Path Loss Models for Air-to-Ground Radio Channels in Urban Environments

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***Abstract*—This paper provides new statistical models for air-to-ground channels in an urban environment. The model is derived to operate at frequencies from 200MHz to 5GHz. Issues such as path loss and shadowing are evaluated as a function of the elevation angle to the airborne platform, rather than the more usual separation distance used for terrestrial mobile communications. Results demonstrate the advantages of an air-to-ground channel for urban communication, and relayed peer-to-peer links in particular.**

Keywords-Radio propagation; air-to-ground channel; path loss; shadowing; statistical channel models; urban environment

I. INTRODUCTION

For terrestrial mobile communications in a dense urban environment, radio propagation suffers extremely high path loss due to the presence of buildings, foliage and other manmade and natural clutter. Models for peer-to-peer (P2P) radio channels indicate that the channel deteriorates dramatically, with non-line-of-sight (NLoS) path loss indices as high as six reported in the literature [1]. For urban peer-to-peer links, the probability of line-of-sight (LoS) drops sharply with increasing transmitter-receiver separation distance. By comparison, airborne communication nodes are able to increase the likelihood of LoS to ground based terminals and, when NLoS does occur, the resulting diffraction loss is generally less severe. Airborne platforms are therefore able to play a vital role in situations such as urban peacekeeping and public protection and disaster relief (PPDR). The airborne radio node is able to act as a relay extension for long range P2P mobile ad-hoc communications.

The air-to-ground mobile radio channel has been traditionally studied for land mobile satellite communications; while Unmanned Air Vehicles (UAVs) have been studied in military applications. Previously, Lutz *et al* [2] and Kanatas and Constantinou [3] have reported measurements at L-band from low and high elevation angles respectively in the streets of several European cities, using a moving vehicle-mounted receiver. Their measurements are only valid for mobiles in the middle of a road, since mobiles close to buildings suffer a much higher shadow loss. Tirkas, Wangsvick and Balanis [4] proposed a ray-based theoretical model, but they did not consider the distributions of buildings, streets and terrain in an actual city.

This paper develops statistical propagation models for the link between an airborne platform (denoted as Tx) and a mobile terminal (denoted as Rx), with the terminal located within a dense urban environment. We derive a simple representation of path loss and shadowing from the simulated propagation data extracted from a three-dimensional outdoor deterministic ray-tracing model [5]. The ray model operates by processing terrain, building and foliage data for a central region of Bristol. A series of frequencies (200MHz, 1GHz, 2GHz, 2.5GHz, 5GHz) are studied to cover a wide range of applications. Compared to terrestrial radio channel models, where path loss increases with log-distance, we find that it is more convenient to represent the channel in terms of the air platform height and elevation angle.

II. RAY-TRACING SIMULATION

The ray-tracing simulator is based on a combination of geometric optics and empirical models, integrating topography, antenna patterns, and principal parameters of the Tx/Rx system such as carrier frequency, transmit power and receiver sensitivity, into a series of ray tracing algorithms. The outputs include spatial and temporal multipath data, and predictions of received power, Rician K-factor, r.m.s. delay spread and coherence bandwidth [5] [6].

The operating environment is a 1.4km × 1.4km area of central Bristol. It is a typical European city, with a mean building height of 11.7m. 28% of the area is covered by buildings (see Fig. 1 for a map of building locations and heights). The terrain is hilly with a terrain height standard deviation of 17.5m.

We place mobile nodes at more than 20,000 uniformly distributed outdoor locations with a terminal height of 1.5m above ground level (AGL). Nine airborne nodes are deployed (see circles in Fig. 1), resulting in over 180,000 Tx/Rx pairs for each configuration. The transmit power is configured to 30dBm, and a receiver sensitivity of –150dBm is assumed, allowing for a maximum path loss of 180dB. To achieve mathematical accuracy, it is vital to ensure that the maximum path loss in the ray model exceeds the values expected in the radio system.

Practical antenna selection involves many factors such as gain, beamwidth, polarization, size and weight. Polarization matching is the first limitation to be considered. In the simulations, we adopt 0dBi gain crossed dipoles for both the

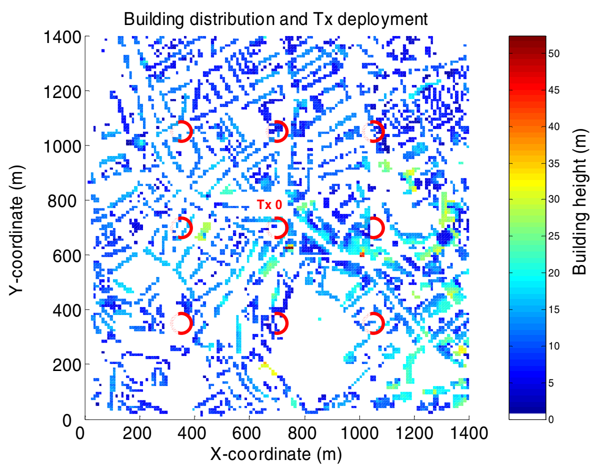


Fig. 1. Deployment of airborne Tx's in Bristol centre

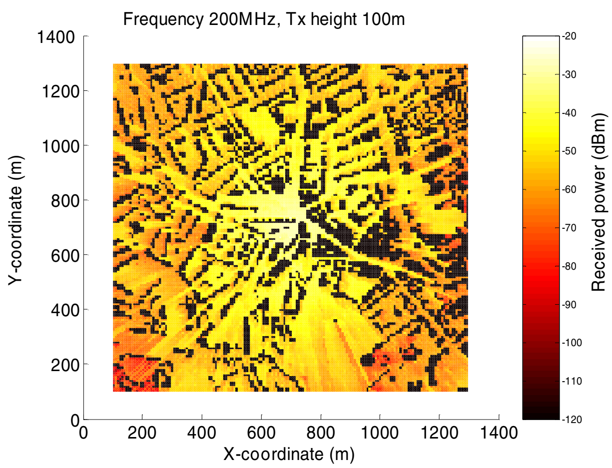


Fig. 2. Coverage of an airborne Tx (200MHz, 100m) (the black pixels represent buildings)

Tx and Rx to obtain circular polarization [7]. In practice, a narrow beamwidth antenna would be used on the air platform to achieve greater gain and thus improve the link budget.

We conduct ray tracing simulations for airborne heights of 100m, 200m, 500m, 1000m and 2000m at the following frequencies: 200MHz, 1GHz, 2GHz, 2.5GHz and 5GHz. Fig. 2 shows an example of the received power coverage on the ground, for an airborne transmitter located in the centre of the operating area at a height of 100m and operating at a frequency of 200MHz.

III. LOS / OLOS / NLOS Channels and Their Probabilities

We consider two major clutter types in our urban environment: buildings and foliage. According to blockage, we classify each radio channel into LoS, obstructed LoS (OLoS) and NLoS. LoS requires a direct path with sufficient clearance of the first Fresnel zone [8]. If the direct path is partially attenuated by foliage only, the channel is defined as OLoS. If the direct path is blocked by one or more buildings, the channel is regarded as NLoS.

The probabilities of the three types of channel for all configurations are shown in Fig. 3. It can be seen that the LoS probability decreases with decreasing elevation angle and operating frequency; however, all the probabilities are independent of the air platform height.

OLoS channels usually suffer less path loss than NLoS channels, but this depends on the foliage distribution. In the Bristol region, the likelihood of OLoS is around 10–20%, as shown in Fig. 3.

For P2P propagation at 2GHz, the required Tx/Rx separation distance is approximately 30m and 50m to obtain combined LoS and OLoS probabilities of 90% and 50% respectively [1]. For the air-to-ground channel, they correspond to elevation angles of 60° and 20°, equivalent to ground distances of 120m and 300m for an air platform height of 100m.

IV. Mean Path Loss Modelling

In terrestrial mobile communications, both analytical and statistical models indicate that the mean path loss (MPL) can be approximated using a simplified log-distance model [8]:

$$\boldsymbol{L}(\boldsymbol{d})[\mathrm{dB}] = \boldsymbol{L}(\boldsymbol{d}_0) + 10\boldsymbol{n}\log(\boldsymbol{d}/\boldsymbol{d}_0) \quad \text{for } \boldsymbol{d} \geq \boldsymbol{d}_0 \tag{1}$$

where n is the path loss exponent, d is Tx/Rx distance, and d_0 is the close-in reference distance. d_0 is commonly expressed as the free space reference distance [8]. In airborne communications, we set d_0 to be the relative height of the platform directly above the mobile, i.e. $d_0 = h_t - h_r$, where h_t and h_r are the heights of the airborne and mobile nodes respectively. Assuming that the elevation angle from the mobile is θ, thus, $d/d_0 = 1/\sin\theta$, and equation (1) becomes

$$\boldsymbol{L}(\theta)[\mathrm{dB}] = \boldsymbol{L}_f(\boldsymbol{d}_0) - 10\boldsymbol{n}\log\sin\theta \quad \text{for } \boldsymbol{d} \geq \boldsymbol{d}_0 \tag{2}$$

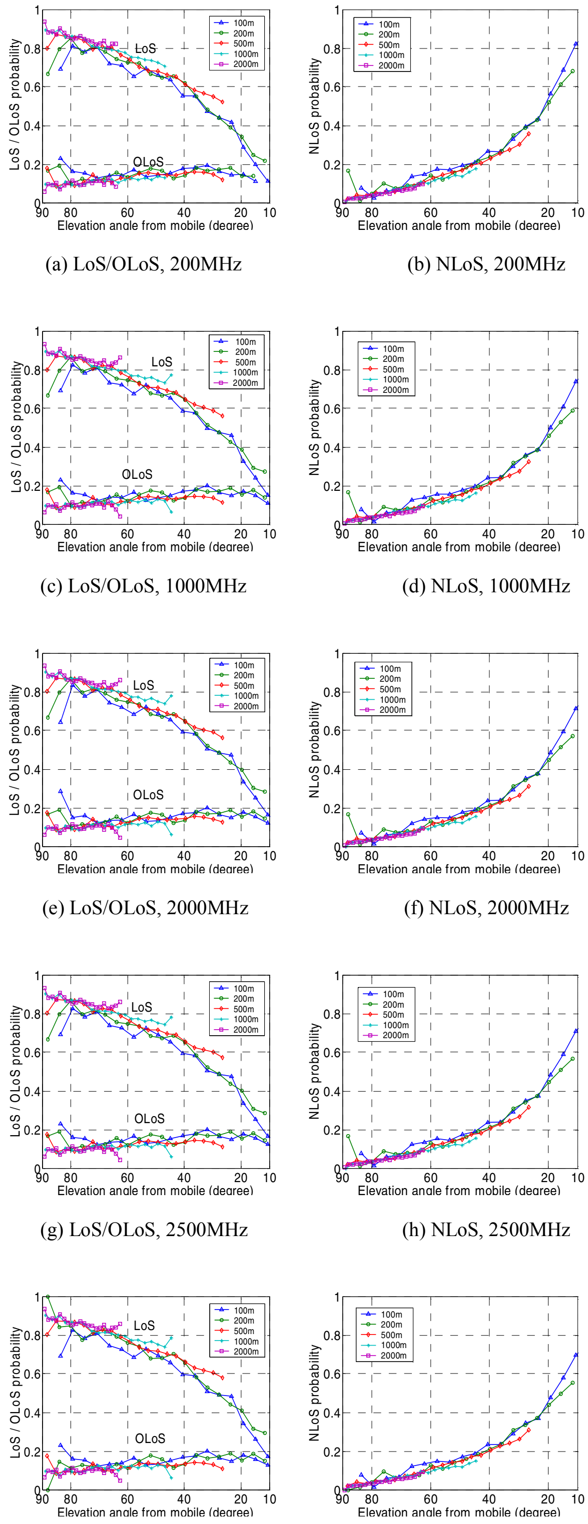
where $L_f(d_0)$ is the free space path loss given by the Friis equation [8].

We note that when the elevation angle $\theta > 10°$,

$$-10\log\sin\theta \approx -0.3115 + 0.2656e^{(90-\theta)/23.8} \tag{3}$$

The root mean square (r.m.s.) error for the above approximation is around 0.046dB on average for $10° < \theta < 90°$. This equation suggests the existence of an intrinsic relationship between path loss and elevation angle. Inspired by this, we now attempt to model the air-to-ground radio channel in terms of the air platform height and elevation angle, and equation (1) is now modified as shown below:

$$\boldsymbol{L}(\theta)[\mathrm{dB}] = \boldsymbol{L}_f(\boldsymbol{d}_0) + \boldsymbol{L}_2(\theta) \quad \text{for } \theta > 10° \tag{4}$$



(a) LoS/OLoS, 200MHz (b) NLoS, 200MHz

(c) LoS/OLoS, 1000MHz (d) NLoS, 1000MHz

(e) LoS/OLoS, 2000MHz (f) NLoS, 2000MHz

(g) LoS/OLoS, 2500MHz (h) NLoS, 2500MHz

(i) LoS/OLoS, 5000MHz (j) NLoS, 5000MHz

Fig. 3. LoS / OLoS / NLoS probability

where

$$L_2(\theta)[\text{dB}] = \alpha_0 + \alpha_1 e^{(90-\theta)/\beta} \tag{5}$$

and α_0, α_1 and β are coefficients. In (1), the path loss exponent n is most likely to vary with antenna height; whereas α_0, α_1 and β in (5) are found to be independent of antenna height for the majority of the cases studied in this paper, and thus we tend towards a general model for various antenna heights.

Fig. 4 shows the received power in terms of elevation angle at 200MHz for an airborne unit at a height of 100m. It can be seen that the OLoS path loss is much less than the NLoS path loss, and the received power for LoS/NLoS/OLoS channels is seen to decrease exponentially with decreasing elevation angle.

After compensating for the antenna gains and the removal of $L_f(d_0)$, the mean path loss for the LoS channels can be modelled using (4) and (5). Upon analysis of the data (using curve fitting), $L_2(\theta)$ is discovered to be independent of frequency and antenna height. We now construct the following general equation:

$$\begin{aligned} L_{2,LoS}(\theta)[\text{dB}] &= -0.58 + 0.5496 e^{(90-\theta)/24} \\ &\approx -20 \log \sin \theta \end{aligned} \tag{6}$$

The result is very close to free space path loss, with an r.m.s. error of less than 0.11dB on average for $10° < \theta < 90$. We calculate the total received power from an algebraic summation of the power from each arriving rays, thus street canyon effects, which arise from the vector summation of multipaths, are not considered in the path loss model.

Similarly, we model the OLoS path loss using equations (4) and (5) after compensating for the antenna gains. Table I (OLoS) and Fig. 5 are now based on the OLoS model.

For NLoS channels, the extra path loss over that of free space is often quoted in measurements [2] [3]. We follow this convention, and model the mean path loss using a variant of (4):

$$L(d,\theta)[\text{dB}] = L_f(d) + L_3(\theta) \quad \text{for } \theta > 10° \tag{7}$$

where

$$L_3(\theta)[\text{dB}] = \eta_0 - \eta_1 e^{-(90-\theta)/\nu} \tag{8}$$

and the coefficients η_0, η_1 and ν are independent of antenna height. The best fit parameters for various frequencies are shown in Table I (NLoS) and Fig. 6. It can be seen that the extra path loss $L_3(\theta)$ increases at higher frequencies. $L_3(\theta)$ also increases with decreasing elevation angle, initially rising quickly, and then slowing with further decreases in elevation angle.

V. Shadowing Model

Shadowing is the slow variation observed around the mean path loss, denoted as ΔL[dB] in this paper. It has been found from analysis that the shadowing (in dB) follows a zero-mean

Normal distribution about the mean path loss (in dB), with a distance-dependent standard deviation σ_s (in dB) [8].

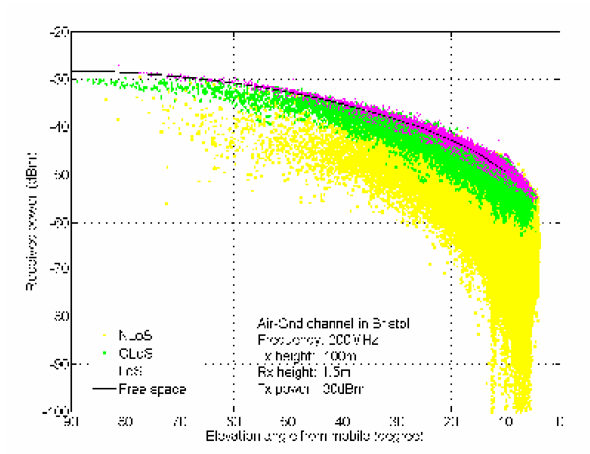


Fig. 4. Received power in terms of elevation angle from mobile

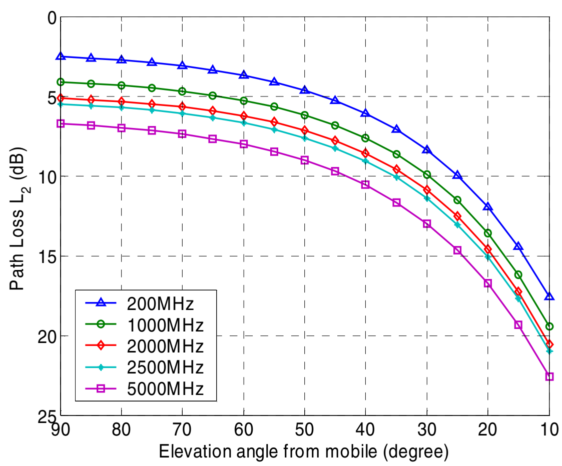


Fig. 5. Path loss L2 for OLoS channels

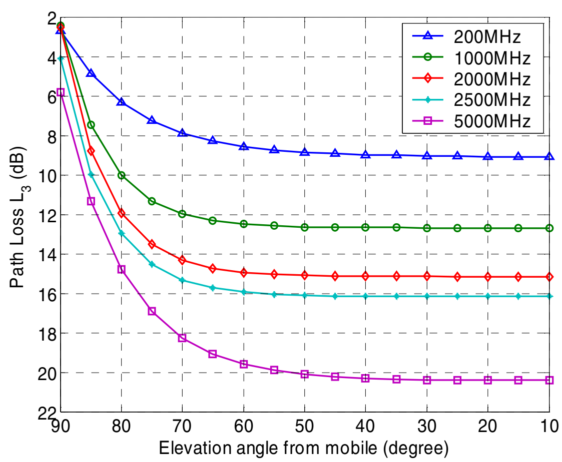


Fig. 6. Path loss L3 of NLoS channels

TABLE I
PARAMETERS FOR MEAN PATH LOSS MODELS

Frequency	OLoS			NLoS		
	α_0	α_1	β	η_0	η_1	ν
200MHz	2.11	0.4125	22.07	9.08	6.4058	12.01
1000MHz	3.76	0.3724	21.38	12.68	10.2576	7.42
2000MHz	4.77	0.3530	21.04	15.15	12.6238	7.32
2500MHz	5.12	0.3895	21.58	16.16	12.0436	7.52
5000MHz	6.23	0.4787	22.65	20.43	14.6048	10.50

Fig. 7 shows the histograms, probability density functions (PDFs) and cumulative distribution functions (CDFs) of the shadowing process for an airborne height of 100m and a frequency of 200MHz. For each type of channel, the Normal distribution is not a perfect representation for ΔL[dB] since the PDF plot skews to the left; however a Normal distribution is still considered to be a reasonable and simple assumption. As shown in Fig. 7(c), a Normal distribution fits better than a shifted log-Normal distribution, i.e. log (ΔL[dB] + C), where C represents the shift, or a Rayleigh distribution.

We have found that the standard deviation (STD) of the shadowing, or the variations in the mean path loss for LoS channels, can be represented as:

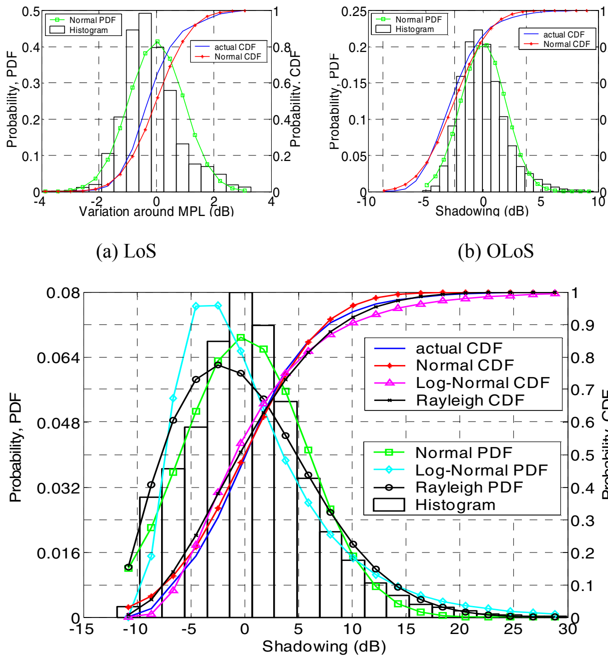
$$\sigma_s[\text{dB}] = \rho(90-\theta)^{\gamma} \tag{9}$$

For LoS channels, σ_s is modelled for different frequencies and antenna heights; whereas σ_s for OLoS and NLoS channels depends only on frequency. The results are shown in Table II and Fig. 8.

For LoS channels, a higher Tx (air platform) height or carrier frequency leads to a smaller variation, whereas for OLoS and NLoS channels, a higher frequency leads to a higher variation. This can be explained as follows. The reflection, diffraction and foliage loss increase with frequency. For a LoS channel, the variation is caused by random components, such as diffracted and reflected rays; a higher frequency leads to weaker random components and thus a smaller variation in the mean path loss. For a NLoS channel, the most significant rays include the shadowed direct ray, the ground-reflected ray, and the opposite building wall-reflected ray. A higher operating frequency results in larger differences from location to location at the same elevation angle. For an OLoS channel, the direct path is not diffracted but partially obstructed by foliage, and thus suffers less loss relative to a NLoS channel; hence the shadowing is less severe than a NLoS channel.

VI. Conclusion

In this paper we provide statistical models for air-to-ground radio channels in a dense urban environment. The results show that air-to-ground channels have a much higher LoS probability, less NLoS path loss compared to LoS channels, and less shadowing than terrestrial P2P channels. Thus, airborne platforms may serve as relaying nodes to extend the range and improve the connectivity between terrestrial ad-hoc terminals.



(a) LoS (b) OLoS

(c) NLoS

Fig. 7. Shadowing distribution

Although the models are based on hilly terrain, considering that the airborne height is much larger than the terrain irregularity, and thus terrain obstruction is infrequent, the diffraction loss is mainly caused by the building height above ground level. Therefore, these models are also suitable for flat terrain with similar building clutter.

These models can be used for satellites and UAVs with elevation angles greater than 10 degrees. The models can be used at frequencies from 200MHz to 5GHz, and thus serve both civilian and military applications. Airborne units can be used to enhance emergency, public safety, and disaster recovery networks in a civilian application, or to enhance Commercial Off The Shelf (COTS) military WLANs.

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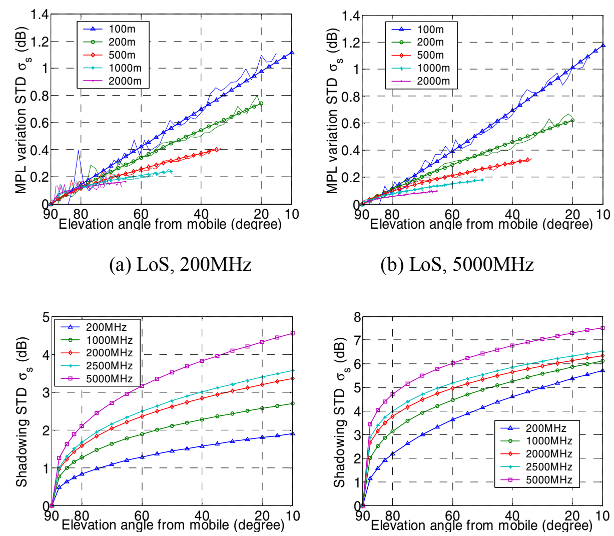
TABLE II
PARAMETERS FOR SHADOWING MODELS

Frequency	LoS (Mean path loss variation)							
	100m		200m		500m		1000m	
	ρ	γ	ρ	γ	ρ	γ	ρ	γ
200MHz	0.0143	0.9941	0.0153	0.9131	0.0214	0.7308	0.0418	0.4746
1000MHz	0.0154	0.9751	0.0218	0.8135	0.0186	0.7512	0.0307	0.5455
2000MHz	0.0187	0.9268	0.0338	0.6935	0.0375	0.5367	0.0536	0.3426
2500MHz	0.0148	0.9843	0.0272	0.7475	0.0306	0.5901	0.0389	0.4256
5000MHz	0.0086	1.1222	0.0140	0.8926	0.0181	0.7236	0.0184	0.6186
Frequency	LoS		OLoS		NLoS			
	2000m		(Shadowing)		(Shadowing)			
	ρ	γ	ρ	γ	ρ	γ		
200MHz	0.0513	0.3656	0.3334	0.3967	0.7489	0.4638		
1000MHz	0.0353	0.4730	0.5568	0.3598	1.5036	0.3200		
2000MHz	0.0499	0.2975	0.6877	0.3619	2.1139	0.2508		
2500MHz	0.0398	0.3179	0.7224	0.3643	2.3197	0.2361		
5000MHz	0.0160	0.5574	0.8937	0.3713	2.7940	0.2259		



(a) LoS, 200MHz (b) LoS, 5000MHz

(c) OLoS (d) NLoS

Fig. 8. Standard deviation of shadowing

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