MIMO Propagation Channel Modeling

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The Multiple-Input Multiple-Output (MIMO) Channel

A MIMO system consists of several antenna elements at both transmitter and receiver, plus adaptive signal processing; this combination exploits the spatial dimension of the radio propagation channel.
Goals of MIMO

- **Array Gain**
  - increase receive power
  - beamforming

- **Spatial Multiplexing**
  - multiply data rates

- **Interference Suppression**

  But will the propagation channel support what you devise?

- **Diversity**
  - mitigate fading

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MIMO Channel Matrix $H$

Consists of $M \times N$ impulse responses $h_{ij}$ of transmit antenna $j$ to receive antenna $i$.

\[
H(t, \tau, \varphi) =\
\begin{bmatrix}
    h_{11}(t, \tau, \varphi) & h_{12}(t, \tau, \varphi) & \ldots & h_{1N}(t, \tau, \varphi) \\
    h_{21}(t, \tau, \varphi) & h_{22}(t, \tau, \varphi) & \ldots & h_{2N}(t, \tau, \varphi) \\
    \vdots & \vdots & \ddots & \vdots \\
    h_{M1}(t, \tau, \varphi) & h_{M2}(t, \tau, \varphi) & \ldots & h_{MN}(t, \tau, \varphi)
\end{bmatrix}
\]

Time $t$

Signal delay $\tau$

Angular dependence $\varphi$
Outline

Modeling Philosophies
- random or deterministic channel?
- individual multipath or MIMO matrix?

MIMO Measurements

Two Models
Deterministic vs random MIMO channels

In general, the MIMO channel is *random*.
A snapshot of the MIMO channel is a single *deterministic*
realization of the random MIMO channel.
Deterministic and random MIMO channels have to be treated
quite differently!

We model the channel for *network planning and deployment*: as
deterministic, *site*-specific – by Maxwell, UTD,…

We model the channel for *system design* and testing: as random,
*scenario*-specific – by statistics (distribution & moments)
Sources of MIMO Randomness

WSS

Scatterers may move, but the environment remains wide-sense stationary (WSS)
Sources of MIMO Randomness

Nonstationary

Rx moves *beyond the limits of a stationary environment*
Common mistakes in MIMO channel modeling

- Make ONE model from measurements in different, albeit stationary scenarios
- Make ONE model, believed to be stationary, from measurements in non-stationary scenario
  (Correction due to J.-C. Oestges’ question)

- AVERAGE channel that never exists
What to model?

A. Electromagnetic propagation in detail => multipath

- scattering objects
- path loss
- (de-)polarization, XPD
- angular distribution
- temporal evolution
- Doppler

… and eventually $H$, the MIMO channel matrix

B. MIMO channel matrix $H$ directly
Geometry-based stochastic channel modeling (GSCM)

- If A: deterministic ray-tracing or random scattering objects?
- Compromise: Geometry-based Stochastic Channel Modeling (GSCM)

- Select sample scenarios
- Prescribe *probability density function* of near-by scatterers
- Prescribe regions of distant scatterers such as high-rise building groups or mountains (fixed in space)
- Simple ray tracing with specular reflection
- Excellent for time evolution and interference modeling
Outline

Modeling Philosophies

MIMO Measurements
- massive postprocessing
- double-directional channel
- clusters
- diffuse multipath
… and common mistakes

Two Models
Measurement equipment

Figure 2. Element radiation pattern measured in the spherical array.

The 6-dB beamwidth of the element is 90° in the E-plane and 100° in the H-plane. The polarization discrimination is better than 18 dB within 6-dB beamwidth. The measured gain of the element is 7.8 dB. The reflection loss is over 10 dB inside the whole measurement band (2.154 ± 0.1 GHz).

The antenna elements are mounted on a spherical surface consisting of two hollow aluminum hemispheres with outer diameter of 330 mm. The elements are isolated from the mount, and the distance from the center of the fed patch (see Fig. 1.1) to the center of the sphere is 170 mm. The elements point towards the normal of the sphere and they are oriented so that the polarization vectors are parallel to unit vectors $u_\phi$ and $u_\theta$. The 64-channel RF switching unit is placed inside the ball together with its control electronics. Only the RF signal cable, two coaxial control cables, and the power supply wires are lead outside the ball. Figure 3 and Figure 4 present the configuration of the spherical array and the switching unit placed inside it.

Figure 3. Spherical array of 32 dual-polarized microstrip patch elements.
Superresolution Estimation of Multipath Components

- Massive signal processing
- Direction finding by
- ESPRIT, MUSIC, SAGE, RIMAX,...
The Double-directional Propagation Channel

Radio Channel

"Single-directional" Channel for DOAs

h(t, τ, φ_R, θ_R)

Double-directional Propagation Channel

h(t, τ, φ_R, θ_T, θ_R)

h(t, τ)

M. STEINBAUER, COST259 TD(98)027, Feb.1998, Berne, Switzerland
M. STEINBAUER et al., IEEE VTC-2000-Spring, Tokyo, May 15-18, 2000
M. STEINBAUER et al., IEEE AP Magazine, August 2001, pp. 51-63

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Backyard - OLOS: Tracing Individual Multipath
Observed MIMO effects

- DOA depends on DOD => double-directional
- DOAs and DODs different for different delays
- Strong discrete multipath components, which appear in clusters…
- plus diffuse power
- As a consequence, MIMO exhibits
  - extremely high local variation
  - time dependence
  - frequency-selectivity
• Discrete multipath does not fully account for power delay profile
• “diffuse” remainder due to multiple small scattering contributions
• not noise!
Multipath Clusters

- Clusters modify the temporal and angular dispersion:

- Global dispersion parameters:
  - rms delay spread
  - (total) rms angular spreads (“composite AS”)

- Cluster dispersion parameters:
  - cluster rms delay spread
  - cluster rms angular spreads (“intra-cluster AS”, “component AS”)

scatterers

Tx

Rx

Tx azimuth spread

Rx cluster spreads

Tx cluster spreads

scatterers

Rx azimuth spread
Outline

Modeling Philosophies

MIMO Measurements

Two Models
- WINNER II
- why-sell-burgers?
WINNER II: MIMO link with details

$N$ clusters (“paths”) each defined with:

- Delay
- AoD
- AoA
- Gain
- Cross-pol. (XPR).
- Sub-paths (“MPCs”, “rays”)
WINNER Channel Model for 4G evaluations

- A Geometry-based Stochastic Channel Model
  - as 3GPP SCM, COST 273, etc. models.
- Based on extensive measurements in WINNER (+ literature).
  - Parameters for more than 10 propagation environments
  - Two levels of randomness
  - for system-level modelling
- Carrier frequency range 2 – 6 GHz
- Bandwidth 100 MHz
- Drop-based time evolution

- Selected by ITU-R for IMT-Advanced validation (4G)
- COST 2100 => MIMO Multilink Model
Model MIMO matrix directly (Plan B)

Advantageous for system simulations
- when Rx and Tx arrays already have been specified \((N,M,d,\text{polarization},\ldots)\)
- when we need to produce a set of MIMO matrices

We treat \(H\) as a random variable
- completely random? No, correlation comes into play

- **Correlation** of sub-channels as a consequence of both
  - the antenna arrays and
  - the propagation environment

- In MIMO it is always a correlation between sub-channels, not antenna signals!

Full CSI, partial CSI, no CSI?
- no CSI: full correlation matrix \(R_H\) matters \(M \times N\)
Modeling the correlation matrix $R_H$

1. No correlation between any two elements of $H$
   \[ R_H = I_{MN} \quad H = H_u \quad \text{(i.i.d., “rich scattering”)} \]

2. receive correlation \[ R_R = E[H^*H^T] \]
   transmit correlation \[ R_T = E[H^HH] \]

3. Separately correlated “Kronecker model” \[ R_H = R_R \otimes R_T \]

Any transmit antenna weight results in one and the same receive correlation!
The [why]-[x]-[sell]-[burger] model is based on MIMO eigenmodes. It models the channel by a coupling matrix $\Omega$ of transmit and receive eigenmodes, accounting for joint correlation of Tx and Rx sides. It reveals which MIMO scheme is best in a given environment and has been proven independently to render mutual information (“capacity“), diversity order, etc. better than any other model so far. It works in any environment (in-, outdoor, LOS) and at any frequency 0.3 through 5.8 GHz. Weichselberger et al., IEEE Trans Wireless Comm, 2006
Weikendorf 34, TX diversity, RX beamforming
Weikendorf 32, multiplexing up to 5 streams

Position: Weiken-32
Model Fit: 0.90498
Weikendorf 1, beamforming at RX and TX
What is a good MIMO channel model?

Let’s look on some metrics

- **Mutual information**
  - Eigenvalues $\lambda_i$ of $HH^\dagger$
  - Distribution of $\lambda_i$
  - Condition number CN
  - Outage capacity

- **Diversity order** (Ivrlac & Nossek)

- **Which effect?**

- **How many parameters?**

- **Which effect?**

- **How many parameters?**

![Cumulative Distribution Function](image)

- Median mutual information
- 10% outage capacity

\[ \sum_{i=1}^{\infty} \lambda_i \]
A myth: „Capacity is a sufficient metric for deciding whether a MIMO model is good or not“

- All MIMO models I have seen render ergodic capacity within + - 20% correctly
- So what does agreement of modelled and measured capacities tell us?
- Not very much!

Ergodic MIMO capacity is a necessary but neither a sufficient nor a sensitive metric.
Open challenges

- Diffuse multipath
- Vehicle-to-vehicle
- Body-area networks
- Over-the-air (OTA) MIMO terminal testing
“Didn’t we have already enough channel research?”

No, we have been interested in the *average* channel,
but in the future we will have to be interested in the MIMO channel *here and now*.

Link to collection of NEWCOM++ MIMO measurements
https://portal.ftw.at/workspaces/channeldb/measurements

Thank you!