Millimeter-Wave Connectivity in Real World Vehicle-To-Vehicle Network Scenarios

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ABSTRACT

Upcoming technologies like Millimeter-Wave (mmWave) communication can facilitate Inter-Vehicular communication. These Vehicle-To-Vehicle (V2V) networks provide the potential for cooperative driving. However, obstacles in the Line-of-Sight (LoS) of transmitting and receiving vehicles can significantly impact the signal quality of mmWave transmission. Therefore, having a high availability of LoS is important when using mmWave communication. This paper investigates the real world availability of LoS and number of reachable vehicles with mmWave communication. Current research into the availability of LoS mostly utilizes simulations. This research is based on a large dataset of real world traffic situations, provided by the Waymo Open Dataset. By analyzing this data, it has been concluded that at relatively short distances, less than 15 meters, most vehicles are reachable with mmWave communications. Furthermore, it has been concluded that there is a higher availability of LoS and vehicles in mmWave communication range in highway environments.

KEYWORDS

mmWave communication, Vehicle-To-Vehicle networks, Line of Sight, Waymo Open Dataset

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1 INTRODUCTION

Modern day vehicles collect a lot of information about their surroundings using sensors. Being able to exchange this sensor data with other vehicles in the area would be useful. This would provide vehicles with more information about their surroundings and vehicles in it's neighbourhood and could pave the way for cooperative driving. This is called Vehicle-To-Vehicle (V2V) communication. This communication of sensor data requires a high-bandwidth connection. Using millimeter-wave (mmWave) communication could provide this high-bandwidth and low-latency connection as opposed to the current sub-6Ghz technologies. Currently, ongoing efforts towards standardization are being undertaken by IEEE 802.11bd and 3GPP NR V2X [8]. However, the use of the mmWave spectrum introduces some challenges. In order to effectively use mmWave communication, beam forming is required. Furthermore, the signal deteriorates quickly when obstructed by obstacles such as other vehicles. Because of this, Line-of-Sight (LoS) between transmitter and receiver is preferred in mmWave V2V networks.

Most research about the availability of LoS between vehicles is based on simulations or on the traffic of a relatively small section of road [2][4]. The goal of this paper is to research the availability of LoS based on real life scenarios from a large dataset. The dataset used will be the Waymo Open Dataset [3]. Waymo is a company that develops autonomously driving vehicles. In the process of developing these autonomous vehicles, a large amount of sensor data of the surroundings of the vehicle is gathered. This data includes, but is not limited to, camera imagery and LiDAR data. More about the dataset used in this research can be found in Section 3.1.

This paper aims to investigate to which extent neighbouring vehicles are reachable using mmWave communication in real life scenarios. Specifically, the following questions will be answered.

(1) What is the average number of direct Line-Of-Sight neighbours of a vehicle?
(2) What is the average number of vehicles in mmWave communication range of a vehicle?
(3) What percentage of vehicles within a certain radius can be communicated with?
(4) How do the results of the previous three questions compare in highway environments against city environments?

This paper will first take a look at the current research that is relevant to this topic. Secondly, the methodology that is used in this research in order to obtain the results will be described. Next, the results of the research will be shown and discussed. Lastly, Section 6 will discuss how this research can be expanded upon.

2 RELATED WORK

Zugno et al. [8] discussed the general state of mmWave V2V networks. The researchers reviewed the current efforts of specifying new standards, namely IEEE 802.11bd and 3GPP NR V2X. Lastly, the researchers performed a complete end-to-end performance evaluation of mmWave transmission in V2V networks. In this evaluation, it was noted that the Packet Perception Ratio (PPR) was generally better in highway environments than in urban environments. This is due to having a higher LoS probability in highway scenarios. Our research will hope to confirm this difference in LoS availability

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between highway environments and urban environments.

When using a wider beamwidth with mmWave transmission, multiple receivers can be reached with a single transmission. In 2021, Mendler and Heijenk [2] explore the usability of multicast transmissions in mmWave communincations. Furthermore, in this research paper, measurements have been done on how many neighbouring vehicles can be reached with mmWave transmissions. The dataset for these measurements is based on the traffic of a 640 meter section of a US highway. The researches conclude that an average of 6.3 vehicles is in communication range.

In 2021, Townend et al. investigated the line of sight probability between mmWave urban macro base stations (uMa). The research was conducted by using high resolution LiDAR data of certain areas in the UK. In total, the dataset used covers around 1875 sq km. The paper concludes that established probability models for LoS with uMa are not suitable for forecasting LoS availability in a real networks. This research does not specifically apply to V2V networks. However, it does showcase that expected line of sight availability might not align with the actual line of sight availability. Therefore, it is useful to find out to what regard this applies to V2V networks.

Yamamoto et al. present an empirical path-loss prediction model for mmWave transmissions [7]. The model was derived from propagation tests conducted between two moving vehicles. The presented model is both applicable to LoS situations and Non Line of Sight (NLOS) situations. Coll et all. [1] use this path-loss prediction model in their research into 802.11ad Medium Access Control and beamforming mechanisms. In their paper, Coll et al. present the constants that they used in the path-loss formula. These constants can also be used in our research.

3 METHODOLOGY

3.1 Dataset

The research of this paper is based on the Waymo Open Dataset [3]. Waymo is a company that develops autonomously driving cars. These cars use different ways of sensing the environment. These sensors include LiDAR and camera vision. A lot of this sensor data is made publicly available, together with a Python package to parse the data [6]. The Waymo Open Dataset is comprised of the motion dataset and the perception dataset. Our research uses the training and validation data from the perception dataset of May 2022. The data consists of 1000 segments (scenes) that each span about 15 seconds. Each of these segments consists of roughly 200 frames. Each frame includes images of the 5 cameras that are on the vehicle. The cameras on the vehicle take images from the front, side-left, side-right, left and right of the vehicle. These images can be used to identify cars and people in the area. The LiDAR data can be used to create a 3D map of the environment. As of March 2022, the perception dataset also includes 3D segmentation labels [5]. These segmentation labels identify every single point in the LiDAR data. The segmentation labels include among others, labels for cars, pedestrians, road signs, vegetation and buildings. In this research, only the frames that include segmentation labels are used. Roughly 15% of frames include segmentation labels, meaning that for each segment about 30 frames are analysed. All vehicles in the segment are identified and contain information about location, speed and acceleration. Each vehicle in a segment has a unique ID that is consistent trough out all frames of the segment. This ID can be used to track a vehicle trough out the segment.

Transmission power	10 dBm
Transmitter antenna gain	11.5 dBi
Receiver sensitivity	066 dBm
Receiver antenna gain	11.5 dBi
Constant A	1.77 (0 obstacles); 1.71 (1 obstacle)
Constant C	70 (0 obstacles); 78.6 (1 obstacle)

Table 1: Assumptions and constants used in the propagation model.

3.2 Obstacle detection

For every pair of vehicles in a frame, it is determined whether or not they are in LoS with each other. This is done by checking for each object in the frame if it intersects with the direct line between the centers of the vehicles. This way, it can be determined how many obstacles there are between any two vehicles. If there are zero obstacles, the vehicles are in LoS. Using the propagation model described in Section 3.4 it can be determined if the two vehicles are in communication range, taking into account the distance and number of obstacles between the transmitter and receiver.

3.3 Parked vehicles

The Waymo Open Dataset tracks all vehicles in the scene, this also includes parked vehicles. Unfortunately, the dataset does not provide the information to distinguish between parked vehicles and vehicles that are actively participating in traffic. This is problematic, since there is not much use in communicating with parked vehicles. Therefore, it is important to not include parked cars when determining the level of LoS availability and vehicles in communication range. In order to determine whether a vehicle is parked, the speed of every vehicle is tracked throughout the entire scene, if a vehicle has a speed of zero throughout the entire scene, the vehicle is classified as parked. Unfortunately, this way of determining parked vehicles also includes false positives like vehicles that are waiting for a red light. This is not ideal, but because of time constraints, a better solution was not available. For sake of transparency, the rest of this paper includes the results with both all vehicles in a scene (so including parked vehicles) and only moving vehicles.

3.4 Propagation model

Vehicular communication with mmWave transmission can be used for high bandwidth, low latency communication. However, mmWave signals can be heavily impacted by obstacles. In order to analyze whether a receiving vehicle is in the transmission range of the transmitter a propagation model is needed. Firstly, some assumption about the connection need to be made. The assumptions regarding the propagation model can be found in Table 1. In order to model the propagation loss, the empirical path-loss model described in [7] is used. Equation 1 describes the formula to calculate the path-loss

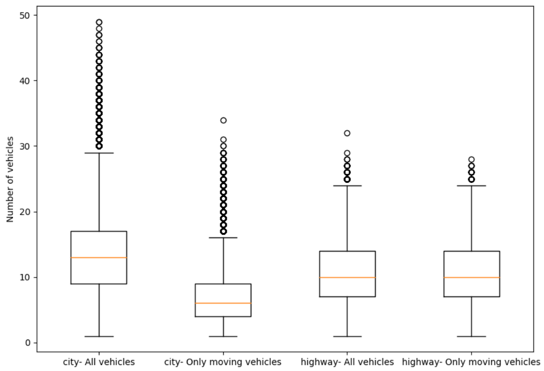

Figure 1: Box plots showing the spread of the number of vehicles in LoS in different environments.

in decibels. In this formula, D is the distance between transmitter and receiver. Furthermore, A and C are constants that depend on the number of obstacles between the transmitter and receiver. The values used for these constants can be found in Table 1. With the combination of the transmission parameters in Table 1 and the path-loss model, it can be determined whether two vehicles are in transmission range.

$$L = A * 10 * log_{10}(D) + C + 15 * D/1000 \quad (1)$$

3.5 Answering of Research Questions

Research Question 1 is answered with the dataset described in Section 3.1. All that data is used to create a mapping of all positions of all vehicles for each frame. Using this mapping, it is determined for each pair of vehicles if they are in LoS at a certain moment. Determining whether a pair of vehicles is in LoS is done by checking if there are any obstacles between the centers of both vehicles.

Research Question 2 will be answered similarly to Research Question 1. However, this time it includes the path-loss model described in Section 3.4. This will take into account the vehicles that are not necessarily in LoS, yet still reachable by mmWave transmissions or vehicles that are in LoS but at too great of a distance.

Research Question 3 will be answered by comparing the number of vehicles within a certain radius that are reachable with mmWave communication and the total number of vehicles in that radius. After doing this for all vehicles in all frames, an average percentage can be calculated for different radii.

Finally, in order to answer Research Question 4 the data needs to be labelled on highway or city type. Unfortunately, the dataset used does not include this information. Ideally, the task of labelling the data is done automatically. However, the author is not aware of any automated method of labelling road environments types. Therefore, the labelling of this data is done manually by the author.

Situation	Mean	Standard deviation
City - All vehicles	13.16	5.85
City - Only moving vehicles	6.79	4.02
Highway - All vehicles	10.52	4.94
Highway - Only moving vehicles	10.28	4.72

Table 2: Means and standard deviations of the number of vehicles in LoS in different situations.

4 RESULTS

4.1 Line of Sight availability

On average, every vehicle is in direct LoS with 13.09 vehicles. This is an average of 7.06 vehicles when only considering moving vehicles. Figure 1 shows the box plots of the number of neighbours in direct LoS in different situations and Table 2 shows the means and standard deviations of the number of neighbours in LoS in different situations. When comparing the availability of direct LoS between city and highway environments, it is clear that more vehicles are in LoS on highways. However, this is only when considering only moving vehicles. When taking into account stopped vehicles, the average number of vehicles in direct LoS is higher in the city. Almost half of the vehicles in the city that are in LoS are stopped vehicles. With, on average, 13.16 vehicles in LoS when including stopped vehicles and 6.79 when only considering moving vehicles. Comparing only moving and all vehicles in the highway environment, it is clear that their is no significant difference. This makes sense because there should not be any stopped vehicles on the highway, unless there is a traffic jam or if there are stopped vehicles on the side of the road.

Considering these numbers, we can conclude that a large portion of LoS vehicles in city environments are stopped vehicles. This makes sense, since most stopped vehicles are parked at the side of the road and there are few obstacles between vehicles driving and vehicles parked by the side of the road. When considering just the moving vehicles, the average number of vehicles in LoS is higher on highways compared to cities. There are multiple potential explanations for this, one reason could simply be that there is more activity in city environments and thus more potential obstacles. Furthermore, in general there is more open space around highways than in cities which results in less obstacles. Lastly, generally speaking, vehicles drive closer together in cities. Therefore, a vehicle that is in LoS blocks more of the view comparing to a vehicle on the highway. Making it easier to be in LoS with more vehicles on the highway.

4.2 Vehicles in communication range

When looking at the number of vehicles that are within communication range, it is clear that a large portion of reachable vehicles is standing still. Overall, an average of 8.95 vehicles is within communication range, this goes down to 5.04 vehicles when only considering moving vehicles. Figure 2 shows box plots of the number of vehicles in communication range in different situations and Table 3 shows means and standard deviations of the number of vehicles in communication range in different situations. Similar to LoS cases, there are on average fewer vehicles within communication range in city environments compared to highway environments. Except

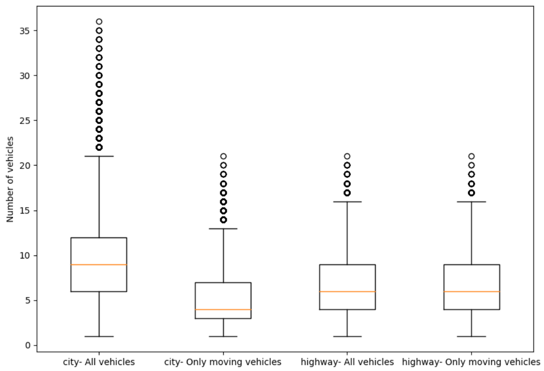

Figure 2: Box plots showing the spread of the number of vehicles in mmWave communication range in different environments.

Situation	Mean	Standard deviation
City - All vehicles	9.01	4.44
City - Only moving vehicles	4.91	3.01
Highway - All vehicles	6.65	3.88
Highway - Only moving vehicles	6.67	3.84

Table 3: Means and standard deviations of the number of vehicles in mmWave communication range in different situations.

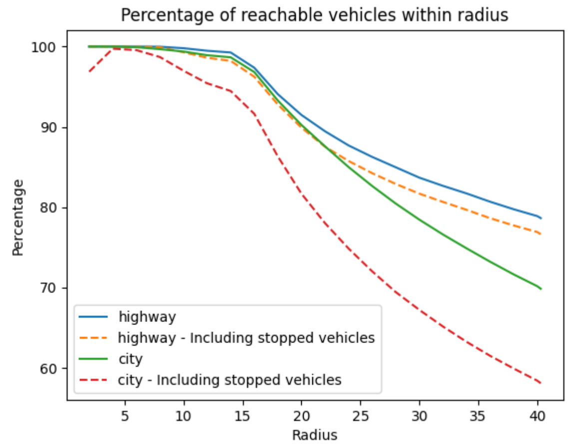

Figure 3: Percentage of vehicles in mmWave communication range at different radii.

when also including the stopped vehicles, in that case there are more vehicles in range in city environments. This shows again, that most vehicles that are in communication range in cities are stopped vehicles.

4.3 Percentage of vehicles within mmWave communication range

Figure 3 shows the average percentage of vehicles reachable with mmWave communication at different radii in different environments. The percentage of reachable vehicles is calculated by comparing for every vehicle in each frame the number of vehicles reachable by mmWave communication to the total number of all vehicles within the radius. Figure 3 shows the average of these percentages at different radii with an interval of 2 meters. The maximum radius is 40.21 meters, since that is the maximum transmission range according to the model described in Section 3.4. Figure 3 shows that that up to 10 meters, nearly 100% of vehicles is reachable, except when looking at all vehicles in the city. This is most likely due to parked vehicles. Parked vehicles are in general quite close together. Furthermore, it is also a cause for a lot of obstacles. Take for example the situation of a row of parked vehicles. The distance between the first and last vehicle might very well be within the maximum transmission range, but there are so many obstacles in between them that the percentage of reachable vehicles is quite low. This is because with two or more obstacles between the transmitter and receiver, the maximum transmission range goes down to only a couple of centimeters. This is especially true in case of motorcycles. The Waymo Open Dataset includes categories for objects in a scene, the category 'vehicle' is used to determine which objects in the scene are vehicles. Unfortunately, motorcycles are also included in this category. Often, multiple motorcycles are parked close to each other in a row. The decrease in percentage below 5 meters for all vehicles in the city that is visible in Figure 3, is likely due to these rows of motorcycles. Unfortunately, it was not possible to fix this issue in the algorithm due to time constraints, however it is unlikely that this has a significant influence in the other results.

The percentage of reachable vehicles starts declining faster after 15 meters. This makes sense since the maximum transmission range between 2 vehicles is 15.2 meters if there is 1 obstacle between them. Meaning that every vehicle past 15.2 meters has to be LoS for communication to be possible. All in all, Figure 3 shows that mmWave communication in V2V networks are most reliable at distances less than 15 meters, since at these distances nearly all vehicles can be reached. At distances larger than 15 meters, LoS is required in order to use mmWave communication. This means that the number of vehicles reachable with mmWave communication decreases significantly.

4.4 Comparing city and highway environments

In order to compare the results between different environments, the scenes have to be labeled. All 1000 scenes where labeled by hand. A scene is labeled as 'highway' if the cars are driving on separated lanes, divided by guardrails. Furthermore, the road has on and off ramps instead of junctions. If these criteria are met, the scene is labeled as highway. All other scenes are labeled as 'city'. The dataset contains 1000 scenes, of these, 54 are set in highway environments and the remaining 946 in city environments.

As the previous sections already describe, in general there is more LoS availability and vehicles in communication range on the highway. At least when considering only moving vehicles. When considering the stopped vehicles as well, there is more availability in city environments. However, since wireless communication between parked vehicles has little use, it can be concluded that there is more availability for mmWave communication in highway environments.

Figure 3 shows that up until about 20 meters, the percentage of vehicles within mmWave communication range is about equal in highway and city environments. At radii greater than 20 meters, the percentage drops quicker in case of city environments. Thus, at larger distances, the percentage of vehicles in mmWave communication range is higher in highway environments. When taking into account the stopped vehicles as well, the difference between the highway and city environments is much bigger. This is mostly because of the difference at radii less then 15 meters, where the percentage is much lower in city environments due to parked vehicles.

5 DISCUSSION

Several aspects of the research conducted have room for improvement. In this section, these possible improvements and other issues will be discussed.
First of all, in order to effectively draw conclusions, it is of importance to know for sure that all vehicles participating in traffic are included in the analysis and that parked vehicles are not. This is currently not the case, an attempt has been made to exclude parked vehicles. However, since the method of doing this is simply excluding any vehicle that does not move during the entire scene, this also excludes vehicles that are, for example, waiting for a red light. Unfortunately, the Waymo Open Dataset does not include information about whether or not vehicles are participating in traffic or if they are parked. Furthermore, due to time constraints, it was not possible to improve the detection of parked vehicles. All in all, an effort was made to paint as clear as picture as possible by showing results for both only moving vehicles and all vehicles trough out this entire paper. However, in order to draw better and stronger conclusions, either the method of detecting parked vehicles should be improved, or a different dataset that already includes this information has to be used.

Secondly, all data in a frame is gathered from a single point, namely the vehicle that is used to capture the data. In this research, when calculating the number of neighbours in LoS or communication range, this was done for every vehicle in a scene. However, images and LiDAR data are captured from a single source vehicle meaning that potentially not all neighbours of other vehicles vehicle are captured. This is especially true for vehicles that are near the edge of the captured scene. This issue could be mitigated by only taking into account vehicles that are at least a certain distance away from the edge. However, it was difficult to reliable define where the edge is in every scene. Additionally, this method reduces the dataset considerably since fewer vehicles can be used.

Third, 1000 scenes from the Waymo Open Dataset have been used to obtain the results in this paper. For each scene, multiple frames have been analyzed. For most scenes, 30 frames are analyzed. But some scenes contained different number of frames that could be analyzed. For example, 669 scenes contain 30 analyzed frames, 171 scenes contain 20 analyzed frames and 96 scenes contain 40 analyzed frames. The remaining scenes contain varying different number of analyzed frames. Since all frames in a single scene are very similar, the results for each frame in a scene will be quite similar to the other frames in said scene. All in all, this means that scenes that contain relativity many analyzed frames weigh bigger in the calculated average. The same goes for scenes with fewer analyzed frames, but these scenes weigh smaller in the calculated average. Consequently, both the scenes with many analyzed frames and the scenes with fewer analyzed frames could skew the results.

Lastly, the comparison between city environments and highway environments resulted in some interesting takeaways. However, no strong conclusions can be formed due to the size of the dataset and dis-proportioned number of scenes from highway environments compared to city environments. Not only is the absolute number of highway scenes, 54, relatively low, there are about 17 times more scenes set in a city environment. This difference makes it somewhat difficult to accurately compare the two. Furthermore, determining whether a scene is set in a city or highway was done manually by the author. This means that the labelling was slightly subjective, sometimes it is quite difficult to determine if a road is a highway or rather a big, wide road but ultimately not a highway. This could be improved upon by finding a more objective way of determining the environments of a scene.

6 FUTURE WORK

There are a few questions that could be interesting to investigate, but were not able to be investigated in this research either by limitations of the dataset or because of time constraints.

Firstly, it would be interesting to further investigate the availability of direct LoS and vehicles in communication range in different types of environments. This paper already did some comparisons between highways and city environments, but the city category was quite broad. It included all kinds of environments like city centers, suburban, wide open roads. really anything but highways. Further comparing different types of environments would be interesting, for example looking into the differences between city centers and suburbs, or differences between residential, commercial and industry environments. This would require a clear and objective way of determining the different types of environments.
Secondly, investigating the duration that a vehicle is in LoS or within communication range would be very interesting and could provide more insights into the type of mmWave communication that is possible. Unfortunately, answering this question is not possible with the Waymo Open Dataset since all scenes are roughly 15 seconds long and thus determining the duration one vehicle is within communication range would result in inaccurate results. After all, it is unknown for how long the vehicle is in range before and after the scene.

7 CONCLUSION

This paper investigated the availability of direct LoS and mmWave communication between vehicles. Furthermore, this was compared between highway and other environments. The results are obtained by analyzing data from the Waymo Open Dataset. It has been concluded that on average there are 7.06 vehicles in direct LoS and on average 5.04 vehicles within communication range. The difference between the number of vehicles in LoS and in communication range is due to the fact that not all vehicles in LoS are within the maximum transmission distance. On the other hand, there are also vehicles that are not in LoS, yet close enough to be within communication range. At distances less than 15 meters, nearly 100% of vehicles are within mmWave communication range. At larger distances this decreases to roughly 70% to 85% depending on the environment. In general, there is more availability of direct LoS and mmWave communication in highway environments compared to city environments, this is due to the higher number of obstacles in city environments. The percentage of vehicles in mmWave communication range is nearly equal in highway and city environments for small distances. However, when looking at distances bigger than 20 meters, this percentage is higher at highway environments. All in all, more vehicles can be reached in highway environments than in city environments.

Considering all these results, it can be concluded that the availability for mmWave communication is the highest at relatively small distances. At distances larger than 20 meters, the availability for mmWave communication is higher in highway environments than in city environments.

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