A Dual-Polarisation Modelling Method for Simulation-Based Propagation Models

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***Abstract*—In this paper, we propose a universal dual-polarisation modelling method for the simulation-based propagation models. We adopt the universal definition of dual-polarisation radiation pattern and apply the definition to model the dual-polarised propagation channel. By adopting the universal definition of dual-polarisation using the ray reference, we clarify the misunderstanding caused by the widely accepted polarisation definition using ground reference. Furthermore, we integrate the universal dual-polarised model to a simulation-based propagation model. Simulation results demonstrate the effectiveness and potential of this dual-polarisation model in the simulation-based propagation models.**

I. Introduction

Polarisation is a characteristic of wave propagation. Wireless communication engineering has long utilised polarisation as a way of diversity [1]. Recently the wireless communication research has seen a trend of employing dual-polarised antennas at both the transmitter and the receiver to support extra diversity gain and capacity gain [2], [3]. Polarization provides an extra degree of freedom over the same radio frequency band. It is an efficient technique supported in the current and future wideband wireless communication networks [4].

For wireless networks planning and optimisation purposes, therefore, a dual-polarised propagation channel model is highly sought after. The major challenge to model a dual-polarised propagation channel lies in the modelling of the cross-polarisation channel components. Due to the lack of understanding the physical mechanism of the cross-polarisation term, researchers resort to statistical method to model the cross-polarisation terms [2], [3]. Although such models are efficient and provide certain guidance in the designing and planning of wireless networks, they still lack accuracy comparing to the deterministic models based on physical propagation mechanisms.

Few researchers made the effort to model the dual-polarised channel based on deterministic models. The authors of the work of [5] presented an early model for urban environment based on such modelling principles. The work of [6] proposed a physical model for indoor environments based on uniform theory of diffraction(UTD) with heuristic diffraction coefficients. In the work of [7], the authors analysed the causes of the cross-polarisation components in the channel as from 3 main sources: antenna radiation, elevation and diffraction. Based on this analysis the authors presented a deterministic dual-polarised MIMO model that is based on ray-tracing and diffuse scattering.

In this work we propose an efficient model to incorporate dual-polarisation in propagation modelling. The model is focused on providing a dual-polarised model for computer simulation based propagation prediction tools such as in [8]. The model is based on the dual-polarised radiation pattern definition originally given in [9]. By adopting this universal definition of dual-polarised radiation pattern we are able to model the dual-polarised channel through the two orthogonal radiation patterns, at both the transmitter antenna and the receiver antenna. The modelling is universal because it can easily be integrated to the propagation modelling simulators based on ray tracing such as [8] and other computer simulation based models such as [10].

Later in the paper, using this universal modelling method, we build our dual-polarised ray-tracing model employing UTD. Furthermore, we present the simulation results of an indoor office environment using our model. It demonstrates the potential application of the proposed model in wireless communication networks planning and optimisation.

The paper is organized as follows. In Section II we give the definition of dual-polarised radiation pattern. In Section III we analyse the cross-polarisation using UTD, and propose our model based on the analysis. In Section IV, we present the simulation results of a typical indoor office environment. In Section V, we discuss and conclude our model.

II. Dual-Polarised Antenna Radiation Patterns

In this section we first introduce the definition of dual-polarised antenna radiation pattern and use the concept to define the types of polarisation in ray-tracing model. This is the foundation of the dual-polarized ray tracing model that we propose later in the paper.

Here we adopt the definition (3) of the reference-polarisation and the cross-polarisation from the work of [9]. In the work of [9], the author gave 3 definitions of dual-polarised radiation pattern. The author further pointed out that the definition 3 is the most widely used in antenna engineering. Figure 1 shows an illustration of the definition (3) of the reference-polarisation and the cross-polarisation from [9].

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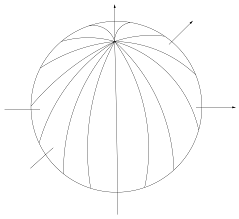

Fig. 1. Dual-Polarised Antenna Radiation Patterns

We adopt this definition to define the two orientations in linear polarisation in wireless engineering application: horizontal polarisation and vertical polarisation. The widely accepted polarisation categorisation of vertical and horizontal in engineering application is based on using the ground as the reference plane. However, the definition in [9] uses the ray or the polarisation axis as a reference. This difference in the reference of the two definition can easily lead to misunderstanding. In the case when we fixed the antenna orientation, we can extend the concept of the reference-polarisation and cross-polarisation in [9]. For horizontally and vertically placed antenna source currents, we simply define the vertical polarisation as the reference-polarisation; and the horizontal polarisation as the cross-polarisation. By adopting this definition, we have a universal dual-polarised radiation pattern. The dual polarisation antenna radiation patterns are given as:

$$\begin{aligned} A_r(\theta,\phi) &= E(\theta,\phi)\cdot(\sin\phi\vec{i_\theta}+\cos\phi\vec{i_\phi}) \\ A_c(\theta,\phi) &= E(\theta,\phi)\cdot(\cos\phi\vec{i_\theta}-\sin\phi\vec{i_\phi}) \end{aligned} \tag{1}$$

where the functions $A_r(\theta,\phi)$ and $A_c(\theta,\phi)$ are the reference-polarisation radiation pattern and cross-polarisation radiation pattern, respectively, in [9]. Both the horizontal and vertical source currents generate reference-polarisation pattern and cross-polarisation patterns. By assuming the ground reference is in the $\vec{x}-\vec{y}$ plane, the two source currents displaced at orthogonal directions of $\vec{z}$ and $\vec{y}$ correspond to horizontal and vertical polarisation, respectively.

First we assign the reference-polarisation and the cross-polarisation radiation pattern to the horizontal polarisation. Following this definition we obtain the horizontal polarisation radiation pattern and the vertical polarisation radiation pattern of the horizontal source current as:

$$\begin{aligned} A_{HH}(\theta,\phi) &= A_{rh}(\theta,\phi) \\ A_{HV}(\theta,\phi) &= A_{ch}(\theta,\phi) \end{aligned} \tag{2}$$

Next, we assign the reference-polarisation and the cross-polarisation radiation pattern to the vertical source current. This is simply done by turning the source current from the $\vec{x}$ axis to the $\vec{z}$ axis. Then, we have the following results:

$$\begin{aligned} A_{VV}(\theta,\phi) &= A_{rv}(\theta,\phi) \\ A_{VH}(\theta,\phi) &= A_{cv}(\theta,\phi) \end{aligned} \tag{3}$$

In the above equations the functions $A_{rh}(\theta,\phi)$, $A_{ch}(\theta,\phi)$, $A_{rv}(\theta,\phi)$ and $A_{cv}(\theta,\phi)$ are the radiation patterns which can be obtained according to Eq (1). Here we take a simple dual-polarized half-wavelength dipole antenna as an example to illustrate the definition of polarisation in the dual-polarised channel. By displacing two source currents at the two perpendicular directions of $\vec{z}$ and $\vec{y}$, we generate a dual-polarized dipole antenna. We specify the dipole at $\vec{z}$ direction as vertical polarisation, and the dipole at $\vec{y}$ direction as horizontal polarisation. The two source currents generate reference-polarisation and cross-polarisation radiation patterns as in [9]. Following our definition of vertical and horizontal polarisation, we further assign the reference-polarisation and cross-polarisation of the vertically polarized dipole as A_{VV} and A_{VH}, respectively. And the reference-polarisation and cross-polarisation of the horizontally polarized dipole as A_{HH} and A_{HV}, respectively. Thus, we have the following radiation patterns of the dual-polarized dipole antenna as:

$$\begin{aligned} A_{VV}(\theta,\phi) &= E(\theta,\phi)\cdot(\sin\phi\vec{i_\theta}+\cos\phi\vec{i_\phi}) \\ A_{VH}(\theta,\phi) &= E(\theta,\phi)\cdot(\cos\phi\vec{i_\theta}-\sin\phi\vec{i_\phi}) \\ A_{HH}(\theta,\phi) &= E(\theta+\pi/2,\phi)\cdot(\sin\phi\vec{i_\theta}+\cos\phi\vec{i_\phi}) \\ A_{HV}(\theta,\phi) &= E(\theta+\pi/2,\phi)\cdot(\cos\phi\vec{i_\theta}-\sin\phi\vec{i_\phi}) \end{aligned} \tag{4}$$

The radiation pattern of the vertically placed half-wavelength dipole $E(\theta,\phi)$ is given as:

$$E(\theta) = j\omega\mu\frac{2I}{k}\frac{\exp(-jkr)}{4\pi r}\sin\theta\frac{\cos[(\pi/2)\cos\theta]}{\sin^2\theta}$$

where $k = 2\pi/\lambda$ is the wave number.

In [9], the definition is confined to study the antenna radiation pattern. However, we extend the definition to model the polarized wave in ray-tracing model.

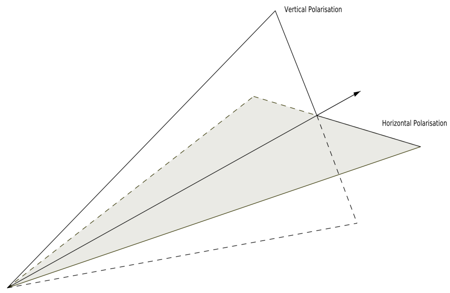

Fig. 2. Polarised Ray Model With Dual-Polarisation

The extension of the definition of vertical polarisation and horizontal polarisation in ray-tracing model is given in Figure 2. We can see in the figure the ray-tracing model incorporating linear dual-polarisation. For the horizontal polarisation plane (the shaded plane) in the figure, even though it is not perfectly parallel to the horizontal planes, according to the definition of horizontal polarisation, it is still horizontal polarisation.

By extending Definition 3 in [9] to ray-tracing model, we obtain a wider definition of horizontal polarisation. Horizontal polarisation are not necessarily in strictly horizontal planes; the planes rotating around one line in horizontal planes define horizontal polarisation. Using this wider definition of horizontal polarisation facilitates our analysis of cross-polarisation in the next section.

III. DUAL-POLARISED CHANNEL MODELLING IN UTD

In the last section we see one cause of the cross-polarisation component of the dual-polarised channel is antenna radiation. In this section we analyse the other cause of the cross-polarisation component in the dual-polarised channel during propagation: diffraction. Our proposed dual-polarized channel model is based on ray tracing which is based on geometrical optics(GO). The UTD was introduced in [11] as an extension of GO to include the characterisation of diffraction. The UTD inherently models the two directions of polarisation separately using the diffraction plane as the reference: polarisation is categorized as parallel and perpendicular with respect to the diffraction plane. In this regard, the UTD has an innate capability of modelling the dual-polarised channel. We present a typical diffraction scenario in the UTD framework.

The vector $\vec{i}$ is the unit vector of the incident ray; the vector $\vec{d}$ is the unit vector of the diffracted ray and $\vec{E}$ is the edge of the diffraction. The direction $\vec{i}$ and edge $\vec{E}$ decide the plane of incident, giving the parallel and perpendicular polarisation directions as

$$p_{\perp} = \vec{i} \times \vec{E} \qquad p_{\parallel} = p_{\perp} \times \vec{i}$$

These two directions are also the directions of horizontal polarisation and vertical polarisation. Again, we can see they are not in a perfectly horizontal plane, but they are horizontal polarisation and vertical polarisation by definition.

For the diffracted rays, the direction of the diffracted ray $\vec{d}$ and the edge $\vec{E}$ decide the diffraction plane. The directions of the two perpendicular directions of polarisation are given as:

$$p_{\perp}^{d} = \vec{d} \times \vec{E} \qquad p_{\parallel}^{d} = p_{\perp}^{d} \times \vec{d}$$

Here the perpendicular direction and parallel direction are with respect to the diffraction plane. According to the UTD, the field of the diffracted field is given in a matrix form as:

$$\begin{bmatrix} E^d(s)_{\perp} \\ E^d(s)_{\parallel} \end{bmatrix} = \begin{bmatrix} -D_{\perp} & 0 \\ 0 & -D_{\parallel} \end{bmatrix} \begin{bmatrix} E_{\perp}^{i} \\ E_{\parallel}^{i} \end{bmatrix} S(s) \exp(-jks) \tag{5}$$

where $S(s)$ is the spreading factor and s is the distance from the diffraction point; the quantities $D_{\perp}$ and $D_{\parallel}$ are the diffraction coefficients and are calculated according to the following equations from [12]:

$$\begin{aligned} D_{\parallel}^{\perp} = & \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k}} \left[\cot\left(\frac{\pi + (\psi - \psi')}{2n}\right) F(kLa^{+}(\psi - \psi')) \right. \\ & + \cot\left(\frac{\pi - (\psi - \psi')}{2n}\right) F(kLa^{-}(\psi - \psi')) \\ & + R_{\parallel}^{\perp} \cot\left(\frac{\pi - (\psi + \psi')}{2n}\right) F(kLa^{-}(\psi + \psi')) \\ & \left. + R_{\parallel}^{\perp} \cot\left(\frac{\pi + (\psi + \psi')}{2n}\right) F(KLa^{+}(\psi + \psi')) \right] \end{aligned}$$

where

$$F(x) = 2j\sqrt{(x)} \exp(jx) \int_{\sqrt{x}}^{\infty} \exp(-j\tau^2) d\tau \tag{6}$$

is a Fresnel integral, and

$$L = \frac{ss'}{s + s'}$$

$$a^{\pm}(\beta) = 2\cos^2\left(\frac{2n\pi N^{\pm} - \beta}{2}\right), \quad \beta = \psi - \psi'$$

where $N^{\pm}$ are obtained from the following equations:

$$2\pi n N^{+} - (\beta) = \pi$$
$$2\pi n N^{-} - (\beta) = -\pi$$

The quantities $R_{\parallel}^{\perp}$ are the reflection coefficients of perpendicular and parallel polarisations; the angle β is the incident angle between the incident ray and the edge in the parallel plane; the angle ψ' is the angle between the edge and incident ray in the perpendicular plane; and the angle ψ is the angle between the edge and diffracted ray in the perpendicular plane.

The categorisation of polarisation as perpendicular and parallel is with respect to the incident plane or diffraction plane. If the incident plane and diffraction plane are in the same plane, then polarisation remains in same planes. However, diffraction produces a cone of diffracted rays and hence a set of diffracted planes rotating around the edge. When the incident plane and diffracted planes are not in the same plane, the directions of polarisation switch to other directions. Thus cross-polarisation component channel is generated during diffraction.

Assuming the incident plane is in the plane 'a', for diffraction plane 'a' and 'c', the diffracted rays have the same polarisation directions as the incident ray. For diffracted rays in other planes, the polarisation directions changed from the polarisation directions of the incident ray. The diffracted ray in plane 'b' changes 90 degree as the diffraction plane rotated 90 degree. This results in the exchange between vertical polarisation and horizontal polarisation: the vertical polarisation in plane 'a' is horizontal polarisation in plane 'b', and vice versa.

The UTD includes reflection as a special case. The computation of the diffraction coefficients involves the Fresnel integral in Eq 6. In many engineering applications, such highly inefficient calculation should be further simplified. We simplify the computation of diffraction by reflection.

The reflected fields are calculated as:

$$\begin{bmatrix} E^r(s)_{\perp} \\ E^r(s)_{\parallel} \end{bmatrix} = \begin{bmatrix} -R_{\perp} & 0 \\ 0 & -R_{\parallel} \end{bmatrix} \begin{bmatrix} E_{\perp}^{i} \\ E_{\parallel}^{i} \end{bmatrix} S(s) \exp(-jks) \tag{7}$$

where $R_{\perp}$ and $R_{\parallel}$ are the reflection coefficients of the material; the signs '$\perp$' and '$\|$' specify the directions of polarisation.

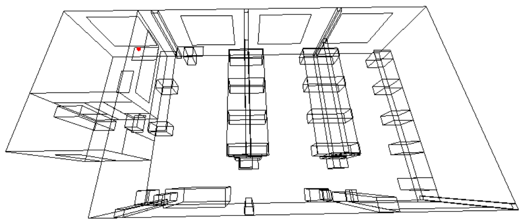

Fig. 3. 3-Dimensional Office Environment

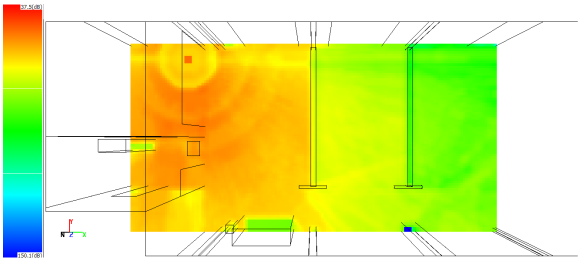

Fig. 4. Cross-polarisation Channel(HV) Coverage

At the receiver end, we also specify the displacement of the dual-polarised receiver antenna. By matching the received ray as in the horizontal and the vertical planes, we can project the ray based definition of polarisation back to the ground reference based polarisation orientation categorisation. Since throughout this paper, we aim to simulate the widely used ground reference system of the vertical and horizontal polarisation. We also need to specify the receiver antenna displacement for the purpose to project the ray-based UTD propagation model to the ground-based polarisation definition.

IV. Simulation Results

In this section, we present the computer simulation results of the proposed dual-polarized ray tracing incorporated in an efficient 3-dimensional ray tracing simulation software package [8]. The simulation scenario is a typical indoor office environment. The dimensions of the room are: $16m \times 9m \times 4m$. There are over 250 polygon shape surfaces in the environment. The materials include: wood, plastic, metal, and gypsum. Figure 3 shows the 3-dimensional building construction of the indoor environment.

The simulation settings are: the radio frequency is 3.5GHz; the transmitter power is 6dBm. The transmitter is located 1.35 meters over the ground. The exact location is specified by the red point in the figure. Both the transmitter antenna and receiver antenna are dual-polarized half-wave length dipole. We assume they are both ideally displaced in a horizontal plane. The receiver antennas are assumed to be placed on a grid of $10cm \times 10cm \times 10cm$ over the whole coverage space. The vertical polarisation horizontal polarisation radiation patterns of the antenna are given in Section 2.

The simulation of signal coverage of cross-polarisation channel (HV) is shown in Figure 4. And the simulation of the signal coverage of co-polarisation channel (VV) is shown

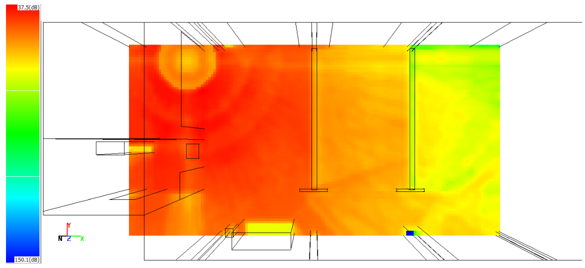

Fig. 5. Co-polarisation Channel(VV) Coverage

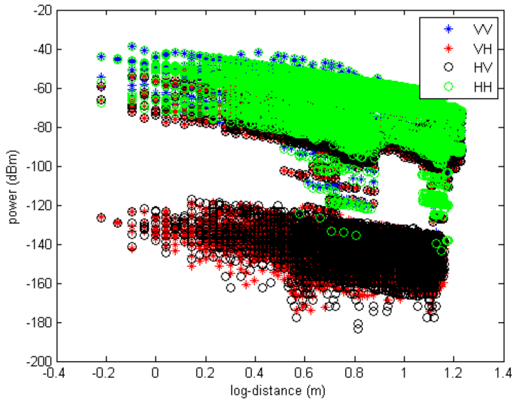

Fig. 6. Power versus time delay in LoS

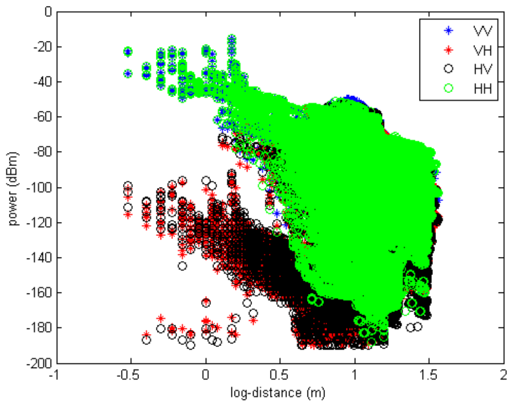

Fig. 7. Power versus time delay in NLoS

in Figure 5. We can see that the co-polarisation channel has a better signal coverage in terms of signal strength. This is because the co-polarisation propagation mechanism is dominant in the environment.

The plot in Figure 6 shows the receiving power strength against the distance in line-of-sight(LoS) situation. we can see that the co-polarised channels (VV, HH) have overall better signal strength over the whole LoS range. The same power figure in Non-line-of-sight(NLoS) situation is shown in Figure 7. It has a similar behaviour as in the LoS scenario. However, in this case, the co-polarisation and the cross-polarisation overlaps over a wide distance range. This is because the NLoS scenario has more de-polarisation effects such as diffraction.

Such results agree with the previous models from other researchers such as [3] and [6].

V. Conclusion and Discussion

In this work we propose a universal dual-polarisation propagation modelling method for computer simulation models. We adopted the polarisation direction definition from [9] and extended the definition from antenna radiation to ray propagation model. We clarify the widely existing misunderstanding of the categorisation of polarisation orientation among wireless engineering. Then, we integrated the polarisation model to a ray-based propagation simulation model within the framework of UTD. Furthermore we identified that diffraction generates cross-polarisation channel components besides antenna radiation in our dual-polarised channel. Simulation shows promising results that demonstrate the potential of the model in applications of indoor wireless networks design and optimisation. Our analysis gives new insight to the generation of cross-polarisation channel components. Such analysis provides insightful understanding of the mechanism of the dual-polarised channel and it further provides grounds for further elaboration and development of the deterministic channel models.

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