Exploiting the Height of Vehicles in Vehicular Communication

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***Abstract*—One of the most challenging research issues in vehicular ad hoc networks (VANETs) is how to efficiently relay messages between vehicles. We propose a heuristic that uses the physical dimensions of vehicles to help determine whether or not a vehicle is an appropriate next hop. We base the heuristic on the intuition that taller vehicles have an advantage over shorter ones because the former are less susceptible to shadowing from other vehicles. We implement a model that evaluates the efficacy of the proposed heuristic and we perform the experiments to validate the model. Based on both the experimental measurements and the simulations performed using the model, it is shown that tall vehicles consistently and significantly increase both the effective communication range and the message reachability. The effective communication range increased by more than 50%: from 290 meters when short vehicles are communicating to 450 meters in the case of tall vehicles. The results suggest that, when available, tall vehicles are significantly more likely to be better relays than short vehicles. The proposed heuristic is not dependent on any specific routing technique and can be used to improve the performance of different classes of routing protocols.**

***Index Terms*—vehicular networks, VANET, vehicle-to-vehicle communication, routing, experimental evaluation**

I. INTRODUCTION

Vehicle-to-vehicle (V2V) communication is the main message exchange paradigm for a number of applications proposed for Intelligent Transportation Systems (ITS), ranging from safety [1], [2] to traffic management [3], [4] and infotainment [5], [6]. The relatively low height of the antennas makes V2V communication susceptible to obstruction by other vehicles on the road, where the non-communicating vehicles obstruct the line of sight (LOS) between the communicating vehicles. It was shown in [7] that other vehicles often obstruct the LOS between the communicating vehicles, thus significantly decreasing the received power. This results in a reduction of the effective communication range by 40%-60%, depending on the environment [8].

Motivated by these findings, in this paper we explore how much of the adverse effects of vehicular obstructions (and other obstacles on the road) can be ameliorated by opting for the taller vehicles as next hop relays, provided such vehicles are available. We distinguish between tall vehicles, such as commercial and public transportation vehicles (e.g., vans, buses, trucks, etc.), and short vehicles (e.g., passenger cars). We base this distinction on the analysis performed in [7], which showed that the dimensions of the most popular passenger cars differ significantly from the dimensions of commercial freight and public transportation vehicles. Specifically, it was observed that the latter are, on average, more than 1.5 meters taller than personal vehicles. Similar differences were observed with respect to length, where tall vehicles were also more than 3 meters longer on average.

We hypothesize that mounting the antennas on top of tall vehicles, and selecting these vehicles as more likely message relays, will result in a communication channel which will not be as affected by obstruction from other vehicles as in the case of short vehicles (i.e., the probability of having LOS conditions should increase). Furthermore, due to their length, we propose that tall vehicles should have at least two antennas mounted on their rooftop: one at the front and another one at the back. This would prevent the vehicle itself from significantly deteriorating the channel characteristics by blocking the LOS path between its own antenna and the antenna of the vehicle it is communicating with. Therefore, in our analysis and subsequent experiments, we set up the tall vehicles with two antennas, one at the front and the other at the back.

Through both analytical modeling and experiments, the results show significant benefits of selecting tall vehicles as relays. The main contributions of this work can be summarized as follows:

- We quantify the benefits of selecting tall vehicles as next hops in terms of: 1) LOS communication; 2) received signal power; and 3) effective coverage area.
- We show that using knowledge about vehicles' dimensions and type to appropriately select the next hop vehicle consistently results in a better effective coverage and larger per-hop message reachability. This was proven to be true through both experiments and simulations that used a validated model.

The rest of the paper is organized as follows. Section II

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describes previous experimental and modeling work which analyzed the impact of vehicular obstructions on the radio channel, as well as differences arising from using different antennas heights in vehicular communications. The model-based analysis of received power is presented in Section III, including the difference between LOS communication for short and tall vehicles (subsection III-A), impact on received signal power (subsection III-B), and the analysis of the selection of best next hop relay based on its height (subsection III-C). The experimental setup and results are described in Section IV. Section V concludes the paper.

II. RELATED WORK

With respect to the impact of height in vehicular communications, Paier *et al.* in [9] performed experiments to evaluate the performance of the physical layer vehicle-to-infrastructure (V2I) links. Significantly better results were observed with a road-side unit (RSU) that was placed above the height of the tallest vehicles. According to their experiments this results in a more reliable communication channel, which is of great importance for safety related applications. Since the RSU radio design is essentially identical to the on-board unit (OBU) radios, this finding suggests that the same applies for V2V communication, and that placing the antennas on taller vehicles is likely to result in improvements of the radio channel.

A similar study was reported by Paier *et al.* in [10], where the authors analyzed the performance of a downlink between an RSU and an OBU installed in a vehicle. Antenna heights and traffic had a severe impact on the downlink performance, and the authors pointed out that "shadowing effects caused by trucks lead to a strongly fluctuating transmission performance, particularly for settings with long packet lengths and higher speeds." This reinforces the findings reported by Meireles *et al.* in [8], where high losses were observed when obstructing vehicles were present between communicating vehicles.

Regarding the performance analysis and modeling of LOS and non-LOS (NLOS) channels, Tan *et al.* [11] performed V2V and V2I measurements in urban, rural, and highway environments at 5.9 GHz. The results point out significant differences with respect to delay spread and Doppler shift in case of LOS and NLOS channels (NLOS was often induced by trucks obstructing the LOS). The paper distinguishes LOS and NLOS communication scenarios by coarsely dividing the overall obstruction levels. Similarly, Otto *et al.* [12] performed V2V experiments in the 2.4 GHz frequency band in an open road environment and reported a significantly worse signal reception during a heavy traffic, rush hour period in comparison to a no traffic, late night period. In the WINNER project [13], a series of 5.3 GHz wireless experiments where performed with a stationary base station and a moving node. The results were then used to derive channel models for use in simulation. Higher antenna heights were found to be beneficial to communication: the higher the antenna, the lower the path-loss exponent. Several other experimental studies established that non-communicating vehicles often have a significant impact on the channel quality: [14], [15], [16], [17], [18] and [19].

TABLE I
ANALYZED A28 HIGHWAY DATASET

Dataset	Size	# vehicles	# large vehicles	Veh. density
A28	12.5 km	404	58 (14.36%)	32.3 veh/km

With respect to the metrics used for relaying messages in vehicular networks, the most common are: **1)** hop count-based metrics (e.g., [20]), **2)** received power metrics (e.g., [21]), **3)** metrics based on geographic characteristics such as vehicle position, direction, or map information, etc. (e.g., [22], [23]); and **4)** vehicular density based metrics (e.g., [24]). Combination of two or more of these metrics is also common in the literature. Using taller vehicles could prove beneficial for some of these metrics (e.g., relaying the messages over tall vehicles so as to decrease the number of required hops or increase the received power).

However, to the best of our knowledge, none of the existing studies proposed utilizing the information about the type and height of vehicles to improve the performance of V2V communication, with the goal of improving the message relaying and routing process.

III. MODEL-BASED ANALYSIS OF THE BENEFITS OF SELECTING A TALL VEHICLE AS A RELAY

We modified the model developed in [7] to evaluate the impact that the higher antenna placement on tall vehicles has on the received signal power. The model accounts for vehicles' physical locations and first determines whether or not there is a LOS between the two communicating vehicles. The LOS test is performed geometrically by drawing a line segment (in three-dimensional space) between sender and receiver and checking whether the segment is intersected by any other vehicle.

In Fig. 1, *Car 1* and *Car 2* do not have LOS conditions, whereas the *Truck* has LOS with both *Car 1* and *Car 2* (note that it is assumed that the *Truck* has two antennas, one in the front and another in the back). In the case of NLOS communication (i.e., between *Car 1* and *Car 2*), the additional attenuation is calculated using the knife edge model as described in [25], taking into account the attenuation on a radio link due to vehicles intersecting the ellipsoid corresponding to 60% of the radius of the first Fresnel zone (the dashed ellipsoids shown in Fig. 1). Each vehicle is abstracted as a single knife edge: in case of multiple obstructing vehicles, the multiple knife edge model described in [25] is employed. Based on the number of obstructing vehicles and the severity of the LOS obstruction, the additional attenuation is calculated.

Note that because lines between sender and receiver are drawn in 3D-space, the model takes into account communication across multiple lanes, curves and altitude changes, thus accurately determining the (non)existence of LOS between vehicles in different lanes and even traveling in different

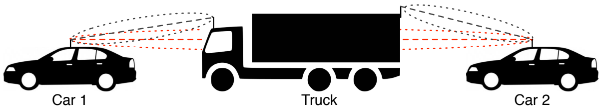

Fig. 1. Explanation of the model for determining the existence of LOS and for calculating the received power).

directions[1].

We distinguish three types of links:

- **Car-to-car** — A link between two passenger cars is used to establish a baseline for comparison.
- **Van-to-van** — A link between two full-size vans is used to quantify the potential benefit of tall relays. When both vehicles are tall, the likelihood of their LOS being obstructed is minimized.
- **Van-to-car** — A link between one passenger car and one van is used to evaluate the channel between vehicles of different types.

However, we grouped all links that contained *at least* one tall vehicle together (i.e., we group van-to-van and van-to-car links), since we are interested in analyzing how a tall vehicle acts as a relay, regardless of the type of vehicle on the other end of the link.

We obtained accurate vehicle positions by analyzing the aerial photography datasets of the A28 highway near Porto, Portugal (dataset described in Table I; more details on the method of data collection available in [26]). In this dataset, each vehicle is annotated as either short or tall. To assign accurate heights to the vehicles, we used the empirically derived distributions of the heights of tall and short vehicles described in [7]. Heights of both types of vehicles are normally distributed, with a mean of 3.35 meters for tall and 1.5 meters for short vehicles, and a standard deviation of 0.08 meters for both vehicle types.

A. Impact of Vehicles on Line of Sight

We first set out to determine the frequency of occurrence of LOS blocking by non-communicating vehicles and the difference in LOS blocking between short and tall vehicles. Figure 2 shows the difference in the probability of having a LOS for links between tall and short vehicles. With tall vehicles participating in a link, the probability that a LOS will be available is notably higher. Even though the LOS obstruction will vary with the road structure (number of lanes, road shape, etc.) and with traffic conditions (vehicle density and ratio of tall and personal vehicles), the latter being a function of time of day and the location of the road, it was shown in [7] that the LOS obstruction is significant in both sparse and dense environments. Therefore, it is expected that the relation of LOS obstruction for tall and short vehicles will remain comparable to the one shown in Fig. 2 across different environments.

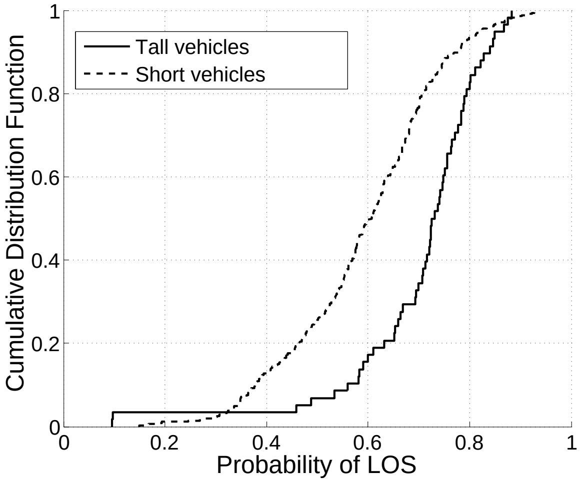

Fig. 2. Probability of LOS for tall and short vehicles. The tall vehicle curve includes all links with *at least* one tall vehicle (i.e., either van-to-van or van-to-car vehicle links).

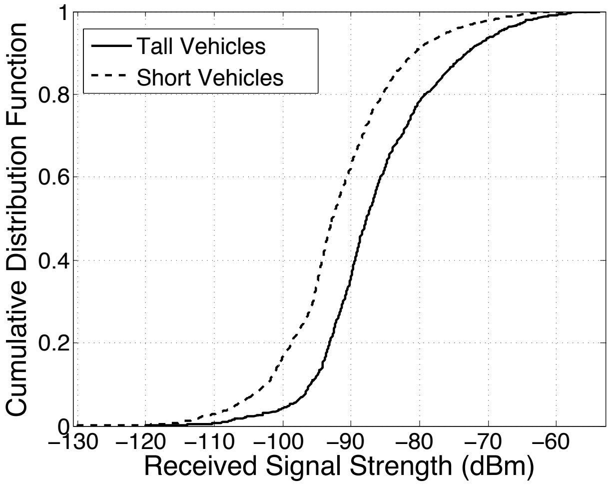

Fig. 3. Empirical CDF of received signal strength for tall and short vehicles. Different distance bins are equally represented for tall and short vehicle links.

B. Difference Between Received Signal Strength for Tall and Short Vehicles

Figure 3 shows the empirical cumulative distribution function of the received signal strength for tall and short vehicle links. Despite the fact that the average distance between the communicating vehicles for tall and short vehicle links is roughly the same, the received signal strength for tall vehicle links is consistently higher by approximately 5 dB. This result implies that having at least one tall vehicle in the communicating link results in a significantly higher received power.

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[1] Throughout the paper the NLOS will be referring to Line of Sight obstructed by *other vehicles*, since we were performing the experiments and modeling on highways and the vehicles were the main cause of obstruction.

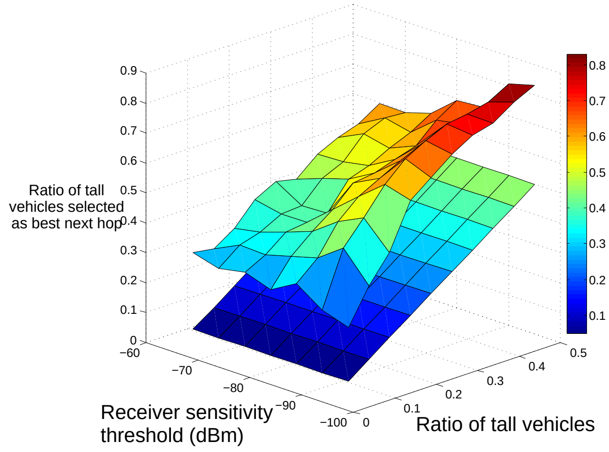

Fig. 4. Ratio of tall vehicles that are a better next hop. Method of selection: largest number of second hop neighbors for farthest tall and farthest short vehicle. The bottom plane in the figure shows the linear increase with regards to ratio of tall vehicles (X-axis) and the ratio of tall vehicles selected as the best next hop (Y-axis), where $X = Y$.

C. The Benefit of Having a Tall Vehicle as a Next Hop

Next, we analyzed the difference between having a tall and a short vehicle as a next hop relay by using the received power analysis explained above. We determined the benefits based on the following criteria. For each vehicle in the analyzed A28 highway dataset:

1) We find the farthest neighboring tall and farthest neighboring short vehicle (i.e., the farthest tall and short vehicle whose received signal power is above the radio sensitivity threshold as defined for DSRC [27]).
2) Next, we determine which of the two has the largest number of new neighbors (i.e., which adds the largest number of second hop neighbors to the vehicle under consideration).
3) Finally, if the largest number of new neighbors is gained by using a tall vehicle, we select it; otherwise, we select the short vehicle as the best next hop.

We artificially varied the ratio of tall vehicles from 0.05 to 0.5 in order to analyze the benefits of selecting a tall vehicle depending on the relative number of tall vehicles on the road[2]. We also varied the receiver sensitivity threshold based on the DSRC parameters for various data rates (from 3 Mbit/s to 27 Mbit/s) [27]. The transmit power was fixed at 10 dBm.

Figure 4 shows that, despite being on average closer to the sender, tall vehicles consistently provide a larger number of new (second hop) neighbors to the vehicle in question, across different tall vehicle ratios and sensitivity thresholds. Tall vehicles seem to be more beneficial for lower sensitivity thresholds (i.e., lower DSRC data rates): the sensitivity thresholds between -100 and -85 dBm exhibited the highest rate of tall vehicles selected. For the actual ratio of tall vehicles on A28 of 15%, across all sensitivity thresholds tall vehicles are selected more than twice that value (tall vehicles are selected between 30%-45% of the time).

In the extreme case where half of the vehicles on the road are tall, up to 80% of the best next hops will be tall vehicles. The reason tall vehicles are not favored even more often than short vehicles lies in the fact that, at a ratio of tall vehicles of, say, 10%, due to the fact that there are nine times fewer tall vehicles than short ones, the farthest tall vehicle is likely to be the physically much closer to the transmitting vehicle than the farthest short vehicle (assuming there is no difference in the spatial distribution of tall and short vehicles on the road).

Furthermore, this result implies that the use of tall vehicles in relaying should also be correlated with their relative distance to the farthest short vehicle (i.e., if the farthest tall vehicle is significantly closer to the current sender than the farthest short vehicle, then the former is less likely to be a better next hop).

TABLE II
DIMENSIONS OF VEHICLES USED IN THE EXPERIMENTS

Vehicle	**Dimensions (m)** **Height**	**Width**	**Length**
2007 Kia Cee'd	1.480	1.790	4.260
2002 Honda Jazz	1.525	1.676	3.845
2010 Mercedes Sprinter	2.591	1.989	6.680
2010 Fiat Ducato	2.524	2.025	5.943

IV. EXPERIMENTAL ANALYSIS OF THE BENEFITS OF TALL VEHICLES AS RELAYS

A. Experimental setup

We performed small-scale experiments to complement the model-based analysis by measuring the benefits of choosing a tall vehicle as a relay in a real-world scenario. Using regular passenger cars to represent the short vehicle class and full-size vans to represent the tall vehicle class (vehicles depicted in Fig. 5), we performed experiments comprising two-node networks of three different types, as explained in Section III-A: car-to-car, van-to-van and van-to-car. Due to logistical reasons, we were limited to two-node, single-hop networks, where there is no actual relaying. However, if tall vehicles lead to a better communication channel in the single hop case, then it is likely they will also be better relays.

The dimensions of the vehicles are listed in Table II. The two cars have a height of approximately 1.5 meters, which coincides with the statistical mean height for personal vehicles [7], whereas both vans are approximately 2.5 meters tall. Each vehicle was equipped with a NEC LinkBird-MX V3, a development platform for vehicular communications [28]. The devices contain DSRC radios that operate in the 5.85-5.925 GHz frequency band and implement the IEEE 802.11p wireless standard [27]. Each node was configured to send periodic position beacons that were then used to record Received Signal Strength Indicator (RSSI) and Packet Delivery Rate

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[2] The ratio of tall vehicles in the real world is usually well below 50% (e.g., it is approximately 15% in the analyzed dataset); however, we were interested in the behavior in the extreme case of having both very few and many tall vehicles.

Fig. 5. Vehicles used in the experiments. Clockwise from top left: Kia Cee'd, Honda Jazz, Fiat Ducato and Mercedes Sprinter. The vans are approximately one meter taller than the passenger cars.

Parameter	Value
Channel	180
Center frequency (MHz)	5900
Bandwidth (MHz)	20
Data rate (Mbps)	6
Tx power (dBm, measured)	10
Antenna gain (dBi)	6
Beacon frequency (Hz)	10
Beacon size (Byte)	40

TABLE III
HARDWARE CONFIGURATION PARAMETERS

(PDR) information during the experiments. The position information was given by an external GPS receiver connected to each LinkBird. The system parameters are shown in Table III.

For the experiments, we used Mobile Mark ECOM6-5500 omnidirectional antennas, which measure 26 centimeters in height. On the passenger cars, the antenna was positioned at the center of the roof, which was empirically shown to be the overall optimal position [29]. As discussed earlier, this does not hold for the full size vans, as the long body of the van itself would block the LOS in a van-to-car communication scenario. To avoid this issue, we mounted the antennas at the front or at the rear of the roof, depending on whether the van was driving behind or in front, respectively.

To make the results comparable to the model-based analysis described in the previous section, we performed the experiments on the same stretch of the A28 highway that was analyzed through aerial photography (Table I). The car-to-car and van-to-van experiments were performed with the respective vehicle pairs, and the van-car experiments with the Mercedes Sprinter and Kia Cee'd. We used the exact same part of the A28 highway on different days, yet with similar traffic conditions: medium to moderately dense traffic during the 3pm-8pm period on weekend days. Each experiment was approximately one hour long, with the vehicles traversing the highway south to north and vice versa. Speeds ranged from 60 to 120 Km/h, in accordance with traffic conditons.

To help us distinguish between LOS and NLOS conditions, we filmed the experiments from the vehicle following in the rear. We then synchronized the video to the experiment data using a custom web-based visualization suite [30] and classified each part of the experiment as LOS or NLOS, with a one second resolution. We classified the conditions as NLOS whenever one or more vehicles, short or tall, where present between the two communicating parties. Given that this was a highway scenario, the number of static obstructions such as buildings was negligible and thus not considered.

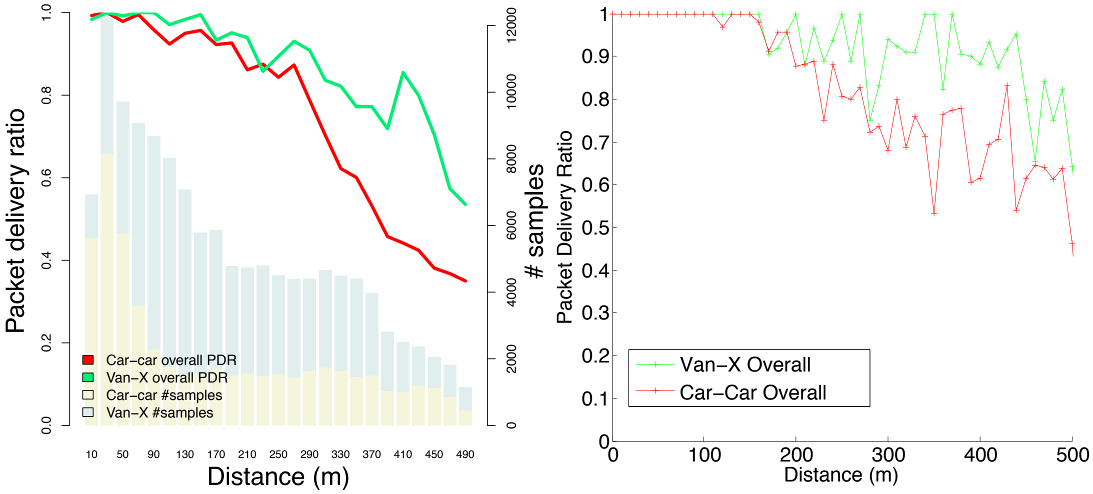
B. Experimental results

We first present the Packet Delivery Ratio (PDR) as a function of distance, depicted in Fig. 6. The figure shows the PDR results obtained through experiments and the model described in the previous section. Similarly to the model-based results, we aggregate the van-to-van and van-to-car cases to analyze the benefit of tall vehicles regardless of the height of the other communicating party. We call this combined scenario van-to-X. For each message sent, we check whether it was received or not and place that information in a distance bin with a 20 meter granularity based on the distance between the communicating parties. In addition to the PDR, for experimental data we plot the number of samples placed in each bin.

Figure 6a presents the overall PDR registered in our experiments for both car-to-car and van-to-X, regardless of LOS conditions. As expected, PDR stays fairly high up to a certain distance and then starts to drop sharply as the signal level approaches the reception threshold. The van-to-X PDR is consistently better than the car-to-car PDR. Up to 280 meters, the difference is slight but after that it becomes quite significant, with van-to-X offering an improvement of around 20% over car-to-car communication up to the limit of the recorded data. Figure 6b depicts the model-derived overall PDR, based on the aerial photography of the same A28 highway. The PDR exhibits a behavior similar to that of the experimentally collected PDR data (Fig 6a).

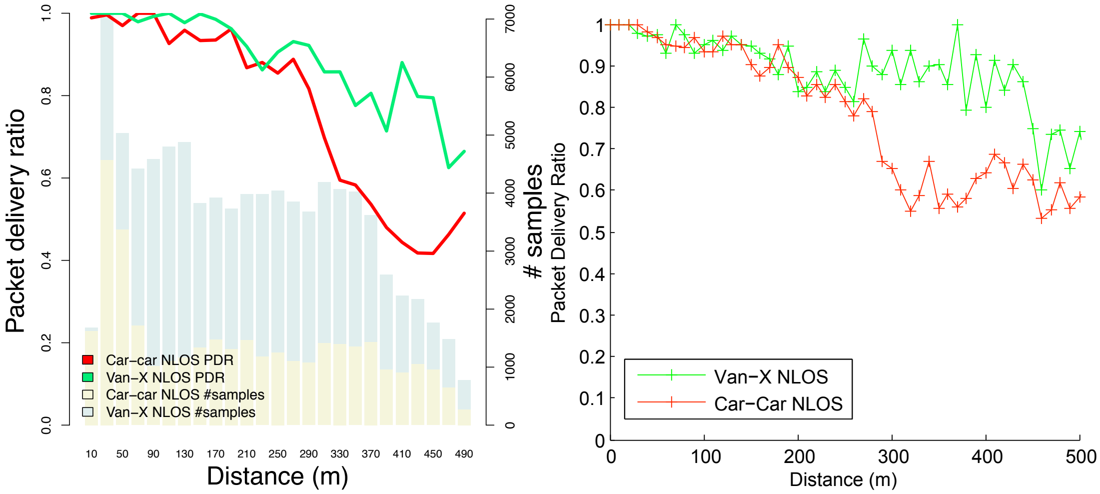
Figure 6c depicts the PDR for NLOS cases only, where there were other vehicles between the communicating vehicles that potentially obstructed the LOS. The shape of the curve is very similar to the overall case, with van-to-X providing a clear advantage when compared to car-to-car communication above 250 meters. When the received power is close to the reception threshold, the improved channel made possible by the use of tall vehicles often makes the difference between a decodable and a non-decodable packet. Figure 6d shows the PDR for NLOS data as predicted by the model. As with the overall case, the correlation with the experimental results is high, therefore providing validation of the employed model.

When under LOS conditions, there were no significant differences between the two types of communication (van-to-X, car-to-car), implying that in LOS conditions tall vehicles



(a) Experimental overall results

(b) Model-based overall results



(c) Experimental NLOS results

(d) Model-based NLOS results

Fig. 6. Packet Delivery Ratio (PDR) results.

perform at least as well as short vehicles, provided the antennas are appropriately placed.

From the viewpoint of an application, the benefit of using tall vehicles as forwarders can be seen as an increase in the effective communication range given a certain delivery probability requirement. Figure 7 shows the difference in communication range under NLOS conditions, using the data derived from the graph in Fig. 6c, as a function of the desired delivery rate. Using a van can increase the effective communication range by approximately 100 meters for a target delivery rate of 95%, 150 meters for a target of 70% and almost 200 meters for a target of 60% delivery rate.

The results show that significant benefits can be achieved by differentiating between different types of vehicles according to their height. Selecting tall vehicles allows for higher probability of LOS, increased network reachability and received signal power, all of which result in a higher packet delivery ratio.

A routing heuristic based on vehicle height will potentially

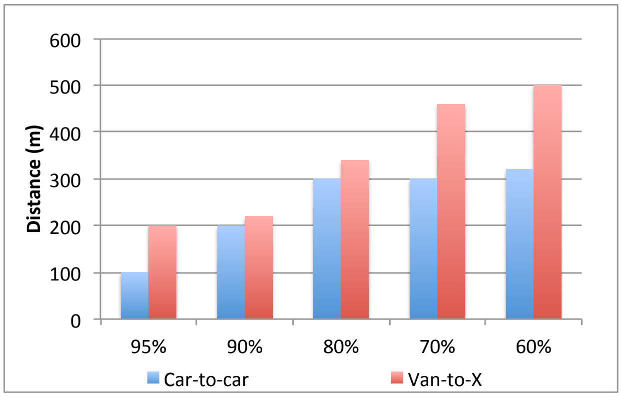


Fig. 7. Experimental results on the effective communication range as a function of desired packet delivery rate for NLOS conditions.

influence the network load in several different ways. Provided that all the vehicles implement the tall vehicle heuristic, a large portion of the packet traffic may be centered around tall vehicles, which might create bottlenecks. Furthermore, load at the device level will tend to increase for tall vehicles. On the other hand, having a smaller set of nodes contending for medium access using the IEEE 802.11 Distributed Coordination Function (DCF) is likely to result in less congestion and better channel utilization at the network level. Also, the longer hops that result from the use of tall vehicles have the potential to reduce network load. These and other tradeoffs need to be quantified in the future.

V. CONCLUSIONS AND FUTURE WORK

We analyzed the benefits of utilizing the dimensions of vehicles, in particular height, in order to enable more efficient V2V communication. A model was implemented to determine the frequency of LOS obstruction and the difference in received power with and without discriminating the vehicles based on their height. We also performed experiments in order to validate the results of the model and to gauge the real world benefits of selecting tall vehicles as relays.

The results show that tall vehicles are significantly better relay candidates than short vehicles. Selecting tall vehicles likely results in a higher received signal power (i.e., more robust and longer lasting links), increased packet delivery ratio, and larger effective communication range.

It is important to note that our findings can be used to enhance any type of routing protocol, be it unicast [31], broadcast [32], geocast [23] or multicast [33]. On highways, trucks can be used as moving hotspots that relay the messages between the shorter vehicles. In urban environments, public transportation vehicles such as buses and streetcars can be used for the same purpose. One of the ways to leverage the vehicle type information is to assign different next hop probabilities to different vehicle types. Similarly, for non-probabilistic routing protocols, such information can be used to discriminate between potential next hops in a route. However, the information about the height of vehicles should be correlated with the distance from the transmitter: if the tall vehicle is significantly closer to the transmitter than the short vehicle, the height benefits might be offset by the distance difference.

Based on the employed model and the experimental data collected, we plan to design large-scale simulations in order to evaluate the benefits of the proposed heuristic in different environments (highway, urban, rural) and with different routing protocols. Large-scale simulations will give insights in how the single-hop benefits we observed will translate into the system level performance benefits, in terms of packet delivery and end-to-end delay in a multi-hop vehicular environment.

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