A Generic Validation Framework for Wideband MIMO Channel Models

Yu Zhang*†, Jianhua Zhang†, Guangyi Liu‡, Xinying Gao† and Ping Zhang*
* Key Lab. of Universal Wireless Communications (Beijing Univ. of Posts and Telecom.), Ministry of Education
Email: zhangyu@mail.wtilabs.cn, pzhang@bupt.edu.cn
† Wireless Technology Innovation Institute, Beijing Univ. of Posts and Telecom., P.O. Box #92, China, 100876
Email: jhzhang@bupt.edu.cn, gaoxinying@mail.wtilabs.cn
‡ Research Institute of China Mobile, Beijing, China, 100053
Email: liuguangyi@chinamobile.com

***Abstract*—In this paper, a generic framework for validating wideband MIMO channel models based on channel measurement results is proposed. The framework is formulated as a series of continuous functions (metrics) and a definition of distance of continuous function space (degree of approximation). The metrics characterize the MIMO channel from different perspectives, and the distance provides a quantiative measure of the degree of approximation for the specified model. Several fundamental metrics which reflect the spatial multiplexing gain, diversity capability, time and frequency variability, are derived for exploring the frequency-selective fading property. Based on an extensive measurement campaign at 5.25 GHz, the propagation channel is reconstructed by a WINNER-like model. The metrics are calculated from both the model generated channel realizations and the measured impulse response as a demonstration. The proposed framework can be applied to compare different channel models and to evaluate the simplified version of channel models.**

I. Introduction

Multiple-Input Multiple-Output (MIMO) systems are promising candidate for future wireless communication systems. Wideband wireless transmission is also required to support the growing need for higher data rate access demanded by future mobile applications and services. It is well known that channel model has a crucial impact on the design, simulation, and deployment of new communication systems. Therefore, the realistic wideband MIMO channel model is an important prerequisite. In general, deterministic channel models may lose some generality because it focus on regenerate the physical propagation charateristics as accurately as possible. At the meanwhile, the statistical models may describe the realistic radio environment behavior by introducing many random variables which lead to a heavy computational complexity.

As a consequence, it is a common sense that a "good" channel model is a tradeoff among reality, generality and complexity. This raises question like "How to define the *goodness* of a MIMO channel model?" Many researches on this topic have been reported. In [1], some different metrics has been proposed to compare narrow band analytical MIMO channel models including the Kronecker model [2], the Weichselberger model [3], and the virtual channel representation [4]. Spatial-temporal correlation properties of the 3GPP Spatial Channel Model (SCM) [5] and the Kronecker model are compared in [6]. Properties of three geometry based stochastic models: SCM, SCME [7], and WINNER channel models [8], [9] are compared and summarized in [10]. The above comparisons of channel models can be divided into three categories: a) analytical model validation based on measurements; b) theoretical analysis on properties of analytical model and physical model; and c) comparison on architecture of physical models. The validation of the measurement-based physical models has not been reported yet.

The main contribution of this paper is the generic validation framework for wideband MIMO channel models based on measurement results. Some useful metrics are also developed to provide different aspect of views on the wideband MIMO channel model. The proposed framework and metrics are verified with the measurement results.

The outline of the remaining of the paper is as follows. The channel model validation framework is explained in Sec. II. Derivation of various metrics for the wideband MIMO channel validation is presented in Sec. III. The measurement campaign which the result is used for demonstrating the framework and channel reconstruction is described in Sec. IV. The comparison analysis and conclusion are showned in Sec. V and Sec. VI, respectively.

The following notations will be used throughout this paper: $(\cdot)^{\mathrm{H}}$ stands for matrix Hermitian transposition; $(\cdot)^*$ stands for complex conjugation; $\|\cdot\|_{\mathrm{F}}$ denotes the Frobenius norm; $\mathcal{E}_x\{\cdot\}$ denotes the expectation operator over x; $\overline{\mathbb{R}^-}$ stands for the set of all non-negative real numbers.

II. Measurement-based Validation Framework for Channel Models

A. Signal Model

Considering an $N_{\mathrm{R}} \times N_{\mathrm{T}}$ MIMO channel with bandwidth B, we denote the channel impulse response (CIR) at time t to

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delay τ as

$$\boldsymbol{h}(\tau,t) = (h_{ij}(\tau,t))_{N_{\mathrm{R}}\times N_{\mathrm{T}}} \in \mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{T}}}. \quad (1)$$

The channel response at frequency f is given by [11]

$$H_{ij}(f,t) = \int_0^{\infty} h_{ij}(\tau,t)e^{-j2\pi f\tau}\mathrm{d}\tau. \quad (2)$$

Assume that, h_{ijps} is the discrete sample of $h_{ij}(\tau,t)$, while H_{ijqs} is the sample of $H_{ij}(f,t)$, we have

$$h_{ijps} = h_{ij}(p\cdot\Delta\tau, s\cdot\Delta t), \quad (3)$$
$$H_{ijqs} = H_{ij}(q\cdot\Delta f, s\cdot\Delta t), \quad (4)$$

where $\Delta\tau$, Δf and Δt is the sampling interval in the delay, frequency, and time domain, respectively. Let $\mathcal{H}$ be a set of realizations of either a measured channel or a channel model. For the delay domain, we have

$$\mathcal{H} = \{\boldsymbol{h}_{ps} = (h_{ijps})_{N_{\mathrm{R}}\times N_{\mathrm{T}}},\ 1\leqslant p\leqslant P,\ 1\leqslant s\leqslant S\}. \quad (5)$$

For the frequency domain, we have

$$\mathcal{H} = \{\boldsymbol{H}_{qs} = (H_{ijqs})_{N_{\mathrm{R}}\times N_{\mathrm{T}}},\ 1\leqslant q\leqslant Q, 1\leqslant s\leqslant S\}. \quad (6)$$

We use a superscript $^{(k)}$ to designate the real propagation environment and different channel models from each other. The set $\mathcal{H}^{(0)}$ represents CIRs obtained by channel sounding, while $\mathcal{H}^{(k)}, k = 1,2,\ldots,K$ represents the set of channel realizations generated by a measurement-based channel model $C^{(k)}$ with the same antenna configuration as the channel sounder. The model $C^{(k)}$ is controlled by a set of parameters $\mathcal{P}^{(k)}$ extracted from $\mathcal{H}^{(0)}$. For convenience, we call the real propagation channel as channel $C^{(0)}$. Based on these assumptions, we developed a tool to help us to find the most accurate one among the K models with respect to the channel $C^{(0)}$.

B. Validation Framework

The proposed channel model validation framework $\mathcal{F}$ can be formulated as a $(R+1)$-tuples $\{M_1, M_2, \ldots, M_R; D\}$, where M_r is a mapping from a set of $\mathcal{H}$ to the continuous function space $C(\mathbb{R})$ with parameters in $\mathbb{R}$. The mapping $D : (C(\mathbb{R}), C(\mathbb{R})) \to \overline{\mathbb{R}^-}$ defines a distance $D(f,g)$ between the continuous function f and g. The set

$$\mathcal{M}^{(k)} = \{m_r^{(k)} : m_r^{(k)} = M_r(\mathcal{H}^{(k)}); r = 1,2,\ldots,R\} \quad (7)$$

provides metrics from different perspectives (e.g. spatial multiplexing gain, diversity gain, and time variability, etc.) of the MIMO channel $C^{(k)}, k = 0,1,\ldots,K$, while $D(m_r^{(k)}, m_r^{(0)})$ allows us to have a quantitative measurement of the degree of approximation between the modeled value $m_r^{(k)}$ and the measured value $m_r^{(0)}$.

The workflow of the framework is shown in Fig. 1. The procedure of validating model C_k is as follows:

Step 1: Compute metrics over channel $C^{(0)}$ to obtain a set of reference values of metrics $\mathcal{M}^{(0)}$;

Step 2: For model $C^{(k)}$, extract model parameters $\mathcal{P}^{(k)}$ based on the measured CIRs $\mathcal{H}^{(0)}$;

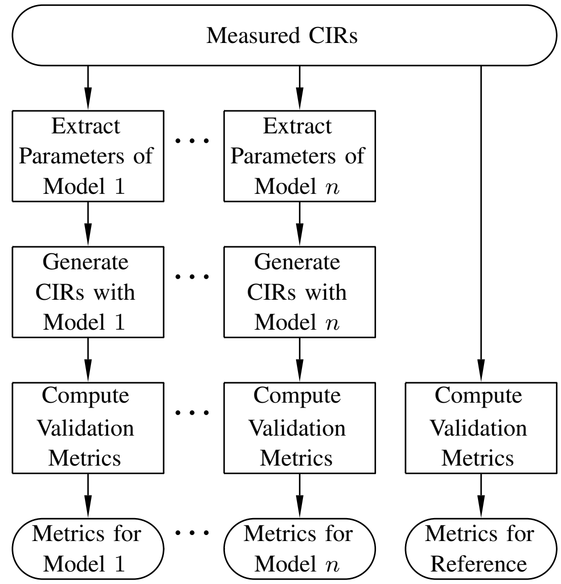


Fig. 1. Workflow of measurement-based channel model validation framework

Step 3: Generate a set of channel coefficients realizations $\mathcal{H}^{(k)}$ with the model $C^{(k)}$ and its parameters $\mathcal{P}^{(k)}$. The cardinary of $\mathcal{H}^{(k)}$ need to be sufficiently large so that the ergodicity can be guaranteed;

Step 4: Compute matrics $\mathcal{M}^{(k)}$ from $\mathcal{H}^{(k)}$;

Step 5: Judge the "goodness" of model $C^{(k)}$ according to $D(m_r^{(k)}, m_r^{(0)})$.

By utilizing the framework, we can elect the most realistic channel model from a number of candidates. It can also be applied to investigate the parameter which influences the behavior of the propagation significantly and which one is not. Consequently, we can simplify the channel model by keeping these dominate parameters as random variables while fixing others as constants.

III. Metrics for Wideband MIMO Channel Model Validation

In general, there are two distinct practical MIMO systems: spatial mulitplexing and space-time coding. It's intuitive that a "good" MIMO channel model should present such benefits as accurately as possible, which leads to a spatial multiplexing metric and a diversity metric. On the other hand, for wideband mobile communication sytems, both the time and frequency variablity of the propagation channel may influence the system designs, e.g. frame architectures, radio resource allocation schemes, and etc. So metrics to quantify both the time variablity and frequency variablilty are also presented. For clarity and simplicity, the superscirpt $^{(k)}$ is omitted in the follow derivations.

A. Spatial multiplexing

Channel capacity is selected as the metric for spatial multiplexing, because it is the main benefit resulted by applying this MIMO mode. The outage capacity, i.e. the cummulative distribution function (CDF) of the channel capacity, when the channel is unknown to the transimitter is prefered instead of the ergodic capacity which can be derived from the CDF. The capacity of time-invariant frequency-selective fading MIMO channel is given by [12]

$$C = \frac{1}{B}\int_B \log_2 \det\left(\boldsymbol{I}_{N_\mathrm{R}} + \frac{\rho}{N_\mathrm{T}}\boldsymbol{H}(f)\boldsymbol{H}(f)^\mathrm{H}\right)\mathrm{d}f, \quad (8)$$

where ρ denotes the signal-to-noise ratio (SNR), $\boldsymbol{H}(f)$ is the frequency domain channel matrix. For each channel realization $\boldsymbol{H}_{qs}$ in $\mathcal{H}$, an approximation can be given by

$$\tilde{C}_s(\rho) = \frac{1}{Q}\sum_{q=1}^{Q} \log_2 \det\left(\boldsymbol{I}_{N_\mathrm{R}} + \frac{\rho}{\beta^2 N_\mathrm{T}}\boldsymbol{H}_{qs}\boldsymbol{H}_{qs}^\mathrm{H}\right), \quad (9)$$

where β is a common normalization factor for all channel realizations in $\mathcal{H}$ such that the average channel power gain is unitary [13], [14], i.e.,

$$\mathcal{E}_\mathcal{H}\left\{\frac{1}{\beta}\|\boldsymbol{H}_{qs}\|_\mathrm{F}^2\right\} = N_\mathrm{R}N_\mathrm{T}. \quad (10)$$

Define the mapping M_1 with parameter ρ as

$$(M_1(\mathcal{H};\rho))(x) \overset{\mathrm{def}}{=} \mathrm{EDF}_\rho^\mathrm{cap}(x), \quad x \in \mathbb{R}, \quad (11)$$

where $\mathrm{EDF}_\rho^\mathrm{cap}(x)$ is the *empirical distribution function* (EDF) of the observations $\{\tilde{C}_s(\rho)\}_{s=1}^S$ calculated from $\mathcal{H}$.

B. Spatial diversity

When the channel is known to the transmitter, spatial diversity is related to the dominant eigenmode of the channel matrix [15]. So we choose the marginal CDF of each ordered eigenvalues of the channel matrix as the spatial diversity metric. Let $\lambda_n(\boldsymbol{H}_{qs}), n = 1, 2, \ldots, N_\mathrm{T}$ are the eigenvalues of $\frac{1}{\beta}\boldsymbol{H}_{qs}\boldsymbol{H}_{qs}^\mathrm{H}$ in descending order, i.e.

$$\lambda_1(\boldsymbol{H}_{qs}) \geqslant \lambda_2(\boldsymbol{H}_{qs}) \geqslant \cdots \geqslant \lambda_{N_\mathrm{R}}(\boldsymbol{H}_{qs}). \quad (12)$$

Define the mapping M_2 with parameter n as

$$(M_2(\mathcal{H};n))(x) \overset{\mathrm{def}}{=} \mathrm{EDF}_n^\mathrm{eig}(x), \quad x \in \overline{\mathbb{R}^-}, \quad (13)$$

where $\mathrm{EDF}_n^\mathrm{eig}(x)$ is the EDF of the observations $\{\lambda_n(\boldsymbol{H}_{qs}) : \boldsymbol{H}_{qs} \in \mathcal{H}\}$.

C. Time variability

For exploring whether the model can characterize the time variation of the real propagation, a correlation coefficient based metric is adopted. Let $\hat{h}_{ijps} = h_{i,j,p,s-x}$ be the channel realization with a time delay $x\Delta t$. The cross-correlation coefficient of the p-th delay tap is given by

$$\rho_p = \frac{\mathcal{E}_s\left\{(h_{ijps} - \mu_h)(\hat{h}_{ijps} - \hat{\mu}_h)^*\right\}}{\sqrt{\mathcal{E}_s\left\{|h_{ijps} - \mu_h|^2\right\}} \cdot \sqrt{\mathcal{E}_s\left\{|\hat{h}_{ijps} - \hat{\mu}_h|^2\right\}}}, \quad (14)$$

where μ_h and $\hat{\mu}_h$ are mean values of observations h_{ijps} and $\hat{h}_{ijps}$, respectively. We employ the power weighted average of $|\rho_p|$ over all delay tap p as the time variability measure. Define the mapping M_3 with parameters $\{i, j\}$ as

$$(M_3(\mathcal{H};i,j))(x) = \frac{|\rho_p| \cdot \sum_{s=1}^S |h_{ijps}|^2}{\sum_{p=1}^P \sum_{s=1}^S |h_{ijps}|^2}. \quad (15)$$

D. Frequency variablity

The *frequency cross-correlation function* (FCF) can be utilized as a metric to evaluate the frequency variation. Let $\hat{H}_{ijqs} = H_{i,j,q-x,s}$ be the channel realization with a frequency shift $x\Delta f$. The mapping M_4 is defined as

$$(M_4(\mathcal{H};i,j))(x) = \left|\frac{\mathcal{E}_{s,q}\left\{(H_{ijqs} - \mu_H)(\hat{H}_{ijqs} - \hat{\mu}_H)^*\right\}}{\sqrt{\mathcal{E}_{s,q}\left\{|H_{ijqs} - \mu_H|^2\right\}} \cdot \sqrt{\mathcal{E}_{s,q}\left\{|\hat{H}_{ijqs} - \hat{\mu}_H|^2\right\}}}\right|, \quad (16)$$

where μ_H and $\hat{\mu}_H$ are mean values of observations H_{ijqs} and $\hat{H}_{ijqs}$, respectively.

E. Distance function

The distance function of continuous function space is another core component of the validation framework. There are two commonly used different distance functions of $C(\mathbb{R})$, one is defined as

$$D(f,g) \overset{\mathrm{def}}{=} \int_{-\infty}^{\infty} |f(t) - g(t)|^2 \mathrm{d}t. \quad (17)$$

The other is given by

$$D(f,g) \overset{\mathrm{def}}{=} \max_{t\in\mathbb{R}} |f(t) - g(t)|. \quad (18)$$

The first definition leads to an overall deviation of two functions from each other, while the second one provides the maximum error. Either (17) or (18) can be regarded as the distance function in the framework $\mathcal{F}$.

IV. Measurement Campaign and Parameter Extraction

A. Measurement Campaign

Extensive channel measurements were performed at the center frequency of 5.25 GHz with 100 MHz bandwidth with Elektrobit PropSound Channel Sounder [16] at Beijing University of Posts and Telecommunications (BUPT), China [17]. The transmitter (Tx) employed a three-dimensional dual-polarized omnidirectional array (ODA) with maximum 50 elements shown in Fig. 2(a); the receiver (Rx) employed eight elements of vertically polarized uniform circular array (UCA) shown in Fig. 2(b). The element spacing of both ODA and UCA is half of a wavelength. The schematic plot of both antenna arrays is shown in Fig. 3.

A seven-floor building was selected as the measurement site representing the indoor hotspot environment. Both the Tx and Rx were mounted on the trolley during the measurements. The Tx arraywas about 1.5 m above the ground using all 50 elements of ODA; the Rx array was about 2.5 m above the ground with eight elements of UCA. Figure 4 illustrates the

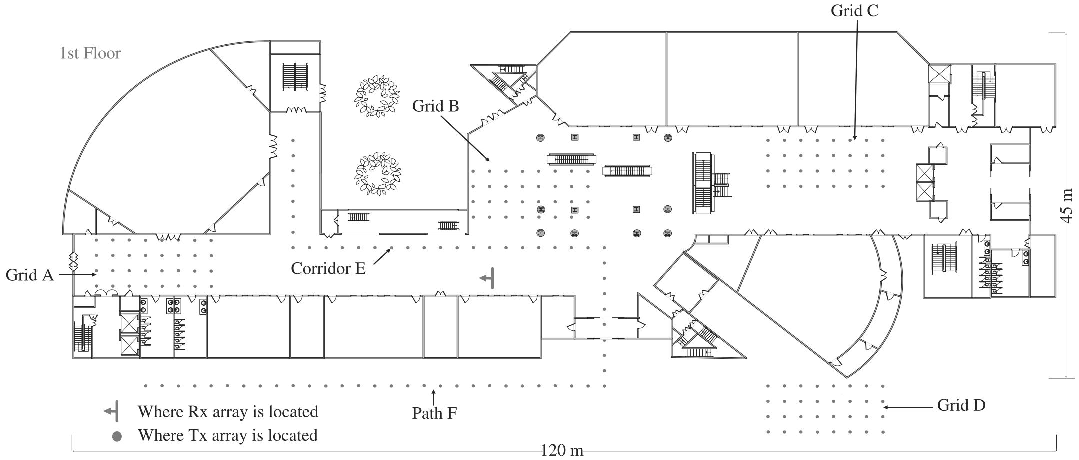
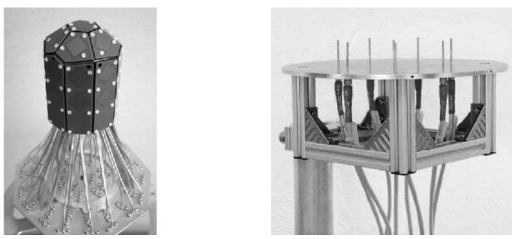
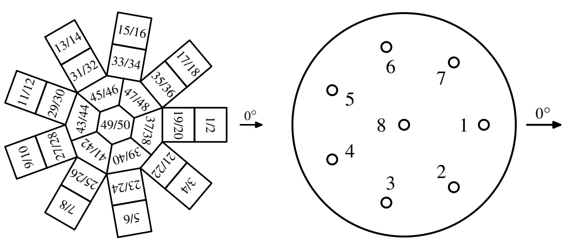


Fig. 4. Floorplan of the measurement scenario.



(a) 2×9 ODA (b) $7 + 1$ UCA

Fig. 2. Picture of antenna arrays.



(a) 2×9 ODA (b) $7 + 1$ UCA

Fig. 3. Schematic plot of antenna arrays.

measurement campaign on the first floor of the building. The Rx was fixed as the arrow shows during all the measurements; while the Tx moved to every location denoted as dots.

B. Extraction of Model Parameters

The Parameters of scenario Grid A (LOS) for the Cluster Delay Line (CDL) model [9] are extracted from the measured CIR by utilizing the Space-Alternating Generalized Expectation-maximization (SAGE) algorithm [18]. The parameters are extraced with all measured CIRs of the 50×8 sub-channels. The responses of both the antenna array and the sounder itself are removed from the measured raw data. So the parameters can present the radio propagation.

V. Numerical Results

A. Channel Reconstruction

The channel model is a double directional channel model which describes the physical wave propagation [19]. To re-generate a set to MIMO channel matrix realizations, we need to constrain the antenna configuration and bandwidth exactly as of the measurement campaign. The complex electrical field strength of linear horizontal and vertical polarizations which is used with the SAGE algorithm is also applied to generate the channel coefficient with a modified version of [20]. We concerntrates on a 9×7 downlink MIMO channel with bandwidth of 100 MHz at 5.25 GHz. The BS antenna array is a 7-element uniform circular array, which is just like the $7 + 1$ UCA without the center element. A 9-element uniform circular array is supposed be at the MS, which can be thought as the center ring of the 2×9 ODA (from element #19 to #36 in Fig. 3(a)). For both antenna arrays, the element spacing is half of a wavelength. All other parameters of the model are set as their correspondence in the measurement campaign, include radiation patterns of each elements, and reference directions of both antenna arrays. Assumptions are summarized in Table I.

TABLE I
ASSUMPTIONS OF CHANNEL RECONSTRUCTION

Parameters	Description
Carrier frequency	5.25 GHz
Bandwidth	100 MHz
BS antenna array	7-element UCA, vertical polarized
MS antenna array	9-element UCA, $\pm 45°$ dual polarized
MS velocity	3 km/h
Sample density	64 samples per half wavelength
No. of time samples	10^5
Delay sampling density	5 ns
No. of frequency bins	513

B. Spatial Multiplexing Metric

Figure 5 shows the plots of the metric defined in (11) for both measured and reconstructed CIRs at three different SNR levels, 0 dB, 10 dB, 20 dB. The distance in (17) for $\rho = 0$ dB, 10 dB, and 20 dB equals 1.975, 1.149, and 0.385, respectively. It shows that the modified model has a better approximation to the real channel in the high-SNR regime. However, no matter what value is assigned to the SNR, the model always overestimates the channel capacity.

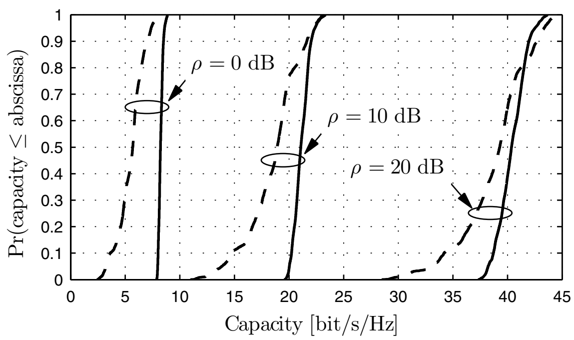


Fig. 5. Empirical distribution function of capacity (solid lines—model generated, dash lines—measured)

C. Spatial Diversity Metric

The metric defined in (13) for all ordered eigenvalues are shown in Fig. 6. The eigenvalues decend from right hand to left hand side. It shows that the statistic characteristics of dominate eigenvalue are well modeled.

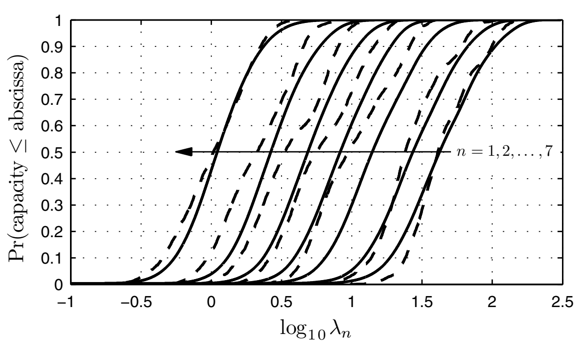


Fig. 6. Empirical distribution function of ordered eigenvalues (solid lines—model generated, dash lines—measured)

VI. Conclusion

In this paper we proposed a generic framework for wideband MIMO channel model validation based on measurements. Metrics for evaluate different MIMO channel characteristics are derived. The framework is demonstrated with the measured CIR and a reconstructed CIR from a WINNER-like model. It's obviously that by defining different metric mapping, this framework can be applied to explore various aspects of MIMO channel models.

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