Lateral Position Dependence of MIMO Capacity in a Hallway at 2.4 GHz

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Hallway Scenarios of Interest

Universities
Study areas often located within hallway-like spaces

Courthouses
Laptop/PDA users seated on benches

Hospitals
Wireless-enabled gurneys and monitoring equipment parked in hallways

Related but significantly different:
Aircraft passenger cabins
Ship corridors
Tunnels

Relatively low loss
MIMO in Hallways


“Rank collapse” within a few 10s of meters

Field strength in horizontal plane drops off near walls

Fig. 3. Average capacity of the measured channel in the hallway for SNR=20 dB, receiver array facing east.
Simple Model for Hallway Propagation

Transmitted field imagined as plane wave “bounce modes”

Mode loss with distance in horizontal plane increases with mode order

Vertical plane: Assuming $\sigma$ or $\varepsilon_r$ large for floors/ceilings, mode loss with distance in vertical plane decreases more slowly

**Rank collapse** occurs because low-order modes propagate best

**Wall taper** occurs because reflected wave from walls tends to cancel incident wave as grazing angle is approached

Seems to explains “downrange” capacity and “crossrange” signal strength – now interested in crossrange capacity and dependence on height
Test Conditions

Hallway 1.5 m wide \times 2.7 m high
False ceiling
Doors closed
Range = 12 m
2.45 GHz w/ B \ll \text{coherence BW}

V-Pol, \lambda/4-monopole arrays
4-element, \lambda/2 spacing
(positioner not shown)

Matrix Channel Measurement System (MCMS)
http://www.ece.vt.edu/swe/mcms
\[ |K_{4i}| \], Horizontal Cut

\( i = 1, 2, 3 \) (transmit antennas)

Sample spacing \( \sim \frac{\lambda}{10} \)

Results repeatable to within a few %
(variations between antennas are real)

Not a classical fast fading environment!
$|K_{4i}|$, **Vertical Cut**

$i = 1, 2, 3$ (transmit antennas)

Sample spacing $\sim \lambda/10$

Starting to see some classical fast fading
\[ Tr\{KK'\} \] (Total Power Transferred)

Small variation across vertical cut; Large variation across horizontal cut.

Traditional SNR normalization

\[ HH' = KK' \frac{N_T^2}{Tr\{KK'\}} \]

will significantly overestimate performance in horizontal cut.
Problem: This is varying from trial to trial; in fact it should be constant so as not to neutralize the SNR variation

\[ \kappa \equiv E\{Tr\{KK'\}\}_{\text{vertical}} \]

Use vertical cut, over which SNR appears to be approximately constant

Computed capacity now varies properly with SNR

\[ HH' = KK' \frac{N_T^2}{Tr\{KK'\}} \]

\[ HH' = KK' \frac{N_T^2}{\kappa} \]
Capacity in Horizontal Cut

\[ \rho = 10 \text{ dB} \]

3 x 4 in all cases
Assuming perfect CSI.
Ideal 1 x 1 is 3.5 bps/Hz.

Ideal full-rank MIMO channel
MIMO, measured
Ideal rank-1 channel
Best rank-1, measured
Facing beams, measured
Capacity in Vertical Cut

\[ \rho = 10 \text{ dB} \]

3 x 4 in all cases. Assuming perfect CSI. Ideal 1 x 1 is 3.5 bps/Hz.
Concluding Remarks

• **3 x 4 results** (10 dB SNR, ideally 11.5 bps/Hz)
  - Vertical cut: ~ 7.5 ± 1 bps/Hz
  - Horizontal cut: ~ 9 bps/Hz near center,
    ~ 4-6 bps/Hz near walls due to reduced signal strength
  - MIMO benefit clearly evident; although much less than might be expected

• **Scenarios involving hallways are unlike other indoor scenarios**
  - Expect rank collapse, unusual & non-”spatially ergodic” fading behaviors
  - Implications for antenna array design and placement
  - Implications for reduced-rank/antenna-select strategies, cross layer design

  - Elaboration on propagation models & comparisons with measurements
  - Comparison with rank-1 schemes
One-Slide MIMO Primer

Generalized Shannon Bound:

\[ C = \sum_{i=1}^{k} \log_2 \left( 1 + \frac{\rho}{N_T} \lambda_i \right) \]

Mean SNR per RX antenna

\[ \text{Capacity [bps/Hz]} \]

Mean SNR per RX antenna

Eigenvalues of \( HH' \), where \( H \) is the \( [N_R \times N_T] \) matrix of channel coefficients

\[ N_T=1 \text{ or } N_R=1 \rightarrow \text{rank}\{HH'\}=1 \quad \rightarrow \quad C \propto \log_2 N \]
\[ N_T>1 \text{ and } N_R>1 \text{ and } \text{rank}\{HH'\}>1 \quad \rightarrow \quad C \propto N \]

Up to \( k=\min\{N_T,N_R\} \) independent MIMO "subchannels", each with \( \text{SNR} \propto \) the associated eigenvalues of \( HH' \)
**MIMO Capacity**

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http://www.ece.vt.edu/swe/mcms
High-Level Block Diagram

- Multi-Channel Transmitter (MCT)
- Multi-Channel Receiver (MCR)
- Clock & LO Synthesis & Distribution
- Matrix Channel Under Test
- Aggregation & Corner Turning
- Dig I/O
- cPCI
- Embedded PC

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MIMO Capacity
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Measurement / Processing

• 4 CW signals used on transmit (1 per antenna) with frequency offset \(<<\) coherence bandwidth used to discriminate between antennas

• 4 receive antennas coherently sampled with 40 MHz BW and recorded in 156 \(\mu\text{s} \ (<<\ \text{coherence time})\) segments

• 4 complex channel coefficients (1 per transmit antenna) extracted from each of the 4 receive antennas signal captures (16 coefficients)

• System “nose-to-nose” self-response calibrated out, yields measurement matrix \(K\)

• Data checked to confirm:
  – No noise-dominated eigenvalues (sufficient SNR)
  – No corruption due to RFI (esp. from IEEE 802.11 WLAN)

• The usual SNR normalization: \(\frac{N_t^2}{\text{Tr}\{KK'\}}\)
Calibration / Sanity Check

Eigenvalues of $\mathbf{HH}'$

“Wired” Full Rank Channel

```
MCT
```

```
MCR
```

“Wired” Keyhole Channel

```
MCT
```

```
combiner
```

```
splitter
```

```
MCR
```
Antenna Array

Identical broadside-pointing uniform linear arrays at both ends

- V-polarized ¼-wave monopoles
- ¼-wave spacing at 2.4 GHz
- Ground plane 25 cm x 2.5 cm
- -10 dB max return loss over bandwidth
- -13 dB max coupling
Horizontal Cut w/ Propagation Model

3D polarimetric orthoplane (no "twisting" rays)
model infinitely thick walls with $\varepsilon_r = 4.4$;
ininitely thick floor/ceiling with $\varepsilon_r = 6.0$;
LOS + 15 bounce modes (31 terms)
$|K_{4i}|$, **Vertical Cut Prop Model**

$i = 1, 2, 3$ (transmit antennas)

- **Graph:**
  - Y-axis: Power [dB]
  - X-axis: Distance from floor [m]
  - Three curves representing different transmit antennas

- **Diagram:**
  - Utility space with dimensions and walls labeled
  - Reference wall labeled
  - R = 12 m
“Similarity” Metric: Horizontal Cut

“Similarity”
≡ \([1 1 1 1] \cdot k_i / 4|k_i|\)
= 1 for LOS channel
= 0 for an orthogonal channel

Channel structure changes slowly, so must be simple!

Similar trends (as expected, since array elements are following same path), but significant differences

Note repeatability (max, mean, min shown)
“Similarity” Metric: Vertical Cut

Note LOS-like conditions over extended portions of the cut – quite different from horizontal cut.

Dissimilar trends (as expected, since array elements are following different paths) – consistent with simple hallway prop model.

Note repeatability (max, mean, min shown).
“Raw” Eigenvalues - Vertical Cut

Eigenvalues of $KK'$

Rank collapse is evident – clear that MIMO potential is limited.
“Raw” Eigenvalues - Horizontal Cut

Eigenvalues of $KK'$

Rank collapse is evident – clear that MIMO potential is limited.

However, also that magnitude taper is quite pronounced – effect on SNR normalization?
Capacity in Horizontal Cut, Traditional Norm

- Ideal full-rank MIMO channel
- MIMO, measured
- Ideal rank-1 channel
- Best rank-1, measured
- Facing beams, measured

$\rho = 10 \text{ dB}$

3 x 4 in all cases. Assuming perfect CSI. Ideal 1 x 1 is 3.5 bps/Hz.
Brief Digression: Eigenvalues & Capacity

- Indoor: Cluttered laboratory, approx 5 m x 10 m
- About 2 meters between arrays
- Transmit Array: 4 $\lambda/4$ monopoles, V-pol, 0.25$\lambda$ spacing
- Receive Array: same

4 x 4: Optical LOS Exists

4 x 4: Optical LOS Blocked using 1 m x 2 m metal plate
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4 x 4: **Optical LOS Exists**

4 x 4: **Optical LOS Blocked** using 1 m x 2 m metal plate

High mean SNR; Capacity here is *better.*

Low mean SNR; Capacity here is *worse.*

**Eigenvalues of $HH'$**