Transmitter Multiuser Precoding for Synchronous CDMA Systems

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Introduction

Multiple Access Interference

- In TDMA systems (GSM and IS136), MAI comes from overlapping slots originating in other cells and from users in the same cell due to channel dispersion.
- In orthogonal CDMA systems (IS95, CDMA2000 and WCDMA), the orthogonality can not be guaranteed at each receiver once they go through the channel. Especially in asynchronous case. MAI is hard to be avoided even in the absence of channel distortion or other-cell interference.
- In FDMA systems (AMPS), extra guard bands have to be used to separate different users.
- In some other MIMO system, such as OFDM and DMT, MAI can appear as ISI or cross talk.

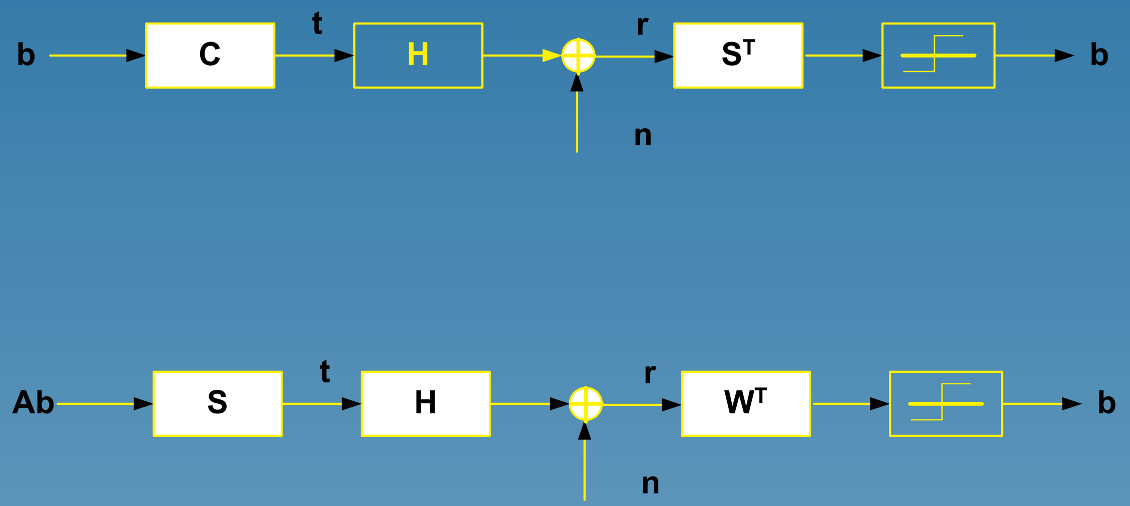
Emerging Mitigation Technologies

- Transmitter Design
  - ⋆ Multiuser precoding: optimal (nolinear) and linear.
  - ⋆ Transmitter diversity. selective transmission and advanced channel coding.
- Receiver Detection
  - ⋆ Multiuser detection: optimal, linear and nolinear.
  - ⋆ Receiver diversity (smart antenna): switch beamform, adaptive beamform.
- Tansceiver Design (system level)
  - ⋆ Power control: fast, open-loop and closed-loop.
  - ⋆ Sequence design (generalized orthogonal sequences): ZCZ sequences, LCZ sequences.

Uplink/Downlink of Synchronous CDMA System

- Uplink of CDMA system
  - ⋆ MS: Limited computation capacity and power supply. Perfectly synchronized transmission can not be guarantee. Almost no knowledge of other active users.
  - ⋆ BS: Enough computation capacity and power supply in most cases. Complex receiver signal precessing can be affordable.
- Downlink of CDMA system
  - ⋆ BS: Nearly know everything about each active user in its cell. The signals for each user are synchronously transmitted.
  - ⋆ MS: Complex signal precessing for receiver usually can not be used.

Basic Synchronous CDMA System Models



Classic K-user system models for multiuser precoding and multiuser detection.

Transmitter Multiuser Precoding I

- Compared with multiuser detection at receiver, multiuser precoding refers to data detection in non-orthogonal multiplexes with optimizing transmitter design,
- The transmitter has usually known much prior information about all the active users, such as power spectrum and symbol shaping, in multiuser precoding.
- The correlations among different sub-channels may be utilized to enhance the transmission for each user in multiuser precoding. (Multiple Access Enhancement)
- It is much difficult for transmitter(s) to the obtain channel information, such as channel distortion and multipath delay, except with the help of receivers in reserve links.

Transmitter Multiuser Precoding II

- It can alleviate the signal processing burden at receivers, especially where the mobile stations have no enough power supply and computation capacity.
- With multiuser precoding, the non-orthogonal spreading sequences may be used without receiver multiuser detection. Therefore, it can increase the number of sustainable users in system as multiuser detection does.
- If channel information is available, it can compensate channel distortion at transmitters as Tomlinson pre-equalization.
- It can also reduce the reliance on tight and accurate power control. In some cases, we can even utilize the correlations among different spreading sequences to enhance the transmission for desired users.

Classification of Transmitter Multiuser Precoding

- Most concepts in multiuser receiver design can also be applied for transmitter multiuser precoding.

- Nonlinear/optimal multiuser precoding:
  - ⋆ individually optimum multiuser precoding.
  - ⋆ jointly optimum multiuser precoding.

- Linear multiuser precoding:
  - ⋆ decorrelating multiuser precoding.
  - ⋆ minimum mean squares error (MMSE) multiuser precodings.
  - ⋆ maximum asymptotic multiuser efficiency (MAME) multiuser precoding.
  - ⋆ approximated maximum likelihood (AML) multiuser precoding.

Other Related Techniques

- Tomlinson pre-equalization (M. Tomlinson, 1971). With moving receiver equalization up to transmitter design, receiver design may be greatly simplified.

- Spreading sequence design for CDMA (N. Suehiro, 1994). With exploring the algebraic properties of binary, quadriphase and non-binary sequences, the spreading sequence can be designed to be resistant to the multipath interferences of small delays.

- Convolutional FEC coding (P. Elias, 1955) and block channel coding (T. Liew and L. Hanzo, 2002). With adding redundancy and using special combination, the coded input bit stream has more resistance to channel distortion and interference.

Optimum Multiuser Precoding

Optimum Multiuser Precoding

- In optimum multiuser precoding, all the users' BER are minimized with some criterium.
- Optimum multiuser precoding is decided not only by spreading sequences and SNRs but also by input vector and transmission power distribution for each user.
- The definitions of individually optimum multiuser precoding and detection may be different.
- The channel matrix $\mathbf{H}$ is to be $\mathbf{I}$ in optimum multiuser precoding.

Jointly Optimum Multiuser Precoding I

- Jointly optimum multiuser precoding $\mathbf{C}_{JP}$ is design to minimize the errors in output bit vectors.

$$\mathbf{C}_{JP} \quad = \quad \min_{\mathbf{C}} P[\hat{\mathbf{b}} \neq \mathbf{b}]$$

- Decision regions. The decision region for user k is given by

$$\hat{b}_k \quad = \quad \min_{\bar{b}_k} \|\mathbf{C}\mathbf{b} + \mathbf{n} - \bar{b}_k \mathbf{s}_k\|$$

- Bit-error rate.

$$P_e \quad = \quad 1 - \frac{1}{(2\pi\sigma^2)^{L/2}} \mathsf{E}\left\{ \int_{\mathcal{R}(\mathbf{b})} e^{-\frac{1}{2\sigma^2}\|\mathbf{x}-\mathbf{C}\mathbf{b}\|_2^2} \mathsf{d}\mathbf{x} \right\}$$

Jointly Optimum Multiuser Precoding II

- the jointly optimum precoder $\mathbf{C}_{JP}$ can be expressed as

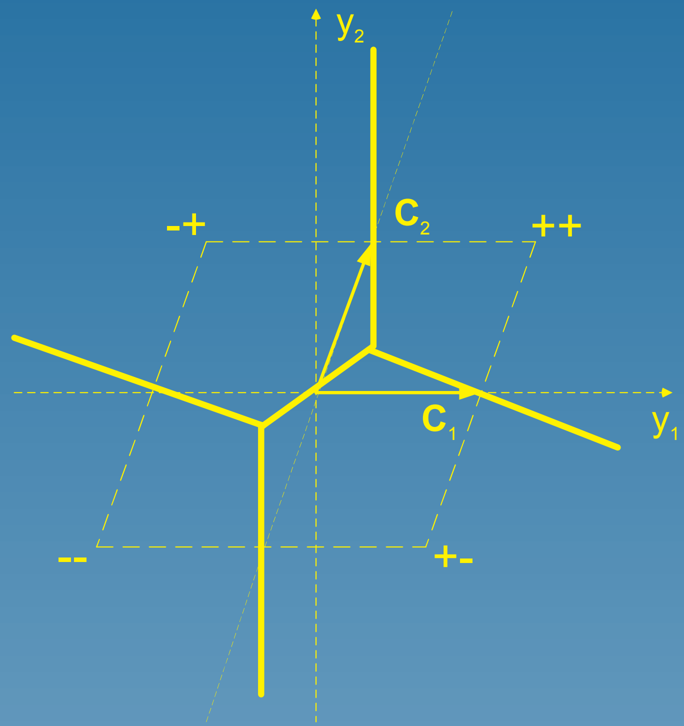
$$\mathbf{C}_{JP} \quad = \quad \bar{\mathbf{S}}\mathbf{A}$$

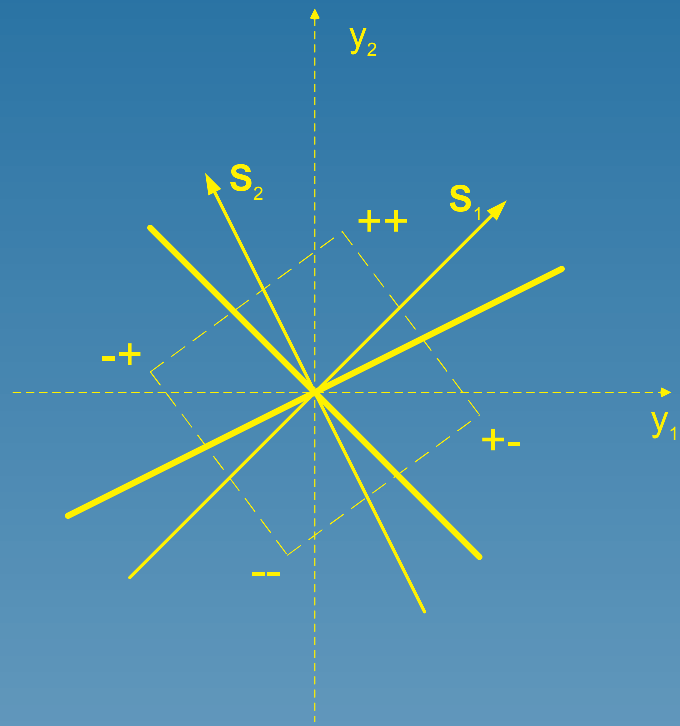
  where $\bar{\mathbf{S}} = [b_1\bar{\mathbf{s}}\ b_2\bar{\mathbf{s}}\ \ \ldots b_K\bar{\mathbf{s}}]$ and $\bar{\mathbf{s}} = \|\mathbf{S}\mathbf{b}\|_2^{-1}\mathbf{S}\mathbf{b}$

- Actually, all the user share the same spreading sequence $\bar{\mathbf{s}}$.

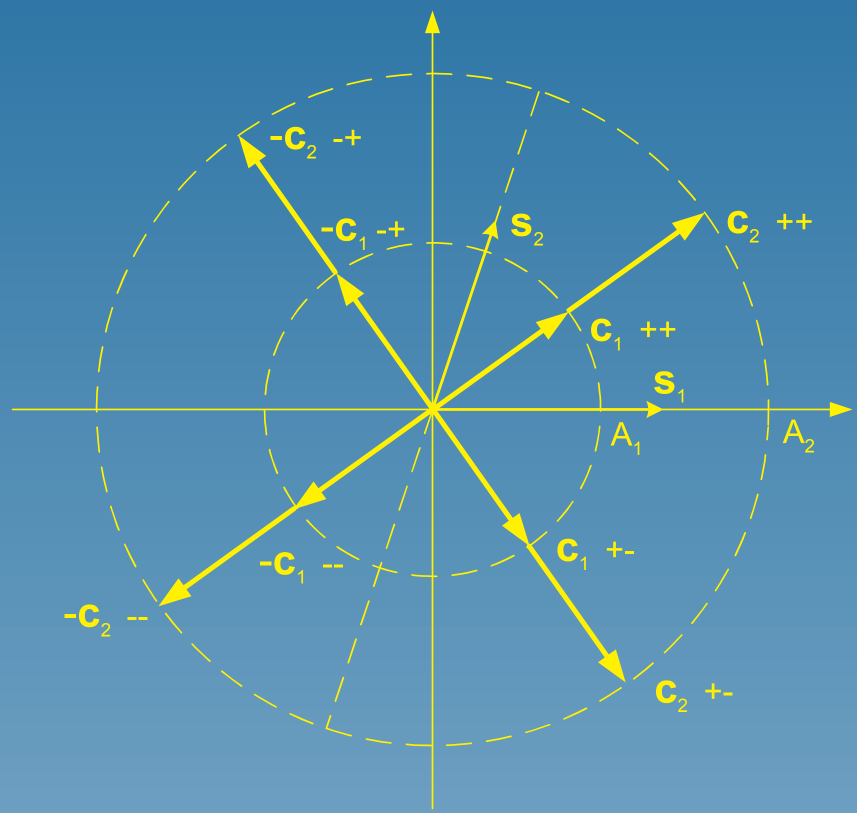
- Different input $\mathbf{b}$ and amplitude distribution $\mathbf{A}$ lead to different optimum precoder $\mathbf{C}_{JP}$ and spreading sequence $\bar{\mathbf{s}}$.

Example: Decision Regions For A 2-User Case





Example: Signal Space Demonstration for A 2-User Case



Individually Multiuser Precoding

- Different to individually optimum multiuser detection, the individually optimum multiuser precoding $\mathbf{C}_{IP}$ is given by

$$\mathbf{C}_{IP} = \arg\min_{\mathbf{C}} \prod_{k=1}^{K} (P_{ek})^{w_k} = \arg\min_{\mathbf{C}} \prod_{k=1}^{K} \left\{ \mathsf{E}\left[Q\left(\frac{\mathbf{s}_k^T \mathbf{C} \mathbf{d}_k}{\sigma} \right) \right] \right\}^{w_k}$$

- The w_k is introduced to separate BER performances for different users.

- Due to the absolution functions and integral functions in the definition, it is hard to give a close-form solution here.

Example: 2-User Individu. Optimum Multiuser Precoding I

Example: Suppose that there are only two users with $A_2 = 2A_1$ and $\rho = 1/3$. The 2nd user's weight w_2 is set to be 4.

Numerical Solution: The individually optimum precoding can be searched out and expressed is

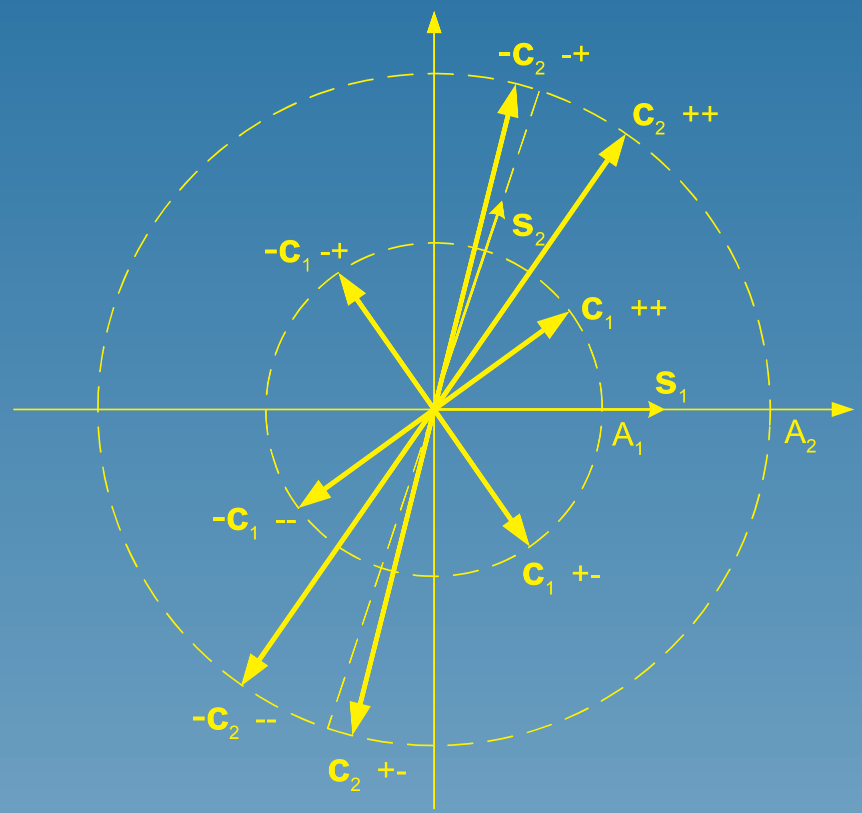
- when $b_1 = b_2$

$$\mathbf{C}_{IP} \approx [\, A_1(0.7089\mathbf{s}_1 + 0.7053\mathbf{s}_2) \quad A_2(0.1724\mathbf{s}_1 + 0.9850\mathbf{s}_2)\,]$$

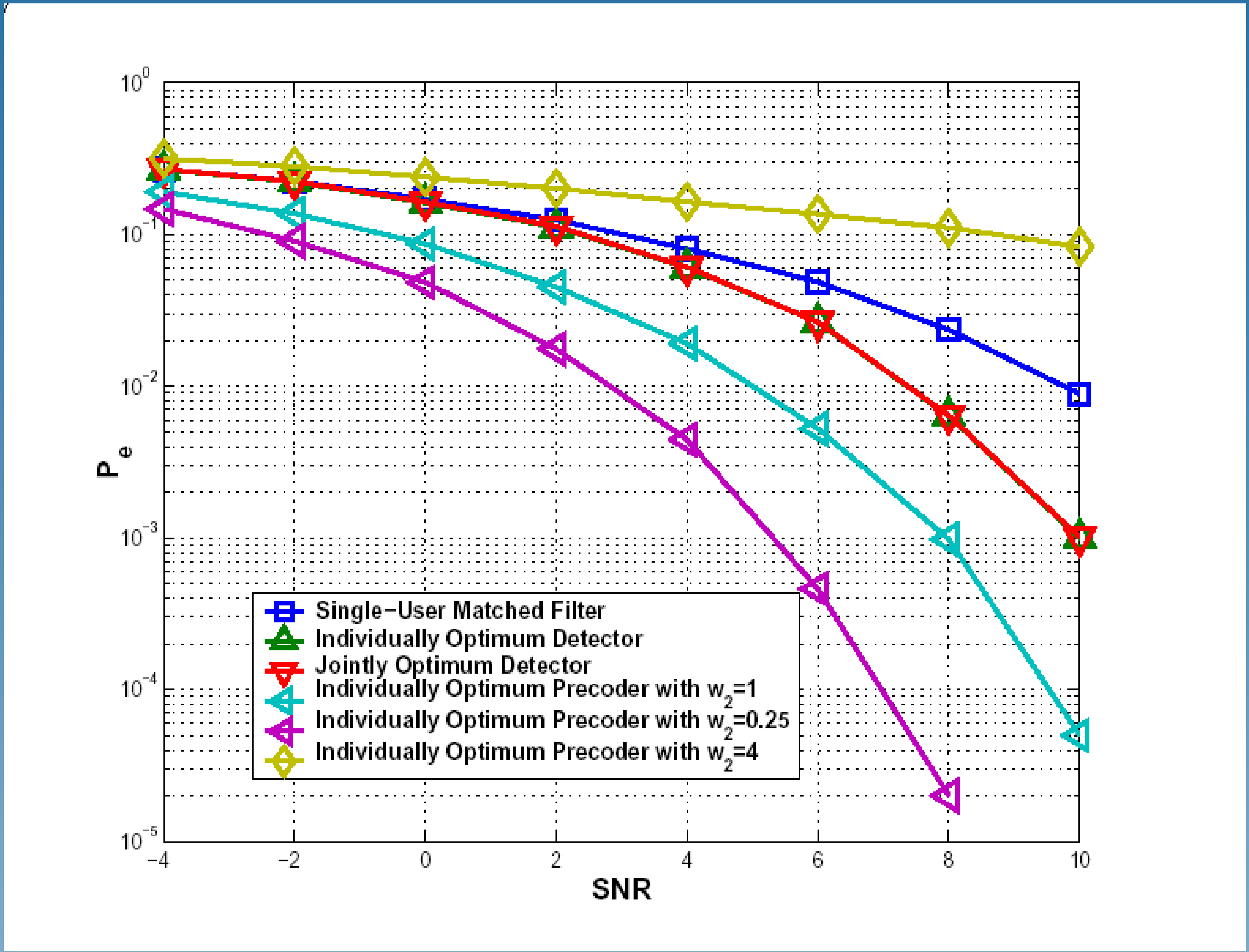
- When $b_1 = -b_2$

$$\mathbf{C}_{IP} \approx [\, A_1(0.7071\mathbf{s}_1 - 0.7071\mathbf{s}_2) \quad A_2(-0.0698\mathbf{s}_1 + 0.9976\mathbf{s}_2)\,]$$

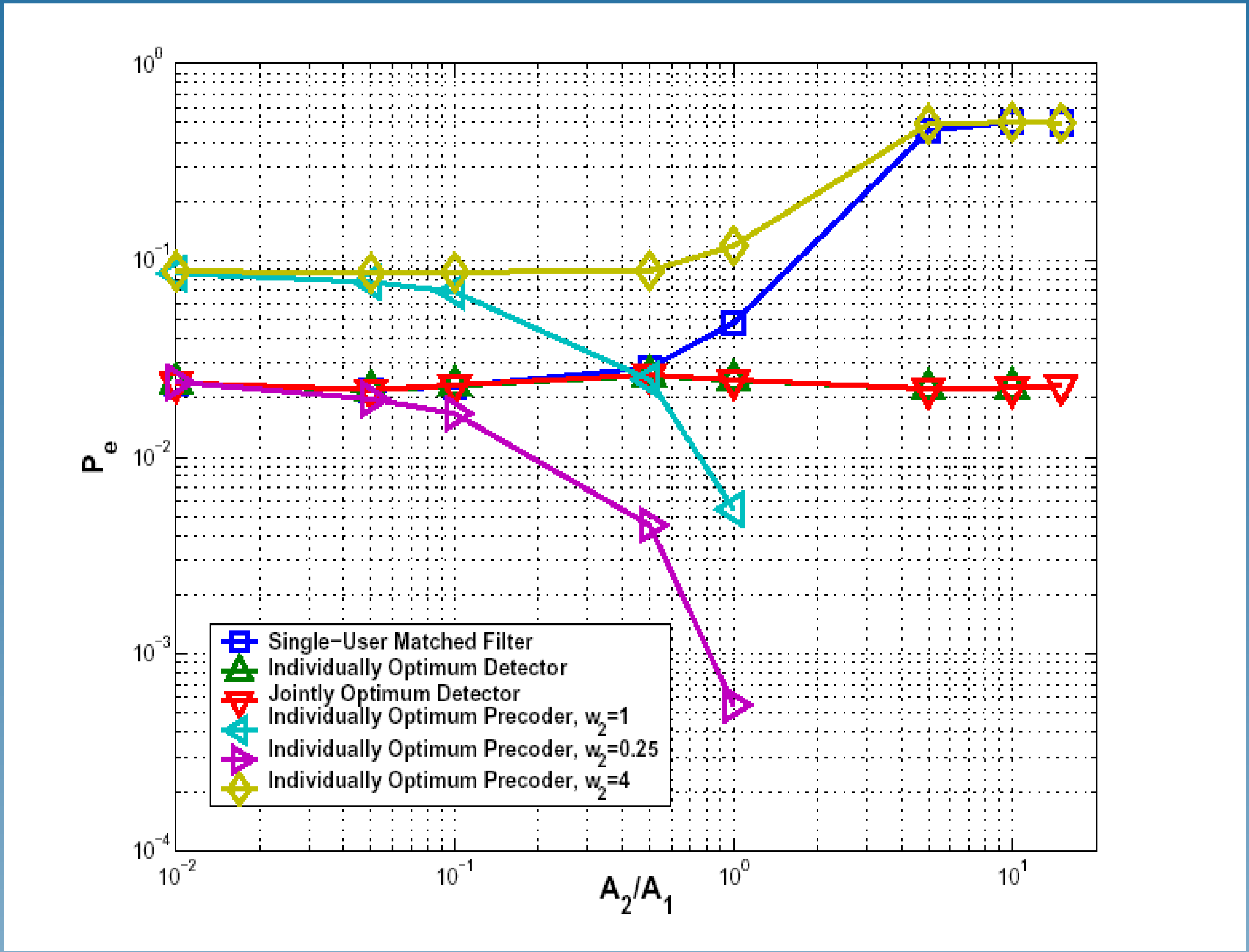
Example: 2-User Individu. Optimum Multiuser Precoding II II



Computer Simulations I



Computer Simulations II



Linear Multiuser Precoding

Linear Multiuser Precoding

- The linear precoding $\mathbf{C}$ is independent to input bit vector $\mathbf{b}$.

- Most of linear multiuser receiver optimization schemes are applicable here:

  - ⋆ minimizing multiple access interference. (decorrelating multiuser precoding)
  - ⋆ minimizing mean squares error. (MMSE multiuser precoding)
  - ⋆ maximizing likelihood function. (ML or approximated ML multiuser precoding)
  - ⋆ maximizing asymptotic multiuser efficiency. (MAME multiuser precoding)

- In most cases, additional constrains should be considered:

  - ⋆ total power constraint. $\sum A_k^2 = P$ is fixed.
  - ⋆ power spectrum constraint. A_k is fixed.
  - ⋆ maximum eigenvector constraint. $P_t = \|\mathbf{C}\mathbf{b}\|_2^2 \leq K\|\mathbf{C}\|_2^2 = K\lambda_{\max}\left(\mathbf{C}\mathbf{C}^T\right)$

Decorrelating Multiuser Precoding

- Decorrelating precoding can be expressed as in the following optimization problem.

$$\mathbf{C}_{DP} = \arg\min_{\mathbf{C}} \left\| \mathbf{S}^T(\mathbf{HCb} - \mathbf{n}) - \mathbf{Ab} \right\|_2 \ ,$$

- The least-square (LS) solution to the above unconstrained optimization problem can be expressed as

$$\mathbf{C}_{LS} = (\mathbf{S}^T\mathbf{H})^{+}\mathbf{A} \ ,$$

- No noise enhancement. This is at expense of signal enhancement.

MMSE Multiuser Precoding I

- A common approach in signal estimation theory to the problem of estimating a random variable $\mathbf{b}$ on the basis of observation $\mathbf{r}$ with given constrains to choose the linear function $\mathbf{C}$ that minimizes that mean-square error (MSE):

$$\mathbf{C}_{MMSE} = \min_{\mathbf{C}} \left\{ \mathsf{E} \left\| \mathbf{S}^T (\mathbf{HCb} + \mathbf{n}) - \mathbf{Ab} \right\|_2 \right\} ,$$

  subject to some possible constraint on $\mathbf{C}$.

- The solution to this optimization equation depends on the constraints imposed on $\mathbf{C}$.

  - ⋆ No constraint. It becomes an unconstraint optimization problem.
  - ⋆ Total power constraint. trace$\{\mathbf{CC}^T\} = P_t$
  - ⋆ Maximum eigenvalue constraint. $\lambda_{\max}\{\mathbf{CC}^T\} = \lambda_t$

MMSE Multiuser Precoding II

- The unconstrained MMSE precoder can be easily derived as

$$\mathbf{C}_{MMSE} \quad = \quad (\mathbf{S}^T\mathbf{H})^{+}\mathbf{A} \ .$$

- The MMSE optimization problem under total power constraint can be solved by means of the Lagrange multiplier method.

$$\mathbf{C}_{TP} \quad = \quad (\mathbf{H}^T\mathbf{S}\mathbf{S}^T\mathbf{H} + \lambda\mathbf{I})^{-1}\mathbf{H}^T\mathbf{S}\mathbf{A} \ .$$

- The solution to the MMSE optimization problem under maximum eigenvalue constraint

$$\mathbf{C}_{MMSE-EV} \quad = \quad \sqrt{\lambda_t}\mathbf{V}$$

MAME Multiuser Precoding

- An asymptotic multiuser efficient vector is introduced here.

$$\bar{\eta}(\mathbf{C}) \quad = \quad \left[\, \eta_1(\mathbf{C}) \quad \eta_2(\mathbf{C}) \quad \ldots \quad \eta_K(\mathbf{C}) \,\right]^T$$

- Instead of only maximizing the AME of one user, the norm of the AME vector is optimized here so that all the users' AMEs are maximized.

$$\mathbf{C}_{MAME} \quad = \quad \text{arg} \sum_{k=1}^{K} \eta_k(\mathbf{C})$$

- Due to the presence of the absolute value function in the optimization equation, it is very hard to give a close-form solution to these nonlinear optimization problems in the K-user case, except $K = 2$

Example: 2-User MAME Multiuser Precoding I

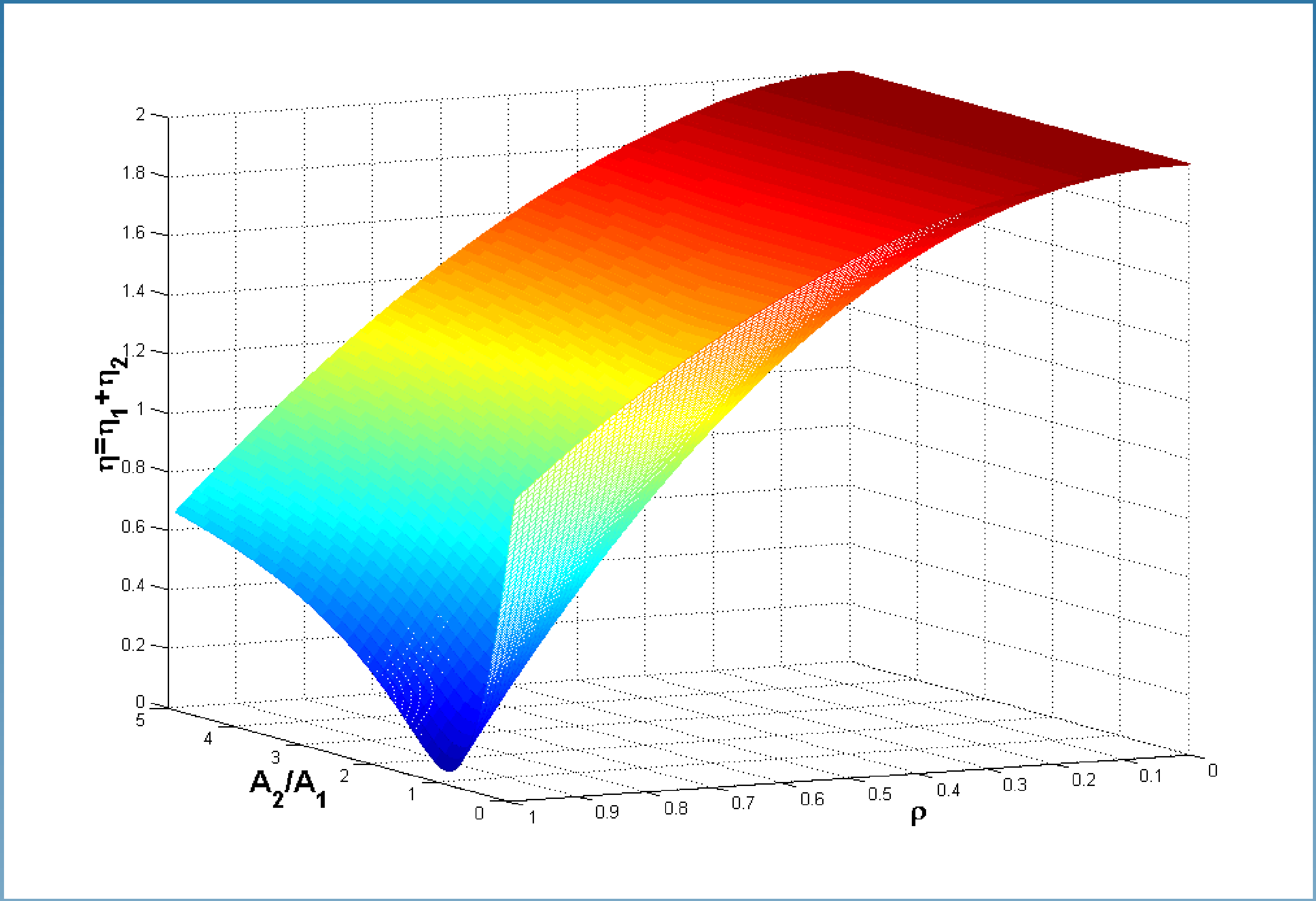
- For two-user case, MAME multiuser precoding can be written as

$$\mathbf{C}_{MAME} = \begin{cases} \mathbf{SP} & \frac{A_2}{A_1} < |\rho| \\ \mathbf{SU} & |\rho| \le \frac{A_2}{A_1} < \frac{1}{|\rho|} \\ \mathbf{SQ} & \frac{1}{|\rho|} \le \frac{A_2}{A_1} \end{cases}$$

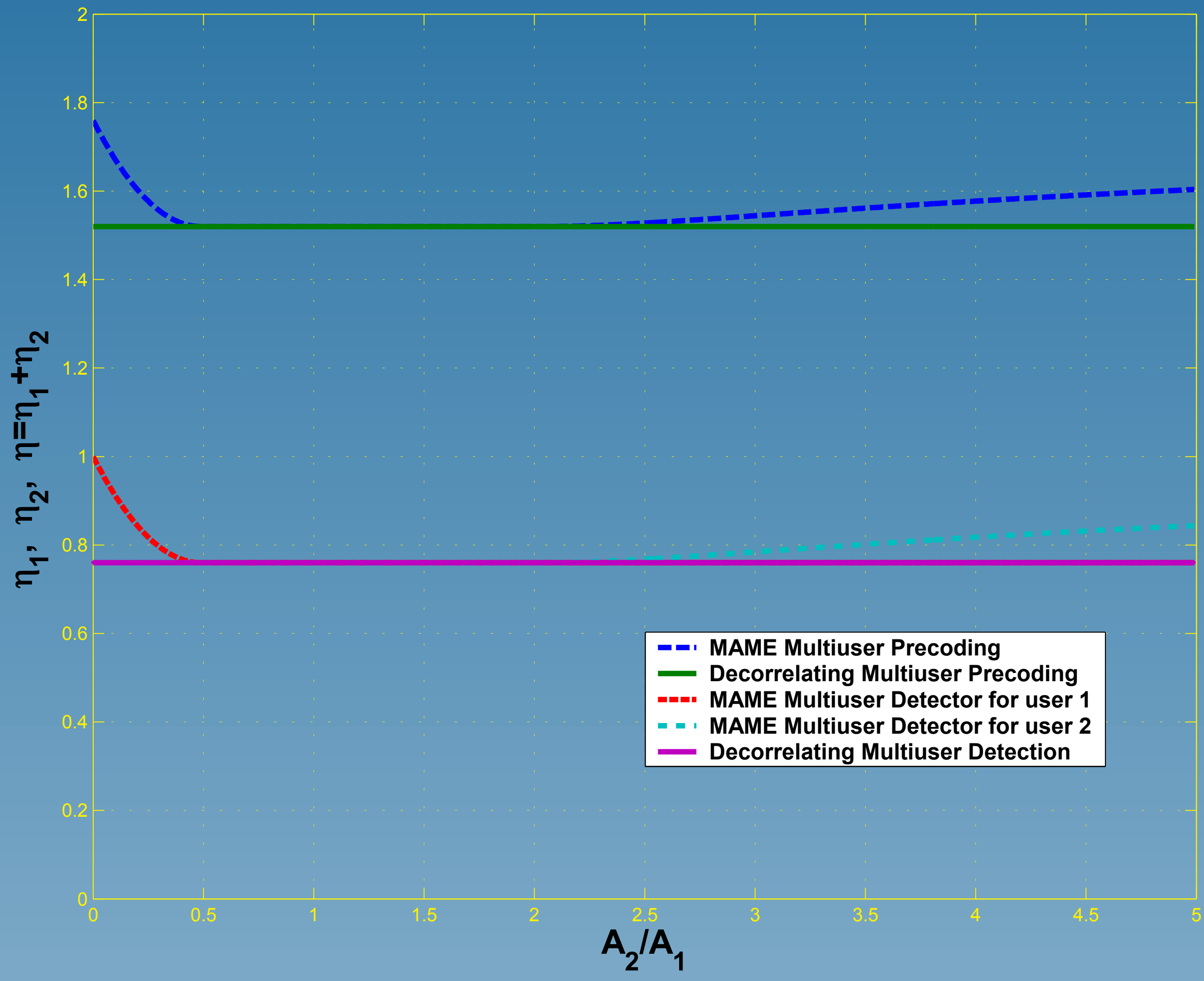
- Two-user MAME multiuser precoding actually is a mixed form of decorrelating multiuser precoding and direct spreading. This is similar to MAME multiuser detection for two-user case.

- It can be shown that the AME of either user with MAME multiuser precoding is similar to that with MAME multiuser detection in two-user case.

Example: 2-User MAME Multiuser Precoding II



Example: 2-User MAME Multiuser Precoding III



AML Multiuser Precoding I

- ML transmitter optimization criterion can be expressed as in the following maximization problem to maximize the minimum ML distance under some possible constraint, e.g., the total transmitting signal power constraint.

$$\mathbf{C}_{ML} = \arg\max_{\mathbf{C}} \left\{ \min_{k} \left[\mathbf{S}^T \mathbf{H} \mathbf{C} \mathbf{b}^k - \mathbf{A}\hat{\mathbf{b}} \right]^T \mathbf{R}_n^{-1} \left[\mathbf{S}^T \mathbf{H} \mathbf{C} \mathbf{b}^k - \mathbf{A}\hat{\mathbf{b}} \right] \right\} ,$$

- The above ML precoding optimization rule can be approximately replaced by

$$\mathbf{C}_{AML} = \arg\max_{\mathbf{C}} \left\{ \lambda_{\min}(\mathbf{C}^T \mathbf{\Pi} \mathbf{C}) \right\} ,$$

where $\mathbf{\Pi} = \mathbf{H}^T \mathbf{S} \mathbf{R}^{-1} \mathbf{S}^T \mathbf{H}$, subject to some possible constraint on $\mathbf{C}$.

AML Multiuser Precoding II

- The solution to AML optimization under total power constraint is given by

$$\mathbf{C}_{AML-TP} \quad = \quad \mathbf{V}\mathbf{\Phi}_{TP}$$

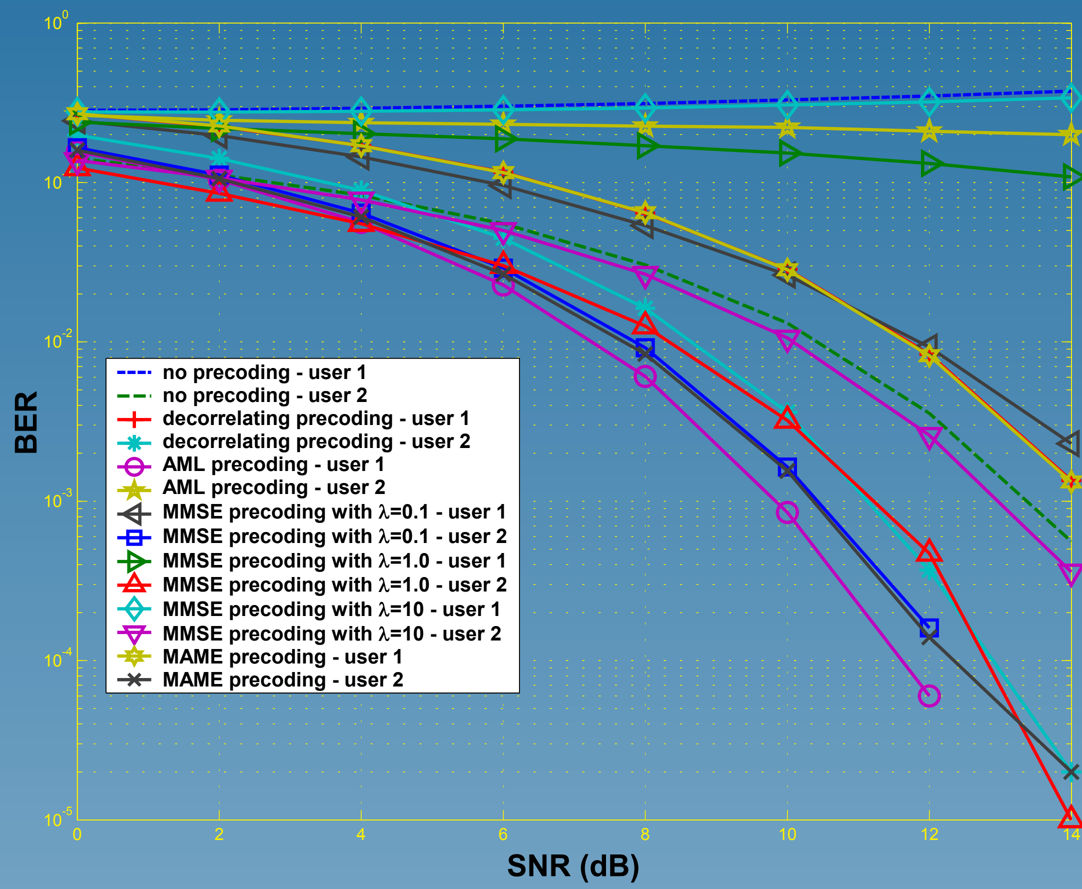
where $\mathbf{V}$ consists of the K orthogonal eigenvectors of the matrix $\mathbf{H}^T\mathbf{S}\mathbf{R}^{-1}\mathbf{S}^T\mathbf{H}$, $\mathbf{\Phi}_{TP}$ is a diagonal matrix with diagonal elements ϕ_{PT}^k and $|\phi_{TP}^k|^2 = P_t(\lambda_k \sum_{i=1}^{K} \lambda_i)^{-1}$

- The solution to AML optimization under maximum eigenvalue constraint is given by

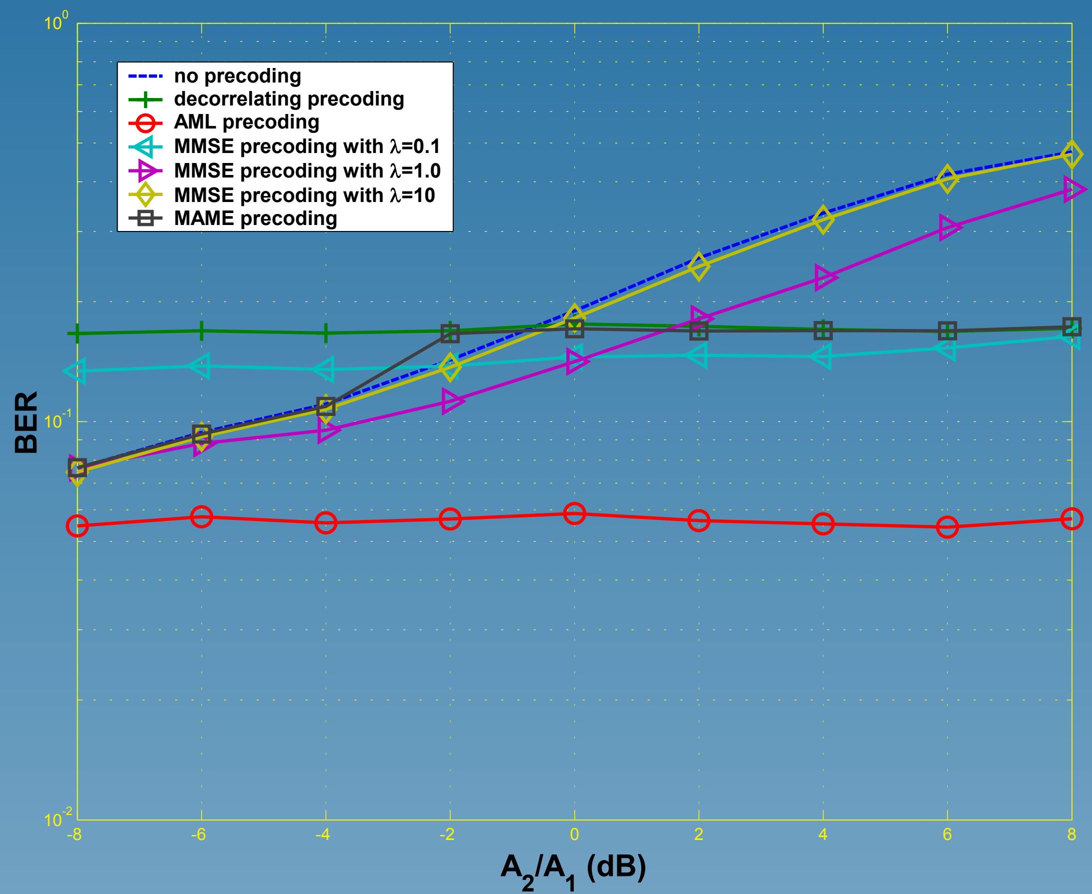
$$\mathbf{C}_{AML-EV} \quad = \quad \mathbf{V}\mathbf{\Phi}_{EV}$$

where $\mathbf{\Phi}_{EV}$ is a diagonal matrix with diagonal elements ϕ_{EV}^k and $|\phi_{EV}^k|^2 = \frac{\lambda_N}{\lambda_k}\lambda_t$.

Computer Simulations I



Computer Simulations II



Conclusion & Future Directions

- With more prior user information, it is possible for optimum multiuser precoding to achieve better performance than multiuser detection. (Multiuser Interference Enhancement)

- With linear system theory, it can be shown that many linear multiuser precoders and detectors can achieve the same performance.

- Additional performance enhancement may be achievable by combining transmitter multiuser precoding and adaptive receivers/transmitters.

- For unknown or time-variable channels, spreading sequence adaption or adaptive multiuser precoding with feedback from receivers can be an interesting topic.

- For unknown or time-variable channels, multiuser precoding can be jointly used with channel coding to achieve a better performance.

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