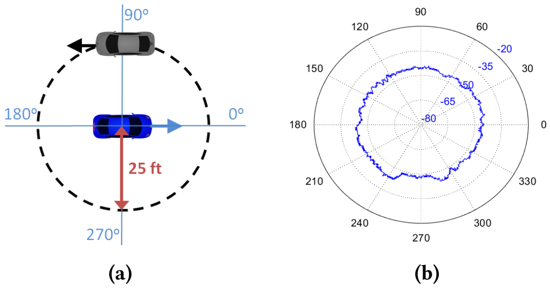


Figure 3: (a) The position of the cars during the Antenna Pattern experiments (b) RSSI against transmitter/receiver angle from the point of view of the static vehicle at center.

close to a circle (i.e., an omnidirectional antenna pattern) in all vehicles. The small deviation observed at 270^o is likely caused by the real-time position monitoring UHF antenna mounted at this position. The antenna was intentionally placed at the side since we prioritized front and rear propagation.

Communication Range Experiment. In this experiment the range of transmissions are examined at two different angles; 0^o and 30^o. At both of these angles, the distance between the transmitter and the receiver is gradually increased and decreased on a straight line, up to 800 meters.

Vehicle Blocking Experiment. We designed a vehicle blocking experiment for evaluating the pathloss caused by the car body as an obstacle. The test consisted of incrementally placing up to 3 obstructing vehicles that moved at very low speed in a line between two static vehicles. We repeated the experiment for separations between static vehicles of 50 and 100 meters. The results from this experiment can be compared with the highway five car convoy experiment to verify that the observations and obstacle models obtained in this isolated environment still apply in the highway.

4 EXPERIMENT METHODOLOGY

Objectives. The main objective of the analysis described in this paper is to understand the repeatability of real-world V2V propagation measurement experiments and the key factors affecting such measurements in the context of DSRC channel modeling. The experiments were also designed to allow future analysis of the effect of oncoming traffic and relative lane position of vehicles on propagation. To this end, we developed an experiment methodology to monitor, and control when possible, factors contributing to the signal degradation, such as the traffic condition, the antenna setup, the vehicles' effects on the signal degradation and the characteristics of the test sites.

Field Operations. The tests were executed in two week-long phases. The first phase, or Small Scale Test, consisted of 4 primary vehicles which were used in all the tests and 4 secondary vehicles, which were used intermittently. The Small Scale Test served as a preliminary trial to develop the test methodology and length of the experiments for an accurate propagation modeling. This first experience also provided insight regarding the necessary monitoring and control system. The second phase, or Large Scale Test, took place about 2 months later and comprised 10 primary vehicles and 2 secondary SUVs. Based on the Small Scale Test experience, it used updated test plans, a refined vehicle setup including GPS real-time car location tracking software and a newly developed remote monitoring and control system for video recording. In both phases, setting up and posterior dismantling of equipment in the vehicles and CnC took two days of work.

To efficiently collect the required data, the movement of the test cars was orchestrated and monitored. For vehicles moving in the same direction, vehicles needed to maintain certain relative spacing, when possible, to collect data for different transmitter-receiver distances. For testing with vehicles moving in opposite directions, the starting time of cars and their speeds needed adjustment so that they meet in the segment of interest under different traffic conditions. The experiment commander benefits from awareness of car positions and their relative distances to provide instructions to our professional drivers.

In addition to the logging of RSSI measurements and transmitter-receiver distances, knowledge about the vehicular traffic condition at the time of data collection was needed for an accurate post-processing of the data. For this purpose, Caltrans Performance Measurement System (PeMS) Level-Of-Service (LOServ) hourly readings were used to classify the traffic density observed during the experiments. The LOServ classifies the traffic condition quality based on speed, flow and vehicle density in levels from A to F [1]. The LOServ data confirmed that our approach of extracting night-time and morning rushhour datasets from the collected data creates two datasets with very different levels of traffic congestion. Furthermore, in order to capture more fine-grained data and to evaluate in detail LOSight links and LOSight obstructed by vehicles, the driver's view was recorded from a dash camera installed in the testing cars.

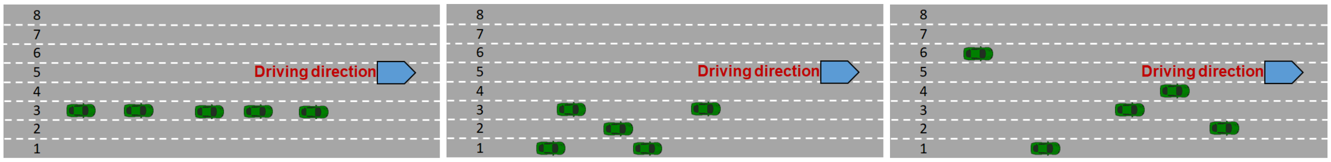
In summary, the collected data comprises: dashboard view videos, GPS traces, DSRC messages transmission and reception logs (with time and received RSSI among other parameters), and traffic condition metrics from Caltrans PeMS. Using the vehicle GPS logs, we then calculate the distance between transmitter and receiver for each received packet.

4.1 Highway Vehicular Configuration

In the public highway experiments, 10 sedans were divided into two groups of 5 cars moving in opposite directions. This allowed simultaneous collection of data for cars in the same and opposite moving direction. The group size was chosen small enough that all vehicles in a group could enter the highway together. Three moving patterns were designed with the goal of collecting RSSI samples across large separation distances between transmitters and receivers, for same or different lanes and for different road traffic conditions.

Five car convoy, as illustrated in Fig. 4a. Cars entered the highway together and spread out on the same lane as they traveled through the ROI. This experiment enables analysis of in-lane propagation for small distances, as provided by the adjacent cars, and obstructed LOSight large distances as provided by the other cars.

Five cars across different lanes, as seen in Fig. 4b. For each moving direction, 5 cars were distributed symmetrically in different lanes, e.g., 2 cars in lane 1, 1 car in lane 2, and 2 cars in lane 3. This moving pattern collected data enabling the comparison between

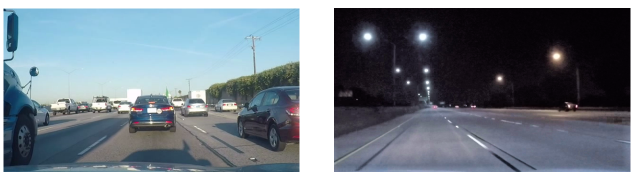


(a) (b) (c)

Figure 4: The designed moving patterns for one group in the I-405 experiments: (a) five cars convoying; (b) five cars across different lanes; (c) five cars semi-randomly moving.

in-lane and cross-lane propagation while capturing LOSight and obstructed LOSight links.

Five cars semi-randomly moving, as illustrated in Fig. 4c. Drivers were allowed to freely choose driving speeds and separation distances but each car was assigned to a separate lane. This semi-random pattern helped collecting data covering a larger set of relative positions of transmitter and receiver.



(a) (b)

Figure 5: The dashboard camera view during the I-405 experiments for: (a) heavy traffic and (b) extremely light traffic.

The moving patterns were repeated for different road traffic conditions and different lane configurations. Primarily, the Team focused on collecting data in lane 1, 3, 6, 7 (HOV lane 1), 8 (HOV lane 2) and moderate to heavy road traffic. However, the Team found it extremely challenging to collect a large amount of LOSight data for wide separation distances between transmitter and receiver during the daytime hours given volume of traffic, as seen in Fig. 5a. Additionally, we were interested in capturing the isolated impact of this highway environment on the signal propagation performance. To tackle these challenges, the cars spread across different lanes and used semi-random moving patterns during the night-time hours between 2 AM and 6 AM. Figure 5b shows the nearly empty roads at this time, which facilitated almost only LOSight links and the freedom to safely space the cars along the region of interest.

4.2 Command and Control Center

To orchestrate the experiments the team set up the Command and Control Center (CnC). As the tests were conducted in different locations, the Team chose a Recreational Vehicle (RV) as a control station that can be moved between these locations, see Fig. 6. The CnC was equipped with a real-time position monitoring system, enabling an *experiment commander* to track vehicles locations and their relative distances during the experiment for a better coordination of cars on the road over a conference call. The monitoring system was especially useful when a larger separation distance was required for cars in convoy formation and when a speed adjustment was necessary to produce opposite direction encounters within the regions of interest, see 4.3 for more details. All monitoring output was recorded in screen capture videos for later analysis.

For the Large Scale test, a remote dashboard camera control and monitoring system was developed allowing CnC personnel to remotely start and stop video recording in the test vehicles. At the same time, this system shows network connectivity health status, camera mode, charging and battery status, as well as the remaining memory card capacity; see more details in section 4.4. This system was developed based on the experience from the Small Scale experiment, where each driver was in charge of manually pushing the start/stop button on the camera. It turned out that this was difficult for drivers and unreliable, leading to a significant number of missing videos. The remote system eliminated these issues and allowed remote detection of camera problems.

Finally, the WiFi-based DSRC radio configuration controller was also installed in the control station. This allowed configuring as well as starting and stopping the DSRC radios and loggers, before and after a test run when the vehicles were within WiFi range.

4.3 Real-time Location Tracking System

We developed a position monitoring system to track and display the location of each vehicle in the control station in real-time. Experiments showed that existing mobile device tracking apps, which rely on a cellular connection with a server, imposed delays larger than 10 seconds. To eliminate these delays, the developed position monitoring system employed commercial UHF-based GPS transponders provided by the Team, which are capable of reporting their position directly over UHF radio communications.

The Team equipped each test car with this transponder and set up an additional transponder as a receiver in the control station. Each GPS transponder includes a built-in 12-channel GPS receiver and can periodically transmit location information through a UHF channel at 1 Hz. The receiver was responsible for collecting the location updates from the vehicles and uploading them to a control computer via a serial cable. As shown in Fig. 6, to improve reception, we placed the receiver antenna on an 18 ft tripod outside the RV. The achieved transmission range was more than 3 km.

We developed a tracking software to visualize vehicle locations on a map and to compute distances between vehicles. Specifically, the software extracts reported ID and GPS coordinates from the received location update message, displays the coordinates as colored icons on Google Earth maps and shows the distances between any two cars in a matrix as seen in Fig. 6.

4.4 Remote Camera Control and Monitoring

We developed a cellular-network-based camera remote control and monitoring system to facilitate front-facing video recording from all vehicles and capture information about obstructions as well

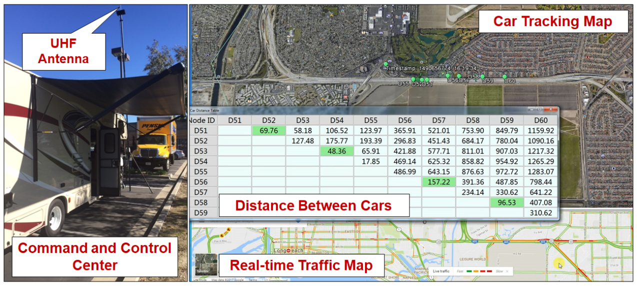


Figure 6: (Left) the UHF receiving antenna setup at the Command and Control Center; (Right) the display of the real-time location tracking software.

as traffic conditions. We found that, even at the minimum quality configuration, the videos were large enough to fill the 64 or 128 GB SD memory cards in less than an experiment day. Since not all drivers were comfortable with operating dashboard cameras, replacing the memory cards could entail bringing cars back to the CnC several times a day. This would disrupt the experiments, potentially causing the loss of opportunities for data collection within the scope of our project, e.g. under traffic jam. Therefore, it was necessary to record exclusively during the driving time within the regions of interest.

For this purpose, we developed a remote camera control and monitoring system using GoPro® cameras and their WiFi interface, from which URL-based commands for starting and stopping video can be issued. The remote control system in the vehicle's end comprised: (1) the camera, (2) a Raspberry Pi 3 with two WLAN interfaces, and (3) a MiFi Verizon LTE hotspot offering Internet connectivity to the Raspberry Pi.

The Raspberry Pi was connected with one WLAN interface to the MiFi hotspot and with the other one to the camera. Every second, a script running in the Raspberry Pi checked camera connectivity, obtained and forwarded the camera status information to the server (e.g. remaining battery, charging status, camera mode, current video length, etc.), and retrieved camera commands from the server.

On the other end, the remote server handled all cameras simultaneously. First, a monitoring webpage displayed a table with one row per camera showing the camera status information in the columns. Second, a password-secured command webpage allowed starting and stopping video for a set of selected cameras or for all cameras.

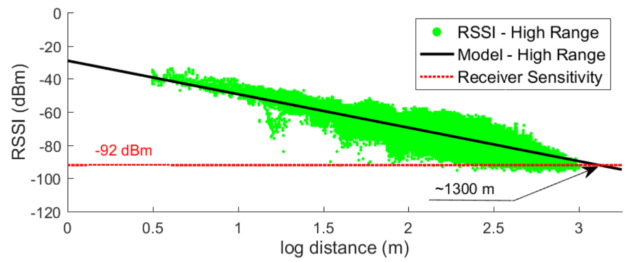
This system allowed operators in the command and control center to monitor and reliably start cameras for 10 vehicles at the beginning of every drive, without distracting drivers. We found that the share of correctly captured video increased substantially with this system.

5 PRELIMINARY RESULTS

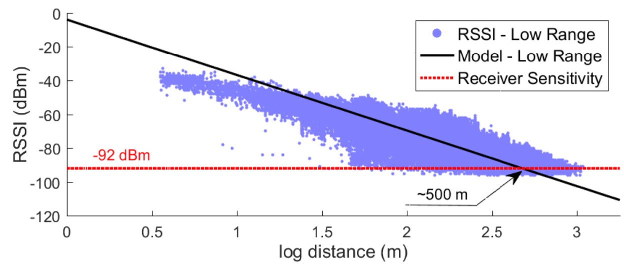
We analyze repeatability of the experiments conducted with this methodology in terms of a key propagation parameter, in particular the pathloss exponent. Specifically, we consider the commonly used log-distance propagation model where the pathloss P in dBm as a function of the distance d is defined by the equation:

$$P(d) = P_0 + 10\,\alpha\,\log_{10} d \qquad (1)$$

where α is the pathloss exponent (PLE) and P_0 represents the pathloss at a close distance to the transmitter. For a given set of RSSI values and transmitter/receiver distances, we estimate P_0 and PLE. While many more sophisticated propagation models have been proposed for vehicular communications, our focus here is not on creating a new propagation model but on understanding repeatability. We therefore begin with the most basic parameter. This parameter is also important in other models which are often composed of the log-distance model presented above, for example, the single slope and dual slope lognormal propagation models. We believe that the repeatability analysis of the PLE we present in this section is also applicable to such models.



(a)



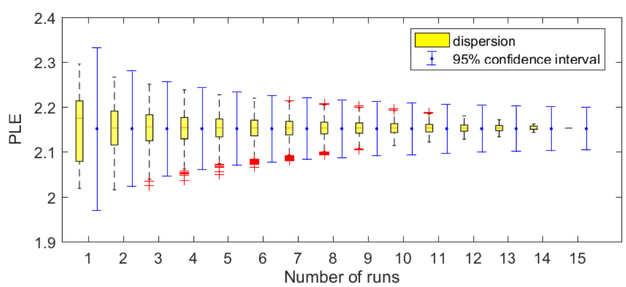
(b)

Figure 7: The RSSI and fitted propagation models for two observed extreme cases: (a) PLE of 2.02 showing an approximate range of 1,300 m and (b) PLE of 3.29 with an approximate range below 500 m.

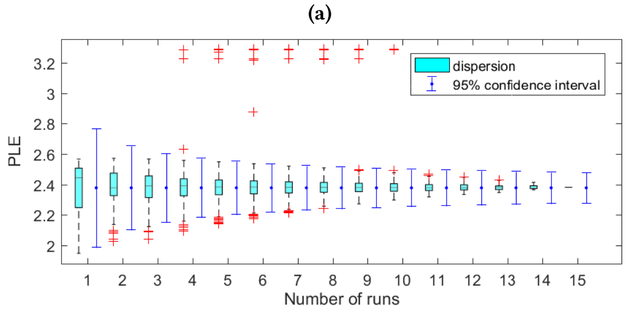
We structure the data in runs, where a run is all cars moving from edge to edge of the highway ROI; that is 5 cars moving North-South and 5 cars moving South-North, including the data from both moving directions and the cross-direction communication data. Given this run definition, the night-time and daytime experiments considered in our analysis comprised 15 runs each.

We select two subsets of the highway RSSI measurements, specifically during the night-time hours (2AM - 6AM) and during the morning rushhour (after 7AM) of two different days. For the night-time, the Caltrans PeMS database reported 100 % of LOServ A, indicating less than 11 vehicles per mile and driving speeds above 65 mph [1]. Then, this scenario corresponds to highway under *extremely light traffic*. On the other hand, the daytime presented primarily LOServ C and LOServ F, the latter especially in the South direction during the first hours of the test. The LOServ C indicates speeds between 54 and 57 mph and 20 to 30 vehicles per mile; while the LOServ F corresponds to speeds under 30 mph and more than 67 vehicles per mile. Accordingly, we classify the daytime experiment as *moderate to heavy traffic*. Note that due to a lower mean speed under heavier traffic, the effective run duration increased from 2:30 to 3:00 minutes on average and consequently more data samples were collected.

We study the PLE parameter because we consider it to be the most relevant factor in the distance dependent component of propagation modeling, as it corresponds to the slope of the model over log-distance. Figure 7 illustrates how the propagation model estimation process can arrive at very different results for the exact same road segment when working with small amounts of data. Figure 7a depicts a PLE of only 2.02, obtained after fitting data from 2 of the 15 runs in the night-time, while Fig. 7b shows a PLE of 3.29, generated after fitting 3 of the 15 daytime runs. The divergence in the PLE yields to a communication range difference of 800 m, where the range is approximately the meeting point between the model and the receiver sensitivity. Such difference demonstrates the critical role of accurate PLE estimation. In this section, we examine the repeatability of the PLE quantitatively based on confidence intervals and dispersion of the estimated PLE values.



(a)



(b)

Figure 8: Pathloss Exponent estimation as a function of the number of runs under: (a) extremely light traffic during the night-time and (b) moderate to heavy traffic during the daytime.

Figures 8a and 8b depict the PLE fluctuation with increasing number of runs selected for the estimation process. In both figures, the blue error bars represent the 95% confidence interval shown over an increasing number of runs. As shown, the night-time measurements present a faster convergence; this is likely due to the reduced number of cars present at that time, making the independent runs nearly identical. Despite the observed deviations, the confidence interval analysis shows that a total of 4 runs, i.e. 11 minutes, achieve a tolerance of ±0.1 in the night-time. In other words, we estimate that during the night-time 4 runs are repeatable within a PLE variation of ±0.1. Similarly, 15 runs, i.e. 48 minutes, are needed to achieve a tolerance of ±0.1 in the daytime.

While the confidence interval offers a tolerance analysis on the mean values, it is also interesting to observe the dispersion of the estimated PLEs. Figure 8 shows box plots of the PLE variation for different amounts of data (number of runs) in the estimation process. For example, if only one of the 15 runs is selected, there are 15 different possible subsets of data to consider; if any two of the 15 runs are selected, there are 105 subsets (15 choose 2) to consider; and so on. Every different subset yields a different estimated PLE. Each box, then, represents the distribution of estimated PLEs over all subsets for a given number of runs. On each box, the central red mark is the median, the edges are the 25th and 75th percentiles, the whiskers are the most extreme data points not considering outliers, and outliers are the red crosses individually plotted. The final converged values are 2.15 and 2.38 for night-time and daytime respectively, showing a higher PLE under denser traffic. Also, these values are quite different from those in Fig. 7, where less data was used and convergence was not yet achieved. The shown deviations complement the confidence interval findings and corroborate that achieving PLE estimation convergence even under the same traffic conditions and on a reduced geographical area (i.e., 2 km highway stretch) requires experiment repetition.

6 CONCLUSIONS

Realistic vehicular propagation modeling entails extensive large-scale real-world experimentation that accomplishes averaging the effect of singular communication events within a defined scenario. In this paper, we described the methodology and execution of a week-long V2V communication experiment involving 10 vehicles where a tight coordination and control of pertinent factors was achieved, resulting in a rich and precise measurement database. We learned that such propagation data can be efficiently collected with precisely coordinated and monitored paths of multiple vehicles. While some uncontrolled factors might still remain, the data shows that achieving a tolerance of ±0.1 in the estimation of the pathloss exponent requires at least 4 runs (11 minutes with 10 vehicles) under extremely light traffic and 15 runs (48 minutes with 10 vehicles) under moderate to heavy traffic on our evaluated 2 km highway stretch. Future work will focus on obtaining highly parameterized realistic propagation models suitable for V2V communication simulation under various traffic conditions.

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