Antenna Design and Site Planning Considerations for MIMO

Steve Ellingson
Mobile & Portable Radio Research Group (MPRG)
Dept. of Electrical & Computer Engineering
Virginia Polytechnic Institute & State University
ellingson@vt.edu
http://www.ece.vt.edu/swe/

Fall 2005 IEEE Vehicular Technology Conference (Dallas)

A One-Slide MIMO Primer

Generalized Shannon Bound:

$$C = B \log_2 \det \left[\mathbf{I}_{N_R} + \frac{\Gamma}{N_T}\mathbf{HH}' \right]$$

Mean SNR
per RX antenna

Capacity [b/s]

Bandwidth [Hz]

Matrix of Channel Coefficients
[N_R x N_T]

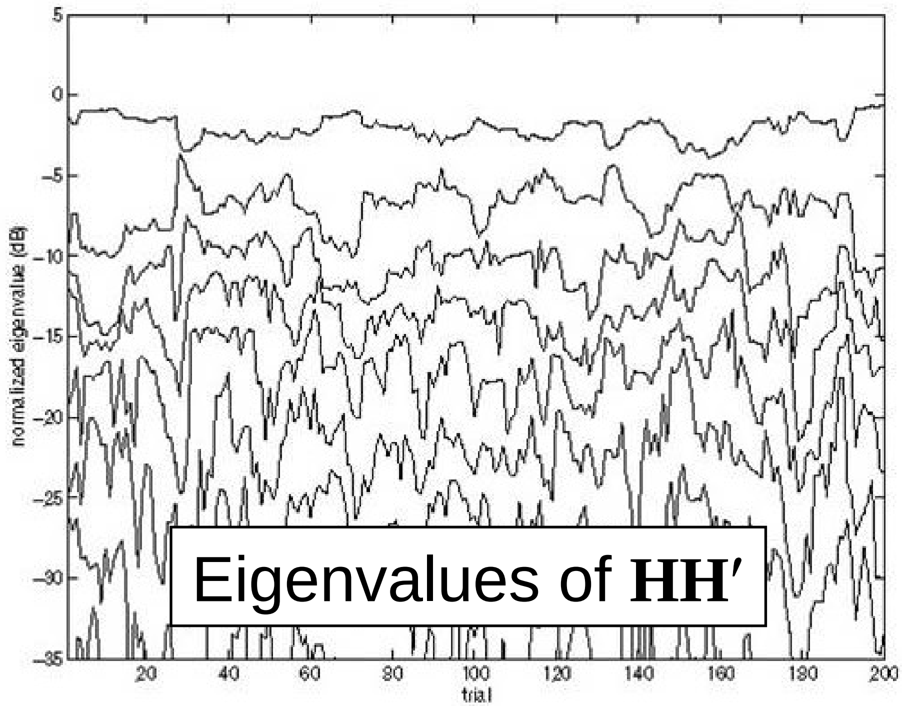
G.J. Foschini and M.J. Gans, "On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas", *Wireless Personal Communications* (Kluwer), **6**:311-335, 1998.

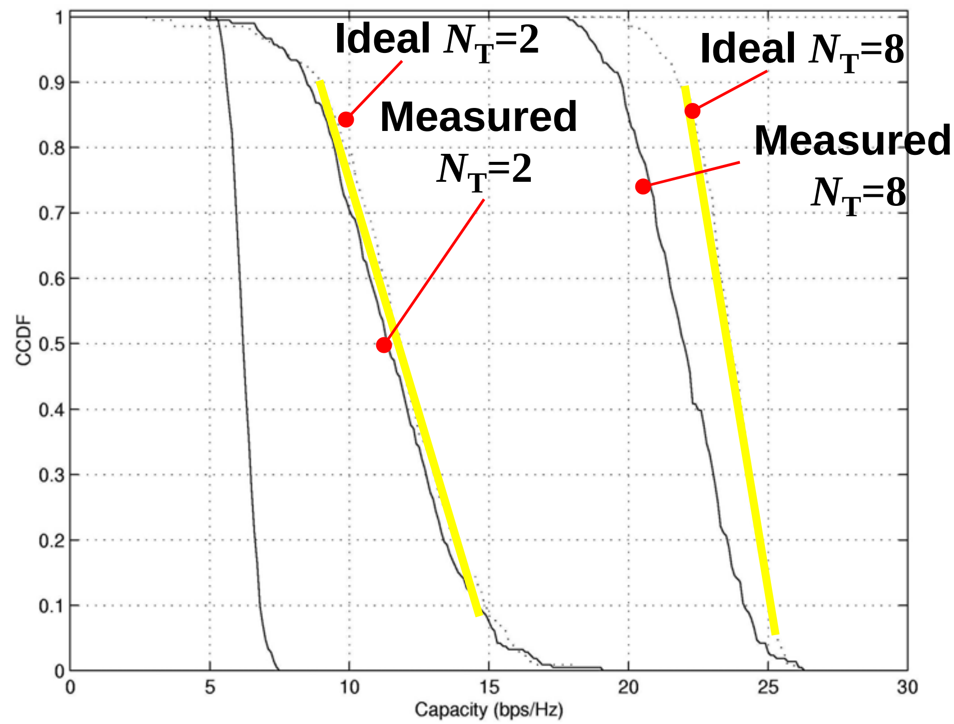
N_T=1 or N_R=1 $\rightarrow$ $rank\{\mathbf{HH}'\}=1$ $\rightarrow C \propto \log_2 N$

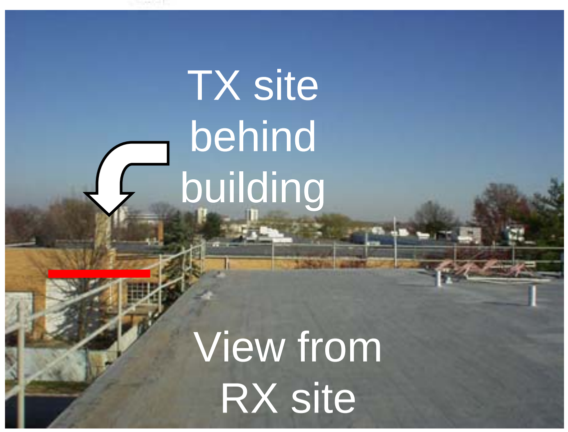
N_T>1 and N_R>1 <u>and</u> $rank\{\mathbf{HH}'\}>1$ $\rightarrow C \propto N$

Up to $k = min\{N_T,N_R\}$ independent MIMO "subchannels", each with SNR $\propto$ the associated eigenvalues of $\mathbf{HH}'$

What We Like to See!



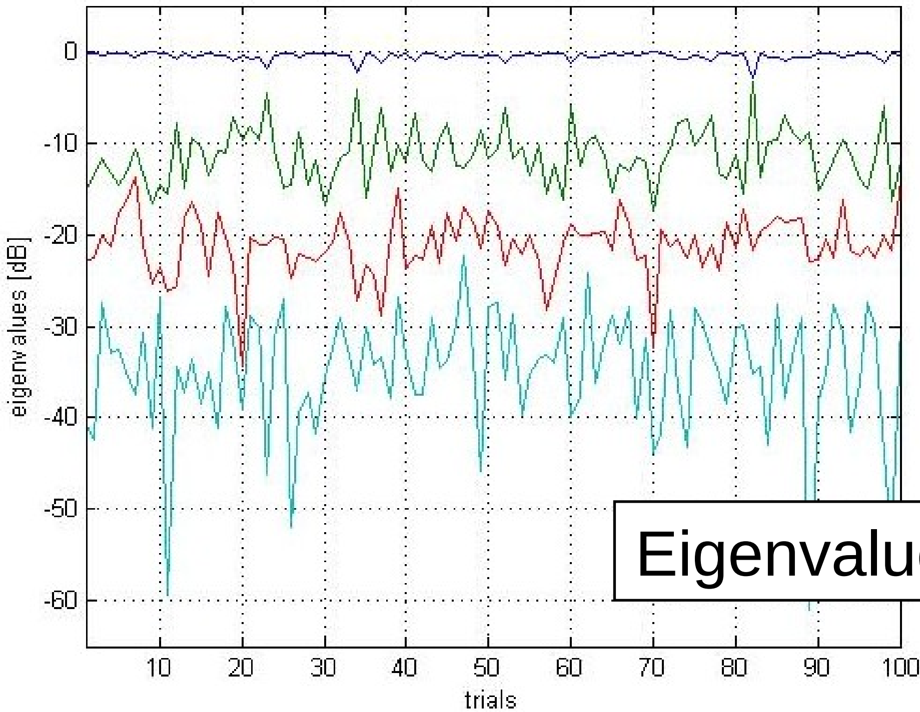


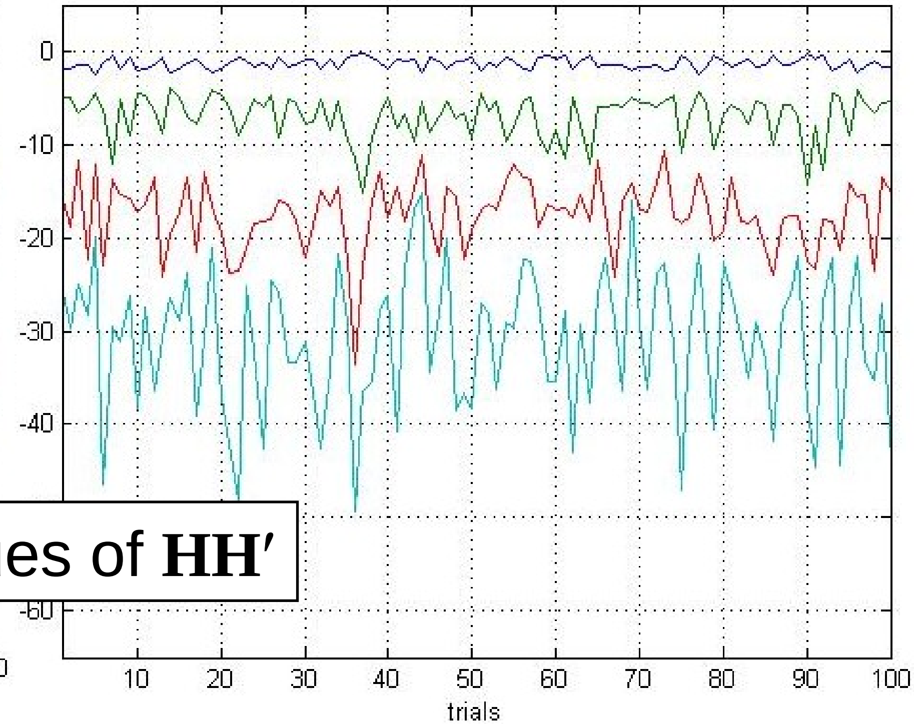


- **2.4 GHz**
- N_R**=8**

What We Like to See?

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





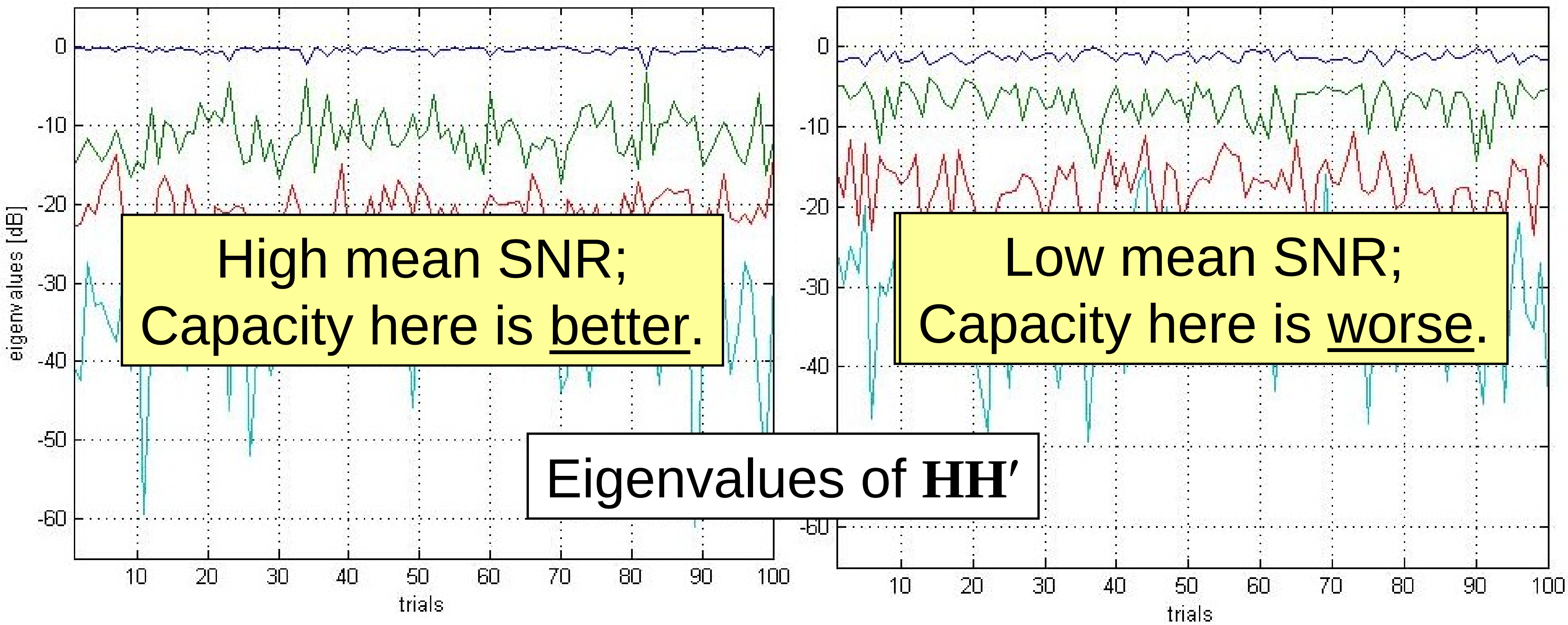
Eigenvalues of $\mathbf{HH}'$

4 x 4: <u>Optical LOS Exists</u>

4 x 4: <u>Optical LOS Blocked</u> using 1 m x 2 m metal plate

What We Like to See?

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



4 x 4: <u>Optical LOS Exists</u>

4 x 4: <u>Optical LOS Blocked</u> using 1 m x 2 m metal plate

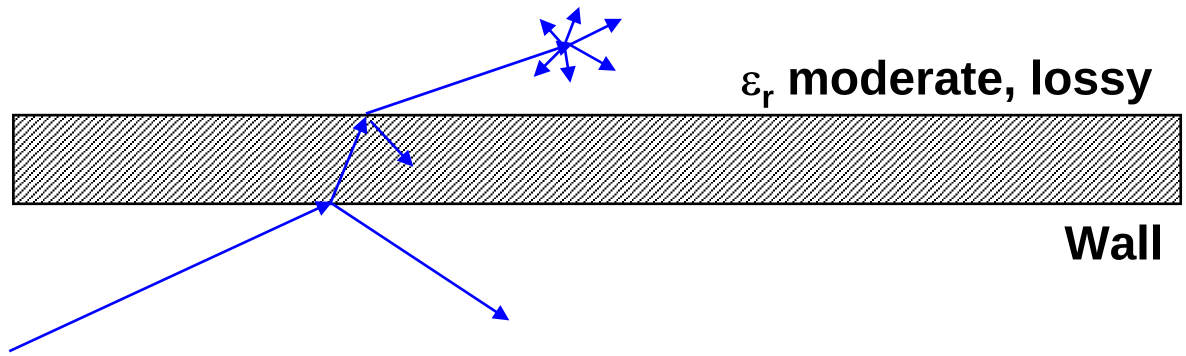
Antenna Array Design for MIMO

- **[CNR: "SNR averaged over a period >> coherence time"]**
- **A well-designed MIMO antenna system should:**
  - **Achieve size and cost goals (constrains N_T and N_R)**
  - **Achieve the required CNR over the coverage area**
  - **Maximize the diversity order**
  - **Maximize the "effective rank" k_e (i.e., the number of accessible MIMO subchannels with "useable" CNR)**
- **Some dimensions of this optimization:**
  - **Number, type, and polarization of antenna elements**
  - **Element spacing and geometry**
  - **Location and orientation of arrays within rooms and hallways**
- **Really two problems:**
  - **How to design arrays that perform OK anywhere (the "Circuit City" problem)**
  - **How to design & place arrays for specific sites**
- **This talk is really about the latter, but has implications for the former**

Indoor Propagation Characteristics

Horizontal Plane:

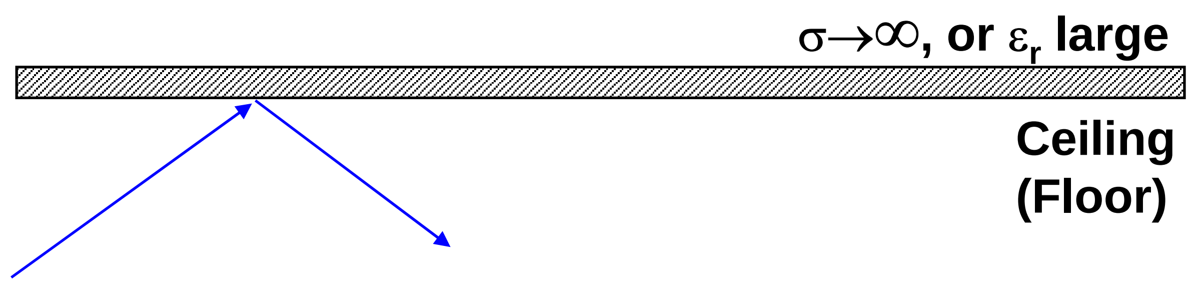
- **Copious scattering,**
- **Leakage,**
- **Loss**



Vertical Plane:

- **Some coherent scattering**
- **Efficient Containment**

(Most office buildings)



Indoor Propagation Consequences

- **Rooms:**
  - **Angle spread (AS) is large $\rightarrow$ Exploitable space diversity**
  - **High xpol; no pol. preference $\rightarrow$ Exploitable pol. diversity**

- **Hallways:**
  - **AS is narrower**
    - **Confined in <u>elevation</u> plane by floor and ceiling**
    - **Dominated in <u>azimuth</u> plane by coherent scattering**
  - **Lower xpol compared to rooms $\rightarrow$ pol. diversity often not available**

- **Delay spread usually small compared to inverse bandwidth**
  - **Usually flat fading only, so:**
  - **Spatial diversity is <u>very</u> important**

Element Pattern and Polarization

- **Element pattern:**
  - **Usually preferred to match this to the AS to intercept all available power**
  - **<u>Rooms</u>: Low gain elements for sure**
  - **<u>Hallways</u>: Low gain elements usually OK since poor match to angle spread is usually offset by reduced path loss**

- **Polarization:**
  - **Match to dominant polarization to maximize CNR**
  - **In <u>rooms</u>, received signals are only weakly polarized, so polarization diversity can be an effective option**
  - **In <u>hallways</u>, received signals tend to be strongly polarized, so polarization diversity is often not effective (thus using it squanders CNR). Better to match to the dominant polarization.**

- **These guidelines apply equally to MIMO arrays.**

Diversity vs. Beamforming vs. MIMO

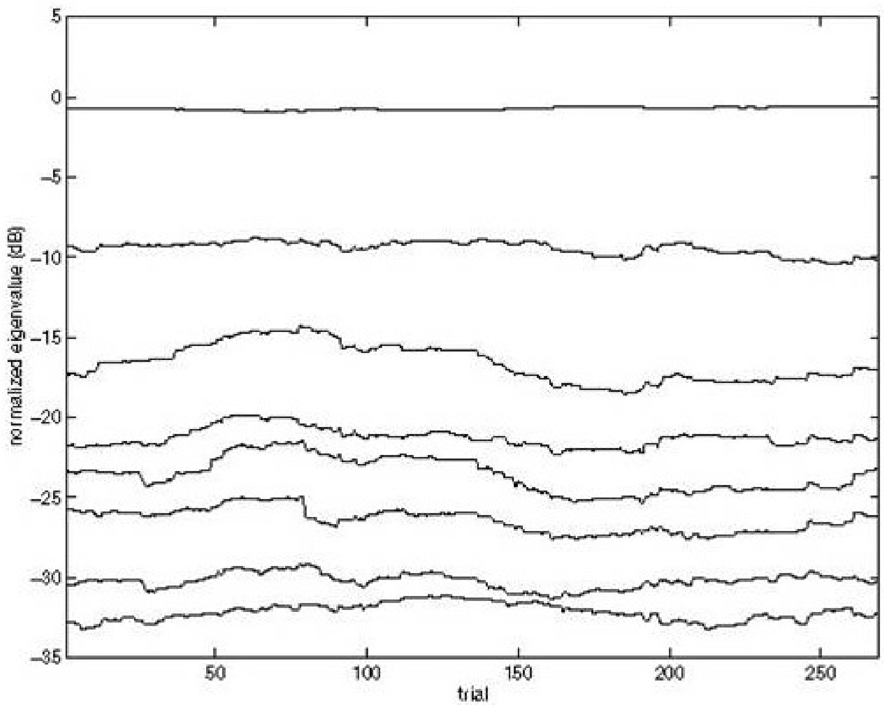
- **Nothing works unless the CNR is sufficiently large…so that is the first priority.**

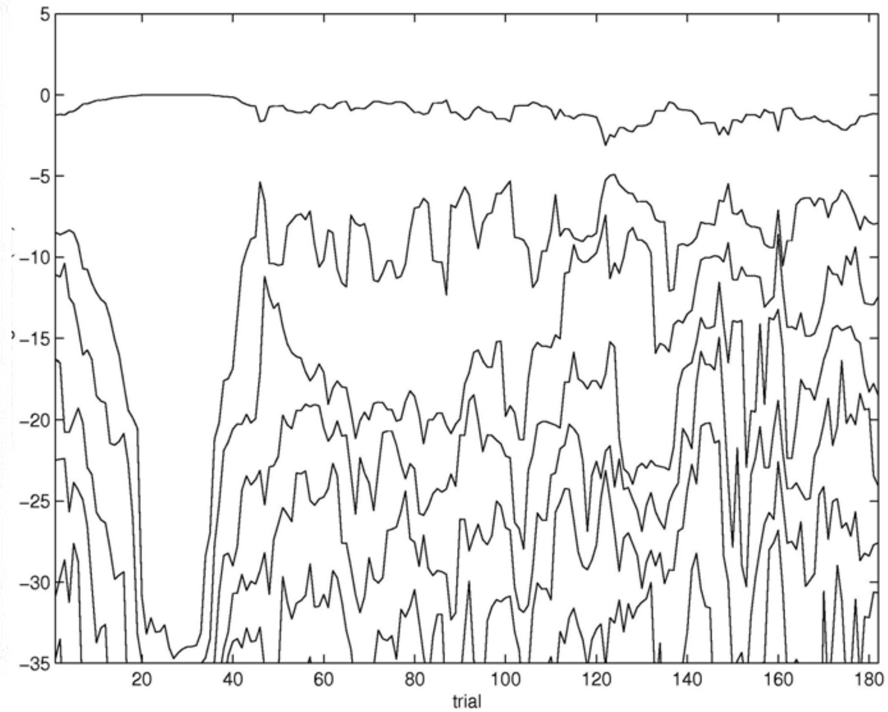
- **When CNR is reasonable, the ability to maximally exploit (rank=1) diversity is important, since the indoor channel is almost always limited by flat fading.** This will be good for MIMO as well.

- **When the CNR is low, the ability to make directional patterns, or form beam(s), to improve CNR is important** (in this case, might as well make array “compact” with spacings $< 0.7\lambda$)

- **Then, consider ability to access MIMO subchannels…**

Real-World MIMO Can Be Quirky





Persistent (minutes…)
Near-Keyhole Condition
Poor CNR conditions

Capacity: LOW

Transient (seconds…)
“Hard” Keyhole Condition
High CNR conditions

Capacity: HIGH

- **So, the actual rank of the channel may not mean much.**
- **Also, SNR normalization can yield very misleading results!**

Optimizing for Large AS (Rooms)

- **"Environmental" spatial autocorrelation $\rho \sim J_0(2\pi d/\lambda)$ requires d on the order of λ to be significantly decorrelated**
- **This is in fact the case for arrays of low gain elements when $d > 2\lambda$ or so**
- **For d on the order of $A_e^{1/2}$ (0.36λ for a resonant dipole) or less, mutual coupling becomes dominant:**
  - **Coupling modifies element impedance $\rightarrow$ degrades match WRT a standard impedance $\rightarrow$ degrades radiation efficiency $\rightarrow$ CNR suffers**
  - **Coupling alters element patterns (pattern diversity…?), but:**
  - **Studies that address both issues show that poor radiation efficiency tends to dominate for $d < A_e^{1/2}$.**
- **So for large AS (and in general…):**
  - **Linear arrays with spacings > λ or are preferred**
  - **Arrays with spacings down to ~ $A_e^{1/2}$ are useable**
  - **Arrays with spacings less than this require EM-savvy design and matching networks to stave off CNR degradation**

How Close Can Two Parallel Dipoles Be?

d	$\|\rho\|$	$d\ /\ A_e^{1/2}$	$\|Z_{12}\ /\ Z_1\|$	Remarks
$>\lambda$	<.3	>2.7	<0.3	**Tend to be limited only by environmental correlation**
$\lambda/2$	~.3	1.4	(0.1)	**Onset of "significant" MC effects**
$\lambda/3$	(~.2)	0.9	0.4	**Tailored Impedance matching becomes important for reasonable SNR; Pattern diversity becomes useable**
$\lambda/4$	~.5	0.7	0.7	**Mutual coupling directly degrades correlation**
$\lambda/10$	~.9	0.3	0.9	**Practical limit of impedance matching AND channel-provided decorrelation**

Optimizing for Small AS (Hallways)

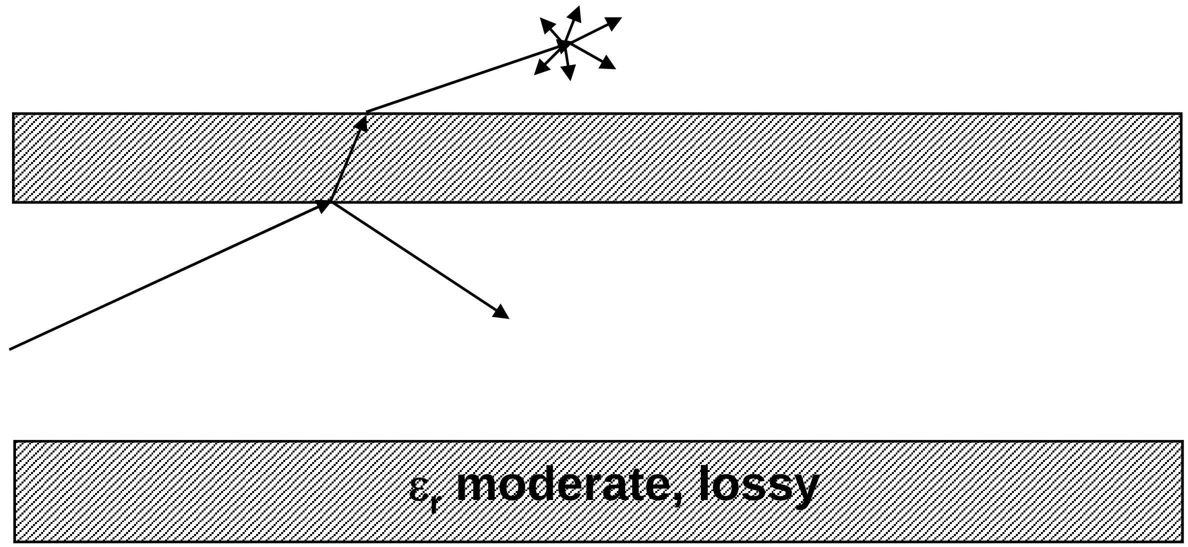
- **Greater spacings now required to achieve the same level of diversity, so it is now easy to be dominated by this issue as opposed to mutual coupling**

- **Rule of thumb: d/λ > 60°/AS lambda required for significant decorrelation** (Diversity requires a "beamwidth" that is narrow enough to resolve multipath clusters)

- **Geometry should be linear and perpendicular to mean angle of arrival**

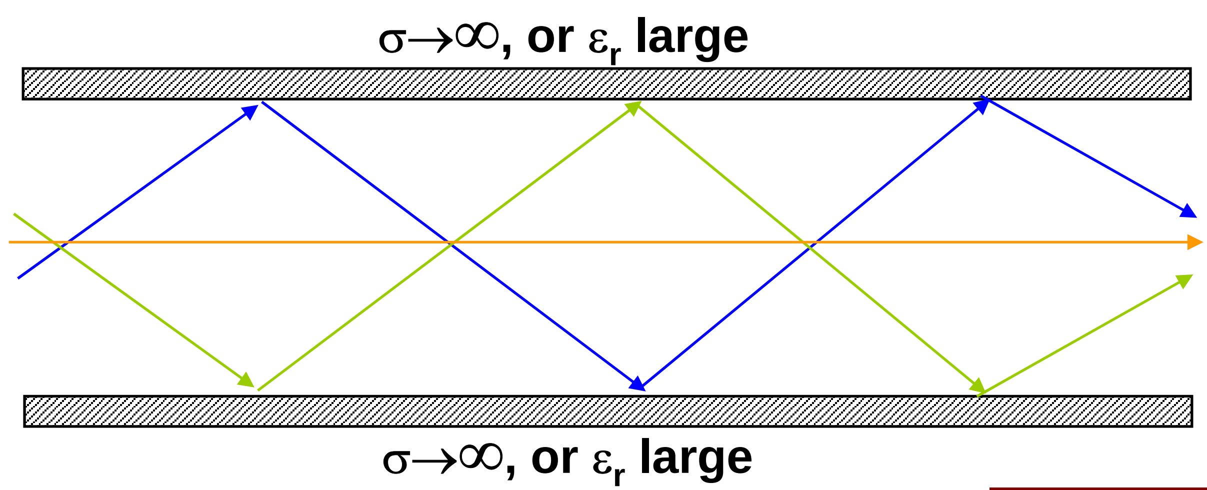
- **It is often impossible to achieve significant diversity in available aperture due to space limitations**
  - **In this case consider directional elements or beamforming (recall, defined here as maximizing the CNR, not the SNR)**

How Hallways Can be a Headache (1)



Horizontal Plane:

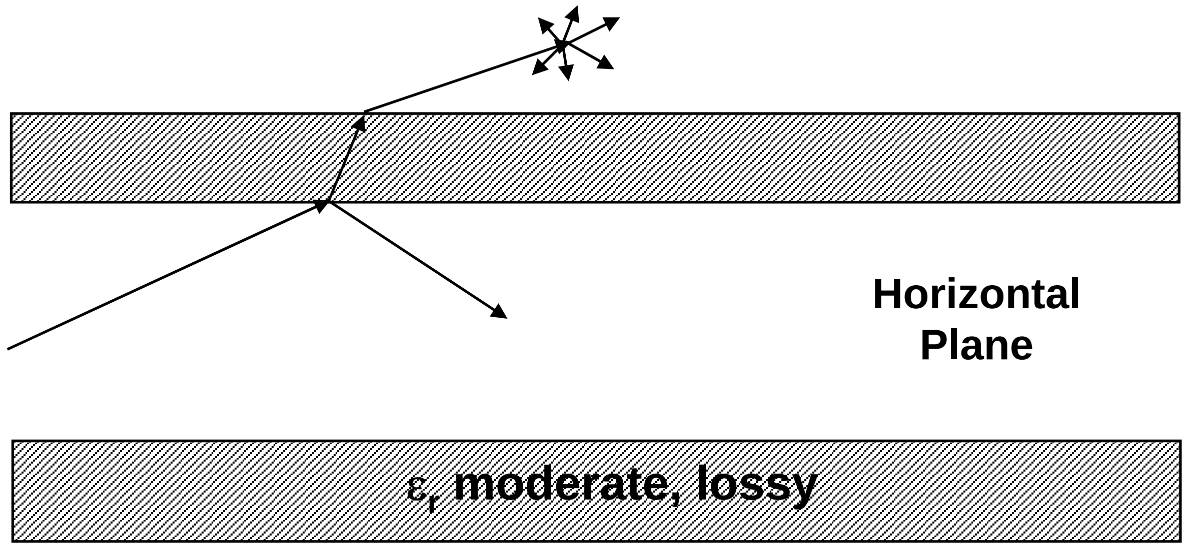
- Leakage into rooms,
- Incoherent scattering,
- Loss

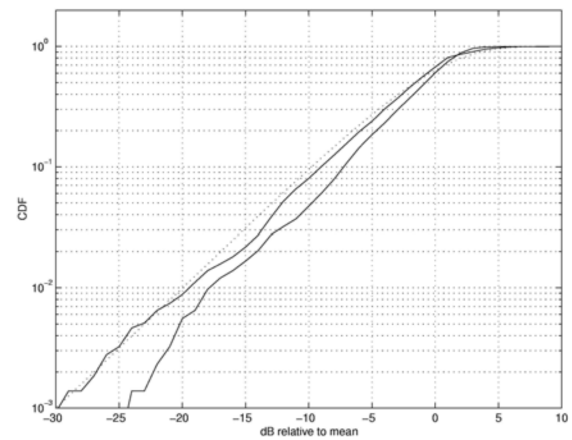


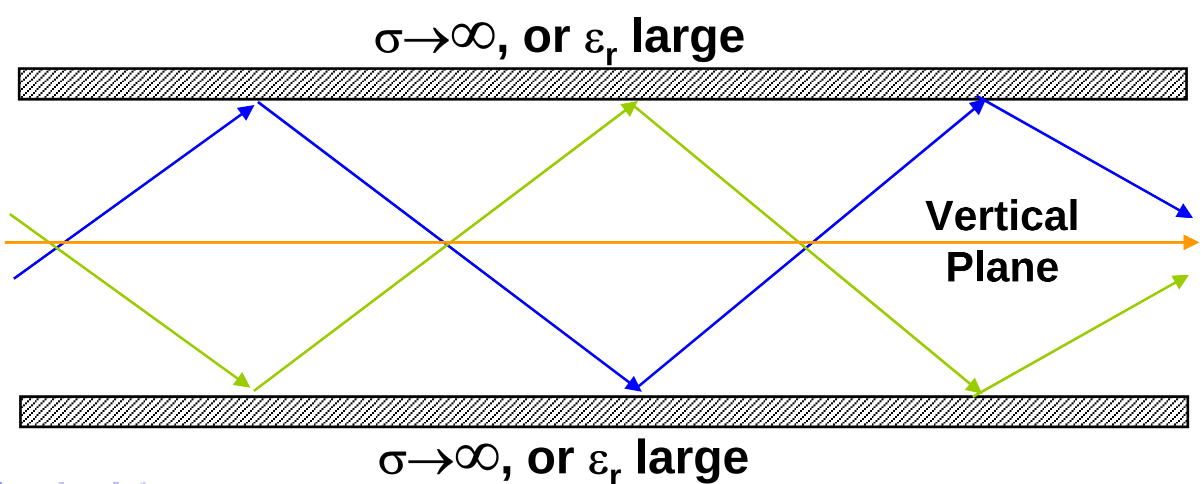
Vertical Plane:

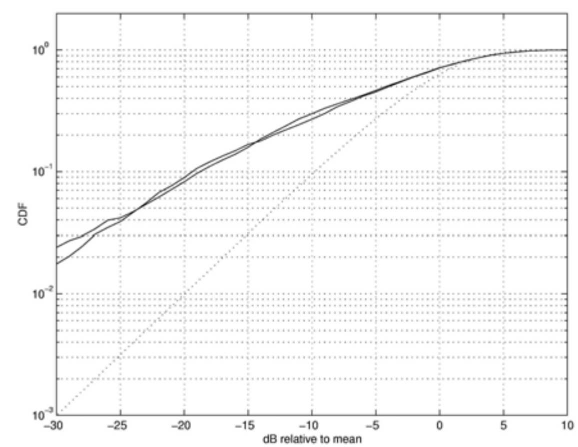
- Efficient Containment,
- Lossy propagation due to horizontal plane loss,
- Low-order modes propagate best

How Hallways Can be a Headache (2)









This is a recipe for rank collapse!

Hallway Countermeasures

- Short links (<10 m or so at 2.4 GHz)
- Distributed arrays (Single elements widely spaced)
- Vertical or 2D distribution of array elements

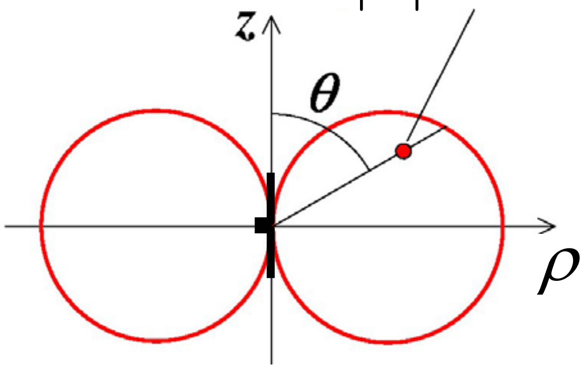
Summary

- **Take care of CNR first, rank-1 diversity second, then think MIMO**
  - **Spatial diversity is <u>very</u> important… Indoor channels - including MIMO subchannels - always experience flat fading**
- **An array that is well-designed from a CNR and diversity perspective will tend be suitable for whatever MIMO subchannels can be found**
- **It is not sufficient to simply find MIMO subchannels; they must be received with sufficient SNR and diversity to significantly contribute to the capacity.**
  - **It is easy to be fooled by techniques such as SNR normalization**

Resonant Half-Wave Dipoles as Elements

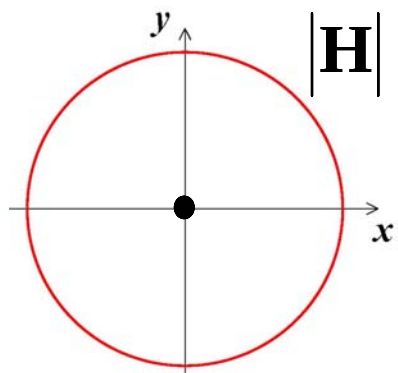
$A_e^{1/2} = 0$

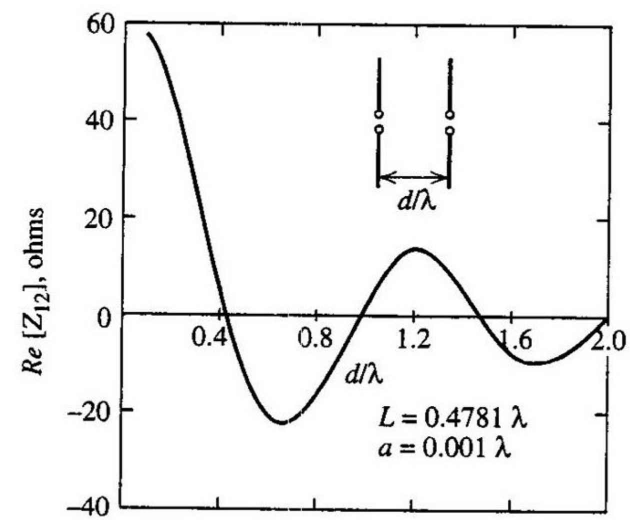
$$|\mathbf{E}| \propto \sin\theta$$

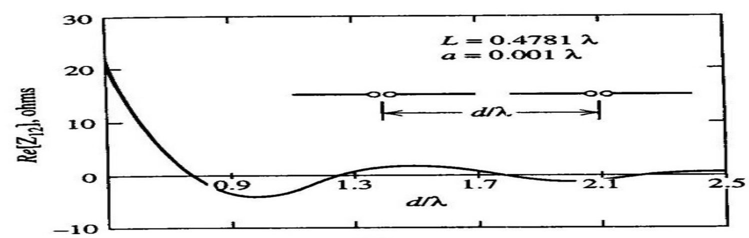


$A_e^{1/2} =$ 0.36λ

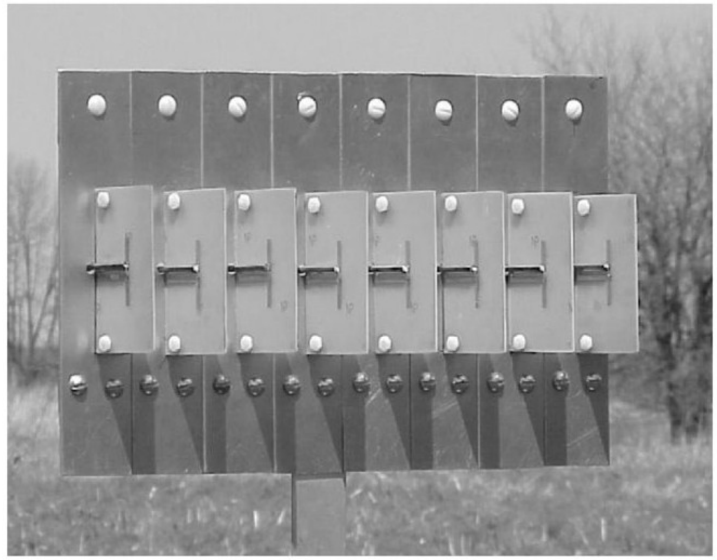
$$|\mathbf{H}| \propto 1$$







Pattern Modification from Mutual Coupling



HWD's spaced about 0.5λ apart at 2.4 GHz (1.4 relative to $A_e^{1/2}$)

Fig. 1. Photograph of an eight-element linear array of printed dipoles.

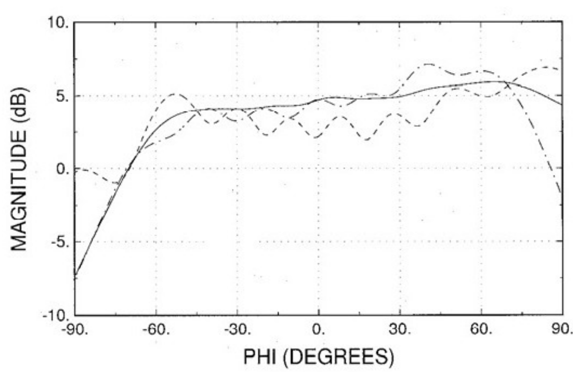


Fig. 2. Radiation pattern of element #1 of the linear array of dipoles at 2.45 GHz. (—) measured pattern, (- - -) predicted pattern with the single element in front of the small plate, and (- · · -) predicted pattern with the single element in front of the large plate.

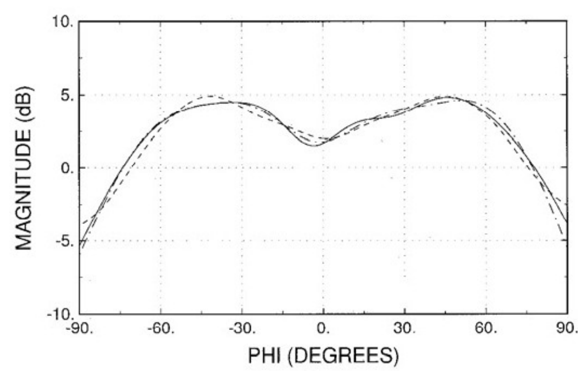


Fig. 3. Radiation pattern of element #4 of the linear array of dipoles at 2.45 GHz. (—) measured pattern, (- - -) predicted pattern with the single element in front of the small plate, and (- · · -) predicted pattern with the single element in front of the large plate.

Pattern Modification from Mutual Coupling

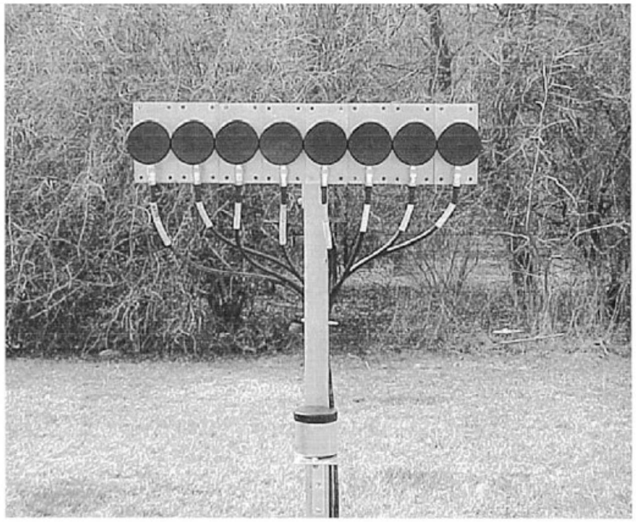


Fig. 4. Photograph of an eight-element linear array of model P-2406 antennas.

Cylindrical horn antennas spaced about 0.7λ apart at 2.4 GHz (7.8 relative to $A_e^{1/2}$)

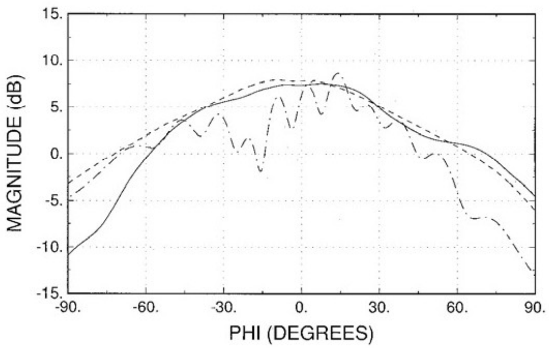


Fig. 5. Radiation pattern of element #1 of the linear array of model P-2406 antennas at 2.45 GHz. (—) measured pattern, (- - -) predicted pattern with identity coupling matrix, and (- · · -) predicted pattern with calculated coupling matrix.

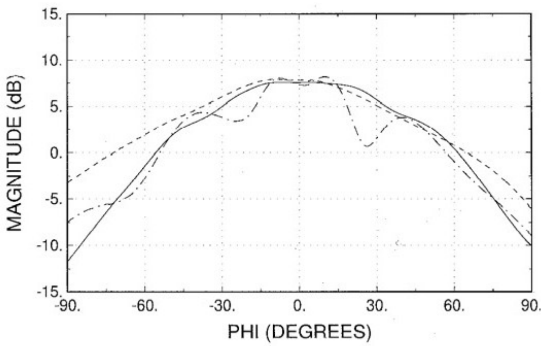


Fig. 6. Radiation pattern of element #4 of the linear array of model P-2406 antennas at 2.45 GHz. (—) measured pattern, (- - -) predicted pattern with identity coupling matrix, and (- · · -) predicted pattern with calculated coupling matrix.