Information Theoretic Comparison of MIMO Wireless Communication Receivers in the Presence of Interference

Daniel W. Bliss and Keith W. Forsythe
MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02420-9108
phone: 781-981-3300
email: bliss@ll.mit.edu
email: forsythe@ll.mit.edu

Abstract Multiple-input multiple-output (MIMO) wireless communication provides a number of advantages over traditional single-input single-output (SISO) approaches, including increased data rates for a given total transmit power and improved robustness to interference. Many of these advantages depend strongly upon the details of the receiver implementation. For practical communication systems a competition between communication performance and computational complexity exists. To reduce computation complexity, suboptimal receivers are commonly employed. In this paper, the details of a variety of receivers are incorporated into the effects of the channel so that information-theoretic performance bounds can be exploited to evaluate receiver approaches. The performance of these receivers is investigated for a range of environments. Two classes of environments are considered: first, channel complexity, characterized by the shape of the narrowband channel-matrix singular-value distribution, and second, external interference. Receiver approaches include minimum-mean-squared error, minimum interference, and multichannel multiuser detection (MCMUD), given various assumed limitations on channel and interference estimation. Receiver performance implications are also demonstrated using experimental data.

Report Documentation Page

Form Approved OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
20 DEC 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	
Information Theoretic Comparison of MIMO Wireless Communication Receivers in the Presence of Interference	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **MIT Lincoln Laboratory 244 Wood Street Lexington, MA 02420-9108**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also, ADM001741 Proceedings of the Twelfth Annual Adaptive Sensor Array Processing Workshop, 16-18 March 2004 (ASAP-12, Volume 1)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**29**	

Information Theoretic Comparison of MIMO Wireless Communication Receivers in the Presence of Interference

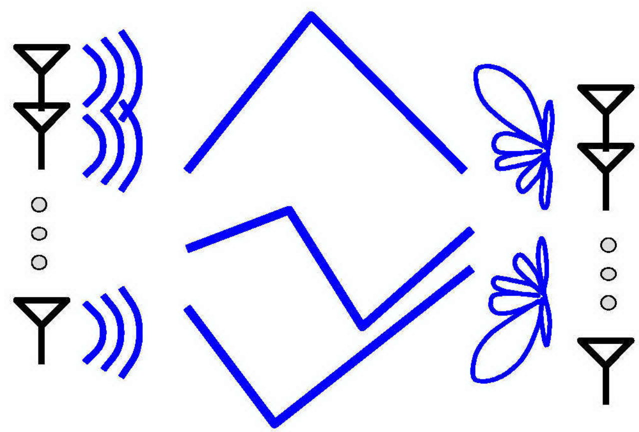
Daniel W. Bliss
Keith W. Forsythe

MIT Lincoln Laboratory
bliss@ll.mit.edu

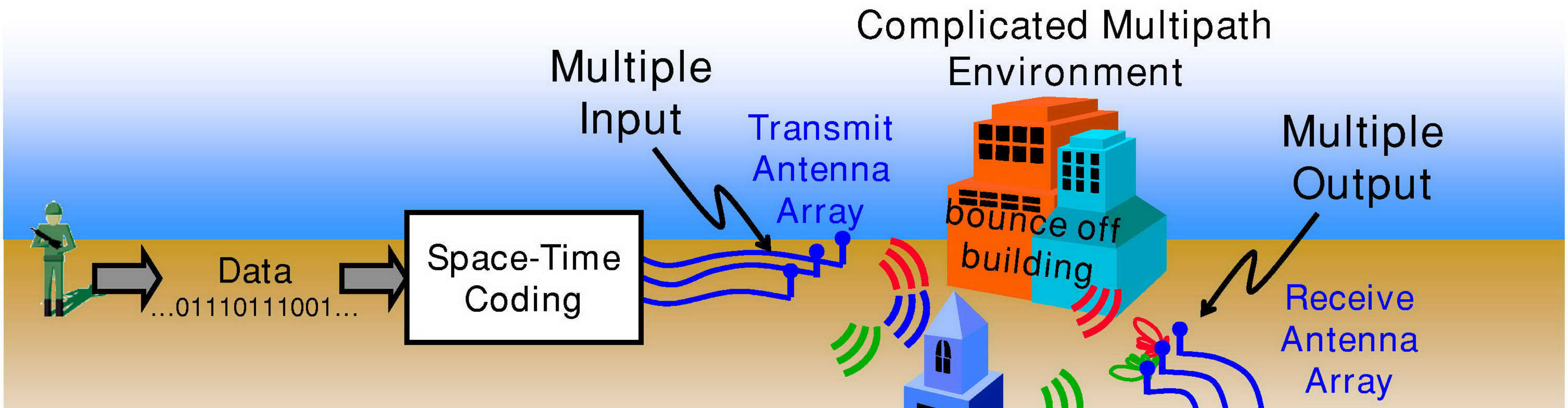
This work was sponsored by the United States Air Force under Air Force Contract F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

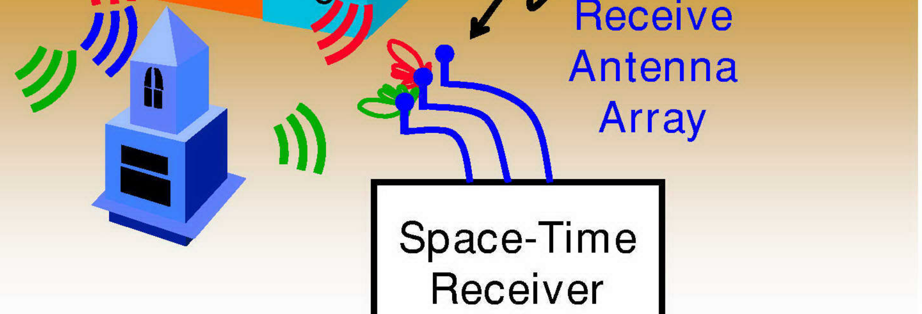
Topics
MIMO Communication

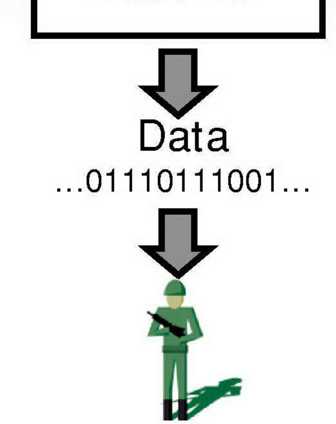
- Introduction
- MIMO Phenomenology
- Receiver Approaches
- Receiver Performance Bounds
- Performance Comparison



MIMO Communication
Multiple-Input Multiple-Output

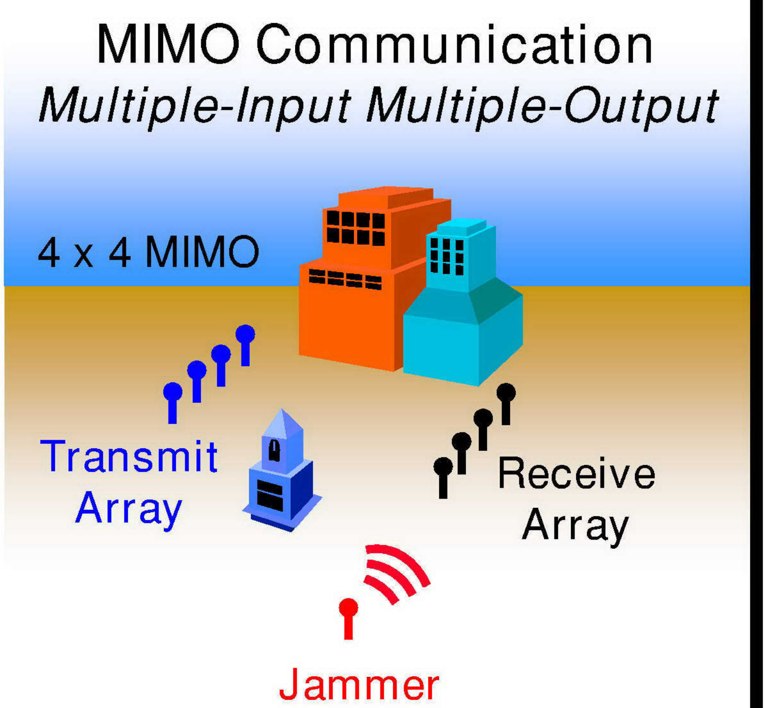




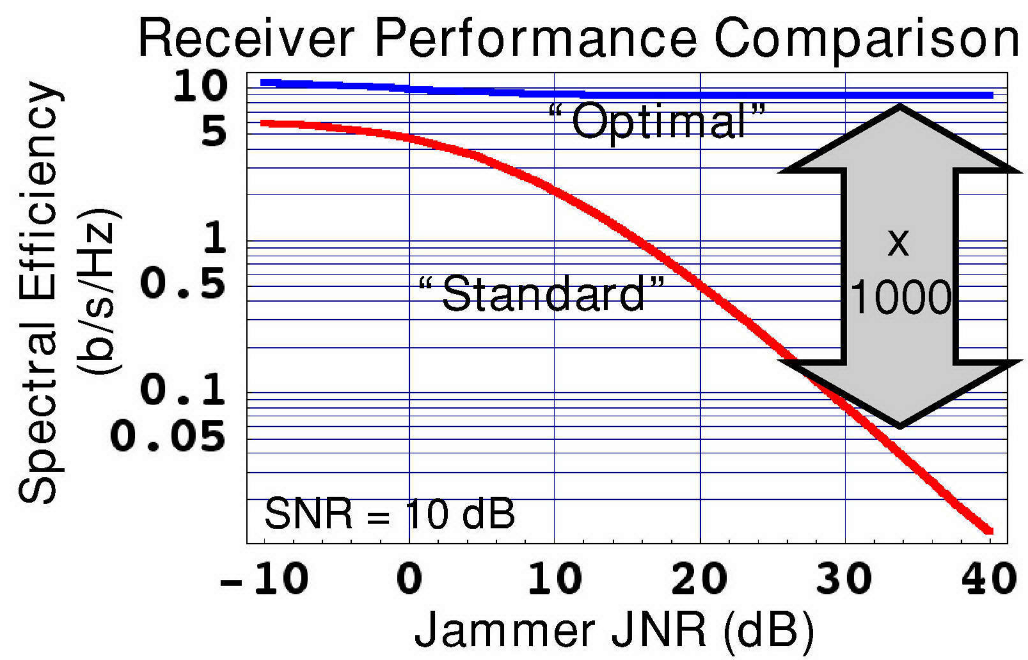


- Single transmitted data stream
- Single received data stream
- Employ multiple modes through environment
- Potential advantages over single-input single-output
  - Diversity
  - Robustness to interference
  - Spectral efficiency

Not All MIMO Receivers Are Equal

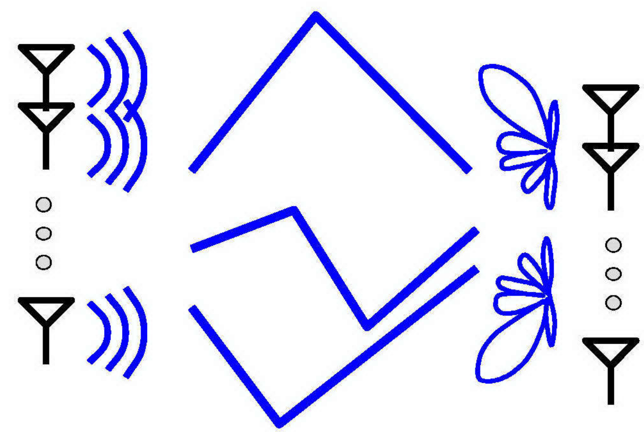


- "Standard" MIMO receivers perform badly in difficult environments
  - Ignore the possibility of jamming or external interference
  - Lower computational complexity
- "Optimal" MIMO receiver barely affected by jamming



Topics
MIMO Communication

- Introduction
- MIMO Phenomenology
- Receiver Approaches
- Receiver Performance Bounds
- Performance Comparison

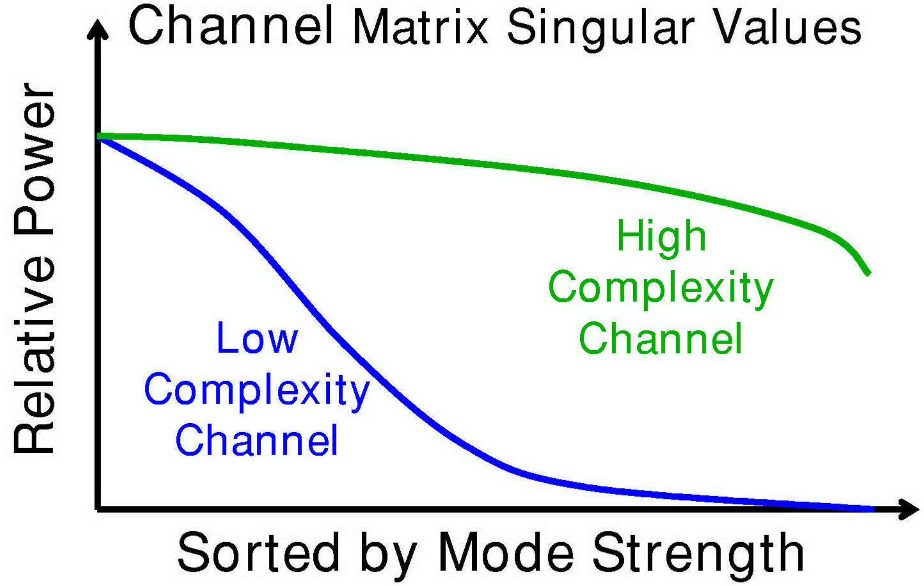


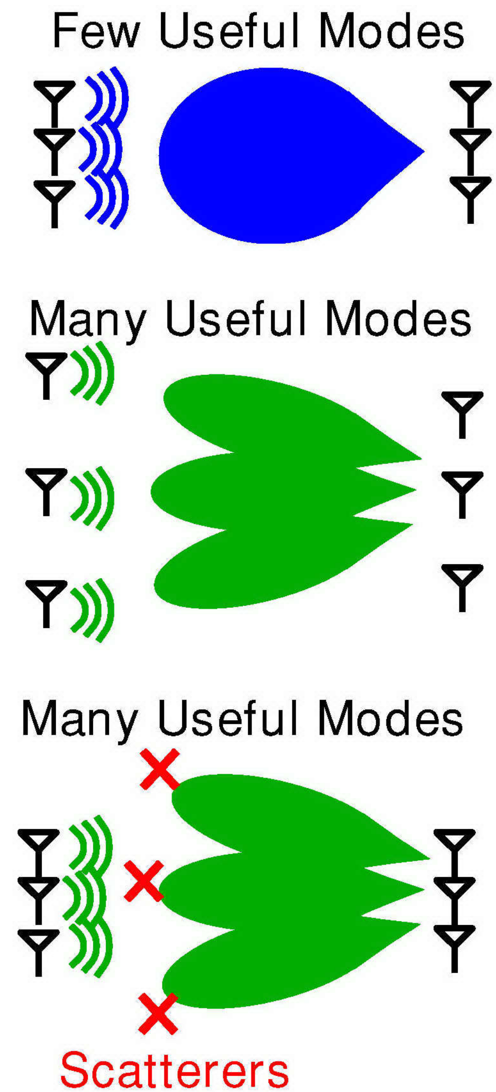
The Channel Matrix

- Channel matrix, H, contains complex attenuation between each transmit and receive antenna

$$\vec{z}(t) = \mathbf{H}\,\vec{x}(t) + \vec{n}(t)$$

- Large channel matrix singular values are useful



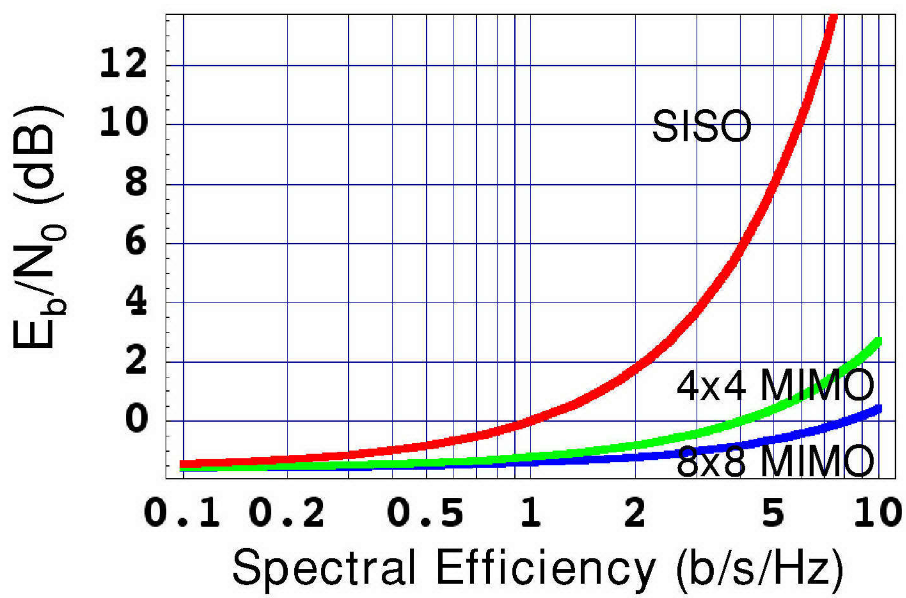


MIMO Capacity Bound(s)

SISO

$$C_{SISO} = \log_2(1 + \mathrm{SNR})$$

Shannon Limit



Informed Transmitter

$$C_{IT} = \max_{\mathrm{P}\,;\,tr\mathrm{P}=P_o} \log_2 \left| \mathrm{I} + \mathrm{HPH}^\dagger \right|$$

Uninformed Transmitter

$$\mathrm{P} \rightarrow \frac{P_o}{n_T}\mathrm{I}$$

$$C_{UT} = \log_2 \left| \mathrm{I} + \frac{P_o}{n_T}\mathrm{HH}^\dagger \right|$$

$$= \sum_m \log_2 \left(1 + \frac{P_o}{n_T} \|s_m\|^2 \right)$$

Channel Singular Values

Channel Complexity Parameterization

- Gaussian channel matrix, $\mathbf{G}$
- Simulate more realistic eigenvalue distributions by introducing spatial correlation
  - Parameterized by α
- Modified parameterized random channel matrix, $\mathbf{F}$

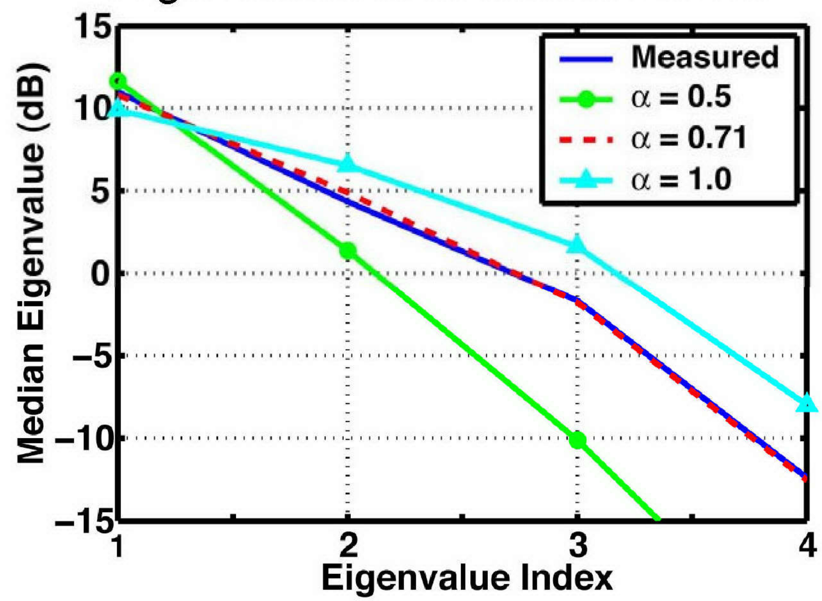
Introduce Spatial Correlation

$$\mathbf{F} = a\,\underbrace{\mathbf{U}\,\mathbf{A}_\alpha\,\mathbf{U}^\dagger}\,\mathbf{G}'\,\underbrace{\mathbf{V}\,\mathbf{A}_\alpha\,\mathbf{V}^\dagger}$$

$$= a\,\mathbf{U}\,\mathbf{A}_\alpha\,\mathbf{G}\,\mathbf{A}_\alpha\mathbf{V}^\dagger$$

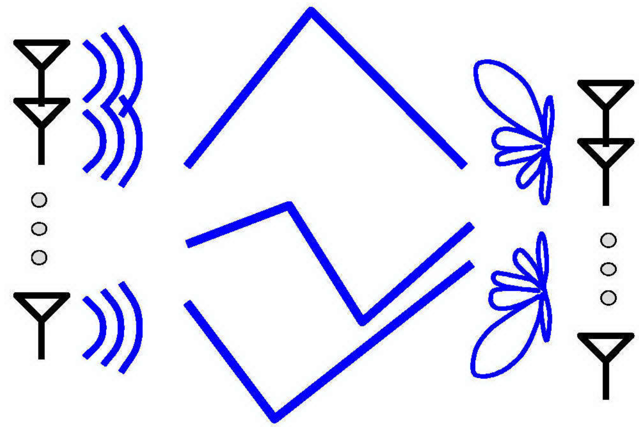
$$\mathbf{A}_\alpha = \sqrt{n}\frac{\mathrm{diag}\{\alpha^0, \alpha^1, \cdots, \alpha^{n-1}\}}{\sqrt{\mathrm{tr}\left\{\mathrm{diag}\{\alpha^0, \alpha^1, \cdots, \alpha^{n-1}\}^2\right\}}}$$

Eigenvalue Distribution of $\mathbf{FF}^\dagger$



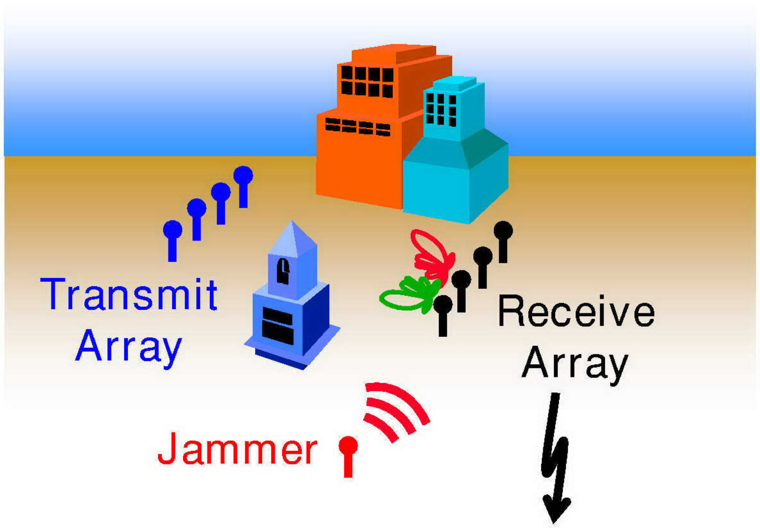
Topics
MIMO Communication

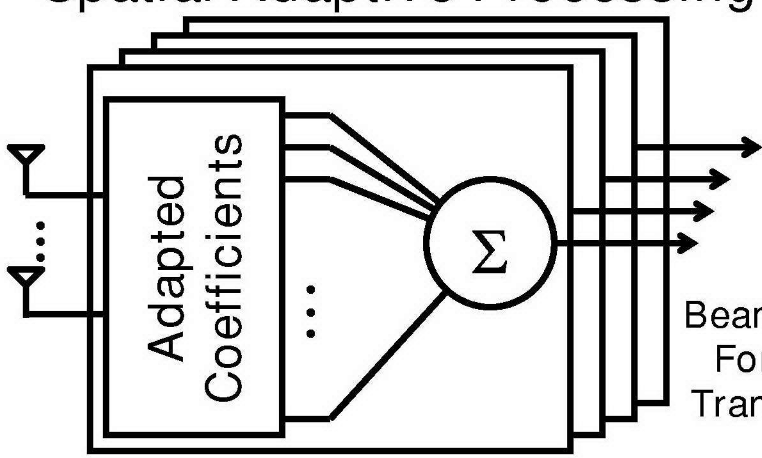
- Introduction
- MIMO Phenomenology
- Receiver Approaches
- Receiver Performance Bounds
- Performance Comparison



Adaptive Beamforming Receivers

Suboptimal





Beamformer Outputs

$$\vec{z}' = \mathbf{W}^\dagger (\mathbf{H}\vec{x} + \vec{n})$$

$$\mathbf{W} \equiv (\vec{w}_1 \ \vec{w}_2 \ \cdots \ \vec{w}_{n_T})$$

Minimum Mean Squared Error

$$\vec{w}_n^{MMSE} \propto \left(\mathbf{I} + \underbrace{\mathbf{R}}_{\text{If Known}} + \frac{P_o}{n_T} \mathbf{H}\mathbf{H}^\dagger \right)^{-1} \vec{h}_n$$

Minimum Interference

Standard MIMO Receiver

$$\vec{w}_n^{MI} \propto \mathbf{P}_n^\perp \vec{h}_n$$

$$\mathbf{P}_n^\perp = \mathbf{I}_{n_R} - \overline{\mathbf{H}}_n (\overline{\mathbf{H}}_n^\dagger \overline{\mathbf{H}}_n)^{-1} \overline{\mathbf{H}}_n^\dagger$$

$$\mathbf{H} \equiv \left(\vec{h}_1 \ \overline{\mathbf{H}}_1 \right)$$

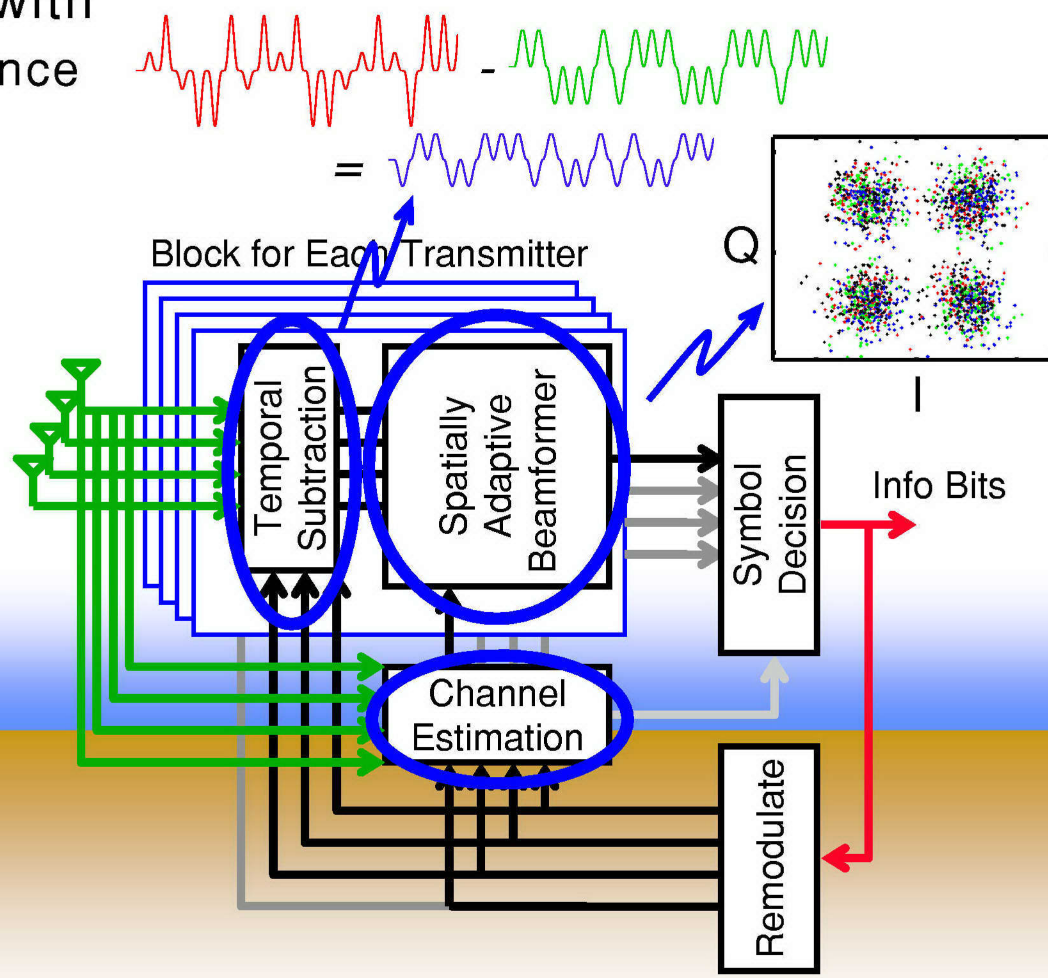
or

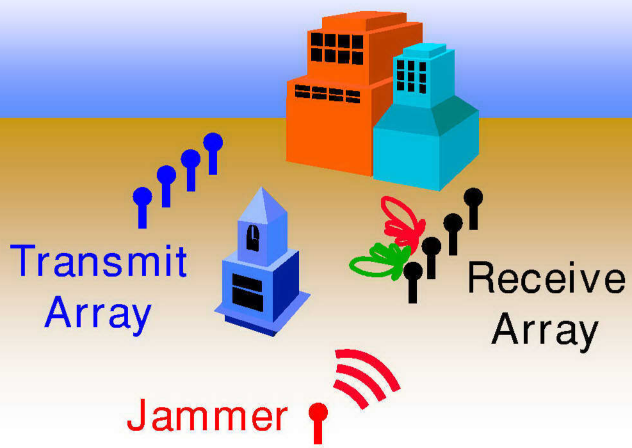
$$\vec{w}_n^{MI} \propto \min \text{eigenvec} \left\{ \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_n \overline{\mathbf{H}}_n^\dagger \right\}$$

Multi-Channel Multi-User Detection (MCMUD)

"Optimal" MIMO Receiver

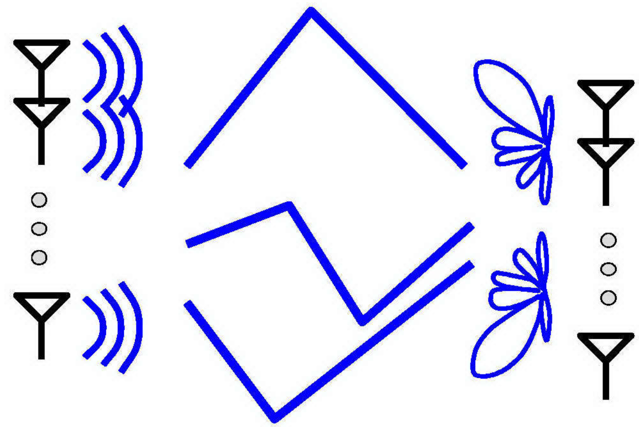
- Effective in environments with
  - Multiple access interference
  - Challenging multipath
  - Jamming
- Iterative decoder
  - Estimation subtraction (multi-user detection)
  - Spatially adaptive beamformers





Topics
MIMO Communication

- Introduction
- MIMO Phenomenology
- Receiver Approaches
- Receiver Performance Bounds
- Performance Comparison



Information Theoretic Capacity
Optimal

Signal Model

$$\vec{z} = \mathbf{H}\vec{x} + \vec{n}$$

Mutual Information

$$\begin{aligned}\mathcal{I}(\vec{z}, \vec{x}|\mathbf{H}) &= h(\vec{z}|\mathbf{H}) - h(\vec{z}|\vec{x}, \mathbf{H}) \\ &= h(\vec{z}|\mathbf{H}) - h(\mathbf{H}\vec{x} + \vec{n}|\vec{x}, \mathbf{H}) \\ &= h(\vec{z}|\mathbf{H}) - h(\vec{n}) \, ,\end{aligned}$$

Receive-Signal Entropy

$$\begin{aligned}h(\vec{z}|\mathbf{H}) &= \log_2 \left|\pi \, e \, \langle \vec{z}\vec{z}^\dagger \rangle\right| \\ &= \log_2 \left|\pi \, e \, \sigma_n^2 \left(\mathbf{I}_{n_R} + \mathbf{H} \langle \vec{x}\vec{x}^\dagger \rangle \mathbf{H}^\dagger\right)\right|\end{aligned}$$

Noise-Like Entropy

$$\begin{aligned}h(\vec{n}) &= \log_2 \left|\pi \, e \, \langle \vec{n}\vec{n}^\dagger \rangle\right| \\ &= \log_2 \left|\pi \, e \, \sigma_n^2 \mathbf{I}_{n_R}\right|\end{aligned}$$

In Interference Environment

$$h(\vec{z}|\mathbf{H}) \leq \log_2 \left\{\pi e \left|\sigma_n^2 \mathbf{I} + \sigma_n^2 \mathbf{R} + \mathbf{H} \langle \vec{x}\vec{x}^\dagger \rangle \mathbf{H}^\dagger\right|\right\}$$

$$h(\vec{z}|\vec{x}, \mathbf{H}) \leq \log_2 \left\{\pi e \left|\sigma_n^2 \mathbf{I} + \underbrace{\sigma_n^2 \mathbf{R}}\right|\right\}$$

Interference Covariance Matrix

Uninformed Transmitter Capacity

$$C_{UT} = \log_2 \left|\mathbf{I}_{n_R} + \frac{P_o}{n_T} \tilde{\mathbf{H}} \tilde{\mathbf{H}}^\dagger\right| \quad ; \quad \tilde{\mathbf{H}} \equiv (\mathbf{I} + \mathbf{R})^{-1/2} \, \mathbf{H}$$

Whitened Channel Matrix

Beamformer Receiver Extension to Information Theoretic Bounds

Signal Model

$$\vec{z} = \mathbf{H}\vec{x} + \vec{n} \quad \longrightarrow \quad \vec{z}\,' = \mathbf{W}^\dagger(\mathbf{H}\vec{x} + \vec{n})$$

$$\mathbf{W} \equiv (\vec{w}_1 \ \vec{w}_2 \ \cdots \ \vec{w}_{n_T})$$

Noise-Like Entropy

$$h_{uc}(\vec{z}\,'|\vec{x}, \mathbf{H}) \rightarrow \sum_l h_{uc}(\vec{z}\,'|x_l, \mathbf{H})$$

← Doesn't take into account correlations between beamformer outputs

$$= \sum_m^{n_T} \log_2 \left(\pi e \sigma_n^2 \vec{w}_m^\dagger \left\{ \mathbf{I}_{n_R} + \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_m \overline{\mathbf{H}}_m^\dagger \right\} \vec{w}_m \right) \quad ; \quad \mathbf{H} \equiv \left(\vec{h}_1 \ \overline{\mathbf{H}}_1 \right)$$

Receive-Signal Entropy

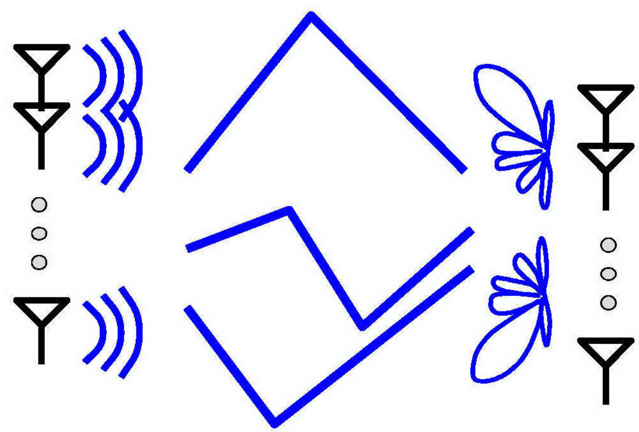
$$h_{uc}(\vec{z}\,'|\mathbf{H}) = \sum_m^{n_T} \log_2 \left(\pi e \sigma_n^2 \left[\vec{w}_m^\dagger \left\{ \mathbf{I}_{n_R} + \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_m \overline{\mathbf{H}}_m^\dagger \right\} \vec{w}_m + \frac{P_o}{n_T} \vec{w}_m^\dagger \vec{h}_m \vec{h}_m^\dagger \vec{w}_m \right] \right)$$

Receiver Beamformer Capacity

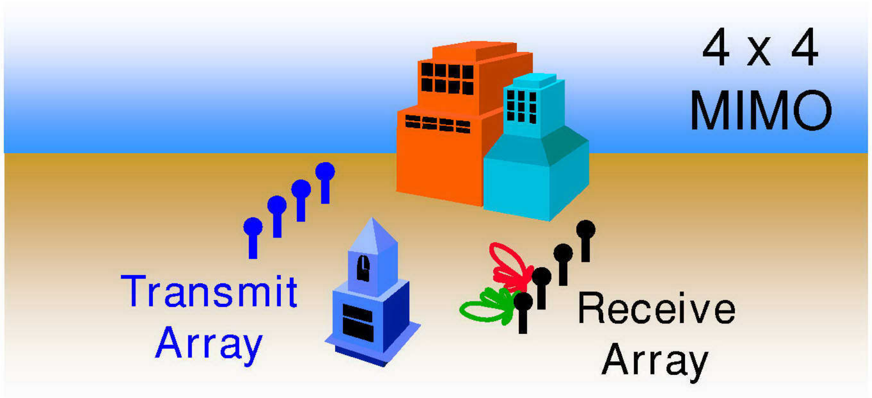
$$C_{uc} = \sum_m^{n_T} \log_2 \left[1 + \left(\vec{w}_m^\dagger \left\{ \mathbf{I}_{n_R} + \mathbf{R} + \frac{P_o}{n_T} \overline{\mathbf{H}}_m \overline{\mathbf{H}}_m^\dagger \right\} \vec{w}_m \right)^{-1} \frac{P_o}{n_T} \|\vec{w}_m^\dagger \vec{h}_m\|^2 \right]$$

Topics
MIMO Communication

- Introduction
- MIMO Phenomenology
- Receiver Approaches
- Receiver Performance Bounds
- Performance Comparison
  - Benign
  - Channel Complexity
  - MIMO Interference
  - Jamming
  - Experimental



Performance Comparison
Benign Environment (No Interference)



Minimum Mean Squared Error

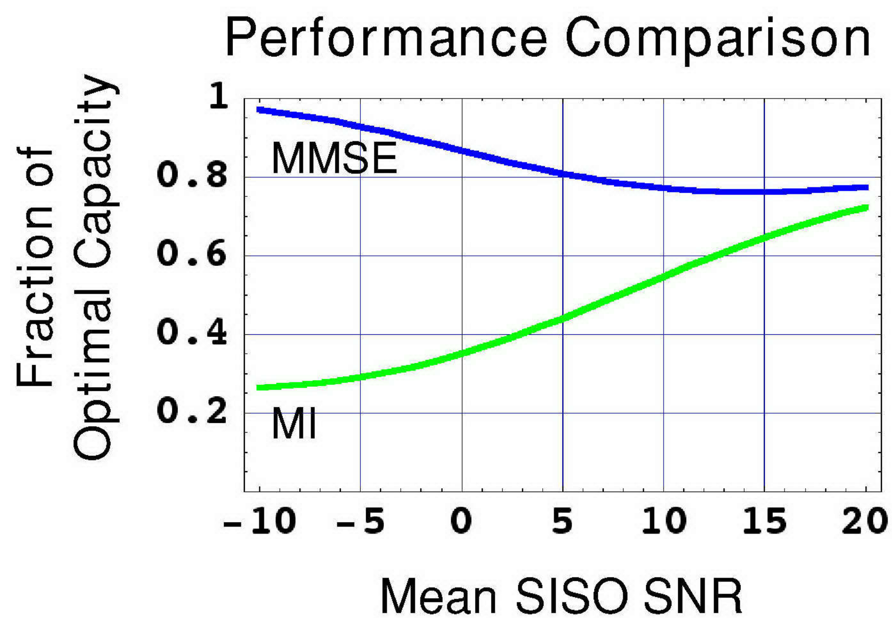
$$\vec{w}_n^{MMSE} \propto \left(\mathbf{I} + \mathbf{R} + \frac{P_o}{n_T}\mathbf{H}\mathbf{H}^\dagger\right)^{-1} \vec{h}_n$$

or

Minimum Interference

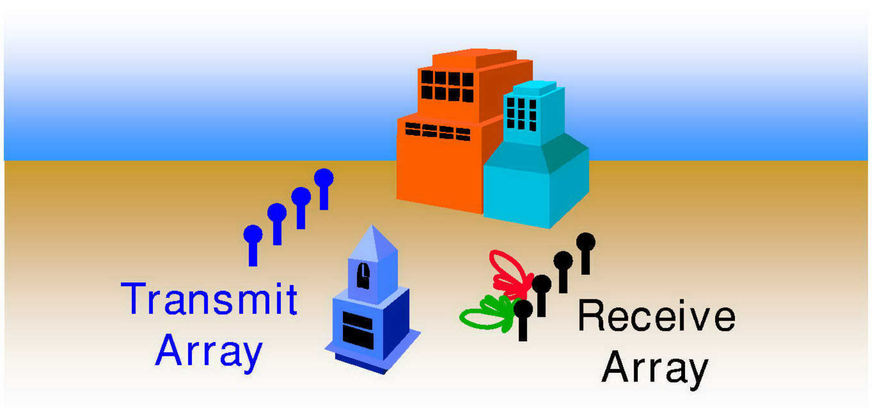
$$\vec{w}_n^{MI} \propto \mathbf{P}_n^\perp \vec{h}_n$$

Versus MCMUD

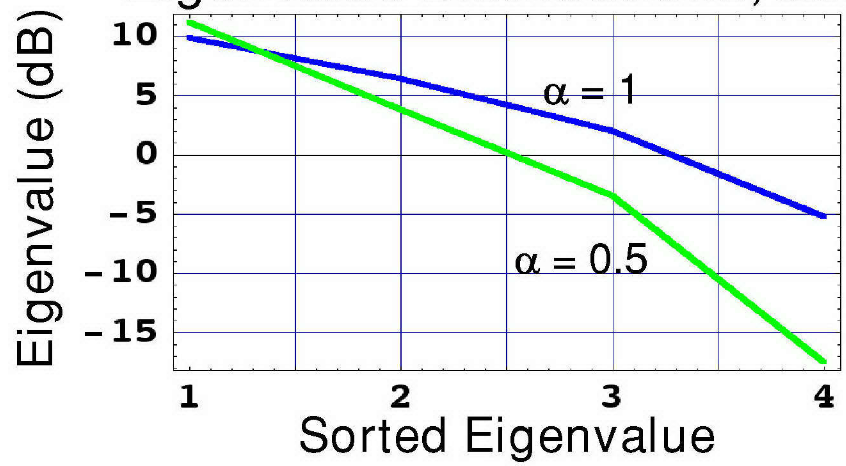


- MMSE has only slight loss compared to MCMUD
- MI performs badly particularly at lower SNR

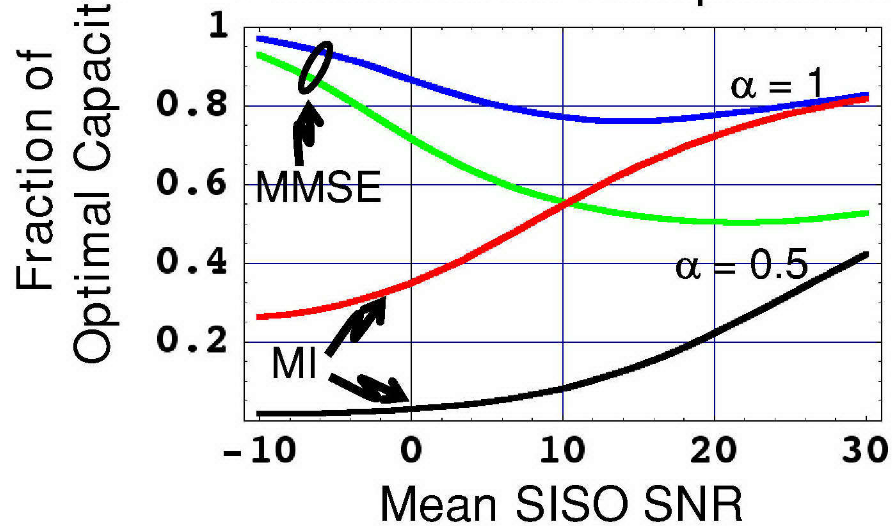
Performance Comparison
Function of Channel Complexity



Eigenvalue Distributions, $HH^{\dagger}$

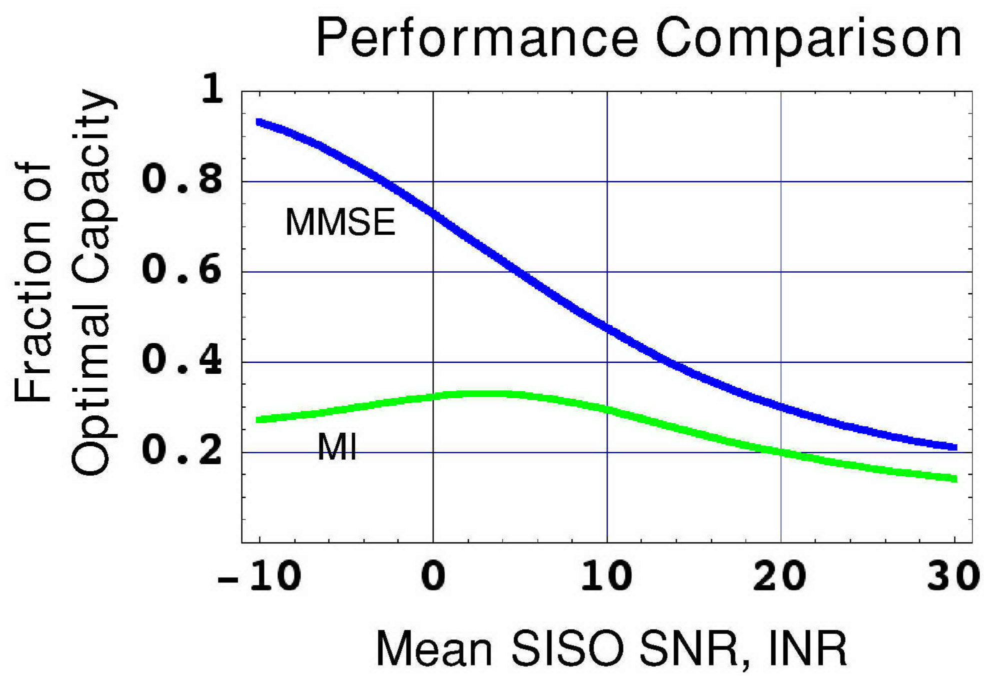


Performance Comparison



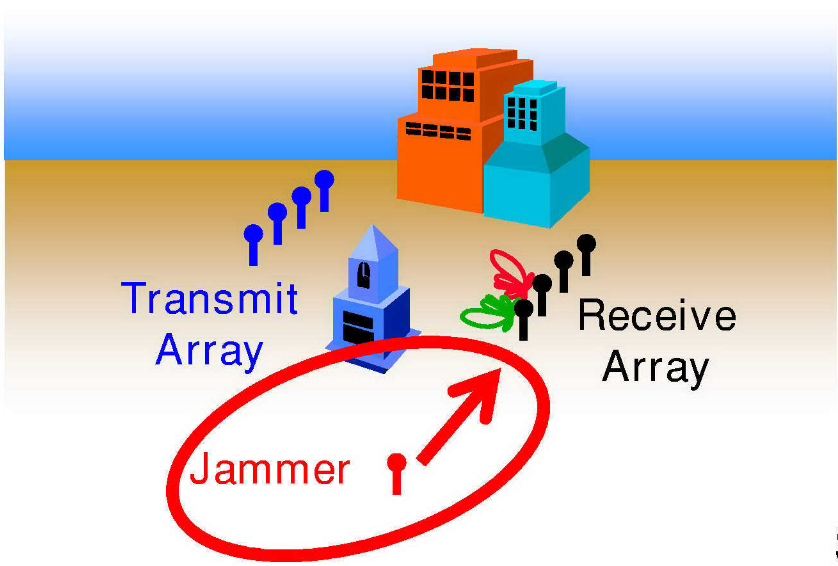
- Study 2 regimes of channel complexity
  - — $\alpha = 1$
  - — $\alpha = 0.5$
- Significant losses for both MI and MMSE at lower channel complexity

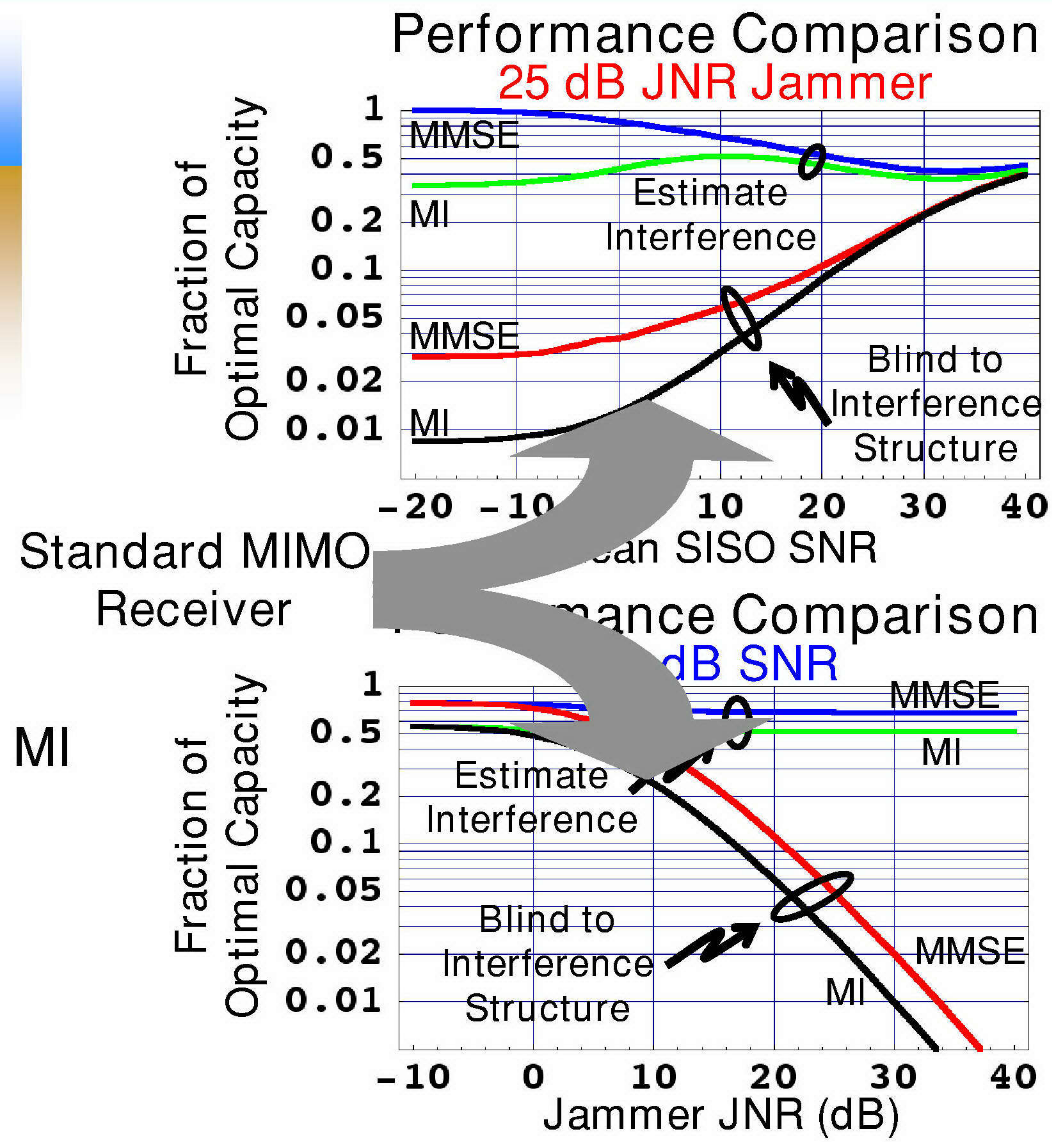
Performance Comparison
Effects of Interference



- Second interfering MIMO transmitter
  - Equal transmit power
- MI performs bad at all SNR
- Both MMSE and MI perform badly compared to MCMUD at high SNR
  - More strong signals than antennas

Performance Comparison
Effects of Jammer





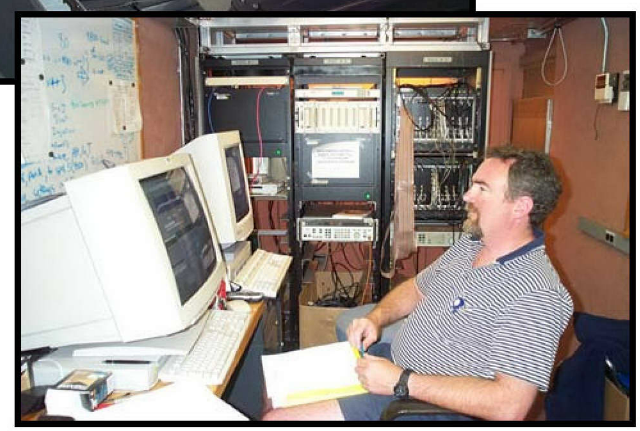
- Significant losses for both MI and MMSE over most SNR
- Terrible performance for receivers that are blind to interference structure

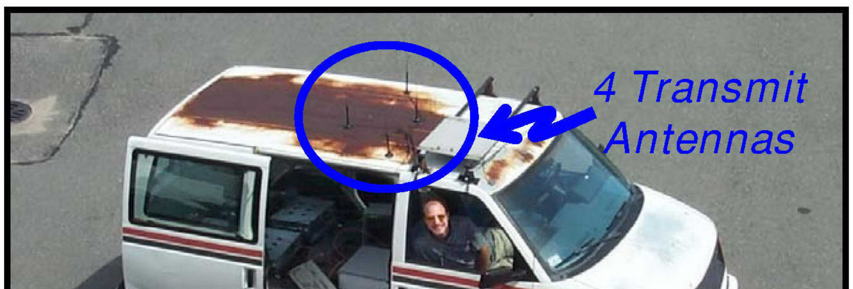
MIMO Experiment

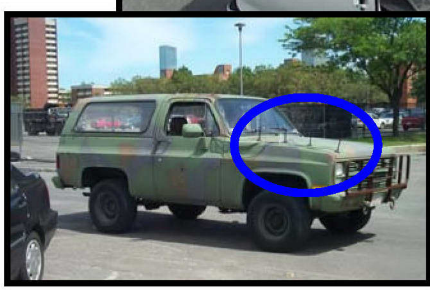
Summer 2002

- Investigate channel phenomenology
- Study space-time coding
- Explore transmitter coherence requirements
- Demonstrate robustness to
  - Jamming
  - Cochannel interference

16-Channel Hi-Fidelity Data Recording System

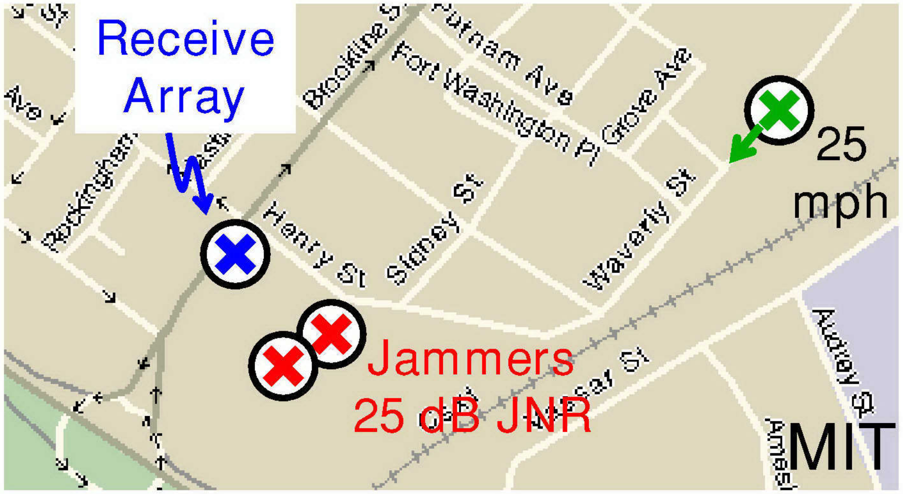




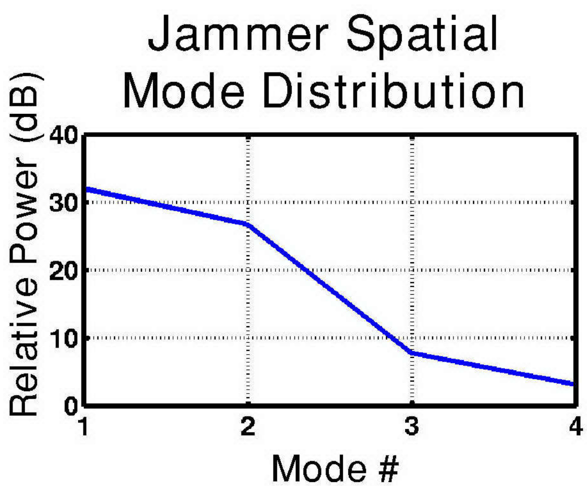


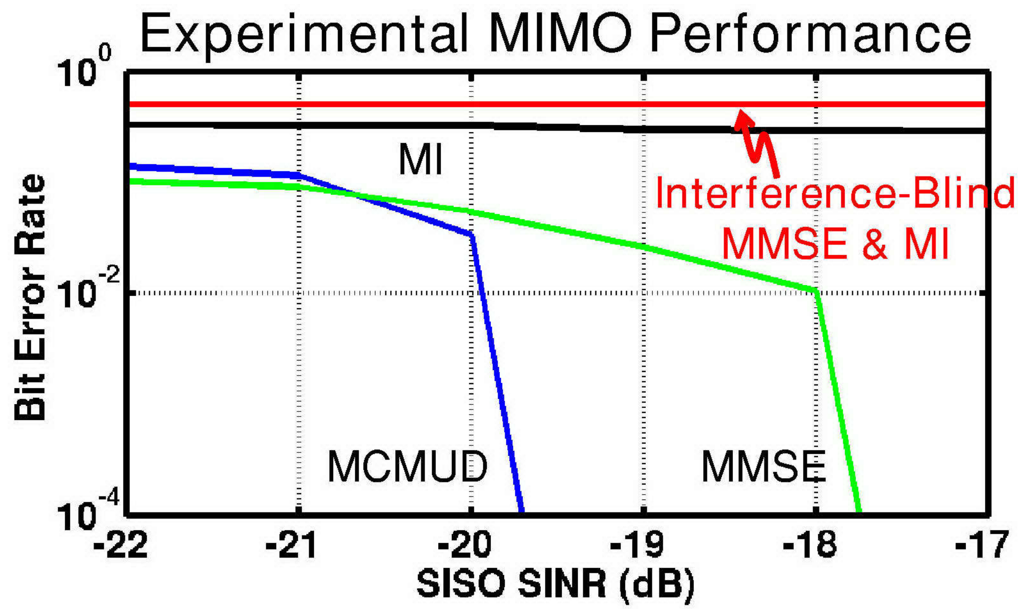
2 Groups of 4, or 8 Coherent Transmitters Near PCS band

4x4 MIMO Performance
Motion, Jammers, and LO Errors



- 2 Noise Jammers (25 dB JNR)
- Moving transmitter (25 mph)
- Error-free 2b/s/Hz data-link
- MCMUD near performance of jammer-free environment!
- Interference-blind & MI receivers perform badly





Summary

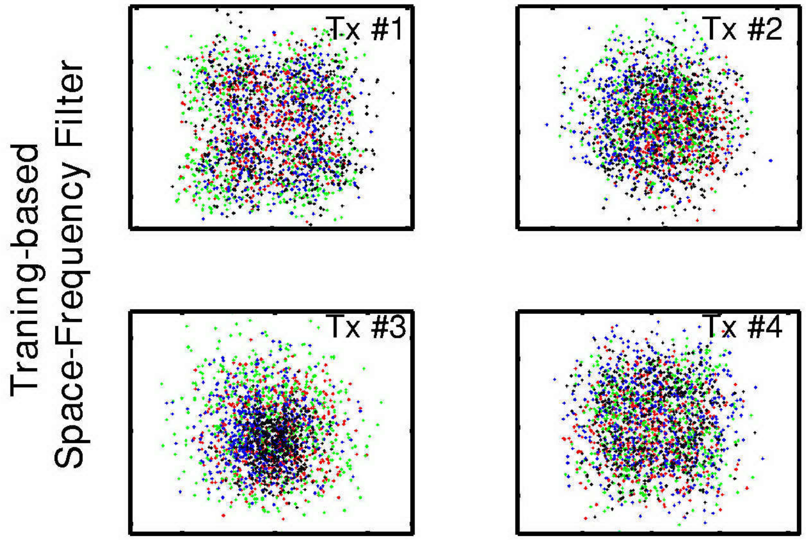
- Presented overview of robust MIMO communication
- Introduced bounds for variety of MIMO receivers
  - MMSE
  - MI
  - MCMUD
- MCMUD advantage significant in many environments
  - Spatially correlated channels (rate improvement > 70)
  - Interference (rate improvement > 5)
  - Jamming (rate improvement > 1000)
- Demonstrated experimental MCMUD immunity to jamming

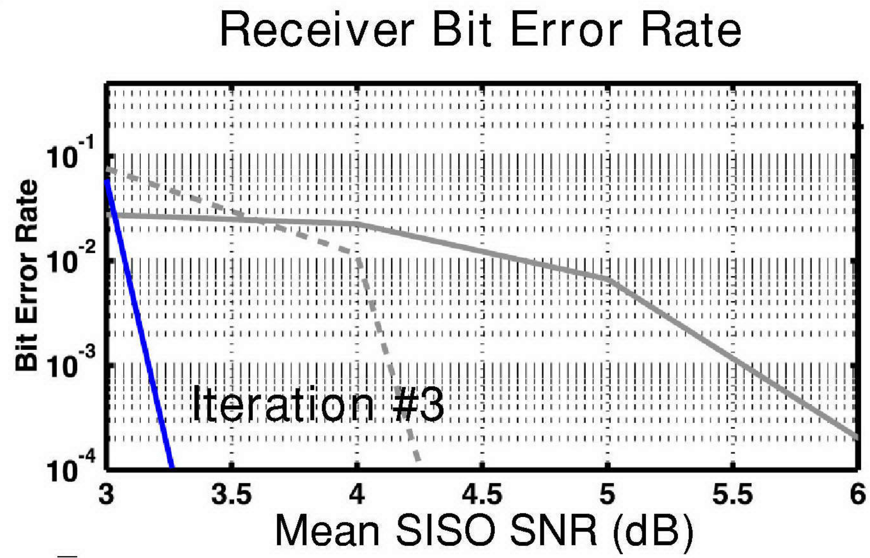
Acknowledgements

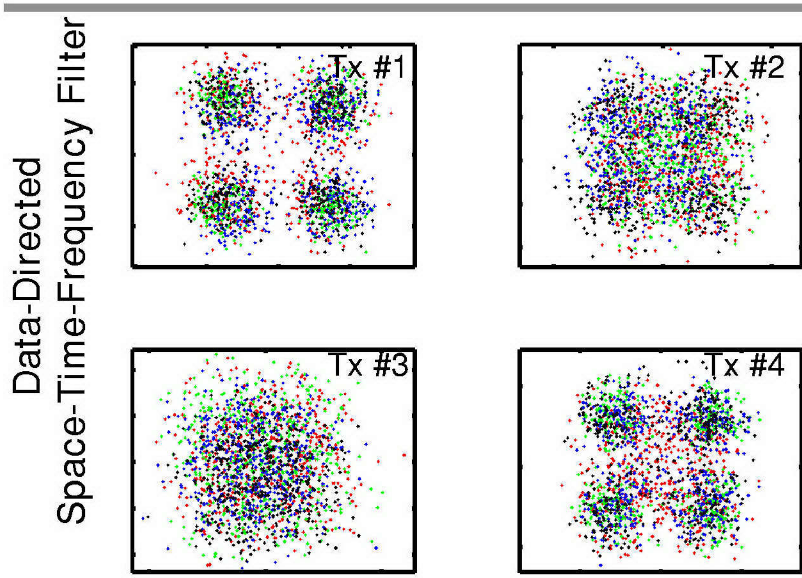
- MIT Linconln Laboratory
  New Technology Initiative Board
- Experiment team
  - Sean Tobin, Jeff Nowak, Lee Duter, John Mann, Bob Downing, Peter Priestner, Bob Devine, Tony Tavilla, Andy McKellips, Gary Hatke
- Code, algorithm and experiment design
  - Keith Forsythe, Peter Wu, Ali Yegulalp
- Analysis support
  - Amanda Chan
- Students
  - Nick Chang (U. Mich),
    Naveen Sunkavally (MIT)

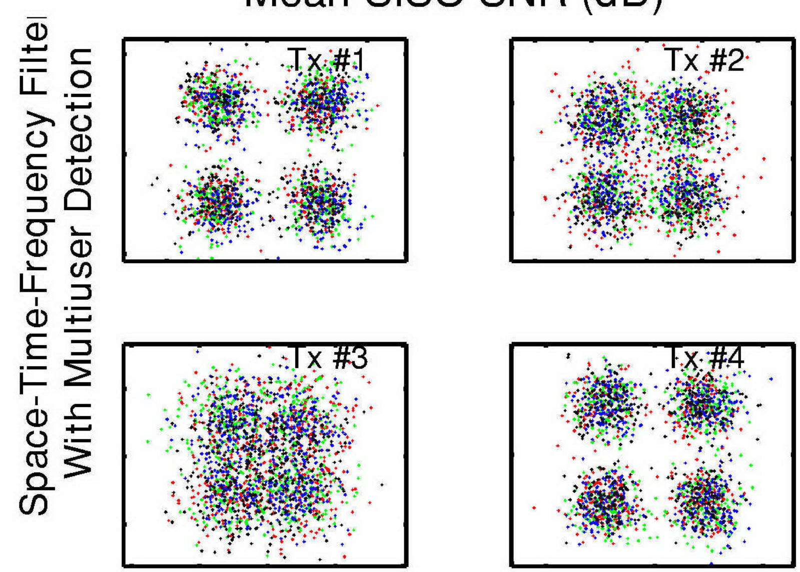
Backups

Experimental Results
Successive MCMUD Iterations

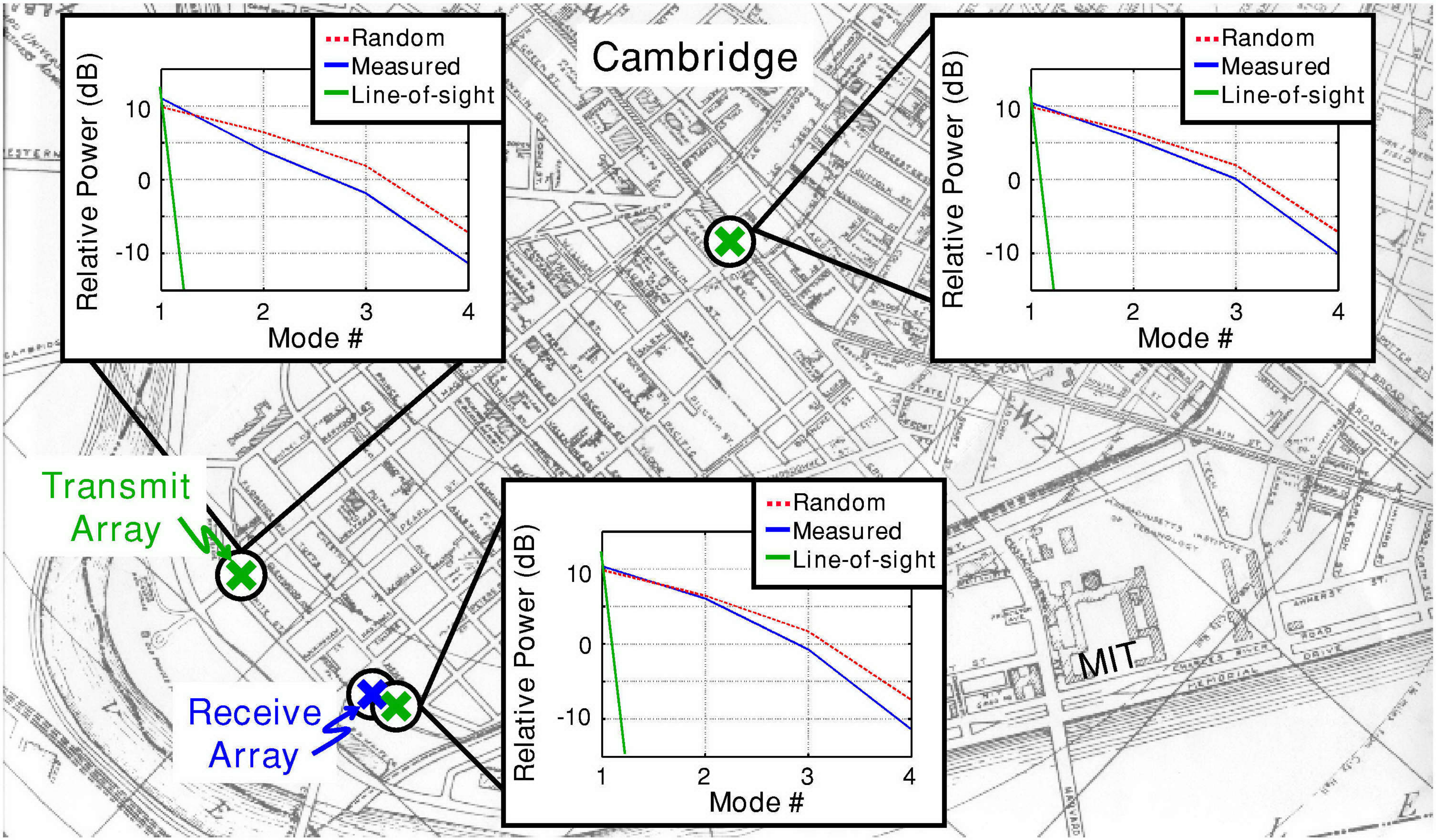




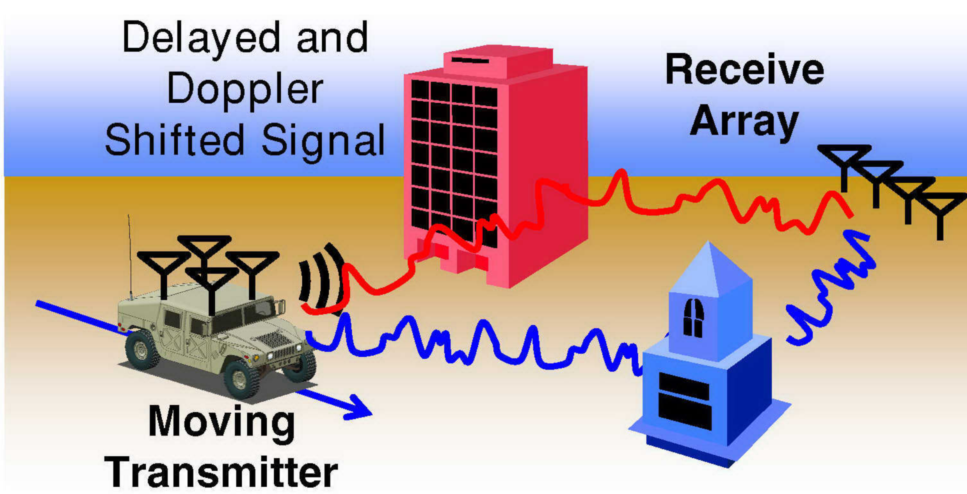


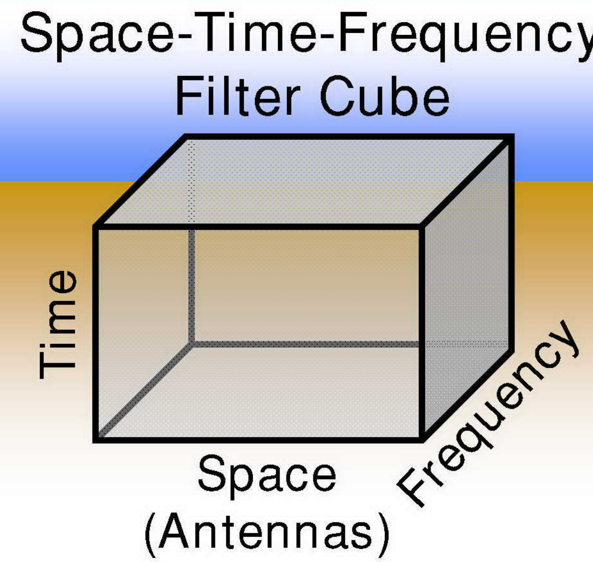


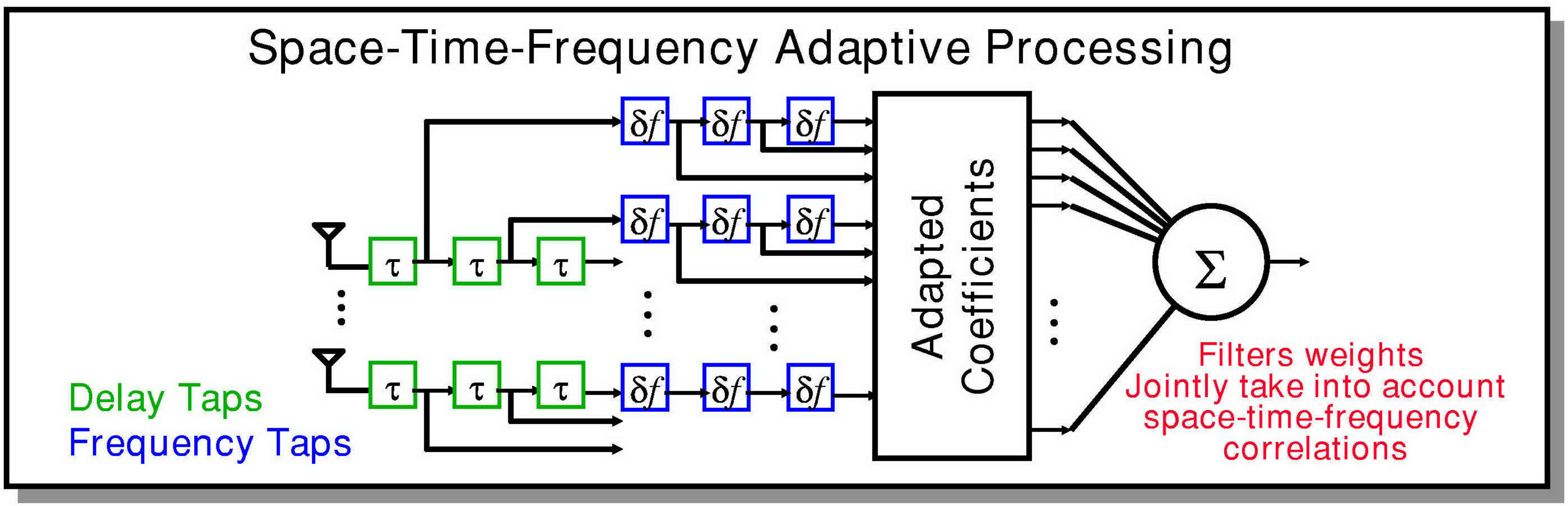
Channel Modes
Experimental Results



Adaptive Beamforming in Multipath







Notional Multiuser Detection