Performance Enhancement of CDMA Systems Using Smart Antennas: Joint temporal-spatial designs

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Motivation for Using Smart Antennas

- The demand for wireless communications is ever growing.
  - Each user requests higher data rates and reliability
  - More users requests request service simultaneously
- **Bandwidth is limited!**
- Radio channel is not particularly ’friendly’
  - Reflections results in signal arriving at the receiver via multiple paths with random phase and amplitude
  - Arrival of multiple paths introduce delay spread, intersymbol interference
  - **Significant problems arise from other users interfering with the signal transmission**

How can Smart Antennas help?

- Antenna arrays at the receiver:
  - M-fold gain for M-antenna elements
  - Diversity gain against multipath fading
    - Depends on correlation of the fading
  - **Interference mitigation**
    - Separation of users with antenna arrays whose radiation pattern is not isotropic

Diversity

- Spatial Diversity
  - If the angle spread is large, then small separation of antennas ($\lambda/4$) is sufficient for low correlation
  - Handsets, indoor base stations, urban area base stations typically have large angle spread
  - High towers may need a lot more antenna spacing (10λ) for low correlation
- Polarization Diversity
  - Limited gain
- Angle Diversity
  - Adjacent narrow beams used
  - Small separation sufficient
- Diversity gain at the base station typically achieved by
  - Selection Diversity (select the antenna with best quality)
  - Maximum ratio combining (weighted sum of signals to max SNR)

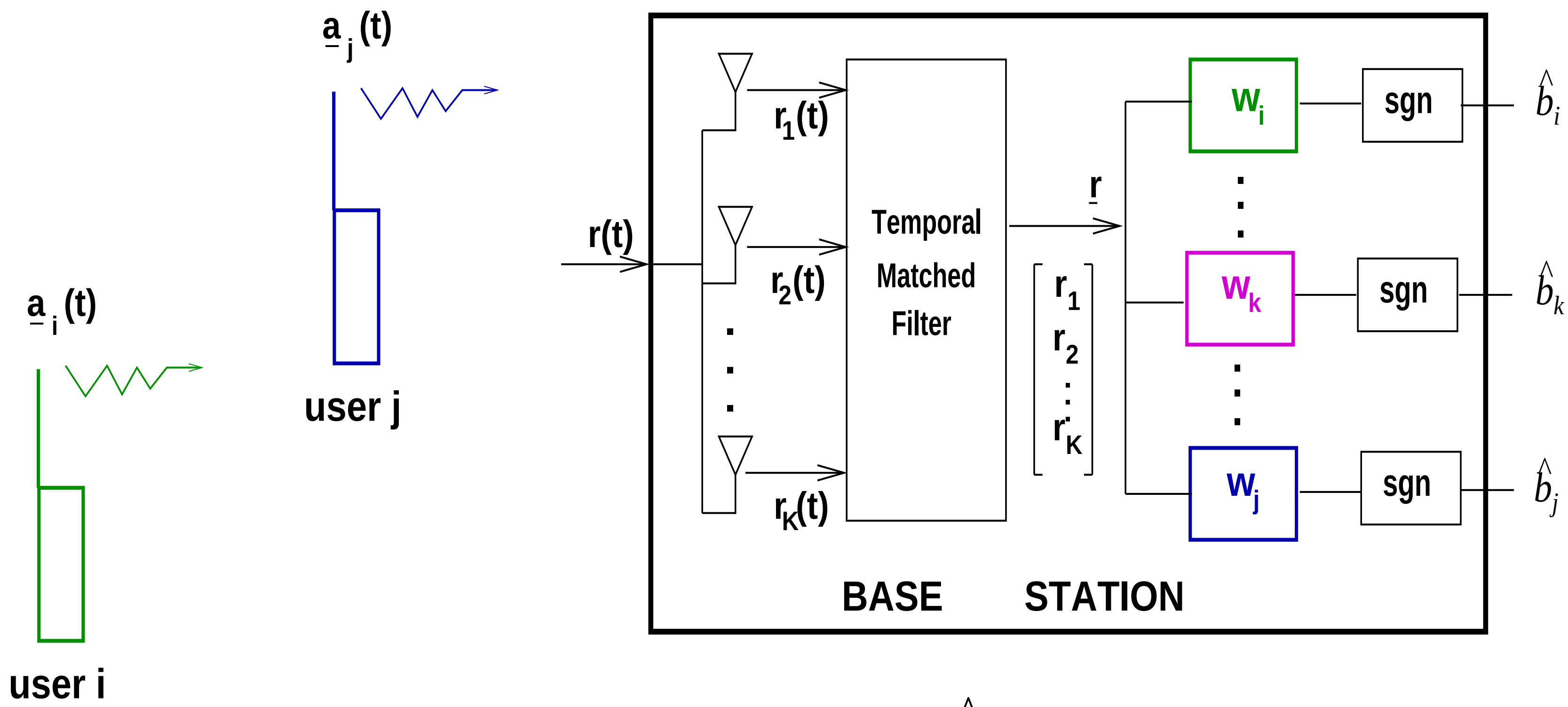
Smart Antennas and Interference Suppression

- Current cellular systems: 3 sector antennas, non-interfering channels
- Channel management becomes difficult (too many hand-offs) with too many sectors
- Multibeam antennas (multiple fixed beams) can cover each sector: No handoffs between beams, limited diversity, limited interference reduction
- **Adaptive Arrays**
  - Combine the signals received at each array element in a way to improve the performance for the signal of each user, e.g., max SIR
  - Effective interference suppression
  - M antennas can null out M-1 interferers, can significantly reduce interference even when there are more than M interferers
  - **A vehicle to provide multiple access capability for a narrow band system: SDMA**

Array Combining (Beamforming)

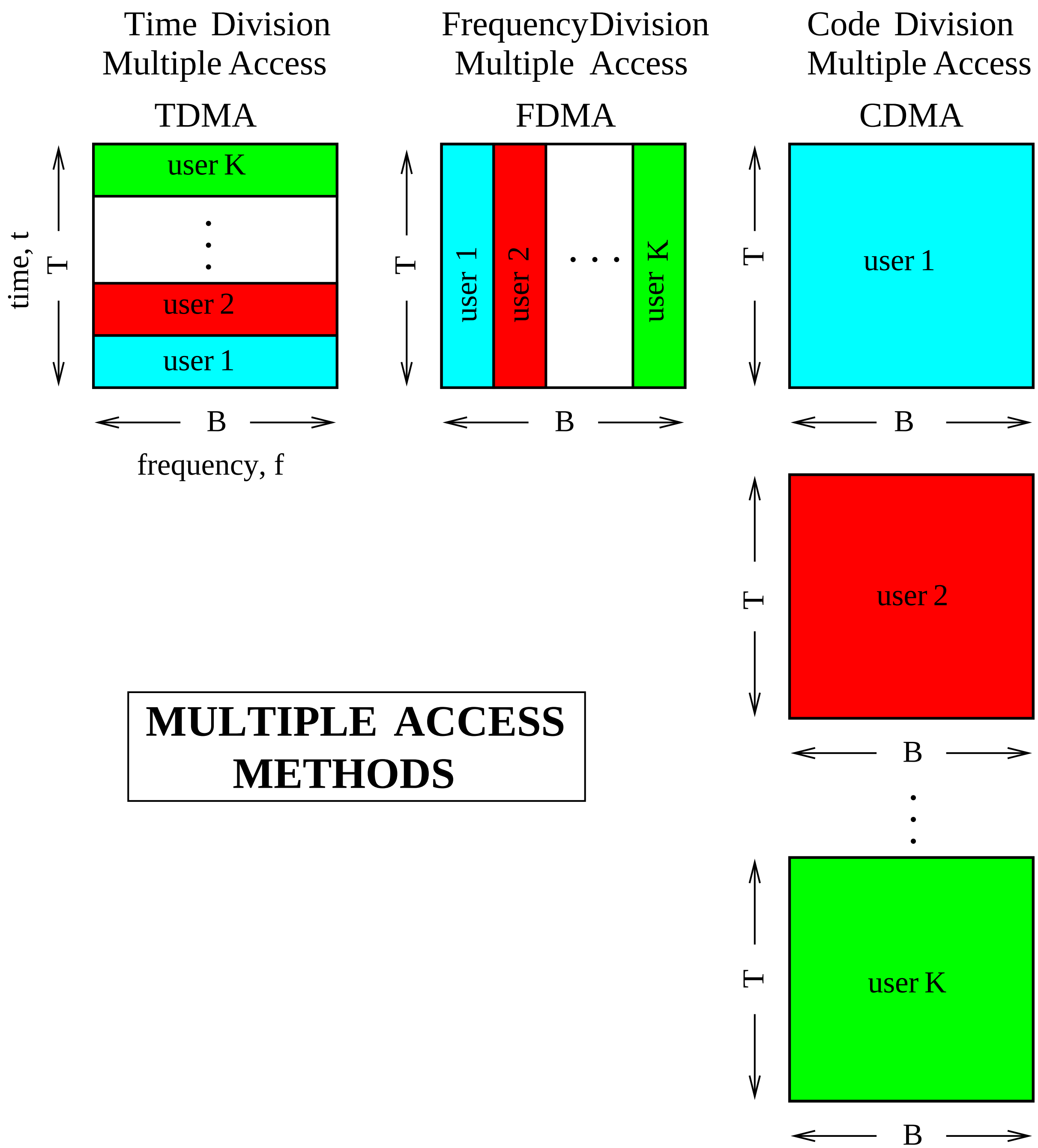
- Suppress interferer's by adjusting the weights with which the signals are combined
- Changes in the channel/interference structure can be tracked with adaptive methods
- More complex than multibeam antennas since **each user** needs a different combiner
- Typically for narrowband systems, if delay spread is non-negligible; temporal equalization is needed
- For wideband systems, i.e., CDMA, a combiner for multiple paths is used
- Adaptive arrays are used in
  - GSM and IS-136 systems along with temporal equalization
  - IS-95 systems along with RAKE receiver
- **The temporal and array combining is done in cascade, each optimized for the corresponding domain**

Beamforming (Spatial Filtering)

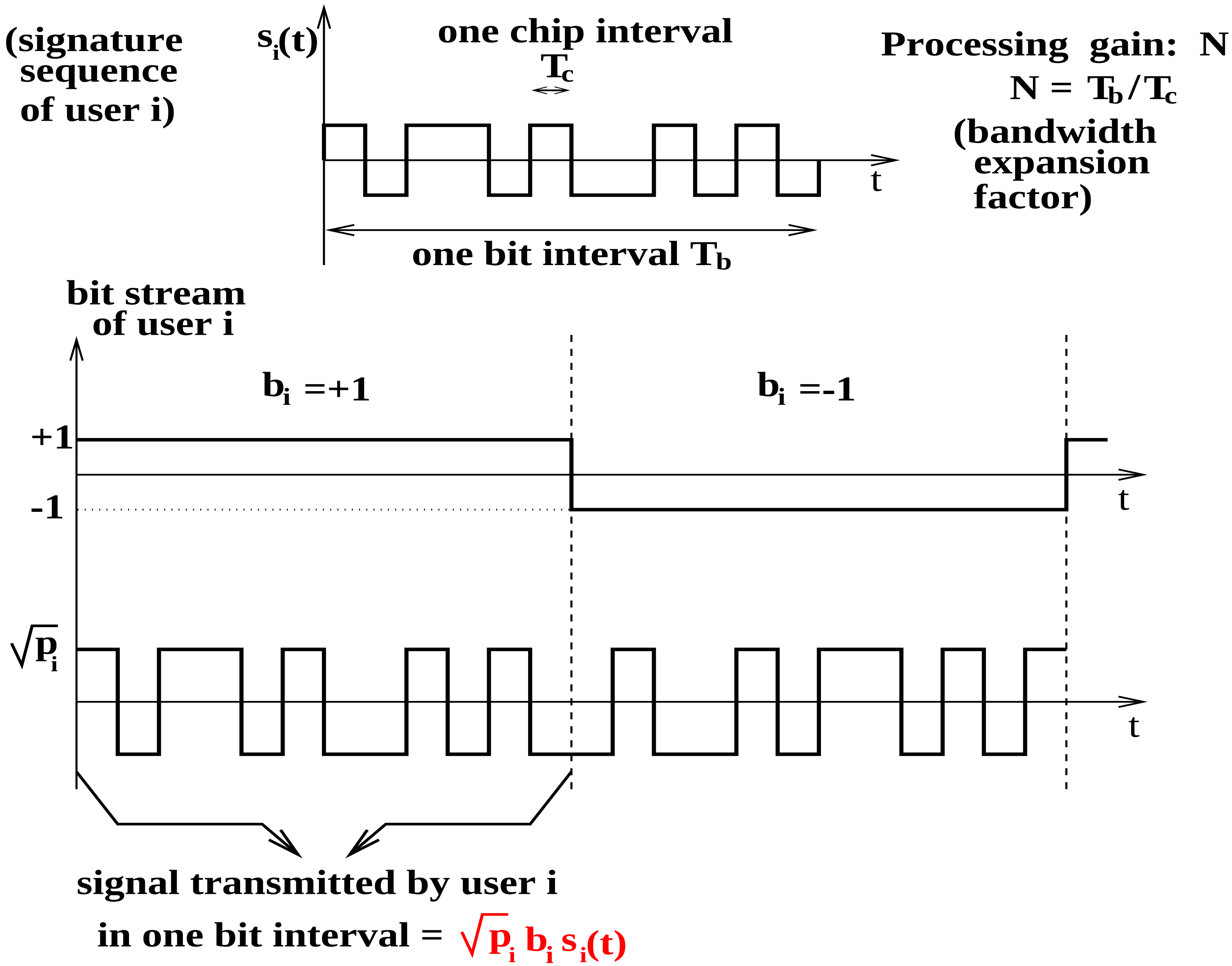


$$\hat{b}_i = \text{sgn}\,(w_i^T r)$$

MULTIPLE ACCESS METHODS

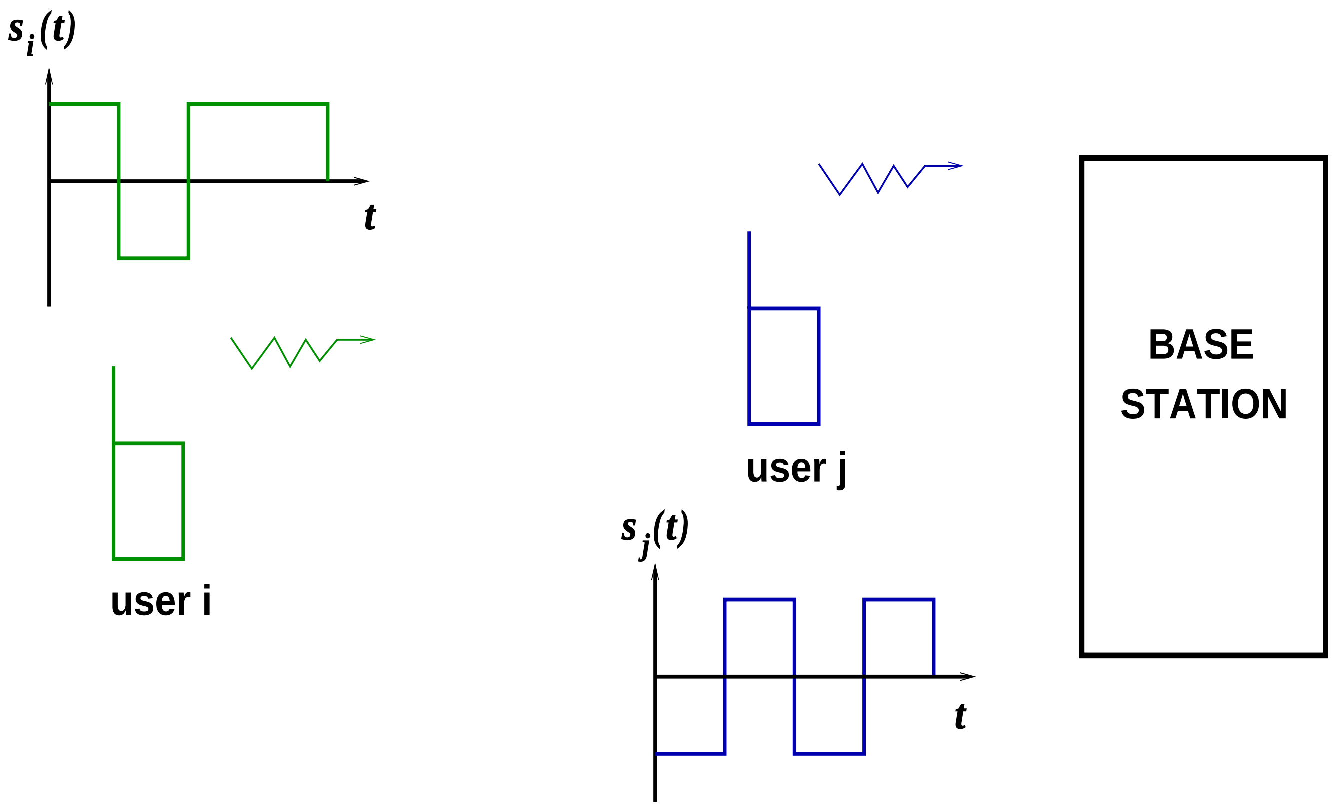


Code Division Multiple Access: Principles



Interference Management for CDMA

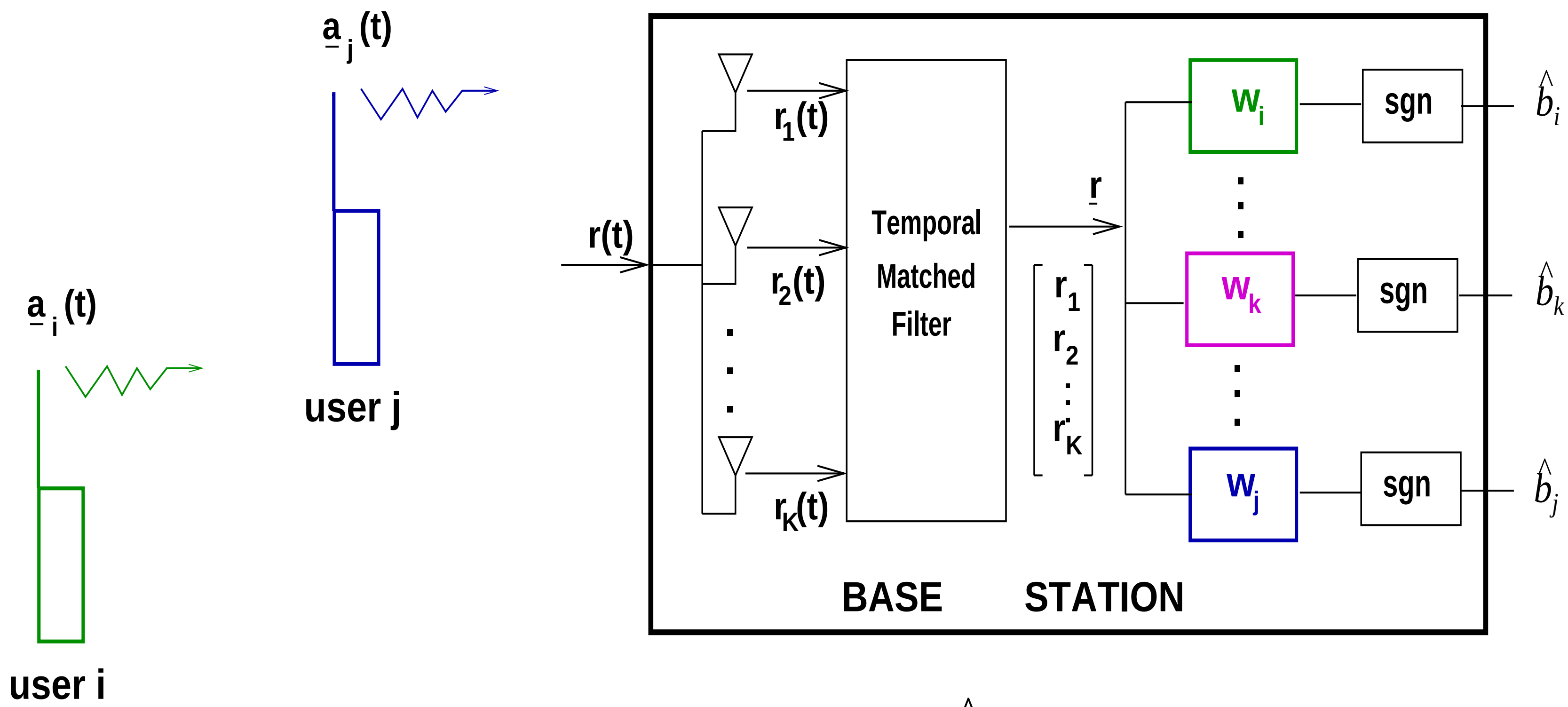
- CDMA systems are interference limited because
  - Users have unique, but non-orthogonal signatures
- Strong users can destroy weak user's communication ← near-far problem
- Interference Management is needed!



Interference Management Techniques

- Power Control [Zander] [Yates] [Hanly]
- Multiuser Detection (Temporal Filtering) [Verdú][Xie et. al.][Madhow,Honig]
- Beamforming (Spatial Filtering) [Naguib et. al.]
- Power Control and Multiuser Detection [Ulukus, Yates]
- Power Control and Beamforming [Rashid-Farrokhi et. al.]
- Multiuser Detection and Beamforming [**Yener**, Yates, Ulukus]
- Power Control, Multiuser Detection, and Beamforming [**Yener**, Yates, Ulukus]
- Power Control and Adaptive cell sectorization [Saraydar, **Yener**]

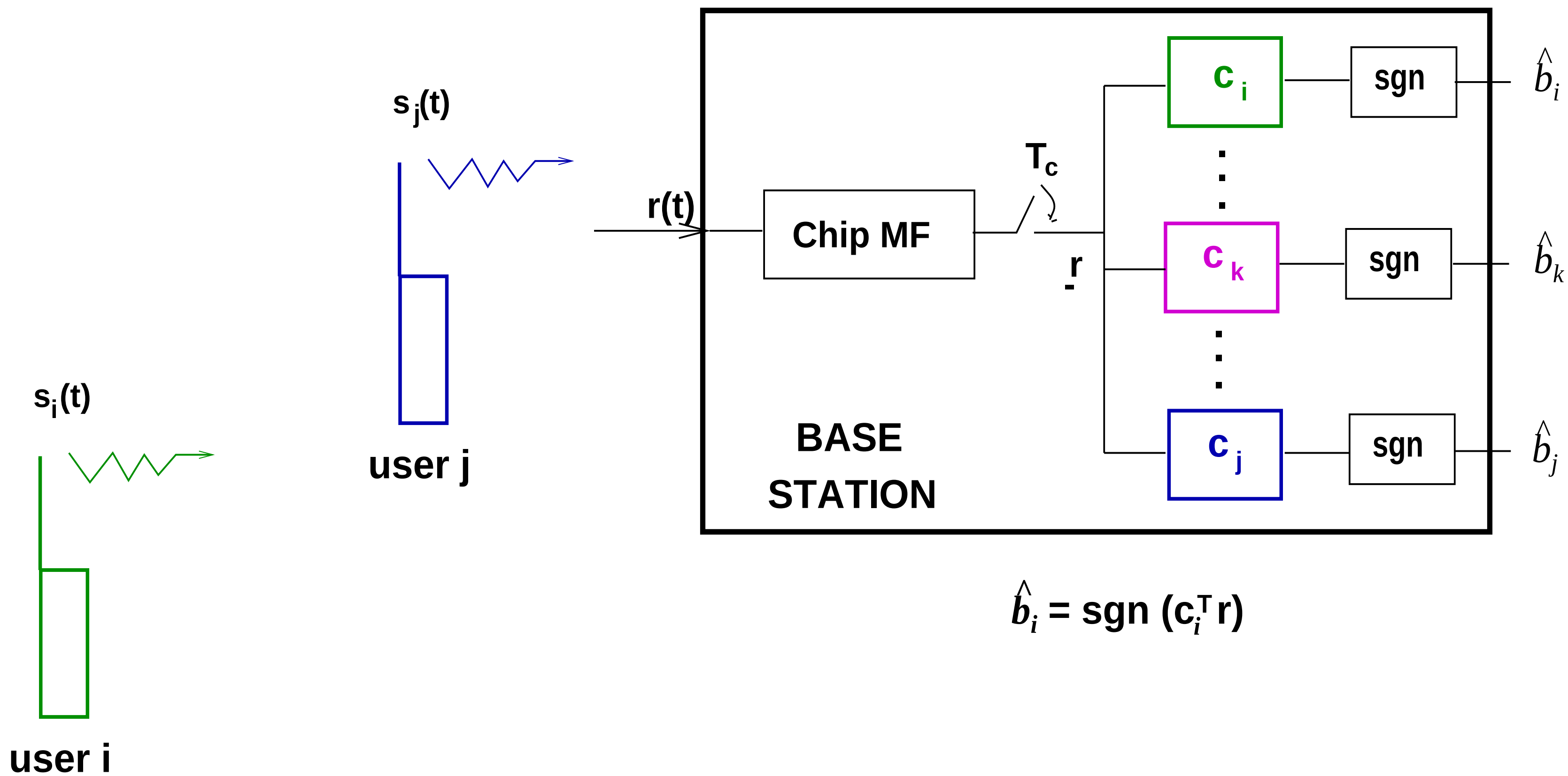
Beamforming (Spatial Filtering)



$$\hat{b}_i = \text{sgn}\,(w_i^T r)$$

- More *intelligent* filters in spatial domain

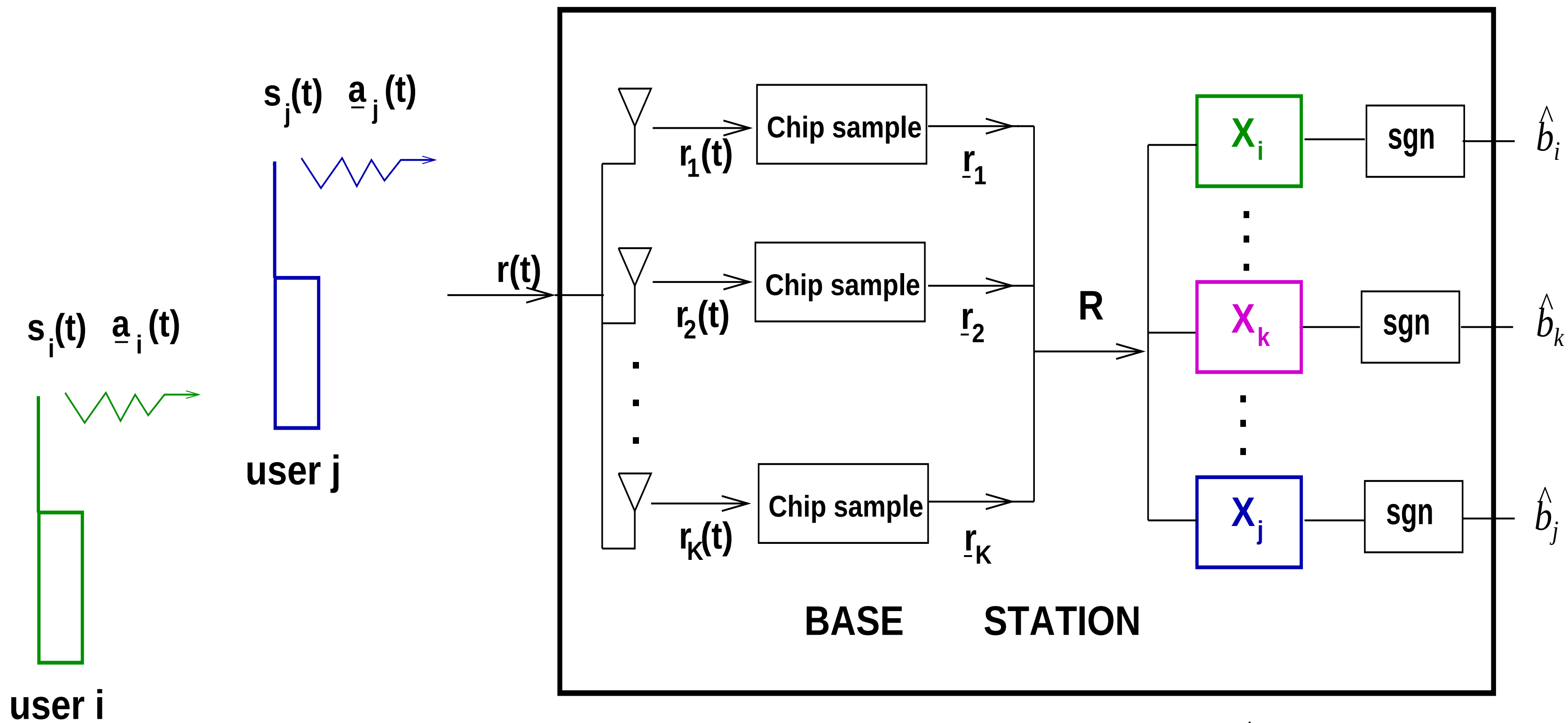
Linear Multiuser Detection (Temporal Filtering)



$$\hat{b}_i = \text{sgn}\,(c_i^T r)$$

- More *intelligent* filters in temporal domain

Temporal and Spatial Filtering



R *and* **X** *are matrices !*

$\hat{b}_i = \text{sgn}(\text{tr}(X_i^T R))$

- More *intelligent* filters in both domains

Temporal-Spatial Filtering

- Several possible filter structures:
  - Single user approach: Temporal-spatial matched filter [Naquib et. al]
  - Single user – multiuser approach: Temporal matched filter + Spatial MMSE or vice versa [Honig et. al] [Rashid-Farrokhi et. al]
  - Cascaded structures: MMSE temporal combiners cascaded with an MMSE spatial combiner, or vice versa [Yener, Yates, Ulukus]
- Each of these filters can be expressed as a matrix filter.
- Joint optimum temporal-spatial filter perform better than any cascade structure [Yener et.al.]
- **We focus on joint temporal-spatial MMSE filter designs.**

Previous work

- Assume synchronous users; single path. Received signal matrix over one bit period:

$$\mathbf{R} = \sum_{k=1}^{K} \sqrt{P_k} b_k \mathbf{s}_k \mathbf{a}_k^T + \mathbf{N}$$

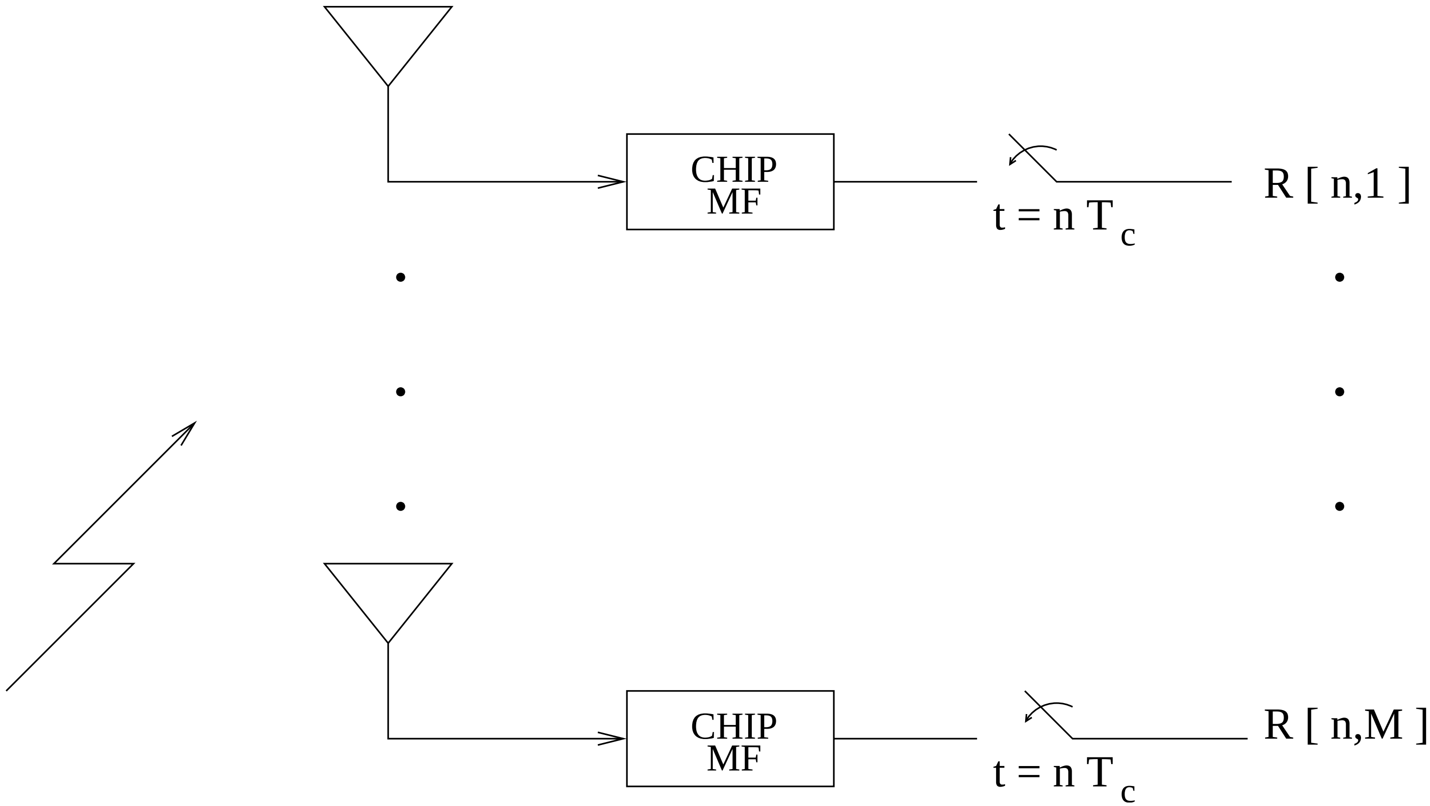
- $E[N_{kl}^* N_{mn}] = \sigma^2 \delta_{km} \delta_{ln}$
- Decision statistic computed via linear matrix filter $\mathbf{X}_i$

$$y_i = \sum_{n=1}^{N} \sum_{m=1}^{M} [X_i]_{nm}^* R_{nm} = tr(\mathbf{X}_i^H \mathbf{R})$$

- Design matrix filters to minimize the MSE

$$\bar{\mathbf{X}}_i = \arg\min_{\mathbf{X}} E\left[\left| tr\left(\mathbf{X}^H \mathbf{R}\right) - b_i \right|^2\right]$$

Received Signal



Synchronous system with processing gain *N*, *M* antenna elements and *K* users

Optimum Temporal-Spatial Filter (OTSF)

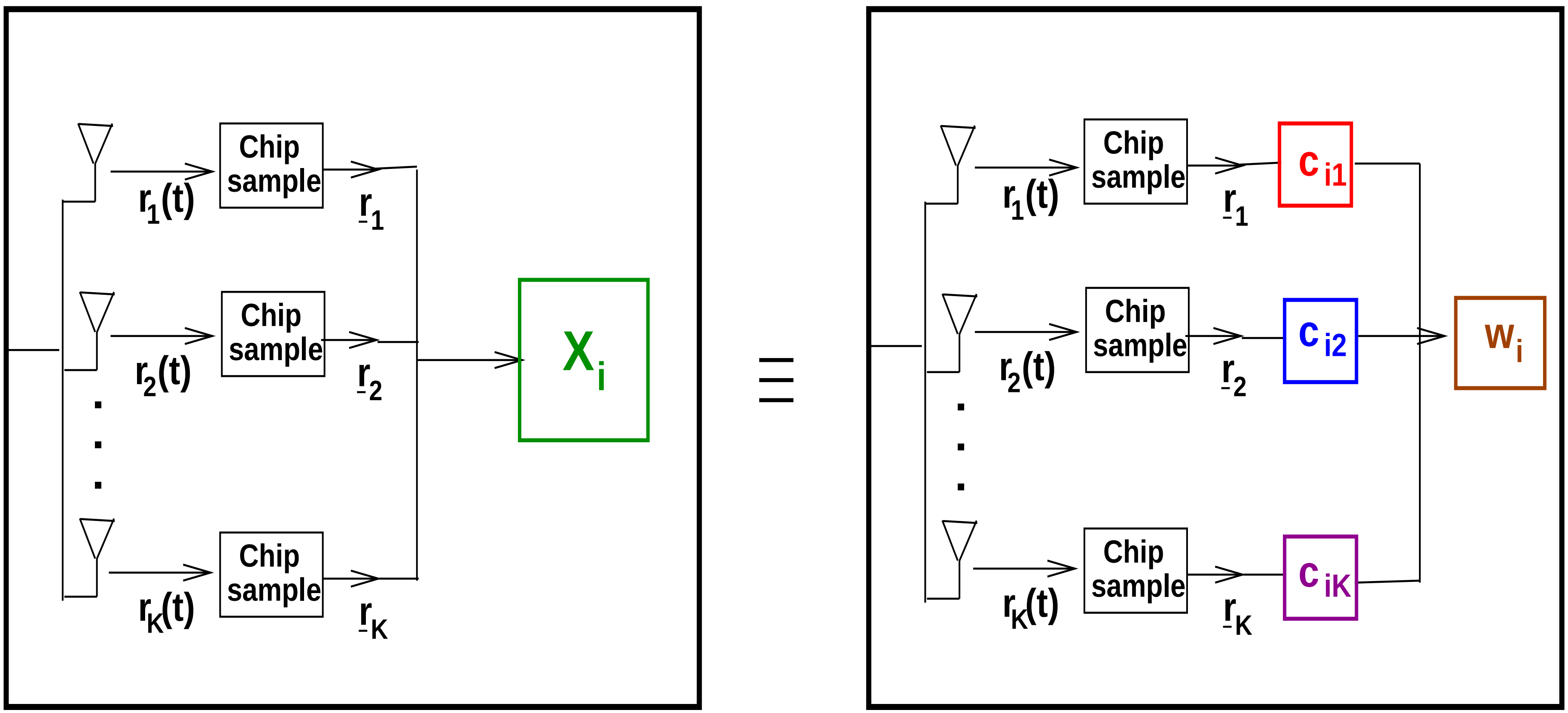
- Find the matrix filter $\mathbf{X}_i$ that yields the minimum MSE between y_i and b_i.

$$\bar{\mathbf{x}}_i = \sqrt{P_i}\left(\sum_{k=1}^{K} P_k \mathbf{q}_k \mathbf{q}_k^H + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{q}_i$$

where $\mathbf{s}_k \mathbf{a}_k^T \rightarrow \mathbf{q}_k$

- This filter results in the minimum MSE over all possible filtering schemes in temporal and spatial domains
- Resulting joint optimum filter has a closed form
- Complexity due to the inversion of a $NM \times NM$ matrix$\Rightarrow$ Find a simpler receiver structure
- MN could be large! (e.g. $N = 64$, $M = 4$)

OTSF Receiver for User i



Constrained Temporal-Spatial Filters (CTSF) [Yener et.al.]

- *Separable* temporal-spatial filters for reduced complexity: $\tilde{\mathbf{X}}_i = \mathbf{c}_i \mathbf{w}_i^\top$
- Decision statistic for user i:

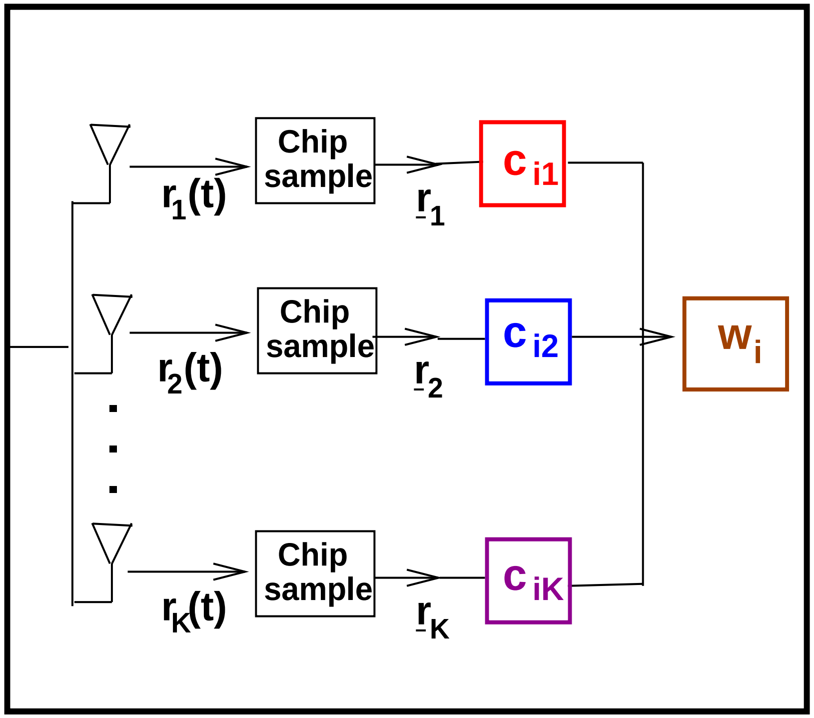
$$y_i = \mathrm{tr}(\mathbf{w}_i \mathbf{c}_i^\top \mathbf{R}) = \mathbf{c}_i^\top \mathbf{R} \mathbf{w}_i$$

- Find the separable filters that are *jointly* optimum in MSE sense
- **Rank-1 filters:** Constrain the feasible set of possible matrix filters to ones of the form

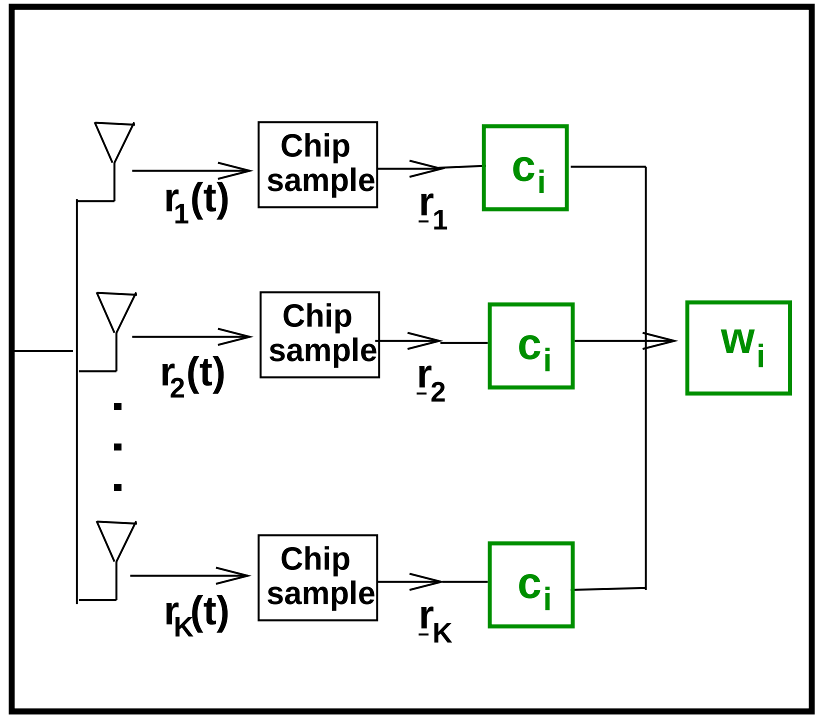
$$\mathbf{X}_i = \mathbf{c}_i \mathbf{w}_i^T$$

  - The same N dimensional temporal filter, $\mathbf{c}_i$ at the output of each antenna
  - Combine the outputs via the M dimensional beamformer, $\mathbf{w}_i$
  - Jointly optimum $\mathbf{c}_i$ and $\mathbf{w}_i$ are found iteratively. Rank-1 filters work well when
    - system is not overloaded
    - reasonably good power control

OTSF vs. CTSF Receiver for User i



OTSF



CTSF

- **CTSF:** First combine all the chip vectors using $\mathbf{c}_i$ then combine the resulting vector using $\mathbf{w}_i$

Motivation for Rank-r Filters **[Filiz, Yener]**

- Rank-1 constrained filters:
  - Suboptimal performance due to the constrained solution space
  - Performance difference can be pronounced in heavily loaded systems

  ***Filters with performance between OTSF and the rank-1 constrained filter are needed**

- Multipath environments: **Need to take advantage of temporal diversity.**
- Adaptive Implementation
  - Suitable for a cellular environment
  - Only the knowledge of training bits is required

  ***Algorithms that do not require the explicit channel estimates are desirable**

Multipath Channel Model

- Transmitted signal of user k

$$z_k(t) = \sqrt{P_k} \sum_{n=-\infty}^{\infty} b_k(n) s_k(t - nT_s)$$

- Multipath channel impulse response

$$h_k(t) = \sum_{l=1}^{L} h_{k,l}\, \delta(t - \tau_{k,l})$$

- Received signal at the output of the antenna array

$$\mathbf{r}(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} h_{k,l}\, z_k(t - \tau_{k,l} - \nu_k)\, \mathbf{a}_{k,l} + \mathbf{n}(t)$$

Simplified Multipath Channel Model

- Synchronous users
- Each user has L paths with chip synchronous delays
- $\tau_{k,l} << T$ such that ISI can be ignored
- Received signal over the observation interval

$$\mathbf{R} = \sum_{k=1}^{K} \sqrt{P_k} b_k \mathbf{S}_k \mathbf{H}_k \mathbf{A}_k^T + \mathbf{N}$$

$$\mathbf{S}_k = \begin{bmatrix} s_k[1] & & \mathbf{0} \\ & \ddots & \\ \vdots & & s_k[1] \\ s_k[N] & & \vdots \\ & \ddots & \\ \mathbf{0} & & s_k[N] \end{bmatrix} \quad \mathbf{H}_k = \begin{bmatrix} h_{k,1} & & 0 \\ & \ddots & \\ 0 & & h_{k,L} \end{bmatrix} \quad \mathbf{A}_k = [\mathbf{a}_{k,1}, \cdots, \mathbf{a}_{k,L}]$$

Rank-r Constrained Filters

- Achieve the performance improvement by relaxing the constraint:

$$\bar{\mathbf{X}}_i = \arg\min_{\mathbf{X}} E\left[\left|tr\left(\mathbf{X}^H\mathbf{R}\right) - b_i\right|^2\right]$$
$$\text{s.t.} \quad \text{rank}(\mathbf{X}) \le r, \qquad 1 \le r \le min\{N+L-1, M\}$$

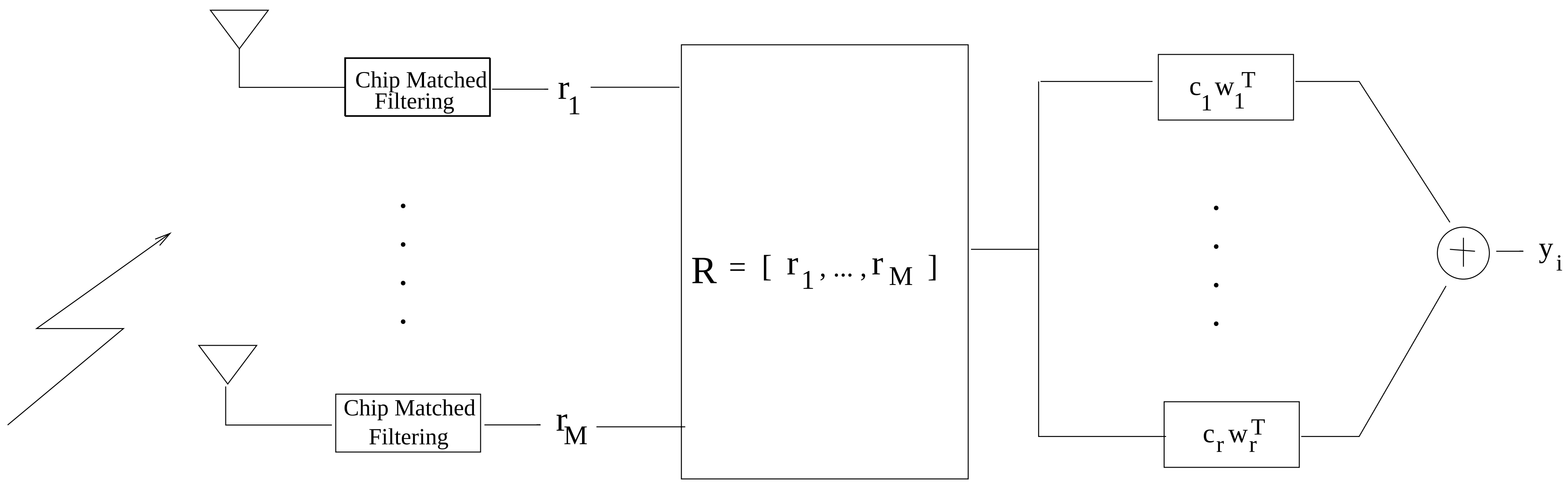
- Satisfy the rank constraint by decomposing $\mathbf{X}_i$ as:

$$\mathbf{X}_i = \sum_{j=1}^{r} \mathbf{c}_{ij}\mathbf{w}_{ij}^T$$

- The MSE and the optimization problem expressions become:

$$\text{MSE} = E\left[\left|\sum_{j=1}^{r} \mathbf{c}_{ij}^H\mathbf{R}\mathbf{w}_{ij}^* - b_i\right|^2\right]$$
$$\{\bar{\mathbf{c}}_{i1}, \ldots, \bar{\mathbf{c}}_{ir}, \bar{\mathbf{w}}_{i1}, \ldots, \bar{\mathbf{w}}_{ir}\} = \arg\min_{\mathbf{c}_{i1},\ldots,\mathbf{c}_{ir},\mathbf{w}_{i1},\ldots,\mathbf{w}_{ir}} E\left[\left|\sum_{j=1}^{r} \mathbf{c}_{ij}^H\mathbf{R}\mathbf{w}_{ij}^* - b_i\right|^2\right]$$

Receiver Structure



Performance Metric

- MSE expression becomes:

$$\mathrm{MSE} = \sum_{l=1}^{r}\sum_{j=1}^{r}\sum_{k=1}^{K} P_k \mathbf{c}_{il}^H \mathbf{V}_k \mathbf{w}_{il}^* \mathbf{w}_{ij}^T \mathbf{V}_k^H \mathbf{c}_{ij} + \sigma^2 \sum_{l=1}^{r}\sum_{j=1}^{r} \left(\mathbf{c}_{il}^H \mathbf{c}_{ij}\right)\left(\mathbf{w}_{il}^H \mathbf{w}_{ij}\right) - 2\sqrt{P_i}\sum_{j=1}^{r} \Re\left\{\mathbf{c}_{ij}^H \mathbf{V}_i \mathbf{w}_{ij}^*\right\} + 1$$

where $\mathbf{V}_k = \mathbf{S}_k \mathbf{H}_k \mathbf{A}_k^T$

- Note that MSE is a function of $2r$ variables

$$\{\mathbf{c}_{i1}, \ldots, \mathbf{c}_{ir}, \mathbf{w}_{i1}, \ldots, \mathbf{w}_{ir}\}$$

- MSE is not jointly convex in all variables
- MSE is convex for a single variable, given that the other $2r-1$ variables are fixed
- Use alternating minimization algorithm to iteratively minimize the MSE

Alternating Minimization Algorithm

- Each step consists of $2r$ *sub-steps*
- At each sub-step, update a single variable to minimize the MSE
- The algorithm can be expressed as

$$
\begin{array}{l}
\text{FOR} \quad t = 1:S \\
\qquad \text{FOR} \quad x = 1:r \\
\qquad\qquad \hat{\mathbf{c}}_{ix} = \text{MMSE}(\{\mathbf{c}_{ij}\}_{j\neq x}, \{\mathbf{w}_{ij}\}_{j=1}^{r}) \\
\qquad\qquad \hat{\mathbf{w}}_{ix} = \text{MMSE}(\{\mathbf{c}_{ij}\}_{j=1}^{r}, \{\mathbf{w}_{ij}\}_{j\neq x}) \\
\qquad \text{END} \\
\text{END}
\end{array}
$$

where $\hat{\mathbf{c}}_{ix}$ and $\hat{\mathbf{w}}_{ix}$ denote the values that minimize MSE
S is the total number of steps

Adaptive Implementation

- All users' parameters needed in deterministic iterations.
- Adaptive implementation is needed in practice.
- Combination of alternating minimization with LMS
  - Keep the main structure of the alternating minimization algorithm
  - Solve each sub-step using the classical LMS approach
- The classical LMS rule:

$$\mathbf{w}_i(n+1) = \mathbf{w}_i(n) + \mu\left(d_i(n) - y_i(n)\right)^* \mathbf{u}(n)$$

- Define the desired response, decision statistic and the input signal

$$\begin{aligned} d_i &\rightarrow b_i - \sum_{j \neq x}^{r} \mathbf{c}_{ij}^H \mathbf{R} \mathbf{w}_{ij}^* \\ y_i &\rightarrow \mathbf{c}_{ix}^H \mathbf{R} \mathbf{w}_{ix}^* \\ \mathbf{u}(n) &\rightarrow \mathbf{R} \mathbf{w}_{ix}^* \quad (\text{or } \mathbf{R}^T \mathbf{c}_{ix}^*) \end{aligned}$$

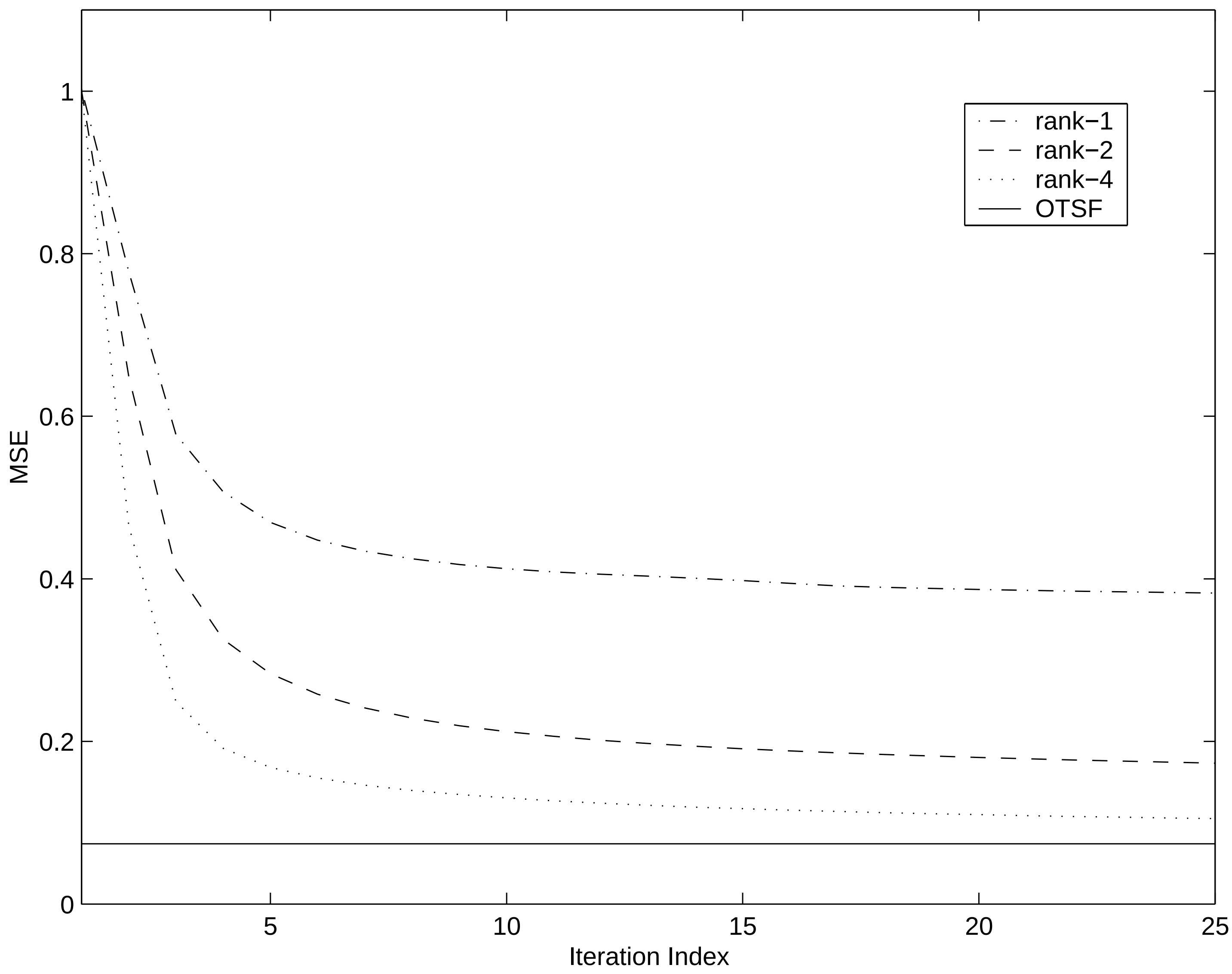
Parameters that Affect Convergence

- Block size B
  - LMS converges to optimum in infinite iterations (training bits)
  - At each sub-step we truncate the LMS after B training bits
  - Smaller $B \rightarrow$ premature jumping to the next step
  - Larger $B \rightarrow$ slower overall algorithm
- Step size μ
  - Smaller $\mu \rightarrow$ slower convergence but higher accuracy
  - Larger $\mu \rightarrow$ faster convergence but more residual error

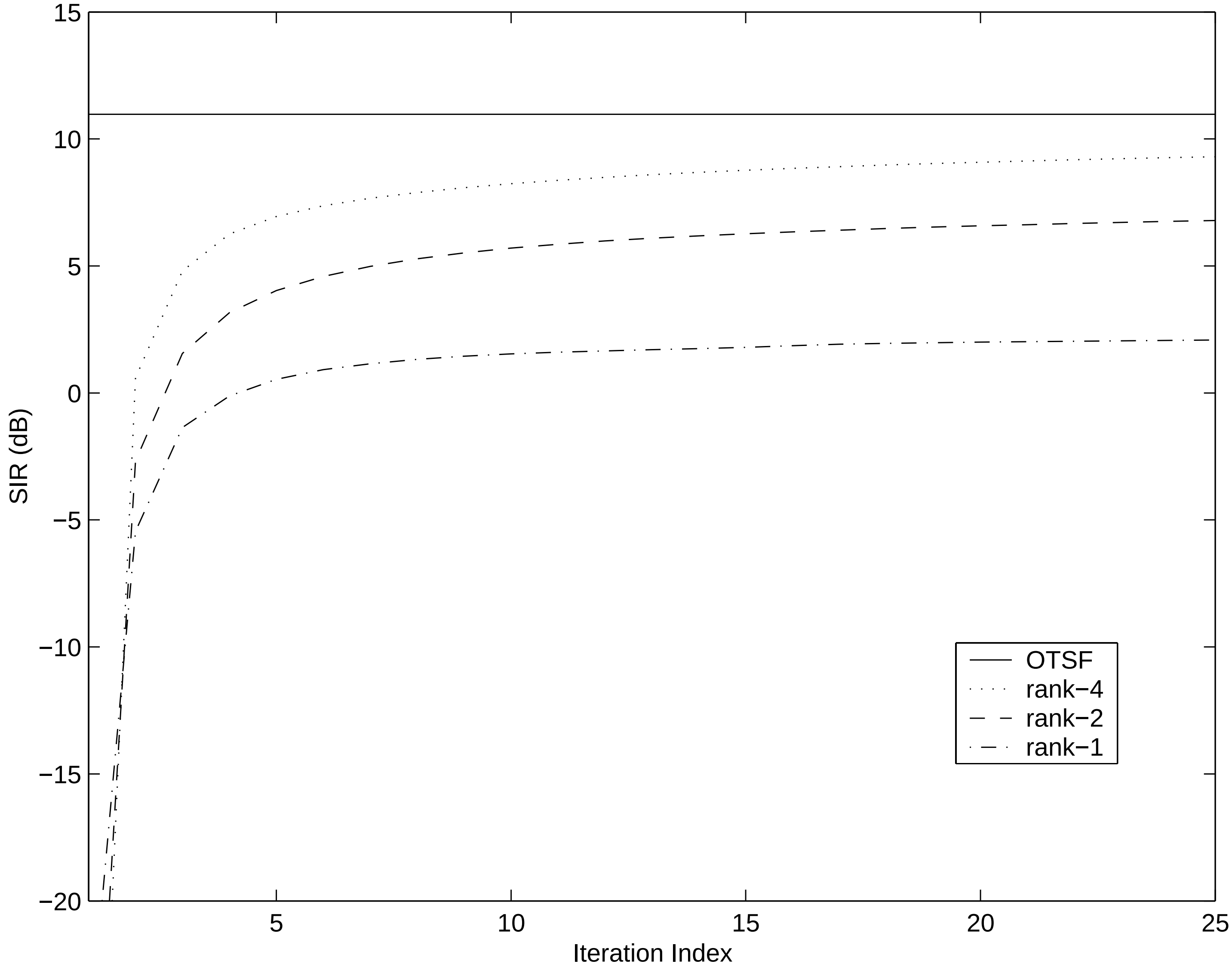
Numerical Results

- A single cell CDMA system with
- $N = 16$ processing gain
- Linear antenna array with $M = 8$ elements, equispaced at $\lambda/2$
- Channel coefficients are zero mean complex Gaussian variables, normalized such that $E[|h_{k,l}|^2] = 1$
- SNR of desired user is 10 dB

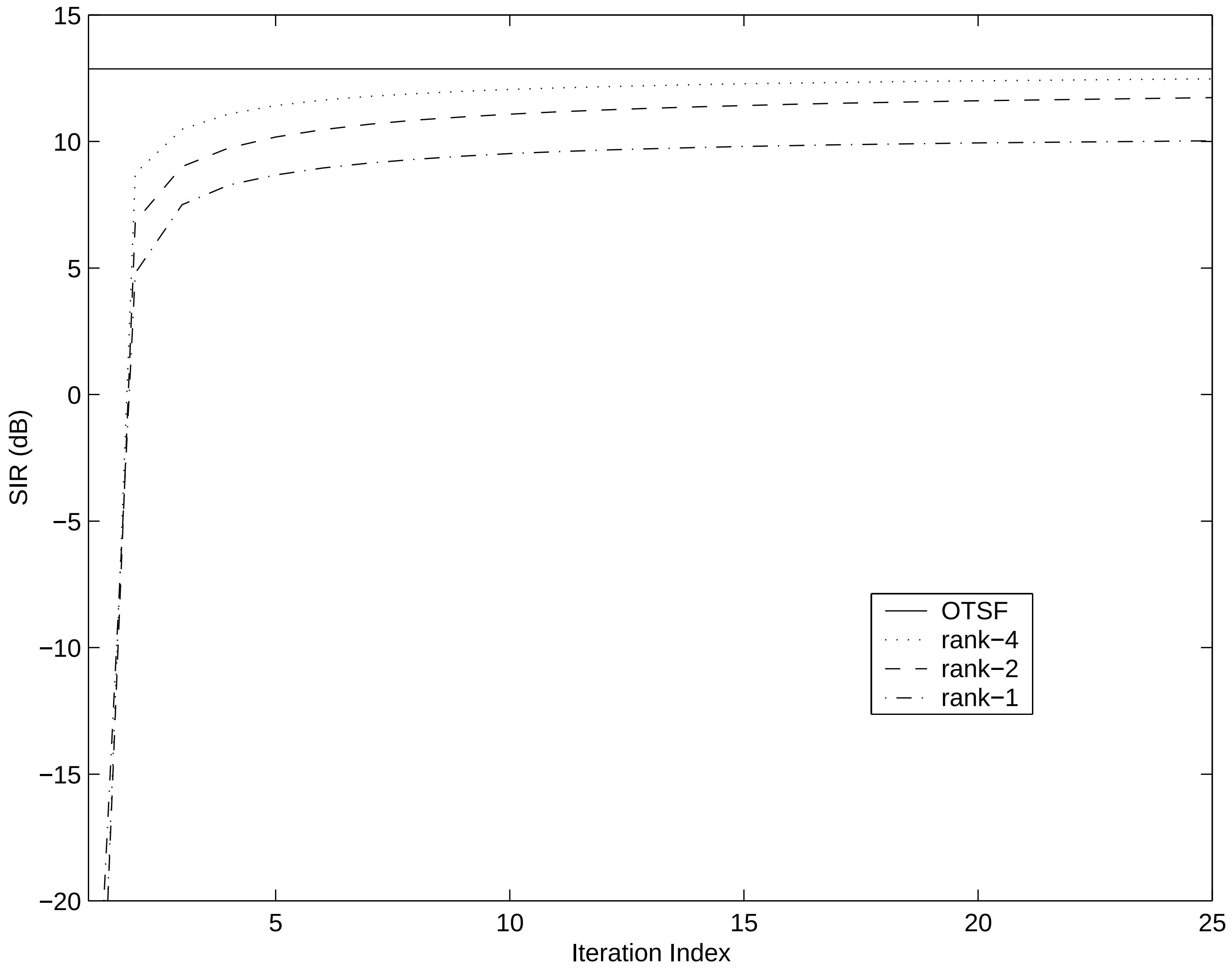
MSE v.s The Iteration Index ($K = 40$, $N = 16$, $M = 8$, $L = 3$)



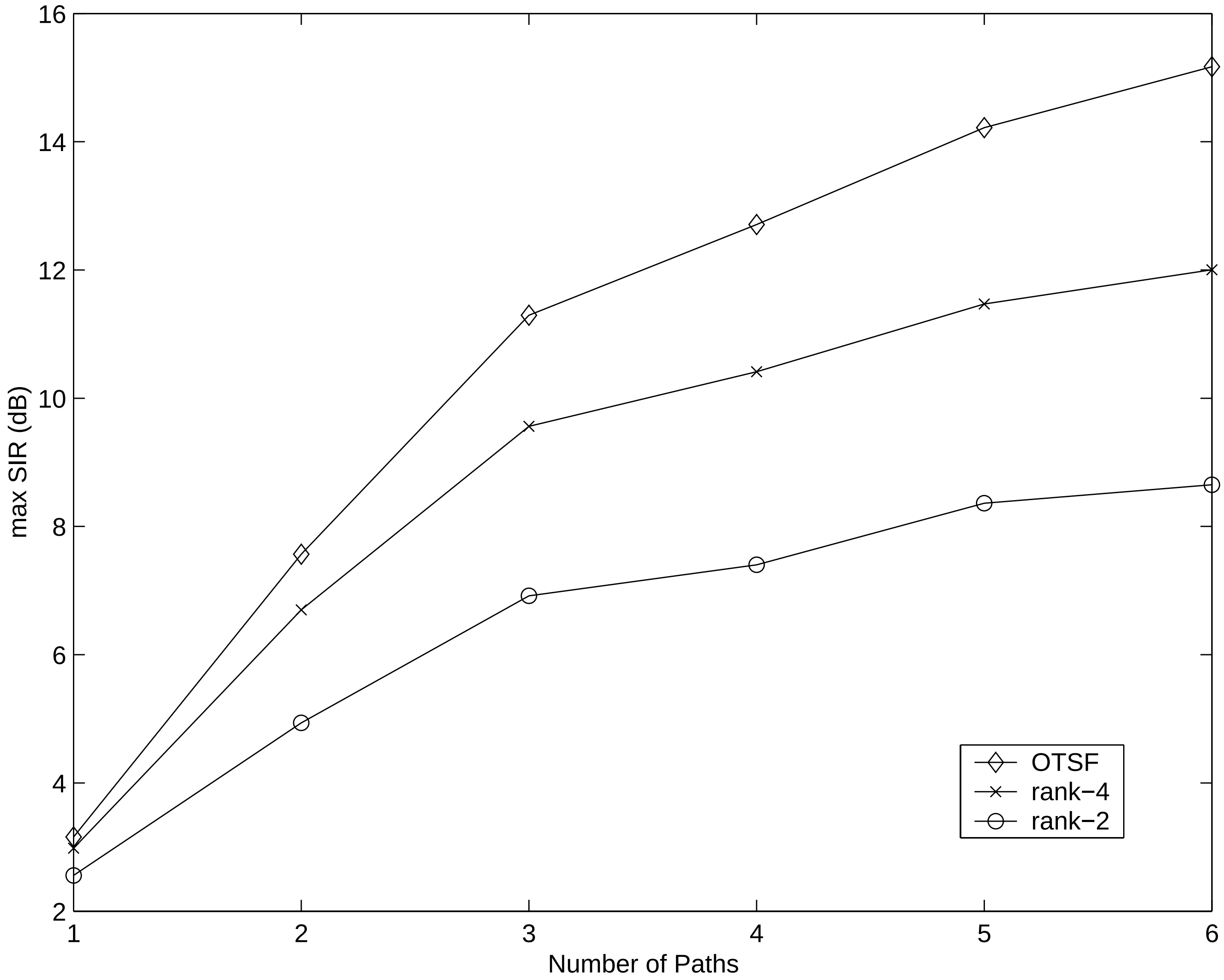
SIR v.s The Iteration Index ($K = 40$, $N = 16$, $M = 8$, $L = 3$)



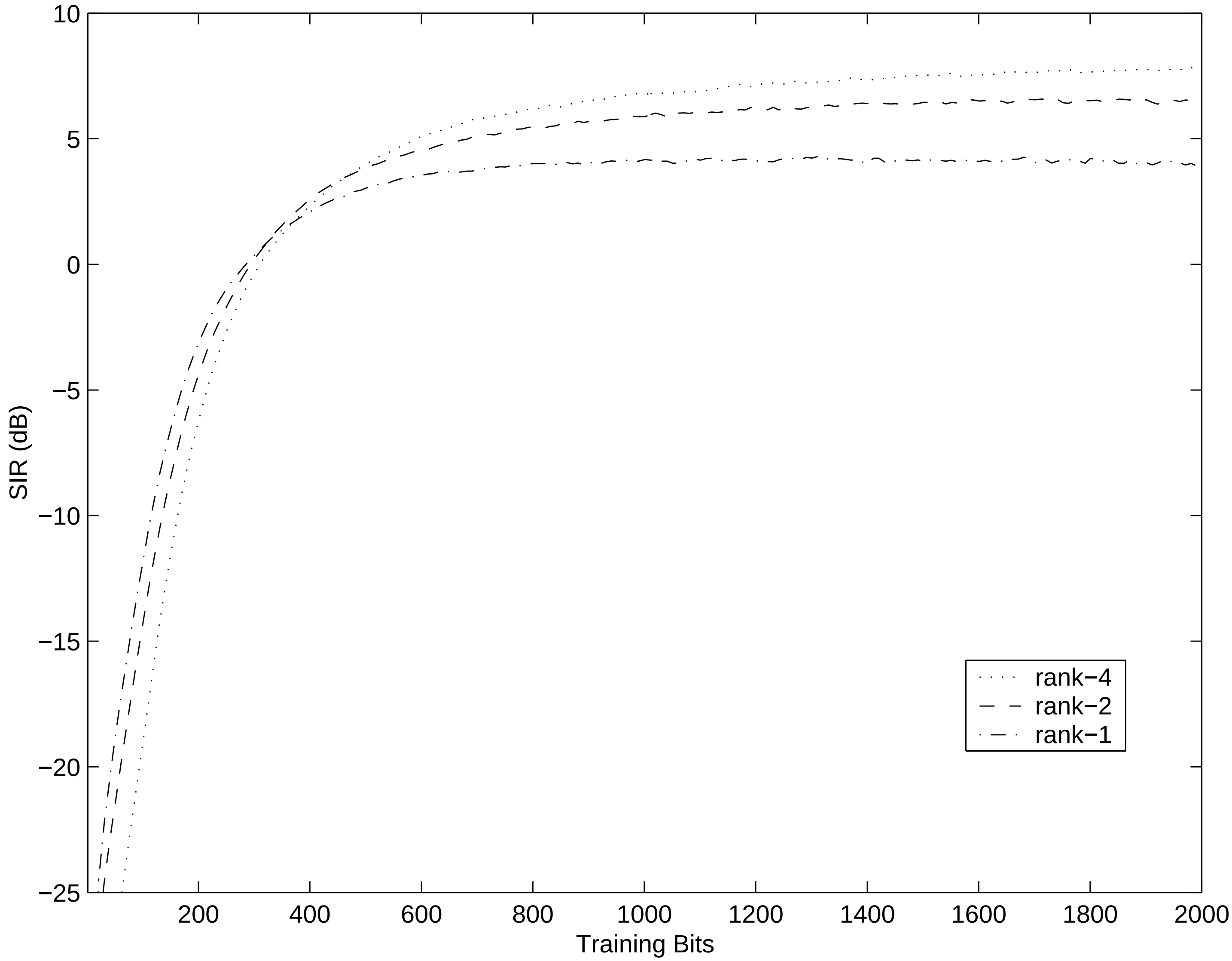
SIR v.s The Iteration Index ($K = 10$, $N = 16$, $M = 8$, $L = 3$)



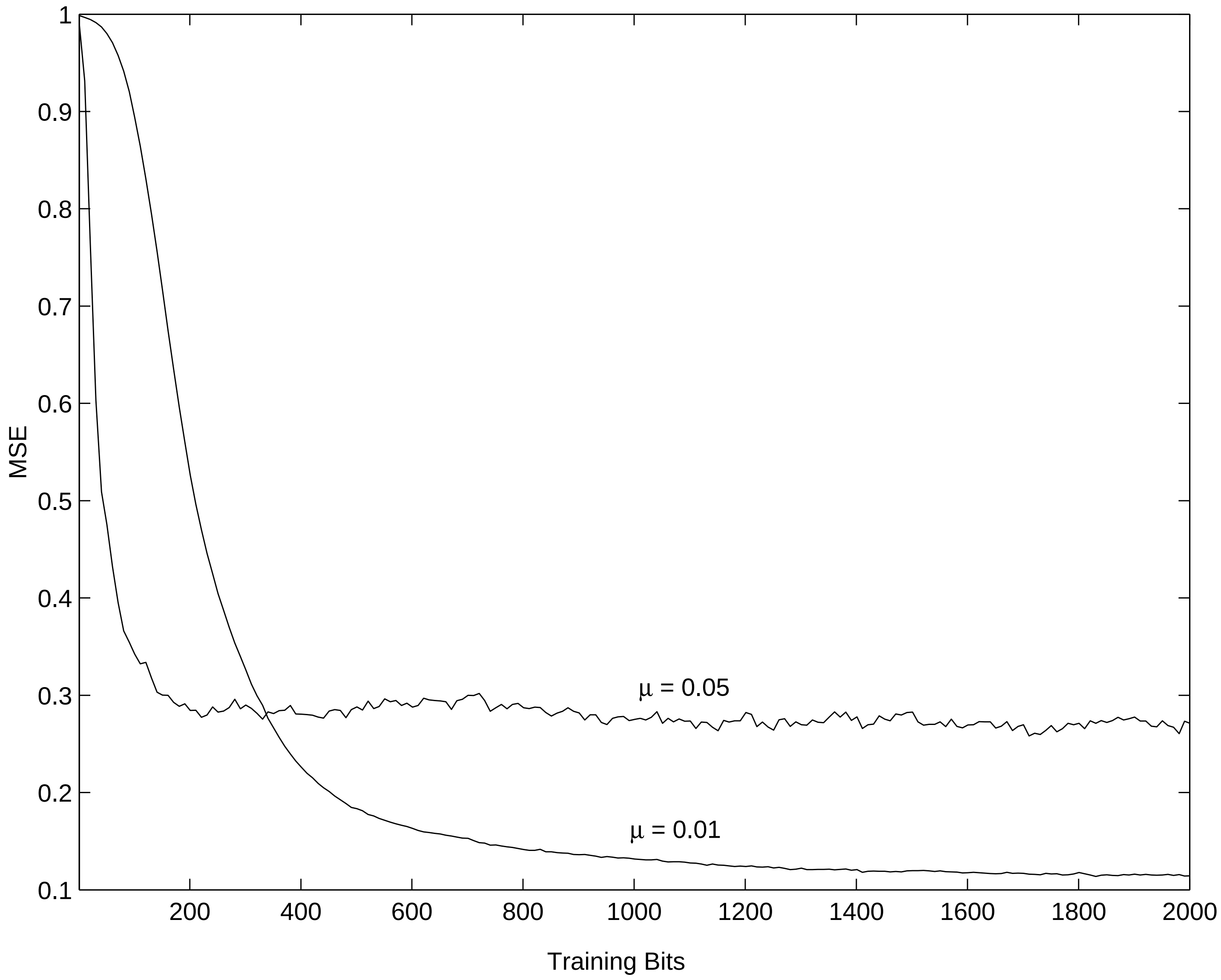
SIR v.s The Number of Paths ($K = 40$, $N = 16$, $M = 8$)



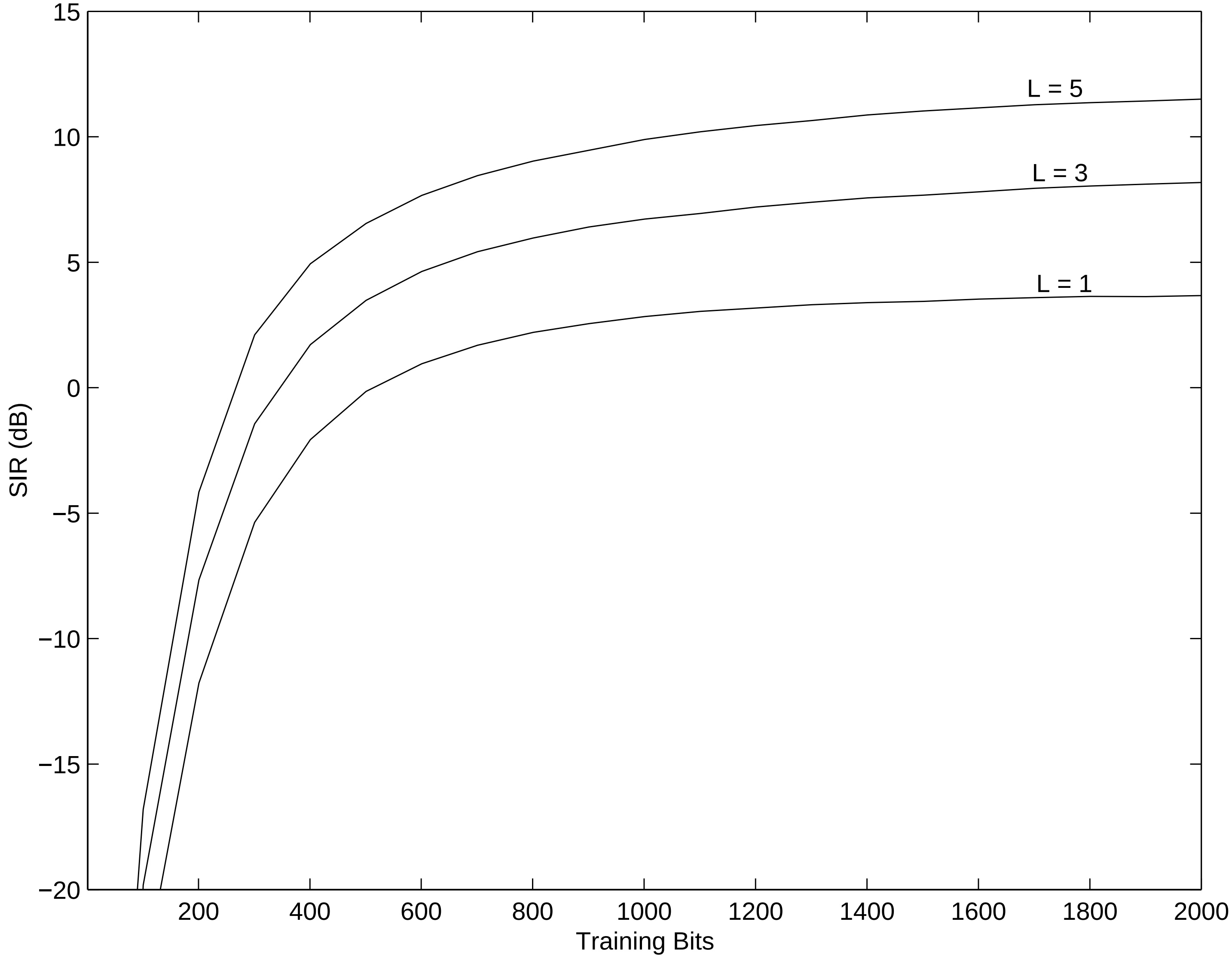
SIR v.s The Training Bits ($K = 40$, $N = 16$, $M = 8$, $L = 3$, $\mu = 0.01$)



SIR v.s The Training Bits ($K = 40$, $N = 16$, $M = 8$, $L = 3$, $\mathbf{rank}(\mathbf{X}) = 2$)



SIR v.s The Training Bits ($K = 40$, $N = 16$, $M = 8$, $\mu = 0.01$, rank$(\mathbf{X}) = 4$)



Conclusions

- Smart antennas provide additional wireless capacity
- Joint temporal-spatial multiuser detectors improve the performance of CDMA systems
- Rank constrained filters
  - Relaxing the constraint increases the performance
  - Near optimal performance can be achieved with a mild increase in complexity
  - Trade-off between complexity and performance
- Adaptive implementations
  - Only the training bits and the timing of the first path of the desired user are required
  - B and μ affect convergence speed and the residual error
- The existence of multipath provides diversity

Further Reading, Current Research

- References
  - J. Winters, "Smart Antennas for Wireless Systems", IEEE Personal Communications, Feb 1998
  - A. Paulraj, C. Papadias, "Space-Time Processing for Wireless Communications", IEEE Signal Processing Magazine, November 1997
  - J. Liberti, T. Rappaport, Smart Antennas for Wireless Communications, Prentice-Hall, 1999
- Transmitter design issues for multiple antenna systems (narrowband)
- Transmit beamformer design for CDMA systems with receiver antenna arrays

See http://labs.ee.psu.edu/labs/wcan for papers and the copy of this talk