



Large-Scale Fading Measurement and Comparison for O2I Channels at Three Frequencies

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Abstract. Channel measurement and modeling are fundamental and critical for the analysis and simulations of communication systems. For the fifth generation (5G) cellular network, the wireless channel characterization in its application scenarios, such as the *enhanced mobile broadband* (eMBB) and *massive machine type of communication* (mMTC), is critical. In this paper, we investigate the radio propagation at 900 MHz, 2.6 GHz, and 3.5 GHz in *Outdoor-to-Indoor* (O2I) scenario. We performed the channel measurements using a multi-frequency narrow-band sounder to derive the large-scale fading parameters such as the path loss and shadow fading. Then, based on the measurement data, we analyze the differences of the large-scale fading parameters at the three frequencies and the impact of frequency on the channel characteristics. Furthermore, we compare the accuracy of three path loss models specified in the WINNER and 3GPP channel modeling standards according to the measurement results. Finally, we propose the modification on the model coefficients to fit the measurement results better for various carrier frequencies in the O2I scenario. The measurement data and revised channel model can support the signal coverage analysis and subsequent communication system optimization.

Keywords: Channel measurement and modeling · O2I · Path loss · Shadow fading

1 Introduction

Wireless communication is conducted by radio wave propagation via wireless channels. Because of the presence of scatterers in the environments, radio waves arrive at receivers along different paths (direct, reflection, scattering, diffraction etc.). Therefore, accurate measurement and channel modeling of the large-scale radio propagation characteristics, such as path loss and shadow fading, facilitates the design, deployment, and management of wireless networks. Using channel models to predict the propagation characteristics of radio waves is the basis of performance simulation and evaluation of wireless communication systems.

The stochastic channel models based on geometry have been widely used for the link and system-level simulation.

The advent of the fifth generation (5G) mobile systems has extended its application scenarios to a broader sense, including the *enhanced mobile broadband* (eMBB), *massive machine type of communication* (mMTC), and *ultra-reliable and low latency communication* (uLLC) [1]. One of the distinguished features of the 5G networks is all-spectrum access which involves *low-frequency* (LF) bands below 6 GHz and *high-frequency* (HF) bands above 6 GHz such as the mmWave bands, where the former is the core bands used for seamless coverage [2]. As such, the channel modeling of sub6G for coverage in the outdoor-to-indoor (O2I) scenario is worth studying. Due to the vision of 5G about mMTC, Telecommunications agencies and organizations around the world have begun to conduct in-depth studies on the spectrum used in mMTC, such as *China Mobile Communications Corporation* (CMCC) who chooses 900 MHz (Band 8) as the spectrum of module test specification. As for the demand of eMBB, Chinese *Ministry of Industry and Information Technology* (MIIT) has also selected 3.5 GHz as the working spectrum of 5G.

Channel measurements have been conducted widely to prove the feasibility of the above 6 GHz [3]. The O2I scenario has also been studied in this frequency range and the signal power loss due to building penetration is assessed especially in [4] and [5]. However, for O2I scenarios in 5G, the application scenarios for both mMTC and eMBB are requested. At present, there are few studies on the hybrid spectrum coverage analysis and channel modeling for mMTC and eMBB in the O2I scenarios.

In this paper, we perform the multi-frequency O2I channel modeling for the sub6GHz band, including 900 MHz, 2.6 GHz, and 3.5 GHz. According to the coverage analysis at the three frequencies, we can provide guidance for base station selection and network planning. Furthermore, a detailed signal channel modeling and analysis is presented for the radio planning in the 5G. The path loss models defined in WINNER II, WINNER+, and 3GPP technological report are compared based on our measurement data. The results show that the WINNER+ model is closet in this measurement O2I scenario for the three frequencies. Then we further improve the model by revising the model coefficients to fit the measurement data better.

The rest of the paper is organized as follows. Section 2 introduces the channel sounding and presents the measurement environments. Section 3 investigates three standard channel models, select the most suitable channel model, and modifies it with the measurement data. Section 4 concludes the paper with the future research issue.

2 Measurement Campaign

2.1 Measurement System

This measurement campaign was conducted using a triple-band large-scale channel sounder. Figure 1 shows the measurement equipments. The system uses a

continuous wave (CW) narrow-band sounding scheme, the transmitter (TX) generates and transmits a single tone at each carrier frequency. In Fig. 1(a), the antennas working at 900 MHz, 2.6 GHz, and 3.5 GHz are installed on the pylons.

As for the receiver (RX), a wide-band antenna, as shown in Fig. 1(b), is adopted to receive all the transmitted signals. In the field measurements on propagation path loss, the three radio frequency (RF) chains in the TX transmit signals simultaneously. The multi-band sounding signals are received on the wideband antenna and input into a *spectrum analyzer* (SA). The SA has been programmed to record the received power at the three marked frequency points for 30 times continuously with the interval of 100 ms. Then it calculates the average power at each frequency and transfer the data to a computer via Ethernet for storage.



Fig. 1. The photos of the multi-band channel sounder. (a) TX System; (b) RX System

2.2 Scenario Description

The measurement campaign was conducted in Chengdu, China, in a typical urban microcell (UMi) O2I scenario. The measurement environments and the placement of the RX are shown in Fig. 2.

As shown in Fig. 1(a), the TX was installed on top of a building to emulate a base station (BS). The height of the three antennas was about 26 m. The RX was moved on the floors in a modern apartment building on the opposite side of the TX to emulate a user equipment (UE), as shown in Fig. 1(b) and (2b). The minimum three-dimensional distance between the TX and RX was 50 m.

Figure 2 shows the apartment building layout. Figure 2(a) includes the satellite map of the measurement environment, indicating a typical O2I scenario. In Fig. 2(e), the red number i ($i=0, 1, 2, \dots, 38$) represents the RX locations, including three typical indoor scenarios, which are displayed in (b), (c), and (d). Figure 2(b) shows the interior room scenario which is defined as Area One (A1). Figure 2(c) displays the short hall, defined as Area Two (A2). Figure 2(d) is the long hall, namely Area Three (A3). In this campaign, we put the RX on the 10th, 8th, 6th, 4th and 3rd floors where the positions of the RX in all the A1, A2, and A3 were accurately recorded.

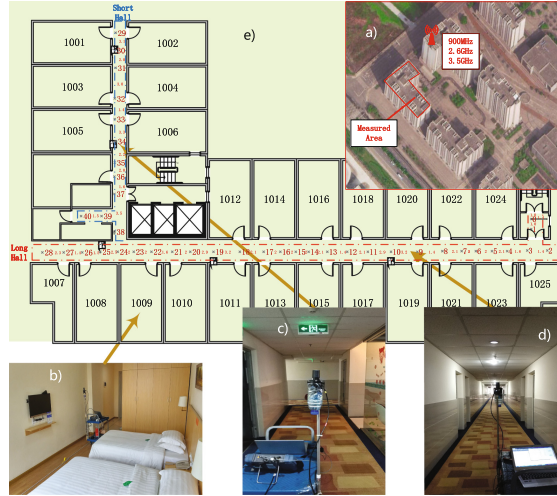


Fig. 2. The measurement environment. (a) Satellite map; (b) A1; (c) A2; (d) A3; (e) Measured area layout

3 Measurement Results and Modeling

3.1 Measurement Results

The diagrams in Fig. 3 demonstrate the distributions of the path loss at the three frequencies on the 10th floor. For the room (A1) scenario, the signals can propagate through the windows and achieve good coverage at all the three frequencies. According to the link budget design, the maximum tolerable path loss for the BS-to-UE links is $PL_{th} = 140$ dB. It can be seen that the path loss in the rooms was much smaller than PL_{th} at 900 MHz and 2.6 GHz. Therefore, the BS can cover the room entirely at both the frequencies. It is noticed that the path loss of 3.5 GHz is largest in Room 1016 but Room 1015 and 1019 could be covered very well. It is unexpected and will be discussed in details later.

For the ease of comparison, we defined the *average path loss* (APL) of A1 as the mean path loss of the rooms of 1001, 1002, 1016, and 1020, on each floor in the apartment building. In the short hall (A2) scenario, the path loss at all the three frequencies was obviously larger than that in the rooms of 1001 and 1002, but the path loss at the three frequencies was well below PL_{th} , ensuring good coverage in A2. The APL in A2 at 900 MHz, 2.6 GHz, and 3.5 GHz were larger by 12, 18, and 25 dB, respectively, than those in A1.

In the long hall (A3) scenario, it is obvious that the path loss of 900 MHz was almost 110 dB, which was much below PL_{th} . However, the path loss of 2.6 and 3.5 GHz was closed to PL_{th} , and thus these two bands may not meet the path loss requirement except the locations near the windows. The APLs in A3 at 900 MHz, 2.6 GHz, and 3.5 GHz were larger by 27, 39, and 49 dB, respectively, than that in A1.

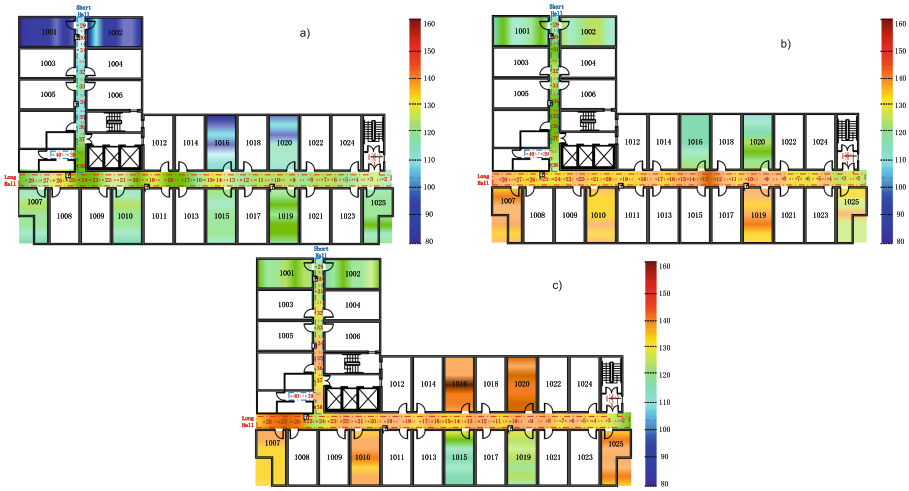


Fig. 3. The path loss variation at different locations. (a) 900 MHz; (b) 2.6 GHz; (c) 3.5 GHz.

The unexpected phenomena of 3.5 GHz may be explained with Fig. 4. There was a high-rise building to the west of the measurement apartment building, as shown in Fig. 4. Thus, some signals were reflected into the rooms through the windows, resulting in the decreasing trend of the path loss from the south to the north.

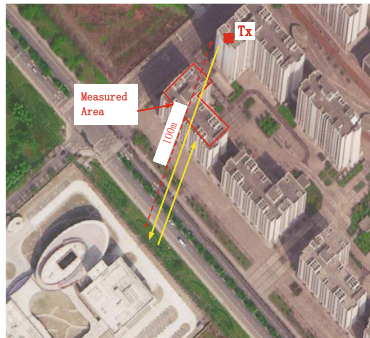


Fig. 4. Building reflection

In summary, we can see that the 900 MHz band could provide good coverage for all the areas. Therefore, CMCC has selected 900 MHz as the spectrum band of NB-IoT, which not only can be deployed quickly based on the existing cellular systems, but also can achieve wide area coverage for the terminal devices. As for the 2.6 GHz band adopted in the LTE system, the coverage of the signal

basically achieved the coverage requirements. As for the spectrum of 5G, the 3.5 GHz band could provide basic coverage of A2 and the propagation through windows provided the received power and hence determined the O2I coverage for 3.5 GHz in A1. Meanwhile the received power decayed quickly with the depth of the indoor position due to the large path loss. Consequently, the radio signal at 3.5 GHz cannot cover the inner space of buildings without direct propagation through exterior windows. Hence it is necessary to deploy more BSs or increase the transmission power to achieve better coverage.

3.2 Channel Model Selection

WINNER II Channel Model [6] has been widely used for link and system-level simulations. The measurement setting of this research is consistent with the definition of the O2I scenario in WINNER II. The model is specified as

$$PL = PL_b + PL_{tw} + PL_{in} + X_{winnerII}, \quad (1)$$

$$\begin{cases} PL_b = 22.7\log_{10}(d_{3D}) + 41 + 20\log_{10}(f_c), \\ PL_{tw} = 14 + 15(1 - \cos\theta)^2, \\ PL_{in} = 0.5d_{in}. \end{cases} \quad (2)$$

In (1) and (2), f_c is the carrier frequency in GHz. d_{3D} is the 3D Tx-to-Rx separation distance in the unit of meters, θ is the wall-piercing angle of wave, and d_{in} is the distance from the exterior wall to the RX. $X_{winnerII}$ is known as the shadow fading (SF) factor representing the large-scale signal fluctuations resulted from obstructions in propagation environment, PL_b represents the propagation model of signal in free space, while PL_{tw} describes the loss of walls and PL_{in} indicates the additional indoor loss relative to the free space.

WINNER+ Channel Model [7] defines O2I scenario similar as that of Winner II. The model is expressed as (3) and (4) which adds the effect of wall-piercing angle and frequency on path loss of PL_{tw} .

$$PL = PL_b + PL_{tw} + PL_{in} + X_{winner+} \quad (3)$$

$$\begin{cases} PL = 22.7\log_{10}(d_{3D}) + 27 + 20\log_{10}(f_c) \\ PL_{tw} = 31.64 + 15(1 - \cos\theta)^2 - 25.2\log_{10}(f_c) \\ PL_{in} = 0.5d_{in} \end{cases} \quad (4)$$

3GPP TR38.900 V14.3.1 [8] specifies the O2I path loss model as (5), (6) and (7), which takes path loss through the glass and walls in the propagation link into consideration.

$$PL = PL_b + PL_{tw} + PL_{in} + X_{TR38.900} \tag{5}$$

$$\begin{cases} PL_b = 32.4 + 21\log_{10}(d_{3D}) + 20\log_{10}(f_c) \\ PL_{tw} = PL_{npi} - 10\log_{10} \sum_{i=1}^N (P_i \cdot 10^{\frac{l_{material_i}}{-10}}) \\ PL_{in} = 0.5d_{in} \\ l_{material_i} = a_{material_i} + b_{material_i} \cdot f_c \end{cases} \tag{6}$$

$$PL_{tw} = \begin{cases} 5 - 10\log_{10}(0.3 \cdot 10^{\frac{-l_{glass}}{10}} + 0.7 \cdot 10^{\frac{-l_{concrete}}{10}}) \\ low - lossmodel \\ 5 - 10\log_{10}(0.7 \cdot 10^{\frac{-l_{iirglass}}{10}} + 0.3 \cdot 10^{\frac{-l_{concrete}}{10}}) \\ high - lossmodel \end{cases} \tag{7}$$

In (5), (6) and (7), PL_{npi} is an additional loss and added to the external wall loss to account for non-perpendicular incidence. $l_{material_i}$ represents the loss factor of each materials, and $l_{material_i}$ of windows and walls are $l_{glass} = 2 + 0.2f_c$ and $l_{concrete} = 5 + 4f_c$, respectively. Using the low or high loss model is a simulation parameter that should be determined by the channel models depending on the use of metal-coated glass in buildings and the deployment scenarios. Considering that all the windows of the measurement apartment building did not use the metal-coated glass, we select low-loss model in this work.

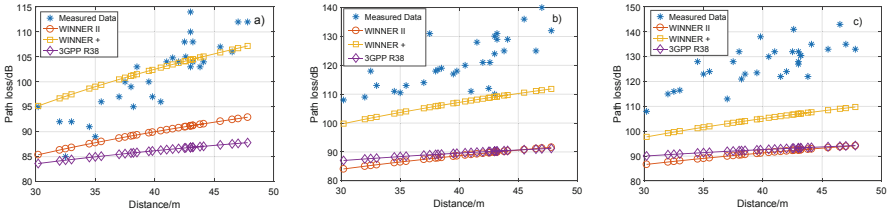


Fig. 5. The measurement results and models of the path loss in the A2 scenario. (a) 900 MHz; (b) 2.6 GHz; (c) 3.5 GHz

Because of the large amount of data, the scenario of A2 is selected for modeling and analysis. The results are shown in Fig. 5. According to (1) to (7), the path loss of the three standard models with respect to d_{3D} can be calculated. To observe the difference between the models and the actual measurement data, we conduct the curve fitting. It can be observed that the fitting curve according to the WINNER+ model is the closest to the measurement data. At the same time, comparing the mean and variance of the fitting results, WINNER+ has the smallest mean error and variance. Further, the O2I scenario are slightly different in these models, such as base station height, receiver and transmitter distance, which also results in the discrepancies. Based on the observations from Fig. 5, WINNER+ Channel Model is selected for the multi-band large-scale modeling according to our measurement results.

3.3 Revision of Winner+ Channel Model

According to (2), the two main factors, namely, f_c and d_{3D} , can be selected to adjust the coefficients of the model. The model is revised according to the Gradient Descent (GD) algorithm, and the appropriate interval is determined to select suitable coefficients of f_c or d_{3D} . The *hypothetical function* ($h_\theta(x)$) of the Gradient Descent algorithm is

$$h_\theta(d_{3D}, f_c) = \theta_0 \cdot \log_{10}(d_{3D}) + \theta_1 \cdot \log_{10}(f_c) + \theta_2. \tag{8}$$

Considering that this measurement campaign mainly involves three spectrum bands, we can set the variable f_c as a constant, and thus we reduce the Binary Gradient Descent into one dimensional Gradient Descent and obtain path loss models depending on f_c . Hence $h_\theta(x)$ can be updated as

$$h_\theta(d_{3D}) = \theta_0 \cdot \log_{10}(d_{3D}) + \theta_1, \tag{9}$$

and the cost function ($J(\theta)$) is

$$J(\theta_0, \theta_1) = \frac{1}{2m} \sum_{i=1}^m (h_\theta(d_{3D}^{(i)}) - PL^{(i)})^2. \tag{10}$$

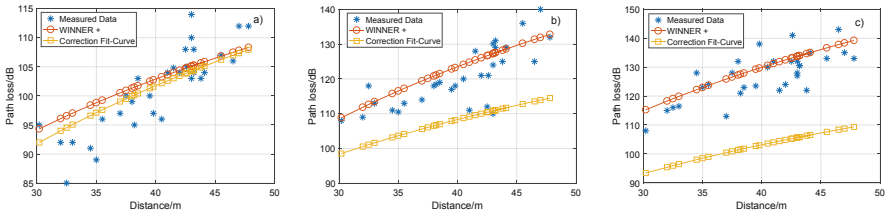


Fig. 6. The measurement results and corrected models of the path loss. (a) 900 MHz; (b) 2.6 GHz; (c) 3.5 GHz (Color figure online)

The results are demonstrated in Fig.6. The blue markers represent the actual measurement data and the red and yellow curves represent the WINNER+ Channel Model and its correction. It can be observed that the modified model can fit the measurement data better at 900 MHz, and the great deviation between the original model and the measured data is avoided at 2.6 GHz and 3.5 GHz. The revised path loss models at the three measurement frequency points are given as

$$PL = 34.26 \log_{10}(d_{3D}) - 15.98 \log_{10}(f_c) + 15(1 - \cos\theta)^2 + 0.5d_{in} + 38.25 \tag{11}$$

$$PL = 39.58 \log_{10}(d_{3D}) - 20.56 \log_{10}(f_c) + 15(1 - \cos\theta)^2 + 0.5d_{in} + 59.08 \tag{12}$$

$$PL = 40.21 \log_{10}(d_{3D}) - 17.78 \log_{10}(f_c) + 15(1 - \cos\theta)^2 + 0.5d_{in} + 65.10 \tag{13}$$

3.4 Shadow Fading

SF is an important large-scale fading parameter. Differences between the measured path loss and path loss model at the RX positions are the SF factor. We use the *Kolmogorov-Smirnov* (K-S) check method to test whether these data are consistent with the lognormal distribution. Theoretically, SF should follow the logarithmic distribution, because SF is due to the power losses caused by barriers such as walls and trees. SF can be counted by multiplying all power losses along a propagation path, which is transformed to the addition of the losses in the logarithmic domain. In accordance with the central limit theory, SF should comply with a normal distribution in the logarithmic domain. Hence, the SF derived from the proposed revised path loss model can also be used to verify the reasonability of the model itself.

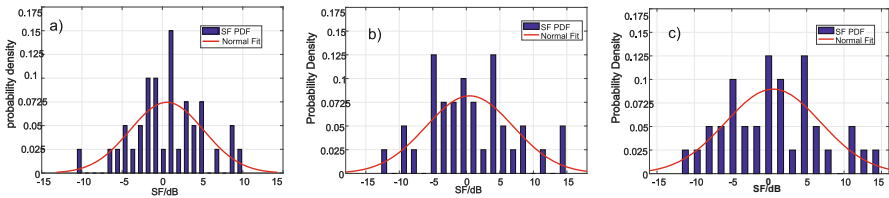


Fig. 7. The measurement results and normal distribution of the SF. (a) 900 MHz; (b) 2.6 GHz; (c) 3.5 GHz

As depicted in Fig. 7, the x -axis represents the value of the SF in the logarithmic domain, and the y -axis represents the probability density of each SF interval. The calculated SF samples at the three frequency points with the modified path loss model basically conforms to the lognormal distribution with the mean value of 0, and the standard deviations, namely σ , of 900 MHz, 2.6 GHz and 3.5 GHz are 4.5913, 6.6289, and 7.421, respectively.

4 Conclusion

In this paper, we select a typical UMi O2I scenario for signal coverage analysis in three spectrum bands, namely 900 MHz, 2.6 GHz, and 3.5 GHz. We conducted extensive field measurement on the signal power attenuation for rooms, short hall, and long hall. We conclude that 900 MHz and 2.6 GHz signals can achieve good coverage for the indoor areas, and by benefitting from the reflection on adjacent buildings, the 3.5 GHz signal guarantees the basic signal coverage in most areas. The observations and analysis can provide guidance for BS deployment and network optimization. At the same time, we compare several standard path loss models by fitting the measurement data. The WINNER+ O2I path loss model is selected and the model coefficients are further adjusted according to the measurement data. Then, the lognormal distributions of the SF samples

at the three frequencies are obtained for this O2I channel model. The observation and revised channel models can be used in the analysis and simulation of the cellular systems, and to compare the network performance when working in different frequency bands. The BS deployment and network optimization based on the channel models will be studied in the future works.

Acknowledgement. This work was supported in part by the National Natural Science Foundation of China (61571370 and 61601365), in part by the Natural Science Basic Research Plan in Shaanxi Province (2016JQ6017), in part by the Fundamental Research Funds for the Central Universities (3102017O-QD091 and 3102017GX08003), in part by the China Postdoctoral Science Foundation (BX20180262) and sponsored by the seed Foundation of Innovation and Creation for Graduate Students in Northwestern Polytechnical University.

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