A Path Loss Calculation Scheme for Highway ETC Charging Signal Propagation

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Abstract: Nowadays, Electronic Toll Collection (ETC) technology is widely used in many countries for highway toll charging. Actually, the ETC charging process can be treated as wireless communication between On Board Unit(OBU: in the vehicle side) and Road Side Unit(RSU: in the ETC exclusive lane side). After the communication link is built between the OBU and RSU, the highway toll gate will be open automatically, and meanwhile, the toll will be charged from drivers' bank accounts. This process asks for higher accuracy of the propagated signal. For path loss calculation of the charging signal, many previous researches only considered the direct path. However, in our realistic architectures of the highway toll stations, the signal propagation between the OBU and RSU is made up of several paths. Not only the direct path, but also many un-direct paths. Therefore, it is necessary to consider the realistic architectures of the toll stations, and give out a more feasible calculation method. This paper proposed a more feasible path loss calculation scheme for the ETC charging signal, which has considered the reflections impacts from the roof and ground of the station. By simulation, our method indicates that, the reflection effects from the roof and ground cannot be ignored in the realistic charging process. This paper also gives two advices for reducing the reflection impacts: 1) increase the reflection coefficients of roof and ground, which can be used to reduce the path loss brought by reflections; 2)the best suitable distance between the RSU and OBU is about $3m \sim 5m$, within this distance, the signal path loss is much lower than other distance ranges.

Key–Words: Path Loss, ETC signal, reflection impact, realistic toll station architecture

1 Introduction

In recent decades, much attention has been devoted to the research fields of Intelligent Transportation Systems (ITS). In general, the ITS combined with many technologies to achieve goals of different requirements. e.g., it combined with automatic engineering technologies for road traffic congestions control, combined with Global Positioning System(GPS) for better road navigation, or combined with city information servers for better entertainments.

As the most successful application services of the ITS, Electronic Toll Collection (ETC) becomes the world's most advanced charging system, and widely used all over the world. ETC is used for highway toll charging, which is especially suitable for heavy traffic on the highway, bridge and tunnels[1]. In an ETC charging system, each vehicles is installed with an On Board Unit(OBU) located in the inner window of vehicle. Meanwhile, at the toll station, a Road Side Unit(RSU) (e.g., antenna) is equipped on the top of ETC exclusive lane(refer to Fig.1). By the wireless communication, the OBU and RSU can communicate with each other for identity authentication. Hence, the gate of the station can be opened automatically, and the toll can be deducted from the driver's bank card.

Figure 1: An Architecture of ETC Toll Station[2]

Thus, utilization of ETC has several significant advantages over traditional human-window charging. First, vehicles can go through the toll station without stopping, thus the travel time will not be wasted. In addition, vehicles do not have to stop-and-go to pay tolls, therefore the exhaust emissions and noise emissions around the toll station will be reduced[3], which contributes to the improvement of surrounding environment. Second, the toll will be automatically charged, the drivers do not need to prepare cash. And in some countries, the toll paid by the ETC can be saved by some discount policies. Thanks to the greatly conveniences brought by ETC, the number of ETC vehicles are increased a lot in recent years.

As ETC charging fee is deducted from drivers' bank accounts, the accurate signals propagation for identity authentication and toll charging are becoming very important. In other words, the accuracy of signal is strongly affected by the propagation path.

There are many signal propagation models, such as the Okumura-Hata model and enchainment Okumura-Hata model [4][5][6][7], which is based on the direct ray path to calculate the propagation path length; some proposed terrain-based propagation model by integral equation [8][9]; and some provide a Non-line-of-sight single-scatter propagation model [10]. All these kinds of propagation model are widely used by researchers under different scenarios. Nevertheless, these existing models cannot be directly used in the ETC scenario, especially cannot be used for the highway toll stations if they were built the same as the scenario illustrated in the Fig.1. In fact, most toll stations in China, Japan and other many countries were built just as illustrated in the Fig.1.

Take China as an example, the ETC cannot totally take place of the human-window charging method, so the ETC exclusive lane is always built together with the human-window lanes, as presented in the Fig.1. Clearly, from the Fig.1, the toll station has a roof, and the RSU is installed near to the roof. When vehicles communicate with the RSU, the multi-path ray will be happened due to the reflections of the roof and ground. Therefore, this kind of specific station is determined that the existing models cannot be employed.

In this paper, we proposed a more feasible path loss calculation scheme for propagating the ETC charging signal, which is considered the reflection impacts from the roof and ground. By the proposed scheme, a more accurate communication will be built between the OBU and RSU. Thus, the accuracy of the ETC charging signal propagation can be ensured.

The structure of this paper is as follows. In Sect. 2 and Sec.3, the proposed path loss calculation scheme for ETC charging signal propagation is described. The performance is evaluated in Sect. 4. Finally, we conclude the paper in Sect. 5.

Table 1: Parameters presented in the Fig.2

Name	Meaning
L	Height of Roof
D_1	Height of RSU
D_2	Height of OBU
x	Horizontal distance between RSU and OBU
y	Vertical distance between RSU and OBU
d	Direct distance between RSU and OBU
φ	Incidence angle of the signal to the OBU
θ	Inclination angle of the OBU (window glass)

2 Analysis of The Proposed System Model

According to the realistic architectures of highway toll station (as shown in the Fig.1), it is necessary to design a more suitable and more accurate ETC signal propagation model to ensure the safety and accuracy of the ETC users' bank accounts. This is also the research goals of this paper.

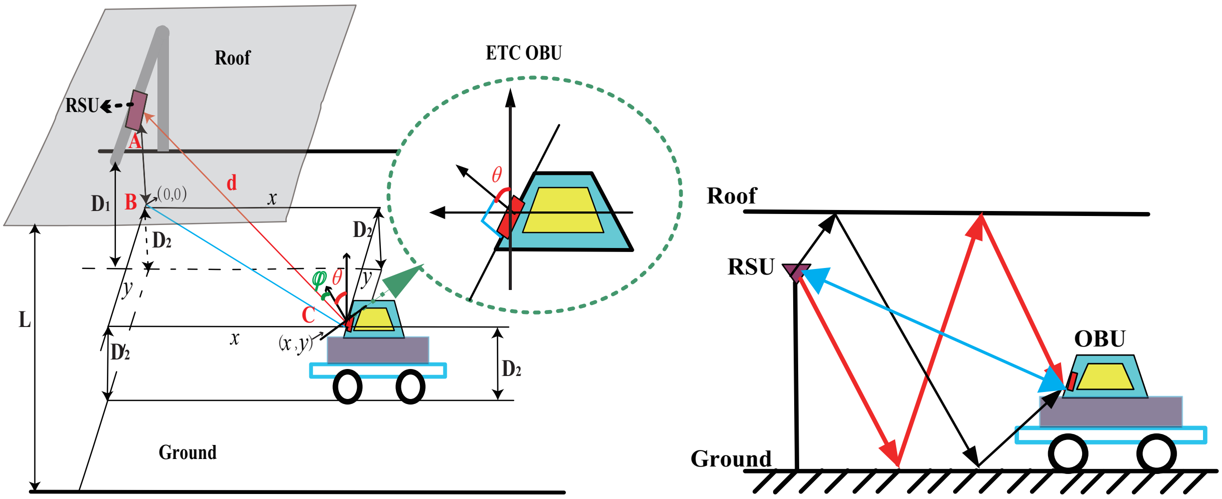
2.1 Proposed System Model

Before the presentation of the proposed system model, some assumptions are made as follows:

- Each ETC exclusive lane has only one ETC RSU, and each ETC vehicle has only one ETC OBU. Each RSU don't interrupt with each other, and each OBUs don't interrupt with each other either.
- The window of the ETC vehicle has no impacts for the ETC signal. In other words, there is no obstacle between the ETC RSU and ETC OBU.
- For the toll station, the roof and ground will be considered as flat, and the radio wave reflected by the roof and ground can be treated as specular reflection.
- For simplicity, we suppose the ground and roof have the same reflection coefficient.

The proposed system model is shown in Fig.2, and related parameters presented in the Fig.2 is listed in Table I.

To ensure the accuracy of the signal propagation, the calculation of the propagation path length is very important. The Fig.2(a) shows a general idea of the proposed signal propagation path length calculation. In reference [7], the authors proposed a more suitable calculation scheme than the Okumura-Hata model. However, even they took into account of the reflection impacts from the ground and the roof, the path



(a) General Illustration of the Proposed Model

(b) Elevation View for Fig.2(a) from the Plane ABC section

Figure 2: Proposed system model

length calculation is still need to improve, as the author treated the positions of the RSU and the OBU are always in a line which paralleled to the horizontal distance x. It is known to all that, different drivers have quite different driving habits, we cannot vouch for each drivers can keep a line that paralleled to the x with the RSU when approaching to the toll station. Therefore, when they are not in a line paralleled to the x, the path length should be calculated by the horizontal distance x and vertical distance y both, as illustrated in Fig.2(a).

For easily to draw the possible propagation paths, an elevation view from the plane ABC of the Fig.2(a) is obtained, as shown in Fig.2(b).

In the Fig.2(b), when the RSU acts as signal transmitter, there are three kinds of paths for the signal to arrive at the receiver. The first kind, which is also the main path, is the direct path, this is the most common path considered by many other researchers(illustrated in blue line in Fig.2(b)). For the second kind, the signal first reaches the roof, and after reflected by the roof, the reflected signal will arrive at the receiver(please refer to Fig.3, the blue line); or the signal reaches the ground first, reflected by the ground, and then arrives at the receiver(please refer to Fig.3, the red line). The third kind is that, the signal will be reflected by the roof and ground both: first reflects by the ground and then by the roof(the red line in Fig.2(b)), or first reflects by the roof and then by the ground(the black line in Fig.2(b)).

One of the most significant of the proposed model is that, the proposed model considers the impacts of the ground and the roof both. When the signal propagates between the RSU and the OBU, the reflection effects of the ground and roof will result in multi-path effects. The features of the proposed system can be summarized as follows:

(1) Considering the reflection impacts from the roof and ground, focus on four kinds of propagation paths as the complementary situations.

(2) Utilization of the geometrical position of the ETC vehicles to calculate the propagation path length.

(3) Applicable to not only the ETC station, but also other situations, such as railway stations, subway stations, etc.

3 Theoretical Performance Analysis of The Proposed Scheme

3.1 Path length Calculation

In the following, a detail analysis of four kinds of paths will be presented in detail.

(1)The first kind: direct path

As shown in the Fig.2(a), d is the path length for the first kind propagation, which is given by

$$d = \sqrt{(D_1 - D_2)^2 + x^2 + y^2} \tag{1}$$

Clearly, the direct path d is decided by the x and y. When the $y = 0$, the d will get the same result as in [6], this is also the difference between the proposed model and the model presented in [6].

(2)The second kind: only one reflection.

It is well known to all that, the reflected and incident waves are always in one plane. When vehicle's position is fixed, the successful propagated signal between the RSU and OBU also should be deployed in a fixed plane. Take the scenario in the Fig.2(a) as example, when the vehicle's position is at (x, y), the RSU and OBU both are in the plane ABC. If take the plane ABC as the vertical section, the elevation view is shown in Fig.3.

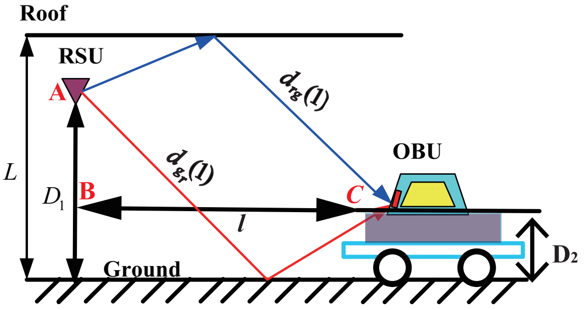


Figure 3: The second kind path

In the Fig.3, l represents the length of line segment BC, which is given by $l^2 = x^2 + y^2$(please refer to Fgi.2(a)). $d_{gr}(1)$ and $d_{rg}(1)$ are the path length by the ground reflection and roof reflection, respectively.

According the the geometric properties of the Fig.3, it is easily to get the results of $d_{gr}(1)$ and $d_{rg}(1)$ as

$$d_{gr}(1) = \sqrt{(D_1 + D_2)^2 + x^2 + y^2} \quad (2)$$

$$d_{rg}(1) = \sqrt{(2L - D_1 - D_2)^2 + x^2 + y^2} \quad (3)$$

(3)The third kind: only two reflections.

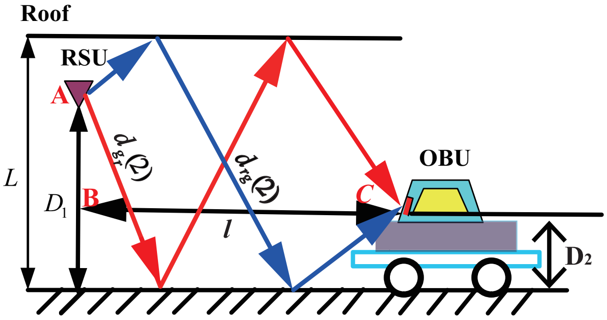


Figure 4: The third kind path

The Fig.4 shows the third kind path. The red line stands for the reflection first by the ground and then by the roof. The blue line stands for the reflection first by the roof and then by the ground. According to the geometric properties of the Fig.4, the path length of the two cases can be described as

$$d_{gr}(2) = \sqrt{(2L + D_1 - D_2)^2 + x^2 + y^2} \quad (4)$$

where $d_{gr}(2)$ represents the path length for the signal that first reflected by the ground.

$$d_{rg}(2) = \sqrt{(2L + D_2 - D_1)^2 + x^2 + y^2} \quad (5)$$

where $d_{rg}(2)$ represents the path length for the signal that first reflected by the roof.

(4)Apply into general cases: n times reflections

Similarly with the cases presented in the Eq.(4) and Eq.(5), by inductive method, a calculation for n times reflections by the ground and roof can be obtained as follows

$$d_{gr}(n) = \sqrt{[(n - n\,mod\,2)L + D_1 + (-1)^{(n-1)} D_2]^2 + x^2 + y^2} \quad (6)$$

where $d_{gr}(n)$ represents the path length for the signal that first reflected by the ground.

$$d_{rg}(n) = \sqrt{[(n + n\,mod\,2)L - D_1 + (-1)^{(n)} D_2]^2 + x^2 + y^2} \quad (7)$$

where $d_{rg}(n)$ represents the path length for the signal that first reflected by the roof.

3.2 Path Loss Calculation

The Eq.(2)-(7) represent the calculation method for path length. It is easily to get the path length difference between the direct path and n times reflections path, which is obtained as

$$\Delta d_{gr}(n) = d_{gr}(n) - d \quad (8)$$

$$\Delta d_{rg}(n) = d_{rg}(n) - d \quad (9)$$

For the direct propagated signal, the signal power is obtained as

$$P_d = \sqrt{(G_t G_r)} \frac{\lambda}{4\pi} \Gamma \left| \frac{e^{(-j2\pi d/\lambda)}}{d} \right| \quad (10)$$

where $\lambda = \frac{c}{f}$ is the wavelength (f stands for frequency, and c is the speed of light), G_t and G_r are the gains of the RSU and OBU antenna.

For the signal after n times reflections by the ground first, the signal power can be calculated as

$$P_{dgr}(n) = \sqrt{(G_t G_r)} \frac{\lambda}{4\pi} \Gamma \left| \frac{e^{(-j2\pi d_{gr}(n)/\lambda)}}{d_{gr}(n)} \right| \quad (11)$$

where Γ is reflection coefficient of the ground(or roof).

Similarly, the signal power after n times reflections by the roof first is

$$P_{drg}(n) = \sqrt{(G_tG_r)}\frac{\lambda}{4\pi}\Gamma\left|\frac{e^{(-j2\pi d_{rg}(n)/\lambda)}}{d_{rg}(n)}\right| \quad (12)$$

Therefore, the total signal power at the OBU is

$$P_{OBU} = P_d + \sum_{i=1}^{n} P_{dgr}(i) + \sum_{i=1}^{n} P_{drg}(i) \quad (13)$$

Compared with the direct path signal, the path loss of at the OBU can be written as

$$L_{OBU} = -10log_{10}\left|(\frac{P_{OBU}}{P_d})\right| \quad (14)$$

Applying the Eq.(8)-Eq.(13), the Eq.(14) can be written as

$$L_{OBU} = -10log_{10}\left|[1 + d\Gamma e^{-\lambda}\sum_{i=1}^{n}(\frac{e^{-j2\pi\Delta d_{gr}(i)}}{d_{gr}(i)} + \frac{e^{-j2\pi\Delta d_{rg}(i)}}{d_{rg}(i)})]\right| \quad (15)$$

The path loss in the free space can be predicted by the following equation [10]:

$$L_{free} = -27.56 + 20log_{10}(f) + 20log_{10}(d) \quad (16)$$

Thus, the total path loss is

$$L = L_{free} + L_{OBU} \quad (17)$$

Through the above analysis, it is clear that, the total path loss is related to the following parameters:

1) Fixed parameters in a given ETC toll station: L, D_1, D_2, f, and λ;

2) Vehicles positions: (x, y);

3) Reflection coefficient: Γ;

4) Reflection times: n.

In the following section, we will evaluate the effects brought by the above parameters.

4 Performance Evaluation

In simulation, the fixed parameters are set as: $L = 4m$, $D_1 = 3m$, $D_2 = 1m$. As the frequency of the radio wave for ETC system is 5.8GHz [1], so the $f = 5800MHz$, thus $\lambda = \frac{c}{f} = 0.05m$.

As the $\lambda = 0.05m$, after n times reflections, the signal should be about equaled to $\Gamma^n = 0.5^n$. When $n \geq 6$, the $0.5^6 \leq 0.0156$, this value is very small, thus the reflections after 6 times can be ignored. Here, we only consider the first 5 times reflections. Considering the realistic ETC toll station cases, the range of x is $0 \leq x \leq 10m$ and y is $0 \leq y \leq 2m$.

4.1 Path loss VS. Horizontal distance x

Here, set $y = 0$, we will evaluate the relationships between the path loss and the horizontal distance x under different reflection times n and different reflection coefficients Γ. The simulation results are listed in Fig.5-Fig.9.

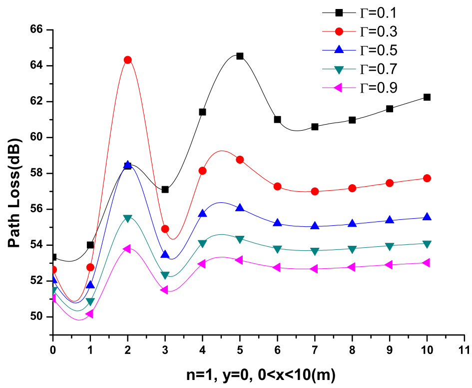


Figure 5: Path loss under different reflection coefficients when n =1

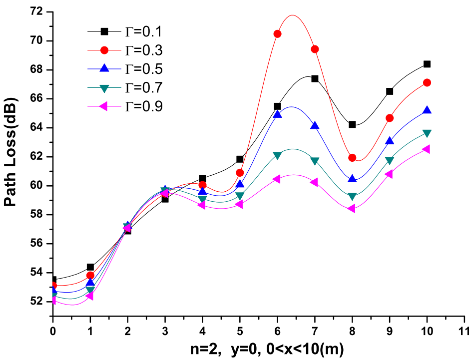


Figure 6: Path loss under different reflection coefficients when n =2

For the Fig.5, when $n = 1$, the path loss differences under different Γ are quite distinguish. When $0 \leq x \leq 5m$, the minimum value is about 50dB (when $\Gamma = 0.9, x = 1m$), and the maximum value is about 64dB (when $\Gamma = 0.1, x = 2m$). However, when $x > 5m$, especially when $x \geq 6m$, the

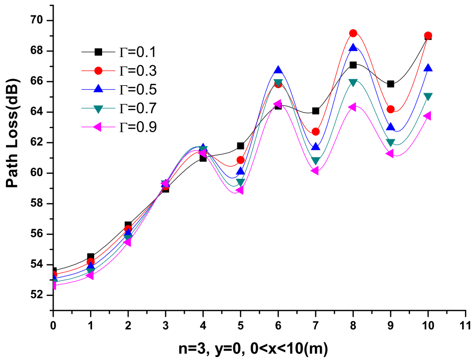


Figure 7: Path loss under different reflection coefficients when n =3

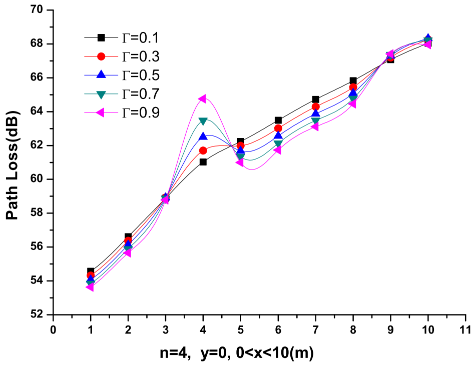


Figure 8: Path loss under different reflection coefficients when n =4

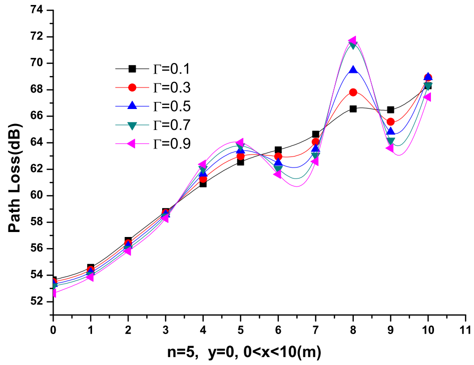


Figure 9: Path loss under different reflection coefficients when n =5

curves of path loss become flat. For the Fig.6,when $0 \leq x \leq 5m$, the path loss differences under different Γ are not clear. But when $x > 5m$, the path loss differences are distinguished. The case shown in Fig.6 is almost the same as Fig.6. When $n = 4$ and $n = 5$, the path loss curves almost have the same trends as illustrated in Fig.8 and Fig.9.

Meanwhile, in each figures of the Fig.5, all are clearly to show that, even under the same Γ, the difference value for the minimum and maximum path loss is more than 10dB. This indicates that the reflection impacts cannot be ignored. Besides, the path loss value is reduced when Γ increased.

From the results shown in Fig.5-Fig.9, we can easily to get the conclusions that, the reflection effects from the ground and roof cannot be ignored, as the path loss difference value can be reached more than 10dB. Especially, when $n = 1, n = 2$ and $n = 3$, the differences are quite distinguish.

4.2 Path loss VS. Position (x, y)

From the Fig.5 to Fig.9, the path loss value is very distinguish for different Γ when $n = 1$ and $n = 2$. Therefore, in this subsection, we only evaluate the performance of path loss VS. position (x, y) when the reflection times $n = 1$ and $n = 2$. The simulation results are shown in Fig.10-Fig.15.

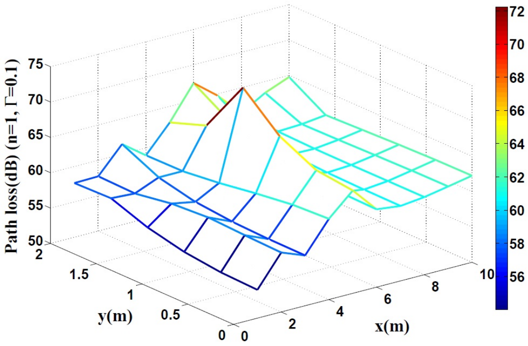


Figure 10: Path loss VS.Position (x, y) when n=1,Γ=0.1

The simulation results when $n = 1$, and $\Gamma = 0.1, 0.5, 0.9$ are shown in Fig.10, Fig.11 and Fig.12. From these three figures, when $5 \leq x \leq 10m$ and $0 \leq y \leq 1.5m$, the path loss value surfaces are quite flat, but when the x and y in the other ranges, the surfaces changed a lot.

When $n = 2$, and $\Gamma = 0.1, 0.5, 0.9$, the results are presented in Fig.13, Fig.14 and Fig.15. Compared with the $n = 1$ cases, the value of the path loss is increased under the same Γ.

The results in Fig.10-Fig.15 indicate that the vertical distance y has greatly impacts on the path loss,

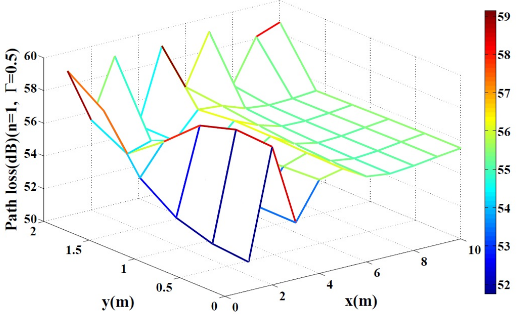


Figure 11: Path loss VS.Position (x, y) when n=1,Γ=0.5

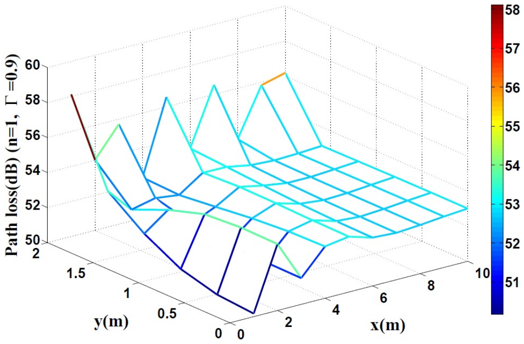


Figure 12: Path loss VS.Position (x, y) when n=1,Γ=0.9

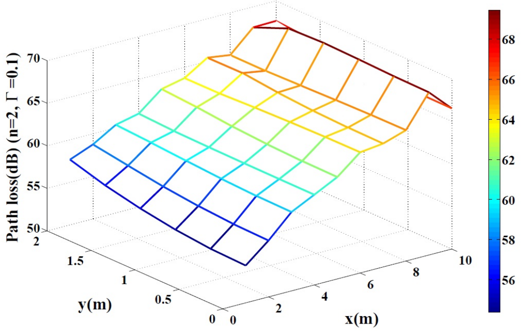


Figure 13: Path loss VS.Position (x, y) when n=2,Γ=0.1

and the y cannot be ignored when calculating the path length. Thus, compared with the [7], our proposed scheme is more feasible for calculation the path loss of the realistic ETC charging signal propagation.

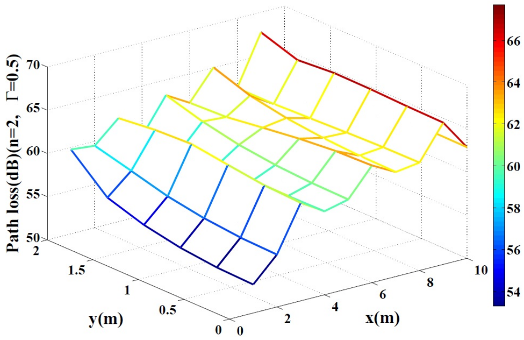


Figure 14: Path loss VS.Position (x, y) when n=2,Γ=0.5

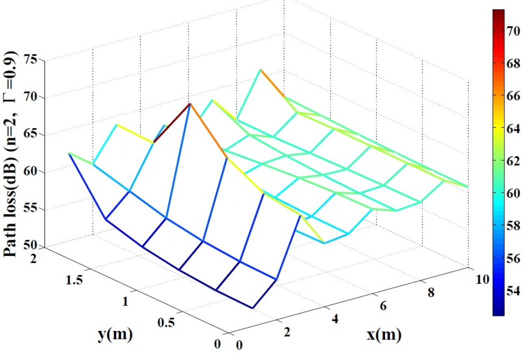


Figure 15: Path loss VS.Position (x, y) when n=2,Γ=0.9

4.3 Path loss VS. Reflection times n under fixed (x, y)

For simulation of this part, we set the $x = 3m, y = 0.1m$, the results are shown in Fig.16.

The Fig.16 illustrates that when the reflection times $n \leq 3$, the path loss value is quite different under the different Γ, while when $n > 3$, the path loss value is almost the same even under the different Γ. This conclusion is the same as we get from the Fig.5-Fig.9.

From the above results, we can get the following conclusions:

(1)The path loss is greatly affected by the multipath effects due to the difference of path length. Besides, the more reflection times by the ground/roof, the more path loss will be caused.

(2)Under the same reflection times, the reflection coefficient of the ground/roof also will result in a worse path loss. The higher reflection coefficient,

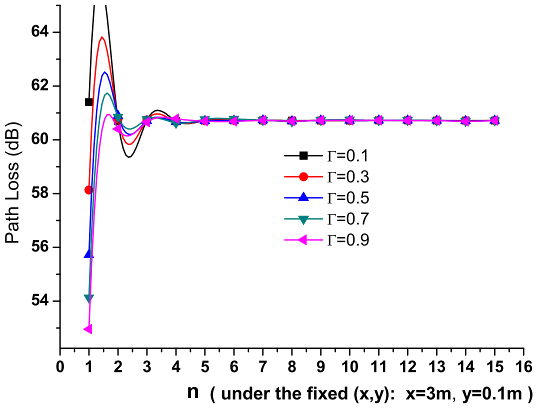


Figure 16: Path loss VS. Reflection times n under fixed (x, y)

the less path loss. Therefore, it is a necessary way to reduce the path loss by improving the reflection coefficients of the ground and roof.

(3) A more reliable horizontal distance x for toll charging is about $3m \sim 5m$. As the longer distance, the higher path loss. However, too close to the RSU is also not good.

(4)Vehicles' vertical distance y cannot be ignored, especially when $y > 1.5m$, the path loss will increase a lot.

5 Conclusion

In this paper, we analyzed the importance of accurate path loss calculation when applied in the highway ETC charging process. We indicated that the reflection impacts from the ground and roof cannot be ignored during the ETC charging signal propagation. However, this issue was ignored by most ETC related researchers and designers. Thus, it is necessary to inform this important information to the related researchers and designers. To address this problem, we proposed a feasible path loss calculation scheme for the signal propagation of the highway ETC charging, which gave a detail description for calculating the accurate path length under different parameters, such as the positions of vehicles (x, y), the reflection coefficient Γ, and the reflection times n. Besides, we also gave out several useful advices for reducing these impacts: 1) improve the reflection coefficients of the ground and roof. 2) Suggest the vehicle to driver along the center of the ETC lane (here, $y = 0$), and $3m \sim 5m$ is the best distance for charging.

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