

Three-Dimensional Fading Channel Models: A Survey of Elevation Angle Research

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ABSTRACT

The explosive increase of mobile traffic demands higher spectrum efficiency for future wireless communications. By properly configuring a 2-dimensional (2D) antenna array at the basestation, the system capacity can be improved with 3 dimensional (3D) multiuser Multiple Input and Multiple Output (MIMO) techniques without modifying the terminal antennas. Therefore, the signal will propagate in a 3D space with angle dispersion in both horizontal and vertical planes. Due to its role in facilitating research and development of 3D MIMO technology, the 3D fading channel model is receiving increasing attention. However, existing fading channel models mostly focus on the azimuth angle characteristics, while neglecting the elevation angle impact. This article provides a state of the art review on 3D fading channel models, emphasizing research related to the elevation angle. We also report some recent field measurements for 3D MIMO and investigate the comprehensive propagation characteristics of the elevation angle.

INTRODUCTION

With the rapid penetration of mobile applications and smart phones into our daily life, the mobile traffic has experienced an explosive increase in the past decade. It is predicted that the mobile traffic will grow more than 1000 times in the next 10 years [1]. To fulfill this increasing demand, the mobile communications industry has started to work towards International Mobile Telecom System-2020 (IMT-2020), which is set as the research and standardization objective in International Telecom Union-Radio communication Sector (ITU-R) Working Party 5D.

For all these activities, one of the most important topics is to improve the spectrum efficiency of the mobile communication system. For Long Term Evolution (LTE) and LTE-Advanced, Multiple Input and Multiple Output (MIMO) technology has been introduced to improve the system spectrum efficiency, where the physical signal processing has been extended to the spatial domain. Fundamentally, the joint

spatial-temporal-frequency signal processing is expected to boost the peak data rate by 100 times and the spectrum efficiency by 2–3 times in comparison with what has been achieved in the 3rd generation (3G) system [2]. Similarly, at the physical layer, it is possible to further enhance the spectrum efficiency if one can exploit an additional signal processing domain in addition to the so-called spatial-temporal-frequency domain. For the MIMO technology in LTE/LTE-Advanced, only the horizontal plane of the spatial domain has been utilized in the spatial signal processing. For the conventional MIMO technology, a linear antenna array with vertical polarization or cross-polarization is usually deployed in the horizontal plane at both ends of the communication link, while a fixed down-tilting angle is configured at the antenna array of the basestation (BS). Limited by the antenna size at both the mobile station (MS) and BS, the number of elements is assumed no more than 8 in practice since the current frequency bands for cellular networks are typically below 3.5 GHz. It is well known that the capacity of the single user MIMO system is determined by the smaller number of antenna elements between the transmitter and the receiver, while the capacity of the multiuser MIMO system may be determined by the number of BS antenna elements. In other words, the system capacity can be improved by increasing the number of antenna elements. However, it is difficult to increase the MS antenna element number beyond 8 due to the smart phone constraints such as low cost, small size and multiple operating bands. Hence, the most feasible way is to increase the number of BS antenna elements.

Typically, each BS antenna is composed of 8–10 dipole elements and vertically stacked to achieve high antenna gain, e.g., 18 dBi. To form the fixed down-tilting angle, these dipole elements are fed with the same signal but different phases. If the dipole elements of an antenna can be regarded as independent elements and fed with different signals, as shown in Fig. 1, then the possible antenna number at the BS can be extended by 8–10 times. Considering the multiuser MIMO scenario, the system capacity could be significantly improved even without changing the

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number of antenna elements at the MS. Such properly configured 2 dimensional (2D) antenna arrays at the BS are termed as 3 dimensional MIMO (3D MIMO) or full dimension MIMO (F-MIMO). Recently, 3D MIMO or F-MIMO has been identified as one important technique for performance enhancement in LTE Release 12 for 3rd Generation Partnership Project (3GPP) [2].

Although the 3D MIMO communication technology appears to be promising, several research challenges have to be addressed. Since reliable and realistic channel models of propagation characteristics are critical and fundamental in research and evaluation of 3D MIMO techniques, how to characterize 3D MIMO communication channels becomes one of the most important challenges of 3D MIMO development.

In conventional MIMO systems, linear antenna array is deployed only in the horizontal direction. Then the azimuth angle dispersion is taken into account for calculating the correlation between different antenna elements in the horizontal plane. While the signal propagates through a 3D space, the fading channel is modeled in a 2D space because the complexity of the model is acceptable and the resolution of the antenna in the vertical plane is limited. When the linear antenna array can be extended to an antenna matrix in full dimensions by regarding the stacked elements as independent antenna elements in the elevation domain, as shown in Fig. 1, the elevation angle should also be used to obtain the correlation of the antenna matrix in the vertical direction. In this case, both azimuth and elevation angles should be involved in the radio channel model. The azimuth angle of departure (AAoD) and azimuth angle of arrival (AAoA) have been well studied and standardized in the most recent 2D channel models under different scenarios. However, the elevation angle of departure (EAoD) and elevation angle of arrival (EAoA), which are expected to have significant influence on the performance of the channel model, have only been touched upon in very recent years.

Research on the elevation angle can be traced back to 1979 by T. Aulin, who extended Clark's scattering model to a 3D space for the first time [3]. Since then, a growing number of researchers observed and reported the significance of elevation angles in describing the radio signal propagation more precisely. Recently, M. Shafi extended the spatial channel model (SCM) to 3D [4]. World Wireless Initiative New Radio + (WINNER+) report summarizes some results at the MS in terms of the angle spread (AS) and attempts to extend the 2D geometry based stochastic model (GBSM) model into 3D [5]. From January 2013, 3GPP Technical Specification Group-Radio Access Network (TSG-RAN) Working Group 1 (WG1) initiates the discussion on the 3D fading channel model. Some conclusions could be expected in April 2014. Though many research entities have shown interests in such endeavors, the 3D fading channel model research is still at a very early stage. First, most of the literature only considers the elevation angles at the MS, with

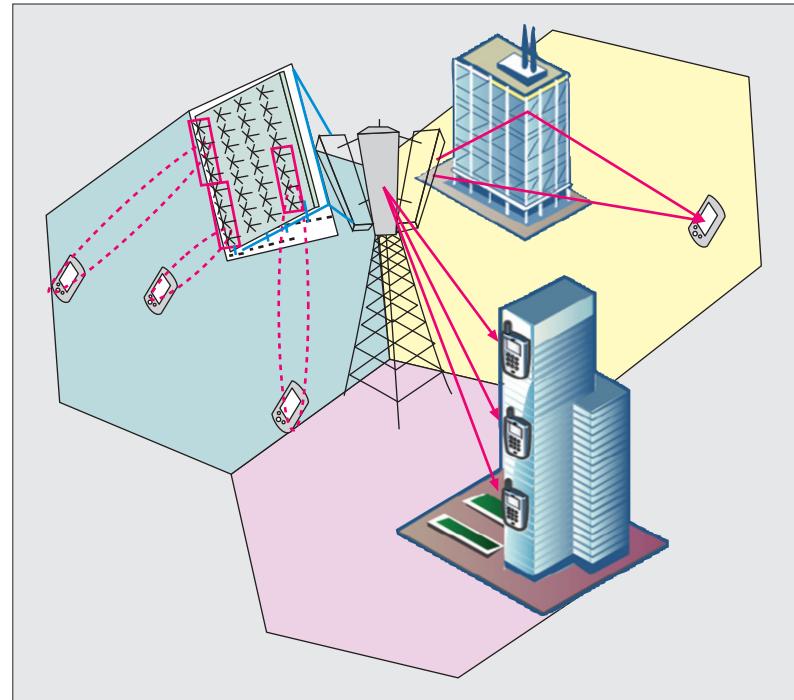


Figure 1. The principle of 3D MIMO.

very few results discussing the BS side. Secondly, it is usually assumed that the azimuth angle in the signal spatial distribution is independent of the elevation angle. This assumption is not reasonable for signals propagating through a 3D space with both elevation and azimuth angles. Third, the existing channel models, including ITU-R M.2135, 3GPP SCM and spatial channel model extension (SCME), do not include the elevation angles for simplification. Therefore, there exists no 3D fading channel model accounting for different scenarios for mobile communication bands.

The remainder of this article is outlined as follows. In the next section we give an overview of the 3D fading channel model framework and review the state of the art in 3D fading channel models, especially research related to the elevation angle. We then present our field measurements and propagation characteristics of the elevation angle. Finally, conclusions are drawn in the last section.

3D CHANNEL MODEL

The knowledge of the 3D MIMO fading channel characteristics for different scenarios is of great importance for the design and performance evaluation of 3D MIMO communication systems. In this section, the generic 3D fading channel model framework is presented. Then the research of the elevation angle is introduced in further detail.

CONVENTIONAL 2D FADING CHANNEL MODEL

According to the existing standardized channel models, including ITU-R M.2135 and 3GPP SCM, the characteristics of the spatial domain mainly focus on the horizontal direction. The models of angles have been given in the azimuth

$$h_{u,s}(\tau_l; t) = \sum_{m=1}^M \begin{bmatrix} F_{rx,u,\theta}(\Omega_{l,m}) \\ F_{rx,u,\phi}(\Omega_{l,m}) \end{bmatrix}^T \begin{bmatrix} \alpha_{l,m,\theta,\theta} & \alpha_{l,m,\theta,\phi} \\ \alpha_{l,m,\phi,\theta} & \alpha_{l,m,\phi,\phi} \end{bmatrix} \begin{bmatrix} F_{tx,s,\theta}(\Phi_{l,m}) \\ F_{tx,s,\phi}(\Phi_{l,m}) \end{bmatrix} \times \exp(j2\pi\lambda_0^{-1}(\Omega_{l,m} \cdot \bar{r}_{rx,u})) \exp(j2\pi\lambda_0^{-1}(\Omega_{l,m} \cdot \bar{r}_{tx,s})) \exp(j2\pi f_{d,l,m} t) \quad (1)$$

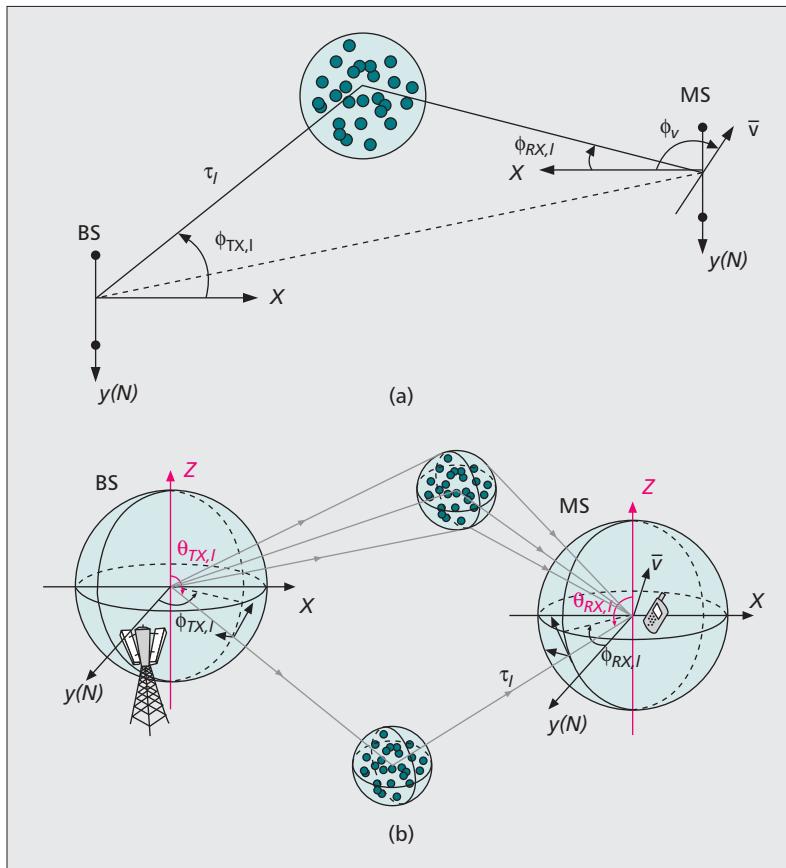


Figure 2. The generic fading channel model.

domain, including AAoA and AAoD. The antenna array has been modeled as a linear array. A single link in a 2D fading channel model is shown in Fig. 2a. The spatial characteristics of radio propagation channel in the 2D model can be defined as $\phi_{TX,I}$ and $\phi_{RX,I}$, which represent the AAoD and the AAoA for the l^{th} multipath component, respectively. Due to the complexity and the applicability of the channel model, the elevation domain is neglected in these standardized channel models.

In order to characterize the spatial fading channel, power angle spectrum (PAS) and AS of the azimuth angle have been introduced. They have a substantial impact on the spatial correlation among different antennas and also have an influence on the degree of the diversity and multiplexing in MIMO systems. In the existing channel models, PAS of the azimuth angle is well fitted by Gaussian distribution or Laplace distribution at the BS. At the MS, it is usually assumed to be uniform distribution. In conventional MIMO systems, the performance of the horizontal multiuser MIMO scheme can be well evaluated according to the information of the spatial fading characteristics in the horizontal domain.

FRAMEWORK OF 3D FADING CHANNEL MODEL

A solid framework of 3D fading channel modeling can be developed based on some of the well-known 2D channel models, i.e., IMT-Advanced channel model defined by ITU-R M.2135 [6]. A single link in the 3D fading channel model is shown in Fig. 2b.

As given in Fig. 2b, for an S element BS array and a U element MS array, the channel environment includes multiple 3D scatterers. Firstly the multipath component parameters, such as angles of departure, angles of arrival, and path delays, and the direction of mobility are defined in Global Coordinate System (GCS). Parameters $\theta_{TX,I}$ and $\theta_{RX,I}$ represent EAoD and EAoA for the l^{th} multipath component, respectively. Therefore, the angle information at the BS is defined as $\Phi_l = \{\theta_{TX,I}, \phi_{TX,I}\}$, while the angle information at the MS is defined as $\Omega_l = \{\theta_{RX,I}, \phi_{RX,I}\}$. In summary, the spatial 3D propagation characteristics are defined by these four parameters.

Based on the elevation angles $\theta_{TX,I}$ and $\theta_{RX,I}$, the 2D channel model based on the IMT-Advanced channel model can be transformed into a 3D model. The channel impulse response (CIR) for the resultant 3D model from BS antenna element s to MS element u , for cluster l can be expressed by Eq. 1.

The λ_0 is the wavelength of the carrier frequency. The number of paths is indexed by l and the number of the subpaths is m . The $F_{rx,u}$ and $F_{tx,s}$ are defined as the field pattern of the receiving and the transmitting antenna elements. The $\bar{r}_{rx,u}$ stands for the vector between the u receiving antenna element and the first element. For transmitting antenna elements, the $\bar{r}_{tx,s}$ holds the same meaning as the $\bar{r}_{rx,u}$. The $\tau_l, f_{d,l,m}, \Phi_{l,m}$ and $\Omega_{l,m}$ denote the propagation delay, the Doppler shift, the angle of departure (AoD), and the angle of arrival (AoA) of the (l, m) propagation subpath. And the polarization matrix of the (l, m) subpath from the p_1 polarization component to the p_2 polarization component is defined by α_{l,m,p_1,p_2} .

PREVIOUS RESEARCH ACHIEVEMENT ON ELEVATION ANGLE

In order to fully take advantages of spatial diversity, some earlier researchers started to investigate the elevation angle of the signal arrival. In Table 1, the main contributions on 3D channel modeling from 1973 to date are summarized.

At the earlier stage of elevation angle research, due to the limited capability of the channel sounding equipment and the number of measurement antenna elements, many initial studies can only experimentally confirm the existence of a wide elevation angle range in both suburban and urban areas. The range of the elevation angle may vary when the carrier frequency or the measurement scenario change. With

the development of technology, researchers are able to investigate the stochastic characteristics of elevation angle. Based on measurements, T. Taga found that the elevation angles follow a wide dispersive Gaussian distribution in Tokyo urban area at 900MHz. K. Kalliola *et al.* observed that a double-sided exponential function is more suitable with different slopes on the negative or positive sides of the peak. J. D. Parsons and A. M. D. Turkmani propose four conditions that a realistic PAS of elevation angle should satisfy [11]. Combining the measurement results and earlier scatter model research, S. Qu and T. Yeap found a family of functions satisfying the four conditions [12], including a set of asymmetric function, to describe the PAS of elevation angle. Recently, M. Shafi *et al.* extend the 3GPP SCM model to 3D channel model at the MS side and the capacity is evaluated by different PAS of elevation angle. In 2011, WINNER+ summarizes literature results at both MS and BS sides about the AS and try to extend 2D model to a 3D space [5].

In Fig. 3, the proposed PAS of elevation angle at the MS is summarized. Based on Clark's scattering model [3], T. Aulin first generated 3D scattering model and assumed rectangular and truncated cosine function as the PAS of elevation angle in Fig. 3a and Fig. 3b. It is simple and easy to handle such models mathematically. However, such distributions are only realistic for small elevation angle. Their limitations are obvious because the edge of their distributions is like a cliff and such discontinuity cannot be the real situation of elevation angle. Therefore, J. D. Parsons *et al.* [11] give a compressed cosine function for PAS of elevation angle in Fig. 3c, makes them more practical with four conditions. Based on the measurement, T. Taga [10] found that both horizontal and vertical incoming signal angles follow the Gaussian distribution but have different mean values and variances in Fig. 3d. For the more general case in which the PAS of elevation angle is not necessarily symmetrical, S. Qu and T. Yeap [12] modeled the PAS of elevation angle with the parameter weighted cosine function in Fig. 3e-h, which can fit many kinds of scenarios with an asymmetric shape.

OPEN ISSUES FOR 3D FADING CHANNEL MODEL

After collecting the field channel measurement data, the multipath channel parameters can be extracted from the raw data by multidimensional parameters estimation algorithm. The challenges discussed in this section can be considered as guidelines for setting up future measurement campaigns and proposing more realistic and reliable 3D channel models for future 3D MIMO research.

Characteristics of Elevation Angle — Similar to the horizontal domain, basic parameters of the vertical domain, such as PAS and AS, should be studied first. Furthermore, the height of the antenna at both the BS and MS, especially the relative height between the BS and the building, will have significant impact on the PAS and AS of the elevation angle. Then, the characteristics

Year	Ref	Main contributions
1973	[7]	Experimentally confirm that a wide elevation angle in suburban area indeed exist and it is somewhat large than 16° and less than 39°.
1977	[8]	Based on 205 MHz band measurement in an urban area, elevation angle is in the range of [0°, 50°].
1979	[3]	Extend Clarks' scattering model with the elevation angle and a rectangular or truncated cosine function is assumed as PAS of elevation angle.
1987	[9]	Elevation angle decreases rapidly as a function of maximal elevation angle and it is empirically values in the range of [10°, 20°].
1990	[10]	Based on 900MHz band measurement in Tokyo urban area, a wide dispersive Gaussian distribution of elevation angle is observed.
1991	[11]	Propose four conditions that a realistic PAS of elevation angle should satisfy and a compressed cosine function is given. The conditions are: 1) have a mean value of 0°; 2) be heavily biased toward small angles; 3) have no discontinuities; 4) not lead to infinity in distribution.
1999	[12]	Give a family of functions satisfying the conditions proposed by Pakson about the PAS of elevation angle, including a set of asymmetric function, is given to describe the PAS of elevation angle.
2003	[13]	Both elevation angle and cross-polarization power ratio (XPR) in different radio propagation environments at 2.154 GHz were analyzed. In non line-of-sight (nLoS) case, a double-sided exponential function is more suitable with the different slope the negative and positive sides of the peak. XPR varied within 6.6 and 11.4dB.
2005	[14]	The measured average power for cross-polarized antenna is more than 7dB lower than for co-polarized antenna. The elevation spread is smaller at the MS indoor location than at the outdoor location.
2006	[4]	Extend the SCM model with 3D element at MS side and the capacity is evaluated with the different elevation angle distributions.
2011	[5]	Summarize literature results at both MS and BS sides about the AS and try to extend 2D GBSM model to 3D space considering 3D antenna arrays. Moreover, five scenarios are considered as: indoor, outdoor-indoor (O2I), urban-micro-cell (UMi), urban-macro-cell (UMa) and suburban-macro-cell (SMA).

Table 1. Summary of previous research about 3D modeling.

of vertical domain will also depend upon the distance between the BS and MS. AS will change with the relative distance. More importantly, the offset angle, which is defined as the difference between the line-of-sight (LoS) direction and the mean angle of the elevation PAS, is also a distance dependent function. The proper incorporation of the elevation offset angle into 3D

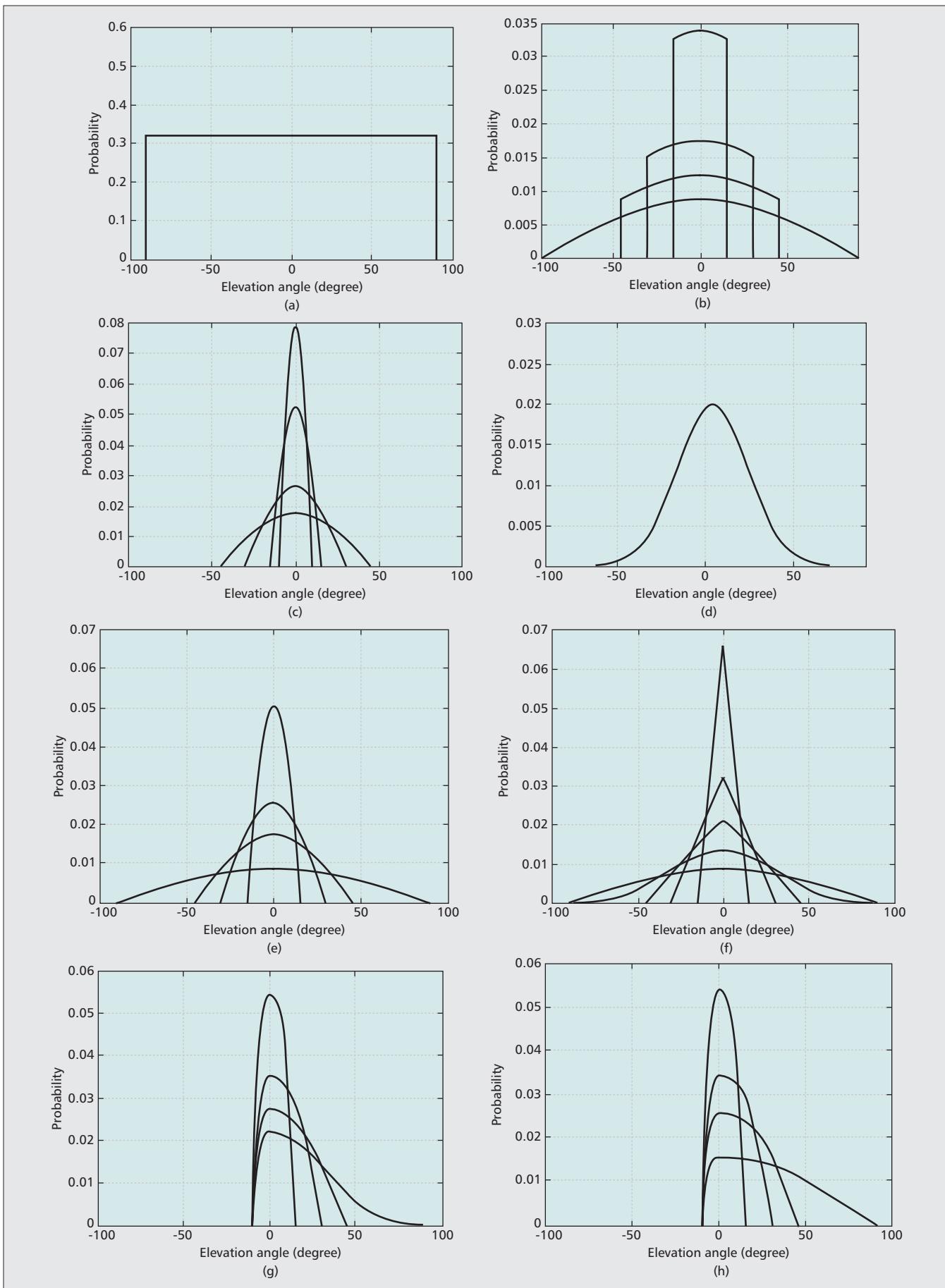


Figure 3. Elevation angle models of MS.

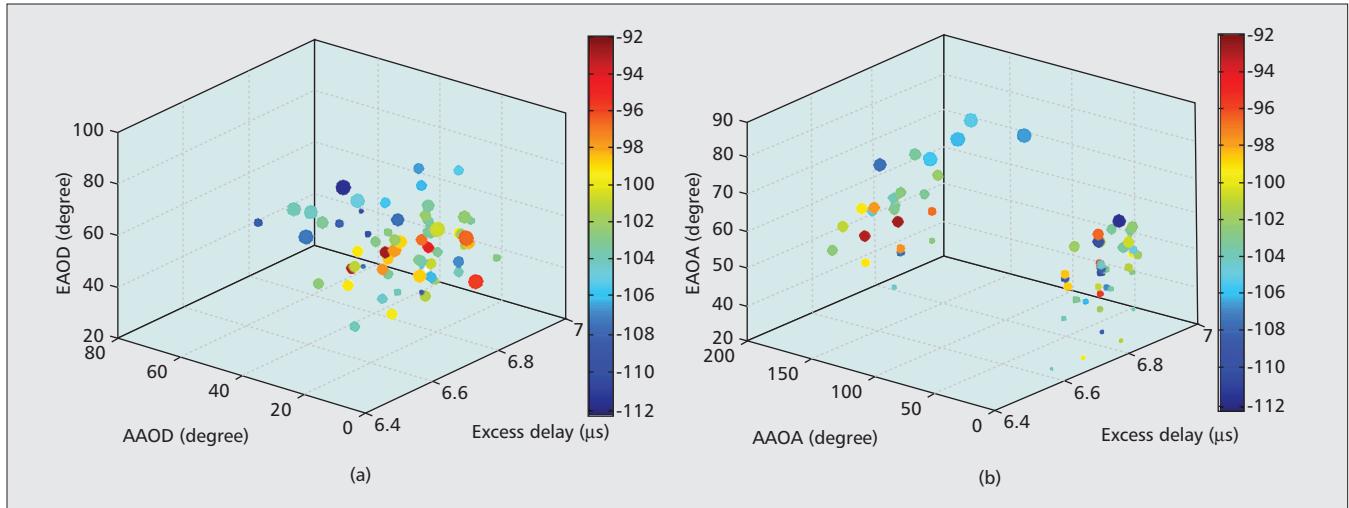


Figure 4. The distribution of 3D channel gain in O2I scenario.

fading channel model is presented in [15]. Results therein show that the offset angle is distance dependent and can be modeled by continuous functions such as a distance-dependent exponential function.

Angle Correlation in 3D Fading Channel Model — While WINNER+ [5] has introduced the elevation angle as a parameter in 3D fading channel models, the modeling of the azimuth angle is considered independent from that of the elevation angle. Since the azimuth and elevation angles of electromagnetic wave both depend on the position of scatterers and reflectors in a 3D space, a certain level correlation between the two is expected. Therefore, by introducing joint azimuth and elevation angle information, more realistic and accurate channel models will be possible.

Impact of Elevation Angle on Kronecker Channel Model — A model based on the Kronecker structure of the channel covariance matrix has been assumed to analyze the channel capacity and has been extended to some prevalent MIMO channel models. This type of channel modeling requires the knowledge of the transmitter and receiver correlation matrix. The correlation matrix can be calculated by the azimuth spectrum and the geometry of the antenna array. With the research of the elevation angle in 3D channel model, the Kronecker channel model should also take into account the elevation PAS when obtaining the correlation matrix.

3D Channel Modeling Including the Multi-Path Fading Characteristics — The 3D fading channel model follows the framework of the traditional 2D fading channel model. Hence, the 2D channel model parameters can be extended to a 3D space. The updated parameters in 3D channel models include elevation AS of arrival (ESA), elevation AS of departure (ESD), cluster ESD (CESD), cluster ESA (CESA), cross-correlations etc.. At the same time, these parameters for different scenarios should be further studied.

Among existing channel models based on the GBSM, only WINNER+ [5] accounts for the elevation angle. The necessary parameters include the elevation AS, the cluster AS, and the cross-correlation coefficients among these parameters. However, these parameters only summarize the results of some early articles. There is still a lack of reliable channel measurement for the verification of these parameters.

THE MODELING OF 3D ELEVATION ANGLE

To provide an intuitive understanding on the elevation angle in 3D channel modelling and to validate some of the existing research conclusions, we give an example of 3D channel measurement and modelling in this section.

CHANNEL MEASUREMENT AND POST-PROCESSING

In order to obtain the field CIRs from the real environment, and extract the channel spatial parameters from data post-processing, the channel sounder with high precision is necessary and we use Propsounder with carrier frequency at 3.5 GHz [15]. Lots of measurement campaigns have been conducted to obtain 3D MIMO channel data and extract their propagation characteristics. The measurement scenarios include O2I, and UMa. During the field measurement, the omnidirectional array (ODA) and uniform planar array (UPA) are used to get the field CIRs with 3D channel characteristics. The detailed information of the measurement environment and measurement antenna has been presented in [16].

After collecting the field channel measurement data, the multipath channel parameters can be extracted from the raw data by multidimensional parameters estimation algorithm, i.e., Spatial-Alternating-Generalized-Expectation-maximization (SAGE). These channel parameters are the delay, Doppler frequency, EAoA, AAoA, EAoD, AAoD, and polarization complex matrix.

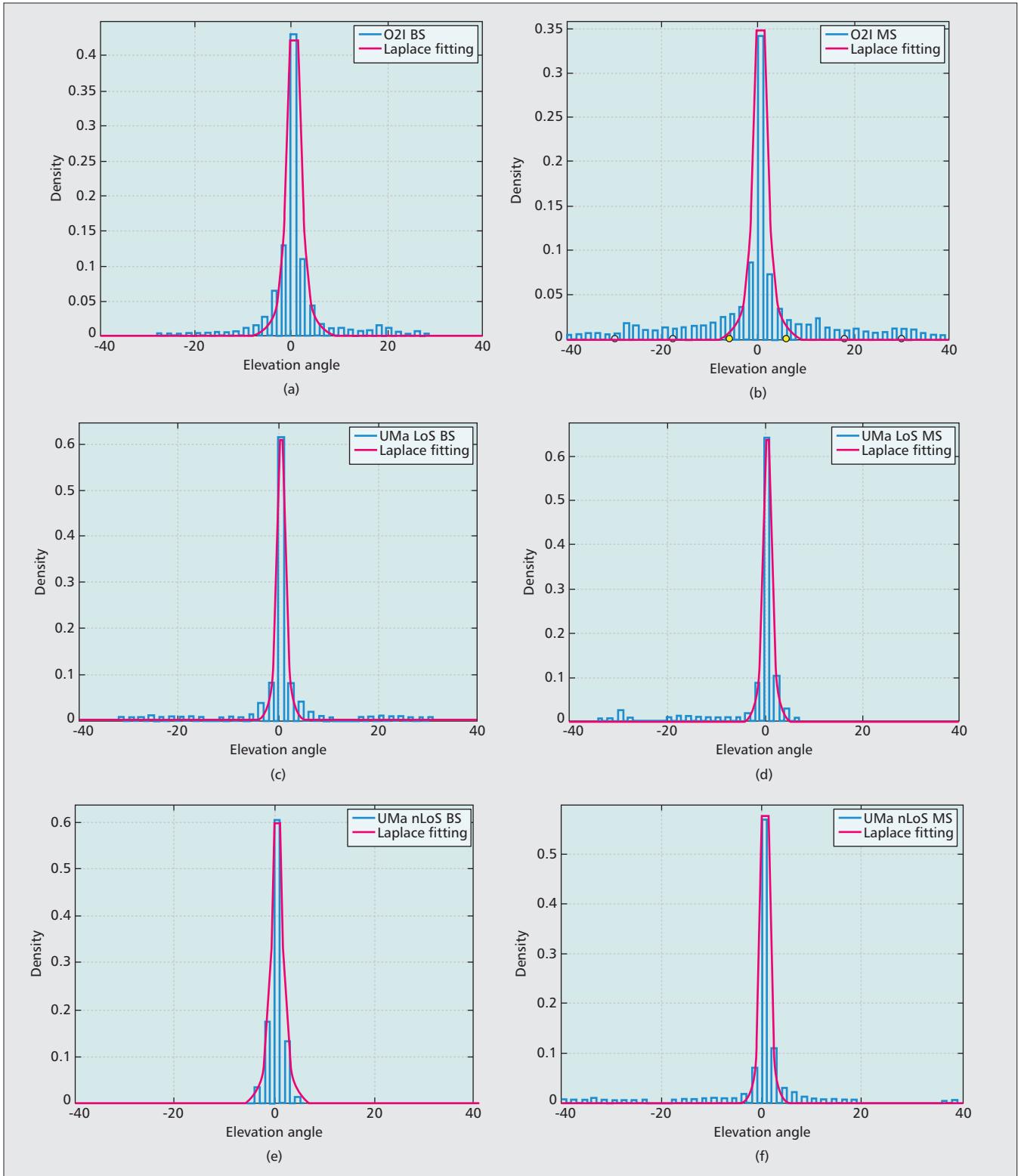


Figure 5. Elevation angle spectrums in O2I and UMa scenario.

Figure 4 shows one sample of 3D channel gain in O2I scenario. The angle of departure and the angle of arrival are shown in Fig. 4a and Fig. 4b, respectively. It is clear that the signal actually propagated in 3D space, i.e., not only in the azimuth plane, but also in the vertical plane. And the characteristics of the angle distribution are discussed in the following subsections.

ELEVATION ANGLE SPECTRUM

The elevation PAS and their fitting shapes in O2I scenario are shown in Fig. 5a-b. It should be noted that the elevation PAS has different mean values at different measurement spots. The mean value has been removed before calculating the elevation PAS. As shown in Fig. 5a, the PAS at BS can be well fitted by the Laplace

		O2I		UMa			
		nLoS		LoS		nLoS	
		B	W	B	W	B	W
ESD $\log_{10}(^\circ)$	μ	0.96	0.88	0.85	0.70	0.92	0.90
	σ	0.24	0.34	0.04	0.2	0.14	0.2
ESA $\log_{10}(^\circ)$	μ	1.18	1.01	0.87	0.95	1.05	1.26
	σ	0.16	0.43	0.05	0.16	0.09	0.16
CESD($^\circ$)		5	3	5	3	5	3
CESA($^\circ$)		9	3	10	7	11	7
ESD vs ASD		-0.19	0.5	-0.17	0.5	0.33	0.5
ESA vs ASD		-0.16	0	0.55	0	0.16	-0.4
ESD vs ASA		-0.24	0	-0.26	0	-0.02	0
ESA vs ASA		-0.02	0.5	0.55	0.4	0.33	0
ESD vs ESA		-0.06	0.5	0.01	0	-0.03	0

W: WINNER+[5]
B: Measurements from BUPT (Beijing University of Posts and Telecommunications)

Table 2. ESD and ESA in O2I and UMa.

distribution. And the main power concentrates in the range of $[-10^\circ, 10^\circ]$. However, as shown in Fig. 5b, the Laplace distribution can not fit the power at MS as well as that at the BS in the O2I scenario. The reason is that the scatterers in the vertical domain, including ceiling and floor, will bring other multipath components in indoor scenarios. These reflected components will extend the PAS of the elevation angle. Therefore, the Laplace distribution can only match the central range of the PAS at the MS.

Figure 5c-f show the elevation PAS and their fitting shapes in the UMa scenario including both LoS and nLoS. Different from the O2I scenario, the elevation PAS at both MS and BS in UMa scenario can be well fitted by Laplace distribution. The reason is that in UMa scenario the number of scatterers distributed in the vertical plane is smaller than that in the O2I scenario.

ELEVATION AS AND CORRELATION

The lognormal distribution is used to fit the elevation AS for both BS and MS. The statistical values of elevation AS for both O2I and UMa scenarios are shown in Table 2. It is shown that the ESD and ESA from our measurements match well the results of WINNER+. However, the CESD and CESA from our measurements are larger than those of WINNER+. The reason is that the complex measurement environment, such as dense buildings and heavy traffic, makes the number of scatterers around both BS and MS much larger than that of WINNER+. Based

on our measurements, it also appears that the correlation between azimuth spread and vertical spread actually exists but the ESD is fully independent of the ESA.

CONCLUSIONS

3D MIMO is an effective means of utilizing the spatial resource, increasing spectrum efficiency, and improving the network throughput. However, all these benefits can only be achieved with better understanding of the fading characteristics of the wireless channel in the elevation domain.

This article provides a brief overview of 3D fading channel modeling, which is expected to build the foundation for 3D MIMO research in future mobile communication systems. At the beginning, we briefly introduced the feasibility and fundamental principle. Then, we described the methodology of 3D channel modeling, which shows that the PAS and AS of elevation angle are two crucial parameters. Next, the previous research contribution to elevation angle was summarized in this article. Moreover, examples of 3D measurements in O2I and UMa scenarios were given and its elevation angle was stochastically analyzed. New challenges in 3D fading channel modeling have also been identified and discussed. Examples included the elevation angle variation with respect to the distance between the BS and MS, correlation between the azimuth and elevation angles, and the extension of antenna array modeling from 2D into 3D. Summarizing, research on 3D MIMO channel propagation

3D MIMO is an effective means of utilizing the spatial resource, increasing spectrum efficiency, and improving the network throughput. However, all these benefits can only be achieved with better understanding of the fading characteristics of the wireless channel in the elevation.

characteristics and modeling methodology are essential for 3D MIMO research.

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