A Novel Coupling-based Model for Wideband MIMO Channel

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Abstract—In this paper, a novel analytical model structure for wideband multiple-input multiple-output (MIMO) channel is presented. It is based on the power coupling between direction of arrival (DoD), direction of arrival (DoA) and delay domain. As its realizations, firstly the singular value decomposition (SVD) based model is introduced and the virtual presentation model is extended to the wideband situation. Then a hybrid model is given on basis of the power coupling between the transmit eigenmodes, receive eigenmodes and frequency steering vectors. The hybrid model can provide the tradeoff between the complexity and accuracy. At last, the novel coupling-based model structure is summarized. With a 3.52 GHz wideband MIMO sounder, measurements are carried out in different indoor scenarios. Monte Carlo simulations are used to generate the channel realizations according to these proposed wideband models. Good agreements are achieved between the discussed models and measured data.

Index Terms—Wideband channel, channel model, multiple-input multiple-output (MIMO), coupling-based, virtual presentation, channel capacity.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) technology has attracted increasing attention recently because of the capacity gain led by it. As the basis of the multiple antennas system design, MIMO channel modeling is one of the research hotspots. Analytical MIMO models [1] are very popular because they can describe the spatial structure of the propagation environment. A MIMO model based on Kronecker structure is presented in [2]. Weichselberger proposes a singular value decomposition (SVD)-based model [3] and Sayeed develops a virtual presentation MIMO model [4].

However, the above models are all for narrowband channel. In [5], Yu extends the Kronecker model to wideband case by calculating the channel correlation matrix for each tap. However, this model assumes that the channel at each delay tap is independent. In [6], Costa establishes a structured model using the eigenvalue decomposition of the wideband channel correlation matrix. Although this structured model performs very well, it needs numerous parameters and calculations to generate the channel impulse response (CIR) tensor. It is necessary to propose other simpler models with the tradeoff between the complexity and accuracy.

At the same time, both the Weichselberger model and the virtual presentation model are narrowband coupling-based models. It is reasonable to build a wideband power coupling framework, which can reflect the relationship between CIR and propagation environment.

This paper is organized as follows. In Section II, the most popular narrowband coupling-based models are introduced. Section III presents the novel coupling-based model structure and its three realizations including the SVD-based model, the wideband virtual presentation model and the hybrid model. Section IV provides a brief introduction of our channel sounder and measurement campaign. Measured data and simulation results are also shown in Section IV to evaluate these wideband coupling-based models’ performance. Finally, conclusion is contained in Section V.

II. NARROWBAND COUPLING-BASED CHANNEL MODEL

Consider a static narrowband MIMO system that employs $N$ transmitter elements and $M$ receiver elements. The transmitted and received signal are related as

$$y = Hx + v$$  \hspace{1cm} (1)

where $x$ is the $N \times 1$ transmitted signal, $v$ is the noise and $y$ is the $M \times 1$ received signal. $H$ is the $M \times N$ CIR matrix between the transmitter and receiver elements.

The narrowband coupling-based channel model, which is an important set of the analytical models, uses the power coupling matrix (or amplitude coupling matrix) to describe the spatial structure of the propagation environment. The Weichselberger model and virtual presentation model are the most popular narrowband coupling-based models.

A. Weichselberger Model

Weichselberger Model [3] is a coupling-based model which is based on the eigenvalue decomposition of the transmitter and receiver correlation matrices.

$$R_{Tx} = U_{Tx} A_{Tx} U_{Tx}^H \hspace{1cm} R_{Rx} = U_{Rx} A_{Rx} U_{Rx}^H$$  \hspace{1cm} (2)

where the unitary matrices $U_{Tx}$ and $U_{Rx}$ are eigenbases at the transmitter and receiver, respectively. $A_{Tx}$ and $A_{Rx}$ are the diagonal matrices of the corresponding eigenvalues. Then the
channel matrix $\mathbf{H}$ in Weichselberger model could be written as
\[
\mathbf{H} = \mathbf{U}_{\text{Rx}}(\tilde{\Omega}_{\text{weichsel}} \odot \mathbf{G})\mathbf{U}^T_{\text{Tx}}
\]
where $\tilde{\Omega}_{\text{weichsel}}$ is the element-wise square root of the power coupling matrix $\Omega_{\text{weichsel}}$, whose elements are all positive and real-valued. $\mathbf{G}$ is an $M \times N$ random matrix with zero-mean i.i.d complex circularly symmetric Gaussian elements. $\odot$ stands for the Schur-Hadamard multiplication.

In Weichselberger model, the power coupling matrix $\Omega_{\text{weichsel}}$ is used to present the power coupling links between the eigenmodes at transmitter and receiver. In Weichselberger model, the eigenbases $\mathbf{U}_{\text{Rx}}, \mathbf{U}_{\text{Tx}}$ and the coupling matrix $\Omega_{\text{weichsel}}$ need to be specified using measured CIR samples.

### B. Virtual Presentation Model

Virtual presentation model, another narrowband coupling-based model supposed by [4], is considered to be only feasible for uniform linear array (ULA). In this model, the angular ranges at both link ends are fixed at discrete angles (virtual angles). The array size determines the number of these virtual angles and the spatial resolution. Then the MIMO channel is modeled as the power coupling between these virtual angles at transmitter and receiver.
\[
\mathbf{H} = \mathbf{A}_{\text{Rx}}(\tilde{\Omega}_{\text{virt}} \odot \mathbf{G})\mathbf{A}^T_{\text{Tx}}
\]
where $\tilde{\Omega}_{\text{virt}}$ is the amplitude coupling matrix, $\tilde{\Omega}_{\text{virt}}$ is the element-wise square root of the power coupling matrix $\Omega_{\text{virt}}$. $\mathbf{A}_{\text{Rx}}$ and $\mathbf{A}_{\text{Tx}}$ are the steering matrices into the virtual angles at transmitter and receiver, respectively.

\[
\mathbf{A}_{\text{Rx}} = (a_{\text{Rx}}(\theta_{\text{Rx},1}), ..., a_{\text{Rx}}(\theta_{\text{Rx},M}))
\]
\[
a_{\text{Rx}}(\theta_{\text{Rx},m}) = (1, e^{-j2\pi\alpha_{\text{Rx},m}}, ..., e^{-j2\pi(M-1)\alpha_{\text{Rx},m}})^T
\]
\[
\mathbf{A}_{\text{Tx}} = (a_{\text{Tx}}(\theta_{\text{Tx},1}), ..., a_{\text{Tx}}(\theta_{\text{Tx},N}))
\]
\[
a_{\text{Tx}}(\theta_{\text{Tx},n}) = (1, e^{-j2\pi\alpha_{\text{Tx},n}}, ..., e^{-j2\pi(N-1)\alpha_{\text{Tx},n}})^T
\]
where $\alpha = d\sin(\theta)/\lambda$ is the normalized antenna spacing. $\lambda$ is the wavelength of propagation. $\theta_{\text{Rx},m}$ and $\theta_{\text{Tx},n}$ is the $m$-th virtual Direction of Arrival (DoA) and the $n$-th virtual Direction of Departure (DoD), respectively.

For ULA, the space angular domain can be divided by the $N$ virtual DoDs and $M$ virtual DoAs. A common selection of the virtual DoDs or DoAs is to make $\alpha$ divide the normalized antenna space uniformly.

The DoDs and DoAs in virtual presentation model are actually the spatial samples of scatterers in propagation environment. Therefore, the accuracy of virtual presentation model relies on the number of antennas. Selecting large array in both link ends can improve the model’s spatial resolution. Fig. 1 shows the physical mechanism of the virtual presentation model. If there is a path between the specified DoD and DoA, the element of the amplitude coupling matrix $\tilde{\Omega}_{\text{virt}}$ equals the path’s amplitude, while the element is zero if there is no path joining the virtual DoD and DoA.

In the virtual presentation model, only the amplitude coupling matrix which includes $MN$ parameters needs to be determined. At the same time, the computation complexity is cut down because no SVD operation is carried out.

### III. WIDEBAND COUPLING-BASED MIMO MODEL

For a wideband MIMO system, the received signal in delay domain could be written as [6]
\[
y(i) = \sum_{d=1}^{D} h(d)x(i - d + 1) + v(i)
\]
where $x(i)$ is the transmitted signal, $v(i)$ is the noise and $y(i)$ is the received signal at instant $i$. $\mathbf{H}(d)$ is the $M \times N$ narrowband channel impulse response (CIR) matrix for delay $d = 1, ..., D$.

\[
\mathbf{H}(d) = \begin{pmatrix} h_{1d} & \cdots & h_{1Nd} \\ \vdots & \ddots & \vdots \\ h_{M1d} & \cdots & h_{MNd} \end{pmatrix}
\]

$\mathbf{H}(d)$ can be transformed to an $M \times N \times D$ tensor $\mathcal{H}$, whose element $h_{md}$ is the complex gain of the path between transmitter $n$, receiver $m$ and delay $d$ [6].

The wideband MIMO model can also be expressed in frequency domain.
\[
\mathbf{H}(f) = \begin{pmatrix} h_{1f} & \cdots & h_{1Nf} \\ \vdots & \ddots & \vdots \\ h_{M1f} & \cdots & h_{MNF} \end{pmatrix}
\]

Here the element $h_{mf}$ is the complex gain at transmitter $n$, receiver $m$, and frequency bin $f$. $\mathbf{H}(f)$ is the CIR matrix in each frequency bin $f = 1, 2, \cdots, F$. $F$ is the number of frequency bins. $F = f_s/\Delta f$; $f_s$ is the sampling rate and $\Delta f$ is the interval between adjacent frequency bins. Obviously, $\mathbf{H}(f)$ and $\mathbf{H}(d)$ are Fourier transform pairs. For Discrete Fourier Transform (DFT) convenience, let $F = D$.

In this paper, we choose $\mathbf{H}(f)$ and corresponding tensor $\mathcal{H} \in \mathbb{C}^{M \times N \times D}$ as the channel model to be generated, which is a little different with [6]. The purpose is to construct the corresponding power coupling matrix in the delay, DoA and DoD domain.
The wideband channel could also be modeled as the power coupling-based form. The power coupling matrix can depict the relationships between the specified DoAs, DoDs and delays. In the next subsections, SVD-based model will be introduced firstly, which reflects the coupling between the eigenmodes. Then we will extend virtual presentation model to wideband situation by building power coupling links between the steering vectors. At last, a hybrid model will be presented and the universal coupling-based structure will be summarized.

A. SVD-based Model

Structured model, which is presented in [6], is a wideband extension of Weichselberger model in transmitter-receiver-delay domain. The similar idea can be applied in the generation of the transmitter-receiver-frequency tensor $H_v$.

$$H_{svd} = (W_{svd} \otimes G) \times_1 U_{Rx} \times_2 U_{Tx} \times_3 U_{Fre},$$  \hspace{1cm} (10)$$

where $W_{svd}$ is an $M \times N \times D$ amplitude coupling tensor. The elements of $G$ are zero-mean i.i.d. complex Gaussian variations. $U_{Rx}$, $U_{Tx}$ and $U_{Fre}$ are the eigenbases of transmitter, receiver and frequency domain, respectively. $\times_j$ means multiplication in the $j$-th tensor dimension.

The SVD-based model is a typical wideband coupling-based MIMO model. The element of $W_{svd}$ reflects the coupling amplitude between the transmitter, receiver and frequency eigenmode.

In SVD-based model, $U_{Rx}$, $U_{Tx}$, $U_{Fre}$ and $W_{svd}$ need to be computed to generate $H_{svd}$, so there are totally $M^2 + N^2 + D^2 + MND$ real-valued parameters that have to be extracted from measured data.

B. Extension of Virtual Presentation Model

Similarly, it is reasonable to extend the virtual presentation model to wideband case.

$$H_{vir} = (W_{vir} \otimes G) \times_1 A_{Rx} \times_2 A_{Tx} \times_3 A_{Fre}$$ \hspace{1cm} (11)$$

where $W_{vir} \in \mathbb{C}^{M \times N \times D}$ is the amplitude coupling tensor between the steering vectors in the transmitter, receiver and frequency domains. $A_{Rx}$, $A_{Tx}$ and $A_{Fre}$ are the steering matrices in the transmitter, receiver and the frequency domain, respectively.

$$A_{Fre} = (a_{Fre}(\tau_1), ..., a_{Fre}(\tau_d), a_{Fre}(\tau_D))$$

$$a_{Fre}(\tau_d) = (1, e^{-j2\pi \Delta f \tau_d}, ..., e^{-j2\pi (D-1) \Delta f \tau_d})^T$$ \hspace{1cm} (12)$$

where $\{\tau_d|d = 1, ..., D\}$ are the selected virtual delays.

The element of $W_{vir}$ is $\sqrt{w_{mnd}}$, where the power coupling coefficient $w_{mnd}$ is defined as

$$w_{mnd} = \langle a_{Fre,d} \otimes a_{Rx,n} \otimes a_{Rx,m} \rangle^H R_{WB}$$

$$\times (a_{Fre,d} \otimes a_{Tx,n} \otimes a_{Rx,m}).$$ \hspace{1cm} (13)$$

Here, $\otimes$ means the Kronecker product. $a_{Rx,m} = a_{Rx}(\theta_{Rx,m})$, $a_{Tx,n} = a_{Tx}(\theta_{Tx,n})$ and $a_{Fre,d} = a_{Fre}(\tau_d)$. $R_{WB}$ denotes the estimation of the MIMO channel full correlation matrix.

$$R_{WB} = \text{E}\{\text{vec}(H)\text{vec}^H(H)\}. \hspace{1cm} (14)$$

The physical explanation of this wideband virtual presentation model is as Fig. 2 shows. If there exists a path at the fixed DoA, DoD and delay, then the element of amplitude coupling matrix $W_{vir}$ equals to this path’s amplitude. In Fig. 2, there are two scatterers in the propagation environment and only single-reflection happens. Then each scatterer causes an individual path. The DoAs, DoDs and delays of the two paths are $(\theta_{Rx,1}, \theta_{Tx,1}, \tau_{Fre,1})$ and $(\theta_{Rx,2}, \theta_{Tx,2}, \tau_{Fre,2})$, separately. Then the power coupling coefficients $w_{111}$ and $w_{222}$ equal to the power of the first and the second path, respectively. Physical meaning of multi-reflection situation is similar to that of single-reflection, but the topology of multi-reflection is more complex.

The spatial resolution of the wideband virtual presentation model depends on the size of antenna arrays in both link ends. For example, $M$ receiver elements can only provide the paths which arrive at these $M$ virtual DoAs. The number of samples in frequency domain specifies the resolution in delay domain.

In the wideband virtual presentation model, only amplitude coupling matrix $W_{vir}$ needs to be computed.

From another perspective, the wideband virtual channel model $H_{vir}$ is the 3-D Fourier transform of the amplitude coupling matrix $W_{vir}$. $A_{Rx}$, $A_{Tx}$ and $A_{Fre}$ are DFT matrices. The coupling relationship between DoD, DoA and delay can be transferred to the transmitter-receiver-frequency domain by these DFT matrices.

Traditionally, the virtual presentation model is considered only feasible for ULA. In fact, this model can be applied at arbitrary array if the steering matrix is replaced. At the same time, the antenna pattern can be added to the steering matrix, too.

C. Hybrid Coupling Model and Universal Coupling-based Structure

In practice, the number of antennas is often finite, which results in the limitation in spatial domain resolution. However, the number of samples in the frequency domain (or the delay domain) is usually large. If the SVD-based model is used to generate $H$, numerous parameters need to be extracted from measured data. At the same time, the size of frequency correlation matrix will be very huge for the SVD operation. The wideband virtual presentation model needs only a few parameters and no SVD operation, while its accuracy is coarse with limited array size.
A hybrid coupling-based wideband model could be supposed by combining these two models together. The spatial characteristics can still be described by the eigenmodes while the delay characteristics are depicted by the steering vectors. In this way, the hybrid model can keep the performance in the spatial domain. Meanwhile, the computation complexity in frequency domain, which plays a major role in total model, will be reduced.

Then the coupling between the transmitter eigenmodes, the receiver eigenmodes and the frequency steering vectors can be modeled by matrix $H_{hybrid}$.

$$H_{hybrid} = (M \otimes F) \times U_{Rx} \times U_{Tx} \times A_{Fre}$$  \hspace{1cm} (15)

where the element of $H_{hybrid}$ is

$$w_{mnd} = (a_{Fre,d} \otimes u_{Tx,n} \otimes u_{Rx,m})^H R_{WB} (a_{Fre,d} \otimes u_{Tx,n} \otimes u_{Rx,m}).$$  \hspace{1cm} (16)

SVD-based model, wideband virtual presentation model and hybrid model are all coupling-based wideband models. They can be summarized as a universal structure.

$$H = (F \otimes F) \times X_{Rx} \times X_{Tx} \times X_{Fre}.$$  \hspace{1cm} (17)

$X_{sub}$ ($sub \in \{Rx, Tx, Fre\}$) could be the eigenbase $U_{sub}$ or steering matrix $A_{sub}$. The choice between the eigenbase and steering matrix is determined by the sample numbers in the transmitter, receiver and frequency domain. If the array size of one link end is large enough, the steering matrix could also be used in the hybrid model. $H$ is the amplitude coupling tensor whose element is $\sqrt{\omega_{mnd}}$. $\omega_{mnd}$ reflects the power coupling between the DoD, DoA and delay.

$$\omega_{mnd} = (x_{Fre,d} \otimes x_{Tx,n} \otimes x_{Rx,m})^H R_{WB} (x_{Fre,d} \otimes x_{Tx,n} \otimes x_{Rx,m}).$$  \hspace{1cm} (18)

Under this coupling-based framework, the amplitude coupling matrix $H$ can be transformed to the transmitter-receiver-frequency domain CIR tensor $H$. The SVD-based model, wideband virtual presentation model and hybrid model are all realizations of this universal wideband coupling-based structure.

IV. EXPERIMENTAL RESULTS

A. Measurement Setup

To evaluate the performance of these wideband models in Section III, a MIMO channel sounder [7] is built and some measurement campaigns are carried out in different indoor scenarios. The configuration of this MIMO channel sounder is shown in Table I.

Fig. 3 is the channel sounder’s block diagram. At the transmitter, a signal generator outputs the test signal. The signal is distributed to transmit antennas by fast time-division multiplexed switching (TDMS). Fast switching is also employed at the receive array. The synchronization between the transmitter and the receiver is achieved by using well-adjusted Rubidium frequency references. Due to the TDMS principle, the channel impulse responses between antenna pairs can be estimated and stored as continuous snapshots.

Some indoor measurement campaigns are completed in the FIT building of Tsinghua University (THU) with the channel sounder. The measured scenarios include office, corridor-to-room and lobby.

B. Performance Evaluation

Two respects should be taken into account when we evaluate a wideband channel model. On one hand, a good channel model must be very accurate and realistic to describe the real channel. On the other hand, the channel model is required to be as simple as possible.

In section III, we present three typical wideband models including the SVD-based model, the wideband virtual presentation model and the hybrid model. Through these above models, the SVD-based model needs more parameters than other two models to rebuild the channel. When $(M, N, D) = (7, 7, M)$, Table II gives the number of parameters needed to be computed in different models. Full correlation model is defined in [6]. The eigenvalue decomposition operations are required in the SVD-based model, too. With the increase of the frequency samples’ number, the structured model will be more complicated for generation. The hybrid model can omit the SVD operation over the frequency domain and its parameter number doesn’t increase too much compared with the wideband virtual presentation model.

The accuracy of models can be evaluated by several metrics. In this paper, the joint DoA-DoD-Delay power spectrum and

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>3.52GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>16MHz</td>
</tr>
<tr>
<td>Transmitted Power</td>
<td>10dBmW</td>
</tr>
<tr>
<td>Max Doppler Frequency</td>
<td>797.2Hz</td>
</tr>
<tr>
<td>Max Mobile Speed</td>
<td>123km/h</td>
</tr>
<tr>
<td>Delay Range</td>
<td>12.8us</td>
</tr>
<tr>
<td>Antenna Pattern</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Antenna Configuration</td>
<td>4dBi gain</td>
</tr>
<tr>
<td>Polarization</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

TABLE I

The Configuration of THU MIMO Channel Sounder.
the average capacity are used as the standard to judge the goodness of the channel models. Monte Carlo simulations are used to generate several CIR tensors based on different model. Then the simulation results is compared with the measured data.

C. Joint DoA-DoD-Delay Power Spectrum

The joint DoA-DoD-Delay Power Spectrum could be calculated using Bartlett beamformer.

\[
P_{Bart} = (a_{f_{\text{TX}}} (\tau) \otimes a_{\text{TX}} (\varphi_{\text{TX}}) \otimes a_{\text{Rx}} (\varphi_{\text{Rx}}))^H \widehat{R}_{\text{WB}} \frac{1}{B} \sum_{f=1}^{B} \log_2 \det \left( I_N + \frac{\text{SNR}}{M} \tilde{H}(f) \tilde{H}^H(f) \right) \]  

(19)

with the normalized steering vector \(a_{f_{\text{TX}}} (\tau)\) at delay \(\tau\), \(a_{\text{TX}}(\varphi_{\text{TX}})\) at DoD \(\varphi_{\text{TX}}\) and \(a_{\text{Rx}} (\varphi_{\text{Rx}})\) at DoA \(\varphi_{\text{Rx}}\). \(\widehat{R}_{\text{WB}}\) is the estimation of the full correlation matrix.

Using data gathered from one location in an office scenario, the joint DoA-DoD angular power spectrums (APS) of the first delay tap is illustrated in Fig. 4. The colors represent the normalization dB. The APS of hybrid model, which can correctly fit the measured APS, is the same as that of SVD-based model because of their same spatial structure. The wideband virtual presentation model is not able to reproduce multipaths properly because the array size limits its spatial resolution.

If the DoD equals to 47°, the joint DoA-Delay spectrum is drawn in Fig. 5. From Fig. 5, although the hybrid model selects

the frequency steering matrix to depict the delay domain, its performance doesn’t degrade much compared with SVD-based model. The reason is that the number of frequency samples is large enough to provide precise resolution in delay domain.

D. Capacity

Consider a channel unknown at transmitter. The capacity of MIMO channel with equally allocated transmit powers is calculated for each realization using

\[
C = \frac{1}{B} \sum_{f=1}^{B} \log_2 \det \left( I_N + \frac{\text{SNR}}{M} \tilde{H}(f) \tilde{H}^H(f) \right) 
\]

(20)

where \(I_N\) denotes the identify matrix, SNR is the average receiver signal power and noise power ratio, and \(\tilde{H}(f)\) is the normalized channel matrix in frequency domain. \(B\) is the number of frequency bins in signal’s bandwidth. \(B = W/\Delta f\) and \(W\) is the bandwidth of the signal.

The data sets are collected from different locations in the corridor-to-room scenario. The bandwidth of transmitted signal is 16MHz and SNR is chosen to be 20dB.

The capacity error of the wideband model can be defined as

\[
\text{Error} (\%) = \frac{|C_{\text{mod}} - C_{\text{mea}}|}{C_{\text{mea}}} 
\]

(21)

where \(C_{\text{mod}}\) and \(C_{\text{mea}}\) are the modeled capacity and the measured capacity, respectively. Table III gives the average capacity error of different models when \((M, N, D) = (7, 7, 20)\). Fig. 6 illustrates the modeled versus measured capacity at all 23 locations. The diagonal dashed line represents no model error.
### TABLE III
CAPACITY ERROR OF DIFFERENT WIDEBAND MODELS.

<table>
<thead>
<tr>
<th>Loc.</th>
<th>SVD Error (%)</th>
<th>VP Error (%)</th>
<th>Hybrid Error (%)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.6 16.2 9.3</td>
<td>13 10.9 21.2 9.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.6 14.5 8.5</td>
<td>14 13.1 17.1 6.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.9 9.6 9.8</td>
<td>15 8.2 12.6 2.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.8 6.2 7.9</td>
<td>16 8.7 10.5 0.3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.8 12.5 8.3</td>
<td>17 10.9 24.1 4.7</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10.2 16.8 15.2</td>
<td>18 10.3 27.3 15.1</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>7.9 20.0 15.0</td>
<td>19 7.2 17.9 17.0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3.0 17.3 5.9</td>
<td>20 6.6 15.6 10.6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>11.9 19.1 13.9</td>
<td>21 6.0 14.5 10.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9.2 35.2 13.5</td>
<td>22 3.7 9.5 12.2</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2.3 8.1 19.8</td>
<td>23 0.3 11.7 10.1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>6.6 11.2 12.6</td>
<td>Avg. 6.1 16.0 10.4</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6. Modeled versus measured capacity using the data sets from 23 locations in corridor-to-room scenarios.

In Fig. 6 and table III, the estimation results show that the SVD-based model fits the measurement results best with the least error, and the wideband virtual channel model overestimates the measured capacity. Hybrid model provides a tradeoff between the complexity and accuracy.

### V. CONCLUSION

This paper presented a new coupling-based model structure for wideband MIMO channel. Firstly, we introduced the narrowband coupling-based models including the Weichselberger model and virtual presentation model. Then the SVD-based model and the wideband virtual presentation model were described. The hybrid model was established to provide a tradeoff between the complexity and accuracy. On basis of these wideband models, we extracted the universal coupling-based MIMO channel model structure. Finally, to evaluate the performance of these models, a MIMO channel sounder was built and some measurements were carried out. Using measured data and simulation results, the joint DoA-DoD-Delay power spectrum and the average capacity were computed. The results proved that the hybrid model worked well in both delay and spatial domain.

### REFERENCES


