Estimation and Capacity of Channels in Smart Antenna Wireless Communication Systems

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Final Oral Examination

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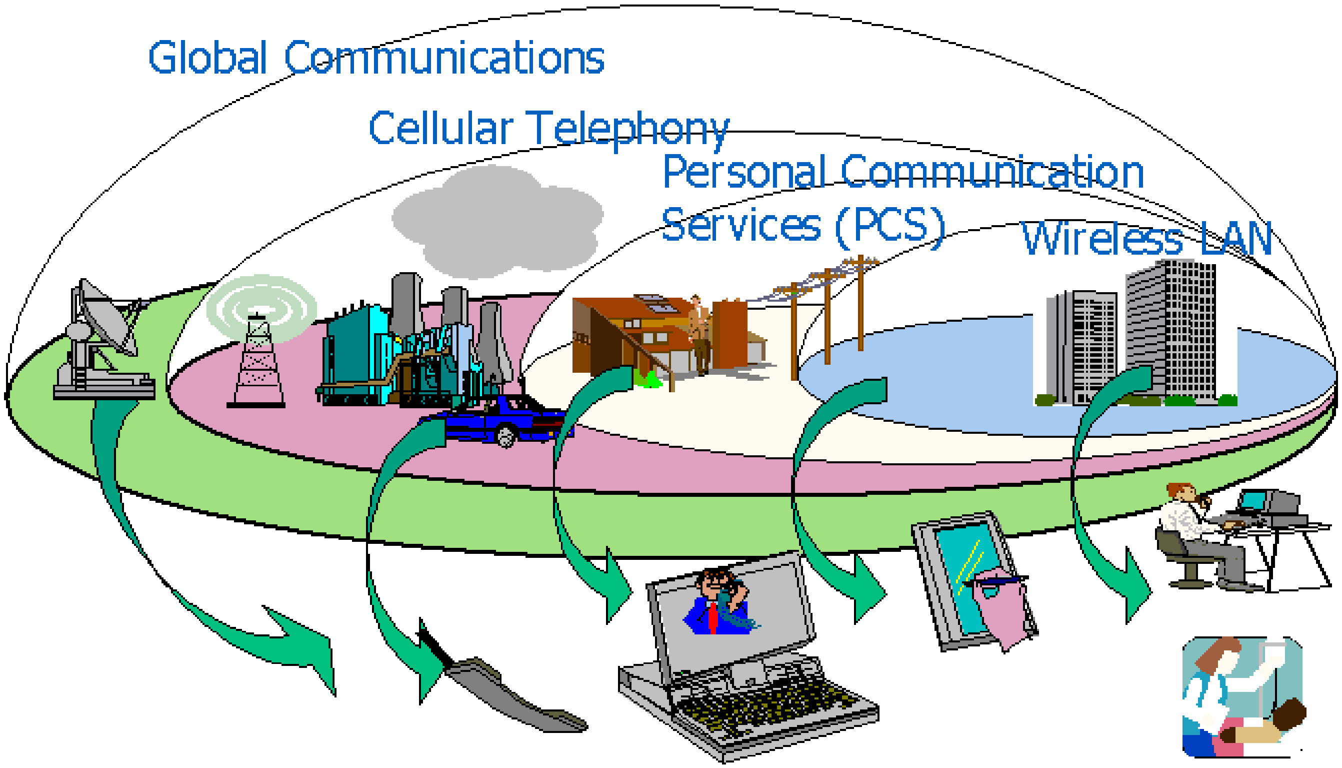
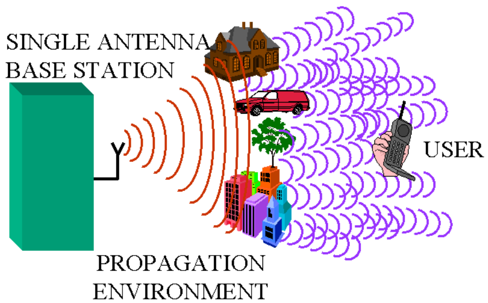
MOTIVATION



- Communication Anywhere-Anytime-Anytype
  - ☞ Increasing Demand for Wireless Services
  - ☞ Unique Problems compared to Wireline communications

SMART ANTENNA SYSTEMS

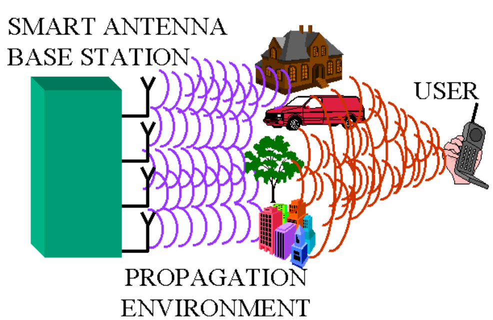
- Wireless systems broadcast signals across wide areas to individual users

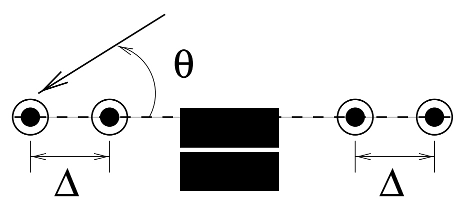


☞ Most of energy is wasted while little reaches the intended user

- Spatial processing characterizes the RF environment

☞ through antenna arrays and innovative digital signal processing sotware





$$\frac{1}{B_s} \ll \tau$$

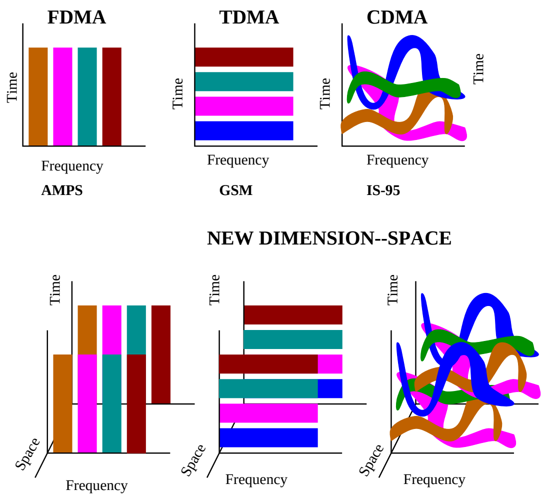
$$\mathbf{a} = [1 \; e^{j2\pi \triangle \cos(\theta)/\lambda} \; \ldots \; e^{j2\pi(M-1)\triangle \cos(\theta)/\lambda}]$$

$$\mathbf{x}(t) = \mathbf{a}(\theta)\mathbf{s}(t) + \mathbf{n}(t)$$

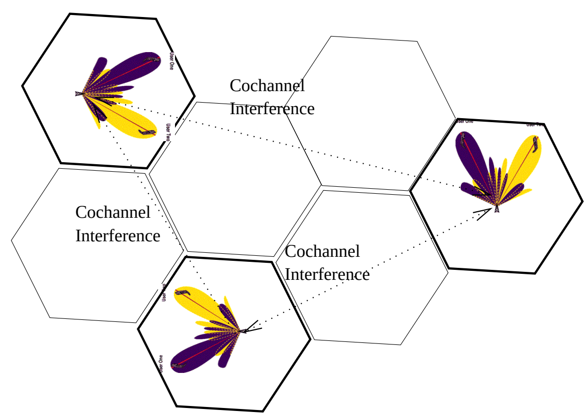
- Additional dimension of functionality

Added Dimension in Wireless Communication

- Space division compelements existing air interfaces



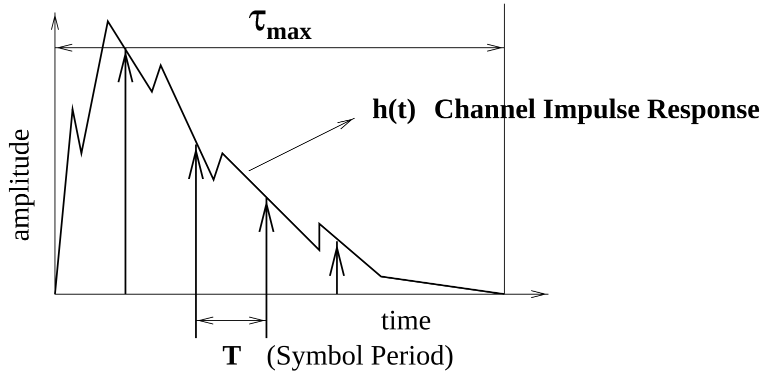
SPACE DIVISION MULTIPLE ACCESS (SDMA)



☞ toward intended users – away from unintended users

Wideband Channel Model

- The symbol period, T, is comparable to multipath spread, τ_{max}



- Single user case with L paths to receiver

$$\mathbf{x}(t) = \sum_{k=1}^{L} \alpha_k s(t - \tau_k) = \mathbf{h}(t) \otimes s(t)$$

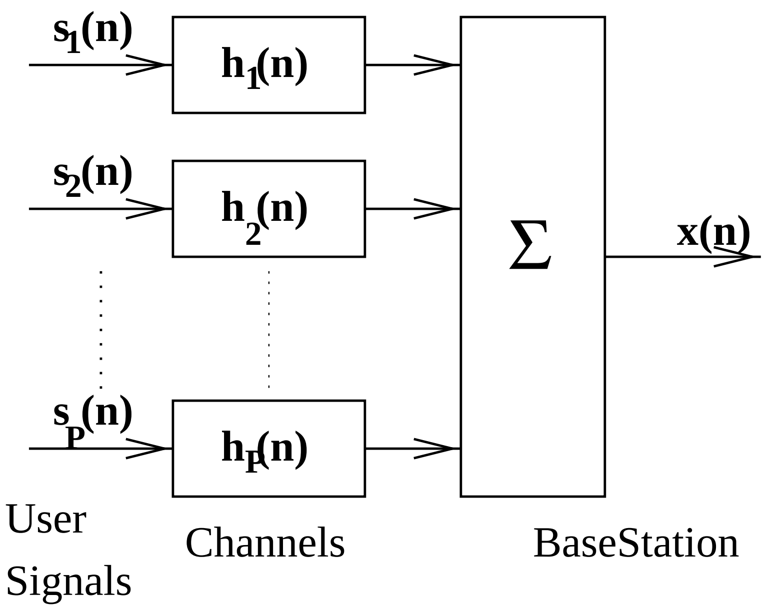
- Vector channel model with an antenna array

$$\mathbf{x}(t) = \sum_{k=1}^{L} \alpha_k \mathbf{a}(\theta_k) s(t - \tau_k) = \mathbf{h}(t) \otimes s(t)$$

UPLINK PROCESSING FOR WIRELESS BASESTATIONS

- **Objective:** Combine the intended user signals while suppressing the co-channel signals.

- **How?** Estimate the wireless channel parameters ($\mathbf{h}_p(n)$) based on the data received

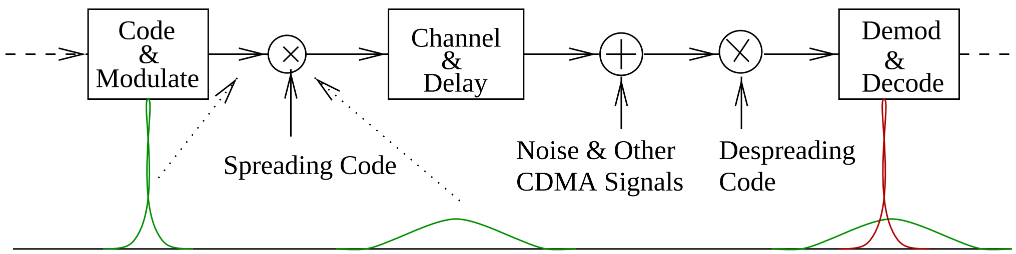


$$\mathbf{x}(n) = \sum_{p=1}^{P} \mathbf{h}_p(n) \otimes s_p(n)$$

CODE DIVISION MULTIPLE ACCESS (CDMA)

- Uses available bandwidth efficiently

  ☞ Distinguishes users by codewords



- Synchronous CDMA ☞ All signals must be synchronized
- Narrowband CDMA

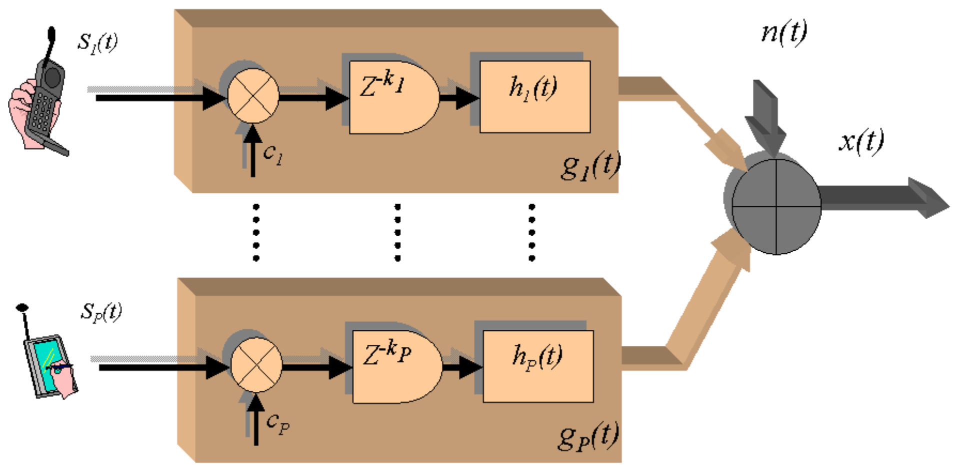
  ☞ RAKE receiver coherently resolves multipath fading
- Wideband CDMA (W-CDMA)

  ☞ Emerging third-generation standards

  ☞ Estimate (vector) FIR channel parameters for symbol estimation

CDMA Systems with Periodic Spreading

- Single receiver with P Users



☞ Blindly estimate $h_1(t), \ldots, h_P(t)$

☞ Assume knowledge of spreading codes $c_1, \ldots, c_P$

☞ Assume knowledge of propagation delays $k_1, \ldots, k_P$.

Data Formulation

- Baseband signal, single receiver, P users:

$$x(t) = \sum_{i=1}^{P} \sum_{n=-\infty}^{\infty} s_i(n) g_i(t - nT_s)$$

  - ☞ i denotes the user index
  - ☞ P is the number of users
  - ☞ $\{s_i(n)\}$ are the information symbols
  - ☞ T_s is the symbol duration
  - ☞ $g_i(t)$ is a signature waveform

$$g_i(t) = \sum_{k=1}^{2L_c} c_i(k - k_i) h_i(t - kT)$$

  - ☞ $\{c_i(1),\ c_i(2), \cdots, c_i(L_c);\ \ c_i(k) = \pm 1\}$ is the spreading code of i^{th} user
  - ☞ L_c is the code length
  - ☞ $\{h_i(t)\}$ are the channels

Matrix Form

- Represent the data vector of samples with a symbol period in a matrix form

$$\mathbf{X}(n) = \begin{bmatrix} x((N-n)L_c+1) & x((N-n+1)L_c+1) & \cdots & x((2N-1-n)L_c+1) \\ x((N-n)L_c+2) & x((N-n+1)L_c+2) & \cdots & x((2N-1-n)L_c+2) \\ \vdots & \vdots & \cdots & \vdots \\ x((N-n+1)L_c) & x((N-n+2)L_c) & \cdots & x((2N-n)L_c) \end{bmatrix}$$

- Stack KL_c successive samples of the signal in vector form

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}(N) \\ \mathbf{X}(N-1) \\ \vdots \\ \mathbf{X}(N-K+1) \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{G}_1 & \cdots & \mathbf{G}_P \end{bmatrix}}_{\mathbf{G}} \underbrace{\begin{bmatrix} \mathbf{S}_1(r) \\ \vdots \\ \mathbf{S}_{P(r)} \end{bmatrix}}_{\mathbf{S}} = \sum_{i=1}^{P} \mathbf{X}_i = \sum_{i=1}^{P} \mathbf{G}_i \mathbf{S}_i(r)$$

☞ K is defined as the *smoothing factor*.

Input/Output Structure

- $\mathbf{X}_i$ shows the algebraic relation between the input and output

$$\underbrace{\begin{bmatrix} \mathbf{g}_i(2) & \mathbf{g}_i(1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{g}_i(2) & \mathbf{g}_i(1) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{g}_i(2) & \mathbf{g}_i(1) \end{bmatrix}}_{\mathbf{G}_i,\ K+1\ blocks} \underbrace{\begin{bmatrix} s_i(1) & s_i(2) & \cdots & s_i(N-r+1) \\ s_i(2) & s_i(3) & \cdots & s_i(N-r+2) \\ \vdots & \vdots & \cdots & \vdots \\ s_i(r) & s_i(r+1) & \cdots & s_i(N) \end{bmatrix}}_{\mathbf{S}_i(r), r=K+1}.$$

- *Signature waveform* matrix $\mathbf{G}_i$ has rich structure

$$\mathbf{G}_i = \underbrace{\begin{bmatrix} \mathbf{c}_i(2) & \mathbf{c}_i(1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{c}_i(2) & \mathbf{c}_i(1) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{c}_i(2) & \mathbf{c}_i(1) \end{bmatrix}}_{\mathbf{C}_i,\ (K+1)\times L} \underbrace{\begin{bmatrix} \mathbf{h}_i & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{h}_i & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{h}_i \end{bmatrix}}_{\mathbf{H}_i,\ K+1\ blocks}$$

Multi-User Channel Estimation

- Estimate signature vectors $\{\mathbf{g}_i\} \Longleftrightarrow$ determine the channel vectors $\{\mathbf{h}_i\}$
- Data model when including additive white noise

$$\mathbf{X} + \mathbf{N} = \mathbf{G}\mathbf{S} + \mathbf{N}.$$

- Perform subspace decomposition on $\mathbf{X}$ by a singular value decomposition (SVD)

$$\mathbf{X} + \mathbf{N} = \begin{pmatrix} \mathbf{U}_s & \mathbf{U}_o \end{pmatrix} \begin{pmatrix} \Sigma_s & \mathbf{0} \\ \mathbf{0} & \Sigma_o \end{pmatrix} \begin{pmatrix} \mathbf{V}_s^H \\ \mathbf{V}_o^H \end{pmatrix}$$

☞ Vectors in $\mathbf{U}_s$ span the *signal subspace*, $\mathbf{G}$.

☞ Vectors in $\mathbf{U}_o$ span the *noise subspace*.

Multi-User Channel Estimation

- Estimate $\{\mathbf{G}_i\}$ from $\mathbf{X}$ without knowledge of $\mathbf{S}$
- Orthogonality between noise and signal subspace

$$\mathbf{U}_o \perp \mathbf{G} \Rightarrow \mathbf{U}_o^H \mathbf{G}_i = \mathbf{0}, \quad i = 1, \cdots, P$$

- Using $\mathbf{G}_i = \mathbf{C}_i \mathbf{h}_i$ yields

$$\mathbf{U}_o^H \mathbf{C}_i \mathbf{h}_i = \mathbf{0}, \quad i = 1, \cdots, P$$

  - ☞ $\mathbf{C}_i$ is a Toeplitz matrix of spreading codes
  - ☞ $\mathbf{h}_i$ is in the null space of $\mathbf{U}_o^H \mathbf{C}_i$

Proposed Algorithm for a Single Receiver

1. Construct data matrix $\mathbf{X}$
2. Apply SVD to $\mathbf{X}$, or eigenvalue decomposition (EVD) of $\mathbf{X}\mathbf{X}^H$, to obtain orthogonal subspace $\mathbf{U}_o$.
3. For each user, estimate the channel vector $\mathbf{h}_i$
4. Reconstruct signature vectors $\{\mathbf{g}_i\}$ and $\{\mathbf{G}_i\}$

☞ Exploits fact that each signature vector is a linear function of a unique spreading code [Torlak & Xu, IEEE-TSP Jan. 1997]

Capacity Increase Using Antenna Array

- *Problem:* Existing systems are not designed to accommodate more than L_c (spreading gain) users, i.e. P $\leq L_c$
- *Goal:* Adjust the algorithm to manage an overloaded system (P $> L_c$)
  - ☞ Proposed algorithm in an overloaded system breaks down since the dimension of the orthogonal subspace $\mathbf{U}_o$ reduces
  - ☞ Additional orthogonal vectors are required to guarantee more equations than unknowns.
- *Solution:* spatially oversample by means of multiple receivers

CAPACITY INCREASE USING ANTENNA ARRAY

- Assume M receivers at the base-station

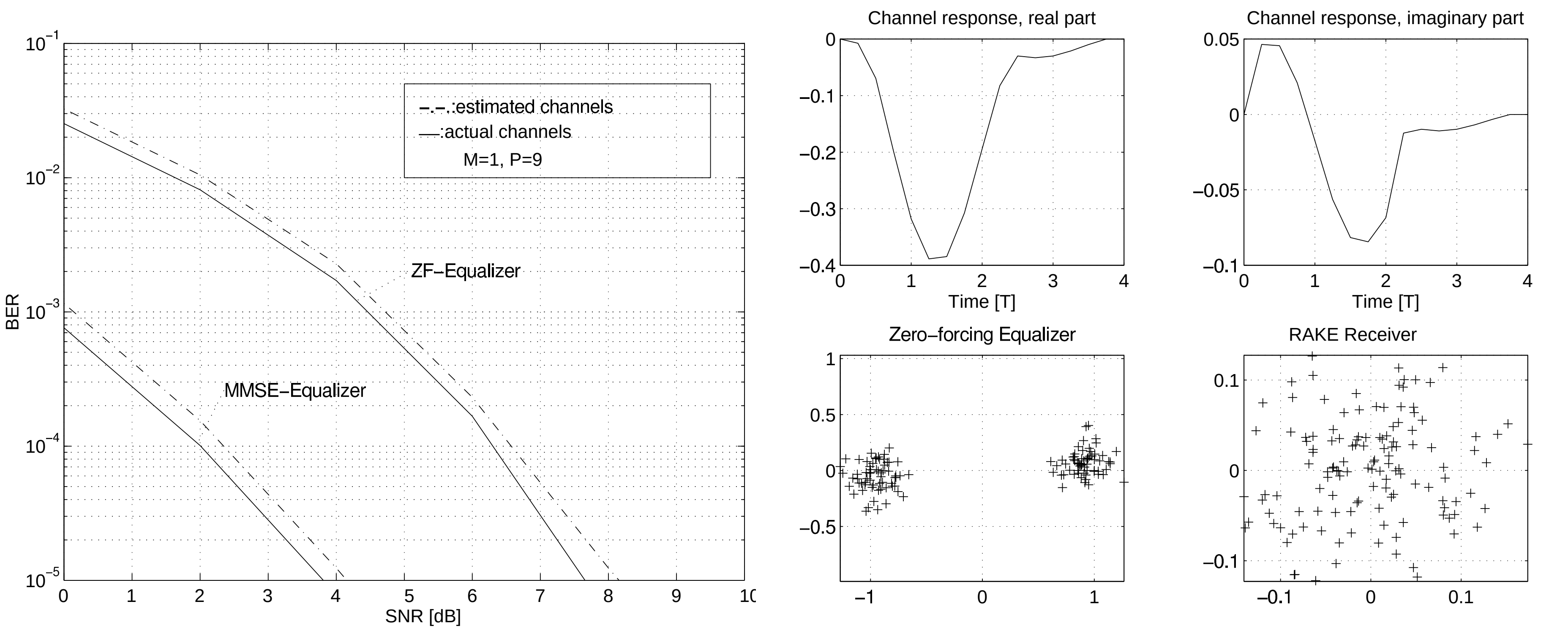
$$\mathbf{X} = \begin{bmatrix} \mathbf{X}^1 \\ \vdots \\ \mathbf{X}^M \end{bmatrix} = \sum_{i=1}^{P} \underbrace{\begin{bmatrix} \mathbf{G}_i^1 \\ \vdots \\ \mathbf{G}_i^M \end{bmatrix}}_{\mathbf{G}_i} \mathbf{S}_i(K+1)$$

- $\mathbf{X} = \mathbf{G}\mathbf{S}$ and subspace space relation between $\mathbf{X}$ and $\mathbf{G}$ still hold
- Orthogonal vectors in $\mathbf{U}_o$ increases from $KL_c - (K+1)P$ to $MKL_c - (K+1)P$
- Signal space remains fixed while noise space increases
- Extend our proposed algorithm to handle $P \geq L_c$

A-CDMA SYSTEM SIMULATION

- Average bit error rate (BER) for different receivers with estimated and actual channels

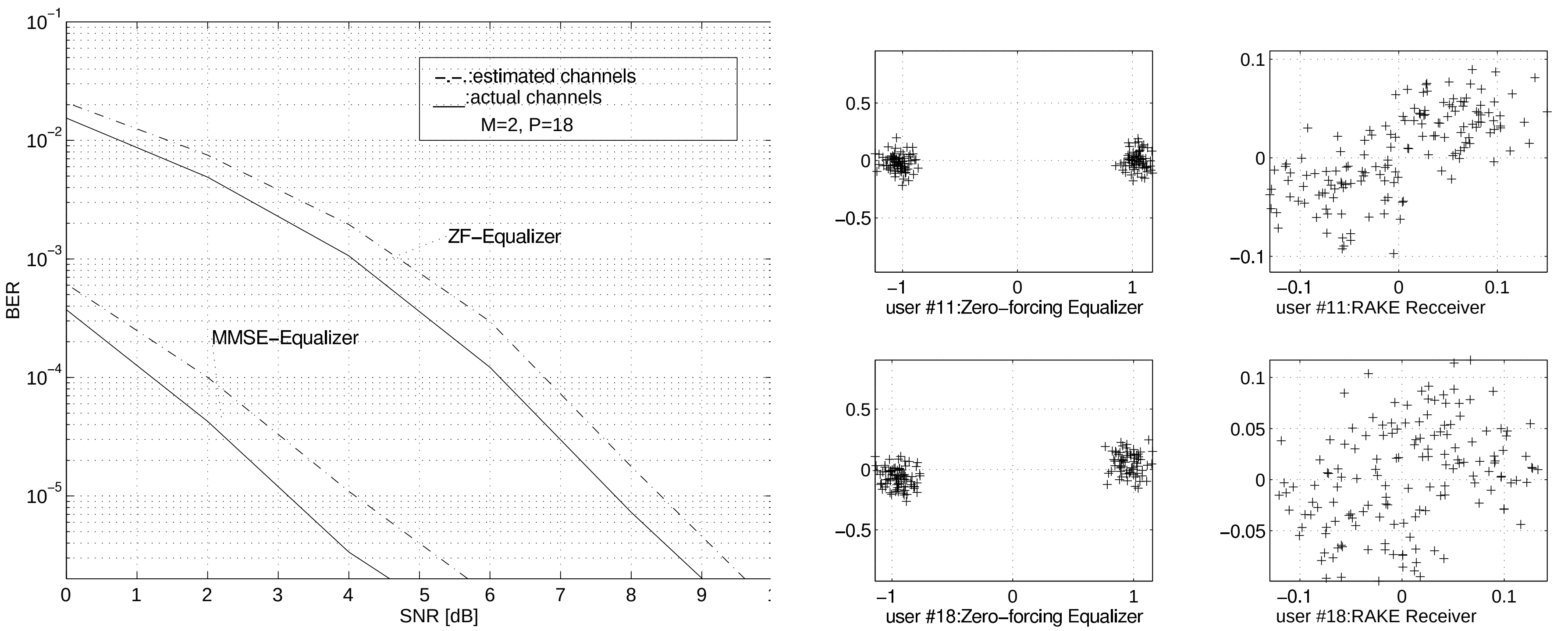
  ☞ Spreading gain=16, M=1, SNR=10 dB, and 9 users



A-CDMA System Simulation

- Average BER for overloaded A-CDMA systems

  ☞ Spreading gain=16, M=2, SNR=10 dB, and 18 users



CDMA with Aperiodic Spreading Sequences

- Aperiodic spreading sequences
  - ☞ distribute signal spectrum uniformly
  - ☞ have inherent interference averaging capabilities
  - ☞ are beneficial to the soft capacity in IS-95 CDMA systems
- Subspace-based methods require periodic spreading sequences
- Current methods in CDMA sytems with aperiodic spreading sequences
  - ☞ 1-D RAKE receivers
  - ☞ 2-D RAKE receivers (with an antenna array)
  - ☞ Principal Component (PC) Algorithm
- Proposed a new iterative blind channel estimation method
  - ☞ Channel estimation at chip level
  - ☞ Joint block equalization at symbol level

Data Model

- CDMA system with P users

$$\mathbf{y}(t) = \sum_{i=1}^{P} \sum_{n=-\infty}^{\infty} w_i(n)\, \mathbf{h}_i(t - nT) + \mathbf{v}(t)$$

  - ☞ T is the chip period
  - ☞ $\mathbf{v}(t)$ is the noise vector
  - ☞ $w_i(k) = s_i(n) c_i(k - nL_c - k_i)$
  - ☞ $n = \lfloor \frac{k-k_i}{L_c} \rfloor$; k_i ($0 \leq k_i < L_c$) is the chip delay index assumed to be known.

- Wideband channel model
- Source symbols are drawn from a finite alphabet
- Pseudo-noise (PN) spreading codes

STEP 1: ESTIMATION OF CHANNELS GIVEN TRANSMITTED SYMBOLS

- Construct the data matrix of the signal

$$\mathbf{Y} = \mathbf{H}\mathbf{W} = \begin{bmatrix} \mathbf{h}_1 & \cdots & \mathbf{h}_P \end{bmatrix} \begin{bmatrix} \mathbf{w}_1(N) \\ \vdots \\ \mathbf{w}_P(N) \end{bmatrix}$$

  ☞ $\mathbf{h}_i = [\mathbf{h}_i(L-1)\,\mathbf{h}_i(L-2)\,\cdots\,\mathbf{h}_i(0)]$

  ☞ $\mathbf{w}_i$ is constructed from the estimated input symbols and the code sequence for ith user

- Solution for the above equation

$$\boxed{\mathbf{H} = \mathbf{Y}\mathbf{W}^{\dagger}}$$

- Most of $\mathbf{W}$ is known due to the known PN spreading sequence.

Step 2: Estimation of Symbols Given Channels

- Stack the spatial data samples so that the data matrix

$$\mathcal{Y} = \underbrace{\begin{bmatrix} \mathcal{G}_1 & \mathcal{G}_2 & \cdots & \mathcal{G}_P \end{bmatrix}}_{\mathcal{G}} \underbrace{\begin{bmatrix} \mathbf{s}_1^T \\ \mathbf{s}_2^T \\ \vdots \\ \mathbf{s}_P^T \end{bmatrix}}_{\mathbf{S}}$$

☞ $\mathbf{s}_i = [s_i(1) \;\cdots\; s_i(N_t)]$ are to be estimated

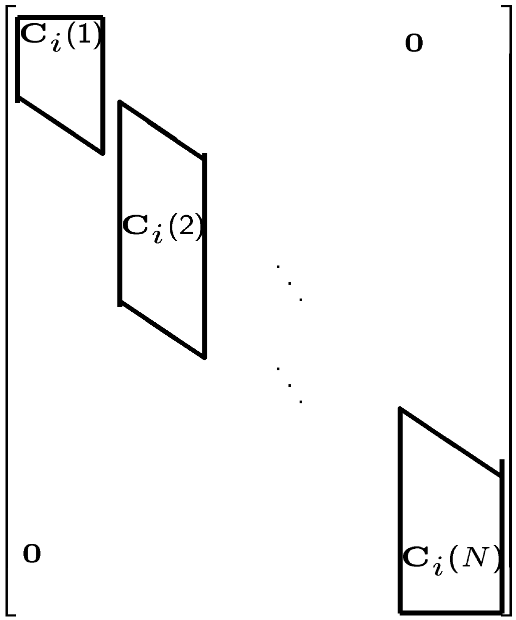
☞ Estimated wideband channel parameters and spreading codes form

$$\mathcal{G}_i = \underbrace{\begin{bmatrix} \mathcal{C}_i & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathcal{C}_i \end{bmatrix}}_{M \text{ blocks}} \begin{bmatrix} \mathcal{H}_i^1 \\ \vdots \\ \mathcal{H}_i^M \end{bmatrix}$$

Definition of $\mathbf{C}_i(n)$ and Solution for $\mathbf{S}$

- $\mathcal{C}_i$ is the shifted blocks of the codes

$\mathcal{C}_i =$



$$\mathbf{C}_i(n) = \underbrace{\left.\begin{bmatrix} 0 & \cdots & 0 \\ \cdots & \ddots & \cdots \\ c_i(nL_c+1) & \ddots & 0 \\ \vdots & \ddots & c_i(nL_c+1) \\ c_i(nL_c+L_c) & \ddots & \vdots \\ 0 & \ddots & c_i(nL_c+L_c) \\ \vdots & \cdots & 0 \\ 0 & \cdots & 0 \end{bmatrix}\right\} 2L_c}_{L \text{ columns}}$$

- Each block covers one symbol period and has Toeplitz structure

- Use $\mathcal{Y} = \mathcal{G}\mathbf{S}$ to solve for $\mathbf{S}$, then

$$\boxed{\mathbf{S} = \mathcal{G}^{\dagger}\mathcal{Y}}$$

ALGORITHM SUMMARY

- $\mathbf{H} = \mathbf{Y}\mathbf{W}^{\dagger}$ and $\mathbf{S} = \mathcal{G}^{\dagger}\mathcal{Y}$ allow us to use both frameworks to exploit the discrete-alphabet property of CDMA signals and knowledge of spreading codes.
- Adopt Iterative Least Squares with Projection (ILSP) algorithm originally developed by Talwar, Viberg, and Paulraj for TDMA systems.
- Update $\mathbf{S}$ iteratively, which updates $\mathbf{W}$, and $\mathbf{H}$ under the constraint that the information symbols $\mathbf{S}$ are from finite alphabets.
- Continue to iterate until $\mathbf{S}$ or $\mathbf{H}$ converge.

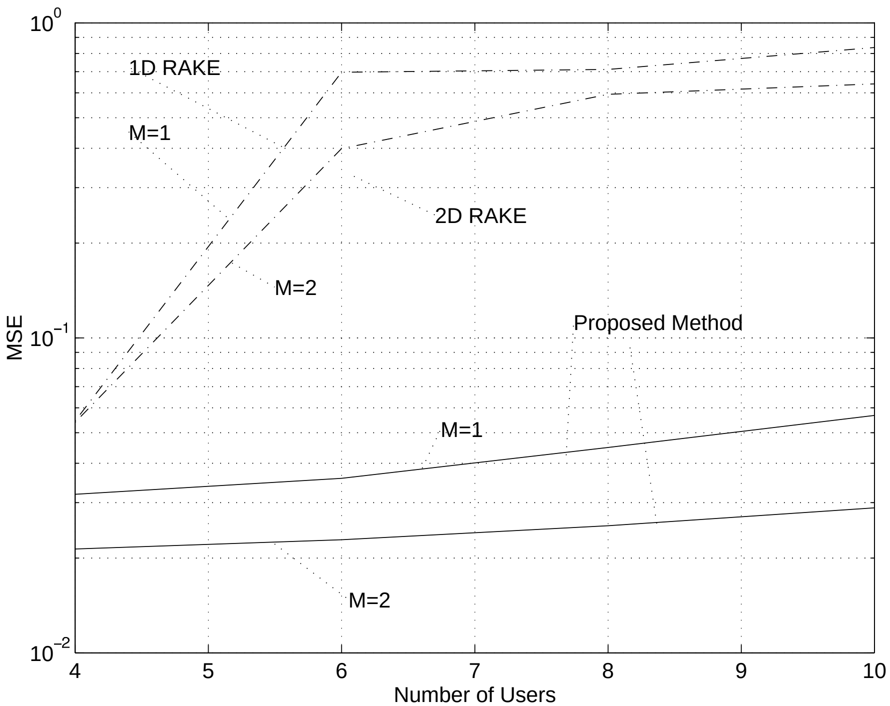
Algorithm Outline

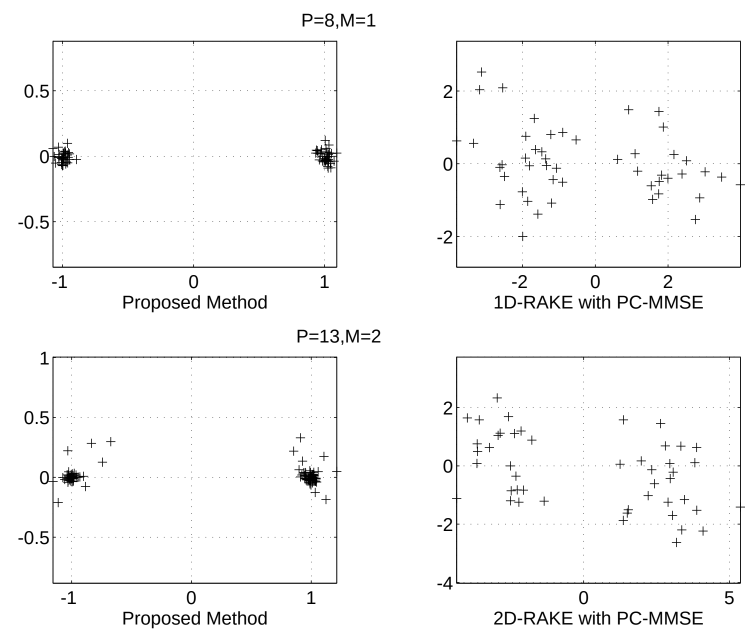
1. Randomly choose $\mathbf{S}_0$ and set $l = 0$
2. $l := l + 1$
   (a) $\begin{bmatrix} \mathbf{h}_{1,l} & \cdots & \mathbf{h}_{P,l} \end{bmatrix} = \mathbf{Y}\mathbf{W}_l^{\dagger}$ where
   $$\mathbf{W}_l = \begin{bmatrix} \mathbf{w}_{l,1}(NL_c) \\ \vdots \\ \mathbf{w}_{l,P}(NL_c) \end{bmatrix}$$
   (b) Construct $\mathcal{G}_l$ with the channel estimates and PN sequences.
   (c) $\mathbf{S}_{l+1}$ is estimated through
   $$\mathbf{S}_{l+1} = \mathcal{G}_l^{\dagger}\mathcal{Y}.$$
   (d) Project $[s_{l,i}(k)]$ to closest discrete values.
3. Continue until $\mathbf{S}_{l+1} - \mathbf{S}_l = \mathbf{0}$.

Simulation of CDMA System with Aperiodic Spreading

- Signal constellation for 1-D RAKE, 2-D RAKE, and the proposed method for M=1 and M=2 cases

  ☞ Spreading gain=16, SNR=15 dB, and $N_t = 15$





Contributions and Other Research

- Uplink processing for W-CDMA with smart antennas
  - ☞ Blind multi-user channel estimation
  - ☞ CDMA with aperiodic spreading codes
- Downlink processing for multi-transmitter diversity
  - ☞ Designing weight vectors for maximum capacity
- Smart Antenna Testbed development
  - ☞ Statistical vector channel modeling
  - ☞ Real-time signal processing
- TDMA with smart antennas
  - ☞ Fast source separation algorithms for Digital Wireless Applications

Future Directions

- 1G and 2G are optimized for Voice Communications (FDMA, TDMA, CDMA) at 8-13 kbps
- 3G technology must deliver data at 144 kbps-2 Mbps
  - Coordinated system concept
  - Wideband-CDMA : The Universal Platform
- Fourth-generation systems
  - Multimedia/Telemedicine/Internet access
  - Accommodating mixed traffic
- Wideband testbed development with antenna arrays
  - Channel propagation studies
  - Experimental validations of algorithms