Double Directional Channel
— Measurements and Data Analysis, Stochastic Modeling and Deterministic Prediction

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Abstract—This paper reviews the double directional channel models mainly for MIMO applications. First, the double directional channel measurements and data analysis are presented, to extract the antenna-independent propagation channel model from the MIMO channel measurement via the parametric modeling and estimation. Next, stochastic modeling approaches are introduced for the link-level simulation for the physical layer of the communication system. Then, a deterministic prediction approach using ray-tracing technique is mentioned for the site planning.

I. INTRODUCTION

Radiowave propagation channels have been investigated for the long period, according to the progress of the radio and wireless communication systems.

The recent progress of multiple-input multiple-output (MIMO) transmission technology has demanded the directional extension of the channel properties. This paper presents three aspects of the double directional channels, i.e., the measurements and data analyses, the stochastic modeling, and the deterministic prediction.

The MIMO channel response can be measured by using array transmitter and array receiver. However, the MIMO channel measured in such a manner is the superposition of the Tx and Rx array antenna responses and the double directional propagation channel response. While the array antennas are the part of MIMO transmission system which can be designed, the double directional propagation channel is a kind of natural phenomenon which can not be controlled. Therefore, the separation of antenna properties from MIMO channel response is very important to know the double directional propagation phenomenon. This double directional channel response can be further utilized for the comparison of different types of array antennas in the MIMO systems. To de-embed the antenna characteristics from the MIMO channel to extract the double directional channel property, the parametric model is needed. The model usually assumes that the double directional channel consists of sum of plane wave paths or geometrical rays, and the these parameters are estimated from the measured MIMO channel matrix via maximum likelihood (ML) estimation or its reduced version.

To conduct the link-level or system-level evaluation of the MIMO transmission system, stochastic channel model is preferred to comprehensively reproduce the variation of the channel responses. The reproducibility and the comprehensiveness are very important for the comparison of the performances among the different systems. Two approaches of the modeling, i.e., power spectrum method and correlation matrix method are introduced. Wide-sense stationary uncorrelated scattering (WSSUS) assumption of the channel guarantees the equivalence of these two approaches.

In the site planning for the operation of wireless systems, such as the location of the base station and the coverage area, the site-specific and deterministic prediction approach is needed. Although the progress of the high performance computing expands the size of the areas for full wave simulation to practical area size for indoor communications, use of the ray-tracing technique is still popular for outdoor case. Although the ray-tracing prediction has been extensively studied, the reliability of the prediction is not enough. The issues to be considered for the future improvement of the accuracy of the prediction are summarized.

II. DOUBLE DIRECTIONAL CHANNEL AND MIMO CHANNEL

The relation between the double directional channel and MIMO channel is depicted in Fig. 1. MIMO channel is represented by the transfer functions (or impulse responses) between \( M \) transmitter (Tx) antenna ports and \( N \) receiver (Rx) antenna ports. The transfer function between \( m \)-th Tx antenna and \( n \)-th Rx antenna is represented as \( H_{mn}(f) \), and the \( N \times M \) matrix \( H(f) \) represents the MIMO channel matrix.

Tx and Rx antennas are the part of the radio equipments which can be designed by the manufacturer. In contrast, the multipath propagation is a natural phenomenon which can not be controlled by the user. Therefore, it is desirable to separate the antennas from the MIMO channel. The remaining propagation channel is so-called double directional channel model, as the directional responses of the multipath are modeled both at Tx and Rx locations [1].

In the ray-optical representation of the double directional channel, each propagation path is expressed as the local plane
wave at both Tx and Rx with a specific delay time as
\[ H_{\text{DD}}^{\beta\alpha}(\tau, \Omega_{\text{Rx}}, \Omega_{\text{Tx}}) = \sum_{l=1}^{L} d_{l}^{\beta\alpha} \delta(\Omega_{\text{Rx}} - \Omega_{l}) \delta(\Omega_{\text{Tx}} - \Omega_{l}) \delta(\tau - \tau_{l}) \] (1)
in delay domain, and
\[ H_{\text{DD}}^{\beta\alpha}(f, \Omega_{\text{Rx}}, \Omega_{\text{Tx}}) = \sum_{l=1}^{L} d_{l}^{\beta\alpha} \delta(\Omega_{\text{Rx}} - \Omega_{l}) \delta(\Omega_{\text{Tx}} - \Omega_{l}) \exp(-j2\pi f \tau_{l}) \] (2)
in frequency domain.

The MIMO channel matrix can be reconstructed from the double directional transfer function as
\[ H_{\text{meas}}(f) = \int_{\Omega_{\text{Rx}}} \int_{\Omega_{\text{Tx}}} \sum_{n} \sum_{\alpha} E_n^{\alpha}(f, \Omega_{\text{Rx}}) H_{\text{DD}}^{\beta\alpha}(f, \Omega_{\text{Rx}}, \Omega_{\text{Tx}}) E_n^{\beta}(f, \Omega_{\text{Tx}}) d\Omega_{\text{Rx}} d\Omega_{\text{Tx}} \] (3)
where \( E_n^{\alpha}(f, \Omega_{\text{Rx}}) \) and \( E_n^{\beta}(f, \Omega_{\text{Tx}}) \) are complex directivity functions of \( \alpha \)-polarization component of \( m \)-th Tx antenna toward \( \Omega_{\text{Tx}} \) direction and \( \beta \)-polarization component of \( n \)-th Rx antenna toward \( \Omega_{\text{Rx}} \) direction, respectively.

III. DOUBLE DIRECTIONAL CHANNEL MEASUREMENTS AND DATA ANALYSIS

The derivation of the MIMO channel matrix from the double directional transfer function is quite simple, and is considered as the forward problem. In contrast, the derivation of the double directional transfer function from the MIMO channel matrix is an inverse problem and is a quite tough work.

A. MIMO channel measurement

There are a few alternative approaches to measure the wideband complex MIMO channel matrix.

First approach is to use a vector network analyzer (VNA). This is suitable for the indoor or short range channels with small mobility, since both Tx and Rx sides should be wired with the same VNA. Synthetic array approach by using the antenna positioner has the flexibility of the shape of the array, although the environment should be static [2].

Second approach is to use a specific instrument for the radio channel, which is known as a channel sounder. Tx and Rx units are separated in the channel sounder, and they are synchronized by using the atomic oscillators such as rubidium or cesium. A typical architecture of the commercial MIMO architecture is so-called time division multiplexing (TDM) type [3]. Array antennas are switched at both Tx and Rx sides sequentially, so that Tx and Rx requires single wireless chains respectively. In addition to saving the cost, only a single back-to-back calibration of the RF chain is sufficient. However, for the stable response of the switch, guard interval is necessary before each measurement of the channel. As the wideband signal, either PN sequence or unmodulated multitone signal is used.

Third approach is to use full MIMO transmitter and receiver. Instead of using the atomic oscillator for the absolute synchronization, it is possible to establish the synchronization at Rx side with the sacrifice of the absolute delay time [4].

Table I compares these three approaches with respect to the number of antennas and the measurement time for the measurement of the wideband MIMO channel matrix.

B. Parameter estimation

As shown in Eq. (3), the MIMO channel matrix can be represented by using the double directional channel parameters and the antenna responses. The removal of the antenna responses from the MIMO channel matrix to get the double directional parameters is called antenna de-embedding, and is recognized as an inverse problem. Usually, the double directional channel parameters are estimated by using maximum likelihood (ML) approach. By knowing or assuming the probabilistic error model, the likelihood function is defined as the a-posteriori probability of the parameter set. In case for double directional channel, parameter set \( \mu \) is represented as
\[ \mu = (\tau_{1}, \Omega_{\text{Tx}}, \Omega_{\text{Rx}}), |l| = 1, \ldots, L \] (4)
Assuming additive white Gaussian noise (AWGN) being the source of the error, the likelihood function is represented as
\[ p(H_{\text{meas}}|\mu) = \exp\left(-\frac{\|H_{\text{meas}} - H(\mu)\|_{F}^{2}}{\sigma^{2}}\right) \] (5)
where \( H_{\text{meas}} \) and \( H(\mu) \) are measured channel matrix by the channel sounder and theoretical channel matrix with parameter set \( \mu \) represented by Eq. (3), and \( \| \cdot \|_{F} \) is Frobenius norm. Maximum likelihood estimate \( \hat{\mu}_{\text{ML}} \) is defined as
\[ \hat{\mu}_{\text{ML}} = \arg\max_{\mu} p(H_{\text{meas}}|\mu) \]
\[ = \arg\min_{\mu} \|H_{\text{meas}} - H(\mu)\|_{F}^{2} \] (6)
However, it is impractical to search $\hat{\phi}_{\text{ML}}$ simultaneously in the 5L-dimension parameter space, and the expectation maximization (EM) algorithm to split the parameter space into its subsets is widely used. Space alternating generalized EM (SAGE) [5] and RIMAX [6] further accelerates the search in EM algorithm.

It is obvious that the accuracy of the parameter estimation is dominated by the accuracy of the array antenna response including the influence of the cables and fixtures [7]. Non-spectral components due to diffuse scattering or unresolved distributed scattering are called dense multipath component (DMC) and the extension of the model from Eq. (??) is needed in the real environment. There are some proposals to model DMC in delay domain [6] and in angular domain [8].

IV. DOUBLE DIRECTIONAL STOCHASTIC CHANNEL MODEL

Stochastic channel models are often used for the link-level simulation for the physical layer of the communication system. In particular, the common models are used for the comparison between different systems.

Stochastic channel models are expressed fully mathematically, so that it can be reproducible. Monte-Carlo simulation is commonly used for the comprehensive dynamic variation of the channel responses.

In line with Sec. II, both double directional stochastic channel modeling and MIMO stochastic channel model can be constructed. However, a MIMO stochastic channel model is usually constructed from the double directional stochastic channel model, and not vice versa. Recently established standard MIMO channel models are also constructed in this manner [9], [10], [11], [12].

A. Double directional stochastic channel model

Wide sense stationary uncorrelated scattering (WSSUS) assumption [13] is commonly used for the stochastic channel modeling. WSS assumption is applicable with respect to time, frequency and position, i.e. the channel response is represented as a stationary stochastic process in wide sense with respect to these variables. It is noted that WSS model is usually applicable within relatively small range, as the shadowing or frequency dependent path loss can not be taken into account. On the other hand, US assumption is applicable in Doppler, delay and wavenumber, which are the Fourier transform (spectral) domains of WSS variables. Multipath components existing in these domains are uncorrelated to one another, and their second order expectation values are represented by the power spectra. For example as a realization of a WSSUS channel model, spatial channel transfer function $H(z)$ and spatial frequency impulse response $A(\nu_z)$, which are related as

$$H(z) = \int_{-\infty}^{\infty} A(\nu_z) \exp(j2\pi\nu_z z) d\nu_z,$$  (7)

are considered [14]. Note that $\nu_z$ is the spatial frequency with respect to $z$ axis defined as

$$\nu_z = \frac{\cos \theta}{\lambda},$$  (8)

where $\lambda$ is the wavelength at the carrier frequency, $\theta$ is the wave propagation angle with respect to $z$ direction, and

$$\nu_0 = \frac{1}{\lambda}.$$  (9)

Since WSS assumption is applicable, the autocorrelation function of the spatial channel transfer function $R_{H(z)}(\Delta z)$ is represented as

$$R_{H(z)}(\Delta z) = E[H(z)H^*(z + \Delta z)].$$  (10)

Spatial frequency power spectrum $S_{H(z)}(\nu_z)$ is derived by using the Wiener-Khintchine relation as

$$S_{H(z)}(\nu_z) = \int_{-\infty}^{\infty} R_{H(z)}(z) \exp(-j2\pi\nu_z z) dz.$$  (11)

Here, it is noted that the power spectrum represents the expectation of the power of impulse response

$$S_{H(z)}(\nu_z) = \lim_{Z \to \infty} \frac{1}{2Z} E \left[ |A(\nu_z, Z)|^2 \right],$$  (12)

where

$$A(\nu_z, Z) = \int_{-Z}^{Z} H(z) \exp(-j2\pi\nu_z z) dz.$$  (13)

is the sample spatial frequency impulse response within the range $-Z < z < Z$.

Assuming the Rayleigh fading channel, the spatial frequency impulse response is modeled by zero mean, variance proportional to $S_{H(z)}(\nu_z)$, complex, circular symmetric Gaussian random value. It is further noted that the US assumption requires that the spatial frequency impulse responses at $\nu_{z1} \neq \nu_{z2}$ should be uncorrelated to each other.

The double directional wideband stochastic channel model is the straightforward extension of the power spectrum for delay, Tx-wavenumber, Rx-wavenumber jointly.

B. MIMO stochastic channel model

In this section, the channel is assumed to be narrowband for simplicity, although the extension to the wideband channel is straightforward. Then, MIMO channel consists of $N \times M$ channel matrix $H$ as shown in Eq. (3). Each element of $H$
is according to the Rayleigh fading, i.e. zero mean, complex, circular symmetric Gaussian distribution in non-line-of-sight (NLOS) environment. To characterize the statistics of $H$, $NM$ dimensional MIMO fading correlation matrix $R_H$ is defined as

$$R_H = E[\text{vec}(H)\text{vec}(H)^H],$$

where

$$\text{vec}(H) = [h_{11} \ h_{12} \ \cdots \ h_{1M} \ h_{21} \ \cdots \ h_{NM}]^T.$$  

By using $R_H$, the random generations of $H$ can be easily implemented in the Monte-Carlo simulation [15]. A square-root matrix of $R_H$ represented by $R_H^{1/2}$ can be derived by using Cholesky factorization [16]. Then, a realization of $H$ is obtained from the $NM$ dimensional vector $h_{ \text{id}}$ with zero mean, unit variance, complex, circular symmetric i.i.d. Gaussian random entries in the Monte-Carlo simulation as

$$\text{vec}(H) = R_H^{1/2}h_{ \text{id}}.$$  

As the extension to the SIMO (single-input multiple-output) case [17], the correlation between $h_{n1,m1}$ and $h_{n2,m2}$ can be expressed as

$$R_{(n_1,m_1),(n_2,m_2)} = \frac{1}{(4\pi)^2} \iint_{\Omega_{Tx}} \iint_{\Omega_{Rx}} \sum_{\alpha} \sum_{\beta} E_{m1}^\alpha(\Omega_{Rx})E_{m2}^\beta(\Omega_{Rx})P_{DD}^{nm}(\Omega_{Tx},\Omega_{Tx})$$

$$E_{m1}^\alpha(\Omega_{Tx})E_{m2}^\beta(\Omega_{Tx})d\Omega_{Tx}d\Omega_{Rx},$$

where $P_{DD}^{nm}(\Omega_{Rx},\Omega_{Tx})$ is the full polarimetric two dimensional double directional joint angular power spectrum of the Tx $\alpha$-polarization toward $\Omega_{Tx}$ direction and the Rx $\beta$-polarization toward $\Omega_{Rx}$ direction.

V. DETERMINISTIC PREDICTION OF CHANNEL

Different from stochastic channel modeling, the deterministic prediction of the propagation channel is necessary for the site planning and coverage examination. Recently, raytracing tools become more mature and utilized in some commercial planning tools [18], [19].

A. Raytracing prediction

Raytracing simulation is commonly used for the purpose\(^1\), as the solvers of Maxwell’s equations can not yet handle so large problems, except for indoor case. In the typical raytracing simulator, specular reflection and edge diffraction are considered. To trace the multiple paths, two alternative methods are available. Imaging method traces the image sources with respect to all the reflection planes [20]. Ray launching method traces the tremendous amount of rays launched from the source toward different solid angles [21]. It is noted that the raytracing prediction is double directional in nature.

B. Issues of raytracing prediction

There are still quite some issues to improve the accuracy of the raytracing prediction.

\(^1\)In the section, the citations are not comprehensive and only the works related to the author are cited since there are already a lot of works in this field.

1) Scattering mechanisms: For the simplicity of the model input and simulation, only the specular reflections at the flat surfaces and the diffractions at the edges of the polygons are considered. However, these simplifications degrades the prediction accuracy quite seriously.

a) Curved surface: Although the geometrical optics theory can be applicable to the curved surface, it is not often implemented in the prediction tool as the treatment of the raytracing becomes much more complicated. Instead, usually the curved surface is modeled as the polygon. In particular for the convex curved surface, the specular reflection may be quite often replaced by the edge diffraction which result in relatively large error.

b) Finite sized scatterer: Geometrical optics assumes that the scatterers are with infinite size. However, when the scatter size is smaller than the first Fresnel zone of the path between Tx and Rx, the specular reflection model overestimates the scattered field. The use of complex radar cross section to model the scatterer in such a case has been examined, and the better accuracy with respect to the measurement has been found [22].

c) Diffuse scattering: Obviously, the surfaces of the buildings and other objects are not as smooth as that modeled in the raytracing simulation. Surface irregularities and the objects attached to the surface are visible through the directional measurements [23], [24], and physical optics approximation can improve the prediction accuracy [24]. Alternatively, a more generic roughness model has been proposed [25].

2) Limitation of the structure model: Although inaccurate models in the geometrical optics have been stated in the previous paragraphs, the input structural data are also the issues.

a) Discrepancy between data accuracy and modeling accuracy: Since the geometrical optics is the approximation applicable only for large scale objects with respect to the wavelength, the detailed structural modeling does not guarantee the more accurate simulation.

b) Availability of building data: Unfortunately, commercially available building data are not so accurate as they are just modeled as the simplified polygons without any surface irregularity nor even without vertical nonuniformity, as they are usually developed from aerophoto together with the number of stories to approximate the height. Moreover, other objects than the buildings are not usually modeled.

c) Objects which can not be modeled using geometrical objects: Cylindrical structures such as lamp posts or utility poles can not be well modeled by the geometrical optics, but still have significant influences to the channels in particular in the microcellular environments [26]. Trees are also influencing to the shadowing properties of the channel.

3) Accuracy and applicability: It is rather difficult to evaluate the accuracy of the raytracing prediction in general due to the above issues. However, it is necessary to check whether the required accuracy is satisfied via the field tests. It is commonly recognized that the path gain is relatively accurate as the most significant path is relatively easily predicted by the
simulation. Instead, angular and delay spread parameters are usually underestimated due to the lack of the diffuse scattering model or rough surface reflection [27]. It seems to be often the case that the measurement data are used for the modification or correction of the simulation model, such as the surface roughness parameters.

VI. CONCLUSION

This paper has reviewed the double directional channel models mainly for MIMO applications. First, the double directional channel measurements and data analysis are presented. Antenna directivities are carefully removed by using the ray path model via parameter estimation. Next, stochastic modeling approaches are introduced for the link-level simulation for the physical layer of the communication system. WSSUS path model via parameter estimation. Finally, a deterministic prediction approach using ray-tracing technique is mentioned for the site planning, and its issues are mainly focused.

There are at least three different applications for the double directional channel models:

1) System evaluation and comparison
2) Array antenna test
3) Site planning

Care must be taken that different kind of channel models are expected for these different applications.

REFERENCES


