Modeling Effect of Road Topology on Signal Analysis in Connected Autonomous Vehicle Communication

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Abstract. Connected car has become one of emerging technology in the automotive industries and vehicular communication studies on the other hand, has become one heavily researched topic in academia which focuses on the performance of various parameters upon vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication-based in the IEEE 802.11p vehicular communication studies. In urban environment, obstructions from existence of building, trees, street’s layout and other obstruction or objects can strongly influence the receive signal levels at 2.4 GHz frequency band. To ensure reliable and stable communication link for efficient future deployments of cooperative RSUs deployments, will require analyses on the signal strength upon environments that generally characterized by challenging propagation conditions. This article presents the results of experimental field testing of signal characteristics of different types of road topology such as grass, gravel and tar surface on open field environment. The results show that road topology or streets layout have an effect on V2I communication and the attenuation resulted from certain types of road’s surface can give significant impact on signal propagation.

1. Introduction

Connected car and autonomous driving or Connected Autonomous Vehicle (CAV) has become one of emerging technology and a heavily researched topic in academic and automotive industry. The evolutions and drastic change in autonomous vehicles technology has been happening since the first radio controlled vehicles was designed in 1920s. In 1960s, similar electronic guide system was used in autonomous cars and this feature is improvised in 1980s [1]. Today, there have been numerous projects, innovations and developments towards autonomous and connected car technology using similar and modified technologies [2]. Most of the projects are vehicular communication (VC) based applications for semi-autonomous cars target to enhance the transportation safety, efficiency and offer services to users or drivers and passengers. One of the famous concepts of wireless based technology in connected cars is such as the vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication. As such, there are other classes of non-automotive applications that use similar concept which existed some time ago namely autonomous underwater vehicles (AUVs), swarm robots and mobile crowd sensing [3][4]. These applications achieve connectivity by connecting nodes directly and come to an agreement by handshaking with each other’s message before proceeding to
other task. There are often used in military which are mostly deployed on the ground and sea and the system can be form of robots, automation and human. On the contrary, mobile crowd sensing is often used for environmental monitoring while there are also other example of methods that can be used to control swarm robot such as cooperative and predictive control. The system can provide information by allowing other system to read its mind so that the other system is able to make decision towards desired goal. All of these requires wireless system and control algorithm.

In automotive industries the use of both V2I and V2V applications are very wide. V2V and V2I communication interact with other cars and objects around the environment in order to communicate, collect and share data among themselves with aims of increasing safety by reducing accidents and increasing efficiency by managing traffic flow. Each application has its own characteristics with assigned latency and beaconing rates that are based on types of applications and its priority. Several examples of semi-autonomous features introduced in modern vehicle that target safety are such as emergency brake, slow warning, hazard warnings, pre-crash sensing, lane change and collision warning. These types of application are very high in priority and must be assigned with high beacon rates and very low latency for accurate positioning and broadcasting. While transportation efficiency is as crucial as safety, it is assigned as medium priority and requires low beaconing rates and high in latency for unicast V2V or cellular communications purposes. Some examples of applications that target on efficiency are such as adaptive cruise control, electronic toll collection, and so on. These projects and application including the service for users are mostly using ad hoc based, vehicle-to-vehicle (V2V) and vehicle to infrastructure (V2I) communication [5].

In transportation safety and traffic efficiency, the 802.11p or Dedicated Short Range Communication (DSRC), LTE, VANET and Wi-Fi such as WAVE are several examples of available wireless technologies that support V2V and V2I communication. In terms of performance, major crucial aspects that need to be considered to ensure an efficient cooperative control are reliability of communication performance as discussed in [6]. Moreover, a few studies in [7] have explored the impact of terrain elevation and street’s topology obstruction in an urban environment where the physical obstruction from the surrounding environment give an impact on the signal strength. In this paper, we aim to investigate the effect of surface attenuation on signal characteristics.

2. Research Background

Empirical study and channel measurement have been used extensively by means to provide understanding of deterministic models for modeling signal propagation thorough surface attenuation. There are a number of research work performed in areas such as agricultural field, environmental monitoring, land and seas for the purpose of future planning and efficient sensor deployment to maintain and sustain reliable communication [8] - [12]. These authors performed indoor and outdoor analysis through wireless sensor network applications and provide RSSI mapping, coverage measurement, antenna positioning impact, data rate measurement and more including modeling signal propagation thorough object, surface and vegetation attenuation. Several data prediction and methods available for modeling signal propagation as recommended by standard ITU-R recommendation for vegetation attenuation [13] and outdoor radio wave propagation [14] are as crucial as to find the right prediction methods through specific objects and types of environment. Recent works have been performed in [15] to model attenuation profile on roadside areas with tall, dense trees and plantation along the roadside area in sub urban environment. The authors analyzed both trees and shrub using different antenna heights. The RMSE and attenuation profiles are compared to existing vegetation attenuation models to find the most suitable models for that particular environment. In this paper, the research work is extended on exploring surface attenuation profile based on several types on surfaces especially flat terrains. Theoretically, there are a number of outdoor propagation models to discuss thorough surface attenuation models. One of the common outdoor propagation models in free space radio-wave propagation is the free space path loss, FSL. FSL model can be used to predict received signal strength when both transmitter and receiver have clear line-of sight (LOS) environment. This model is applicable where one single path between the transmitter and receiver with its received signal
as a function of transmitted power, antenna gain and distance. The received signal power, \( L_{FSL} \) expressed in dB is summarized in equation (1) \([11][15]\).

\[
L_{FSL}(dB) = -27.56 + 20 \log_{10}(f) + 20 \log_{10}(d)
\]

(1)

Where \( f \) is the frequency in MHz, \( d \) is the distance between the isotropic transmitting and receiving antennas in meters. Equation (1) can be calculated originally using Friis free space equation as given in equation (2) \([16]\) which includes antenna gains as unity.

\[
P_R = P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2
\]

(2)

Where \( P_R \) is received signal power, \( P_T \) is transmitted signal power, \( G_T \) and \( G_R \) are antenna gains of both the transmitter and receiver, respectively, with \( G_T=1, G_R = 1 \) (unity gain antenna), \( \lambda = c/f \) is the wavelength in meters.

During field measurement the transmitting and receiving antenna heights are being placed close to the ground. Plane Earth (PE) propagation model can be applied when considering transmitter and receiver which are placed close to the surface within 0 meter to 3 meters range. Thus, PE model can be used to describe path loss of ground wave propagation more accurately. The received power can be described using PE propagation model by calculating cross-over distance value as in equation (3). The relationship between received power, \( P_R \) and distance between communicating vehicle nodes based on values of \( d_{CROSS} \) is given in equation (4).

\[
d_{CROSS} = \frac{4\pi h_T h_R}{\lambda}
\]

(3)

\[
P_R = \begin{cases} 
  P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2, & d \leq d_{CROSS} \\
  P_T G_T G_R \frac{h_T h_R}{d^2}, & d > d_{CROSS}
\end{cases}
\]

(4)

Where \( P_R \) is the received power in dB, \( P_T \) is transmitted signal power \( h_T \) and \( h_R \) are transmitting and receiving antenna heights in meter, \( d \) is distance between transmitter and receiver in meter, \( \lambda \) is wavelength in meter and \( G_T \) and \( G_R \) are antenna gains in unity respectively.

In non-line-of-sight (NLOS) environment, shadowing effect occurs as obstruction blocks the signal path between transmitter and receiver. The average received signal strength which decreases logarithmically can be estimated using Log-Normal shadowing model. This is the basic probabilistic propagation model that distributes the reception power in logarithmic domain by applying variance to a normal distribution. This model can be used to compare with the deterministic model as random variable whereby the received power of this model will follow the Log-normal distribution. Log-normal shadowing model is given in equation (5) \([11][15]\).

\[
P_R(d) = P_{R0} - 10nlog(d) + X_\sigma
\]

(5)

Where \( P_R(d) \) is received power in dBm, \( d \) is distance in meters from the transmitter, \( P_{R0} \) is signal strength at 1 meter antenna separation, \( n \) is path loss exponent and \( X_\sigma \) represents Gaussian random variable with zero mean and standard deviation of \( \sigma \) dB.

Weissberger’s model \([10][15]\) as given in equation (6) is applicable for measuring the transmitter and receiver propagation path that are composed by dense, dry and in-leaf trees in temperate climates.
model plays an important role when modeling propagation path through a groves of trees or vegetation.

\[
L_W(dB) = \begin{cases} 
1.33 \times f^{0.284} d^{0.588}, & 14m < d \leq 400m \\
0.45f^{0.284} d_f, & 0m \leq d_f \leq 14m 
\end{cases}
\]

(6)

Where \( L_W \) is path loss in dB, \( f \) is transmission frequency in GHz, \( d \) is foliage depth along the path not less than 14 meters and not exceeding than 400 meters and \( d_f \) is foliage depth along the path not exceeding 14 meters.

Two-ray ground reflection model is applicable for predicting large-scale signal strength over LOS in urban environment. This model is applicable when modeling propagation path when vegetation is present outside the transmitter and receiver’s path with antenna measurement at significant heights. Two-ray ground reflection model is given in detail in [15] and path loss for Two-ray model can be calculated using equation (7) [16][17].

\[
L_{RAY}(dB) = 40 \log d - (10 \log G_T + 10 \log G_R + 20 \log H_T + 20 \log H_R)
\]

(7)

Where, \( d \) is separation distance of transmitter and receiver in meters, \( G_T \) is transmitter antenna gain, \( G_R \) is receiver antenna gain, \( H_T \) is transmitting antenna heights and \( H_R \) receiving antenna heights in meters.

3. Measurement Location and Equipment

The channel measurement has been conducted in Universiti Malaysia Perlis campus with three different LOS environments such as grass surface (A), tar surface (B) and gravel surface (C). These areas are mainly surrounded by foliage, vegetation and buildings with clear LOS and unobstructed propagation path between the transmitting and receiving antennas. The location of these surfaces based on satellite view is as depicted in Figure1. The view of open field measurement and data collection on grass, tar and gravel surfaces is as depicted in Figure 2, 3 and 4, respectively. Based on Figure 2, the surface is covered entirely with a carpet of grass and only a few crests, hills and trees surrounded the area some distance away. Tar surface in Figure 3 shows a smooth road covered with tar along the way with huge building, trees and hills situated a distance away. Gravel surface as shown in Figure 4 consists of small stones, pebbles and sand but there are vegetation surrounded the compound area quite a distance away. All three medium of surfaces represents similar road surface that can be found along roadways, streets, highways in Malaysia, as such there were chosen for channel measurement and data collection in this paper. This is to ensure that propagation path on different types of surface medium can be obtained to model through surface attenuation specifically for future implementation and effective CAV deployment program on Malaysia’s roadway.

The hardware used in this experiment for channel measurement and data collection is low mobility IEEE 802.15.4 XBee S2C compliant devices which operate under free licensed Wi-Fi at 2.4 GHz frequency band. The XBee S2C wireless sensor nodes were programmed as transmitter and receiver using XCTU software [18], respectively as shown in Figure 5. The transmitter (XBee TX) was programmed as the base or local and connected to a laptop with fixed position whereas receiver (XBee RX) was programmed as remote. A real on-field-setup of these wireless sensor nodes is as shown in Figure 6 and the a more detailed specification of XBee S2C sensor nodes is given in [15].
4. Experimental Design

Before conducting channel measurement, the 1\textsuperscript{st} Fresnel Zone [16] as illustrated in Figure 7 on each surface was calculated based on general equations in [15][19] to measure the maximum distance and allowable heights for obstruction between the transmitting and receiving antennas. This is to ensure that during channel measurement, the 1\textsuperscript{st} Fresnel Zone is free from other source of interference that may affect the performance of data transmission in this particular zone. Knowing the allowable heights of obstruction may prevent or reduce signal interference from unknown source during signal transmission. Measurement setup between transmitting and receiving antenna were estimated to be 100 meters or 0.1 kilometers. The measured clearance radius or maximum allowable height in Fresnel Zone is 1.37 meters. As such when performing channel measurement, objects (e.g. laptop, chair) used...
in-situ during channel measurement between the transmitting and receiving antennas did not exceed 1.37 meters.

![Diagram of Fresnel Zone](image)

**Figure 7.** Transmitter and receiver measurement setup and illustration of Fresnel Zone

The channel measurement for all three surfaces was performed by mounting both transmitter and receiver nodes on metal poles. The transmitter (XBee) TX or road-side-unit (RSU) was programmed as base station and connected to a laptop which runs XCTU software. The receiver (XBee RX) or on-board-unit (OBU) was placed and moved every 1 meter increment until the maximum distance of receiver’s sensitivity can be reached. At every 1 meter distance, RSSI values were recorded for two minutes, repeated two times and averaged. The measurements were taken with two different antenna heights, 1.3 meters and 0.15 meters at all three types of surfaces. The XCTU software was used to output the link’s quality during data transmission in terms of received signal strength indicator (RSSI) in dBm and packets delivery ratio (PDR). In this paper, only RSSI values were used to model the surface attenuation using root mean square error RMSE to find the closest fit model and applicable in this particular environment. The recorded values were concluded and presented in terms of power level or RSSI (dBm) in the following section.

### 5. Results and Discussion

First measurement was carried out on grass field environment for two different antenna heights, 0.15 m and 1.3 m. The bed of grass is about 100 m x 50 m in size and situated at Kompleks Sukan Syed Sirajuddin Areeb Putra UniMAP, highlighted as A in Figure 1. Measurement was carried out over the path length starting from 0 m up to 100 m with 1 m increment. As signal propagates along grass field, it is observed that there are significant differences found in signal power variation for both 0.15 m and 1.3 m antenna heights as shown in Figure 8 and Figure 9, respectively. Based on Figure 8, a significant drop from -19 dBm to -40 dBm is observed at 1 m distance for 0.15 m antenna heights. Signal continues to decrease abruptly up to 20 m distance with signal power of -79 dBm. There is a slight signal fluctuation between 5 m and 8 m as the signal increases before it decreases abruptly between 9 m and 11 m distance which is from -45 dBm to -57 dBm. Uneven surface of the grass caused the signal to fluctuate starting at 31 m onwards until it reaches its maximum range at 64 m distance. The signal only reaches 64 m due to several reasons.

Both transmitting and receiving antenna heights were placed 0.15 m from the ground. As such, within radius of Fresnel Zone the signal has been obstructed by ground effect. This phenomenon creates signal to scatter and disperse hence limits the propagation path. When the antenna height was increased to 1.3 m from the ground, the signal decays gradually starting from 0 m (-23 dBm) to 30 m (-68 dBm) distance as shown in Figure 9. Signal fluctuation is observed between 5 m and 8 m as the signal increases before it decreases abruptly between 9 m and 11 m distance which is from -45 dBm to -57 dBm. Uneven surface of the grass caused the signal to fluctuate starting at 31 m as the signal range is increased further up to 88 m distance. The difference in power loss for first 10 m distance is 30.3 dB compared to antenna height at 1.3 m which is 16.3 dB for grass surface.
Second experiment was carried out on tar surface area along the Universiti Malaysia Perlis Racing Circuit road, highlighted as B in Figure 1. The results of surface attenuation are as shown in Figure 10 and Figure 11 for 0.15 m and 1.3 m antenna heights, respectively. As the signal propagates along the tar surface, signal power drops significantly from -17 dBm to -81 dBm starting from 0 m up to 24 m distance for the 0.15m antenna height as depicted in Figure 10. With antenna heights positioned close to the surface, phenomena known as multipath fading and reflection caused signals to arrive at base station via multiple paths. After decreasing gradually, signal power started fluctuating at 25 m distance for 0.15 m antenna height. After 26 m, signal increased and decreased sharply until it reaches maximum range at 46 m distance due to strong winds during data collection. At 20 m distance, the signal power drop to – 82 dBm because the transmitting and receiving antennas is in clear LOS but strong wind caused the signal to overlap and generate multipath interference. The signal gets distorted and results in signal loss hence the signal only propagated a distance and lost its signal at 47 m.

Results for 1.3 m antenna heights tar surface attenuation shows that signal significantly decreases from -25 dBm to -78 dBm starting from 0 dBm to 26 m distance as shown in Figure 11. Significant drop is observed only at 26 m and 90 m which is – 78 dBm for both distances. Less signal fluctuation is observed as propagation along occurs on smooth and even tar surface which contributed to less signal scattering. The difference in power loss between 0.15 m and 1.3 m antenna heights for the first 26 m is 48.6 dB and 34.21 dB, respectively.

Third experiment was carried out on gravel filled surface which consists of sand, small and large pebbles. The test bed is 60 m in length and located at the entrance of Universiti Malaysia Perlis Racing Circuit entrance, as highlighted in C (Figure 1). The results of 0.15 m and 1.3 m antenna height for gravel filled surface attenuation are shown in Figure 12 and Figure 13, respectively.
Signal drop is observed to be significant for both antenna heights at first 10 m distance as signal propagates along gravel surface. The power loss for first 10 m distance is 37.4 dB and 39 dB for 0.15 m and 1.3 m antenna height, respectively. Signal power is observed to reduce from -15 dBm to -73 dBm for 0.15 m antenna height and from -19 dBm to -66 dBm between 0 m and 10 m distance as shown in Figure 12. The propagation range on gravel surface is very limited when the antenna is placed closed to the ground because signal power continues to diminish at 24 m distance. Due to that, signal scatter and divert in various paths and signal are easily absorbed by ground objects (gravel, sand, pebbles) and low antenna height positioned to ground caused signal degradation and limitation in propagation range.

On the contrary with 1.3 m antenna heights, signal is observed to decline abruptly at 30 m distance from -78 dBm to -89 dBm due to existence of larger gravel size and hump along the signal path. At 31 m distance, signal increased to -74 dBm at 37 m distance. The graph show mild signal fluctuations until 57 m distance before decreasing to -81 dBm at 60m. This phenomenon occurred when multipath propagation caused two and more signals to arrive at receiver at different time intervals and from multiple path lengths. Hence, signals that arrived at receiver simultaneously suffers distortion especially signal power having similar signal strength.

Comparisons between three different surfaces of attenuation profile are as shown in Figure 14 and Figure 15 for 0.15 m and 1.3 m antenna height, respectively. Figure 14 shows significant signal attenuation between first 20 m distance before having fair signal fluctuations for all three surfaces. Figure 15 shows gradual significant signal drop between first 10 m distance. It is observed from the
graphs that having different medium of surfaces could also affect the characteristics of signal propagation. Grass surface shows the least significant followed by tar and gravel surface. In addition, antenna heights, elevation angle and orientation contribute to variations in signal power. Thus these are several key factors to consider when planning incorporating results and execution of future modeling properly. The signal propagation range for each surface is given in Table 1 below.

**Table 1. Signal strength (dBm) and travel distance (m) for grass, tar and gravel surface**

| Surface               | 0.15 m Antenna Height | 1.3 m Antenna Height |
|-----------------------|------------------------|----------------------|
| Grass Field           | 64 m (-94 dBm)         | 88 m (-95 dBm)       |
| Tar Surface           | 47 m (-90 dBm)         | 90 m (-78 dBm)       |
| Gravel Filled Surface | 24 m (-81 dBm)         | 60 m (-86 dBm)       |

Based on the table above, it can be concluded that signal transmission with clear and unobstructed LOS propagation path can transmit farther and in greater range. With appropriate deployment of antenna heights based on surrounding environment, streets layout and road topology can aid in future planning of sensor nodes deployment between road infrastructure and road side unit.

**6. Conclusions**

The importance of modeling and investigating effect of different types of surfaces has been demonstrated in this paper and results have shown that certain types of medium on the road can give significant impact of propagation signal. Street’s layout and road topology including terrain elevation, surface and many more play a major role in V2I communication as they may contribute to changes in link’s connectivity. To implement reliable V2I and V2V communication in order to achieve reliable communication range between vehicle and infrastructure one of the solutions is to investigate the effect of obstruction from the surrounding environment. In our future work, we will model the impact of surface attenuation and develop empirical models to quantify the results.

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