Development of a MIMO-OTA System with Simplified Configuration

Yoshio Karasawa · Yannes Gunawan · Sahrul Pasisingi · Katsuhiro Nakada · Akira Kosako

Abstract

This paper introduces our development of a MIMO-OTA system with simplified configuration. The key element of our proposal is the adoption of an antenna branch-controlled configuration for generating multipath delayed waves. The signal processing is carried out on IF band signal with an FPGA in a fading-emulator-type MIMO-OTA measurement system. The proposed scheme is largely different from available system configurations for the fading simulator method of constructing the OTA test environment. We describe the principle of the proposed scheme, channel model incorporated in the system, basic configuration of the developed system, and its performance.

Key words: MIMO, OTA, Fading Emulator, Wideband Channel, Propagation Channel Model.

I . Introduction

OTA (Over-the-Air) test methods are of growing interest for evaluation of MIMO (multiple-input multiple-output) terminals in LAN, WiMAX, LTE, and other wireless communication systems which adopting MIMO technologies. In the OTA testing, a realistic propagation environment is generated around the receive terminals for measurement of the receiving characteristics. Standardization of OTA measurement methods is currently under consideration by Third Generation Partnership Project (3GPP) [1].

In the OTA test methods, the environment for the MIMO terminals evaluation may be generated either by a reverberation chamber or by a fading emulator. In the reverberation chamber system, a chamber made with metallic walls that effectively reflect waves is used to generate a multipath-rich propagation environment [2]~[4]. In fading emulator systems, hereafter denoted as "FE type", a number of virtual scattering antennas in terms of "probe antennas" are positioned circularly around the terminals being tested (devices under test; DUTs) to generate a fading environment [5], [6]. Although both methods have merits and demerits respectively, we focus our paper on the fading emulator (FE) type OTA systems highlighting channel control flexibility.

In 3GPP, there is one particularly promising configuration among FE-type OTA systems. This system employs an available fading simulator scheme for generating propagation channel paths connecting M input signals and L probe antennas [5]. The fading simulator is able to control propagation parameters such as delay spread, Doppler spread, and angular spread flexibly. Although this type of system can realize all necessary functions easily, the construction cost is generally extremely high. Therefore, in our previous papers [7], [8], we have proposed an FE-type MIMO-OTA system with a simplified configuration characterized by "antenna-branch-controlled type", and narrowband experiments without any delayed paths were carried out there.

Based on the antenna-branch-controlled method, we have developed an actual system using an FPGA board which includes wideband propagation channel generation. In this paper, we introduce the developed FE-type MIMO-OTA system with a simplified configuration that is quite different from existing ones. We describe the principle of the proposed scheme, channel model incorporated in the system, basic configuration of the developed system, and its performance.

II . FE-Type MIMO-OTA System

2-1 Basic Configuration

Fig. 1 shows a total view of FE-type MIMO-OTA test systems. As shown, main components of the overall system are transmitting antenna input ports (M in number), probe antennas realizing actual multipath environment (L), receiving antennas (N) of the measurement terminal (DUT), and also the $M \times L$ network for multipath channel generation which is connecting the transmitting antenna ports and the probe antennas. The network has an essential role in controlling signals to generate the desired propagation channels.
Fig. 1. General configuration of fading-emulator (FE) type MIMO-OTA system.

Fig. 2. Schematic diagram of "multipath channel generation part" in Fig. 1 (● : multipath generation function).

Fig. 2 shows two schemes of the FE-type system for generating multipath fading environment with time-varying amplitude and phase of $M \times L$ paths. Fig. 2(a) shows a configuration adopted in most of available systems, and we call this "path-controlled type" or "FE-1". As introduced in [5], the FE-1 configuration enables the use of a number of fading simulator units that can flexibly control the amplitude, phase, and delay. Since the use of such high-performance fading simulator units is needed, high cost is inevitable for the system construction. Fig. 2(b), on the other hand, is a scheme of the simplified configuration proposed in this paper. We denoted this configuration as "antenna-branch-controlled type" or "FE-2".

In the first stage, desired spatial correlation characteristics among transmission ports between $M$ transmitting antenna ports and $L$ probe antennas are realized using a fixed matrix connection. The second stage generates multipath delays and individual Doppler shifts branch by branch. This kind of functional separation results in a very simple configuration which has a large merit from a practical point of view. Fig. 3 shows a more detailed functional diagram of the proposed system.

The FE-2 configuration enables the independent Rayleigh fading for different input signal ports when receiving those signals at the receiving point via a fixed matrix connection using Walsh-Hadamard (WH) coding [9]. By suitably adjusting each delay path weight, the spatial combining of the signals from those antennas produces each independent Rayleigh fading. This configuration, unlike FE-1, does not require the generation of the Rayleigh variations in the network. Since it does not include any time-varying functions in the signal processing stage, its structure can be quite simple and easily made.

2-2 The Channel Model

Fig. 4 shows statistical expression of MIMO propagation channel which must be realized in MIMO-OTA systems. Propagation characteristics such as Tx-side spatial correlation, Delay profile, Doppler spectrum, and Rx-side spatial correlation, are key factors which must be equipped.

Based on the channel model expressed in Fig. 4, time-varying impulse response of wideband propagation channel in FE-2 type MIMO-OTA system, $H(t, \tau)$, can be expressed after functional decomposition by
\[ H(t, \tau) = A_{\text{RX}} A_{\text{Doppler}}(t) H_{\text{delay}}(\tau) A_{\text{RX}} \]

with

\[ H_{\text{delay}}(\tau) = \sum_{k=1}^{K} A_{\text{delay}}^{(k)} \delta(\tau - \Delta \tau_k) \]

where \( K \) is the number of delayed paths, \( \Delta \tau_k \) is the delay of \( k \)-th path signal, and \( \delta \) is the Dirac delta function. \( A_{\text{TX}} \) is the \( L \times M \) matrix connecting the transmitting array and the probe antenna array (we call this "Connection Matrix"). In our system, we adopt it to make the input antenna port correlation becomes independent, namely, signal from each input port fluctuates independently each other when receiving it at the reception side. In this case, we can use WH code weighting for the connection matrix. For example, in the case of \( M=4 \) and \( L=8 \), the following matrix is used:

\[
A_{\text{TX}} = \begin{pmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & -1 & 1 & -1 & -1 & 1 & -1 & -1 \\
1 & 1 & -1 & 1 & 1 & -1 & 1 & -1 \\
1 & -1 & -1 & 1 & -1 & 1 & -1 & 1
\end{pmatrix}^T
\]

where \((.)^T\) is the transpose of the matrix.

\( A_{\text{Doppler}} \) is the \( L \times L \) diagonal matrix for addition of the Doppler frequency shifts to each probe antenna branch signal, and \( A_{\text{RX}} \) is the \( N \times L \) matrix connecting the probe antenna array and the receiving array. In general, \( A_{\text{Doppler}} \) is automatically determined as a function of the probe antenna position in the direction of \( \theta_l \) as well as the operational frequency \( f \) and assumed vehicular speed \( v \). In order to avoid symmetrical arrangement in probe antenna positions to the assumed vehicular moving direction that can cause same Doppler shift on antenna pairs, we added a small angular offset to each probe antenna direction [7].

### III. Development of FE-2 Type MIMO-OTA System

#### 3-1 The System Configuration

Fig. 5 shows the basic configuration for realization of the proposed method shown in Fig. 3. A prototype system without delay line unit (Part-2 in the figure) has already been constructed using all hardware components in 5 GHz where the performance has been identified through our experiment in an anechoic chamber [7], [8]. The objective of this paper is to extend the narrowband FE-2 configuration to a broadband one, by incorporating a multipath delay function. As we do not know any of commercially available analogue circuit devices capable to generate several tens of \( \mu \)s order delays flexibly, we have to change the design policy from hardware-oriented system like the narrowband one that is using RF circuits to digital signal processing in IF band that is using an FPGA board. To avoid circuit configuration complexity relating to the software implementation into the FPGA, the parameter value settings are entered externally from a personal computer (PC) before starting the measurement operation, and no time-varying signal processing is imposed during the operation. The WH connection matrix (Part-1) is also fixed throughout the operation. The delay amounts and weightings in the delay circuit may also be set in advance and thus remain constant during the operation as shown in Fig. 6 where the weighting scheme of each delayed wave will be discussed later.

Addition of the Doppler shift is realized after the up-conversion to RF signal by adding the frequency shift corresponding to the probe antenna position. The
Doppler generation circuits adopted here are the same as that described in [7] for the narrowband MIMO-OTA system configuration. Fig. 7 shows a block diagram of the up-conversion and Doppler shift stage.

Each multipath-delayed, and Doppler-shifted signal radiated from the sensor antennas is spatially combined at the receiving point, thus obtaining Rayleigh fading in each delayed wave. This means that although the amplitude of each transmitting signal is fixed during the operation period, all of combined delayed paths show independent Rayleigh fluctuations when receiving the signals at the reception side.

In order to realize the above functions, we adopted orthogonal weighting to each delayed wave similar to that for input port signals. The overall channel characteristics given in (1) is finally expressed as

$$H(t, \tau) = \sum_{i=1}^{K} A_i^{(k)}(t) \delta(t - \Delta \tau_k)$$

where

$$A_i^{(k)}(t) = \{a_{mn}^{(k)}(t)\}$$

$$a_{mn}^{(k)}(t) = \sum_{l=1}^{L} w_{ml}^a a_i^{(k)} c_4 e^{j(2\pi f_{sd} t + kd_c \cos \theta)}$$

where $K$ is the number of delayed waves, $m$ and $n$ mean one of input (Tx) and output (Rx) ports, and $a_{mn}^{(k)}$ is complex amplitude for $k$-th delayed signal of a path $(m,n)$. Weight $w_{ml}^a$ is a WH code weight for the input signal $m$ to branch $l$, and $a_i^{(k)} c_4$ is the weight for $k$-th delayed wave of branch $l$ given in Fig. 6. As seen in (6), the two types of weighting ($w_{ml}^a$ and $a_i^{(k)}$) can be expressed as element-by-element multiplication of two vectors ($w$ and $a$). For this reason, if WH codes are used for both, then the code for the weight vectors on $L$ probe antennas becomes the product of two WH codes. Since the product of two WH codes can reproduce WH code also, there is a possibility that the same code composition can occur accidentally. In other words, if we apply

$$w_i^a \cdot w_j^a = w_k^a$$

then among the combinations $i, j$, a number of the same $k$ may occur. The product of $w_2$ and $w_3$, for example, yields $w_4$, but the product of $w_1$ and $w_4$ also yields $w_4$. Using this weighting procedure can result an inability to obtain independence between different delay times. With $L=8$ and $M=2$, for example, if we use $w_1$ and $w_2$ for the input port signal weighting, then just four codes $w_1, w_2, w_3$, and $w_4$ can be used for the delayed wave(s).

If the delayed waves are greater in number than $L/M$, an alternative approach must be adopted by applying weight $a$ with random numbers having 1 and -1 as elements. It is reasonable, in this approach, to apply the WH code for delay waves of higher strength, and random number for delay waves of lower strength (even though this may degrade orthogonality and thus result in correlating variations) [7].

### 3-2 Developed System

Table 1 shows the specification and component used in the developed system. An evaluation board (Xilinx ML623) with an FPGA (Xilinx Virtex-6 LX240T) was
Table 1. System functions and performance of the developed system.

<table>
<thead>
<tr>
<th>Function</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input port: M</td>
<td>4</td>
</tr>
<tr>
<td>Porbe antennas: L</td>
<td>8</td>
</tr>
<tr>
<td>Delayed paths: K</td>
<td>10</td>
</tr>
<tr>
<td>Delay resolution (min)</td>
<td>5 ns</td>
</tr>
<tr>
<td>Maximum delay</td>
<td>50 μs</td>
</tr>
<tr>
<td>Signal sampling rate (max)</td>
<td>180 MHz</td>
</tr>
<tr>
<td>IF frequency (max)</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Signal bandwidth (max)</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Maximum Doppler shift</td>
<td>1 kHz</td>
</tr>
</tbody>
</table>

used for installation of signal processing stage for IF band Input/Output signal. The number of input ports is 4 ($M=4$), and that of probe antennas is 8 ($L=8$). As for multipath generation, the number of delayed paths is 10 (max), and the minimum delay setting is 5 ns while the maximum one is 50 μs. Since the maximum sampling rate of 180 MHz is achieved, we can handle IF band signal where the carrier frequency of about 40 MHz and signal bandwidth is also around 40 MHz. Fig. 8 shows a photo of the FPGA board with a 4-ch ADC and two 4-ch DACs. Fig. 9 shows the RF part composed of eight up-converters and eight IQ modulators for the Doppler shift addition. Although the radio frequency itself is not specified in our system, we set the operation frequency of 5 GHz at this time. For the purpose of the developed system performance assessment, an eight-port combiner, which is not necessary in the actual OTA system is used temporarily, and is seen in the figure. Fig. 10 shows actual antenna arrangement in our radio anechoic chamber.

Fig. 11 shows a signal spectrum of received signal at 5 GHz combined using a combiner shown in Fig. 9. In the figure, signal spectrum with eight different Doppler shifts generated in the circuit shown in Fig. 7 can be seen very clearly. Fig. 12 shows autocorrelation function (ACF) of the received signal $a_{11}$ as a function of the normalized time $f_{D}\Delta t$. A good coincident between two ACFs, one is the theoretical value in the case of sufficiently larger values of $L$ and the other is that generated by the proposed scheme, can be seen in the figure. The generation of multipath delays and their independent fluctuations for $M=2$ and $K=3$ was confirmed by an experimental set up shown in Fig. 13(a). In order to identify each input signal ($m=1$ or $m=2$) and its multipath delays, we used two synchronously-controlled switches shown in the figure. Fig. 13(b) shows an example of re-
Fig. 11. Power spectrum of received signal composed of eight different Doppler shift signals.

Fig. 12. Autocorrelation function of a received signal \((a_{11}(t))\) where values of \(|\rho|^2\) are plotted.

Fig. 13. Confirmation of multipath generation.

Table 2. Correlation coefficient between \(a_{m}^{(4)}\) and \(a_{m}^{(4)}\) (Numerical values in the table are absolute values of the correlation coefficient \(|\rho|\)).

<table>
<thead>
<tr>
<th>Index</th>
<th>(a_{11}^{(1)})</th>
<th>(a_{11}^{(2)})</th>
<th>(a_{11}^{(3)})</th>
<th>(a_{12}^{(1)})</th>
<th>(a_{12}^{(2)})</th>
<th>(a_{12}^{(3)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_{11}^{(1)})</td>
<td>1.0000</td>
<td>0.0069</td>
<td>0.00095</td>
<td>0.0048</td>
<td>0.0029</td>
<td>0.0060</td>
</tr>
<tr>
<td>(a_{11}^{(2)})</td>
<td>0.0069</td>
<td>1.0000</td>
<td>0.0037</td>
<td>0.0041</td>
<td>0.0062</td>
<td>0.0012</td>
</tr>
<tr>
<td>(a_{11}^{(3)})</td>
<td>0.0095</td>
<td>0.0037</td>
<td>1.0000</td>
<td>0.0055</td>
<td>0.30009</td>
<td>0.0076</td>
</tr>
</tbody>
</table>

received signal displayed on an oscilloscope after frequency conversion of the received signal from 5 GHz to IF band signal (40 MHz) again to obtain this picture. Table 2 gives mutual correlation coefficient between \(a_{m}^{(4)}\) and \(a_{m}^{(4)}\) (\(|\rho|\)). As noticed from the table, the independence among multipath delayed waves can be identified. From the results in Fig. 12 and Table 2, we can conclude that the proposed system works correctly as expected.

Eigenvalue characteristics of the generated channel in the case of \(M=2\), \(L=8\) and \(N=2\) were already measured for narrowband signal case [7]. Fig. 14 shows the result of this measurement. The 2x2 MIMO has two eigenvalues. Since antenna separation of the receiving array is one wavelength, we can expect that the characteristics become those of the theoretical i.i.d. case. We can see that measurement result and theory agrees very well.

Therefore, we can conclude that the FE-2 type configuration proposed and developed here can realize the all necessary functions concerning MIMO-OTA systems very accurately with an extremely simple configuration.

IV. Conclusion

We have developed a MIMO-OTA system with simplified configuration. The key element of our proposal is the adoption of an antenna-branch-controlled configura-
Fig. 14. Eigenvalue characteristics of 2×2 MIMO created from the L=8 system.

tion (FE-2) for generating multipath delayed waves. The signal processing part was implemented into an FPGA devices. Too much functions are added into the FPGA, the load on this component would be quite large and lead to increased complexity and high cost. Therefore, we concluded that it is advantageous to divide the overall load of the necessary functions between the digital signal processing component and the high-frequency hardware and thus lighten the load on the digital signal processing component. In the proposed and developed configuration shown in Fig. 3, the IF band signal is processed on an FPGA board without converting to baseband stage, and the Doppler shifts are added at a later stage in the high-frequency circuit. Of course, it seems better from a practical viewpoint if we can incorporate the Doppler shift function into the FPGA. Therefore we intend to develop the software implementation of Doppler shifter on the FPGA.

Based on the system evaluation, we identified that L=8 is the sufficient number for measuring 2×2 MIMO system performance. However, we have to consider that a larger number of probe antennas will be necessary when measuring a larger scale of MIMO systems such as 4×4, and 8×4. As a future work, we are studying more detailed evaluation on the determination of the minimum number of probe antennas needed.

In this paper, we assumed that the spatial correlation between input antenna ports is independent. However in real case, the correlation factor should be taken into consideration. Moreover, before starting the measurement, system calibration scheme must be necessary. These are left as a further study.

References


Yoshio Karasawa received B.E. degree from Yamanashi University in 1973 and M.E. and Dr. Eng. Degrees from Kyoto University in 1977 and 1992, respectively. He joined KDD R&D Labs. in 1977. Currently, he is a professor in the University of Electro-Communications (UEC), Tokyo, and a core member of Advanced Wireless Communication research Center (AWCC) in UEC. Since 1977, he has engaged in studies on wave propagation and antennas, particularly on theoretical analysis and measurements for wave-propagation phenomena, such as multipath fading in mobile radio systems, tropospheric and ionospheric scintillation, and rain attenuation. His recent interests are in frontier regions bridging "wave propagation" and "digital transmission characteristics" in wideband mobile radio systems such as MIMO. Dr. Karasawa received the Meritorious Award on Radio from the Association of Radio Industries and Businesses (ARIB, Japan) in 1998, Research Award from ICF in 2006, two Paper Awards from IEICE in 2006, and Best Tutorial Paper Awards in 2007 and 2008 from ComSoc of IEICE. He is a fellow of the IEEE and IEICE.

Katsuhiro Nakada received the B.E. degree from the University of Electro-Communications (UEC), Tokyo, in 2011, and is now a Master course student in the same university. His research interest is on wireless transmission technologies and digital signal processing architecture.

Yannes Gunawan received the B.E. degree from Yamagata University, Yonezawa, Japan, in 2010, and is now a Master course student in the University of Electro-Communications (UEC), Tokyo. His research interest is on MIMO communication technologies in mobile communication systems.

Akira Kosako received the B.E. and M.E. degrees both from the University of Electro-Communications (UEC), Tokyo, in 2009 and 2011, respectively. He is now with NTT Doicom Co. Ltd. where he is working on mobile communication systems. During his student period, he had engaged in MIMO-OTA technologies where he received a Student Presentation Award from IEICE Antennas and Propagation Technical Committee in 2011.

Sahrul Pasisingi received the B.E. degree from the University of Electro-Communications (UEC), Tokyo, in 2010, and is now a Master course student in the same university. His research interest is on MIMO communication technologies in mobile communication systems.