IEEE 802.16 Presentation Submission Template (Rev. 9)

Document Number:

IEEE C802.16m-07/139r1

Date Submitted:

[07/15/07]

Source:

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Base Contribution:

[If this presentation accompanies a base 802.16 contribution, cite its contribution number (e.g., IEEE C802.16x-07/NNN).]

Purpose:

[For the information of the IEEE 802.16m standardization group]

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Contents

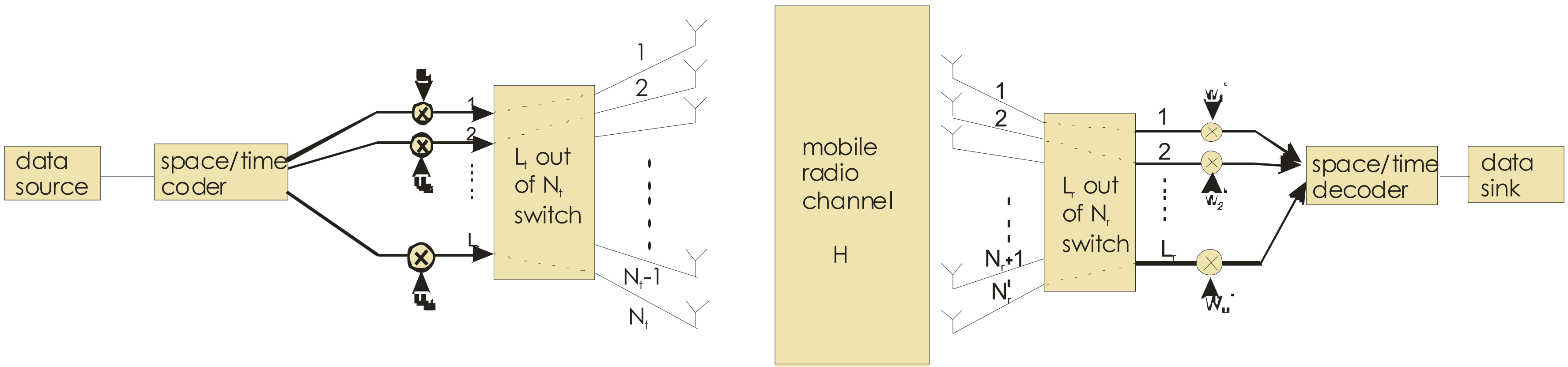
MIMO systems

- Multiple antenna elements at transmitter and receiver
- Hottest topic in wireless communications
- Use for
  - diversity: single data stream with high quality
  - spatial multiplexing: multiple parallel data streams
- History:
  - transmit diversity invented in early 1990s (Wittneben, Winters, Lo); space-time codes (Alamouti, Tarokh)
  - spatial multiplexing: Winters (1987), Foschini, Telatar, Paulraj, Raleigh and Cioffi (mid 1990s)

Antenna Selection

- Additional costs for MIMO
  1. more antenna elements (cheap)
  2. more signal processing (Moore's law)
  3. one RF chain for each antenna element
- Basic idea of antenna selection:
  - have many antenna elements, but select only best for downconversion and processing
  - only at one link end: cost reductions might be more important at one link end (MS) than the other
- Hybrid antenna selection: select best L out of available N antenna elements, use those for processing

System Model



- Received vector $\mathbf{y} = \sqrt{\frac{\rho}{N_t}}\mathbf{Hv}x + \mathbf{n}$
  - **n**: AWGN vector (Nr x 1)
  - **H**: Channel matrix (Nr x Nt)
  - **v**: Transmit weight vector (Nr x 1)
- Kronecker channel model $\mathbf{H} = \mathbf{R}^{1/2}\mathbf{H}_w\mathbf{T}^{1/2}$

Contents

Antenna Selection for Diversity

Weight selection if all antenna elements are used

- Write channel matrix as $\boldsymbol{H} = \boldsymbol{W \Lambda V}^H$
- Excite channel with $\boldsymbol{V}_i$, receive with $\boldsymbol{W}_i^H$
- Received power is λ_i^2

Antenna and weight selection for H-S/MRT

- Create submatrices by striking rows
- Compute maximum singular value for this submatrix
- Search submatrix that gives largest max. singular val.
- Use singular values associated with selected submatrix as antenna weights

$$\gamma = \max_{\mathcal{S}(\widetilde{H})}\left(\max_i(\widetilde{\lambda}_i^2)\right)$$

Bounds for the SNR distribution (I)

- Upper and lower bounds

$$\frac{1}{\min\left(L_t, N_r\right)} \sum_i \widetilde{\lambda}_i^2 \le \max_i \left(\widetilde{\lambda}_i^2\right) \le \sum_i \widetilde{\lambda}_i^2$$

- Determine

$$\gamma_{\text{bound}} = \max_{S(\widetilde{H})} \left(\sum_i \widetilde{\lambda}_i^2 \right) = \max_{S(\widetilde{H})} \left(\sum_i \sum_j \left| \widetilde{h}_{ij} \right|^2 \right) \qquad \gamma_{\text{bound}} = \sum_{i=1}^{L_t} \gamma_{(i)}$$

where $\gamma_{(i)}$ are *ordered* SNRs with distribution

$$p_{\gamma_{(i)}}(\gamma_{(1)}, \gamma_{(2)}, \ldots (N_t)) = \begin{cases} N! \prod_{i=1}^{N_t} \frac{1}{\Gamma(N_r)} \gamma_{(i)}^{N_r - 1} \exp(-\gamma_{(i)}) & \text{for} \quad \gamma_{(1)} > \gamma_{(2)} > \ldots > \gamma_{(N_t)} \\ 0 & \text{otherwise} \quad . \end{cases}$$

Bounds for the SNR distribution (II)

- Characteristic function:

$$\Phi(j\nu) = \frac{N_{\mathrm{t}}!}{\Gamma(N_{\mathrm{r}})^{N_{\mathrm{t}}}} \int_0^{\infty} d\gamma_{(1)} \gamma_{(1)}^{N_{\mathrm{r}}-1} e^{-\gamma_{(1)}} e^{-j\nu\Xi(L_{\mathrm{t}}-1)\gamma_{(1)}}$$

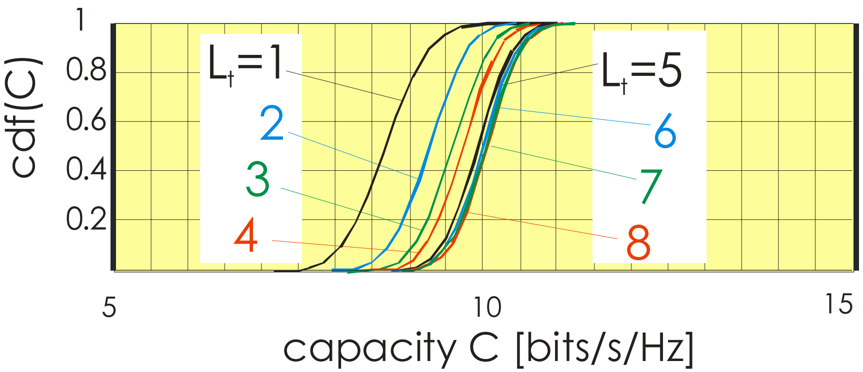
$$\int_0^{\gamma_{(1)}} d\gamma_{(2)} \gamma_{(2)}^{N_{\mathrm{r}}-1} e^{-\gamma_{(2)}} e^{-j\nu\Xi(L_{\mathrm{t}}-2)\gamma_{(2)}} \ldots$$

$$\int_0^{\gamma_{(N_{\mathrm{t}}-1)}} d\gamma_{(N_{\mathrm{t}})} \gamma_{(N_{\mathrm{t}})}^{N_{\mathrm{r}}-1} e^{-\gamma_{(N_{\mathrm{t}})}} e^{-j\nu\Xi(L_{\mathrm{t}}-N_{\mathrm{t}})\gamma_{(N_{\mathrm{t}})}}$$

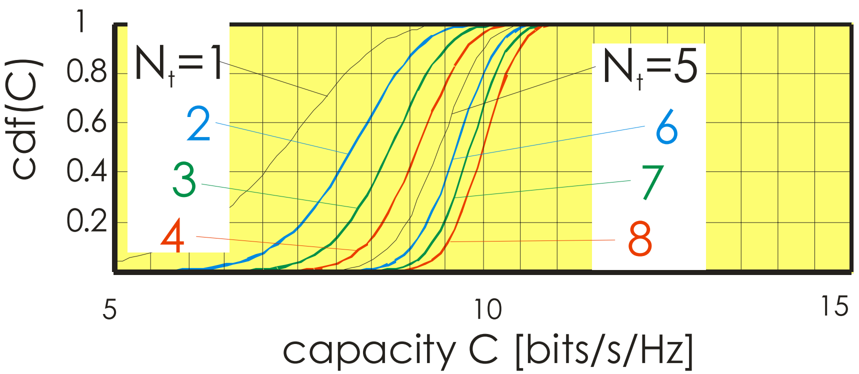
- Analytical evaluation: recursive algorithm

HS-MRT vs. MRT – Diversity Case

Hybrid selection



Maximum ratio transmission



Antenna Selection for Space-time Codes

- Knowledge at transmitter only about statistics of fading
- Performance:
  - full diversity order
  - loss of coding gain
- In correlated systems:
  - select antennas so that determinants of correlation matrices at TX and RX are maximized

Antenna Selection for Spatial Multiplexing

Capacity for full-complexity system

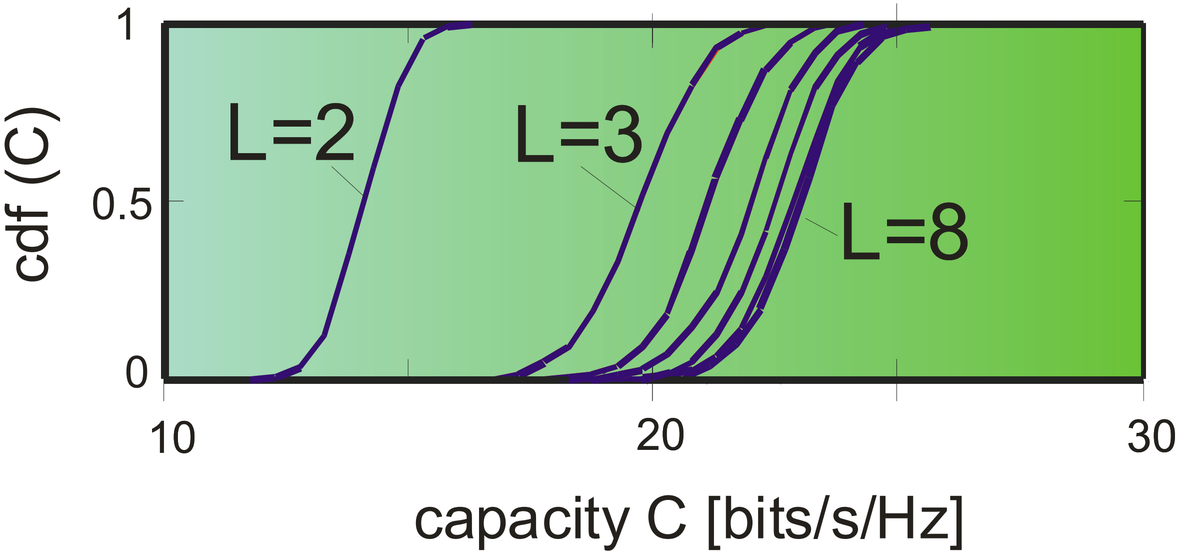
$$C_{\text{full}} = \log_2\left[\det\left(I_{N_t} + \frac{\overline{\Gamma}}{N_t} H H^{\dagger}\right)\right]$$

Antenna selection for H-S/MRT

- Create submatrices by striking rows
- Compute capacity according to Foschini equation
- Search the submatrix that gives largest capacity

$$C_{\text{select}} = \max_{S(\widetilde{H})}\left(\log_2\left[\det\left(I_{N_t} + \frac{\overline{\Gamma}}{N_t} \widetilde{H}\widetilde{H}^{\dagger}\right)\right]\right)$$

Capacity with RX antenna selection



3 transmit antennas, 20dB SNR

Contents

- System model
- Performance analysis
- Antenna selection algorithms
- Effect of nonidealities
- RF preprocessing
- Results in measured channels
- Hardware aspects
- Summary and conclusions

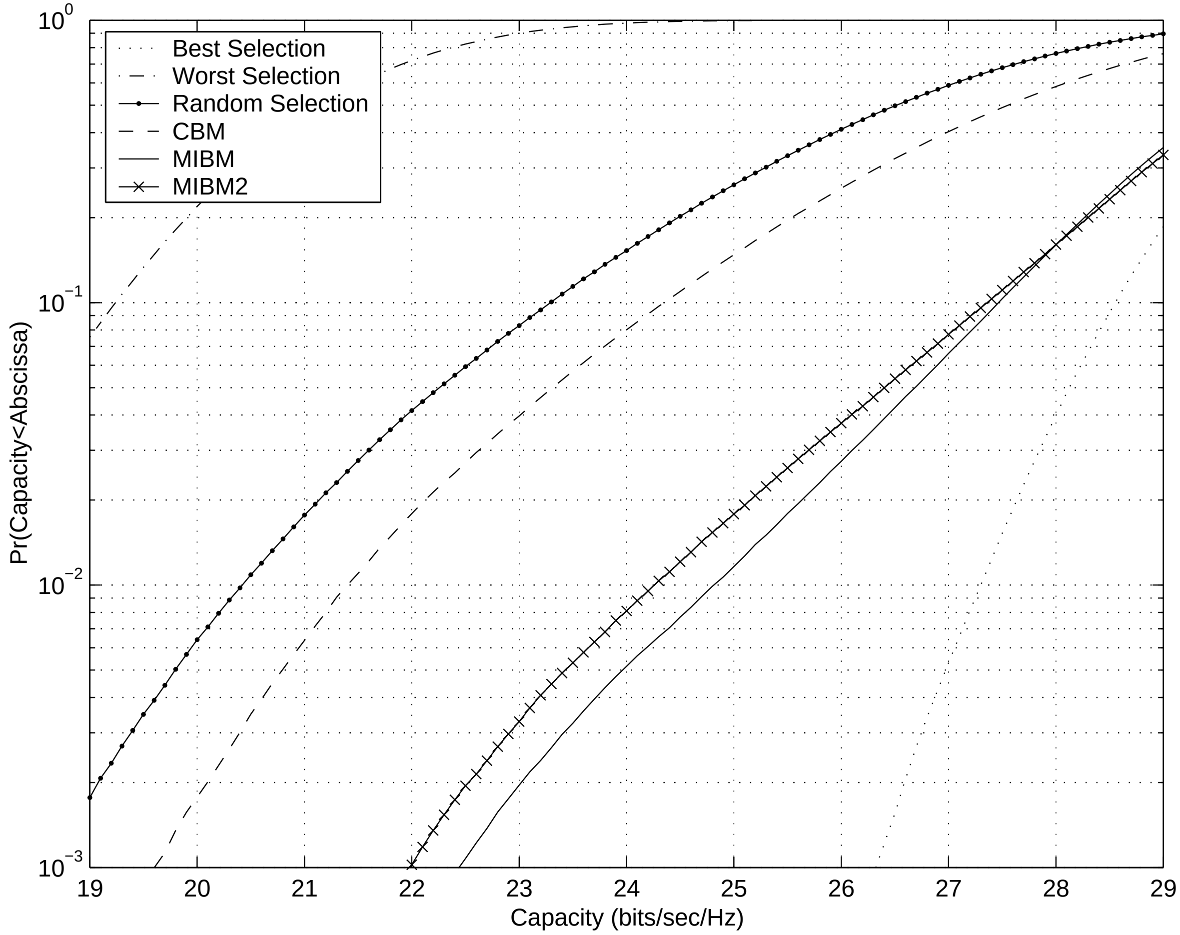
Antenna Selection Algorithms

- Truly optimum selection:
  - Exhaustive search
  - Effort proportional to

$$\binom{N_t}{L_t}\binom{N_r}{L_r}$$

- Approximate methods:
  - Power-based selection: works well for diversity antennas, but not for spatial multiplexing
  - Selection by genetic algorithms
  - Minimize mutual information between antenna elements
  - Gorokov's method

Minimization of mutual information



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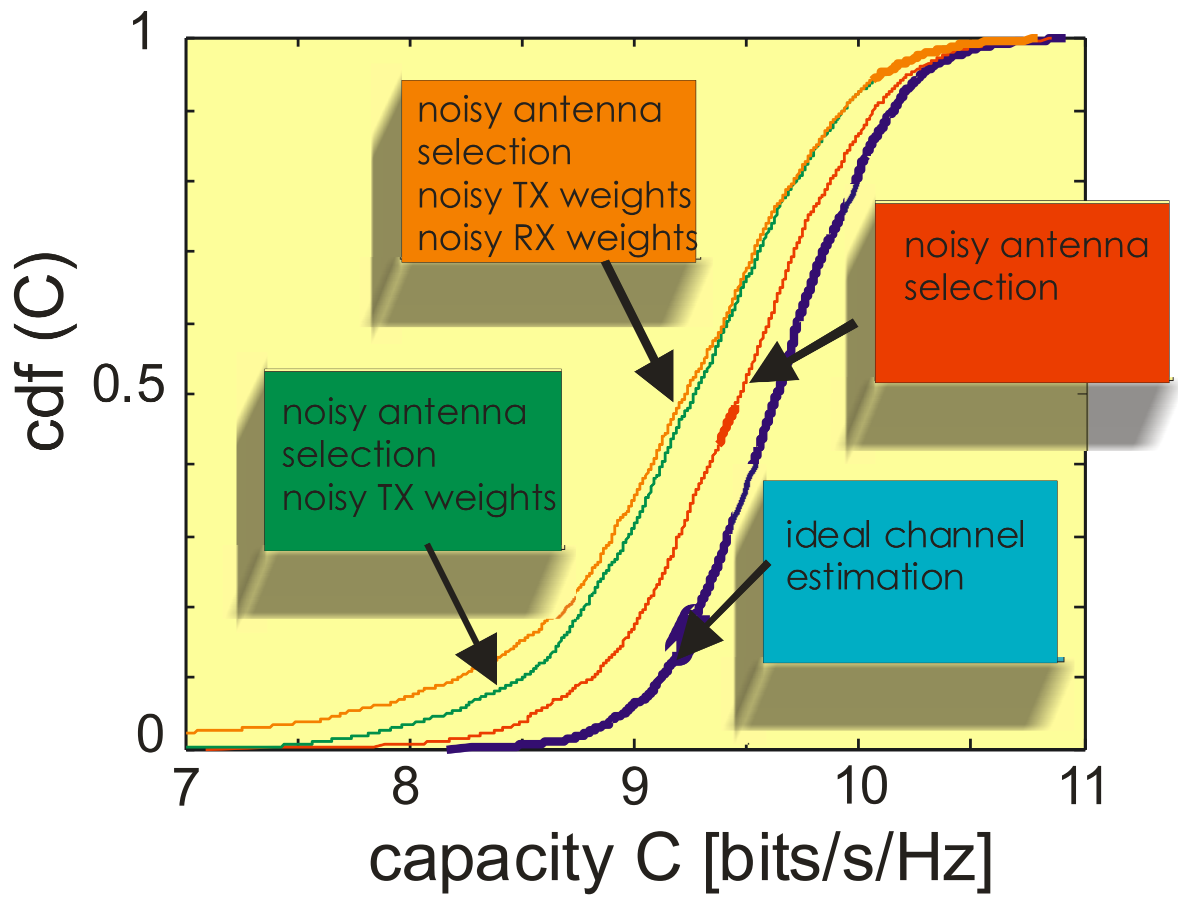
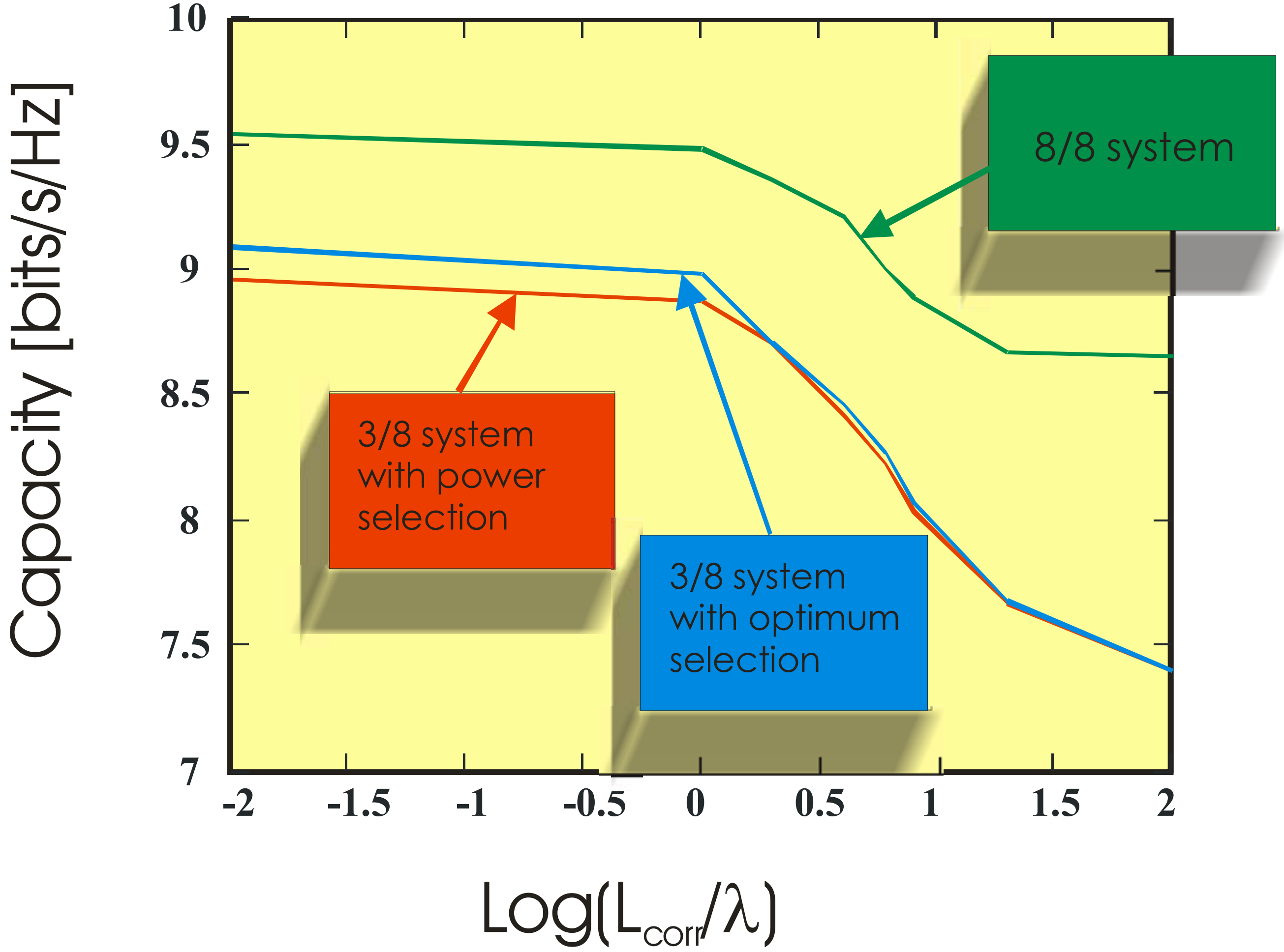
Channel Estimation Error - Diversity



Channel Correlation - Diversity



Key properties of antenna selection

- Number of spatial streams is limited by number of RF chains
- Diversity order is determined by number of antenna elements
- Beamforming gain is limited by number of RF chains

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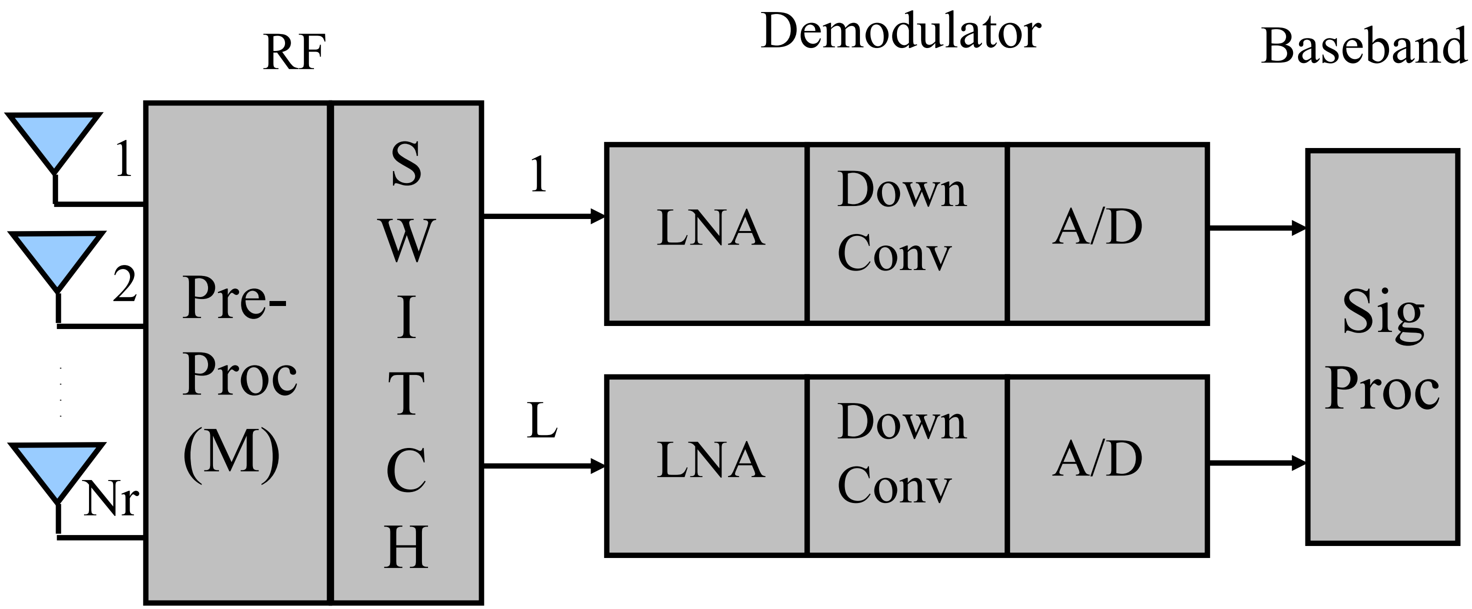
Principle



- Diversity gain AND Beamforming gain maintained
- Beam selection Vs Antenna Selection
- Can be implemented using variable phase-shifters
- In case **M** is of size L x Nr, selection switch/algorithm is not required

RF Pre-processing Solutions

- Channel-independent solution
  - Fixed matrix (FFT Butler matrix)
- Time-variant solution
  - Elements of pre-processing matrix tuned to instantaneous channel state
- Time-invariant solution
  - Elements of pre-processing matrix based only on channel-statistics
  - Can be implemented with or without selection

Channel-independent solution

- Transformation matrix is DFT matrix

$$\mathbf{M} = \frac{1}{\sqrt{r}}\begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j\omega_r} & \cdots & e^{-j(r-1)\omega_r} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{-j(r-1)\omega_r} & \cdots & e^{-j(r-1)^2\omega_r} \end{bmatrix}$$

- Transforms from antenna space to beamspace
- Each output of DFT has full beamforming gain *N*

Time-variant solution (instantaneous CSI)

- For diversity:
  - Achievable performance: same as with full-complexity CSI
  - Phase-shifter only solution: optimum performance with 2 RF chains
- Frequent channel sounding required

Time-invariant solution (average CSI)

Diversity case; only preprocessing (no selection)

Signal after RF pre-processing

$$\tilde{\mathbf{y}} = \mathbf{M}_L \mathbf{H}\mathbf{v}x + \mathbf{M}_L \mathbf{n}$$

Maximize average output SNR

$$\bar{\gamma}_{TI} = \max_{\mathbf{M}_L} E_{\mathbf{H}}\left[\frac{\rho}{N_t}\left(\mathbf{w}^{+}\left(\mathbf{M}_L \mathbf{M}_L^{+}\right)^{-1/2} \mathbf{M}_L \mathbf{H}\mathbf{v}\right)^2\right]$$

Optimum RF and Baseband Solution

- Perform PCA on $\lambda_1 \mathbf{u}_1$

Pre-processing matrix (RF) Receive vector (baseband)

$$\mathbf{M}_{TI} = \mathbf{B}_L \mathbf{Q}_{\text{opt}}$$

$$\mathbf{Q}_{\text{opt}} = [\mu_1, \ldots, \mu_L]$$

$$\mathbf{w}_{\text{opt}} = \frac{\mathbf{Q}_{\text{opt}} \mathbf{u}_1}{\left\| \mathbf{Q}_{\text{opt}} \mathbf{u}_1 \right\|}$$

$\boldsymbol{\mu}_i$: Eigenvector of ith largest eigenvalue of $\mathbf{R}_{uu} = E\left[\lambda_1^2 \mathbf{u}_1 \mathbf{u}_1^+\right]$

$\mathbf{B}_L$: Any full rank L x L matrix

- Extension of principal component combining for a single antenna correlated multipath receiver [Alouini, VTC2000]

Phase-Only Implementation

- Design of variable phase-shifters feasible
- Complex elements of **M** = $[m_{ij}]$ can have arbitrary amplitude and phase

Algorithm

- Retain phase
- Replace amplitude of m_{ij} with a switch a_{ij} = 0/1
- Switch state chosen to maximize correlation between rows of M and its phase-only approximation
- Complexity: O(L log(L))

RF Pre-Processing with Selection Switch

$$\bar{\gamma}_{TI} = \max_{\mathbf{M}_{N_r}} E_{\mathbf{H}}\left[\max_{\mathbf{S}_L} \frac{\rho}{N_t}\left(\mathbf{w}^+\left(\mathbf{S}_L \mathbf{M}_{N_r} \mathbf{M}_{N_r}^+ \mathbf{S}_L^+\right)^{-1/2} \mathbf{S}_L \mathbf{M}_{N_r} \mathbf{Hv}\right)^2\right]$$

- Difficult to handle analytically
- S_L that depends on instantaneous channel state

- Tractable lower bound: Swap max and expectation (E_H)

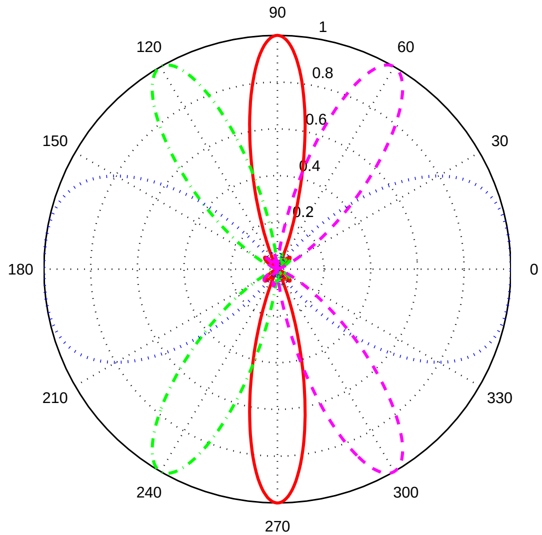
$$\bar{\gamma}_{TI} \geq \max_{\mathbf{S}_L} \max_{\mathbf{M}_{N_r}} E_{\mathbf{H}}\left[\frac{\rho}{N_t}\left(\mathbf{w}^+\left(\mathbf{S}_L \mathbf{M}_{N_r} \mathbf{M}_{N_r}^+ \mathbf{S}_L^+\right)^{-1/2} \mathbf{S}_L \mathbf{M}_{N_r} \mathbf{Hv}\right)^2\right]$$

Solution that Improves Lower Bound

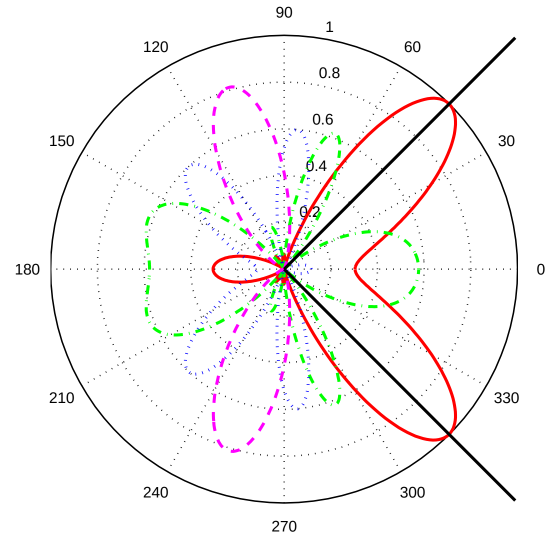
- Given $\mathbf{S}_L$, problem is similar to the $L \times N_r$ case
  - Specifies only L columns of **M**
  - Remaining (N_r - L) columns must be orthogonal to these L columns
- Given $\mathbf{S}_L$, fix corresponding L columns
- Subsequent manipulations should not deteriorate previously considered selections
- Successive improvement of lower bound by fixing remaining columns

$$\mathbf{M}_{TI} = \mathbf{P}\left[\mu_1, \ldots, \mu_L, \ldots, \mu_{N_r}\right]$$

Beam Patterns



FFT Butler

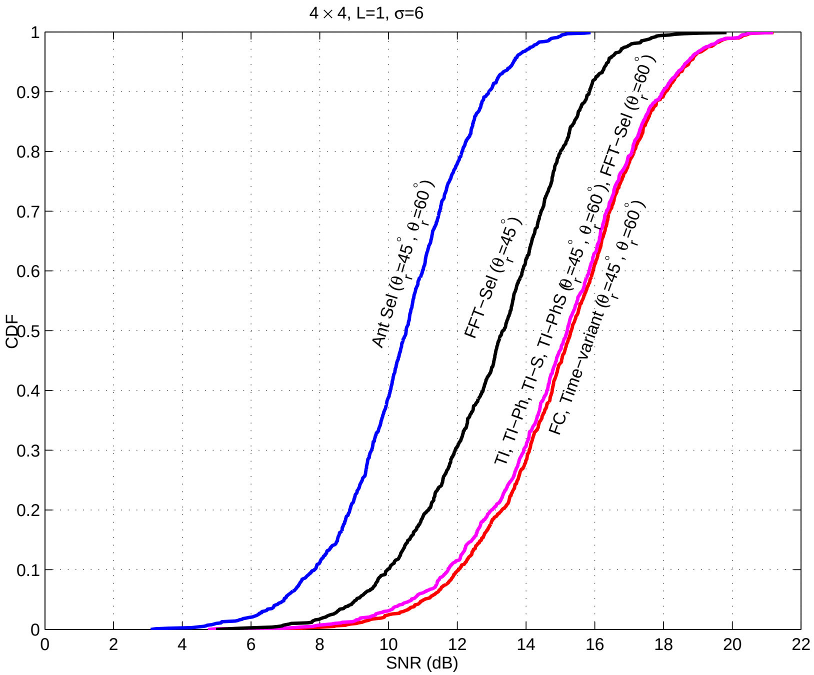


Time-Invariant
(Mean AoA = 45^0)

- TI adapts to mean AoA and angle spread (unlike FFT)
- Adapts to presence of multiple clusters

Comparison: Receivers with L demodulators

CDF of SNR



SNR (dB)

$N_r = N_t = 4$, $L = 1$

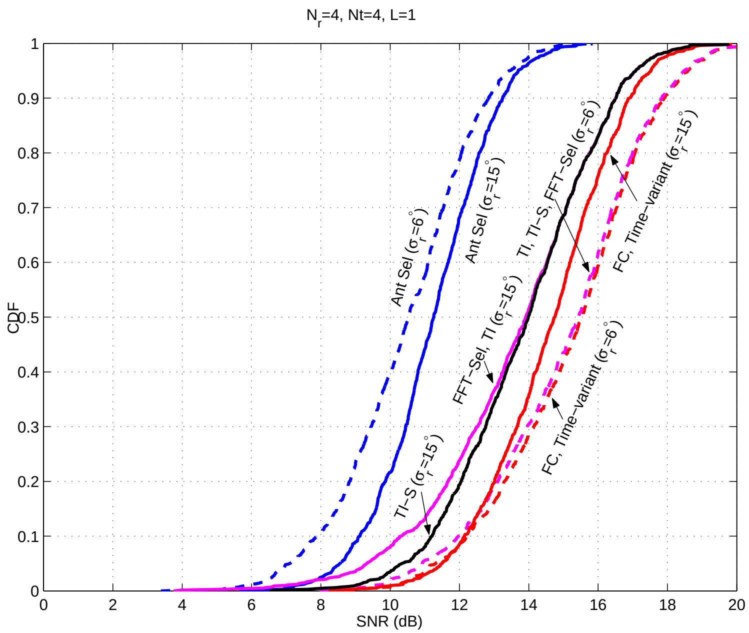
Angle spread = 6^0

$d_t/\lambda = 0.5$

- Gain of over 5.0 dB over antenna selection
- Mean AoA = 45^0: Gain of 2.2 dB over FFT-Selection
- Mean AoA = 45^0: No gain over FFT-Selection

Effect of Spatial Correlation

CDF of SNR



SNR (dB)

$N_r = N_t = 4, L = 1$

Mean AoA = 60^0

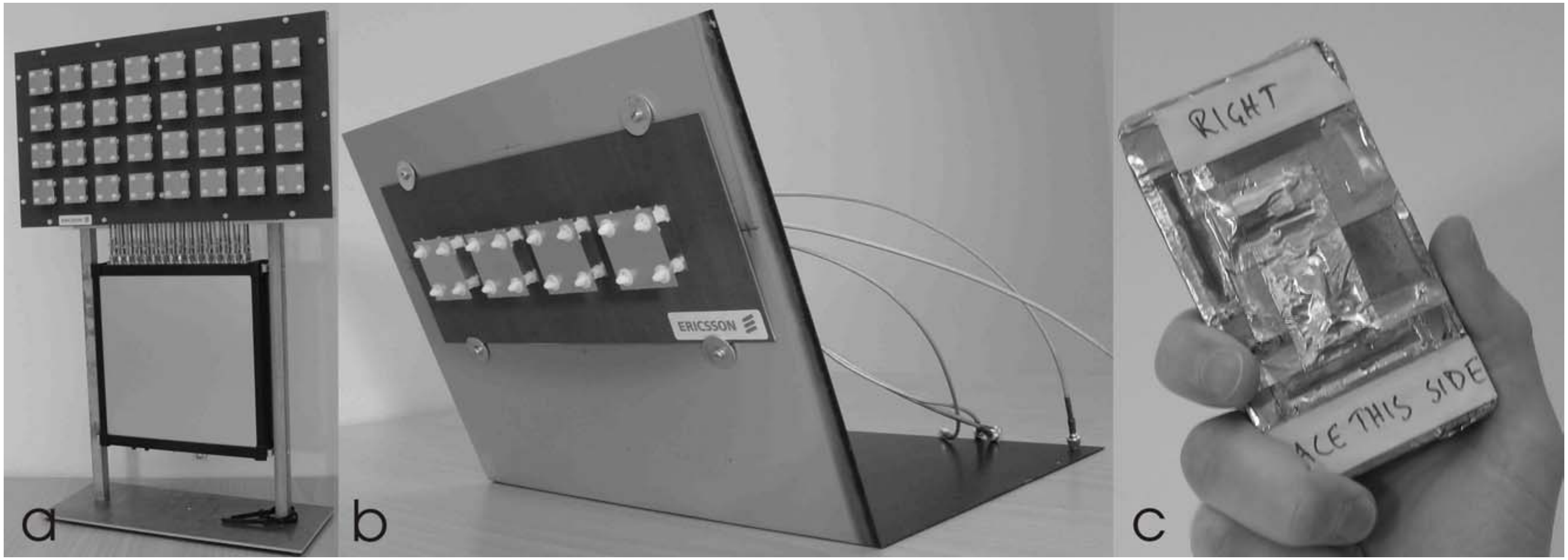
$d_t/\lambda = 0.5$

- Time-invariant solution efficacy decreases as correlation decreases
- Antenna selection efficacy improves as correlation decreases

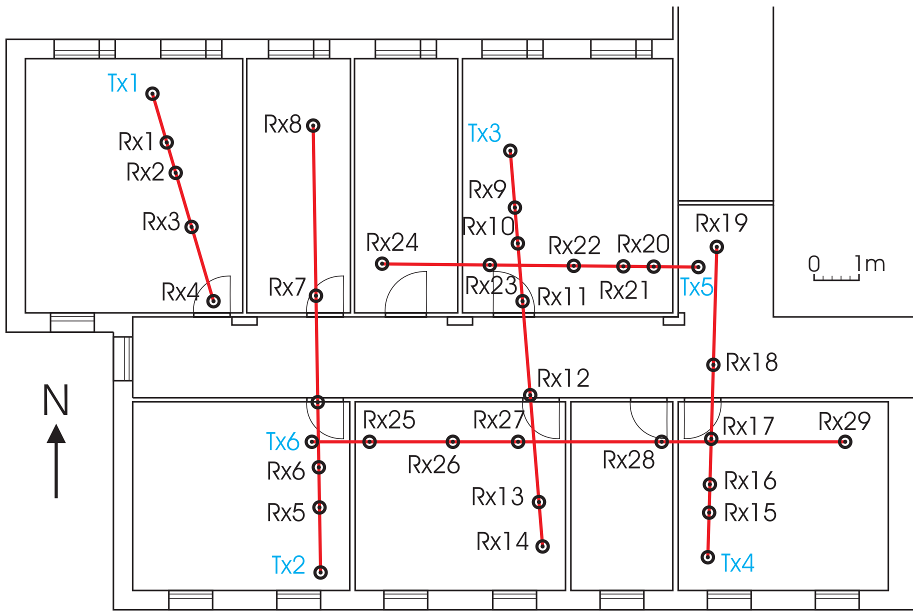
Contents

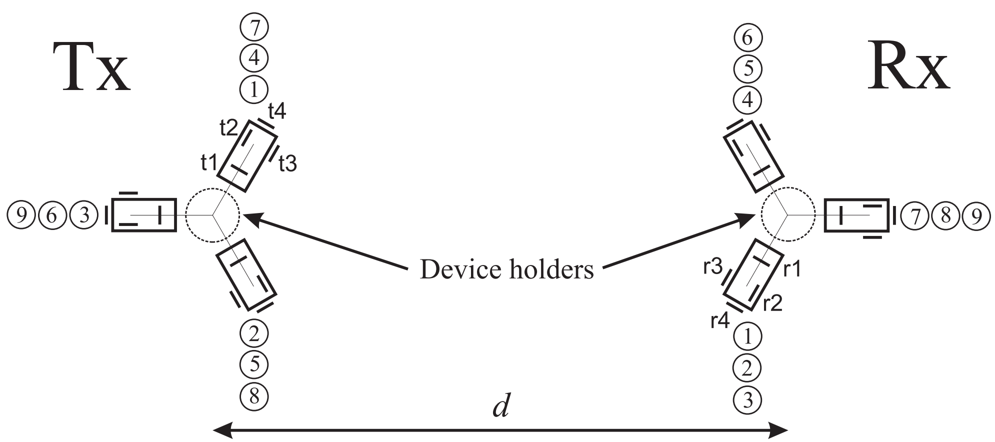
Setup of measurement campaign

- Measure channel for “Personal Area Networks”
- Use access point, PC, and handheld



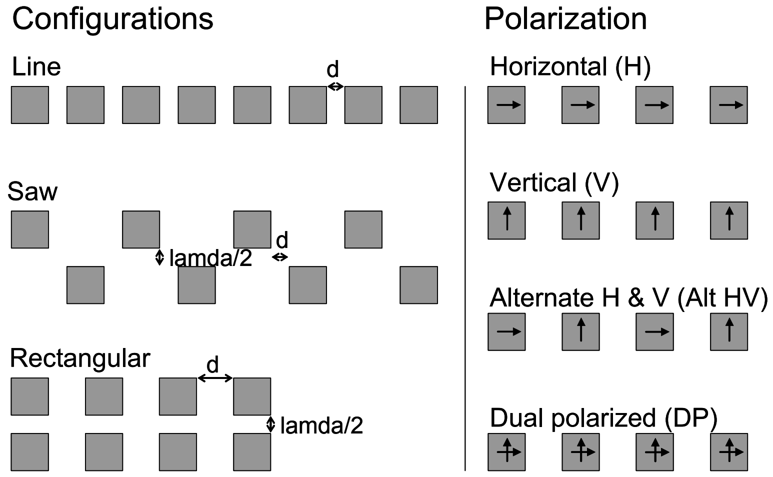
Sitemap and measurement setup





Diversity gain

Impact of antenna configurations



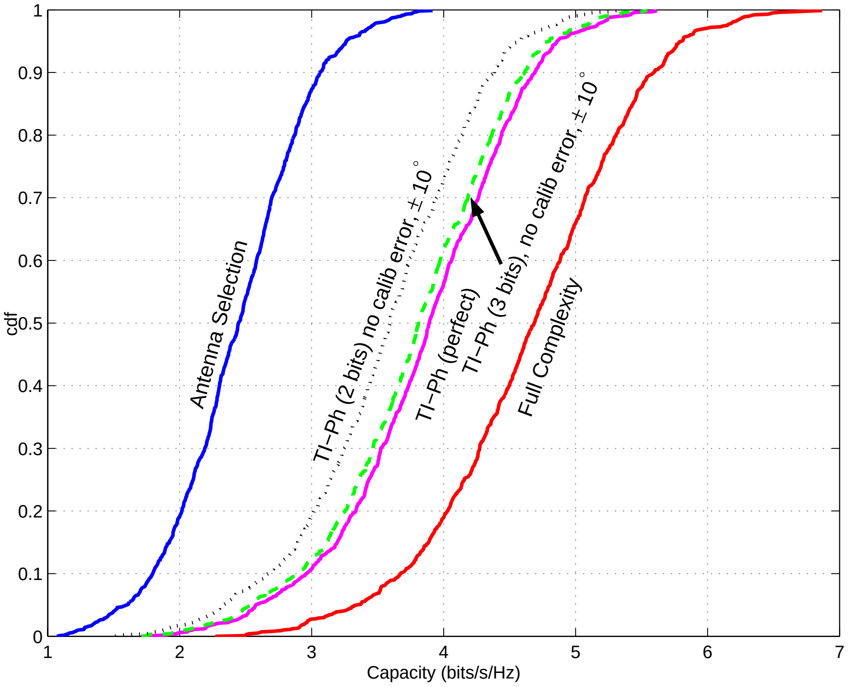
Configuration comparison for the AP - PC scenario HS-B at PC only. LOS. 4:2×2:2.

Contents

Hardware Aspects

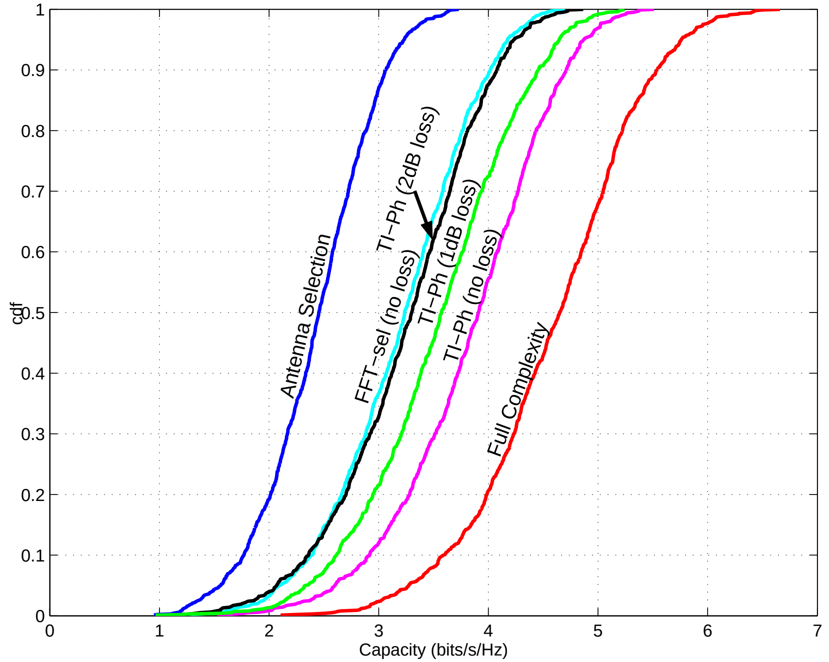
- Attenuation of switches
  - either decrease the effective SNR,
  - or LNA has to be before switch→requires more LNAs
- Switching time: has to be much smaller than duration of training sequence
- Accuracy of switch: transfer function has to be same from each input to each output port
- MEMS switches: have low insertion loss (0.1dB), but large switching time (5 microsec)
- Solid-state switches: high insertion loss (>1 dB), but short switching times (100 ns)

Phase Quantization & Calibration Errors



- 3-bit phase quantization (steps of 45^0): capacity within 0.1 bits/sec/Hz
- 2-bit phase quantization (steps of 90^0): capacity within 0.3 bits/sec/Hz
- Spatial diversity: 1 dB loss in mean SNR observed

Insertion Loss



- 2 dB loss: TI-Ph capacity same as ideal FFT selection
- 5 dB loss: TI-Ph capacity same as conventional antenna selection

Summary and Conclusions

- Antenna selection retains the diversity degree, but SNR penalty
- For spatial multiplexing, comparable capacity if $L_r \geq N_t$
- Optimum selection algorithms have complexity N!/(N-L)!; however, fast, good selection algorithms exist
- For low-rank channels, transmit antenna selection can increase capacity
- Channel estimation errors do not decrease capacity significantly
- Frequency selectivity reduces effectiveness of antenna selection
- RF preprocessing greatly improves performance, especially in correlated channels
- Covariance-based preprocessing especially suitable for frequency-selective channels
- Switches with low attenuation required both for TX and RX

Acknowledgements

- This work was done in collaboration with
  - Moe Z. Win
  - Jack H. Winters
  - Yang-Seok Choi
  - Xinying Zhang
  - Sun-Yuan Kung
  - Neelesh B. Mehta
  - Pallav Sudarshan
  - Yabo Li
  - Peter Almers

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