A Three Dimensional Model for Dual Polarized MIMO Channel of the Planar Array Antennas

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Abstract

Geometry-based stochastic model (GBSM) that describes the excess delay, direction of arrival, and direction of departure of multipath has been used extensively in multiple-input and multiple-output (MIMO) channel modeling. Many two dimensional and very few three dimensional (3D) GBSMs with linear array antennas have appeared in the literature. The models lack properties of the 3D channel for dual polarized planar array antennas, which are practically used in MIMO systems due to its applicability to space division multiple access (SDMA) or beamforming in three spatial dimensions. In this paper, we propose the 3D channel model for dual polarized planar array antennas where the departure and arrival angles are modeled in both azimuth and elevation. We derive the closed form expression of the channel coefficients. Using the proposed channel coefficient, we investigate the effect of azimuth and elevation angular spread on channel capacity.

Keywords: *MIMO, 3D channel model, dual polarized planar array antennas, channel capacity*

1. Introduction

The fourth generation (4G) and beyond 4G wireless communication systems are expected to provide high data rates and a better quality of wireless signals satisfying high speed data transmission such as application software and video streaming from smartphones. The reference [1] presents that the data rate of wireless communication has increased by 100 times every six to seven years. MIMO systems, in which multiple antennas are used at both transmitter and receiver, have been proposed to achieve high data rate due to an improvement in spectrum efficiency. The major issue of MIMO is that capacity is highly dependent on the spatial correlation, which is a function of the antenna structure and several channel characteristics such as angle spread (AS) and cross-polarization discrimination (XPD). There are several polarized channel models taking into account both the azimuth and elevation angles. The 3D channel is analyzed in [2] and the impact of elevation angle on MIMO capacity is studied in [3]. However, the previous 3D channel coefficients are analyzed by uniform linear array antenna (ULAA) which is lack of representing channel capacity of other antenna structures such as uniform planar array antenna (UPAA).

To the best of our knowledge, this is the first study that addresses the channel capacity of UPAA with both the azimuth and elevation angle in 3D space. In this paper, we propose a 3D channel model of ULAA and UPAA which incorporate both the elevation and azimuth angles. In particular, we derived the closed form expressions of the channel coefficient for both UPAA and ULAA in 3D space and the comparisons of capacity performance are represented. Accordingly, the frame work of our proposed 3D channel coefficients will be established in terms of concept and principle of the 2D polarized channel model from 3rd Generation Partnership Project (3GPP) spatial channel model (SCM). The rest of paper is organized as follows. Section 2 describes the 3D channel model for both ULAA and UPAA. Section 3 presents discussion and simulation results and discussions of the simulation results of capacity with different antenna structures. Finally, conclusions are drawn in Section 4.

2. 3D Channel Models

2.1 2D SCM Channel Model

The proposed 3D channel coefficient for UPAA is based on the 2D polarized channel coefficient from SCM which considers the ULAA with the azimuth angle only. In this subsection, the basic concept of SCM is briefly described.

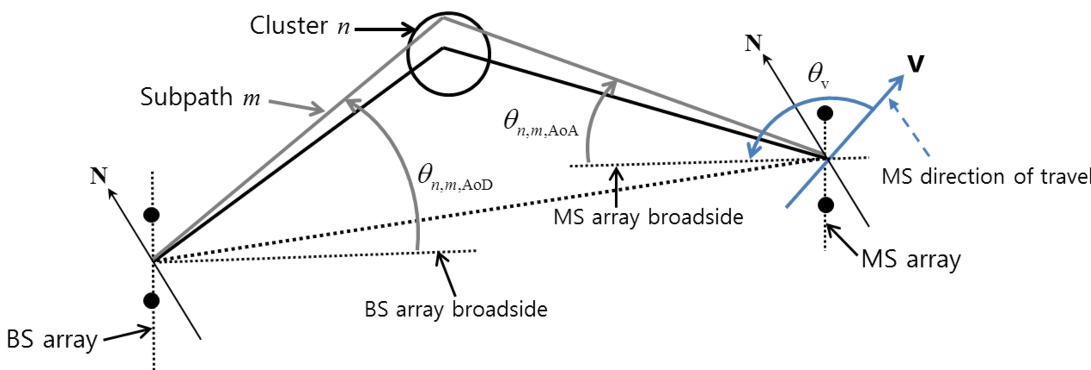

Figure 1. 3GPP SCM for 2D Space

The 2 dimensional (2D) SCM channel model for an S element linear base station (BS) array and a U element linear mobile station (MS) array, the channel coefficients for one of N multipath components are given by a U-by-S matrix of complex amplitudes. The received signal at the MS consists of N time-delayed multipath replicas of the transmitted signal. Each path consists of M subpaths and these N paths are defined by random powers and delays. The channel is analyzed in ULAA antenna structures, angle of departure (AoD) at the BS and angle of arrival (AoA) at the MS. As shown in Figure 1, subpaths are generated only on the horizontal x-y plane for both BS and MS. Therefore, the original SCM channel model is not appropriate to model the 3D channel with other antenna structures such as UPAA.

2.2 3D Channel Model with Uniform Linear Array Antenna

ULAA is the most basic antenna structure of the MIMO systems. The antenna elements are arranged to form a 1 dimensional antenna array. In this paper, we assumed the antenna elements placed along the x-axis and 3D channel coefficients of ULAA is analyzed in this subsection.

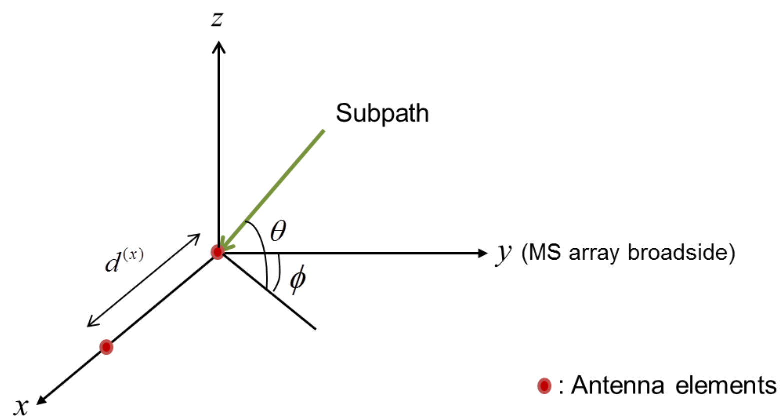

Figure 2. ULAA with 3D Subpath

As shown in Figure 2, the symbols ϕ and θ denote the azimuth and elevation angle respectively. ULAA's antenna elements are equispaced with an interval of $d^{(x)}$ on x-axis. We denote the channel coefficient for the *n*th multipath component (*n*=1,…, N) as $\mathrm{H}_n(t)$ which represents the transmission from the BS to MS. The proposed channel coefficient describes the propagation of mixed horizontal and vertical amplitude of each subpath. Then the (*u*,*s*)th component (*s*=1,…,*S*; *u*=1,…,*U*) of $h_{u_x,s_x,n}(t)$ can be expressed as

$$
\begin{aligned}
h_{(u_x,u_z),(s_x,s_z),n}(t) = \sqrt{\frac{P_n\sigma_{SF}}{M}} \sum_{m=1}^{M} & \begin{bmatrix} \chi_{tx,V}\left(\phi_{n,m,AoD},\theta_{AoD}\right) \\ \chi_{tx,H}\left(\phi_{n,m,AoD},\theta_{AoD}\right) \end{bmatrix}^T \begin{bmatrix} \exp(\Phi_{n,m}^{(v,v)}) & \sqrt{r_{n1}}\exp(\Phi_{n,m}^{(v,h)}) \\ \sqrt{r_{n2}}\exp(\Phi_{n,m}^{(h,v)}) & \exp(\Phi_{n,m}^{(h,h)}) \end{bmatrix} \begin{bmatrix} \chi_{rx,V}\left(\phi_{n,m,AoA},\theta_{AoA}\right) \\ \chi_{rx,H}\left(\phi_{n,m,AoA},\theta_{AoA}\right) \end{bmatrix} \\
& \times \exp\left(j2\pi\lambda^{-1}\left\{(u_x-1)d_s^{(x)}\cos\left(\theta_{n,m,AoD}\right)\sin\left(\phi_{n,m,AoD}\right)\right\}\right) \\
& \times \exp\left(j2\pi\lambda^{-1}\left\{(s_x-1)d_u^{(x)}\cos\left(\theta_{n,mAoA}\right)\sin\left(\phi_{n,m,AoA}\right)\right\}\right) \\
& \times \exp\left(j2\pi v_{n,m}t\right)
\end{aligned}
\tag{1}
$$

where P_n and σ_{SF} are the power of the *n*th path and the lognormal shadow fading respectively and M is the number of subpaths per path. $\chi_{\mathrm{BS,V}}\left(\phi_{n,m,AoD},\theta_{AoD}\right)$ and $\chi_{BS,H}\left(\phi_{n,m,AoD},\theta_{AoD}\right)$ are the complex field pattern of the BS antenna for V polarization and H polarization respectively; $\chi_{MS,V}\left(\phi_{n,m,AoA},\theta_{AoA}\right)$ and $\chi_{MS,H}\left(\phi_{n,m,AoA},\theta_{AoA}\right)$ are the complex field pattern of the MS antenna for V polarization and H polarization respectively. r_{n1} and r_{n2} are the inverse of XPD that present the power ratio for VV/VH and HH/HV respectively. $\Phi_{n,m}^{(x,y)}$ is the phase shift between V(H) component of the BS and V(H) component of MS and $j=\sqrt{-1}$. The 2×2 matrix of equation (1) represents the scattering phases and amplitudes of the plane wave from BS with angles and arriving at MS with different direction and polarization. $v_{n,m}$ is the received Doppler phase-shift of the *n*th multipath component when the movement of MS is assumed to be horizontal plane with velocity, **v**. Doppler phase-shift component of the *n*th multipath component can be calculated by AoA, **v**, direction of travel, φ_v . Doppler phase-shift component of the *n*th multipath component can be calculated by AoA, **v**, direction of travel, φ_v, and carrier wavelength, λ_0.

$$v_{n,m} = \frac{|\mathbf{v}|\cos\varphi_v \cos\theta_{n,m,AoA}\cos\phi_{n,m,AoA} + |\mathbf{v}|\sin\varphi_v \cos\theta_{n,m,AoA}\sin\phi_{n,m,AoA}}{\lambda_0} \tag{2}$$

2.2 3D Channel Model with Uniform Planar Array Antenna

UPAA is an antenna in which all antenna elements are in one plane. In this paper, we focus on 2D UPAA in the x-z plane in 3D space.

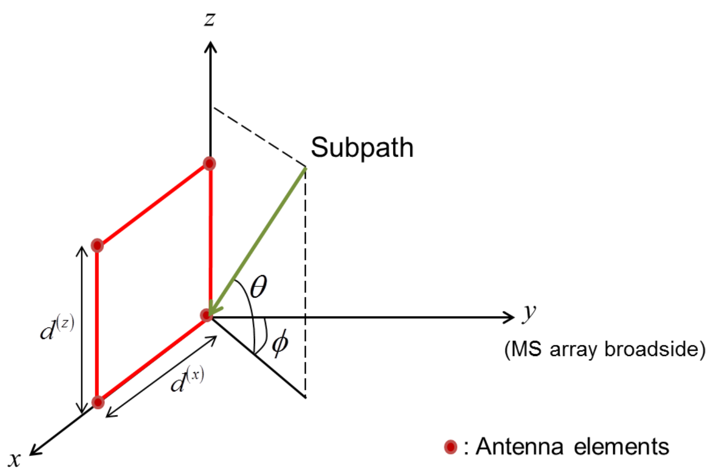

Figure 3. UPAA with 3D Subpath

It is assumed that all UPAA's antenna elements are equispaced on both x-axis and z-axis with an interval of $d^{(x)}$ and $d^{(z)}$ respectively. The (*u*,*s*)th component (*s*=1,…,*S*; *u*=1,…,*U*) of $h_{(u_x,u_z),(s_x,s_z),n}(t)$ can be expressed as

$$\begin{aligned} h_{(u_x,u_z),(s_x,s_z),n}(t) = \sqrt{\frac{P_n\sigma_{SF}}{M}}\sum_{m=1}^{M}\begin{bmatrix}\chi_{BS,V}(\phi_{n,m,AoD},\theta_{n,m,AoD})\\ \chi_{BS,H}(\phi_{n,m,AoD},\theta_{n,m,AoD})\end{bmatrix}^T\begin{bmatrix}\exp(\Phi_{n,m}^{(v,v)}) & \sqrt{r_{n1}}\exp(\Phi_{n,m}^{(v,h)})\\ \sqrt{r_{n2}}\exp(\Phi_{n,m}^{(h,v)}) & \exp(\Phi_{n,m}^{(h,h)})\end{bmatrix}\begin{bmatrix}\chi_{MS,V}(\phi_{n,m,AoA},\theta_{n,m,AoA})\\ \chi_{MS,H}(\phi_{n,m,AoA},\theta_{n,m,AoA})\end{bmatrix} \\ \times\exp\left(jk\{(u_x-1)d_s^{(x)}\cos(\theta_{n,m,AoD})\sin(\phi_{n,m,AoD})+(u_z-1)d_s^{(z)}\sin(\theta_{n,m,AoD})\}\right) \\ \times\exp\left(jk\{(s_x-1)d_u^{(x)}\cos(\theta_{n,m,AoA})\sin(\phi_{n,m,AoA})+(s_z-1)d_u^{(z)}\sin(\theta_{n,m,AoA})\}\right) \\ \times\exp\left(jkv_{n,m}t\right) \end{aligned} \tag{3}$$

The variables are described in subsection 2.2.

3. Simulation Results and Discussions

In this paper, we investigate the effect of different simulation parameters such as antenna structures, mean AS at BS, $E(\sigma_{AS})$, and XPD ratios of ULAA and UPAA on channel capacity. The urban macrocell environment is considered where the uniform distribution of local rich scattering generated around the BS and MS antenna elements within a given AS. The value of AS is a lognormal random variable for urban macrocell scenario which is given by SCM [4].

$$\sigma_{AS} = 10 \wedge (\varepsilon_{AS} x + \mu_{AS}), x \sim \eta(0,1) \tag{4}$$

where x have a random normal distribution with zero mean and unit variance. For simulations, the value of ε_{AS} and μ_{AS} are 0.810 and 0.34 respectively for 8° mean AS, and 1.18 and 0.210 respectively for 15° mean AS. The proposed 3D channel coefficients consider both azimuth and elevation angles for both AoD and AoA. Elevation and azimuth angle distribution follow the angle distribution of the urban macrocell scenario from SCM [4] and the antenna spacing is half a wavelength. The elements of the channel coefficient matrix do not have unit power when polarization exists. Rather, the channel matrix elements' power depends on the XPD ratio from SCM [4]. The XPD ratio can be expressed as XPD=P1/P2 where P2 is the coupled power of each subpath in the horizontal orientation relative to the power P1 of each subpath in the vertical orientation. Then, a single XPD ratio value applies to all subpath and each n path experiences an independent realization of the XPD. For urban macrocells, the realization of the each path's XPD ratio is given by

$$\mathrm{P1} - \mathrm{P2} = \mathrm{A} + \mathrm{B} * \eta(0,1) \text{ (in dB)} \tag{5}$$

where $\mathrm{A} = 0.34 \times (\text{mean relative path power in dB}) + \mathrm{C}$, B is 5.5 dB which is the standard deviation of the XPD ratio, and C is 7.2 dB from SCM[4]. The value C determines the mean value of XPD ratio and $\eta(0,1)$ is the random normal distribution with zero mean and unit variance. We assumed that the channel state information is only known at the MS and the signals are independent. Then, the capacity of MIMO channel is given by [5].

$$C = \log_2 \det\left(\mathbf{I}_{n_{MS}} + \frac{SNR}{n_{BS}} \mathbf{H}\mathbf{H}^T\right) \tag{6}$$

where $\mathbf{I}_{n_{MS}}$ is the identity matrix of size n_{MS}, $\mathbf{H}$ is the channel matrix, and *SNR* is the signal-to-noise ratio. First, we investigate the effect of antenna structures, ULAA and UPAA. The capacities are obtained to compare the performance between the ULAA and UPAA with the same number of antenna elements. We assumed BS with 9 antenna elements and MS with 4 antenna elements for both ULAA and UPAA. The size of UPAA is denoted by $e \times e$ antenna elements. For instance, the 3×3 UPAA represents the uniformly square-shaped UPAA with the size of 3-by-3 antenna elements. For simulation, 8° mean AS is applied to both ULAA and UPAA for fair comparison. The channel capacity of ULAA and UPAA as a function of the SNR is indicated in Figure 4.

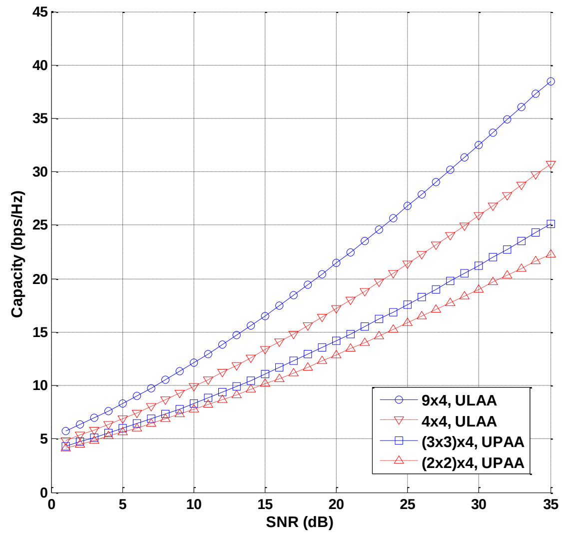

Figure 4. Capacity of the Different Antenna Structures with Mean 8˚ AS

As shown in Figure 4, the capacity of ULAA is always higher than UPAA when the same number of antenna elements is contained at BS and MS. This is because the benefit of the low correlation of ULAA from the linearly arranged antenna elements. For example, the correlation between the first and the last antenna elements is lower than correlation between UPAA's edge antenna elements. This is the advantage from the linearly structured antenna. Second, we study the effect of mean AS by evaluating capacity performance with the same number of antenna elements. The capacities are obtained by both ULAA and UPAA with 9 antenna elements at BS and 4 antennas elements at MS but different mean AS value, 8˚ and 15˚.

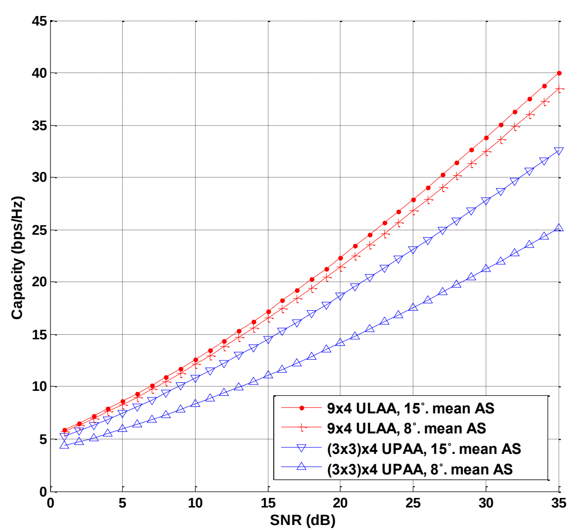

Figure 5. Capacity of the with different mean AS values

As shown in Figure 5, the larger mean AS value leads the higher capacity for both ULAA and UPAA. This result is expected since the smaller mean AS leads to higher correlation and consequently lower capacity. Furthermore, the capacity difference of UPAAs is larger than capacity differences of the ULAAs. It can be seen the UPAA is more sensitive to mean AS changes due to its characteristics of square-shaped antenna structure since correlation occurs between adjacent antenna elements on both x-axis and z-axis. Therefore, the AS sensitivity of UPAA is higher than the linearly structured ULAA. Third, we investigate the effect of XPD ratio with the same mean AS value, 8˚. Figure 6 shows the capacity with different C value of 7.2 dB and 15 dB to change mean value of XPD ratio.

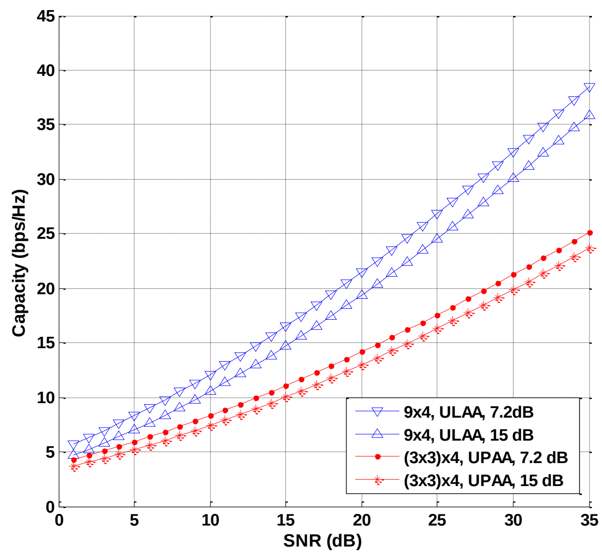

Figure 6. Capacity of the different XPD ratio values with mean 8˚ AS

As shown in Figure 6, the capacity of ULAA and UPAA decreases as XPD ratio increases. The simulation results show that the capacity difference of ULAAs is about 2.3 bps/Hz and capacity difference of UPAAs is about 1.31 bps/Hz. Since $r_n, 1/\mathrm{XPD}$, is the average power ratio of plane wave leaving BS in the vertical direction and arriving at MS in horizontal direction, the high C value will be reduced the power of the plane wave. Therefore, the capacity will be decreased as XPD ratio value increases. This simulation results denote that UPAA antenna is less sensitive to the XPD ratio changes compare to ULAA.

4. Conclusion

In this paper, a 3D channel model of ULAA and UPAA has been proposed and its closed-form expressions of the channel coefficient are derived for urban macrocell environment. Through simulation, we observed the performance in terms of the channel capacity with different antenna structures, mean AS values, and XPD ratios. The simulation results show that the capacity is higher when the same number of antenna elements is engaged on the

ULAA compare to UPAA due to its lower correlation between antenna elements. Furthermore, we study the different antenna properties for ULAA and UPAA through simulation results. Our simulation results denote that the UPAA is more sensitive to mean AS changes and less sensitive to XPD ratio changes. The proposed model is presented here for non-tilted UPAA, but it can be extended to tilted UPAA model with 3D channel model. Also, the different types of antenna such as half-wave dipole antenna can be implemented to consider the antenna element's directivity issues.

Acknowledgements

This research was supported by the KCC (Korea Communications Commission), Korea, under the R&D program supervised by the KCA (Korea Communications Agency) (KCA-2012-12-911-01-108).

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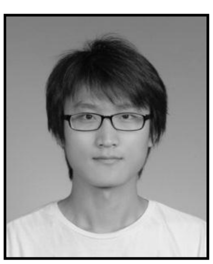

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