Propagation Channel Modeling for Wideband Radio Systems
- How to create realistic MIMO propagation environment for OTA measurements -

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Outline

1. Introduction: MIMO and MIMO-OTA
2. Channel Model for MIMO OTA Systems
   - Simplified Configuration
   - Channel Model
3. Two-Stage Scheme for MIMO Fading Emulator
4. Development of MIMO Fading Emulator using FPGA
5. Application Examples
6. Conclusion
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MIMO Technologies

MIMO covers wide technical areas

Radiowave Propagation

Tx array
Encoding with time and space domain

Rx array
Decoding with time and space domain

Multi-path propagation

Information theory and coding theory

Adaptive array and adaptive signal processing

Applications are from W-LAN to next-generation mobile wireless systems.
Trend of MIMO R&D

- Transmission scheme
- System application (from WLAN to LTE-advanced)
- System development (MU-MIMO, large-scale MIMO)

- Establishment of performance evaluation system for MIMO user terminal (MIMO-OTA)
  - Handset-related problem such as antenna coupling effect
  - High needs to the measurement system development
  - Insufficient research for MIMO-OTA
  - Establishment of standard scheme
We want to evaluate MIMO user terminal performance.

Necessity of evaluation environment

Construction of MIMO-OTA Measuring System

Fading Emulator Type

Reverberation Chamber Type

Hybrid Structure Type
Two Types of MIMO-OTA Systems

Fading Emulator Type (FE)
- Full functions
- Higher Flexibility
- Higher Construction Cost

Reverberation Chamber Type (RC)
- Multipath-rich Environment with large delay
- Lower Construction Cost
- Lower Flexibility

Both have merit and demerit, and I understand there are no almighty method for OTA measurement scheme.
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Required Function for MIMO-OTA Measurement System

- **Tx-side Spatial Correlation** (depending on Angle of Departure)
- **Delay Profile** (Delay Spread)
- **Doppler Spectrum** (Doppler Spread)
- **Rx-side Spatial Correlation** (depending on Angle of Arrival)

**Real Channel**

**Generated OTA Channel**

**Signal Processing** (Fading Emulator)

**OTA Environment**
Fading Emulator-type MIMO OTA System

Multiple Input (Transmitting Antenna ports: M)

Multipath channel generation

Multiple Output (Receiving Antenna ports: N)

Probe Antennas: L

Multipath environment
- Spatial correlation
- Doppler spectrum
- Delay profile

Multiple Output (Receiving Antenna ports: N)
Basic Configuration of Multipath Fading Generation Part

Path-Controlled Scheme

- Number of delay units: \( MLK \)
- Number of Rayleigh faders: \( MLK \)
  \((K: \text{Number of multipath delays})\)
- Almost perfectly controllable
- Large scale configuration

Antenna-Branch-Controlled Scheme

- Number of delay units: \( LK \)
- Number of Doppler shifters: \( L \)
- Flexibly controllable
  \((\text{realization of some functions is limited.})\)
- Simplified configuration
  \((\text{easy to FPGA implementation})\)
Functional Block Configuration of Antenna-Branch-Controlled Scheme

All functional blocks are connected in cascade.

Doppler-shift addition

Time-invariable delay channel generation

Walsh-Hadamard code weighting

Fixed amplitude

+ $f_{DL}$

Delay $\tau$
Received Signal

\[ r(t) = H(t, \tau) \otimes s(t) + n(t) \]

Channel Model

**Channel Characteristics**

\[ H(t, \tau) = A_{RX} A_{\text{Doppler}}(t) H_{\text{delay}}(\tau) A_{TX} \]

Independent fluctuation for each input signal

**Multipath Delay**

\[ A_{TX} = \begin{pmatrix} w_1 & w_2 & \cdots & w_M \end{pmatrix} \]
\[ w_m = \begin{pmatrix} w_{m1} & w_{m2} & \cdots & w_{mL} \end{pmatrix}^T \]

**Doppler shift Generation**

\[ A_{\text{Doppler}}(t) = \frac{1}{\sqrt{L}} \text{diag} \begin{pmatrix} e^{j2\pi f_{D1}t} & e^{j2\pi f_{D2}t} & \cdots & e^{j2\pi f_{DL}t} \end{pmatrix} \]
\[ f_{Di} = \frac{v}{\lambda} \cos(\theta_i + \Delta \theta_i) \]

\[ A_{RX} = \begin{pmatrix} u_1 & u_2 & \cdots & u_L \end{pmatrix} \]
\[ u_l = \begin{pmatrix} u_{l1} & u_{l2} & \cdots & u_{LN} \end{pmatrix}^T \]
\[ u_{ln} = e^{jkd_n \cos(\theta_i - \theta_0)} \]

Array antenna reception in the case of a linear array without antenna coupling
Probe antenna arrangement having all different Doppler-shift values

Regular arrangement (Symmetric arrangement)
Probe antenna arrangement having all different Doppler-shift values

Regular arrangement with fixed offset

![Diagram showing probe antenna arrangement with different Doppler-shift values and a regular arrangement with fixed offset.]
Probe antenna arrangement having all different Doppler-shift values

Proposed arrangement (double offset)

Non symmetrical arrangement for any combination of two antennas
CDF of Generated signal amplitude

- Theoretical (uniform)
- Regular position
- Fixed offset
- Proposed allocation

Cumulative probability
Amplitude (dB)

L=8

1. Regular
2. Single offset
3. Double offset

Rayleigh

Doppler-shift

Amplitude

-50 -40 -30 -20 -10 0 10

Cumulative probability

-0.0001
-0.001
-0.01
-0.1
1

0.0001
0.001
0.01
0.1
1

16
Eigenvalue characteristics of 4 x 4 MIMO in i.i.d. condition

\[ \lambda_1 \sim \lambda_4 : \]

Eigenvalues of \( AA^H \)

where \( A \) is channel matrix.
Weight Matrix (≡Connection Matrix) for realizing independent fluctuations of all delayed paths

Doppler-shifted fixed amplitude delay waves

Independent Rayleigh fluctuations

Input

1

2

Output

FE

\[ W_{WH-L} = W_{WH-delay} \otimes W_{WH-TX} \]

Probe antenna weighting matrix \((KM \times KM)\)

Delay signal connection matrix \((K \times K)\)

Tx-port signal connection matrix \((M \times M)\)
Amplitude distribution of each generated delay paths

Fig. 13

Amplitude (dB)
Cumulative probability

#1 (1.0) #2 (0.8) #3 (0.6)
#4 (0.4) #5 (0.2)
#6 (0.1)

M = N = 2
L = 8
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When the chamber space is not sufficiently large to arrange the probe antennas in the chamber, and if the range in one direction is enough, then ....

For example, antenna array mounted in a car.
Two-Stage Scheme

Second stage

[Multipath Generation Part]

Multipath connection matrix

Multiple Input

Multiple Output

MIMO Fading Emulator

First stage

[Antenna pattern measurement or calculation]
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### Specification and Performance of Developed System based on Two-Stage Scheme

<table>
<thead>
<tr>
<th>FPGA IC Baseboard</th>
<th>XILINX Virtex 6 LX240T XILINX ML605</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input/Output</strong></td>
<td></td>
</tr>
<tr>
<td>ADC</td>
<td>4DSP FMC104 (14bit)</td>
</tr>
<tr>
<td>DAC</td>
<td>4DSP FMC204 (16bit)</td>
</tr>
<tr>
<td>Input ports $M$</td>
<td>4</td>
</tr>
<tr>
<td>Output ports $N$</td>
<td>4</td>
</tr>
<tr>
<td><strong>Signal processing</strong></td>
<td></td>
</tr>
<tr>
<td>Clock frequency $f_s$</td>
<td>160MHz</td>
</tr>
<tr>
<td>IF frequency</td>
<td>40MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>40MHz (max)</td>
</tr>
<tr>
<td><strong>Propagation parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Probe antennas $L$</td>
<td>16 or 32</td>
</tr>
<tr>
<td>Delay paths $K$</td>
<td>8</td>
</tr>
<tr>
<td>Maximum delay</td>
<td>50$\mu$s (for $k=1$-6), 200$\mu$s ($k=7,8$)</td>
</tr>
<tr>
<td>Delay resolution</td>
<td>6.25ns (when $f_s=160$MHz)</td>
</tr>
<tr>
<td>Doppler frequency</td>
<td>up to 10kHz</td>
</tr>
</tbody>
</table>
FPGA Implementation of 4x4 MIMO Fading Emulator

Parameters’ value setting

FPGA

PC

Input

\( s(t) \)

Output

\( r(t) \)

\( M(4) \)

\( W_{TX} \)

\( W_{WH}^{(k)} \)

\( b_k \)

\( A_{Doppler} \)

\( A_{RX} \)
Developed MIMO Fading Emulator with FPGA Implementation

All necessary functions to generate multipath environment is implemented in this small box.

(Size: 28cm × 22cm × 5cm)
Element pattern pattern and corresponding Doppler spectrum

\[
\begin{align*}
&f_{IF} = 40 \text{MHz}, f_D = 334 \text{Hz} \\
&f_{IF} - f_D & \to \text{Power [dBm]} \\
&f_{IF} & \\
&f_{IF} + f_D & \to \text{Power [dBm]}
\end{align*}
\]
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Application Example 1: WLAN (IEEE 802.11n) Throughput Evaluation

AP

UE/UT

WZR-AMPG300NH

Intel Centrino Advanced-n 6200
Application Example 1: WLAN (IEEE 802.11n) Throughput Evaluation

- **WLAN (AP):** BUFFALO WZR-AMPG300NH
- **UE: Intel Centrino Advanced-N 6200**

Diagram:
- **Up Conv.** and **Down Conv.** for signal conversion
- **Circulator** for signal direction change
- **MIMO Fading Emulator (FPGA)**
- **ATT** for signal attenuation
- **Channel-control signal** for communication control
- **PC** for data processing
- **Rx Data** and **Tx Data** for data transmission

- **(5GHz) (40MHz)** for frequency bands

[Diagram detailing the signal flow from WLAN (AP) through MIMO Fading Emulator to WLAN (UE) with ATT for signal treatment and channel control for data transmission]
Evaluation Examples

Change of Doppler spread

Change of delay difference
Evaluation example in Rayleigh fading environment

Throughput [bps]

0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600

Doppler shift $f_D$ [Hz]

0 200 400 600 800 1000 1200 1400 1600

GI

Delay difference [ns]
Application 2: Channel Capacity Evaluation in the case of Antenna Coupling and Spatial Correlation

Sleeve antenna: 33mm (0.56\(\lambda\))

(a) \(d_r = (1/8) \lambda\)

(b) \(d_r = (3/2) \lambda\)
Element Antenna Pattern for N=4

\[ d = (1/8) \lambda \]

\[ d = (1/2) \lambda \]

Each element pattern without coupling
Developed MIMO Fading Emulator

Multiple Input

Multipath Generation Part

Multiple Output

Measured Antenna Pattern data
MIMO Channel Capacity Decrease due to Antenna Coupling

- Experiment in RC using actual antenna
- Simulation using antenna pattern data
- i.i.d. (without SC and AC)

Average channel capacity (bit/s/Hz) vs. Antenna spacing d (wavelength)
Conclusions

- We discussed a propagation channel model for OTA test systems.
- One of the primary practical advantages of the proposed scheme is the realization of a flexible MIMO OTA testing system in a very simplified configuration without the loss of necessary functions.
- Due to the way that the fading functions are configured in a cascade, an implementation of the scheme into FPGA circuit is promising from a practical viewpoint.
- We showed detailed performance of the FPGA-implemented fading emulator and a couple of applications of the system to wireless communication performance evaluations.
What I want to say is

MIMO Fading Emulator/Simulator having all necessary propagation functions can be realized easily without expensive cost.
Thank you very much for your kind attention!!