Multi-User Detection in Frequency-Selective Fading Channels

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Outline

- introduction
- data model for DS-CDMA systems
- receiver structures for frequency-selective fading channels
  - RAKE receiver
  - space-time RAKE receiver
  - multi-user receiver based on RAKE structure
  - multi-user receiver
- block spreading for synchronous DS-CDMA
- we focus on
  - linear receiver structures
  - blind receivers $\rightarrow$ no training sequence necessary

Introduction

- different multiple-access schemes
  - FDMA (OFDMA):
    every user is assigned a different frequency band
  - TDMA:
    every user is assigned a different time interval
  - CDMA:
    every user is spread over the total available time and frequency spectrum (based on some code)
    - DS-CDMA:
      data signal is multiplied by a wideband code signal
      $\rightarrow$ wideband coded data signal
- in this talk we will only focus on DS-CDMA but many ideas can be used for other multiple-access schemes as well

Data Model

- DS-CDMA: every data sequence $s_j[k]$, $j = 1, \ldots, J$ is spread by a code sequence $c_j[n]$ with spreading factor N and length ρN, i.e., $c_j[n]$ is non-zero for $n = 0, 1, \ldots, \rho N - 1$:

$$x_j[n] = s_j[k]c_j[n \bmod \rho N], \text{ with } k = \lfloor n/N \rfloor$$

- $x_j[n]$ is called the chip sequence
- we assume $s_j[k]$ is zero-mean i.i.d.
- N-dimensional code vector used to spread $s_j[k]$:

$$\underline{\mathbf{c}}_j[k] = \begin{bmatrix} c_j[(k \bmod \rho)N] \\ \vdots \\ c_j[(k \bmod \rho)N + N - 1] \end{bmatrix} \quad (N \times 1)$$

- defining

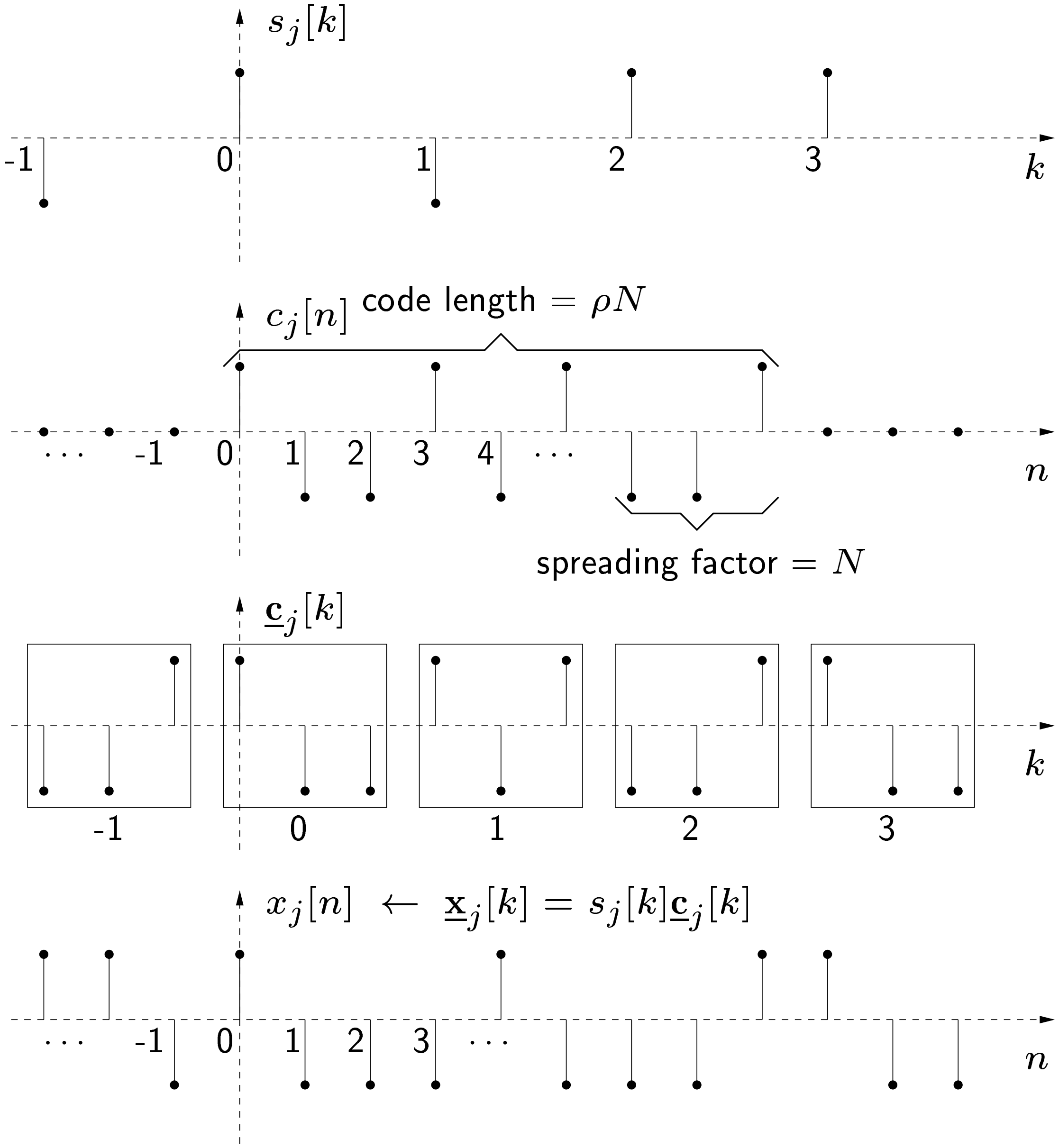
$$\underline{\mathbf{x}}_j[k] = \begin{bmatrix} x_j[kN] \\ \vdots \\ x_j[(k+1)N - 1] \end{bmatrix} \quad (N \times 1)$$

  we can write

$$\underline{\mathbf{x}}_j[k] = \underline{\mathbf{c}}_j[k]s_j[k]$$

- $\rho = 1$: short (periodic) code
  $\rho > 1$: long (aperiodic) code

Data Model


$s_j[k]$
-1
0
1
2
3
k
$c_j[n]$ code length $= \rho N$
$\cdots$ -1 0 1 2 3 4 $\cdots$
n
spreading factor $= N$
$\underline{\mathbf{c}}_j[k]$
k
-1
0
1
2
3
$x_j[n] \leftarrow \underline{\mathbf{x}}_j[k] = s_j[k]\underline{\mathbf{c}}_j[k]$
$\cdots$ -1 0 1 2 3 $\cdots$
n

Data Model

- need for high-rate DS-CDMA systems
  $\rightarrow$ ICI due to frequency selective-fading is no longer negligible
- M receiver antennas sampled at the chip rate

$$\mathbf{y}[n] = \sum_{j=1}^{J} \sum_{n'=-\infty}^{\infty} x_j[n']\mathbf{g}_j[n-n'] + \mathbf{e}[n] \quad (M \times 1)$$

- $\mathbf{g}_j[n]$ is a FIR *vector* filter of order L_j with delay index δ_j
- $\mathbf{e}[n]$ is zero-mean temporally and spatially white noise
- for a single receiver antenna ($M = 1$):

$$\mathbf{y}[n] = y[n], \quad \mathbf{e}[n] = e[n], \quad \mathbf{g}_j[n] = g_j[n]$$

- uplink: from mobiles to base station
  - all users have a different channel
  - type of communication:
    * asynchronous communication
    * synchronous communication:
      when using a special protocol

RAKE Receiver

- single receiver antenna $(M = 1)$
- stacking N successive received symbols with offset l we get

$$\underline{\mathbf{y}}_l[k] = \begin{bmatrix} y[kN+l] \\ y[kN+l+1] \\ \vdots \\ y[(k+1)N+l-1] \end{bmatrix} \quad (N \times 1)$$

- RAKE receiver for user j:
  - bank of $L_j + 1$ correlators:

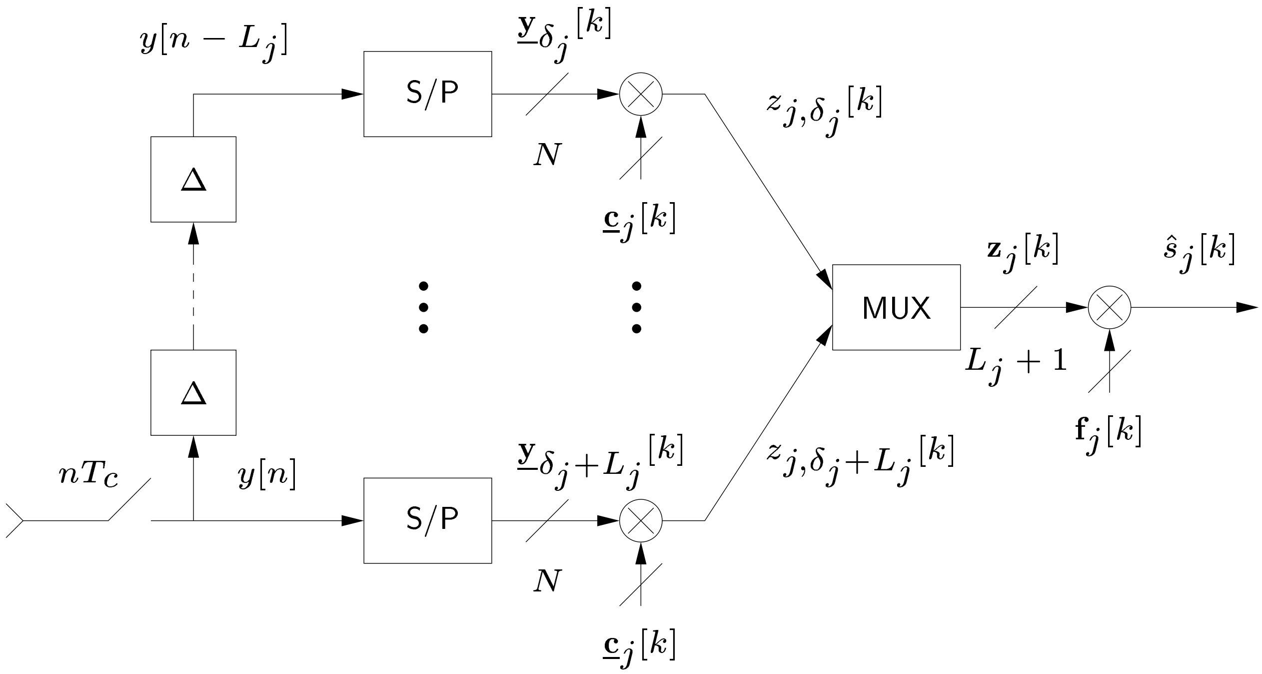
$$z_{j,l}[k] = \underline{\mathbf{c}}_j^H[k]\underline{\mathbf{y}}_l[k], \quad l = \delta_j, \ldots, \delta_j + L_j$$

  - combiner:

$$\hat{s}_j[k] = \mathbf{f}_j^H[k]\mathbf{z}_j[k], \quad \mathbf{z}_j[k] = \begin{bmatrix} z_{j,\delta_j}[k] \\ \vdots \\ z_{j,\delta_j+L_j}[k] \end{bmatrix}$$

- only code and timing of the desired user required
- timing ambiguity within a fraction of the chip period

RAKE Receiver



Space-Time RAKE Receiver

- multiple receiver antennas can be incorporated ($M \geq 1$)
- stacking N successive received vectors with offset l we get

$$\underline{\mathbf{y}}_l[k] = \begin{bmatrix} \mathbf{y}[kN+l] \\ \mathbf{y}[kN+l+1] \\ \vdots \\ \mathbf{y}[(k+1)N+l-1] \end{bmatrix} \quad (NM \times 1)$$

- space-time RAKE receiver for user j:
  - bank of $L_j + 1$ correlators for every antenna:

$$\underbrace{\mathbf{z}_{j,l}[k]}_{M\times 1} = (\underline{\mathbf{c}}_j^H[k] \otimes \mathbf{I}_M)\underline{\mathbf{y}}_l[k], \quad l = \delta_j, \ldots, \delta_j + L_j$$

  - space-time combiner:

$$\hat{s}_j[k] = \mathbf{f}_j^H[k]\mathbf{z}_j[k], \quad \mathbf{z}_j[k] = \begin{bmatrix} \mathbf{z}_{j,\delta_j}[k] \\ \vdots \\ \mathbf{z}_{j,\delta_j+L_j}[k] \end{bmatrix}$$

- only code and timing of the desired user required
- timing ambiguity within a fraction of the chip period

Space-Time RAKE Receiver

- stacking $Q+1$ successive received $M \times 1$ vectors:

$$\mathbf{y}_n = \begin{bmatrix} \mathbf{y}[n] \\ \mathbf{y}[n+1] \\ \vdots \\ \mathbf{y}[n+Q] \end{bmatrix}$$

we obtain

$$\mathbf{y}_n = \sum_{j=1}^{J} \mathcal{G}_j \mathbf{x}_{j,n} + \mathbf{e}_n$$

$$\mathcal{G}_j = \begin{bmatrix} \mathbf{g}_j[\delta_j + L_j] & \cdots & \mathbf{g}_j[\delta_j] & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{g}_j[\delta_j + L_j] & \cdots & \mathbf{g}_j[\delta_j] & \cdots & \mathbf{0} \\ & & & \ddots & & \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{g}_j[\delta_j + L_j] & \cdots & \mathbf{g}_j[\delta_j] \end{bmatrix}$$

$$\mathbf{x}_{j,n} = \begin{bmatrix} x_j[n - \delta_j - L_j] \\ \vdots \\ x_j[n - \delta_j + Q] \end{bmatrix}$$

- user 1 is the desired user: we assume $\delta_1 = 0$ w.l.o.g.

Space-Time RAKE Receiver

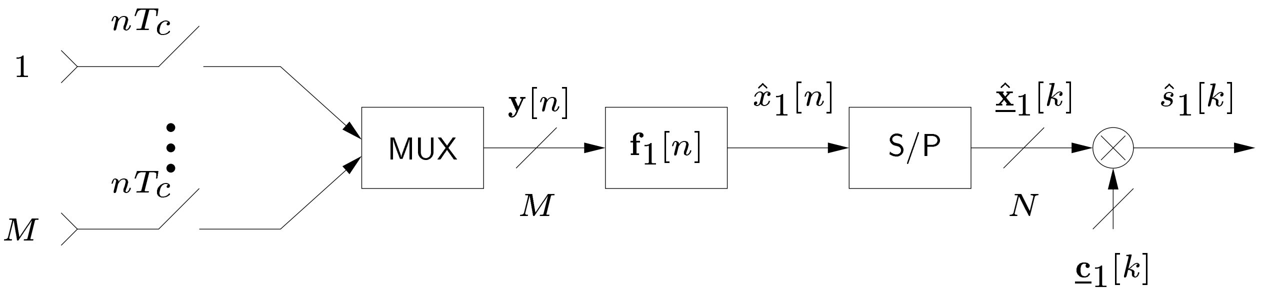
- space-time RAKE receiver for user 1:
  - space-time equalizer:

$$\hat{x}_1[n] = \sum_{n'=-Q}^{0} \mathbf{f}_1^H[n']\mathbf{y}[n-n'] = \mathbf{f}_1^H \mathbf{y}_n$$

  - correlator:

$$\hat{s}_1[k] = \underline{\mathbf{c}}_1^H[k]\underline{\hat{\mathbf{x}}}_1[k]$$

- only code and timing of the desired user required
- timing ambiguity within a fraction of the chip period



Space-Time RAKE Receiver

- space-time equalizer
  - *matched filter equalizer:* [LZ97], [SNXP93], [NPK94] maximizes SNR $\rightarrow$ if noise is Gaussian the receiver is optimal for a single user transmitting a single data symbol

$$\mathbf{f}_1 = \mathcal{G}_1(:, L_1+1)/\|\mathcal{G}_1(:, L_1+1)\|^2$$

$\Rightarrow$ we need $Q \geq L_1$

  - *ZF equalizer:*

$$\mathbf{f}_1^H \left[\mathcal{G}_1 \cdots \mathcal{G}_J\right] = \begin{array}{c} \\ \left[0 \cdots 0 \; \underset{\uparrow}{\overset{L_1+1}{}}\!\!1 \; 0 \cdots 0\right] \end{array}$$

$\Rightarrow$ we need $M > J$ and Q large enough

Space-Time RAKE Receiver

- space-time equalizer
  - *maximal SINR equalizer:* [RZ97], [CZ98]
    maximizes SINR
    ⋆ assume codes are zero-mean i.i.d. (stochastic)

$$\max_{\mathbf{f}_1}\{\sigma_x^2|\mathbf{f}_1^H\mathcal{G}_1(:,L_1+1)|^2/\mathsf{E}\{|\mathbf{f}_1^H\mathbf{i}_n|^2\}\}$$

$$(\mathbf{y}_n=\mathcal{G}_1(:,L_1+1)x_1[n]+\mathbf{i}_n)$$

$\Rightarrow$ complex scaling necessary

  - *MMSE equalizer:* [LZ97], [WLLZ98], [SC98]
    maximizes SINR
    ⋆ assume codes are zero-mean i.i.d. (stochastic)

$$\min_{\mathbf{f}_1}\{\mathsf{E}\{|\hat{x}_1[n]-x_1[n]|^2\}\}$$

$$\mathbf{f}_1=\sigma_x^2\mathsf{E}\{\mathbf{y}_n\mathbf{y}_n^H\}^{-1}\mathcal{G}_1(:,L_1+1)$$

  - *MVDR equalizer:*, [WLLZ98]
    maximizes SINR
    ⋆ assume codes are zero-mean i.i.d. (stochastic)

$$\min_{\mathbf{f}_1}\{\mathsf{E}\{|\hat{x}_1[n]|^2\}\} \text{ subject to } \mathbf{f}_1^H\mathcal{G}_1(:,L_1+1)=1$$

$$\mathbf{f}_1=c\mathsf{E}\{\mathbf{y}_n\mathbf{y}_n^H\}^{-1}\mathcal{G}_1(:,L_1+1)$$

Blind Space-Time RAKE Receiver

- *blind channel estimation:*
  - blind array response vector estimation for frequency-flat channels is presented in [SNXP93]; the extension to frequency-selective channels is presented in [LZ97] and, using a somewhat different approach, also in [WLLZ98]
    - PC analysis techniques (SOS)
    - only code of the desired user is required
    - channel is known up to a phase shift
- *blind equalizer estimation:*
  - blind maximal SINR equalizer estimation [RZ97], [CZ98]
    - based on cyclic correlations (SOS)
    - only code of the desired user is required
    - MMSE/MVDR equalizer known up to a complex scaling
  - blind MMSE and MVDR equalizers in [WLLZ98] (adaptive versions are also discussed)
    - PC analysis technique (SOS)
    - only code of the desired user is required
    - equalizers known up to a phase shift
  - blind MMSE equalizer estimation [LZ97]
    - PC analysis technique (SOS)
    - only code of the desired user is required
    - MMSE equalizer known up to a phase shift

Deterministic Blind Space-Time RAKE Receiver

- SOS based methods are not reliable in fast fading environments $\Rightarrow$ deterministic methods necessary
- defining the following output matrix:

$$\mathbf{Y}_{kN} = \begin{bmatrix} \mathbf{y}_{kN} & \cdots & \mathbf{y}_{(k+w)N-1} \end{bmatrix}$$

  we obtain

$$\mathbf{Y}_{kN} = \sum_{j=1}^{J} \mathcal{G}_j \mathbf{X}_{j,kN} + \mathbf{E}_{kN}$$

$$\mathbf{X}_{j,kN} = \begin{bmatrix} \mathbf{x}_{j,kN} & \cdots & \mathbf{x}_{j,(k+w)N-1} \end{bmatrix}$$

- $\begin{bmatrix} \mathcal{G}_1 & \cdots & \mathcal{G}_J \end{bmatrix}$ has full column rank
- $\begin{bmatrix} \mathbf{X}_{1,kN} \\ \vdots \\ \mathbf{X}_{J,kN} \end{bmatrix}$ has full row rank

Deterministic Blind Space-Time RAKE Receiver

METHOD I

noiseless case:

- there exists a ZF equalizer $\mathbf{f}_{1,kN}$ such that

$$\begin{aligned}\mathbf{f}_{1,kN}^H \mathbf{Y}_{kN} &= \left[x_1[kN] \cdots x_1[(k+w)N-1]\right] \\ &= \left[\underline{\mathbf{x}}_1^T[k] \cdots \ \underline{\mathbf{x}}_1^T[k+w-1]\right]\end{aligned}$$

- using the code information we can write

$$\mathbf{f}_{1,kN}^H \mathbf{Y}_{kN} = \left[s_1[k] \cdots s_1[k+w-1]\right] \underline{\mathbf{C}}_{1,k}^T$$

$$\underline{\mathbf{C}}_{1,k} = \begin{bmatrix} \underline{\mathbf{c}}_1[k] & & \\ & \ddots & \\ & & \underline{\mathbf{c}}_1[k+w-1] \end{bmatrix}$$

- this can be written as

$$\left[\mathbf{f}_{1,kN}^H \middle| s_1[k] \cdots s_1[k+w-1]\right] \left[\begin{array}{c} \mathbf{Y}_{kN} \\ \hline -\underline{\mathbf{C}}_{1,k}^T \end{array}\right] = \mathbf{0}$$

Deterministic Blind Space-Time RAKE Receiver

noisy case:

- *deterministic blind equalizer estimation:*
  solve LS problem for $\mathbf{f}_{1,kN}$ under:
  - unit norm constraint on $\mathbf{f}_{1,kN}$ [LZ97]
    $\rightarrow$ complex scaling necessary
  - linear (monic) constraint on the data symbols [LX96a]
- *deterministic blind symbol estimation:*
  solve LS problem for data symbols under constraint on the data symbols $\Rightarrow$ leads to interesting adaptive implementations:
  - finite alphabet constraint $\rightarrow$ Viterbi scheme (complex)
  - linear constraint $\rightarrow$ RLS scheme [LM98]

Deterministic Blind Space-Time RAKE Receiver

METHOD II

noiseless case:

- the SVD of $\mathbf{Y}_{kN}$ leads to

$$\mathbf{Y}_{kN} = \mathbf{U}_{kN}\mathbf{\Sigma}_{kN}\mathbf{V}_{kN}^H$$

- we can split $\mathbf{V}_{kN}$ in a signal and noise subspace:

$$\mathbf{V}_{kN} = \left[\mathbf{V}_{kN}^s \ \mathbf{V}_{kN}^n\right]$$

- we can then write

$$\begin{aligned}&\left[x_1[kN] \cdots x_1[(k+w)N-1]\right] \mathbf{V}_{kN}^n \\ &\qquad = \left[\underline{\mathbf{x}}_1^T[k] \cdots \ \underline{\mathbf{x}}_1^T[k+w-1]\right] \mathbf{V}_{kN}^n = \mathbf{0}\end{aligned}$$

- using the code information we can write

$$\left[s_1[k] \ \cdots s_1[k+w-1]\right] \underline{\mathbf{C}}_{1,k}^T \mathbf{V}_{kN}^n = \mathbf{0}$$

Deterministic Blind Space-Time RAKE Receiver

noisy case:

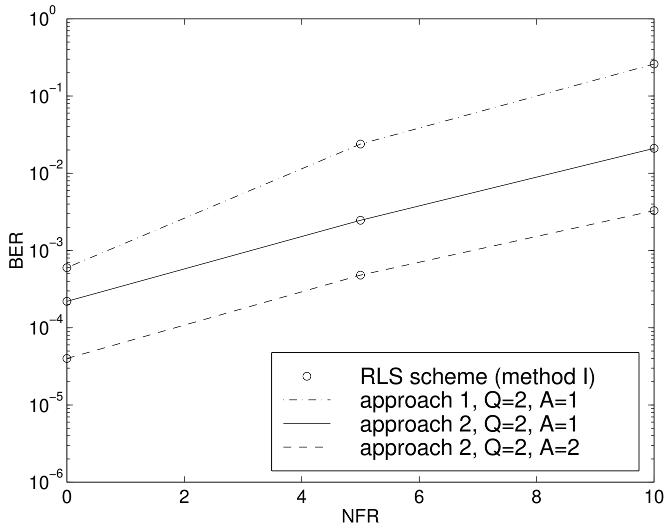
- *deterministic blind symbol estimation:*
  solve LS problem under constraint $\Rightarrow$ leads to interesting adaptive implementations:
  - finite alphabet constraint: Viterbi scheme [LM97a]
  - linear constraint: RLS scheme [LM97b]

Deterministic Blind Space-Time RAKE Receiver

- only code of the desired user is required
- both methods can be extended for the case we want to combine more delays and for the case we perform an additional temporal oversampling, for which we will introduce an additional short code spreading
  $\rightarrow$ these two extensions are used in [LM97a], [LM97b], [LM98]
- for real alphabets, e.g., BPSK, the equations can be split in their real and imaginary parts $\rightarrow$ simple complex multiplicative coding (no increase in bandwidth) is sufficient to achieve source separation [VLM99]
- method I can still be applied when $\left[\mathcal{G}_1 \cdots \mathcal{G}_J\right]$ has not full column rank although it is difficult to predict the performance in that case

Deterministic Blind Space-Time RAKE Receiver

- 5-user system ($J = 5$) with 4 receiver antennas ($M = 4$)
- spreading factor of $N = 12$
- every $\mathbf{g}_j[n]$ has order $L_j = 2$ (Doppler frequency 100 Hz)
- *approach 1:* classical approach
  - multichannel structure of $M = 4$ channels
  - we exploit $N = 12$ code symbols per data symbol
- *approach 2:* we use a long code with spreading factor $N/2 = 6$ and perform an additional temporal oversampling with factor 2 for which we introduce a short code with spreading factor 2 $\rightarrow$ two-fold spreading
  - multichannel structure of $2M = 8$ channels
  - we exploit $N/2 = 6$ code symbols per data symbol



BER as a function of the NFR for SNR=10 dB

(Q is the equalizer order and A is the number of delays taken into account)

Multi-User Receiver Based on RAKE Structure

- for user j: bank of $L_j + 1$ correlators for every antenna

$$\underbrace{\mathbf{z}_{j,l}[k]}_{M\times 1} = (\underline{\mathbf{c}}_j^H[k] \otimes \mathbf{I}_M)\underline{\mathbf{y}}_l[k], \quad l = \delta_j, \ldots, \delta_j + L_j$$

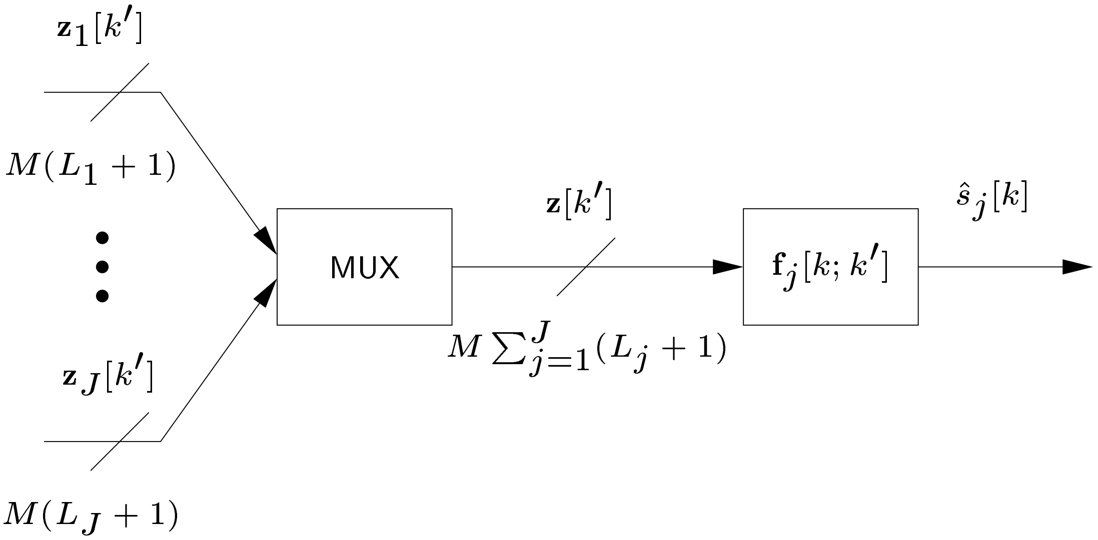
- we stack the results for all users

$$\mathbf{z}[k] = \begin{bmatrix} \mathbf{z}_1[k] \\ \vdots \\ \mathbf{z}_J[k] \end{bmatrix}, \quad \mathbf{z}_j[k] = \begin{bmatrix} \mathbf{z}_{j,\delta_j}[k] \\ \vdots \\ \mathbf{z}_{j,\delta_j+L_j}[k] \end{bmatrix}$$

- linear multi-user detector for user j:

$$\hat{s}_j[k] = \sum_{k'=-\kappa}^{\kappa} \mathbf{f}_j^H[k;k']\mathbf{z}[k-k']$$

- code and timing of every user required
- timing ambiguity within a fraction of the chip period
- sometimes a whole block of data is estimated at once



Multi-User Receiver Based on RAKE Structure

- mostly short codes ($\rho = 1$) are used $\rightarrow \mathbf{f}_j^H[k; k'] = \mathbf{f}_j^H[k']$
- most common linear multi-user detectors are:
  - zero-forcing detector
  - MMSE detector
- if no spatial diversity is used $(M = 1)$ there exists no finite-length zero-forcing detector
  - truncation of infinite-length multipath decorrelating detector (different paths are considered as different users) [ZB96], [KM95]
  - truncation of infinite-length channel-matched decorrelating detector (channel matched filter followed by decorrelator) [KM95]
  - sliding window approach with edge correction [WNM96]
- for the case spatial diversity is used $(M > 1)$ we refer to [Zvo96], [MS95]

Multi-User Receiver

- define the composite channel:

$$\mathbf{h}_j[n] = \sum_{n'=0}^{N-1} c_j[n']\mathbf{g}_j[n-n'] \quad \text{(short codes: } \rho = 1\text{)}$$

- stacking N successive received $M \times 1$ vectors:

$$\underline{\mathbf{y}}[k] = \begin{bmatrix} \mathbf{y}[kN] \\ \mathbf{y}[kN+1] \\ \vdots \\ \mathbf{y}[(k+1)N-1] \end{bmatrix} \quad (NM \times 1)$$

we obtain

$$\underline{\mathbf{y}}[k] = \sum_{j=1}^{J} \sum_{k'=-\infty}^{\infty} s_j[k']\underline{\mathbf{h}}_j[k-k'] + \underline{\mathbf{e}}[k]$$

$$\underline{\mathbf{h}}_j[k] = \begin{bmatrix} \mathbf{h}[kN] \\ \mathbf{h}[kN+1] \\ \vdots \\ \mathbf{h}[(k+1)N-1] \end{bmatrix}$$

- $\underline{\mathbf{h}}_j[k]$ is a FIR *vector* filter of order K_j with delay index Δ_j:

$$\Delta_j = \lfloor \delta_j/N \rfloor, \quad K_j = \lfloor (\delta_j + L_j + N - 1)/N \rfloor - \Delta_j$$

Multi-User Receiver

- stacking $(Q+1)$ successive received $MN \times 1$ vectors:

$$\underline{\mathbf{y}}_k = \begin{bmatrix} \underline{\mathbf{y}}[k] \\ \underline{\mathbf{y}}[k+1] \\ \vdots \\ \underline{\mathbf{y}}[k+Q] \end{bmatrix}$$

we obtain

$$\underline{\mathbf{y}}_k = \sum_{j=1}^{J} \underline{\mathcal{H}}_j \mathbf{s}_{j,k} + \underline{\mathbf{e}}_k$$

$$\underline{\mathcal{H}}_j = \begin{bmatrix} \underline{\mathbf{h}}_j[\Delta_j + K_j] & \cdots & \underline{\mathbf{h}}_j[\Delta_j] & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \underline{\mathbf{h}}_j[\Delta_j + K_j] & \cdots & \underline{\mathbf{h}}_j[\Delta_j] & \cdots & \mathbf{0} \\ & & & \ddots & & \\ \mathbf{0} & \cdots & \mathbf{0} & \underline{\mathbf{h}}_j[\Delta_j + K_j] & \cdots & \underline{\mathbf{h}}_j[\Delta_j] \end{bmatrix}$$

$$\mathbf{s}_{j,k} = \begin{bmatrix} s_j[k - \Delta_j - K_j] \\ \vdots \\ s_j[k - \Delta_j + Q] \end{bmatrix}$$

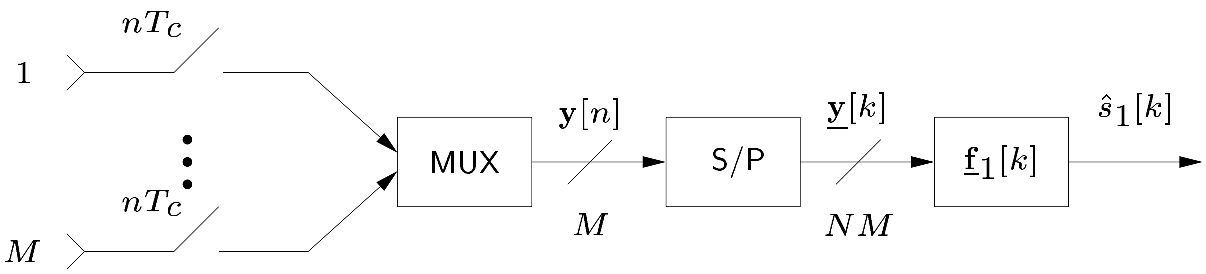
- user 1 is the desired user: we assume $\Delta_1 = 0$ w.l.o.g.

Multi-User Receiver

- multi-user equalizer for user 1:

$$\hat{s}_1[k] = \sum_{k'=-Q}^{0} \underline{\mathbf{f}}_1^H[k']\underline{\mathbf{y}}[k-k'] = \underline{\mathbf{f}}_1^H \underline{\mathbf{y}}_k$$

- only timing of the desired user required
- timing ambiguity within a fraction of the *data symbol* period
- sometimes a whole block of data is estimated at once



Multi-User Receiver

- multi-user equalizer
  - *zero-forcing equalizer:* [TG96], [KB93], [KKKB96], [WP98b]

$$\underline{\mathbf{f}}_1^H \left[\underline{\mathcal{H}}_1 \cdots \underline{\mathcal{H}}_J\right] = \left[0 \cdots 0 \; \underset{\substack{\uparrow \\ K_1+1}}{1} \; 0 \cdots 0\right]$$

$\Rightarrow$ we need $MN > J$ and Q large enough

  - *MMSE equalizer:* [KKKB96], [GSP98]
    maximizes SINR

$$\min_{\underline{\mathbf{f}}_1}\{\mathsf{E}\{|\hat{s}_1[k] - s_1[k]|^2\}\}$$

$$\underline{\mathbf{f}}_1 = \sigma_s^2 \mathsf{E}\{\underline{\mathbf{y}}_k \underline{\mathbf{y}}_k^H\}^{-1} \underline{\mathcal{H}}_1(:, K_1 + 1)$$

  - *MVDR equalizer:* [WP98b]
    maximizes SINR

$$\min_{\underline{\mathbf{f}}_1}\{\mathsf{E}\{|\hat{s}_1[k]|^2\}\} \quad \text{subject to} \quad \underline{\mathbf{f}}_1^H \underline{\mathcal{H}}_1(:, K_1 + 1) = 1$$

$$\underline{\mathbf{f}}_1 = c\mathsf{E}\{\underline{\mathbf{y}}_k \underline{\mathbf{y}}_k^H\}^{-1} \underline{\mathcal{H}}_1(:, K_1 + 1)$$

Blind Multi-User Receiver

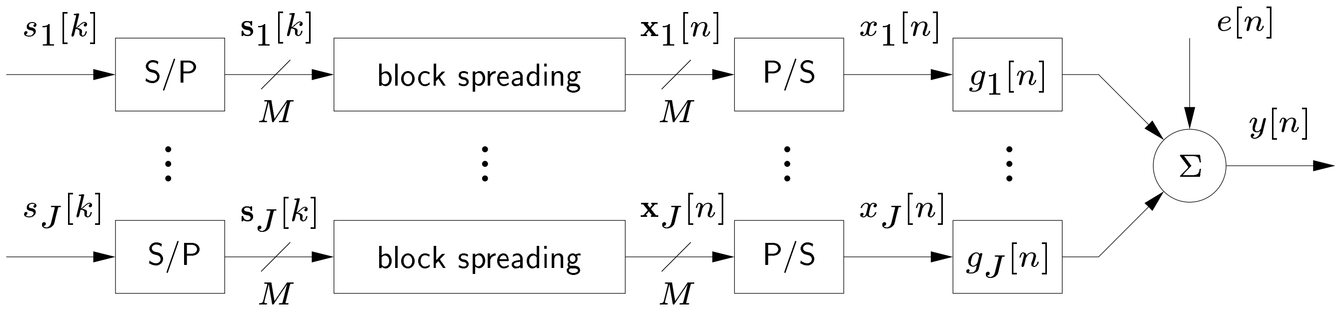
- *blind channel estimation:*
  - subspace technique [BA96], [LX96b], [TX97], [TG97], [AM98], [WP98b] (deterministic/SOS)
    - only code of the desired user is required
    - channel known up to complex scaling factor
    - *byproduct:* ZF and MVDR equalizer can be constructed using only the channel of the user of interest [WP98b]
  - linear prediction technique [LM99b] (SOS)
- *blind equalizer estimation:*
  - blind constrained MOE equalizer estimation is presented in [Tsa97], [TX98]
    - constrained optimization (SOS)
    - only code of the desired user is required
    - if channel is known: MMSE/MVDR equalizer estimation
    - if channel is unknown: optimization of constraint results in an equalizer that asymptotically (SNR $\rightarrow \infty$) has maximal SINR $\rightarrow$ MMSE/MVDR equalizer known up to a complex scaling
  - blind MMSE equalizer estimation is presented in [GSP98]
    - subspace technique (SOS)
    - only code of the desired user is required
    - MMSE equalizer known up to a complex scaling
    - ideas of this method can be combined with ideas of the deterministic MRE approach [GP98]

Blind Multi-User Receiver

- *blind equalizer estimation:*
  - blind implementation of the multi-user equalizer as a special filterbank where each filter collects the useful energy in one path of the desired user and suppresses all the other interferences is discussed in [WP98a]

Block Spreading for Synchronous DS-CDMA

- single receiver antenna
- block spreading (a.k.a. chip interleaving [CT97]): the spreading is done on the block level
- M is the block size and N is the spreading factor



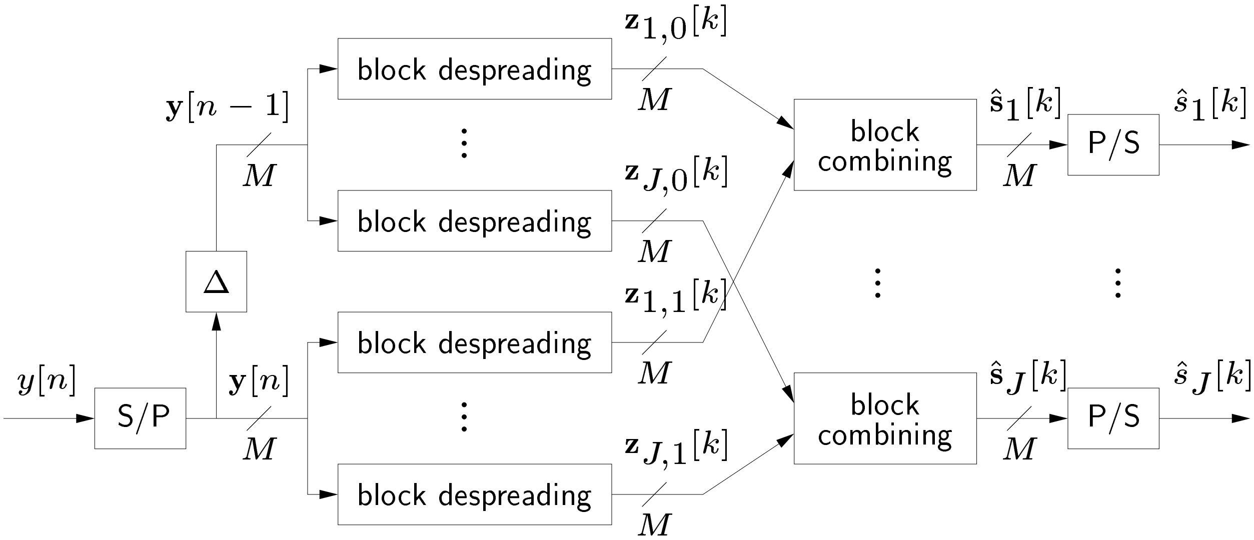
- if we assume that for every $g_j[n]$ the delay index $\delta_j = 0$ and that M is larger than the largest channel order L_j, the received vector sequence looks like

$$\mathbf{y}[n] = \sum_{j=1}^{J} \sum_{n'=0}^{1} \mathbf{G}_j[n'] \mathbf{x}_j[n - n'] + \mathbf{e}[n]$$

- $\mathbf{G}_j[n]$ can be interpreted as the order-1 discrete-time impulse response of a matrix channel, with taps $\mathbf{G}_j[0]$ and $\mathbf{G}_j[1]$

Block Spreading for Synchronous DS-CDMA

- block RAKE receiver with two block correlators can be used



- using a special set of codes we can obtain a symbol-spaced single-user model, free from MUI [LM99a]:

$$\begin{aligned}\mathbf{z}_j[k] = \begin{bmatrix}\mathbf{z}_{j,0}[k]\\ \mathbf{z}_{j,1}[k]\end{bmatrix} &= \nu \begin{bmatrix}\mathbf{G}_j[0]\\ \mathbf{G}_j[1]\end{bmatrix} \mathbf{s}_j[k] + \begin{bmatrix}\mathbf{n}_{j,0}[k]\\ \mathbf{n}_{j,1}[k]\end{bmatrix}\\ &= \nu \mathbf{G}_j \mathbf{s}_j[k] + \mathbf{n}_j[k]\end{aligned}$$

($\mathbf{n}_j[k]$ is residual additive noise and $\nu = (N-1)/N$)

- the remaining ISI can be removed using block combining (zero-forcing or MMSE) with a $2M \times M$ matrix $\mathbf{F}_j$

$$\hat{\mathbf{s}}_j[k] = \mathbf{F}_j^H \mathbf{z}_j[k] = \nu \mathbf{F}_j^H \mathbf{G}_j \mathbf{s}_j[k] + \mathbf{F}_j^H \mathbf{n}_j[k]$$

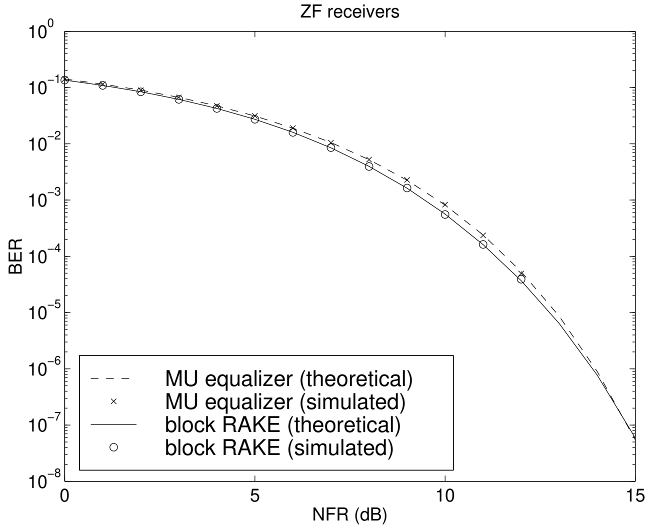
Block Spreading for Synchronous DS-CDMA

- features/advantages
  - the block spreading idea can be used in a DMT-CDMA system [Van95] $\rightarrow$ performing a simple sum of the correlator outputs then removes all ISI [LM99a]
  - blind channel estimation can be performed on the symbol-spaced single user model [LM99a] $\rightarrow$ compared with blind channel estimation techniques performed on the chip-spaced multi-user model (e.g., [LX96b]) this technique is less complex $(M \ll N)$ and has a comparable performance
  - comparison with the recently developed Vandermonde-Lagrange CDMA (VL-CDMA) system [SBG99] (generalization of OFDMA) where every user is assigned R 'roots' (total number of roots is $N - M + 1$):

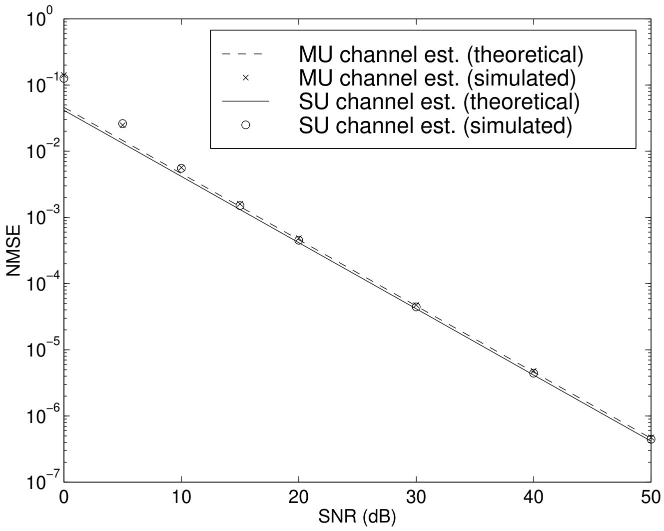
	VL-CDMA	block spreading
MUI removal without channel knowledge	yes	yes
spreading	non-uniform	uniform
maximal number of users	$\lfloor (N - M + 1)/R \rfloor$	$\lfloor (N - 1)/2 \rfloor$
frequency-selectivity exploitation	increases with R	full
blind channel estimation	possible if $R > L$	always possible

Block Spreading for Synchronous DS-CDMA

- 8-user system ($J = 8$) with spreading factor $N = 17$
- every $g_j[n]$ has order $L_j = 3$ (we take $M = 4$)



Average BER as a function of the SNR for NFR=0 dB (known channels)



Average NMSE of channel estimate as a function of the SNR for NFR=0 dB

SU channel estimation: [LM99a] MU channel estimation: [LX96b]

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