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Measurement-based Analysis and Modeling of Multimode Channel Behaviors in Spherical Vector Wave Domain

Yang Miao, Katsuyuki Haneda, Jun-ichi Naganawa, Minseok Kim, Jun-ichi Takada

Abstract—This paper establishes the analytical model and analyzes the statistical behaviors of multimode channels in spherical vector wave (SVW) domain based on the microcellular radio channel measurement in downtown Helsinki at 5.3 GHz band. The multimode channel is the representation of radio wave propagation in the form of the SVW mode coupling between the transmit and receive antennas. The multimode channel does not rely on particular realizations of antennas at link ends, since any transmitting/receiving/scattering fields associated with an antenna can be modeled as a weighted sum of SVW modes where different antennas have different mode weights. The multimode channels are converted from the plane wave channel model parameters that are extracted from measured channels of coherent snapshots along 6 different routes in Helsinki. Based on the analysis of various first and second order statistics of the multimode channels, the main findings can be summarized as follows: 1) the multimode channels are power imbalanced; 2) the envelope short-term fading statistics of the multimode channels can be described with Rician probability distributions with varying K -factors; 3) the auto-correlations of multimode channels along the spatial translation of a mobile node in a propagation environment present varying coherent distances; 4) the cross-correlations of multimode channels vary with the spatial translation too. The obtained results and the proposed multimode channel model provide invaluable insights into the design of antenna systems tailored to a specific propagation environment. Indeed, antenna systems at both link ends can be devised such that the multimode channels with higher power, larger coherent distance and smaller cross-correlation are excited resulting in multiple-input multiple-output antenna systems that exploit efficiently the degrees of freedom of the propagation channel.

Index Terms—Radio propagation channel, mode-to-mode coupling, statistical behaviors, analytical modeling, spherical vector wave expansion, radio channel measurement, system design

I. INTRODUCTION

THE properties of Multiple-Input Multiple-Output (MIMO) radio propagation channels depend on the responses of the antenna arrays at the transmitter and the receiver as well as the physical interactions of the propagating

radio waves with the environment. While the antennas are designable, the radio-environment interactions can hardly be controlled in real-world scenarios. This poses design challenges on the antenna system in order to meet the required performance of a MIMO system. The antennas, if effectively designed, will exploit the inherent degrees of freedom (DoF) of the propagation channel. In this way MIMO systems will benefit from diversity, beamforming or multiplexing gains that will translate to higher reliability, extended coverage, or higher user data throughput. Moreover, in order to assure that the deployed antennas meet required over-the-air (OTA) performance specifications [1], [2], different antenna designs must be tested and compared. Hence, being able to characterize the impact of antennas on the propagation channel will lead to more efficient wireless system design.

The narrowband MIMO channels are completely characterized by their spatial structures, while the wideband MIMO channels require additional modeling over frequency or propagation delay time [3]. The modeling of MIMO channels is classically divided into analytical modeling and physical modeling, where the former characterizes channel impulse response (CIR) or channel transfer function (CTF) of the MIMO channel in a mathematical/analytical way as $\mathbf{H}$, defined by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (1)$$

where $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{n}$ are the complex-valued transmit signal, the receive signal and the receiver noise vectors, respectively, and $\mathbf{H}$ denotes the narrowband MIMO radio propagation channel. Modeling $\mathbf{H}$ mainly focuses on its first and second order statistics, such as the probability distribution of the received signal envelope and the spatial correlation, respectively. Examples of modeling approaches focusing on the spatial correlation are the well-known Kronecker model [4]–[6], the Weichselberger model [7], and the model by Sayeed [8]. Besides, a clear separation between a dominant/deterministic part and a fading/stochastic part has been suggested in the well-known line-of-sight (LOS) MIMO channel model presented in [9]. This was later extended in [10] to include fading statistics for each pair of transmit and receive antennas in wireless personal area networks (WPAN). The models in [9] and [10], however, do not discern between the impacts of the antennas and the propagation channel.

The physical model characterizes double-directional multipath propagation using a set of plane waves. Among the available physical modeling methods [3], [11], the spherical

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wave expansion [12] stands out as a useful tool to study various aspects of antenna-channel interactions. The expansion¹ depicts that arbitrary radiated field can be represented by a weighted sum of spherical vector wave (SVW) functions. The SVW functions are the homogeneous solutions of vector Helmholtz equations in spherical coordinate. The different modes of SVW are orthogonal to each other and form the basic set for composing any radiated field. Examples of the variously considered topics using the SVW expansion are the mutual coupling and correlations of array antennas [13]–[18], the spectral efficiency of antenna configurations [19], the mean effective gain [20]–[22], the channel capacity [23]–[26], and the spatial DoF [27]–[30]. Of particular interest is the clear separation between the antennas and the propagation channel formulated in [31], where the MIMO radio channel matrix $\mathbf{H}$ is expanded into a product of three terms as

$$\mathbf{H} = \mathbf{RMT}, \quad (2)$$

where $\mathbf{T}$ and $\mathbf{R}$ are transmit and receive antenna mode matrices, respectively, and $\mathbf{M}$ is a *transmit-receive mode coupling matrix* all expressed by the SVW coefficients. The propagation channel is completely modeled by the matrix $\mathbf{M}$. The merits of this model in characterizing antenna-channel interactions are as follows. First, it is well-known from the theory of near-field antenna measurements that the field radiated by an antenna can be expanded into a finite number of SVW modes. Hence, the dimensions of matrices $\mathbf{T}$, $\mathbf{R}$ and $\mathbf{M}$ are limited as well, leading to the most compact channel model for known electrical sizes of the transmit and receive antennas. Second, the SVW expansion does not put any constraints on the type of electromagnetic waves impinging at the receive antenna, neither on the physical mechanism originating the waves. For the former, the natural truncation of the discrete SVW modes is able to describe all physical mechanism of the radio-environment interactions, including the line-of-sight, specular reflection, diffraction, refraction or penetration, and diffuse scattering, while the distinct plane waves that are the far-field assumption of the spherical waves can not describe the diffuse scattering in finite number. For the latter, the truncation of the SVW modes is determined by the electrical size of the antennas or sources, but not dependent on the specific realization of geometries of the antennas. SVW expansion can express any polarimetric electromagnetic field distributions on a sphere, such as antenna radiation patterns and multipath profiles. Third, once the most significant SVW modes contributing to the interactions have been estimated, it immediately follows what the radiation patterns of these antennas should be. This makes the mode coupling matrix well suited for modeling the interactions between antennas and the propagation channel.

From the propagation modeling point of view, the estimation of $\mathbf{M}$ as well as its theoretical and physical interpretations are essential. In the earlier works, it is shown in [31] that assuming

the impinging field at the antenna is complex Gaussian, the entries of $\mathbf{M}$ are also complex Gaussian variable whose statistics are determined by the power angular spectrum (PAS) at the transmit and receive sides. In [32], the clustering impact on the statistics of $\mathbf{M}$ was numerically studied, while its statistical behaviors were investigated in [29]. In [33] and [34], linear combinations of $\mathbf{M}$ entries are empirically estimated. $\mathbf{M}$ was generated in various ways, e.g. from plane wave channels [29], [32], [35], from the finite-difference time-domain method [36], [37] and directly from CTF obtained by dedicated spherical arrays [38].

Despite those extensive studies, we still *lack the analytical models of $\mathbf{M}$* to fully describe the measured reality. In order to describe the realistic behaviors, we furthermore need dynamic and mode-specific modelings that allow analysis of propagation channels over large scale cellular mobile routes. Here we define the multimode channels as the entries of the mode coupling matrix over coherent snapshots, and we are among the first to introduce the multimode channels to emphasize the mode-specific behaviors over temporal-spatial transitions in propagation environment, in other words, the modeling of time-varying propagation channel using SVW modes.

This paper provides the statistical analysis of multimode channel behaviors, and subsequent analytical model, based on the measurements performed in an urban microcellular scenario in Helsinki. This paper focuses on the narrowband multimode channel behaviors and modeling, where the frequency-dependent characterizations are not within the scope. The analytical model of $\mathbf{M}$ follows the formulation of [10] as it fits our measured observations. The statistical modeling focuses on the first and second order statistics of the short-term fading behavior of the multimode channels, i.e. the entries of the matrix $\mathbf{M}$. The analysis is based on the computation of the auto- and cross-correlations as well as the envelope statistics of multimode channels along the movement path of mobile stations. We found it important to model variations of multimode channels for their power, small-scale statistics, coherent distance and cross-correlation. The observed statistical behaviors provide a straightforward input into antenna system designs tailored to specific physical environment. The input shall be interpreted as follows: 1) the multimode channels with higher power provide more link gains, 2) the multimode channels with larger coherent distances on the measured routes provide more stable link quality, and 3) the multimode channels with lower cross-correlation with other multimode channels may provide a larger diversity and multiplexing gains in MIMO system. Hence, from knowing the statistical behaviors of the multimode channels, we know what SVW modes shall be excited at the transmit and receive antennas to improve the performance of the multi-antenna systems in a specific propagation scenario.

The unique contributions of this paper are two folds. First, we have investigated the statistical behaviors of antenna-generic multimode channels based on measured data in large scale urban scenario and have summarized these behaviors. Second, we found that the statistical behaviors of the antenna-generic multimode channels resemble that of the antenna-specific radio channels for WPAN where the antenna con-

¹It is a three-dimensional version of the Taylor series expansion in the spherical coordinate system, where basis functions are orthogonal to each other. Taylor series expansion can be found in many math books, while details of SVW expansion of electromagnetic fields are found in Appendix A1.4 in Hansen's book [12].

figurations at link ends are irregular and a subset of the antenna elements are subject to efficiency degradation due to human interaction. Extending the WPAN radio channel model to a more general Rician-fading antenna-generic multimode channel model in the SVW domain broadens the applicability of the presented equations in [10] to model wireless channel of more general scenarios.

The remainder of this paper is organized as follows. In Section II we first review the plane wave (PW) and the SVW representations of the physical MIMO radio channel, and then introduce the proposed analytical model of multimode channels summarizing the statistical behaviors. In Section III we study statistical behaviors of the multimode channels based on the measurements, and parameterize the analytical model to reproduce the measured reality the best. Conclusions are provided in Section IV. The time dependence of radio wave is $e^{j\omega t}$ throughout the paper.

II. MODELS OF MULTIMODE CHANNELS

In this section we propose a novel analytical model for the statistical multimode channels that represent the intrinsic propagation channel without particular realization of antennas at link ends. First, the physical definition of the multimode channel is reviewed. Second, the proposed analytical model is introduced.

A. Physical Model of Multimode Channels

The multimode channels are the $\mathbf{M}$ matrix entries, and the mode coupling matrix $\mathbf{M}$ is a compact representation of the propagation channel independent from the effects of the transmit and the receive antennas as in (2). The multimode channels are defined with respect to the MIMO radio channel representations in both PW and SVW domains.

1) *Radio Channel Representation in PW Domain:* The narrowband channel transfer matrix $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ [39] can be represented by

$$\mathbf{H} = \int \int \mathbf{A}_r(\hat{\mathbf{k}}) \boldsymbol{\alpha}(\hat{\mathbf{k}}, \hat{\mathbf{k}}) \mathbf{A}_t^T(\hat{\mathbf{k}}) d\Omega_r d\Omega_t \quad (3)$$

where N_t and N_r denote the number of transmit and receive antennas, Ω_t and Ω_r are the solid angles subtended by the scatterers as viewed from the transmit and the receive antennas, respectively. $\hat{\mathbf{k}}$ and $\hat{\mathbf{k}}$ are unit vectors oriented in the angle of departure (AoD) $\hat{\mathbf{k}} = [\theta_t, \phi_t]$ and angle of arrival (AoA) $\hat{\mathbf{k}} = [\theta_r, \phi_r]$, respectively. θ_t, θ_r are co-elevation angles, and ϕ_t, ϕ_r are azimuth angles. $\boldsymbol{\alpha}(\hat{\mathbf{k}}, \hat{\mathbf{k}}) \in \mathbb{C}^{2 \times 2}$ is the matrix containing the polarimetric complex gains of a plane wave

$$\boldsymbol{\alpha} = \begin{bmatrix} \alpha_{VV} & \alpha_{VH} \\ \alpha_{HV} & \alpha_{HH} \end{bmatrix}. \quad (4)$$

The vector-valued matrices $\mathbf{A}_t$ and $\mathbf{A}_r$ defined by

$$\begin{aligned} \mathbf{A}_t(\hat{\mathbf{k}}) &= [\mathbf{a}_{t,V}(\hat{\mathbf{k}}) \quad \mathbf{a}_{t,H}(\hat{\mathbf{k}})] \in \mathbb{C}^{N_t \times 2} \\ \mathbf{A}_r(\hat{\mathbf{k}}) &= [\mathbf{a}_{r,V}(\hat{\mathbf{k}}) \quad \mathbf{a}_{r,H}(\hat{\mathbf{k}})] \in \mathbb{C}^{N_r \times 2} \end{aligned} \quad (5)$$

are the array response matrices of the transmit and the receive antennas, respectively. $(\cdot)^T$ denotes vector/matrix transpose.

The narrowband propagation channel in plane wave domain is characterized by parameters $\hat{\mathbf{k}}$, $\hat{\mathbf{k}}$ and $\boldsymbol{\alpha}$. The statistical distributions of these parameters describe the spatial properties of the intrinsic propagation channel. For the polarized behavior of the intrinsic propagation channel, the cross-polarization power ratio (XPR) and the co-polarization power ratio (CPR) [40] are defined in linear scale as:

$$\begin{aligned} \text{XPR} &= 10 \log_{10} \frac{\int \int (|\alpha_{VV}|^2 + |\alpha_{HH}|^2) d\Omega_r d\Omega_t}{\int \int (|\alpha_{HV}|^2 + |\alpha_{VH}|^2) d\Omega_r d\Omega_t}, \\ \text{CPR} &= 10 \log_{10} \frac{\int \int |\alpha_{VV}|^2 d\Omega_r d\Omega_t}{\int \int |\alpha_{HH}|^2 d\Omega_r d\Omega_t}. \end{aligned} \quad (6)$$

For a multipath Rician fading channel, the plane wave parameters can be split into some deterministic dominant path(s) (denoted as "dm") with parameters $\hat{\mathbf{k}}^{\text{dm}}$, $\hat{\mathbf{k}}^{\text{dm}}$ and $\boldsymbol{\alpha}^{\text{dm}}$, and the scattered fading paths (denoted as "fd") with a set of parameters $\hat{\mathbf{k}}^{\text{fd}}$, $\hat{\mathbf{k}}^{\text{fd}}$ and $\boldsymbol{\alpha}^{\text{fd}}$. Note that the dominant path(s) could be composed of a LOS and/or some strong reflected path(s). The ratio of the power of the dominant path(s) over the power of the scattered paths is defined as

$$\gamma = \frac{\int \int |\alpha_{VV}^{\text{dm}}|^2 + |\alpha_{VH}^{\text{dm}}|^2 + |\alpha_{HV}^{\text{dm}}|^2 + |\alpha_{HH}^{\text{dm}}|^2 d\Omega_r^{\text{dm}} d\Omega_t^{\text{dm}}}{\int \int |\alpha_{VV}^{\text{fd}}|^2 + |\alpha_{VH}^{\text{fd}}|^2 + |\alpha_{HV}^{\text{fd}}|^2 + |\alpha_{HH}^{\text{fd}}|^2 d\Omega_r^{\text{fd}} d\Omega_t^{\text{fd}}} \quad (7)$$

where Ω_t^{dm} and Ω_r^{dm} are the channel solid angles as to the dominant path(s), and Ω_t^{fd} and Ω_r^{fd} are for the scattered paths, respectively. $\boldsymbol{\alpha}^{\text{dm}}$ and $\boldsymbol{\alpha}^{\text{fd}}$ are the polarimetric complex gain matrices of the dominant path(s) and the scattered paths, respectively. Because the dominant path(s) could be composed by LOS and/or some strong non-LOS path, the value of γ is estimated from the $\boldsymbol{\alpha}$ of paths of coherent snapshots by the moment method [41] or the maximum likelihood method [42].

2) *Radio Channel Representation in SVW Domain:* The narrowband channel transfer matrix can also be represented as the product of three matrices as in (2), where $\mathbf{M} \in \mathbb{C}^{J_r \times J_t}$, $\mathbf{T} \in \mathbb{C}^{J_t \times N_t}$, and $\mathbf{R} \in \mathbb{C}^{N_r \times J_r}$. J_t and J_r are the numbers of SVW modes of the transmit and receive antennas, respectively. J_t and J_r are determined by the radii r_t and r_r of the minimum circumscribing spheres of the transmit and the receive antennas respectively [12]

$$\begin{aligned} J_t &= 2(\lfloor kr_t \rfloor + n_0) \{(\lfloor kr_t \rfloor + n_0) + 2\} \\ J_r &= 2(\lfloor kr_r \rfloor + n_0) \{(\lfloor kr_r \rfloor + n_0) + 2\} \end{aligned} \quad (8)$$

where λ , $k = \frac{2\pi}{\lambda}$, and $\lfloor \cdot \rfloor$ are the wave length, the wave number, and the floor function, respectively. n_0 is determined by the target accuracy of the spherical wave expansion [12], [43], [44], and $\lfloor kr_t \rfloor + n_0$ (or $\lfloor kr_r \rfloor + n_0$) is often called the truncation number. The (j', ι') -th element of $\mathbf{T}$ represents the coefficient of the j' -th SVW mode of the ι' -th transmit antenna. Similarly, the (ι, j) -th element of $\mathbf{R}$ represents the coefficient of the j -th SVW mode of the ι -th receive antenna. The single indices j' and j are directly related to the triplets $\{\sigma\mu\nu\}$ and $\{smn\}$, respectively [12, p. 15]. $\{\sigma, s\} = 1$ denotes the Transverse Electric (TE) mode, and $\{\sigma, s\} = 2$ denotes the Transverse Magnetic (TM) mode. $\nu = 1, 2, 3, \dots, \lfloor kr_t \rfloor + n_0$ and $n = 1, 2, 3, \dots, \lfloor kr_r \rfloor + n_0$ are mode indices for elevation θ direction, $\mu = -\nu, -\nu+1, \dots, \nu-1, \nu$ or $m = -n, -n+1, \dots, n-1, n$ are for azimuth ϕ direction.

$\mathbf{T}$ can be calculated from the radiation pattern of transmit antenna by the inner product [12, p. 96] or the least square solution [43]. $\mathbf{R}$ of receive antenna can be calculated from $\mathbf{T}$ of receive antenna by reciprocity [12, p. 36].

$\mathbf{M}$ describes the linear relationship between the outgoing and the incoming SVW modes, and it represents the intrinsic propagation channel. Its entry $M_{jj'}$, the multimode channel, represents the radio propagation between the j' -th transmit and j -th receive modes. $\mathbf{M}$ can be transformed from the continuous plane wave channel model parameters by formula [31]:

$$M_{jj'} = (-j)^{n+v+4-s-\sigma} \int \int \mathbf{Y}_{smn}^H(\hat{\mathbf{k}}) \cdot \boldsymbol{\alpha}(\hat{\mathbf{k}}, \hat{\mathbf{k}}) \cdot \mathbf{Y}_{\sigma\mu\nu}(\hat{\mathbf{k}}) d\Omega_r d\Omega_t \quad (9)$$

where the prefix coefficient $(-j)^{n+v+4-s-\sigma}$ corresponds to the far-field spherical Hankel functions. Here the far field SVW functions are used because plane wave is the far-field approximation of spherical waves. The matrix functions

$$\mathbf{Y}_{\sigma\mu\nu}(\hat{\mathbf{k}}) = \begin{bmatrix} \mathbf{y}_{\sigma\mu\nu,V}(\hat{\mathbf{k}}) & \mathbf{y}_{\sigma\mu\nu,H}(\hat{\mathbf{k}}) \end{bmatrix}^T \in \mathbb{C}^{2 \times 1} \quad (10)$$

$$\mathbf{Y}_{smn}(\hat{\mathbf{k}}) = \begin{bmatrix} \mathbf{y}_{smn,V}(\hat{\mathbf{k}}) & \mathbf{y}_{smn,H}(\hat{\mathbf{k}}) \end{bmatrix}^T \in \mathbb{C}^{2 \times 1}$$

are the spherical vector harmonics for far-field patterns, see Appendix A for more details. (9) can be used to estimate the multimode channels using the extracted multipath from the measurement data of channel matrix $\mathbf{H}$, as long as the extracted multipath well represent the 3D spatial dimension information of radio wave propagation. Despite that plane wave parameters are intuitive in linking the radio wave propagation with the geometry of the physical environment, converting them into mathematically complex SVW domain parameters is necessary, for the merits of the mode coupling matrix with entries of multimode channels over the set of plane wave parameters:

- The SVW modes are orthogonal to each other, and the number of necessary dominant modes for representing the propagation channel is determined according to the electrical sizes of the deployed antenna arrays. Hence the SVW multimode channel representation of propagation channel is antenna-friendly. On the contrary, the number of necessary plane waves for representing propagation channel is not only determined by the antenna array radiation patterns, but also by the scatterers/objects in physical environment.
- The multimode channels can be used directly to compute the spatial DoF with the information of the matrix rank, and the DoF calculated by the multimode channels poses an upper-limit of the DoF of radio channels when specific antennas are deployed at link ends [29], [30].
- The multimode channels can be used directly to calculate the intrinsic channel capacity [30], [45]. This capacity depends on the propagation condition and the antenna's electrical size only, and is a more generic estimate that is applicable to various antenna geometries.
- The multimode channels are possible to be measured directly without resorting to the intermediate plane wave representation. Although it needs dedicated design on

the antenna array configuration [38] and/or the excitation currents for each array element [36], the direct measuring of the multimode channels has potential to involve not only the dominant multipath but also the dense multipath like diffuse scattering [46].

B. Proposed Analytical Model of Multimode Channels

1) *Rician Fading Channel Representations*: A conventional Rician fading channel involves the effects of antennas at link ends, and indicates that some of the multi-paths with antenna directivity involved is/are much stronger than the others. The Rician K -factor is classically computed by the method of moments or the maximum likelihood estimate from the time series of the measurable CTF $\mathbf{H}$. In case that 1) different multi-antenna channels have different channel gains, and 2) different multi-antenna channels experience different small-scale statistics, the Rician K -factor can be calculated for each entry of $\mathbf{H}$ and may differ from entry to entry [10].

Although the Rician K -factor or the Rician fading is a concept usually employed for plane wave channel modeling, due to the equivalence between PW and SVW channel representations in (9) when continuous plane wave spectrum is applied, multimode channels in time series or in coherent snapshots can also be characterized by Rician distribution. As in (9), each SVW mode can be imagined as one "antenna" (please refer to Fig. 1 for examples of patterns of spherical harmonics for different modes). The distinctions between multimode channels and multi-antenna channels are that:

- the mode patterns form the orthogonal set for representing any antenna patterns, and the multimode channels are generic and applicable to various antenna geometries;
- the multi-antenna channels are antenna-specific.

To statistically model the multimode channels in the spatio-temporal frequency domains, $\mathbf{M}$ of different frequency samples and different temporal samples needs to be estimated. As was mentioned above, $\mathbf{M}$ can be estimated from the measurable $\mathbf{H}$ directly with dedicated design of array configuration [38], or even be measured with dedicated design on excitation currents to array elements [36]. However, these methods have not been implemented in real-world scenarios with extensive measurement campaigns. Alternatively, the estimation of $\mathbf{M}$ using intensive plane wave parameters extracted from real-world measurements through (9) can work, as long as these parameters are extracted by super resolution algorithm with refined resolution of array patterns, from the measured channels when the arrays used cover 3D spatial domain and dual polarizations.

It has been first theoretically shown in [20], [31] that different multimode channels have different gains and their small-scale fading has varying Rician K -factors. In later chapters, the important statistical behaviors of multimode channels will be verified by the measurement-based investigations. In addition to above mentioned properties, it will also be shown that the multimode channels differ in auto- and cross-correlations.

2) *Proposed Analytical Model*: The statistical characteristics of the multimode channels of $\mathbf{M}$ matrix entries turn out to be similar to the characteristics of the multi-antenna channels

Fig. 1. Examples of the patterns of the first 16 modes of spherical harmonics (phase information is not shown)

of channel transfer matrix $\mathbf{H}$ in WPAN [10]. The PAN channel in [10] models a general Rician fading channel where the antenna configurations at link ends are irregular and a subset of the antenna elements are subject to efficiency degradation due to human interaction. The analytical multi-antenna channel model for the $\mathbf{H}$ matrices in PAN is proposed to be applied to describe the analytical multimode channel for the $\mathbf{M}$ matrices.

Therefore, by analogy, we extend the antenna-specific $\mathbf{H}$ matrix model for WPAN to the antenna-generic $\mathbf{M}$ matrix model for general cases of Rician channel. The analytical expression for the $\mathbf{M}$ matrix is given by

$$\mathbf{M} = [\mathbf{P}]^{\frac{1}{2}} \odot [\psi_1(\mathbf{K}) \odot \hat{\mathbf{M}}^{\text{dm}} + \psi_2(\mathbf{K}) \odot \hat{\mathbf{M}}^{\text{fd}}], \quad (11)$$

where

$$\mathbf{P} = \mathbf{P}^{\text{com}} \mathbf{P}^{\text{rel}} \quad (12)$$

$$\psi_1(\mathbf{K}) = [\mathbf{K} \odot [\mathbf{1} + \mathbf{K}]^{-1}]^{\frac{1}{2}}, \quad (13)$$

$$\psi_2(\mathbf{K}) = [\mathbf{1} + \mathbf{K}]^{-\frac{1}{2}}, \quad (14)$$

$$\hat{\mathbf{M}}^{\text{fd}} = \text{unvec} \left(\{ \mathbf{R}_{\mathbf{M}^{\text{fd}}} \}^{\frac{1}{2}} \mathbf{G} \right), \quad (15)$$

$[\cdot]^{\frac{1}{2}}$ and $[\cdot]^{-1}$ denote the element-wise square root and the element-wise inverse -1 , respectively. $\{\cdot\}^{\frac{1}{2}}$ denotes the matrix square root. $\mathbf{1}$ denotes the $J_r \times J_t$ matrix consisting of all ones. $\mathbf{G} \in \mathbb{C}^{J_r J_t \times 1}$ is populated with the complex Gaussian entries with unit variance. $\text{unvec}(\cdot)$ is the inverse operation to $\text{vec}(\cdot)$, and it changes the vector of dimension $J_r J_t \times 1$ to the matrix of dimension $J_r \times J_t$. The different matrix parameters needed for the proposed model are defined as follows:

- 1) $\mathbf{P} \in \mathbb{R}^{J_r \times J_t}$ is a matrix with entries $P_{jj'} = P^{\text{com}} P_{jj'}^{\text{rel}}$ containing the average power of jj' -th multimode channel defined by

$$P^{\text{com}} = \frac{1}{N_{\text{corr}, \text{snap}} J_r J_t} \sum_{i=1}^{N_{\text{corr}, \text{snap}}} \sum_{j'=1}^{J_t} \sum_{j=1}^{J_r} |M_{jj'}^i|^2, \quad (16)$$

$$P_{jj'}^{\text{rel}} = \frac{1}{N_{\text{corr}, \text{snap}}} \sum_{i=1}^{N_{\text{corr}, \text{snap}}} \frac{|M_{jj'}^i|^2}{P^{\text{com}}},$$

where P^{com} denotes the large-scale effects of the distance decay and shadowing that are common to all multimode channels, and $P_{jj'}^{\text{rel}}$ is the relative individual gain for different multimode channels. $N_{\text{corr}, \text{snap}}$ denotes the number of coherent snapshots.

- 2) $\mathbf{K} \in \mathbb{R}^{J_r \times J_t}$ is a matrix with entries $K_{jj'}$ defining the Rician K -factors of the envelope of the power-normalized multimode channels in coherent snapshots (time series). The normalized multimode channel is denoted by $\hat{M}_{jj'}$ and calculated according to

$$\hat{M}_{jj'} = \frac{M_{jj'}}{\sqrt{P_{jj'}}}. \quad (17)$$

- 3) $\hat{\mathbf{M}}^{\text{dm}} \in \mathbb{C}^{J_r \times J_t}$ is the element-wise normalized deterministic part of the $\mathbf{M}$ matrix, and can be estimated from

$$\mathbf{M}^{\text{dm}} = [-\mathbf{Y}_1(\hat{\mathbf{k}}^{\text{dm}}), \dots, (-j)^{n+2-s} \mathbf{Y}_j(\hat{\mathbf{k}}^{\text{dm}}), \dots, (-j)^{[kr_r] + n_0} \mathbf{Y}_{J_r}(\hat{\mathbf{k}}^{\text{dm}})]^H \cdot [-\mathbf{Y}_1(\hat{\mathbf{k}}^{\text{dm}}), \dots, (-j)^{v+2-\sigma} \mathbf{Y}_{j'}(\hat{\mathbf{k}}^{\text{dm}}), \dots, (-j)^{[kr_t] + n_0} \mathbf{Y}_{J_t}(\hat{\mathbf{k}}^{\text{dm}})] \quad (18)$$

where $\hat{\mathbf{k}}^{\text{dm}} = [\theta_t^{\text{dm}}, \phi_t^{\text{dm}}]$, $\hat{\mathbf{k}}^{\text{dm}} = [\theta_r^{\text{dm}}, \phi_r^{\text{dm}}]$ indicates the dominant AoD and dominant AoA directions, respectively. (18) is based on the fact that SVW modes are orthogonal to each other and weighted SVW modes are linearly combined for representing radiation property. Our idea is that $\mathbf{M}^{\text{dm}}$ is deterministic and can be determined from link application scenario. In practice, the angular information of the dominant paths can be obtained by searching the peak of the power angular spectrum given by the beamforming [40] of $\mathbf{H}$ that we usually measure in channel sounding.

- 4) $\mathbf{R}_{\mathbf{M}^{\text{fd}}} \in \mathbb{R}^{J_t J_r \times J_t J_r}$ is the full cross-mode correlation of the vectorized form of $\hat{\mathbf{M}}^{\text{fd}}$ defined by

$$\mathbf{R}_{\mathbf{M}^{\text{fd}}} = \mathbb{E} \left\{ \text{vec} \left(\hat{\mathbf{M}}^{\text{fd}} \right) \text{vec}^H \left(\hat{\mathbf{M}}^{\text{fd}} \right) \right\}, \quad (19)$$

and can be used to generate $\hat{\mathbf{M}}^{\text{fd}} \in \mathbb{C}^{J_r \times J_t}$ that is the element-wise normalized stochastic part of the $\mathbf{M}$ matrix, i.e.

$$\mathbf{M}^{\text{fd}} = \mathbf{M} - \mathbf{M}^{\text{dm}}. \quad (20)$$

The multi-antenna channel model presented in [10] takes into account the specific stochastic behavior of the Rician

fading WPAN channel. Extending this model to a more general Rician fading multimode channel in the SVW domain **broadens the applicability of the presented equations to model virtually any wireless channel** by the proper choice of the matrix functions P , K , $\hat{M}^{\text{dm}}$ and $R_{M^{\text{rd}}}$ introduced above. Since the multimode channel model is antenna-generic, the impact of any antenna array geometries (with proper setting of electrical size) on the radio propagation channel can be evaluated. The next step is to parameterize P , K , $R_{M^{\text{rd}}}$ as well as the estimation of $\hat{M}^{\text{dm}}$. Moreover, in order to make an appropriate use of the presented analytical model, the statistical behaviors in specific propagation environment must be understood. From which, antenna system with optimized performance tailored to the specific environment can be devised.

III. MEASUREMENT-BASED BEHAVIOR ANALYSIS OF MULTIMODE CHANNELS

In order to demonstrate and validate the stochastic behavior as in proposed model (11), we now proceed to estimate the statistical properties of multimode channels based on measurement data. To gather the appropriate set of M representing the time series of coherent fading statistics of multimode channels, each realization of M matrix is obtained from (9). It is an indirect method because we go through the relationship (9) instead of using the direct de-embedding approach outlined in [36], [38]. The plane wave channel model parameters used in (9) are extracted from the 5.3 GHz MIMO urban microcellular radio channel measurements in downtown Helsinki.

The measurement system covers 3-D directions and two-orthogonal polarizations of the waves at both the transmit and the receive antennas using 32×32 channels [47], [48]. The transmit antenna array is the 4×4 uniform rectangular array with 45° slanted patch elements, the receive antenna array is the semi-spherical array with microstrip patch elements. Their radii of both arrays are equal to $0.8\lambda_c$, where λ_c is the wavelength at center frequency. A map of the measurement area and the measurement routes is given in Fig. 2. The average street width is approximately 15 m, and the height of most buildings is in the range of 20-30 m. The transmit antennas were located at a height of 10 meters representing a micro-cell scenario. The receive antennas were kept at a height of 1.6 m moving along the sidewalks of different streets to create the different routes.

The derivation of the statistics of multimode channels in the following sections is based on a subset of data taken from the LOS and the Non-LOS (NLOS) routes. Routes 1–5 are NLOS routes (some short parts of route 2 and 5 are exposed to LOS), and route 6 is completely LOS. In NLOS routes, the receiver terminal moved along streets perpendicular to the main street where the transmitter was located. In the LOS route, the receiver terminal moved along the main street where the direct LOS component between the transmit antennas exists.

The extracted plane wave channel model parameters include the AoD, the AoA, the polarimetric complex gain α , and the delay τ (wideband parameter). The parameter estimation was accomplished by the initialization and search improved space-

Fig. 2. Measuring routes of 5.3 GHz micro-cell radio channel measurement in downtown Helsinki

alternating generalized expectation maximization (ISIS or ISI-SAGE) algorithm [49]. Given that we focus on the spatial structure of multimode channels, parameters AoD, AoA, α corresponding to the coherent snapshots are used to simulate the wide-sense stationary (WSS) process.

During the measurement, the speed² traveled by the receive antenna was about 0.2 m per second, and the data collection by the channel sounder was maximally about 15 snapshots per second. Now we determine the coherent snapshots. As is shown in Table I, the coherent snapshots are determined according to the large-scale power, the XPR, the CPR, the rms delay spread [40], and the angular spread calculated from the plane wave channel model parameters. The coherence is defined such that the autocorrelation of the above mentioned factors is no less than $\frac{1}{e}$. Note that in the calculation of the angular spread, the complex angle technique [50] which is the unambiguous definition of angles on a circle is used in order to avoid overestimation. Furthermore, the coherent snapshots for each route are chosen as the least amongst the five parameters, which are marked bold in Table I. For a fair characterization of the statistics of the multimode channels for all routes, we choose the least value (marked red) among all routes as the number of the subset of coherent snapshots. We then simulate the WSS process of multimode channels from the AoD, AoA, α of correlated snapshots. The average power, the fast fading, the auto- and cross-correlations of the multimode channels are analyzed.

A. Power imbalance and auto-correlation of multimode channels

The average power of multimode channels on coherent snapshots is calculated by (16). When a route has totally N_{snap} snapshots and the number of the coherent snapshots is $N_{\text{corr,snap}}$, the number of coherent series/subsections one can obtain is $N_{\text{snap}} - N_{\text{corr,snap}} + 1$.

²During this particular outdoor channel MIMO channel measurements, the sounder was triggered at 14.3 Hz, i.e., at every 69.9 ms, for the purpose of limiting the incoming data to the harddisk. The sounder could have been triggered with much faster speed at every 8.7 ms [47], but we did not opt for the option to avoid filling the disk space quickly. We mentioned this in the footnote of Section x; the inserted text is shown below.

TABLE I
NUMBER OF CORRELATED SNAPSHOTS ΔT AND CORRESPONDING COHERENT DISTANCE Δd FOR DIFFERENT CHANNEL PARAMETERS AT THE DIFFERENT MEASUREMENT ROUTES

Indicating parameter	Route index	1		2		3		4		5		6	
	Scenario	NLOS											
		ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]
		LOS											
		ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]	ΔT	Δd [m]
	Power	235	3.1	779	10.4	291	3.9	460	6.1	440	5.9	407	5.4
	XPR	95	1.3	25	0.3	125	1.7	152	2.0	22	0.3	39	0.5
	CPR	39	0.5	20	0.3	21	0.3	19	0.3	21	0.3	42	0.6
	RMS delay spread	156	2.1	945	12.6	548	7.3	669	8.9	629	8.4	461	6.1
	Elevation angular spread	44	0.6	24	0.3	406	5.4	40	0.5	50	0.7	472	6.3
	Azimuth angular spread	59	0.8	295	3.9	91	1.2	325	4.3	422	5.6	386	5.1

Fig. 3. Considering dipole modes with truncation number as 1 so that the modes number is up to 6: (a) P^{com} of all coherent series of all routes where each coherent series contains 19 snapshots or 0.253 m (b) max., min., mean, var. of P^{rel} among entries of all coherent series of all routes (c) example of power imbalance among multimode channels for the 88-th coherent series of route 1 (d) example of power imbalance among multimode channels for the 88-th coherent series of route 6

For multimode channels with modes number up to 6, i.e. the truncation number in SVW expansion [12] is 1 (dipole modes), Fig. 3 (a) and (b) show P^{com} and P^{rel} for all routes, respectively. In Fig. 3 (a), P^{com} of multimode channels in all coherent series of all routes indicates the relative power decay according to distance and shadowing. Fig. 3 (b) shows the maximum (abbr. max.), the minimum (abbr. min.), the mean, and the variation (abbr. var.) of P^{rel} among different multimode channels. Accordingly, Table II shows the average among each route for the above mentioned P^{rel} power imbalance factors. As can be observed, the max. ranges from 5.4 dB to 6.2 dB, the min. ranges from -49 dB to -34 dB, the mean ranges from -12 dB to -8 dB, and the var. ranges from 11 dB to 16 dB. The power imbalance range is very similar, and the maxima of the relative power among different multimode channels is about the same. For demonstration purpose, Fig. 3 (c) and (d) show two examples of the relative power. A power imbalance between the coupling of different SVW modes at the transmitter and the receiver can be clearly observed, as was predicted in [31].

TABLE II
POWER IMBALANCE OF P^{rel} AMONG ENTRIES

Route index	1	2	3	4	5	6
Max. [dB]	5.6	5.5	6.0	5.4	5.4	6.2
Min. [dB]	-35.5	-33.8	-38.6	-49.2	-47.5	-41.0
Mean [dB]	-8.0	-7.9	-10.2	-12.5	-11.9	-10.7
Var. [dB]	11.5	11.2	12.8	16.2	15.6	13.6

Referring to Fig. 1, interestingly, due to the symmetry of the SVW harmonics patterns of modes 1 (TE) and 5 (TE) to that of the mode 3 (TE), the symmetry of the modes 2 (TM) and 6 (TM) to that of the mode 4 (TM), the resulting relative power imbalance seems symmetric to the center mode-to-mode links whose mode indices for azimuth ϕ direction are 0, as are shown in Fig. 3 (c) and (d). The multimode channels mapping the mode $j' = \{1, 2, 5, 6\}$ at Tx side to the mode $j = \{1, 2, 5, 6\}$ at Rx side have similar relative power level, the multimode channels mapping the mode $j' = \{3, 4\}$ at Tx side to the mode $j = \{3, 4\}$ at Rx side have similar relative power level. It is observed that the relative power imbalance depends on the azimuth mode index m and μ .

In addition, the practical channels in the perspective of PW channel modeling are composed of paths lying in between one extreme with isotropic paths and the other extreme with random LOS path only. On one hand, with isotropic paths where the AoA and AoD follow uniform distribution on sphere, and the polarimetric gain with similar envelope for all paths forming CPR close to 0 dB and XPR no less than 10 dB, the resulting M should have orthogonal power imbalance patterns [12]. On the other hand, with random LOS path only, the power imbalance of multimode channels depends mostly on the elevation AoA θ_r and elevation AoD θ_t angles. When θ_r and θ_t are close to the north or south pole, the multimode channels with couplings between modes 1, 2, 5, 6 have higher power levels than those between modes 3, 4, according to the SVW harmonics patterns shown in Fig. 1 and their definition functions in Appendix A. Since the azimuth angle only affects the phase of SVW harmonics, the power imbalance of multimode channels does not depend much on azimuth AoA and AoD when there is only LOS. From above, the power imbalance of multimode channels reflects the angular distributions at link ends. However, the practical channels lie between the above mentioned two extremes, and the angular information that can be observed from power imbalance in Fig. 3 (c) and (d) is limited.

Fig. 4. Autocorrelation (ACF) of power of multimode channels along (a) route 1 (b) route 2 (c) route 3 (d) route 4 (e) route 5 (f) route 6

Furthermore, the correlations of the power of the multimode channels (considering modes up to 6 at both ends) along the successive coherent series for all routes are analyzed. As are shown in subfigures of Fig. 4, the multimode channels pairing different SVW modes at both link ends are correlated with varying coherent distances. The details of the coherent distances of multimode channels in different routes are summarized in Table III, where distinct values of the same transmitting-receiving mode pair can be observed for different routes. The longer the coherent distance, the more stable the multimode channel is. This observation can be reflected in the antenna system design for this site-specific propagation environment, so that the modes with larger coherent distance and larger power should be excited.

B. Fast fading and auto-correlation of multimode channels

To investigate the fluctuations of multimode channels corresponding to the fast fading, the cumulative distribution function (CDF) of its envelope among coherent snapshots is studied. The power normalization of each multimode channel is applied before analyzing the CDF.

Here the Rician distribution is applied to the envelope of normalized multimode channels. The reason why choosing the Rician distribution is the Gaussianity of the PAS [31], [51], [52]. The Rician K -factor for each multimode channel in coherent snapshots is calculated by the moment method [41]. For reference, γ in (7) is also estimated in coherent snapshots by the moment method. The Kolmogorov-Smirnov (KS) test is used to test the null hypothesis that the fitted Rician CDF and the empirical CDF are drawn from the same underlying continuous population. Note that for NLOS scenario, γ is not necessarily a small value, especially when there are coherent power among paths in the coherent snapshots.

Fig. 5 shows two examples of the empirical CDFs and the fitted Rician CDFs. In both cases, the KS test could not reject the null hypothesis at 5% significance level for all the considered multimode channels. For the 88-th coherent series of route 1 in Fig. 5 (a) and (c), the γ estimated from the PW paths is about 26.7 dB, while the max. K -factor among the multimode channels is 7.9 dB (6.2 in linear) and is for the multimode channel coupling between the mode 6 at Rx to the mode 3 at Tx. For the 88-th coherent series of route 8

TABLE III
COHERENT DISTANCES (IN METER) OF POWER OF MULTIMODE CHANNELS

Route 1	j	1	2	3	4	5	6
j'							
1		1.97	1.96	2.05	3.35	3.71	3.69
2		1.99	1.97	0.91	3.33	3.71	2.69
3		2.91	2.92	2.32	1.77	3.29	3.27
4		3.65	3.64	2.71	3.65	3.65	3.53
5		3.37	3.40	1.39	2.40	1.59	1.57
6		3.37	3.40	1.40	2.41	1.57	1.56
Route 2	j	1	2	3	4	5	6
j'							
1		4.31	4.29	2.84	5.60	5.88	5.92
2		4.32	4.31	2.88	5.57	5.87	5.91
3		1.99	1.93	1.77	1.91	2.19	1.88
4		8.53	8.59	6.81	6.93	9.79	9.89
5		5.80	5.83	6.03	4.01	9.60	8.49
6		5.80	5.83	6.01	3.99	9.63	8.52
Route 3	j	1	2	3	4	5	6
j'							
1		2.73	2.79	0.53	0.40	0.37	0.39
2		2.75	2.80	0.52	0.40	0.37	0.39
3		1.81	0.77	2.61	0.39	0.37	0.37
4		0.95	0.89	0.56	1.00	0.60	0.59
5		0.39	0.39	0.41	0.44	3.21	3.17
6		0.39	0.39	0.41	0.45	3.20	3.15
Route 4	j	1	2	3	4	5	6
j'							
1		3.13	3.13	1.12	0.47	2.72	2.72
2		3.13	3.13	1.12	0.47	2.72	2.72
3		1.57	1.56	0.51	4.56	1.47	1.47
4		4.25	4.25	1.57	0.99	6.04	6.04
5		2.21	2.21	0.71	1.17	3.68	3.68
6		2.20	2.20	0.71	1.17	3.68	3.68
Route 5	j	1	2	3	4	5	6
j'							
1		5.19	5.09	6.11	6.25	4.48	4.48
2		5.16	5.07	6.11	6.25	4.48	4.48
3		6.85	6.85	6.44	5.85	6.85	6.85
4		6.80	6.83	3.55	6.17	7.07	7.11
5		4.40	4.40	4.59	5.09	5.83	5.84
6		4.40	4.40	4.59	5.08	5.83	5.83
Route 6	j	1	2	3	4	5	6
j'							
1		0.73	0.73	6.09	0.39	0.67	0.65
2		0.73	0.73	6.11	0.39	0.67	0.65
3		0.67	0.65	0.77	0.87	0.65	0.65
4		0.57	0.57	4.21	0.55	0.61	0.61
5		1.36	1.40	2.95	0.37	0.59	0.59
6		1.35	1.39	2.93	0.37	0.59	0.59

in Fig. 5 (b) and (d), the γ estimated from the PW paths is about 21.1 dB, while the max. K -factor among the multimode channels is 12.3 dB (17.1 in linear) and is for the multimode channel coupling between the mode 1 at Rx to the mode 1 at Tx.

Fig. 6 and Fig. 7 show the max. Rician K -factor among multimode channels (considered mode number up to 6) for each route, and the γ calculated from the PW channel model parameters in coherent series of each route is also shown for reference. The max. K -factors among multimode channels of all the coherent series in the LOS route 6 range from 6.6 dB to 26.8 dB, while the max. K -factor values for route 1, 2, 4, 5 range from 2 dB to 20 dB and that for route 3 ranges from 0 dB to 25 dB. The NLOS routes that have large values of K -factor for certain mode-to-mode coupling are probably due to the highly coherent multipath diffracted from building corners. Furthermore, the auto-correlations of the K -factor of

Fig. 5. Considering dipole modes with truncation number as 1 so that the modes number is up to 6: example of (a) the CDF and its Rician fitting (c) the Rician K -factors of the envelopes of multimode channels for the 88-th coherent series of route 1; example of (b) the CDF and its Rician fitting (d) the Rician K -factors of the envelopes of multimode channels for the 88-th coherent series of route 6

the multimode channels (considering modes up to 6 at both ends) along the successive coherent series for all routes are analyzed. Fig. 8 and Table IV show the results. Similarly as observed in Fig. 4, the multimode channels pairing different SVW modes at both link ends are correlated with varying coherent distance. In particular, in route 4, mode links pairing $j' = 3$ and $j = \{1, 2, 5, 6\}$ are with extremely high coherent lengths in K -factor, but this is not the case for the same mode links in the autocorrelation of power levels.

Now we check whether the Rician K -factor for multimode channels are correlated with the relative power level. Fig. 9 shows the correlation coefficient between $P_{jj'}^{\text{rel}}$ and $K_{jj'}$ for different multimode channels of all routes. The number of multimode channels where the correlation coefficient is above 0.5 is 4, 6, 2, 5, 0, 16 for route 1 – 5 respectively. LOS route 6 has relatively larger probability that the mode coupling relative power is correlated with the mode coupling fading property.

Fig. 6. CDF of the max. K -factor of all routes

As can be seen from above, the fluctuations/fading of multimode channels depend on the propagation conditions, and the interactions between different modes at Tx and Rx sides

TABLE IV
COHERENT DISTANCES (IN METER) OF K -FACTOR OF MULTIMODE CHANNELS

Route 1	j	1	2	3	4	5	6
j'							
1		0.17	0.19	0.35	0.15	0.44	0.44
2		0.17	0.19	0.32	0.15	0.47	0.47
3		0.25	0.24	0.16	0.16	0.19	0.19
4		0.23	0.24	0.13	0.19	0.17	0.17
5		0.77	0.75	0.40	0.16	0.59	0.57
6		0.79	0.76	0.40	0.16	0.57	0.57
Route 2	j	1	2	3	4	5	6
j'							
1		0.12	0.12	0.20	0.15	0.24	0.24
2		0.13	0.12	0.20	0.15	0.25	0.25
3		0.73	0.73	0.43	0.88	0.68	0.67
4		0.23	0.21	0.15	0.17	0.25	0.25
5		0.31	0.35	0.21	0.19	0.15	0.15
6		0.31	0.33	0.20	0.17	0.15	0.16
Route 3	j	1	2	3	4	5	6
j'							
1		1.76	1.73	0.20	0.19	0.15	0.15
2		1.76	1.73	0.20	0.19	0.15	0.15
3		0.33	0.32	0.32	0.17	0.31	0.29
4		0.27	0.28	0.20	0.20	0.33	0.39
5		0.15	0.15	0.29	0.17	2.13	2.04
6		0.15	0.15	0.29	0.17	2.12	2.01
Route 4	j	1	2	3	4	5	6
j'							
1		2.36	2.36	0.16	0.15	0.21	0.21
2		2.36	2.36	0.16	0.15	0.21	0.21
3		6.16	6.13	0.20	0.16	6.60	6.60
4		0.29	0.29	0.23	0.15	0.16	0.16
5		0.23	0.23	0.21	0.15	2.08	2.09
6		0.23	0.23	0.21	0.15	2.07	2.08
Route 5	j	1	2	3	4	5	6
j'							
1		0.13	0.13	0.15	0.21	0.24	0.24
2		0.13	0.13	0.13	0.21	0.24	0.24
3		0.20	0.20	0.11	0.11	0.20	0.20
4		0.17	0.16	0.15	0.13	0.15	0.15
5		0.21	0.20	0.15	0.39	0.16	0.16
6		0.20	0.20	0.15	0.40	0.16	0.16
Route 6	j	1	2	3	4	5	6
j'							
1		0.71	0.68	0.44	0.24	0.39	0.39
2		0.72	0.69	0.44	0.24	0.39	0.39
3		0.29	0.31	0.23	0.15	0.28	0.29
4		0.32	0.32	0.23	0.19	0.33	0.33
5		0.23	0.21	0.35	0.21	0.28	0.24
6		0.23	0.23	0.35	0.21	0.28	0.24

contribute individually to the overall scattering interaction in each propagation scenario. Hence, it is reasonable to model the K -factors of multimode channels in analogy to the method in modeling the K -factors of multi-antenna channels in WPAN [10]. The phenomenon of different K -factors for different multimode channels implies that, each multimode channel can be analytically separated into a dominant part and a fading part. Hence, the power normalized multimode channel can be modeled as

$$\hat{M}_{jj'} = \sqrt{\frac{K_{jj'}}{1 + K_{jj'}}} \hat{M}_{jj'}^{\text{dm}} + \sqrt{\frac{1}{1 + K_{jj'}}} \hat{M}_{jj'}^{\text{fd}} \quad (21)$$

where $\hat{M}_{jj'}^{\text{dm}}$ and $\hat{M}_{jj'}^{\text{fd}}$ are the power normalized deterministic dominant component and the scattered fading component defined by (17), (18), (20).

Fig. 7. The γ of the PW channel model parameters calculated by the moment method and the max. Rician K -factor of multimode channels calculated by the moment method for the successive coherent series in (a) route 1 (KS test failure rate 0.01%) (b) route 2 (KS test failure rate 0.05%) (c) route 3 (KS test failure rate 0.13%) (d) route 4 (KS test failure rate 0.14%) (e) route 5 (KS test failure rate 0.18%) (f) route 6 (KS test failure rate 0.10%)

C. Cross-correlation of multimode channels

In addition to the envelope and the fading statistics, the cross-correlation of the multimode channels among different couplings of SVW modes is also essential to fully describe the multimode channel behavior.

First, the cross-correlation among normalized multimode channels is studied, regardless of the separation of the dominant and the scattered parts. Fig. 10 (a) and (b) show two examples. It can be observed that the example in Fig. 10 (b) has more cross-correlated multimode channels than that in (a).

Next, the separation of the dominant and the scattered parts of normalized multimode channels is implemented. According to (18), we assume $[\theta_t^{\text{dm}}, \phi_t^{\text{dm}}]$ and $[\theta_r^{\text{dm}}, \phi_r^{\text{dm}}]$ are determined according to the peak of the double-directional beamforming of the measurable CTF [40] for both LOS and NLOS scenarios. Fig. 10 (c) and (d) show the examples of the cross-correlations of the scattered part of multimode channels. This cross-correlation can be used to stochastically generate their ensembles, and that's why it is in the analytical modeling of the stochastic behavior of multimode channels in the proposed model (11). It is interesting to observe that there are certain multimode channels, in addition to the matrix diagonal, that are always correlated, even for the route 1 and the route 6 that

Fig. 8. Autocorrelation of K -factor of multimode channels along (a) route 1 (b) route 2 (c) route 3 (d) route 4 (e) route 5 (f) route 6

have different propagation environments. From the common cross-correlated entries of the full correlations among multimode channels for different routes, it is found that the 6 receive SVW modes are all correlated with the first 2 transmit modes. In fact, the same cross-correlated multimode channels are observed in other routes and sub-series as well. This provides us valuable hint for system design and performance, where those cross-correlated multimode channels are not favorable in order to combat against fading.

From above, the proposed analytical model summarized the measurement-based statistical behaviors of multimode channels. In the perspective of system design, the favorable antenna systems at link ends in site-specific propagation environment can excite the SVW modes whose couplings are less cross-correlated, higher auto-correlated, and with higher power according to the knowledge of multimode channel statistics. One method to excite the specifically desired modes is using the cubic [36] or the spherical [38] array configurations where the amplitude and phase of the excitation currents can be tuned to individual antenna elements. The excitation currents can be calculated through point matching [36] to the desired mode pattern.

IV. CONCLUSION

This paper analyzed the statistical behaviors of multipath propagation channels in spherical vector wave domain, i.e. the multimode channels. A narrowband analytical model was summarized from the observations of multimode channels in an urban microcellular environment. The statistical behaviors, namely the average power, the Rician K -factor, the auto- and cross-correlations, were investigated showing the following trends:

- the multimode channels are power imbalanced for different mode-to-mode couplings;
- the multimode channels have varying small-scale statistics, i.e. varying Rician K -factors;
- the multimode channels have auto-correlations with varying coherent distances;
- the multimode channels have varying cross-correlations.

The analytical model of the multimode channel was derived following the model of the multi-antenna radio channel of wireless personal area networks because of its best fit to the statistical behaviors of measured reality. Each multimode channel under Rician fading is divided into a dominant part

Fig. 9. Correlation coefficient between P_{jj}^{rel} and $K_{jj'}$ for (a) route 1 (b) route 2 (c) route 3 (d) route 4 (e) route 5 (f) route 6

and a stochastic fading part modeled by correlation. Since the multimode channels are antenna-generic, the site-specific statistical behaviors provide hints on antenna system design. The SVW modes at link ends whose couplings are with higher relative power, longer coherent distance, and less cross-correlation are favorable; the antennas shall be designed such that these modes are excited to combat attenuation, maintain stability, and combat fading.

The exciting applications of this work are mainly as follows. First, to directly estimate the spatial DoF from multimode channels in temporal-spatial transitions of environment. This estimation on Spatial DoF poses an upper-limit of the DoF of radio channels with specific antennas deployed at link ends. Second, to directly estimate the intrinsic channel capacity which depends on the propagation condition and the antennas' electrical size only. The intrinsic capacity is a generic estimation that is applicable to various antennas geometries. Third, to optimize the antenna (array) system by adjusting array configuration and/or complex-valued excitation currents of antenna elements to excite only the favorable SVW modes whose interactions with radio propagation environment present higher power level, higher auto-correlation, and lower cross-correlation.

Fig. 10. Cross correlation of **normalized multimode channels**, considering up to 6 modes at each link end, therefore the full correlation of the 6×6 multimode channels results in a correlation matrix with dimension 36×36 : (a) an example of the 88-th coherent series in route 1 (b) an example of the 88-th coherent series in route 6; Cross correlation of **normalized scattered parts of multimode channels**: (c) an example of the 88-th coherent series in route 1 (d) an example of the 88-th coherent series in route 6

APPENDIX A SPHERICAL VECTOR HARMONICS

The spherical vector harmonics are defined as follows:

$$\mathbf{y}_{smn,V}(\theta, \phi) = \tilde{\mathbf{y}}_{smn}(\theta, \phi) \cdot \hat{\boldsymbol{\theta}} \quad (22)$$

$$\mathbf{y}_{smn,H}(\theta, \phi) = \tilde{\mathbf{y}}_{smn}(\theta, \phi) \cdot \hat{\boldsymbol{\phi}}$$

$$\tilde{\mathbf{y}}_{1mn}(\theta, \phi) = q_{mn} \left[\frac{-jm\bar{P}_n^{|m|}(\cos \theta)}{\sin \theta} \cdot \hat{\boldsymbol{\theta}} - \frac{d\bar{P}_n^{|m|}(\cos \theta)}{d\theta} \cdot \hat{\boldsymbol{\phi}} \right] \quad (23)$$

$$\tilde{\mathbf{y}}_{2mn}(\theta, \phi) = q_{mn} \left[\frac{d\bar{P}_n^{|m|}(\cos \theta)}{d\theta} \cdot \hat{\boldsymbol{\theta}} + \frac{-jm\bar{P}_n^{|m|}(\cos \theta)}{\sin \theta} \cdot \hat{\boldsymbol{\phi}} \right] \quad (24)$$

$$q_{mn} = \sqrt{\frac{2}{n(n+1)}} \left(-\frac{m}{|m|} \right)^m e^{-jm\phi} \quad (25)$$

where $\bar{P}_n^{|m|}(\cos \theta)$ is the normalized associated Legendre function defined in [12, p. 318].

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