Effect of Antenna Placement and Diversity on Vehicular Network Communications

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Abstract— **In this paper we present empirical results from a study examining the effects of antenna diversity and placement on vehicle-to-vehicle link performance in vehicular ad hoc networks. The experiments use roof- and in-vehicle mounted omni-directional antennas and IEEE 802.11a radios operating in the 5GHz band, which is of interest for planned inter-vehicular communication standards. Our main findings are two-fold. First, we show that radio reception performance is sensitive to antenna placement in the 5Ghz band. Second, our results show that, surprisingly, a packet level selection diversity scheme using multiple antennas and radios, *Multi-Radio Packet Selection (MRPS)*, improves performance not only in a fading channel but also in line-of-sight conditions. This is due to propagation being affected by car geometry, leading to the highly non-uniform antenna patterns. These patterns are very sensitive to the exact antenna position on the roof, for example at a transmit power of 40mW the line-of-sight communication range varied between 50 and 250m depending on the orientation of the cars. These findings have implications for vehicular MAC protocol design. Protocols may have to cope with an increased number of hidden nodes due to the directional antenna patterns. However, car makers can reduce these effects through careful antenna placement and diversity.**

I. INTRODUCTION

Advances in vehicular ad hoc networking technology enable novel safety, information, and entertainment applications. Safety applications such as an extended electronic brake light or intersection collision avoidance reduce vehicle collisions by sending warning messages to notify cars and their drivers of dangerous situations. Other information and entertainment applications include distribution of real-time traffic information and media distribution, which require effective routing and resource management to alleviate congestion. To be effective, these applications require low latency and highly reliable vehicle-to-vehicle communication protocols. The development of coding, automatic repeat request, and cooperative retransmission schemes to achieve high reliability all require a detailed understanding of radio propagation.

To inform protocol development for VANETs, prior research has focused on measuring propagation and packet loss patterns(e.g., [1], [2], [3]) in different roadway and urban environments. These measurements were conducted with a single antenna mounting position and the simulation models based on these measurements all assume omnidirectional propagation from each vehicle. Other prior work in the antenna design community has shown, however, that for the 900Mhz and 2 GHz band [4], [5], [6] achieving omnidirectional propagation with roof-mounted antennas is a non-trivial task. Moreover, these studies show that results vary with the frequency band—thus, it remains unclear how Dedicated Short Range Communications in the 5GHz band is affected by antenna placement.

To add to these physical layer related issues, antenna design for WAVE/DSRC systems is constrained by practical limitations on antenna height and placement. WAVE radios may be packaged in small units that can be mounted on the inside windshield near the rearview mirror, to accelerate deployment.[1] Even longer term designs for new vehicles will have to minimize antenna height to protect them against vandalism and other damage. Antenna designs for cellular networks have been extensively studied [7]. However, it is difficult to directly apply this experience to V2V communications, predominantly because of differences in antenna height and placement. Thus, it is important to experimentally understand how different mounting positions affect V2V communications.

This paper addresses the above by quantifying IEEE

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[1] Several electronic toll collection systems such as EZPass in the New York metro area already use this mounting position for tags.

802.11a performance using a vehicular testbed with 5 antennas mounted on the vehicle rooftop and one inside-windshield position. These 802.11a results provide a useful data point for the IEEE 802.11p standard under development. Although, our experiments focus on characterizing single link performance the results have direct implications for ad hoc network MAC protocol design. Specifically, key contributions include:

- Identifying that 802.11-based communication systems in the 5GHz band with roof-mounted antennas are significantly affected by the car geometry. We characterize the effect on antenna patterns and measure up to 15db received signal strength differences depending on the angle of arrival in an open space environment under line-of-sight conditions.
- Confirming that these received signal strength differences are also reflected in significant packet error rate variations over different angles of arrival.
- Showing that the effect of car geometry can be alleviated through careful choice of the mounting position (center mount) or through antenna diversity. The use of multiple antennas also provides improved receiver performance. These multi-radio diversity gains through selecting among multiple antennas and radios are higher than expected even in a LOS environment due to the effect of vehicle geometry.
- Discussing implications on protocol design for vehicular networks.

The remainder of this paper is structured as follows. The next section briefly discusses prior work in empirical channel modeling studies and antenna design. Section III describes our vehicular testbed as well as a description of the experiments performed. Section IV describes the results and explores the effect of antenna placement on directionality, effect of vehicle (car) geometry and gains from using more than one antenna. We then discuss protocol design issues in section V before concluding in section VI.

II. BACKGROUND AND RELATED WORK

The IEEE 802.11p draft standard [8] adapts the IEEE 802.11a MAC and PHY to provide increased robustness in an outdoor, high-speed vehicular environment. It is designed to operate at 5.9Ghz and for most applications, it uses transmission powers of up to 2W Equivalent Isotropically Radiated Power (EIRP). It also allows for EIRP as high as 30W for critical applications like public safety to enable LOS transmissions up to a distance of 1000m. Despite the use of these high transmission powers, obstructions from roadside features and larger vehicles are expected to affect communication system performance. Since the maximum transmission power is governed by FCC regulations, this motivates research to improve reliability at the antenna and protocol layers.

As we pointed out earlier, antenna design for vehicular networks is constrained by vehicle height and deployment considerations. Thus, we expect a range of different designs to emerge. For example, the DSRC community currently considers antenna mounts on the side-mirror, on the rear-center rooftop, and on the windshield inside the vehicle, to name a few. This motivates our work, in which we explore the performance characteristics of different antenna options and discuss their potential impact on protocol design.

In [9], [10], the authors emphasize the importance of detailed simulation models to describe the wireless channel and point out how changes in these models can affect relative performance of higher-layer protocols. The results of existing 802.11 measurement studies from indoor environments (e.g., [11], [12] or stationary outdoor mesh networks (e.g., [13]), are not directly applicable to vehicle-to-vehicle communications due to difference in antenna type, height, mounting, rate of change in environment, for example.

Thus, several studies have concentrated on short-range vehicle-to-vehicle communications. Using 802.11-based systems, transport layer throughput and packet loss measurements were conducted by Wu and colleagues [14] for vehicle-to-vehicle and vehicle-to-roadside communications, by Hui and colleagues in [15], [3] with a special emphasis on multi-hop routing over vehicles, and by Ott and Kutscher [16] for vehicle-to-roadside communications. These studies characterize throughput, latency, and packet loss at the transport layer. However, they do not characterize propagation effects and antenna dependencies using 802.11 devices.

Channel models for Vehicle-to-Vehicle (V2V) communication were built using empirically measured data by Taliwal and colleagues [2] and for the 60 GHz band in [17]. These studies concentrate on identifying the communication range and on channel modeling and do not address the effects of antenna placement or vehicle orientation on system performance.

Prior work in the 900Mhz spectrum [5], shows that antenna placement affects antenna pattern distortion, that the top-center position on the roof provides near-omnidirectional coverage, and that signal attenuation up to 10dB can occur inside vehicles [18]. For 2 GHz, non-uniform beam patterns for roof-mounted omnidirectional antennas are reported in [4] due to the potential creation of a local multi-path environment on the vehicle's roof. The construction of an antenna with specialized ground plane for omni-direction coverage is described in [6]. Note that these studies consider lower frequency bands and it remains unclear how significant the effects are in the 5GHz (V2V) band. This motivates our effort of conducting measurements for an 802.11 system at 5.18Ghz. Whereas the previous studies used channel sounding equipment, in our experiments we concentrate on characterizing received power and packet error rates of an actual, low-cost 802.11 implementation.

The use of multiple antennas to achieve spatial diversity and the combining of different signals received over different antenna "branches", is a well known technique to alleviate the affects of fading [19]. In general, increasing the number of antennas can mitigate the effect of channel fading [20], [21]. However, these works do not address diversity gains under LOS conditions.

III. EXPERIMENTAL METHODOLOGY

This work seeks to characterize how 802.11 performance is affected by different antenna placements on vehicles. We concentrate on measuring performance characteristics of a complete 802.11 system implementation rather than detailed channel sounding.

Our measurements are based on 802.11a, since these radios are more readily available, as compared to "pre-standard" 802.11p radios. In addition, 802.11a MAC and PHY protocols are similar to those under consideration in the emerging 802.11p standard. Both 802.11p and 802.11a support the same modulation and coding schemes as well as training sequences. However, a few differences remain. The 802.11a radios use 5.18Ghz, compared to 5.9Ghz DSRC band. In addition 802.11p uses a larger guard interval, which makes it less susceptible to inter-symbol-interference in outdoor environments. Moreover, it uses 10Mhz channels, which respond differently to frequency selectivity of the wireless channel in such environments. Overall, due to the smaller guard intervals, our 802.11a measurements likely serve as a lower bound for future 802.11p performance. More importantly, however, our goal is to provide *relative* performance comparisons of different antenna placements, rather than absolute performance bounds. Insights obtained from these comparisons will likely also be valuable for 802.11p designs.

We choose the received signal strength indicator (RSSI) and packet error rate (PER) as performance metrics. RSSI is an estimate of the signal energy at the receiver. According to the standard it is calculated over the PLCP preamble (12 OFDM symbols in 802.11a) of a frame. It is reported by all commodity wireless NICs on proprietary scales. RSSI values reported by the Atheros 5212 chipset used in our experiments can be converted onto a dbm scale by subtracting 95 from the RSSI value. This is substantiated by calibration experiments with a vector signal generator shown in Fig. 1. The graph shows for two different cards the reported RSSI values for a beacon packet with different received power levels. Actual received power is caculated by substracting the cable and connector loss from the vector signal generator's transmission power setting. Note that the RSSI values match actual power values within about 2 db and that a unit change in RSSI corresponds to a db change in received power. For a given received power, the reported RSSI values across across different cards are within 1-2 db of each other.

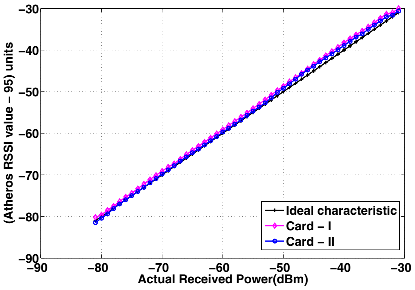


Fig. 1. Atheros RSSI $-95dbm$ vs Actual Received Power. An RSSI unit is equivalent to a db.

While not as accurate as RF instrument measurements, the RSSI measurements are of value for practical mechanisms which must depend on RSSI readings in real deployments. Note that neither RSSI nor PER can individually provide complete information on the radio channel. Since most of 802.11 NICs report RSSI only if a frame is correctly decoded, mean RSSI measurements are biased toward higher values at the fringes of the communication range. On the other hand, PER is meaningful only at the fringes of the communication range, it provides little differentiation on a good channel where all packets are received.

We discuss key aspects of our experimental platform, setup and methodology in the following sections.

A. Hardware and Software Configuration

Each vehicle contains a small form factor PC with a 1-GHz VIA C3 CPU, 512 MB of RAM, and a 20 GB local hard disk running Debian GNU/Linux with the

(a) (b)

Fig. 2. Hardware setup (a) and placement of antennas (b).

TABLE I

DEFAULT EXPERIMENTAL PARAMETERS USED

Parameter	Value
Wireless Card	Atheros 5212 chipset
Driver	MadWifi
MAC and PHY protocol	802.11a
Frequency	5.18 GHz
Transmit Power	40 mW
Antenna Type	folded dipole
Antenna Gain	3dBi
PHY Data Rate	6 Mbps
ICMP Payload size	56 bytes
Transmission Frequency	1000 packets per second

2.6 kernel. These nodes are equipped with two IEEE 802.11a/b/g interfaces based on the Atheros 5212 chipset (this is the same hardware platform as used in the ORBIT indoor testbed, described in more detail in [22]).

In addition, we use

- Magnetic mount external antennas for 2.4/5GHz.
- 12-to-120V power inverter that serves as the power supply (via the car battery).
- Garmin eTrex GPS devices for speed and location.

The main components of the hardware setup are shown in Figure 2(a).

Our software transmits 1000 frames per second at 6 Mbps (the lowest rate), since RSSI is only calculated when a frame preamble is received, and the fade duration in Rayleigh environments can be on the order of milliseconds or less. The use of broadcast mode suppresses MAC-level features such as retransmissions, acknowledgments and RTS/CTS and enables us to measure the packet error encountered due to impairments suffered at the PHY layer. We modified the UNIX *ping* program to control the duration of time between two outgoing frames, each a 56 byte payload ICMP packet, to be on the order of hundreds of microseconds and assign it the highest run-time priority. Using this approach we were able to consistently generate packets at millisecond granularity, without noticeable packet loss in indoor tests.

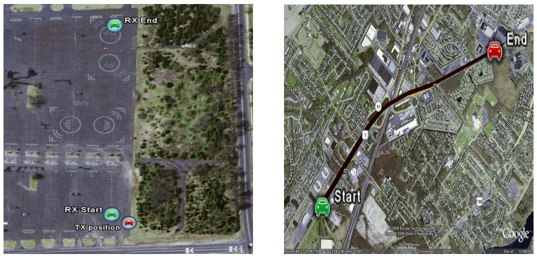
We chose a low transmit power of 40mW, to reduce the amount of space needed for our experiments. The results could be scaled to higher transmit powers considered in DSRC. The default parameters used in our experiments are summarized in Table I.

Since the association protocol has been changed in 802.11p, we disable the 802.11a association protocol by operating all receivers in *monitor* mode. In this mode a node can passively listen to all data on a particular channel without being associated, meaning that packet errors can be caused only if frames are not detected or are corrupted and not by a loss of association. The receiver sniffs the packets from the wireless interface using the *tcpdump* [23] utility, which gives it relevant information on a per packet basis from both the physical layer (PHY) as well as the 802.11 MAC layer. Currently, the information captured includes the PHY layer bit-rate, RSSI as measured by the Atheros wireless card, per-frame Atheros receiver timestamp with a microsecond granularity and complete 802.11 header information (including MAC sequence numbers). The packet error rate (PER) is computed by making use of 32-bit sequence numbers which are incremented by the transmitter for every successive packet. The sequence number is transmitted as a part of the ICMP payload.

In addition, all the nodes continuously log their location and speed information using a GPS device once per second. The system time on each node is set to the GPS time so that the system clocks of all nodes are synchronized. The transmitter includes its timestamp in the ICMP packet's payload so that the receiver can correlate its GPS record with the corresponding GPS record of the transmitter.

Two cars are used in all experiments, one configured as a transmitter (*TX Car*) and the other as a receiver (*RX Car*). Figure 2(a) shows the hardware setup used in the TX Car, which is fitted with a single folded dipole antenna in the center of the roof. The *RX Car* is fitted with a total of six antennas, and carries 3 PCs, with each antenna connected to one of the six radios. Five antennas are placed on the car roof and one inside the car as shown in Figure 2(b). As indicated in the figure, the antenna positions are referred to as Front Driver (FD), Behind Driver (BD), Front Passenger (FP), Behind Passenger (BP), Car roof Center (CC), and Rear View mirror (RV). Note that the RV antenna is attached to the mirror inside the car.

We conducted experiments to evaluate and understand



(a) Receiver moves away from and towards a stationary sender.

(b) The freeway path.

Fig. 3. Experiment locations

the affect of different antenna positions on performance of vehicular networks. Below, we list the different experiment scenarios and their objectives.

B. Open Space Baseline

This experiment evaluates the effect of *RX Car* geometry on the signal transmitted by the *TX Car*. The *effect of car geometry* is the effect on packet reception of the absolute antenna position at the *RX Car* and the relative orientation of the transmit antenna (at the *TX Car*) with respect to the antenna at the *RX Car*. The effect can cause asymmetric antenna patterns at the *RX Car*.

We quantify the effect using the metric of per packet RSSI observed at the *RX Car*. In general the signal received is affected by the signal propagation environment that is a result of various factors like the propagation path, surrounding structures, and mobility of communicating nodes and the surroundings. To reduce effects not due to car geometry, we conduct the experiment in an open space environment with no identifiable nearby scatterers and diffractors. We also begin by characterizing remaining environmental effects using an RX antenna on a tripod stand instead of on the car. The height of the tripod is adjusted to the car height.

During the experiment the *TX Car* transmits packets, see Table I, driving around the tripod in 7 equally spaced circles of radii between 12 feet and 72 feet. Next, the experiment is repeated with the tripod replaced by the *RX Car*, with its six receiving antennas.

C. Parking Lot and Freeway Experiments

The parking lot experiments further characterize the magnitude of antenna performance differences in environments with significant scatterers and diffractors and under NLOS conditions.

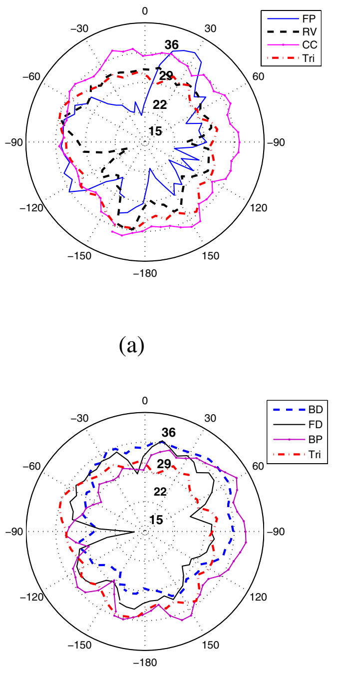
The *RX Car* drives along three rectangular paths of increasing perimeter around the *TX Car*, up to a maximum distance of 60m. Each path is repeated thrice. This experiments aims to collect samples for the same inter-vehicle distance at different locations and with different car orientations, thus it allows averaging out some effects of surrounding structures and other temporal characteristics. Changing orientation of the *RX Car* with respect to the *TX Car* will lead to different parts of the *RX Car* geometry affecting an antenna placed in or on the *RX Car*.

We conducted experiments in two additional parking lots, one office parking lot (WINLAB) and one shopping mall lot (WALMART). The WINLAB parking lot is surrounded by office buildings and a number of vehicles were parked on the lot during the experiment. Movement in the environment (other than the experiment cars) was very limited. The WALMART parking lot contains many rows of densely packed vehicles and a shows a continuous influx and outflow of shoppers. Line of sight between the *RX Car* and *TX Car* was frequently obstructed at WALMART, but more rarely at WINLAB. We also conducted a similar experiment, although with extended maximum inter-vehicle distance of 250m, at the Livingston parking lot to provide a baseline for a largely open-space environment, save for sparsely distributed trees and street lights on the parking lot. No other fixed structures exist in the vicinity of this parking lot.

The freeway experiment is considerably different from a parking lot because both experiment cars are moving, and the presence of other vehicles moving at high speed. We conduct this experiment on a 2.7 mile stretch of US Highway 1, in New Jersey. This is a busy 3 lane freeway and a snapshot of it is shown in Figure 3(b). The *TX Car* and the *RX Car*, drive along this stretch making two loops during moderately high traffic conditions. They maintain an average speed of 50 mph, intermittently switching lanes and overtaking each other, while maintaining a maximum distance of 60m, mostly staying within line of sight.

IV. EXPERIMENTAL RESULTS

In this section we present the results of the experiments defined in Section III. We first show that omnidirectionality of antenna patterns is affected by the antenna's position on the car and its orientation with respect to the transmit antenna (*effect of car geometry*). We quantify the asymmetry introduced in the antenna pattern by showing that the *effect of car geometry* can make considerable difference to the perceived link quality, measured in terms of packet error rate seen at the receiver. The difference is found to be similar in different propagation environments. Finally, we discuss



(a)

(b)

Fig. 4. RSSI received at antenna (a) BD, FD, BP and (b) FP, RV, CC, compared to the antenna on a tripod.

an antenna diversity technique than can alleviate pattern distortion and provide additional diversity gains.

A. *Effect of Car Geometry on Antenna Patterns*

We perform Experiment *Open Space Baseline*, section III-B, to measure the receive patterns of the six antenna placed at the *RX Car*. To accomplish this we measure the change in the RSSI received at an antenna placed on the *RX Car* as the position of the *TX Car* changes. Note that for a circular path the distance of the transmit and receive antennas remains approximately the same. Given that the experiment is performed under strong LOS conditions, one might expect RSSI to remain constant while the *TX Car* circles the receiver. Figure 4 shows the effect of changing *TX Car* position on different RX antennas. The *RX Car* is facing north and is placed at the center of the polar plot. The plots only show the results for 72 ft radius, since other radii lead to similar results.

From these graphs, we make the following observations:(i) most antennas show strong asymmetric patterns, with up to 10dB variance (on Atheros cards one RSSI equals ca. 1 dB); (ii) the CC mounted antenna shows the most omnidirectional pattern, apparently the top-center position is also preferable in the 5 GHz band; (iii) the baseline experiment with the tripod mounted RX antenna, in contrast to most other antennas, shows a typical omni-directional pattern.

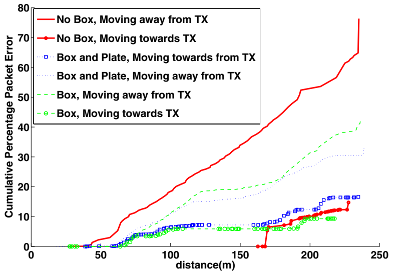


Fig. 5. Performance of antennas at different heights

The tripod baseline indicates that the presence of the car geometry affects these measurements. This motivates us to quantify the effect of asymmetric patterns on the communication link between the *RX Car* and the *TX Car*.

B. *Effect of Car Geometry on Communication Link*

In this experiment the *TX Car* is parked in one corner of an empty and isolated parking lot. The *RX Car* drives away and then returns, at a speed of approximately 5 miles per hour. The *RX Car*'s trajectory is a straight line joining placeholders *RX Start* and *RX End* (approx. 180m apart) shown in Figure 3(a).

We choose the *cumulative percentage packet error* (CPPE) to characterize the relative performance differences due to antenna placement in the following experiment, since the same distances and locations are repeatedly visited during the experiment. We define the cumulative packet error (CPE) for distance d as the total count of lost packets at all distances less or equal to d. We can then derive the CPPE through dividing CPE by the total number of packets sent during the experiment. The slope of a CPPE curve corresponding to an antenna position is determined by the packet error rate at a given distance as well as the distribution of distances covered in the experiment. The latter affects different antenna curves in the same way.

The plots corresponding to *No Box* (antenna placed on car roof) in Figure 5 show PER of the order of 80% at 230m when the *RX Car* moves away from the *TX Car*. In contrast the plot for the return trip shows only 10% PER. Note that the two runs are performed on the exact same path and the vehicles always remain in line-of-sight. This difference is apparent even at small distances of 50-70(m). Repetitions of the experiment at different

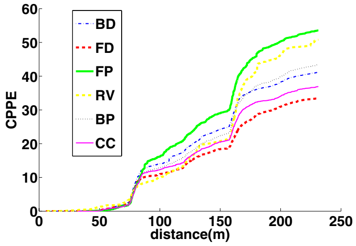
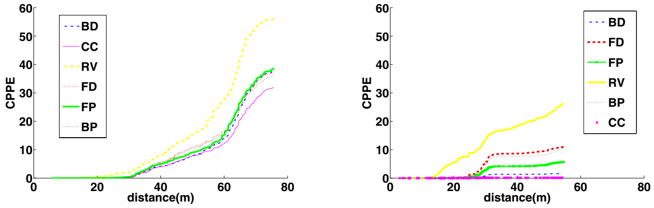


Fig. 6. CPPE comparison of antenna positions, Livingston parking lot experiment (section III-C).



(a) (b)

Fig. 7. Performance comparison of antennas at (a) WALMART and (b) WINLAB.

times of day and in different locations showed similar results. These findings corroborate that car geometry affects propagation significantly.

The car geometry effect should be reduced, if the antenna is raised higher over the vehicle. Thus, we repeated the above experiment by placing a 30cm tall cardboard box on the roof of the car, and fixing the antenna on top of this box. We also experimented with an additional steel plate as a ground plane, motivated by improvements reported in [24].

The results from these experiments are also reported in Figure 5. While the steel plate only provided a marginal improvement, sizeable CPPE improvements were obtained by increasing the height of the antenna placement, above the car roof, using a box. To ensure that our results are not artifacts of a specific antenna make, we further experimented with three different folded dipole antenna makes. While the antennas showed differences in the gain patterns, all showed packet error losses starting at distances of about 50m. The reported results are for the best antenna make.

Substantial differences in packet error rates due to the *effect of car geometry* were obtained in a LOS environment with no other moving traffic. It is not clear whether these effects can also be observed in more realistic dynamic multi-path environments. Next, we will study results from busy parking lots.

C. Effects of Antenna Placement in Dynamic Parking Lot Environments

Here, we compare the effect of vehicle geometry in the near-LOS environment of the isolated Livingston parking lot with the near-NLOS multipath environments at the WINLAB and WALMART parking lots.

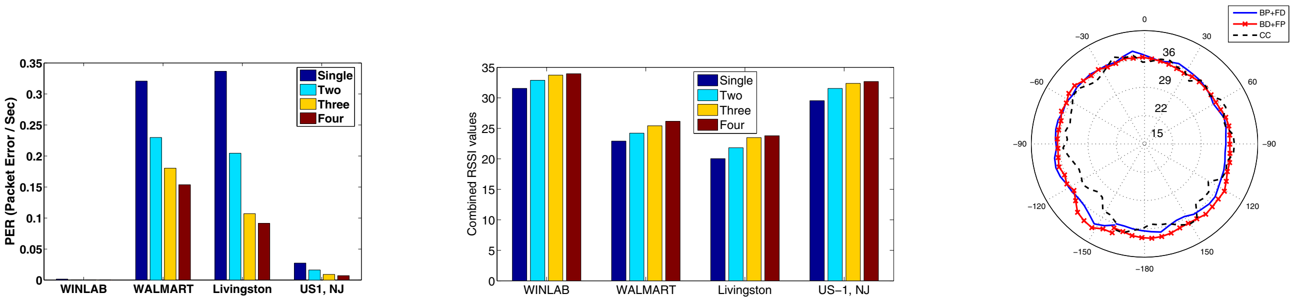
Figure 6 shows the CPPE comparison between all six antennas obtained for the Livingston parking lot experiment. Recall from section III-C, that in this experiment the *RX Car* with the six antennas drives around the *TX Car* in rectangles of different size. All antennas (except the inside antenna RV) are in LOS of the TX during the entire experiment. As expected based on the previous results, Figure 6 shows that a significant 25% CPPE difference exists between antenna positions. In this particular instance, *FD* performs best and FP shows the highest error rate, although this can be expected to vary with different environments.

Note that RV shows good performance for distances of 70-150m after which its performance deteriorates markedly compared to the other antennas. Inspecting the RSSI values of received packets, we find that their mode is about 7 RSSI points higher than other antennas. Its good performance at short distances may be due to less car diffractions and reflections. At longer distances it may be more likely to move into NLOS conditions compared to the other antennas, which would explain its deteriorating performance.

Figure 7, finally shows the CPPE comparison for the NLOS-dominated WINLAB and WALMART parking lots. Here, CC is the best performing single antenna and FD only shows average performance. It is insightful to observe that the difference in the performance of the best and the worst performing antenna at all the parking lots is between 25-30%. This shows that the *effect of car geometry* on antenna performance did not vary much with changing propagation environments (NLOS and LOS).

D. Diversity Gains

The performance differences across antenna positions at the *RX Car* motivated us to investigate the gains obtainable by exploiting multiple antennae. Note, that we can only consider *Multi-Radio Packet Selection (MRPS)*, since our antennas are connected to different radios. We consider a packet correctly received if it passes the CRC check on at least one of the radios. This notion differs from traditional diversity techniques at the physical layer, which counter fading [25]. It is more similar in nature to



(a) Diversity gains, in terms of PER.

(b) Diversity gains in terms of RSSI

(c) Smoothing of antenna patterns using diversity

Fig. 8. Diversity gains using MPRS. Comparison of the best single antenna with the combination of best 2, 3 and 4 antennas.

multi-radio diversity which aims to exploits differences in shadowing across widely distributed receivers [21]. Overall prospects for gain appear low, since the antennas are positioned too close for significant differences in shadowing, and the approach cannot exploit gains achieved by combining uncorrelated fading paths in a highly dynamic radio environment.

Still, our results show 10-15% reductions in PER for two antennas at WALMART and even under LOS conditions in the LIVINGSTON experiment, as depicted in Figure 8(a). A further $5-10\%$ may be acheived by using the best combination of three antennas. Choosing the best combination of four gives a marginal improvement over the combination of three. In terms of PER, the gains for the WINLAB and US1 look smaller, because in these trials the overall number of packet errors was too small.

Figure 8(b) shows the gains in term of RSSI, essentially the RSSI difference between the strongest and weakest antenna for packets that were correctly received on all antennas. The plot shows a gain of 2-5 dB (on the Atheros hardware one RSSI point is approximately equal to one dB). Here, WINLAB and US1 show similar gains.

Overall, this indicates that diversity gains can be achieved in the LOS, multipath, and highly dynamic freeway LOS environment. We attribute these gains to the difference in antenna pattern due to the vehicle geometry effect.

Figure 8(c) also shows that this diversity technique leads to more omni-directional gain patterns. The graph shows combinations of the FD&BP and FP&BD antennas and both cases show more isotropic patterns than the center antenna. This technique may be useful if center rooftop installation of antennas is not possible (e.g., because of light bars in emergency vehicles, or because devices should be mounted inside cars for ease of installation).

V. EFFECTS OF ANTENNA PLACEMENT ON VEHICULAR PROTOCOL DESIGN

Our experimental results show that antenna placement significantly affects receiver performance. Even though the antennas' specifications claim isotropic gain patterns, Figure 4 shows that the RSSI patterns of different antenna positions deviate up to 15dB from the ideal isotropic gain patterns. These differences can cause packet errors at surprisingly short distances of 50m LOS for 40mW transmit power.

The following simulations evaluate the effect of these asymmetric patterns in network sizes beyond experimental capabilities. We conduct the simulations using ns-2 with CMU extensions [26] with the following simulation parameters:

- Number of nodes: 100, Area - 2Km X 2Km, Speed: 40m/s, Mobility model: random waypoint
- Transmission range: 250m, Carrier sense range: 550m.
- Packet size: 100 bytes, sent periodically (period selected randomly from (0.75, 1.25) seconds),
- Simulation time: 500 seconds.

We further modified the propagation model to account for antenna asymmetry. For each antenna in Figure 4, to approximate antenna patterns observed in experiments. The received signal strength is first calculated through ns-2's 2-slope two-ray propagation model. We then subtract the gain loss based on angle of arrival, which is obtained from a lookup table initialized with the empirical data. As in the default ns-2 model, a packet will be received if the resulting signal strength is greater than a reception threshold.

Note that channel utilization is very low and we expect packets to be in error due to limited transmission range

TABLE II

SIMULATION RESULTS.

Antenna Position	#(packets received)	%(packets received)
FP	79437	25.34
RV	138814	44.28
BP	141392	45.11
BD	143005	45.62
FD	164807	52.58
Tripod	182631	58.26
CC	226213	72.17
Ideal Antenna	313425	100.00

or hidden-node collisions, rather than MAC collisions due to congestion.

Table II shows the number of correctly received packets at different antenna positions assuming the asymmetric antenna patterns plotted in Figure 4. For each antenna position, we sum packets received at all the 100 nodes. The last row, corresponding to the *Ideal Antenna*, represents an antenna with unity omni-directional gain. In other words, RSSI for each received packet is obtained using the two-slope propagation model alone, without considering any antenna effects. Our observations are as follows. Since we are only considering the propagation environment, the *Ideal Antenna* receives the maximum number of packets and outperforms other antenna positions. CC performs second best. which may be attributed to the antenna pattern of CC, which is very close to omni-directional. Similarly, the poor performance of FP can be explained by its antenna pattern, which has a lot of significant dips in RSSI with changing angle. In summary, we observe significant imbalances between the different antenna positions, in terms of number of successfully received packets. This will have implications for reliability protocols at the MAC layer.

A. Discussion

We expect that our results could have serious implications on the behavior of higher layer protocols and vehicular networking applications. At the MAC layer, these RSSI patterns could imply hidden terminal problems [27] (due to asymmetric directional gain and the ineffectiveness of RTS/CTS frames), specifically associated with the use of directional antennas. Node deafness [28] is another problem that could arise, where two nodes are unable to communicate because their antenna beams are formed in different directions. At the network layer, neighbor discovery (a node needs to be aware on which antenna beam its one hop neighbors lie on)[29] could be affected by the non-uniform RSSI gains reported here. Further, our results (in section IV-D), which show the advantages of using multiple antennas on a car's roof, motivate further investigation of diversity techniques in higher layer protocols (e.g., [21]). From an applications perspective, safety messages need to be delivered with low latency and high reliability. Differences in the assumptions made about the effect of antenna position can lead to significant differences in the results of different broadcast protocols. To conclude, we also hope that our results motivate, and contribute toward the continuous improvements to simulation models for VANETs.

VI. CONCLUSIONS

This paper presented an experimental study of the effect of antenna position in vehicular networks that use frequencies in the 5Ghz band. We have measured the relative performance of several vehicle mounted antennas connected to 802.11a radios in terms of packet error rate and received signal strength indicator, in an open space isolated parking lot, populated parking lots, and a freeway environment. Specifically, we observed that

- Antenna positions lead to 25-30% difference in cumulative link PER performance in our experiments using the 5Ghz band, the band of interest for V2V communications. We showed results using off-the-shelf 802.11a hardware at a frequency of 5.18Ghz.
- Antenna gain patterns of omnidirectional antennas become asymmetric in many mounting positions, showing distortions with a spread of up to 15db over different angles of arrival for an 802.11a radio at 5.18 GHz. To create a good approximation of omni-directional characteristics, the antenna should be mounted in the center of the vehicle.
- A packet level diversity technique that collects packets received from all antennas at the receiver and discards duplicates can provide 10-25% gains in packet reception rate and 2-5dB gains in received packet RSSI in vehicular networks, even in strong LOS environments, as it alleviates the *effect of vehicle geometry*. This provides an alternative if center mounting is not feasible.

We have also discussed the effect of these observations on vehicular network applications. As future work, we plan to build channel models for different antenna configurations in different propagation environments. Such models will be integrated with current network simulators (e.g., NS-2) for more realistic simulations. We are also investigating the tuning of parameters in previously proposed protocols and applications for vehicular networks given the observations mentioned in this work.

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