Multiuser MIMO Systems

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Abstract Communication systems with multiple antennas at both transmitter and receiver (i.e., MIMO systems) have shown considerable promise in providing high-rate, high-quality wireless links. This talk will discuss implications of using MIMO systems in multiple-access networks. The main focus of the talk will be on receiver signal processing for such systems, and in particular on multiuser detection and related issues. Complexity reduction techniques that use turbo processing or adaptive implementations will also be described. Finally, some related issues concerning the spectral efficiencies of such systems will be discussed.

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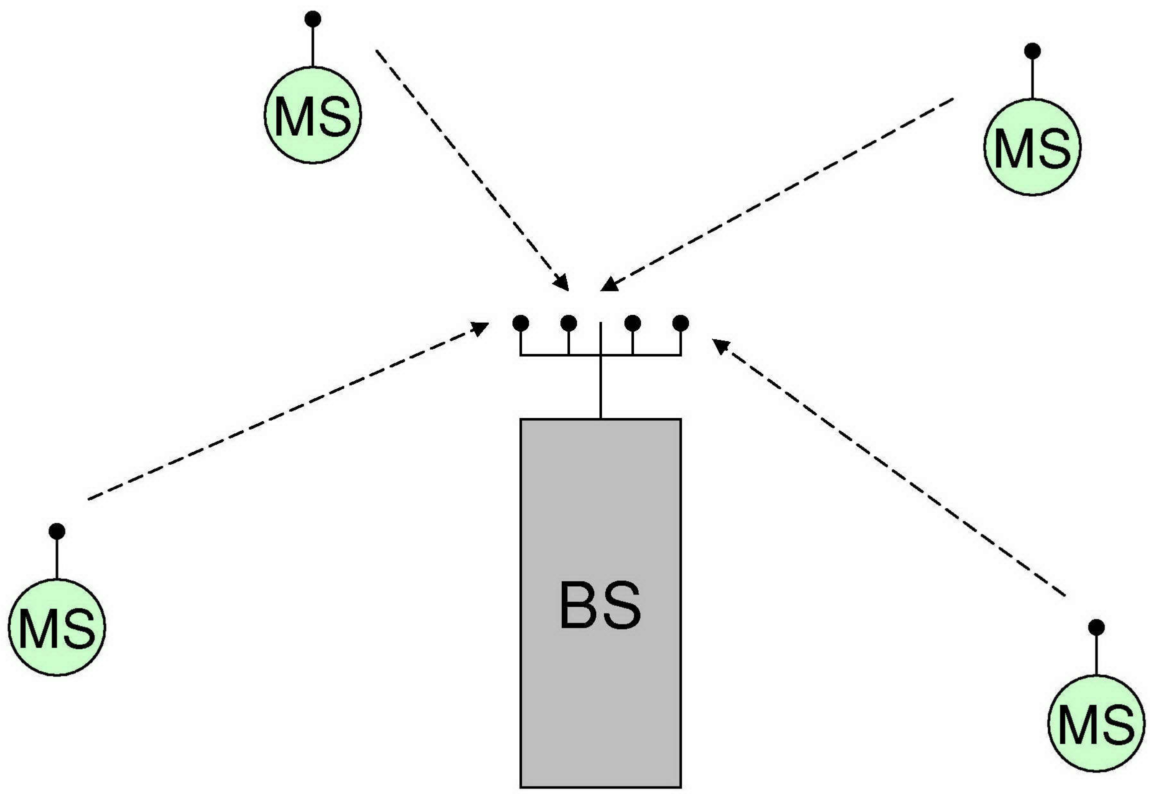
Outline

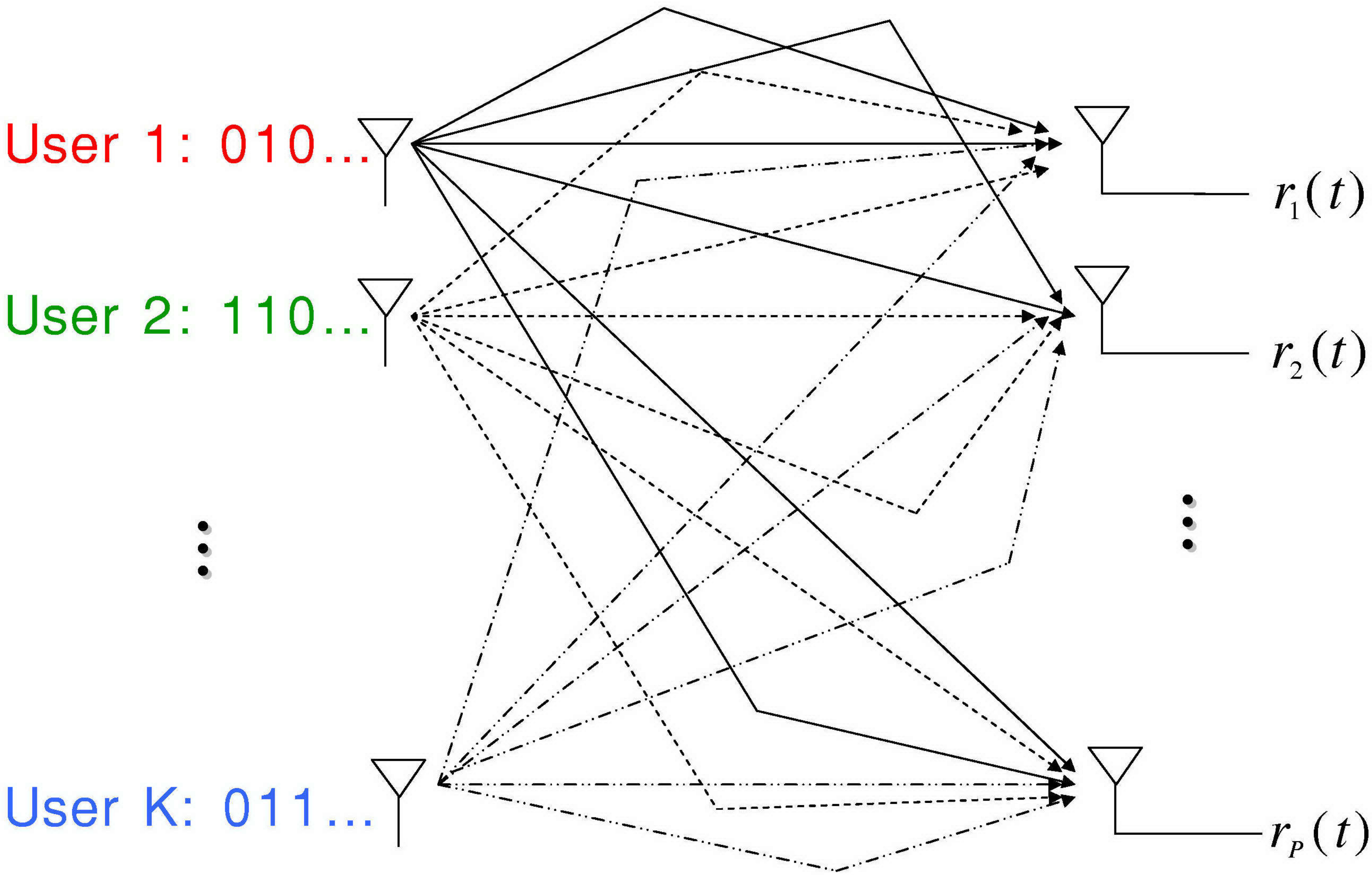
- MIMO Multiuser Detection (MUD)
  - *Space-time MUD: The SIMO Case*
  - *MIMO MUD: Examples*
- Network Utility in Multiuser MIMO Systems
- Spectral Efficiency in Multiuser MIMO Systems (Briefly)

MIMO MUD

SPACE-TIME MUD
(The SIMO Case)

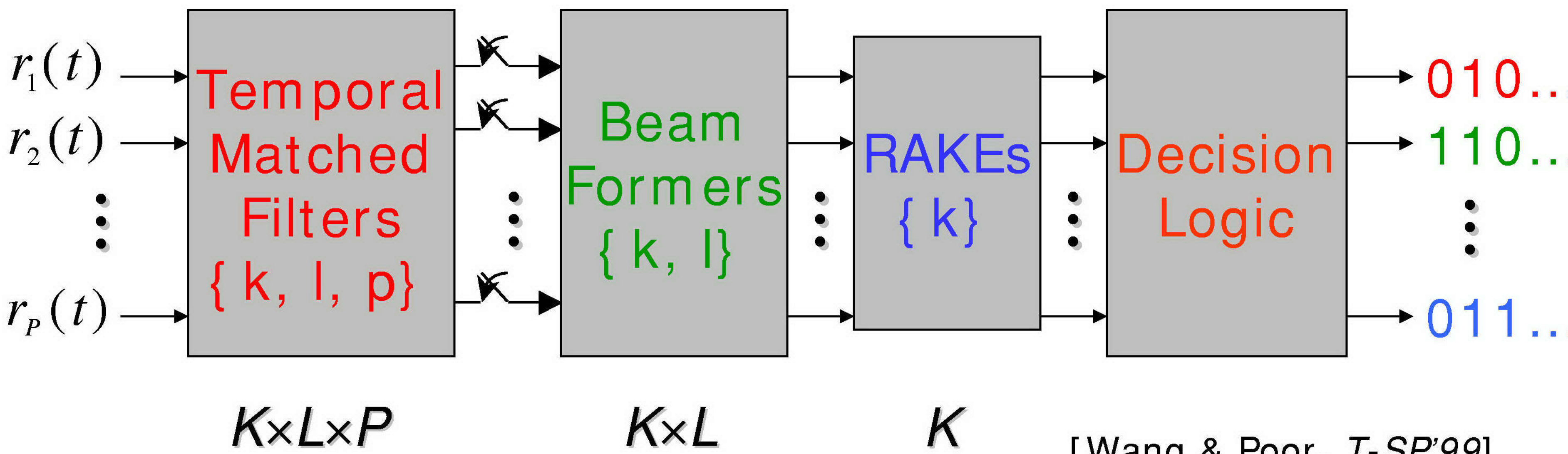


Multipath SIMO MAC



Sufficient Statistic
(Space-Time Matched Filter Bank)

<u>K Users</u>; <u>P Receive Antennas</u>; <u>L Paths/User/Antenna</u>



[Wang & Poor, *T-SP'99*]

<u>Optimal</u>, <u>linear</u>, <u>iterative</u> & <u>adaptive</u> versions

SIMO MUD - Linear Model

K users, each transmitting *B* symbols, yields a linear model:

$$y = H\,b + \mathcal{N}(0, \sigma^2 H)$$

- y = *KB*-long sufficient statistic vector
- b = *KB*-long vector of symbols
- s = $KB \times KB$ matrix of cross-correlations

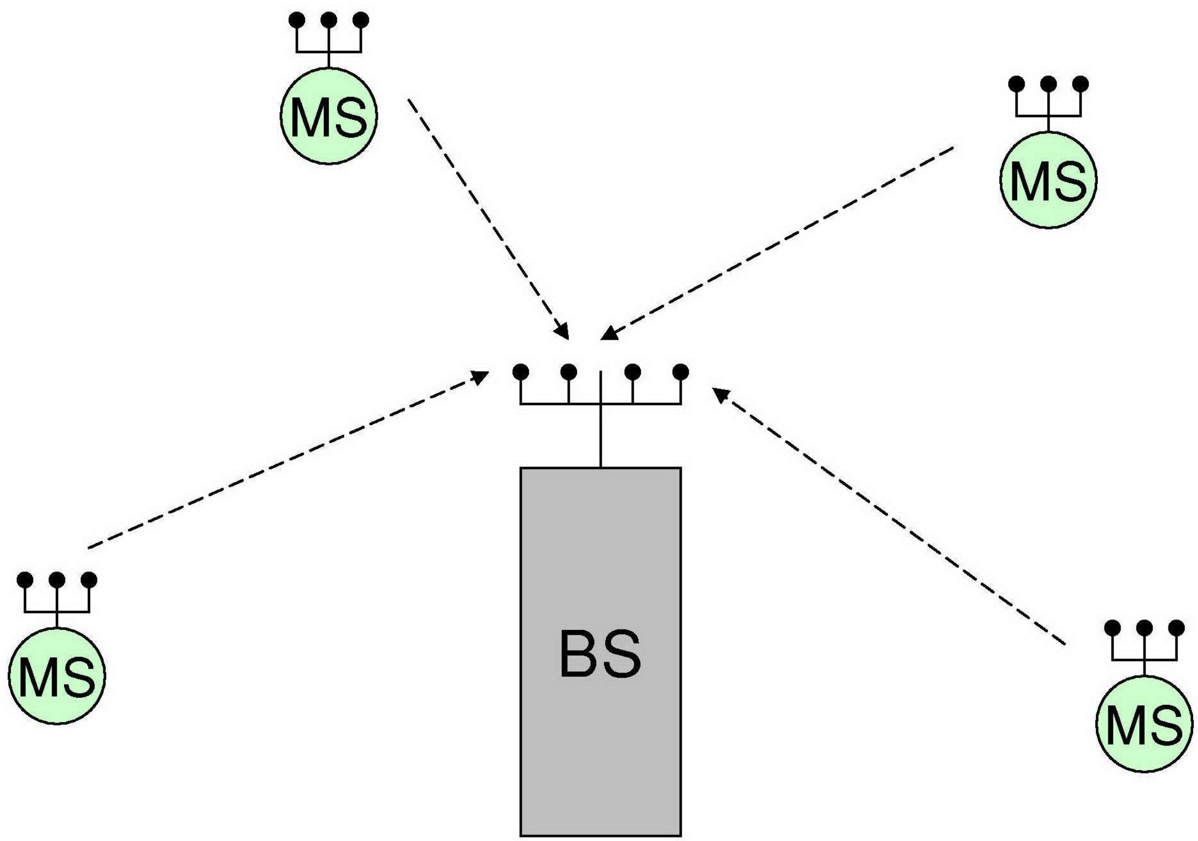
SIMO MUD - Varieties

- Optimal [Complexity $O(2^{K\Delta})$; Δ = *delay spread*]
  - ML: argmax $l(y|b)$
  - MAP: argmax $p(b_{k,i}|y)$
- Linear [Complexity $O((KB)^3)$]
  - Decorrelator: sgn$\{H^{-1} y\}$
  - MMSE: sgn$\{(H+\sigma^2 I)^{-1} y\}$

$$y = H\, b + N(0, \sigma^2 H)$$

- Iterative [Complexity $O(K\Delta n_{max})$, etc.] [Dai & Poor, *T-SP'02*]
  - Linear IC: Gauss-Siedel, Jacobi, conjugate-gradient
  - Nonlinear IC: the above with intermediate hard decisions
  - EM: symbols are stochastic
  - Turbo: symbols are constrained via channel coding
- Adaptive [Sampling, followed by LMS, RLS, subspace, etc.]

MIMO MUD

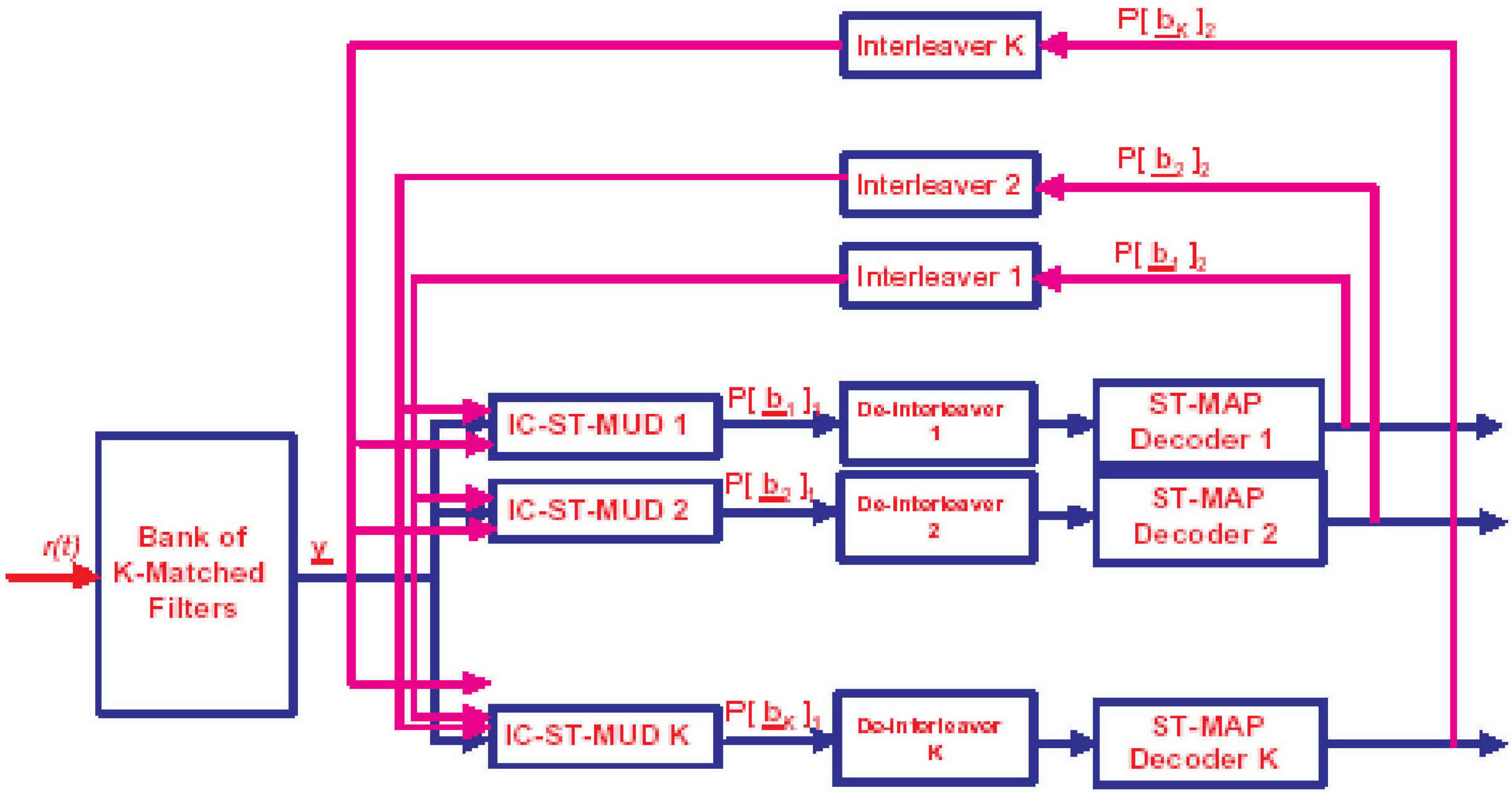


Observation: MIMO MUD is the same as SIMO MUD, except for the decision algorithm - MI adds further constraints on $\mathbf{b}$.

Space-time Coded Systems

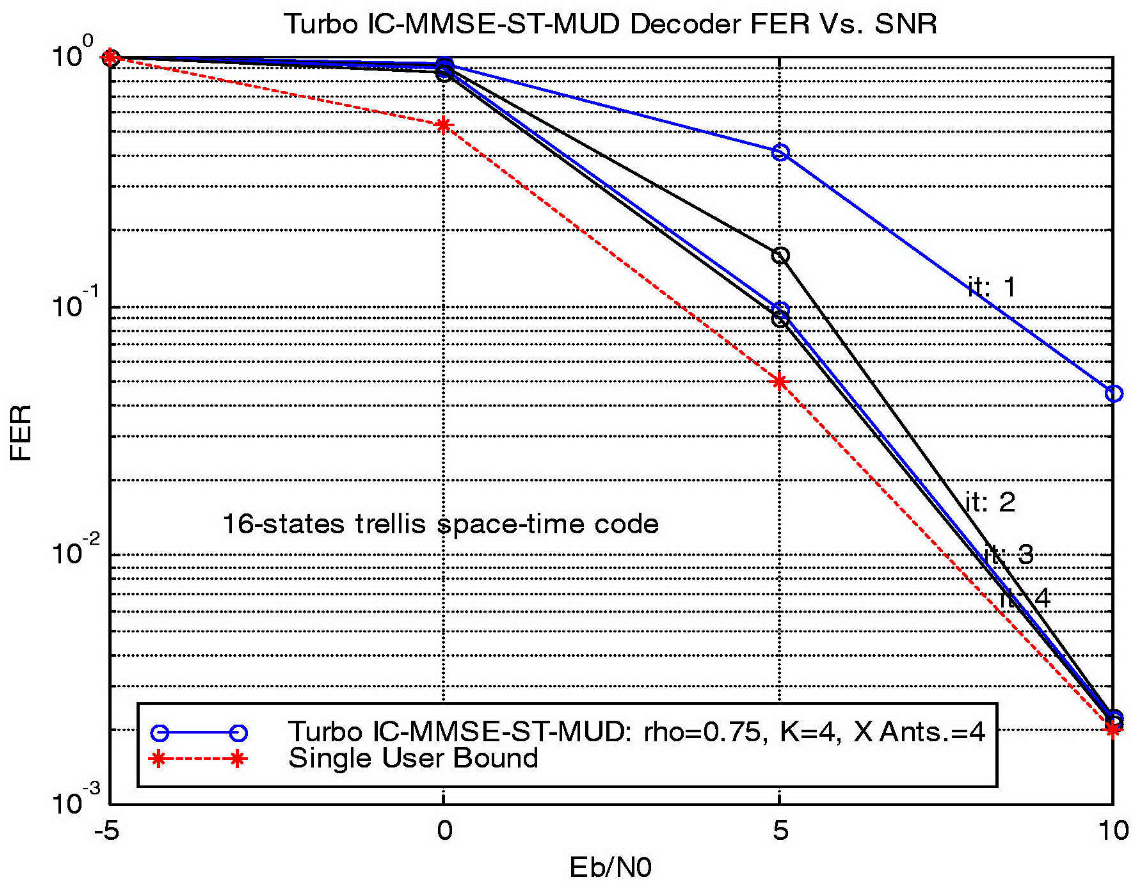
- Space-time Coded Systems
  - Single-user Channels:
    - Encoding of symbols across multiple transmit antennas.
    - ST block codes [Alamouti, Tarokh, et al.]; ST trellis codes [Tarokh, et al.]; unitary ST codes [Hochwald, Marzetta, et al.].
  - Multiuser Channels [Jayaweera & Poor, *EJASP '02*]:
    - Separation Th'm: "Full-diversity-achieving single-user ST trellis codes also achieve full diversity in multiuser channels with joint ML detection & decoding (assumes large SNR, quasi-static Rayleigh fading, etc.)."
    - Turbo-style iteration among ST trellis decoding & MUD achieves near-ML performance.

Turbo IC Space-Time MUD (MISO Case)



Turbo IC-ST Receiver Model

Performance (4 × 1; K= 4)



BLAST-Type Systems

- BLAST (Bell Labs Layered Space-Time Architecture)
  - Basic BLAST [Foschini, et al.]:
    - Distributes symbols of a single user on multiple tx antennas.
    - Uses MUD to separate different streams using spatial signature.
    - Capacity (Rayleigh) linear in the min{#tx,#rx} antennae.
    - Capacity gain degrades in interference-limited channels.
  - Turbo BLAST [Dai, Molisch & Poor, *T-WC'04*]:
    - MUD restores the BLAST capacity gain in interference channels.

NETWORK UTILITY
IN
MU/MIMO SYSTEMS

Joint work with Meshkati, Mandayam & Schwartz.

Competition in a Multiple-Access Network

- Consider a multiple-access network.
- User terminals are like players in a game, competing for network resources.
- The action of each user affects the performance of others.
- Can model this as a non-cooperative game.

Game Theoretic Framework

Game: $G = [\{1, \ldots, K\}, \{A_k\}, \{u_k\}]$

K: total number of users

A_k: set of strategies for user k

u_k: utility function for user k

$$u_k = utility = \frac{throughput}{transmit\ power} = \frac{T_k}{p_k} \left[\frac{bits}{Joule} \right]$$

$T_k = R_k f(\gamma_k)$, where $f(\gamma_k)$ is the frame success rate, and γ_k is the received SIR of user k.

The SIMO Game

- Each user selects its transmit power and uplink (linear) detector to maximize its own utility.
- Nash equilibrium is reached when each user:
  - chooses the MMSE detector as its receiver, and
  - chooses a transmit power that achieves γ^*, the solution to:

$$\boxed{f(\gamma) = \gamma f'(\gamma)}$$

Large-System Analysis

- Consider R-CDMA with spreading gain N.
- As $K, N \to \infty$ with $K/N = \alpha$:

$$u_k = \frac{R_k f(\gamma^*)}{\gamma^* \sigma^2} \bar{h}_k \Gamma \qquad \text{where}$$

$$\Gamma^{MF} = 1 - \bar{\alpha}\gamma^* \qquad \text{for } \bar{\alpha} < \frac{1}{\gamma^*}$$

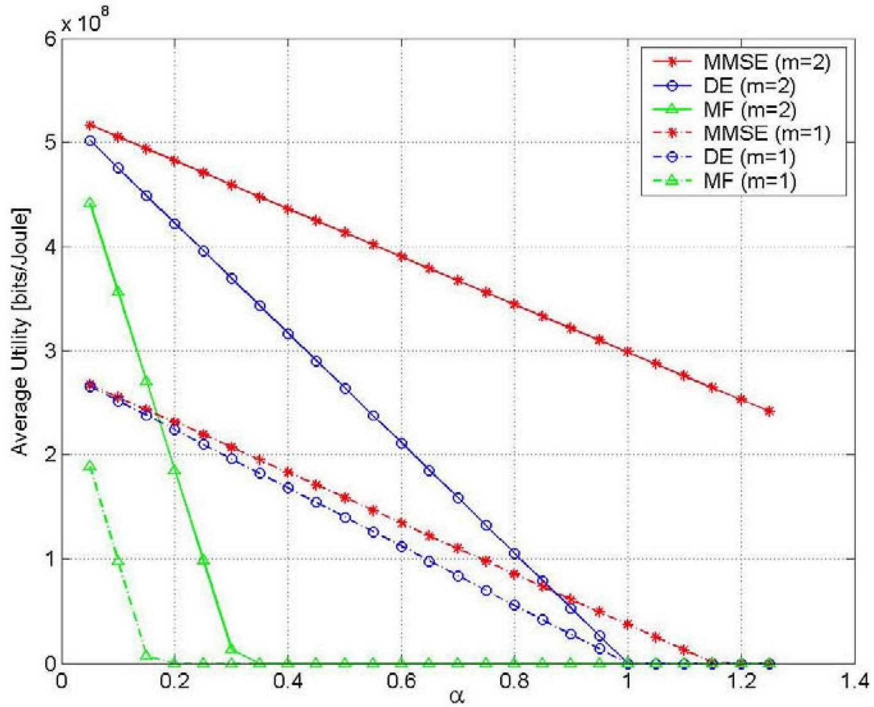
$$\Gamma^{DE} = 1 - \alpha \qquad \text{for } \alpha < 1$$

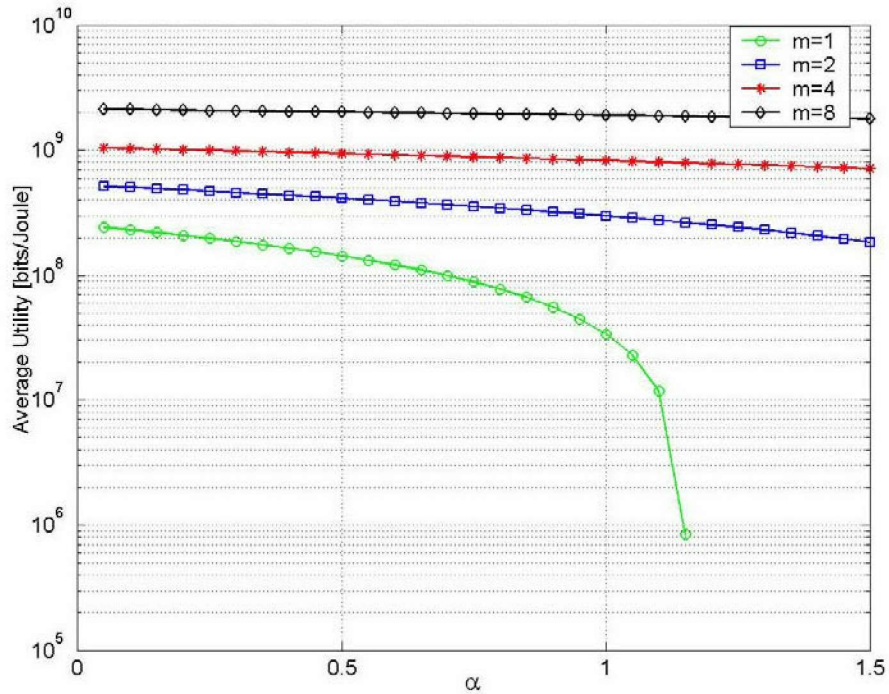
$$\Gamma^{MMSE} = 1 - \bar{\alpha}\frac{\gamma^*}{1+\gamma^*} \qquad \text{for } \bar{\alpha} < 1 + \frac{1}{\gamma^*}$$

$$\text{with} \qquad \bar{h}_k = \sum_{p=1}^{P} h_{kp}^2 \qquad \text{and} \qquad \bar{\alpha} = \frac{\alpha}{P}$$

Two mechanisms:
- power pooling
- interference reduction

Numerical Example





- Multiuser detectors achieve higher utility and can accommodate more users compared to matched filter.
- Significant performance improvements are achieved when multiple antennas are used compared to single antenna case.

The MIMO Game

- Each user selects its transmit power, uplink (linear) detector, and distribution of power among transmit antennas to maximize its own utility.
- Nash equilibrium is reached when each user:
  - chooses the MMSE detector as its receiver,
  - transmits in the direction of the eigenvector corresponding to the maximal eigenvalue of the "effective" channel matrix (*spatial waterfilling*), and
  - transmits to achieve SIR γ^*.

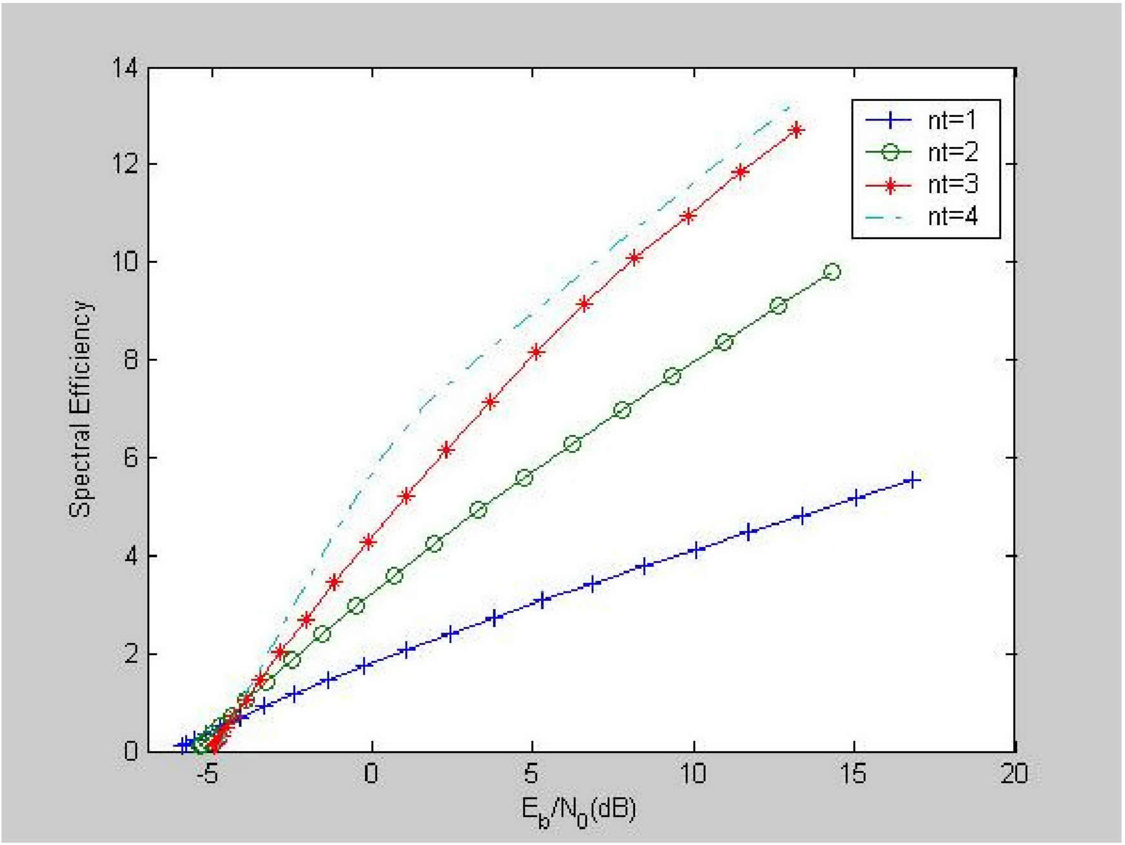
SPECTRAL EFFICIENCY IN MU/MIMO SYSTEMS (BRIEFLY)

Joint work with Husheng Li.

Spectral Efficiency in MU/MIMO Systems

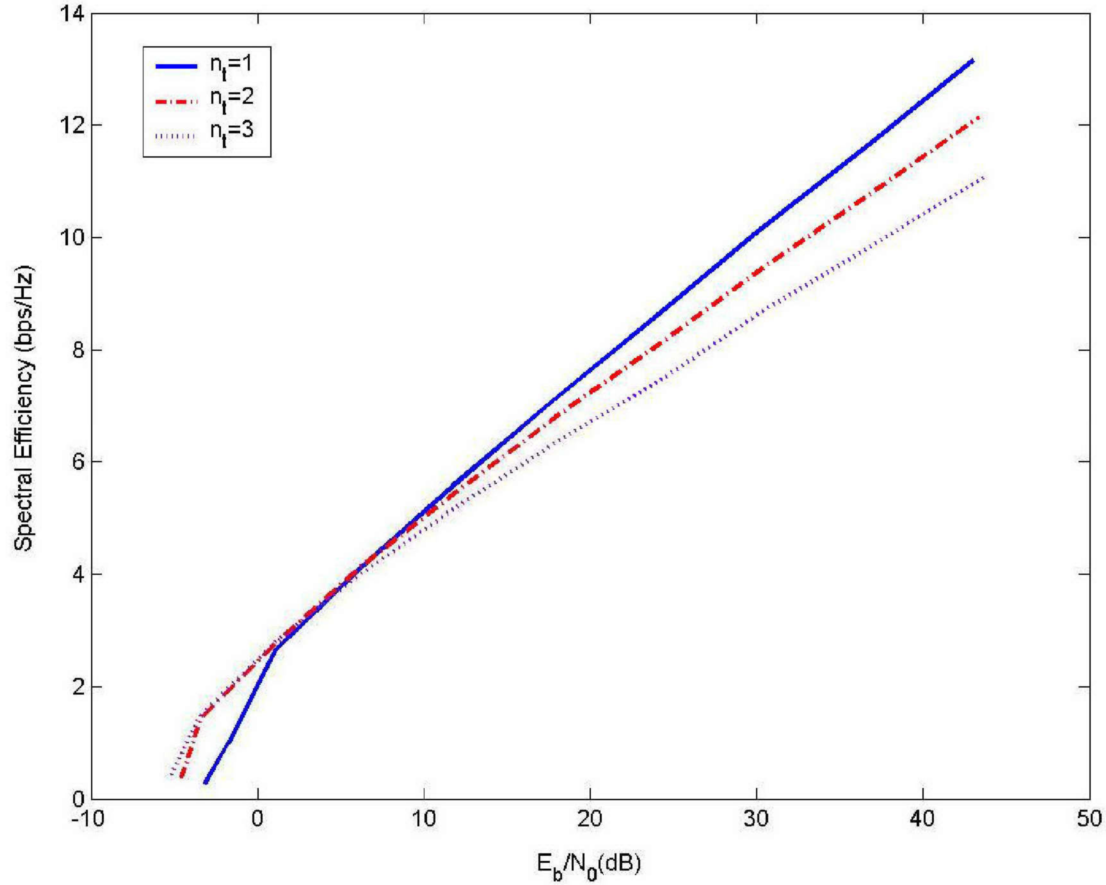
- Consider a system combining DS/CDMA with MIMO.
- Multiple transmit antennas add "diversity" dimensions, but use up "code" dimensions.
- So, there's an overall tradeoff in achieving maximal spectral efficiency (bps/Hz) in such systems.
- For K equal-rate, equal-power R-CDMA users, can be analyzed in closed form as $K, N \to \infty$ with $K/N = \alpha$ fixed.
- Note: with n_t transmit antennas, the "radio" load is $\alpha\, n_t$.

Full-Multiplex MIMO ($\alpha = 0.4 \,;\, n_r = 4$)



- There are diminishing returns for adding antennas when the radio load, αn_t, exceeds 1 (assumes transmitter has no CSI).
- For small SNR, outage issues reverse the advantages of multiple transmit antennas.

Optimal MIMO ($\alpha = 2.0; n_r = 4$)



- For large SNR, multiuser efficiency issues reverse the advantages of multiple transmit antennas. (Again there is no tx CSI.)

Summary

- MIMO Multiuser Detection (MUD)
  - *Space-time MUD: The SIMO Case*
  - *MIMO MUD: Examples*
- Network Utility in MU/MIMO Systems
- Spectral Efficiency in MU/MIMO Systems