Exploratory Study of 802.11ad Vehicular Links

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***Abstract*—IEEE 802.11ad leverages the large channel widths available in the 60 GHz mm-wave unlicensed spectrum to provide high throughput. Due to the high propagation loss at these frequencies, 802.11ad uses highly directional beamforming and constructive multipath to achieve indoor ranges of up to 50 m. It has been shown that 802.11ad links can be used outdoors for vehicular communications, but ranges tend be very short when few or no reflectors are present. While carrying out vehicular experiments with mobility, we occasionally observed communication ranges of up to ∼30 m. We hypothesize that the cause lies in constructive reflections on the vehicles' roofs, which function as ground planes. In this paper, we report preliminary results on the experiments and our efforts to quantify the roof's ground plane effect using TP-Link Talon AD7200 802.11ad routers.**

***Index Terms*—802.11ad, vehicular communications**

I. Introduction

IEEE 802.11ad is a WiFi standard aimed at leveraging the large 2.16 GHz-wide channels available in the 60 GHz frequency band. It uses highly directional beamforming to mitigate the high propagation loss inherent to the high frequencies used, and thanks to constructive multipath it has been shown to achieve indoor ranges up to 50 m [1].

It has been shown that 802.11ad links can be used outdoors for vehicular communications, using laboratory-grade hardware [2]. However, the range can be very short in the absence of reflector objects. While carrying out vehicular experiments with mobility, using Commercial Off-The-Shelf (COTS) equipment, we occasionally observed unexpectedly high throughputs of over 100 Mbps at communication distances of up to ∼30 m. We hypothesise that the cause lies in constructive signal reflections on the vehicles' roofs, which function similarly to ground planes. A ground plane is a reflective surface that has the same effect on the antenna radiation pattern that the Earth's surface would have, were the antenna mounted on the ground. A previous study has shown that sunroofs can have similar coverage range impact for inter-vehicular communication for 802.11p operating in the 5.9 GHz band, in [3]. Other work has shown the impact of antenna attachment to the roof on the radiation pattern [4]. However, the impact of a car's roof, or a similar metallic surface, has not been thoroughly studied for the 60 GHz mm-wave band.

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In this paper, we present preliminary results of real-world measurements with COTS 802.11ad equipment, and attempt to experimentally validate the hypothesis that the roof impacts the inter-vehicle communication range for 60 GHz 802.11ad[1] Our main contributions are as follows:

- We show 802.11ad can support a longer communication range in vehicular environments than initially thought;
- We provide preliminary quantification of the impact of a metal surface placed under a communicating COTS 802.11ad router.

II. Related Work

The behavior of the COTS 802.11ad device available at IT Porto, the TP-Link Talon AD 7200, has been thoroughly characterised in both [5] and [6]. However, these works focused on indoor environments, with either no or low-speed mobility. The use of the 60 GHz unlicensed band for high data rate vehicular applications has also been studied. In [2], the authors showed communication with a moving vehicle over a 60 GHz radio link is possible, using fixed horn antennas of multiple beamwidths. They characterized connection duration in various road environments. In [7], the possibility of using 802.11ad in vehicular scenarios was evaluated using ns-3 simulations. However, these studies neither characterized the communication range, nor used COTS equipment. Recently, a driving study with Tensorcom 802.11ad modules [8] showed that distances up to 20 m can be covered, but throughput at those distances was not measured. Moreover, the modules were installed in such a way that there was no roof beneath the communicating antennas.

III. Real-world 802.11ad Vehicular Experiments

With the goal of analyzing 802.11ad connectivity under vehicular mobility, we performed measurements outdoors, using COTS 802.11ad devices mounted on the roof of two vehicles. The experiments were carried out near an intersection with buildings on just one corner, shown in Figure 1. The distance from the building to the edge of the road was 5 m and to the centerline was 8.6 m (distances estimated from Google Maps).

Experimental Setup: The vehicles consisted of (1) a small van (Peugeot Partner, height: 1.7 m); and (2) a medium-size car (VW Golf Mk3, height: 1.4 m). Three TP-Link Talon

[1]Note that the roof is not exactly a ground plane for the studied routers, because the antenna array is not directly attached to the roof and is actually several wavelengths above it.

Fig. 1: Map of the area where the experiments were carried out. GPS coordinates: 41.111935, -8.631083.

AD7200 routers - call them A, B and C - were mounted on the vehicles' roofs (see Figure 2):

- Router A was mounted on vehicle #1 and configured as a static AP (2.16 GHz channel, centered at 60.48 GHz).
- Router B was mounted on vehicle #2 and configured as a mobile client, connecting to A's network.
- Router C was also mounted on vehicle #2, but configured as a passive monitor. It ran `tcpdump` in order to capture the 802.11ad frames exchanged by routers A and B.

Router A was running TP-Link's original firmware and acted as an AP. Routers B and C ran Linux-based LEDE. The "front" of Router A faced the road, i.e., the direction of the antenna's 0° radiation pattern was perpendicular to the road.

Fig. 2: Experimental setup for the real world experiments.

We used a custom application to send and receive UDP segments at a target throughput of 1 Gbps, from router A to B, i.e. from AP to client. The resulting end-to-end throughput was measured and recorded at the receiver. The sender and receiver applications ran in separate laptops connected to the Gigabit Ethernet ports of routers A and B, respectively, in order to avoid overloading the CPU of the Talon routers.

Each experiment consisted in having vehicle #1 parked at a corner of the intersection, and vehicle #2 following a trajectory in which it approached the intersection from each of the four directions, and going through the intersection in each of the three possible ways (going straight, turning left, and turning right). All experiments began with the moving vehicle stopped next to the parked vehicle in order to guarantee the association of router B to A's 802.11ad network, and to the start of the transmission of UDP segments from A to B. This was done as a practical workaround for a bug/artifact observed and described in [9]. The GPS coordinates of the moving vehicle were recorded with a resolution of 1 Hz, using a Google Nexus 5 smartphone running Android version 6.0.1.

In order to be able to fuse the time-indexed data collected during the experiments, we synchronized all device clocks via NTP over a control 802.11n network, operating in the 2.4 GHz band for maximum range.

Data processing: We first merged GPS data, application-level throughput and 802.11ad frame data, using timestamp values as the merging key. We then divided the data points into blocks of contiguous time, i.e. data segments in which the time difference between each data point is within 1 second. Finally, in order to select segments with both 802.11ad connectivity and vehicle mobility, we selected continuous time blocks for which we had: (1) a mean application-level throughput larger than 0 Mbps and, (2) a mean speed larger than 2.5 m/s. The resulting dataset consists of 8 blocks, with durations ranging from 19 to 141 seconds, mean speed within 2.7 to 7.6 m/s and mean throughput within 17 to 82 Mbps.

IV. Controlled Experiments with Metal Surface

After occasionally observing unexpectedly high throughputs at large distances in the vehicular environment described in the previous section, we conducted experiments designed to test the hypothesis that the cause was reflections off the vehicles' metal roof. The experiments used the 802.11ad router configuration described in the previous section.

Experimental Setup: Figure 3 depicts our physical setup. Two tests were carried out:

- With Metal Surface: A 1.7 $\times$ 1 m aluminum sheet was placed on a wooden surface at a height of 1.35 m. Routers B and C (client and monitor, respectively) were placed directly on top of it. Router A (AP) was placed on a wooden surface 1.8 m above ground level.
- Without Metal Surface: All routers were placed on wooden surfaces. Heights were the same as the ones used in the experiments with the metal surface, so the ground plane construction variable could be isolated.

Measurements were taken at inter-device distances of 2.5, 5.0, 7.5, 10.0 and 12.5 meters, with 3 runs being performed at each distance. Each test had a duration of 60 seconds. The routers' front sides faced each other across an open area.

We used `iperf` for throughput testing. Router A was placed at a distance of 2.5 meters from B and C to initiate the connection, and then moved to the experiment's target distance. This was done as a workaround for connection establishment issues (also observed and described in [9]), equivalent to what was done in the vehicular experiments.

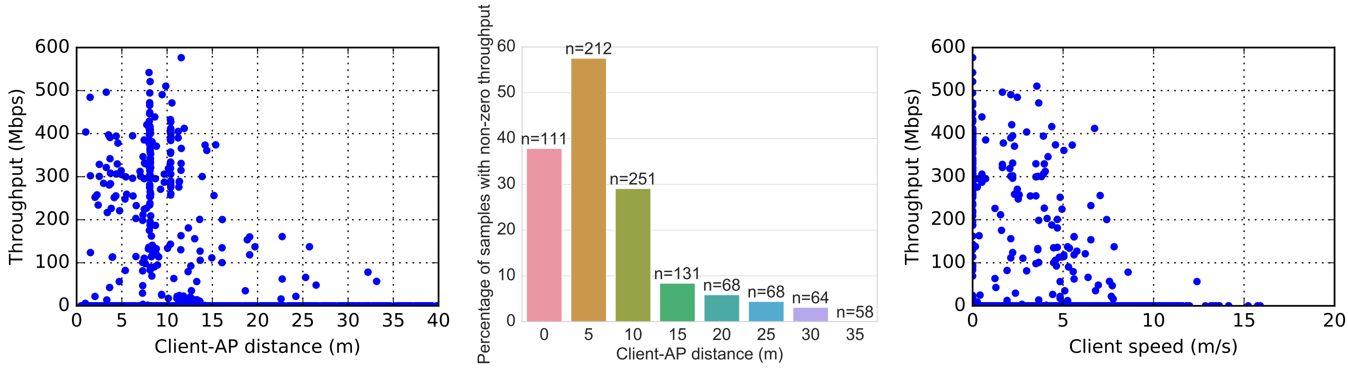
Fig. 3: Experimental setup for controlled ground plane static measurements. Note: plane height shown is not representative.

V. Results

A. *Real-world Vehicular Experiments*

Figure 4a shows the measured throughput, computed every second, as a function of the distance between the client and AP vehicles, calculated from both vehicles' GPS positions.

We can see throughput tends to decrease quickly with increased distance. However, there were occasions where



(a) Throughput function of client-AP distance. (b) Percentage of samples with non-zero throughput function of client-AP distance. (c) Throughput function of client speed.

Fig. 4: Vehicular experiment results.

throughput exceeded 300 Mbps at distances of up to ∼15 m, and 100 Mbps at distances of up to around ∼30 m.

Figure 4b shows the percentage of 1-second samples with non-zero throughput, i.e. where communication occurred, as a function of client-AP distance. Bins are 5-meters wide, and n represents the total number of samples in each bin. Communication occurred in 30% or more of samples for distances of up to 15 m (bin [10,15)). Communication at larger distances was rarer, with the [30,35) bin yielding a success rate of only around 2%.

Nevertheless, these results are better than expected, given the use of COTS devices, and the outdoor scenario with few reflectors. Recall that the only building near the intersection where the tests were performed was 5 m away from the edge of the road, making it unlikely that reflected signals would be strong enough to have a noticeable impact.

Figure 4c shows the measured throughput as a function of client vehicle speed, as measured through GPS. We can observe that speed and throughput are negatively correlated. Instances where non-zero throughput was observed are almost totally confined to speeds under 10 m/s. However, we note that speed and distance are correlated. The AP was placed near the intersection, and the client vehicle had to slow down when approaching it, to look for oncoming traffic.

Figure 5 shows the geometry of the locations where the highest throughput values were achieved, by plotting the average throughput in a 5 × 5 m square grid[2] for the 10 trajectories with the highest throughput. In almost all cases, the vehicle was moving away from the static AP.

The geometries yielding high throughput occurred for azimuths around 45°, and in the range [-25, -100]°, from the perspective of the transmitter (the stationary AP in vehicle #1). The most often-used sectors, which seem to be responsible for the highest measured throughput values by the transmit antenna, were sectors 10, 16, 20, 61 and 63. Their radiation patterns have broad lobes covering those azimuths, according to [6]. However, this was not true for all observations.

B. Controlled Ground Plane Experiments

The goal of these experiments was to validate whether the metallic car roof influences the vehicular link by working as a de facto ground plane. We start by comparing the distributions of average per-second throughput, calculated per-second, with and without ground plane. Figure 6a shows the corresponding boxplot, where the notches represent the 95% confidence interval for the median. We can see that the throughput obtained with a metal plane was higher than without. We did not receive any data packets at a distance of 12.5 m, hence the lack of throughput samples at that distance. However, we did receive the sector sweep frames when the metal plane was present, and both these and the sector sweep feedback frames when it was not. Figure 6b shows the chosen sectors obtained from the sector sweep feedback frames. We observe that the presence of a metal plane influenced the sector choices in a noticeable manner.

Finally, we carried out an unpaired hypothesis test for the received per-sector Signal-to-Noise Ratio (SNR) during the sector sweeps, for both transmitter and receiver, at each distance. We tested whether the lowest bound of the 95% confidence interval for the difference of the SNR means, with and without metal plane, is positive. The results of the various tests can be seen in Table I. Except for two cases, we can conclude with 95% confidence that the SNR received is higher when a metal plane is used. However, although the difference is statistically significant, its value is around 1 dB, which we do not consider sufficient to explain the throughput differences.

Distance [m]	TX	RX
2.5	[0.72;0.86]	[0.94;0.99]
5	[-0.03;0.07]	[0.25;0.29]
7.5	[1.06;1.15]	[1.04;1.08]
10	[0.82;0.88]	[0.93;0.98]
12.5	[0.54;0.65]	[0.00;0.033]

TABLE I: Results of the unpaired hypothesis test: 95% confidence interval for the difference of the means.

From these results, we conclude that the metal plane had a small but positive, and statistically significant, effect on the received signal outdoors. However, we could not replicate the 100+ Mbps throughput observed in the vehicular experiments at distances larger than 10 m. The distribution of used sectors in the controlled tests differed from the sector distribution in the vehicular experiments, and this may be part of the explanation for the different behaviors.

VI. Discussion and Conclusions

The results from our vehicular experiments show that COTS 802.11ad devices can realistically be used for vehicular com-

[2]GPS errors were estimated to be smaller than 5 m.

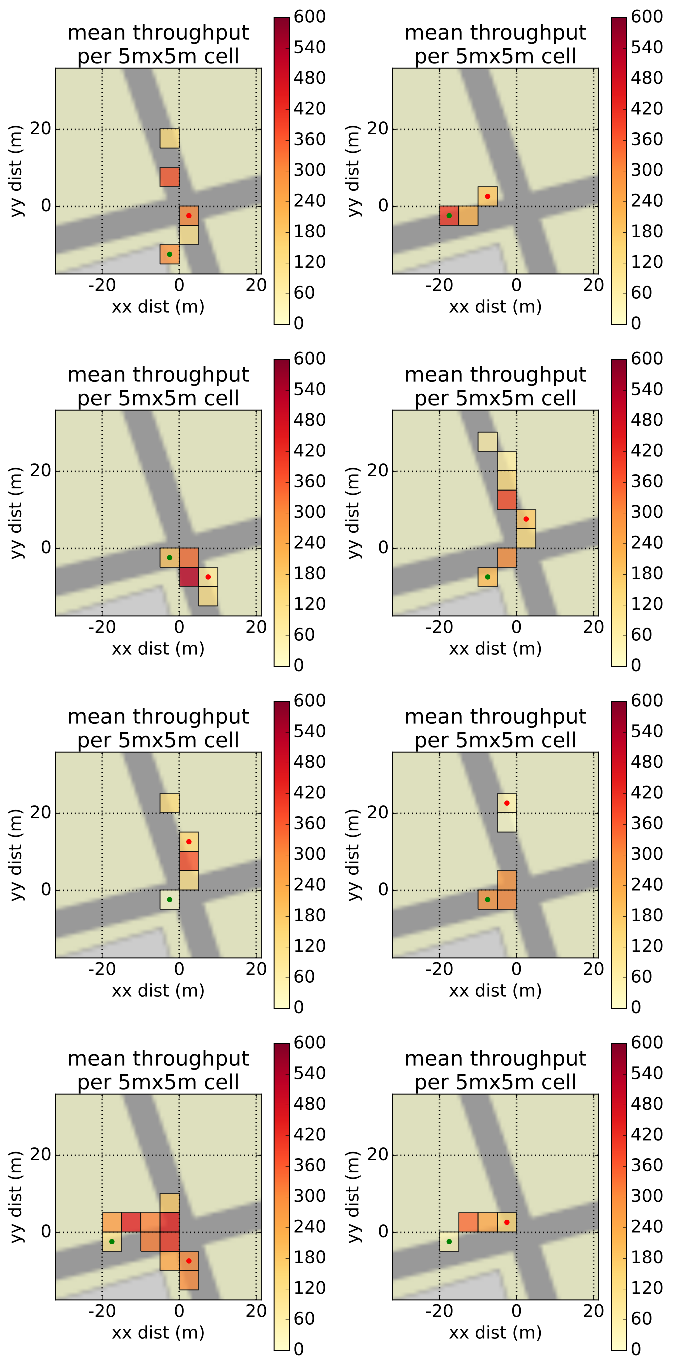
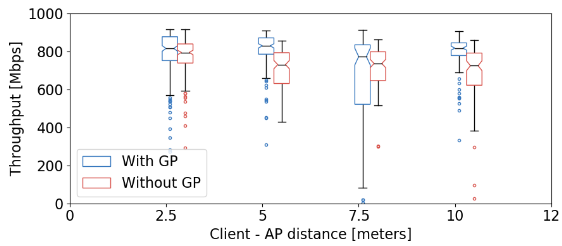


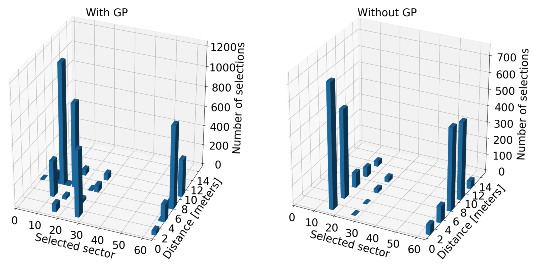
Fig. 5: Geographic representation of throughput for selected high-throughput time blocks. Green and red dots mark the initial and final positions of the client vehicle's trajectory.

munication at distances up to 15 m and sometimes larger. Further, we observe that throughput is highest in geometries in which the receiver can be reached by sectors with broad lobes with significant gain. Further, we explored the possibility that the higher than expected throughput and range are due to the effect of the vehicle roof functioning as a ground plane. Preliminary results show that higher throughput and SNR are achieved when a metal plane is placed under the radio, and that the sectors used change. Nevertheless, we still could not replicate the ranges observed on the road in a controlled experimental setting.

Our next steps include more closely replicating the geometry of the experiments, e.g. by replicating the angles used,



(a) Distribution of average throughput per second.



(b) Distribution of sectors chosen for transmission.

Fig. 6: Ground plane (GP) effect test results.

and fixing the sectors and modulation and coding schemes to reduce variability.

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