Interleave Division Multiple Access

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Outline

- Introduction
- IDMA
- Chip-by-chip multiuser detection
- Analysis and optimization
- IDM space-time coding and IDM coded modulation
- Conclusions

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Background

- Low-rate coded systems: Viterbi and Verdu
- Iterative detectors (1998/1999): Moher, Reed, Schlegel, Alexander, Wang and Poor
- TCMA (2002) Brannstrom, Aulin and Rasmussen
- Graph-code based multiple access (2001): McEliece
- Chip-interleaved CDMA (2002): Mahavadevappa and Proakis
- CDMA power control (2003/2004): Verdu, Shaimai, Caire and Muller

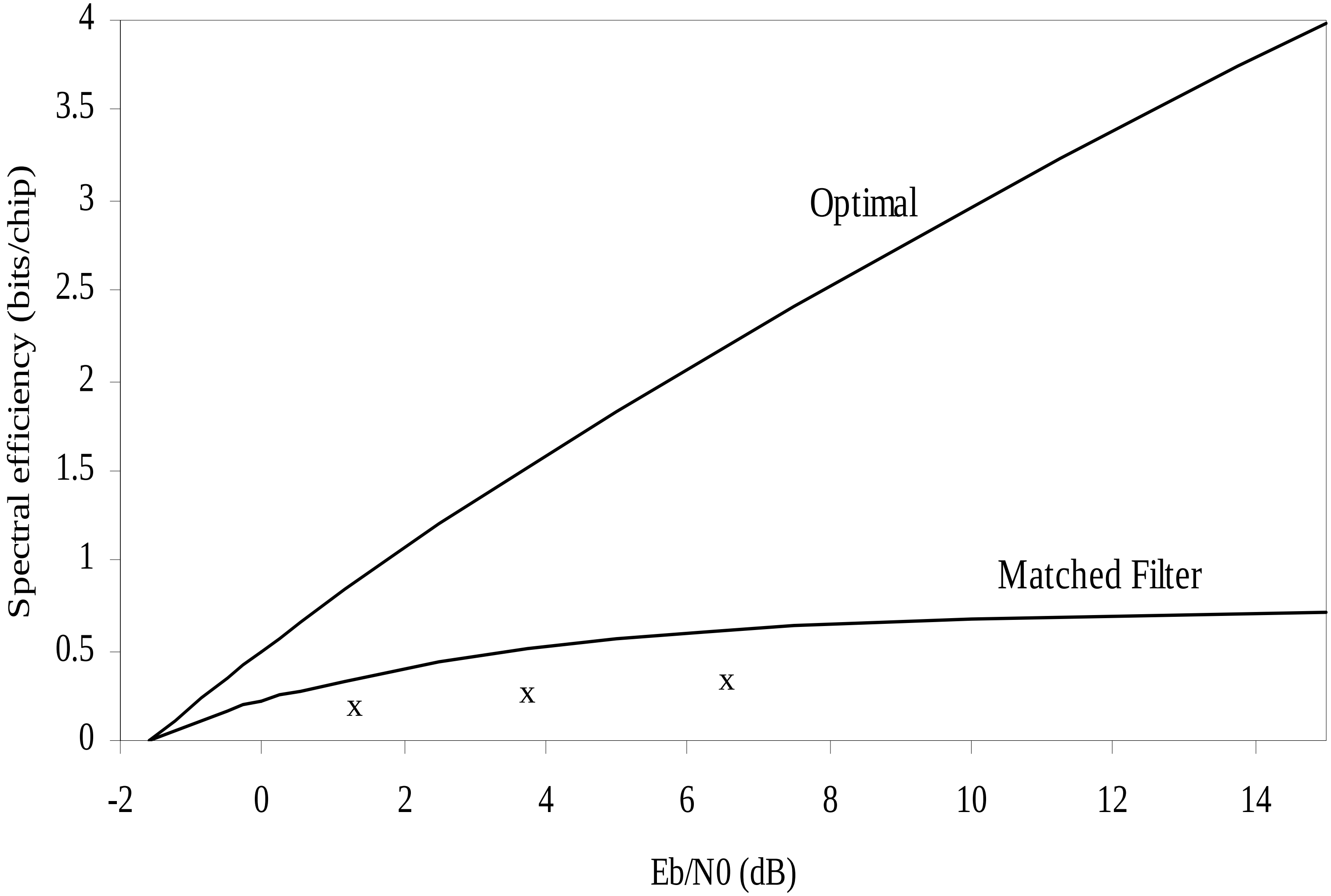
Some Requirements for Future Wireless Systems

- low receiver cost
- de-centralized (i.e., asynchronous) control,
- simple treatment of ISI,
- cross-cell interference mitigation,
- diversity against fading,
- power efficiency (long battery life),

- multi-media services (e.g., mixed voice and IP),
- high user number,
- high throughput and high spectral efficiency,

FDMA ?
TDMA ?
CDMA ?
OFDMA ?

CDMA Spectrum Efficiency (per Dimension)



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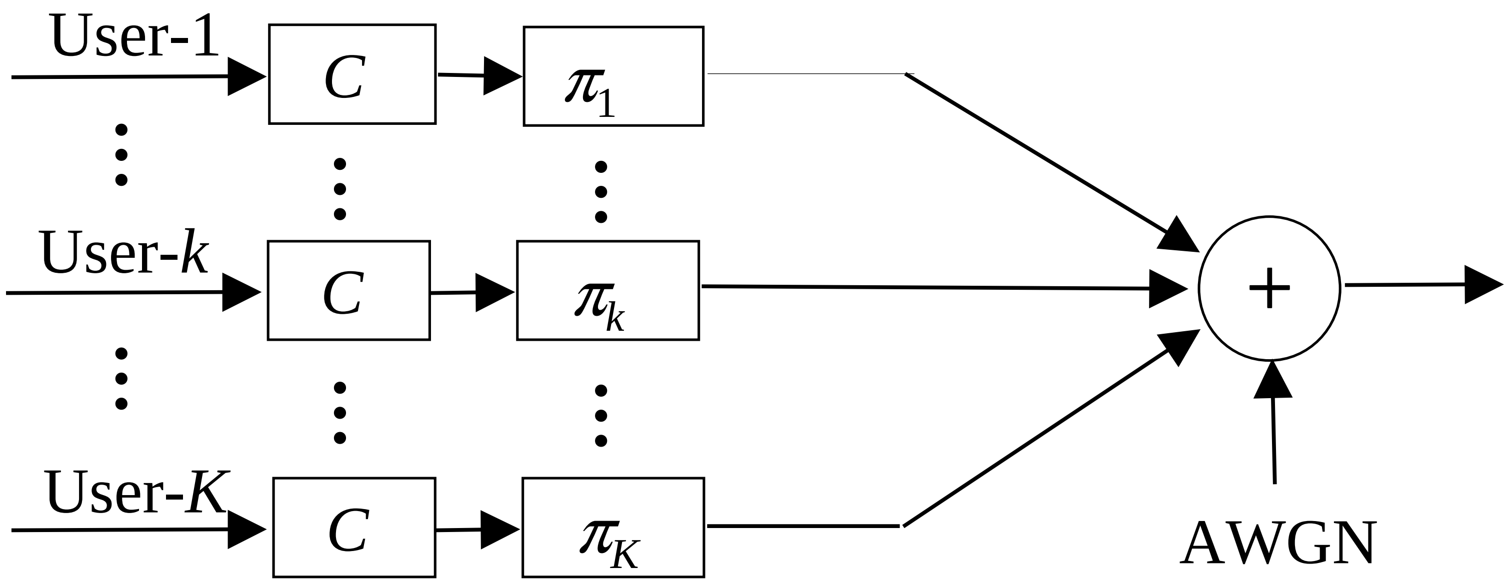
Interleave Division Multiple Access (IDMA)



Key: The interleavers π_1, …, π_K must be user-specific.

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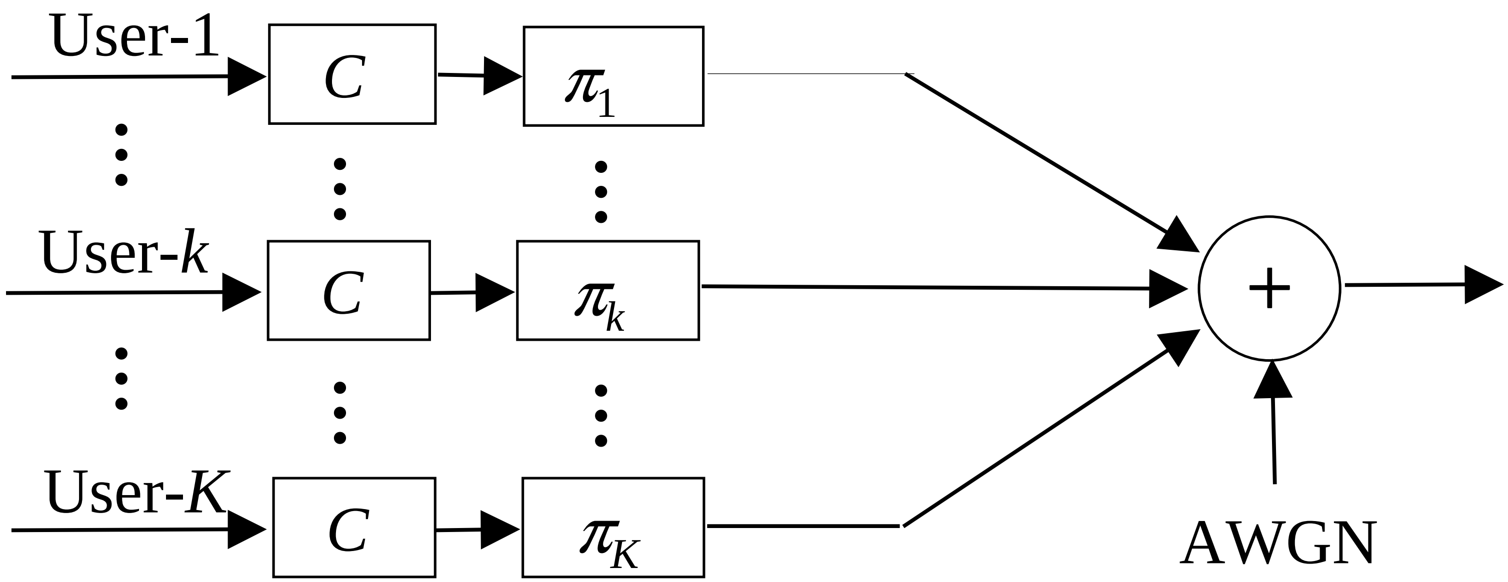
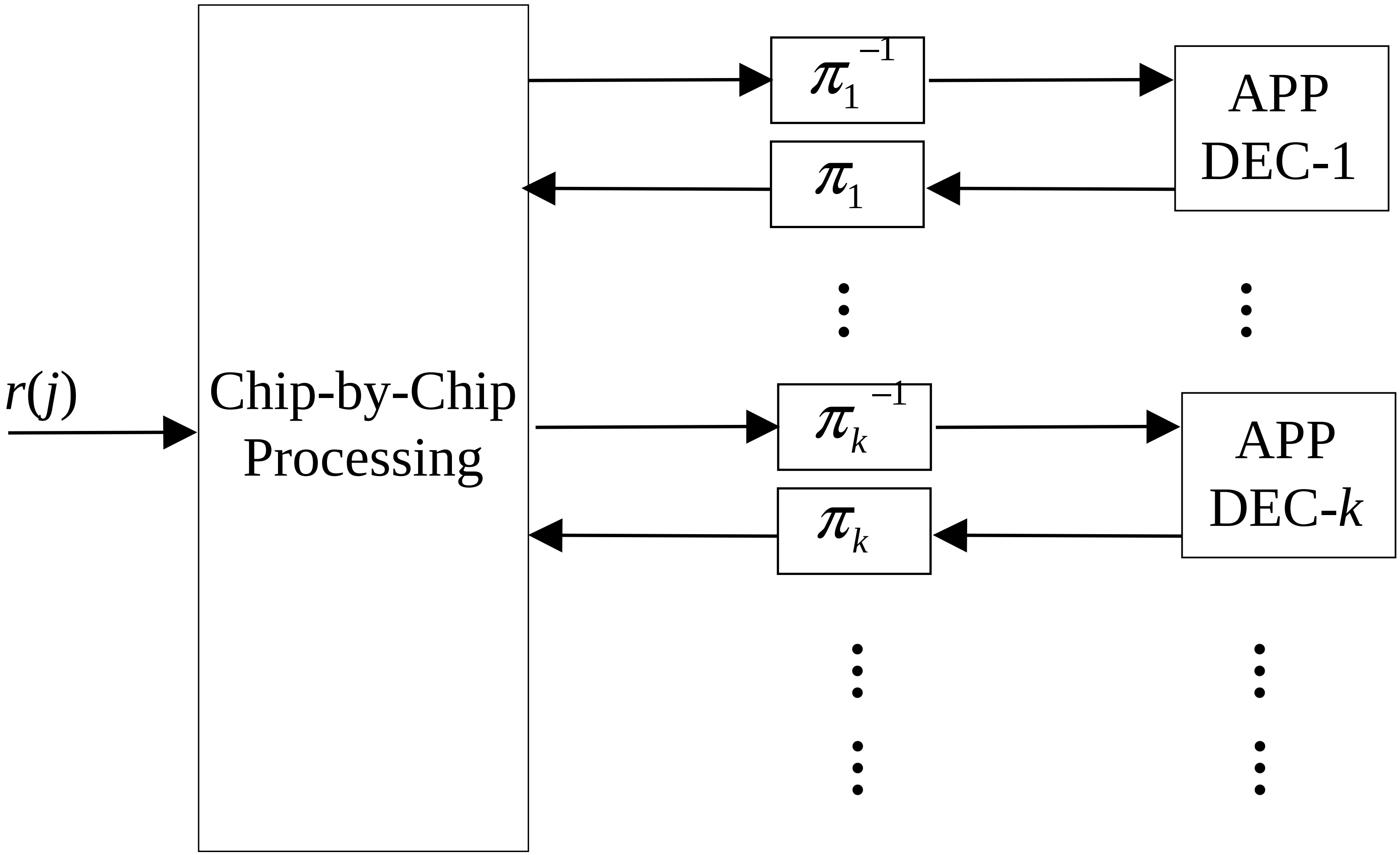


Key: The interleavers $\pi_1, \ldots, \pi_K$ must be user-specific.

Chip-by-Chip Multiuser Detection



Chip-by-Chip Detection

Gaussian

Step 1. Chip-level path model: $r(j) = \sum_{k=1}^{K} h_k x_k(j) + n(j)$

Step 2. Gaussian approximation: $r(j) = h_k x_k(j) + \zeta_k(j)$

Step 3. Estimation: $e\left(x_k(j)\right) = \log \dfrac{\Pr(x_k(j)=+1)}{\Pr(x_k(j)=-1)}$

$$= \log \frac{\exp\left(-\dfrac{(r(j) - \mathrm{E}(\zeta_k(j)) - h_k)^2}{2\mathrm{Var}(\zeta_k(j))}\right)}{\exp\left(-\dfrac{(r(j) - \mathrm{E}(\zeta_k(j)) + h_k)^2}{2\mathrm{Var}(\zeta_k(j))}\right)}$$

$$= \frac{2h_k}{\mathrm{Var}(\zeta_k(j))} \cdot \left(r(j) - \mathrm{E}(\zeta_k(j))\right)$$

The Single-Path Chip-by-Chip Detection Algorithm

Step 1. $\mathrm{E}\big(r(j)\big)=\sum_{k=1}^{K} h_k \mathrm{E}\big(x_k(j)\big)$ $\qquad$ $\mathrm{Var}\big(r(j)\big)=\sum_{k=1}^{K} |h_k|^2 \mathrm{Var}\big(x_k(j)\big)$

Step 2. $\mathrm{E}\big(\zeta_k(j)\big)=\mathrm{E}\big(r(j)\big)-h_k\mathrm{E}\big(x_k(j)\big)$ $\qquad$ $\mathrm{Var}\big(\zeta_k(j)\big)=\mathrm{Var}\big(r(j)\big)-|h_k|^2\mathrm{Var}\big(x_k(j)\big)$

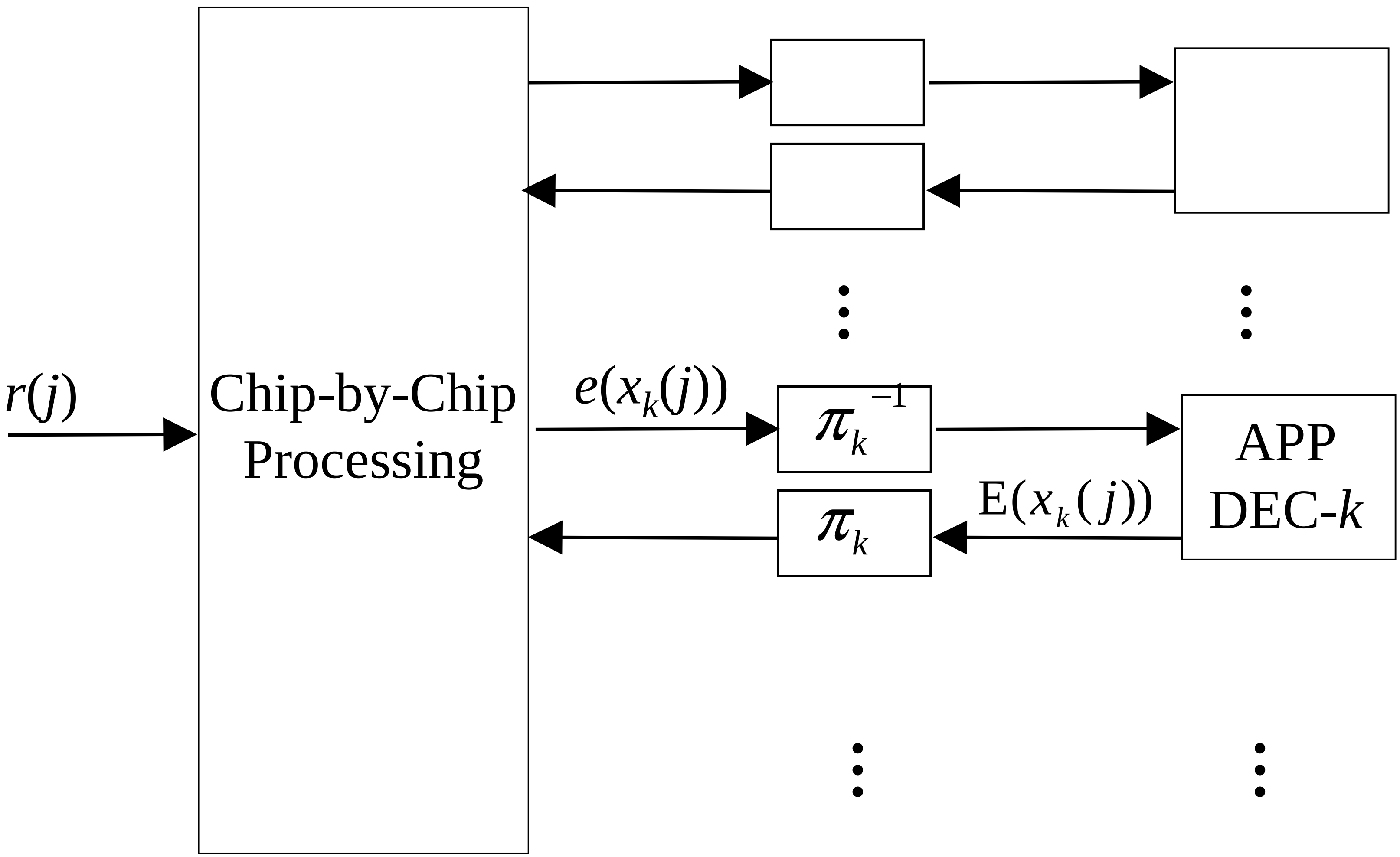
Step 3. $e\big(x_k(j)\big)=\dfrac{2h_k}{\mathrm{Var}(\zeta_k(j))}\cdot\big(r(j)-\mathrm{E}(\zeta_k(j))\big)$

Notes:

(1) This is an extremely simplified version of Wang-Poor Algorithm.

(2) No matrix operations.

Chip-by-Chip Multiuser Detection Again



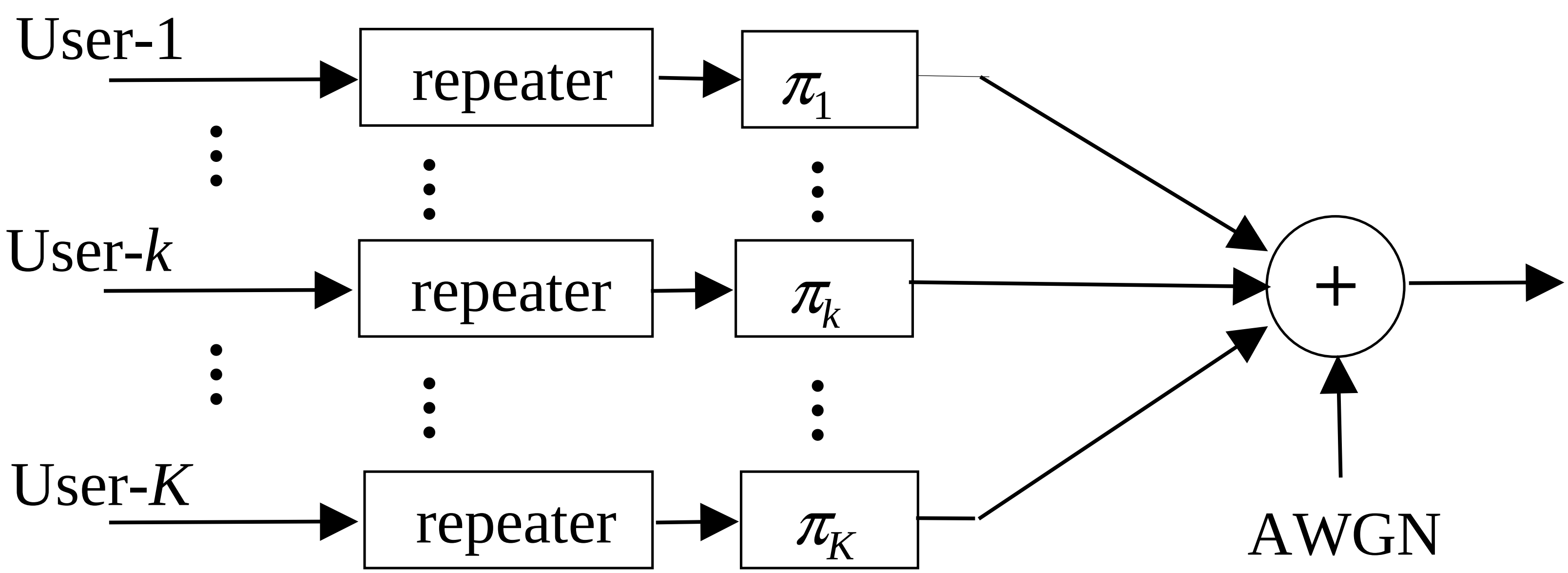
Complexity

- 6 additions and 6 multiplications **per chip** per iteration **per user**.

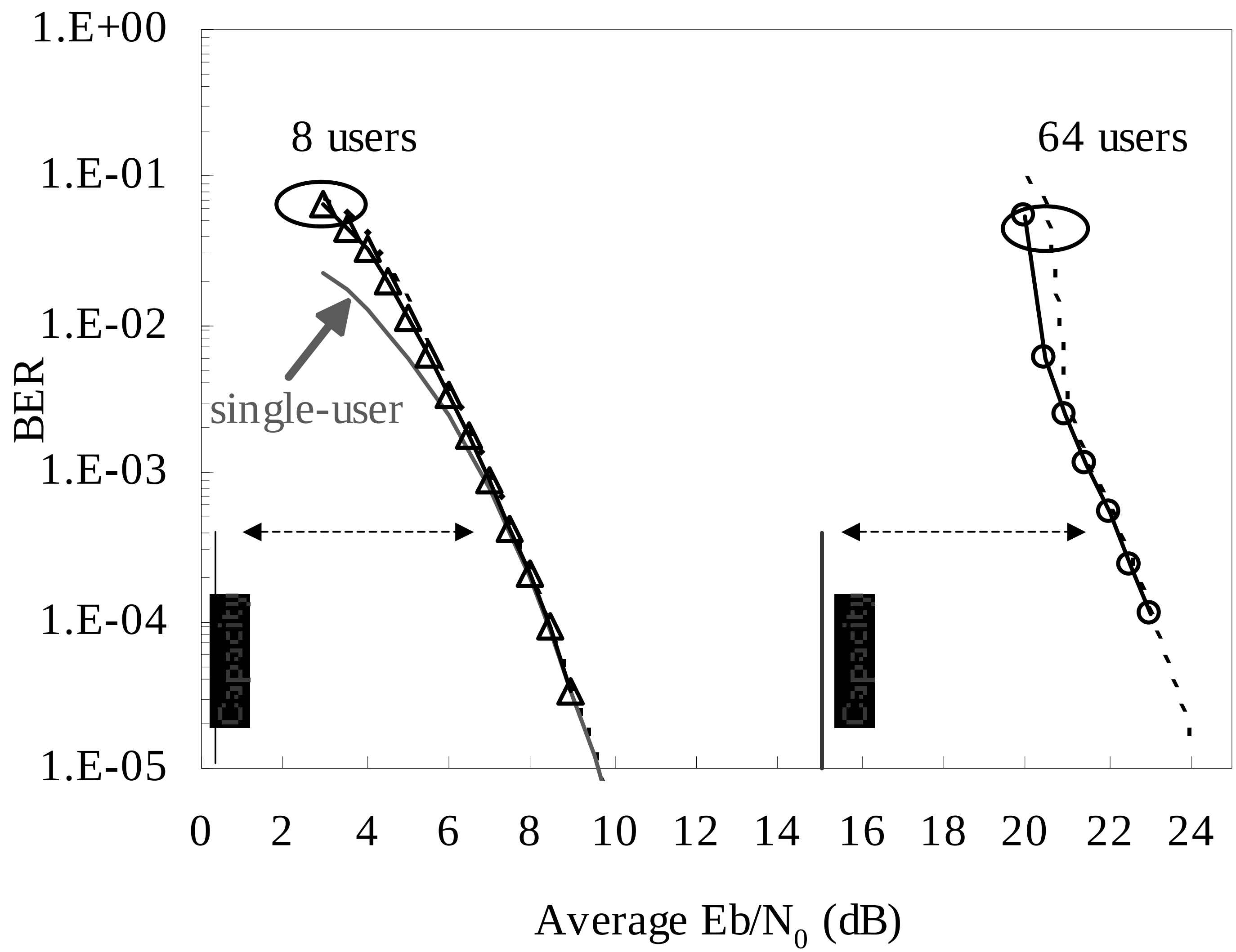
- Complexity (per user) is independent of user number K .

<u>Comparison:</u> To achieve good performance, the cost for MMSE CDMA multi-user detection is $O(K^2)$ due to matrix operations.

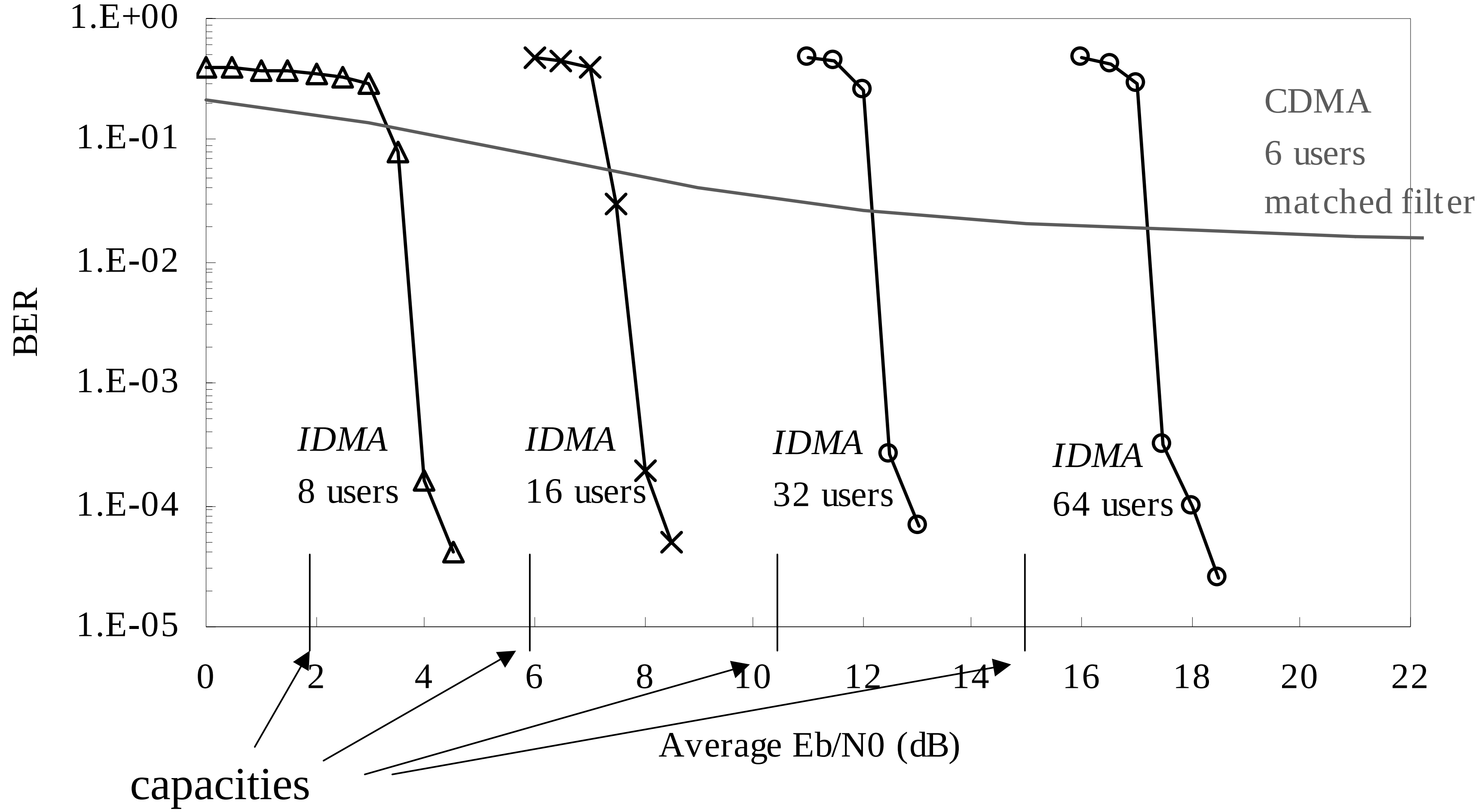
IDMA with Repetition Coding



Un-coded IDMA
(with rate-1/8 repetition coding)



Rate 1/8 Convolutional-Repeat Coded IDMA



Multiuser Detection in Multipath Channels

Step 1. Chip-level path model

$$r(j) \quad = \quad \sum_{l=0}^{L-1}\sum_{k=1}^{K} h_{k,l}\, x_k(j-l) + n(j)$$

Step 2. Gaussian approximation

$$r(j) \quad = \quad h_{k,l}\, x_k(j-l) + \zeta_{k,l}(j)$$

Step 3. Estimation:

$$e\big(x_k(j-l)\big)_l = \frac{2\cdot h_{k,l}}{\mathrm{Var}(\zeta_{k,l}(j))}\cdot\big(r(j) - \mathrm{E}(\zeta_{k,l}(j))\big)$$

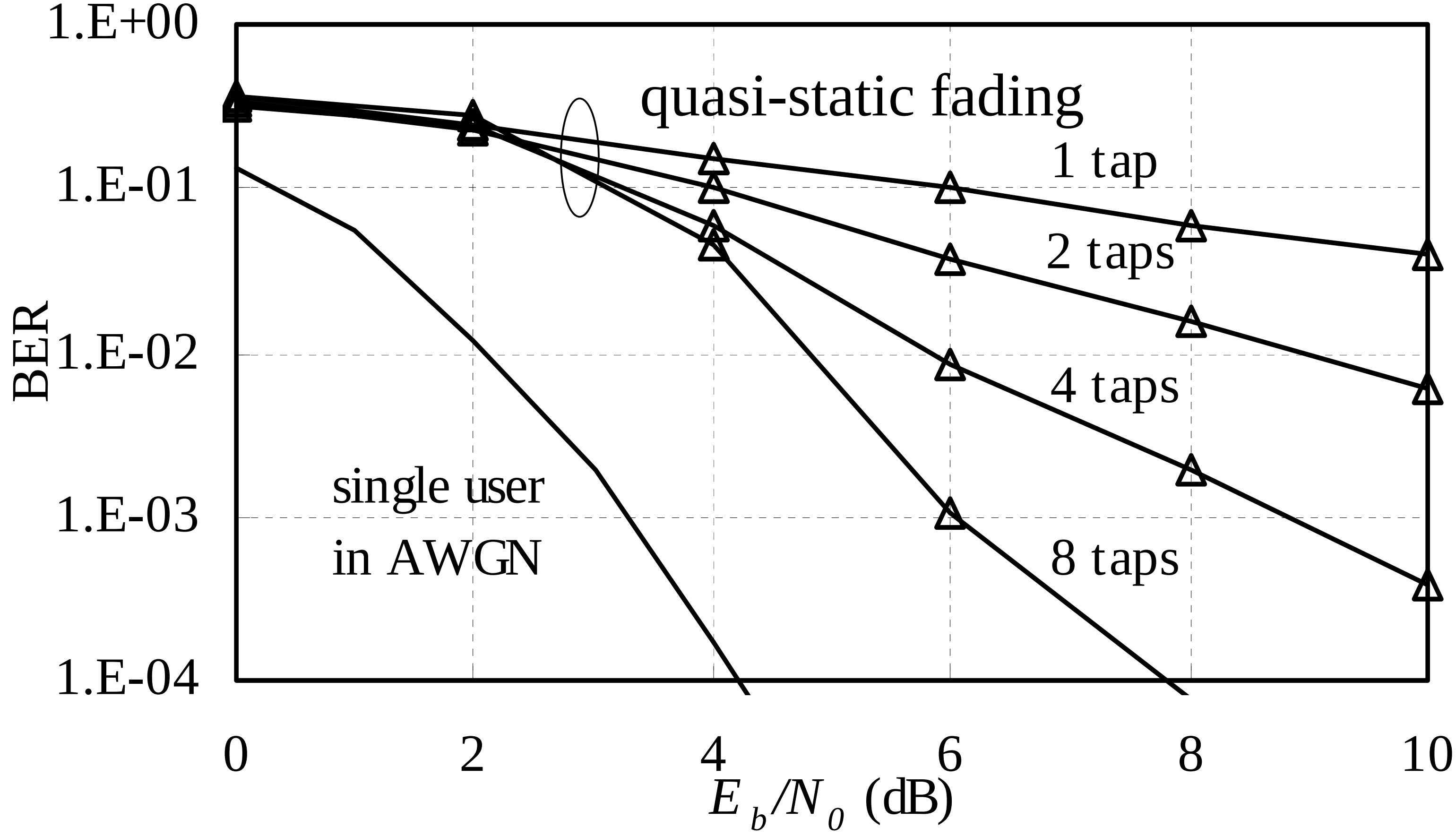
Step 4. Rake combining:

$$e(x_k(j)) = \sum_{l=0}^{L-1} e(x_k(j))_l$$

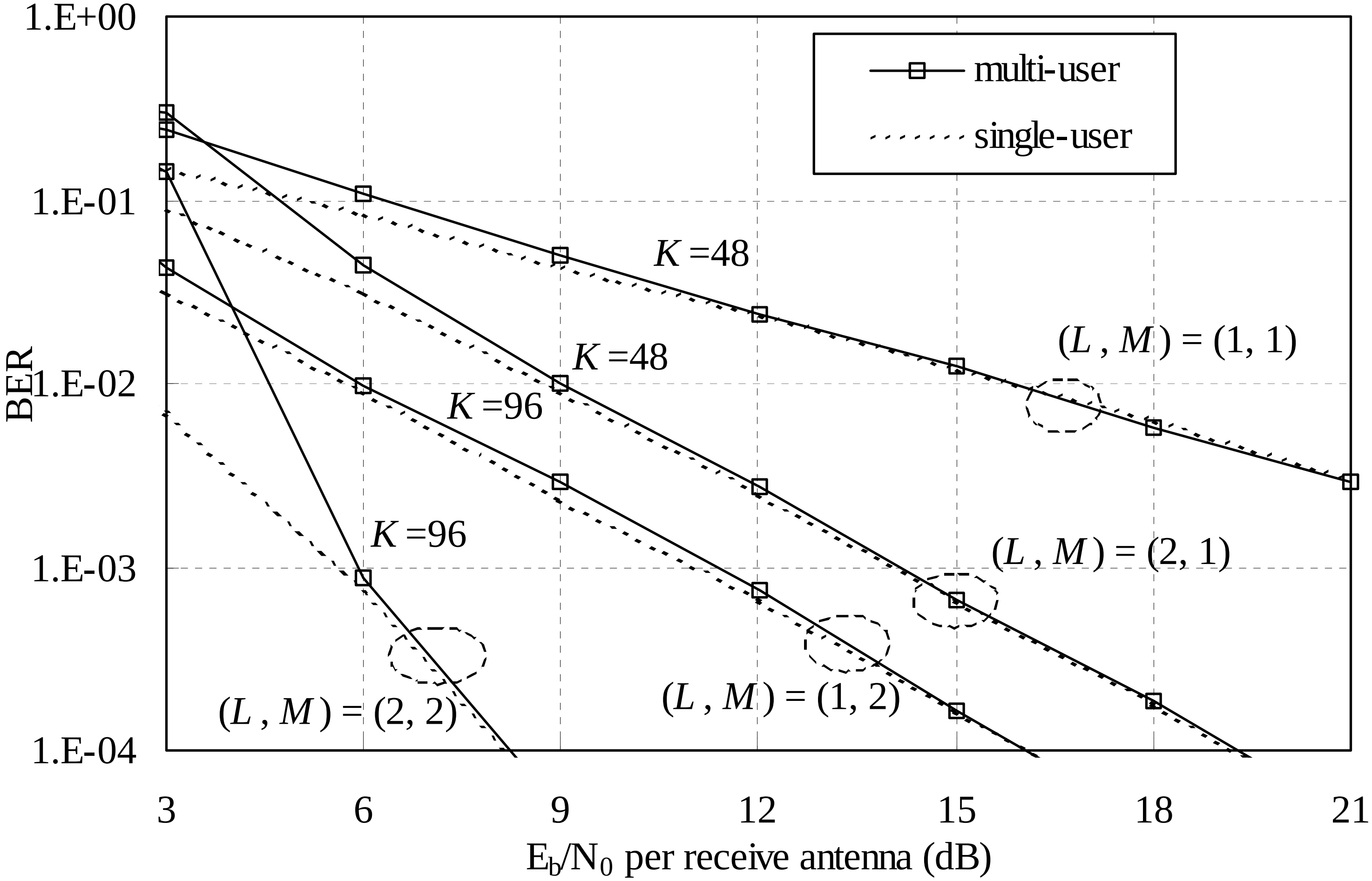
Note: Still no matrix operations here.

Rake Detector in Multipath Channels

(rate 1/2 convolutional & length-8 repetition, 32 users)

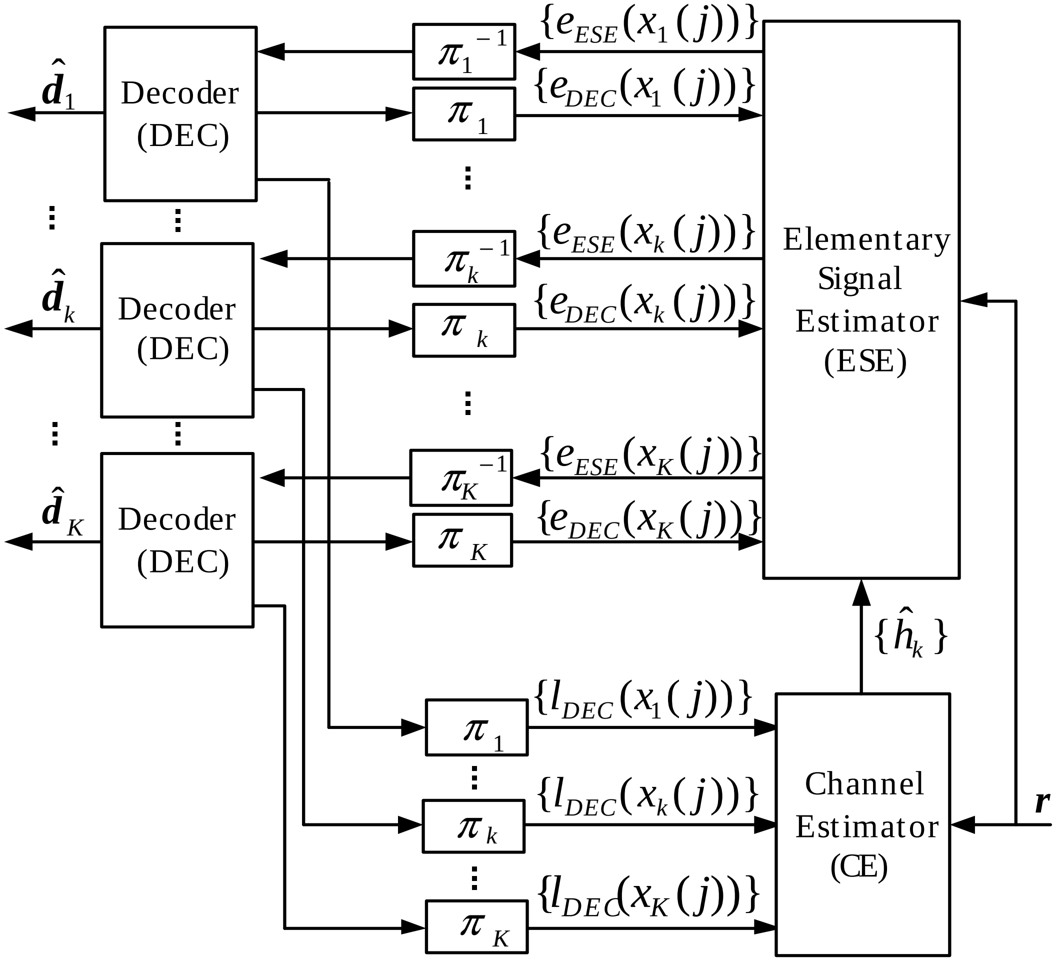


Multipath Performance (rate-1/2 convolutional & length-8 repetition)

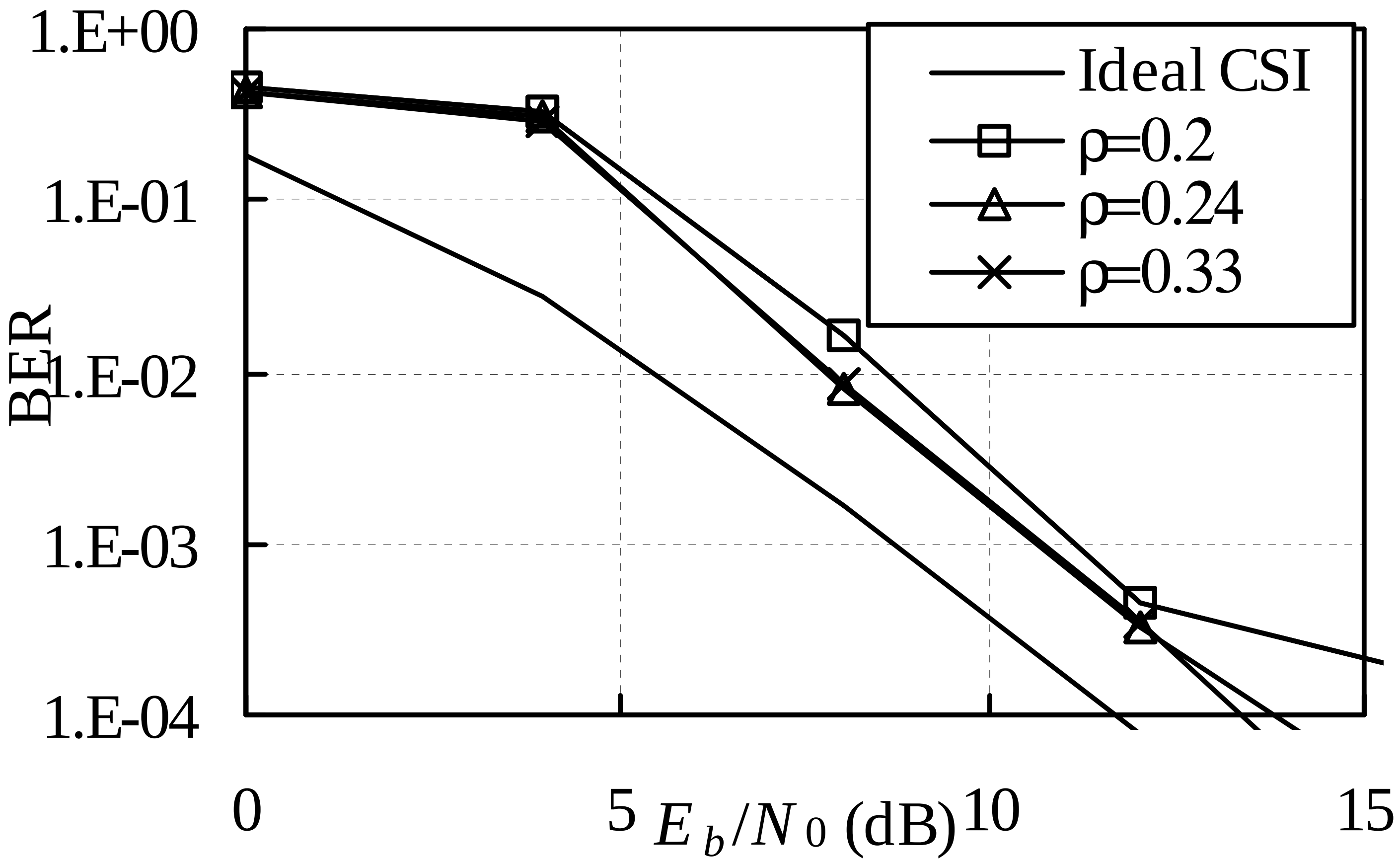


L= the number of taps. *M* = the number of receive antennas. *K*=the number of users

Chip-by-Chip Joint Channel Estimation and Multi-User Detection



Performance with Joint Channel Estimation and Multi-user Detection



16 users

E_b includes the pilot overhead.

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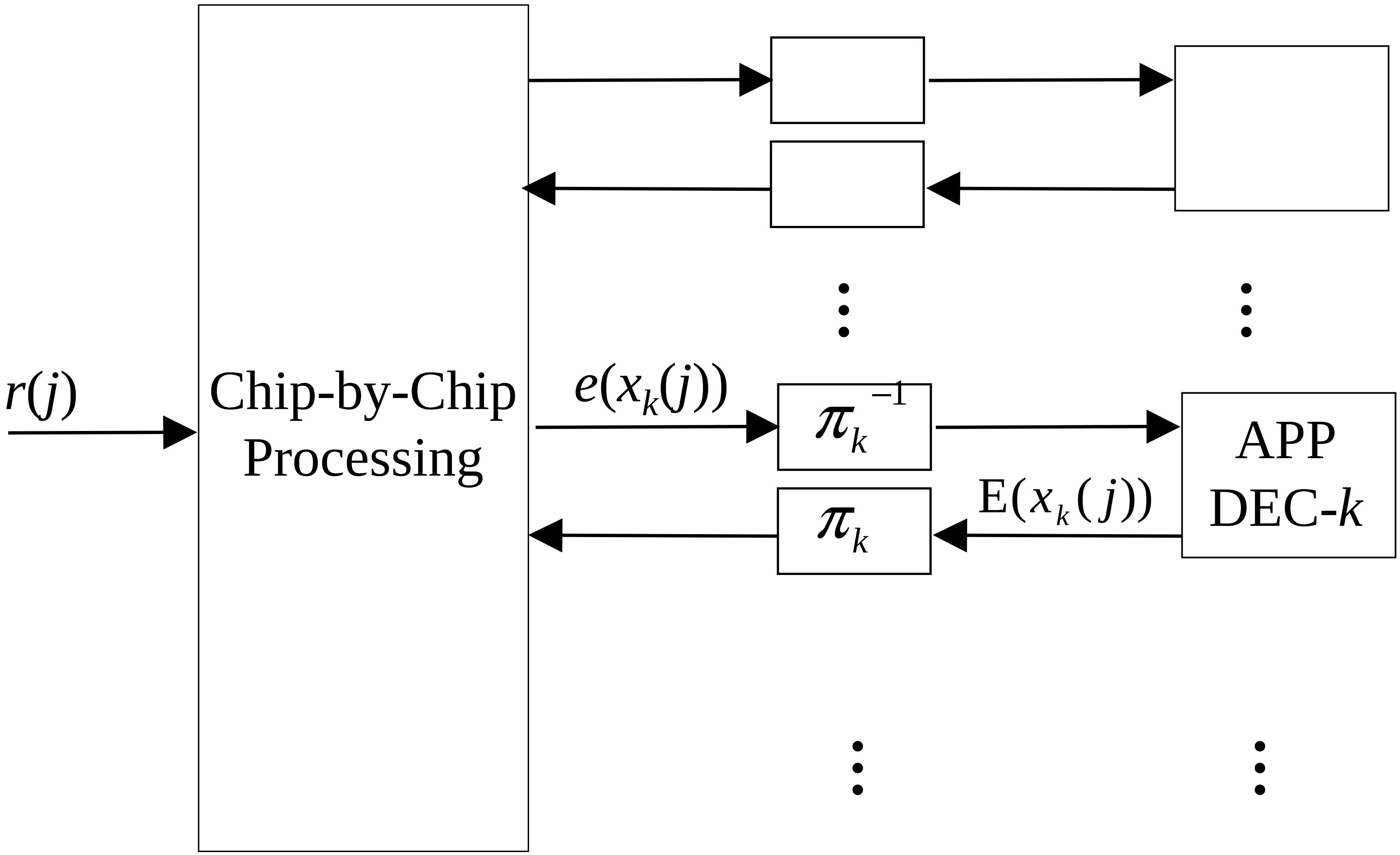
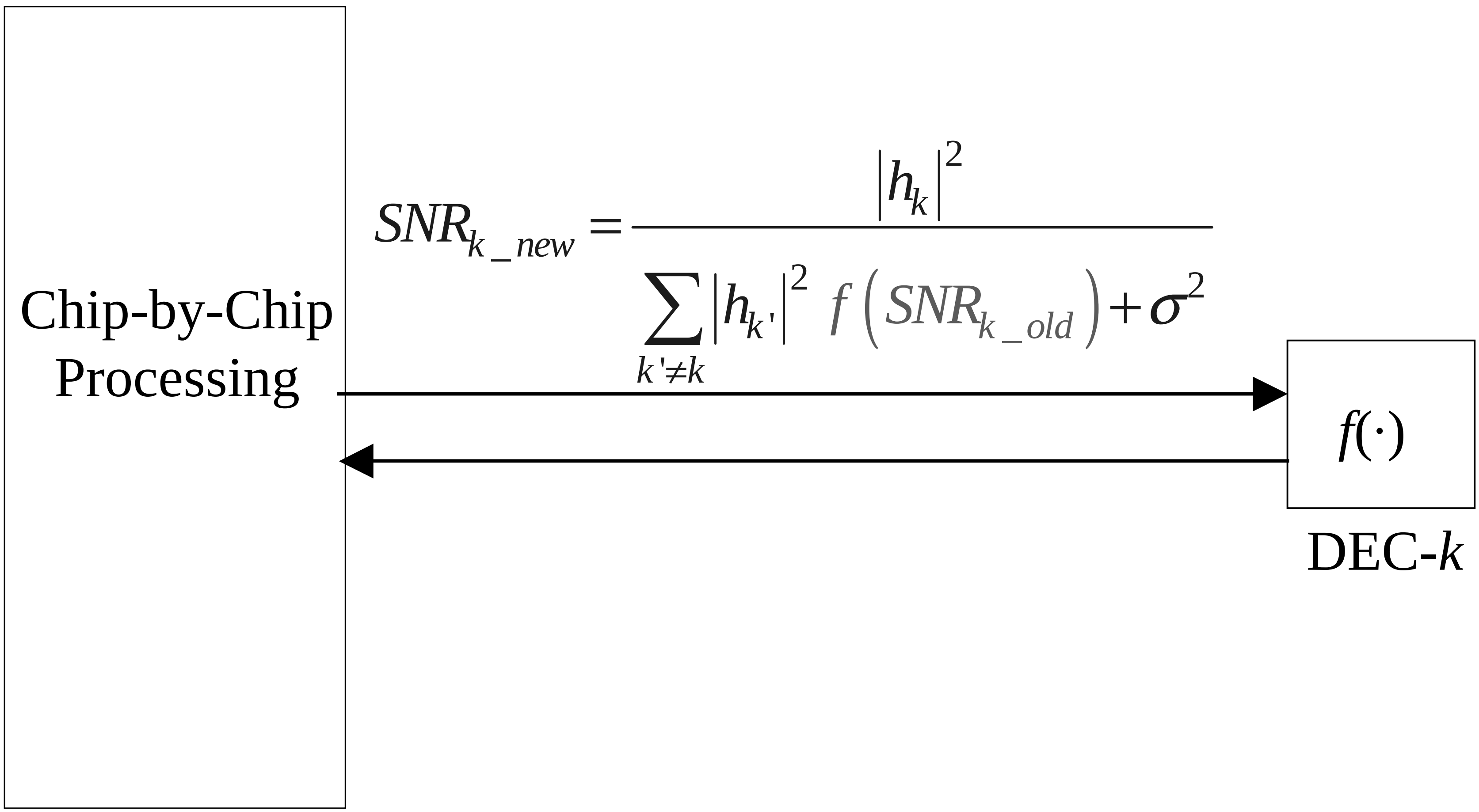
Chip-by-Chip Multiuser Detection Again

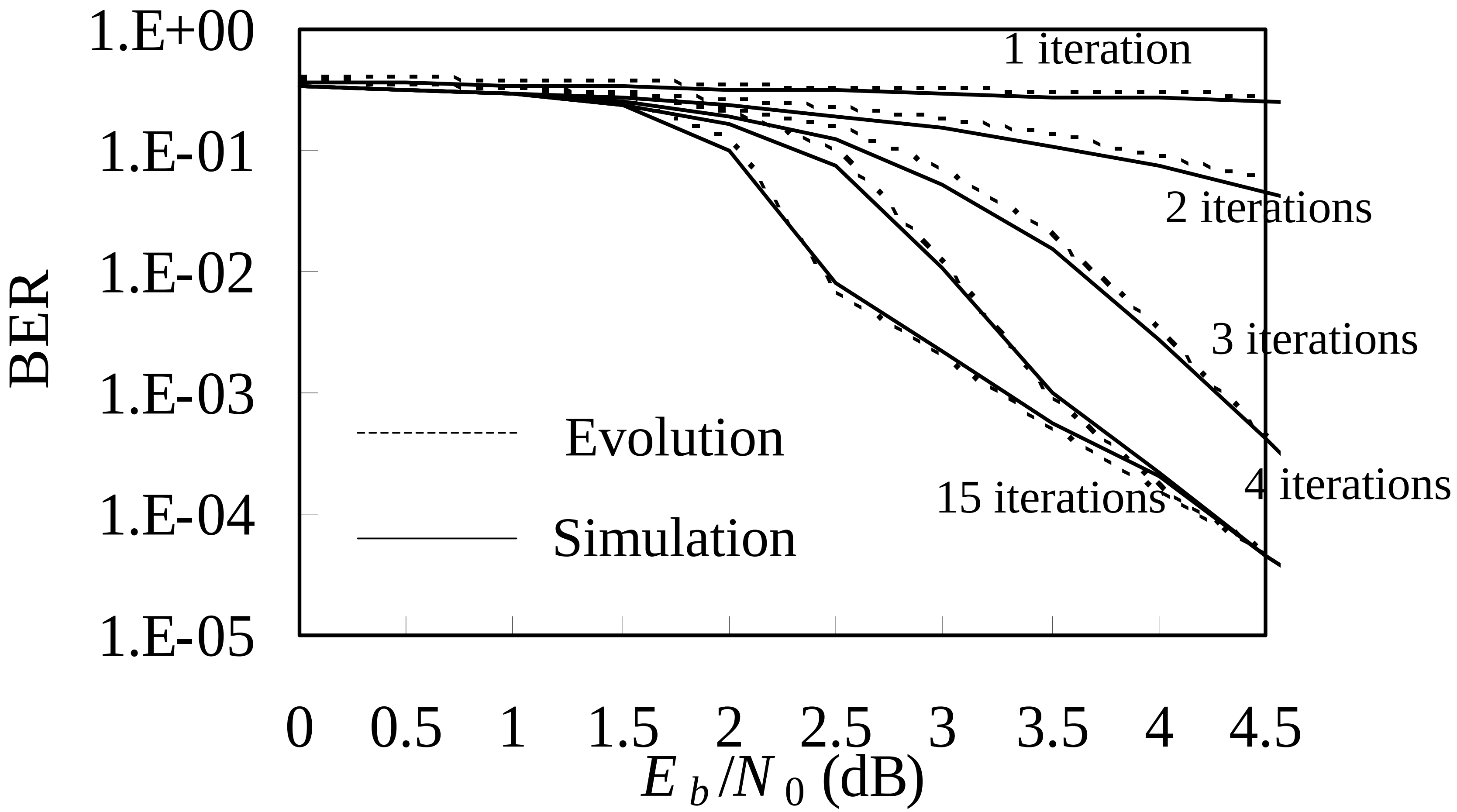


SNR Evolution in the Chip-by-Chip Algorithm



$$SNR_{k\_new} = \frac{\left|h_k\right|^2}{\sum_{k' \neq k} \left|h_{k'}\right|^2 f\left(SNR_{k\_old}\right) + \sigma^2}$$

Number of Iterations Required by IDMA (24 users, 1/2 convolutional + 1/8 repetition coding)



Power Allocation for Non-ideal Coding

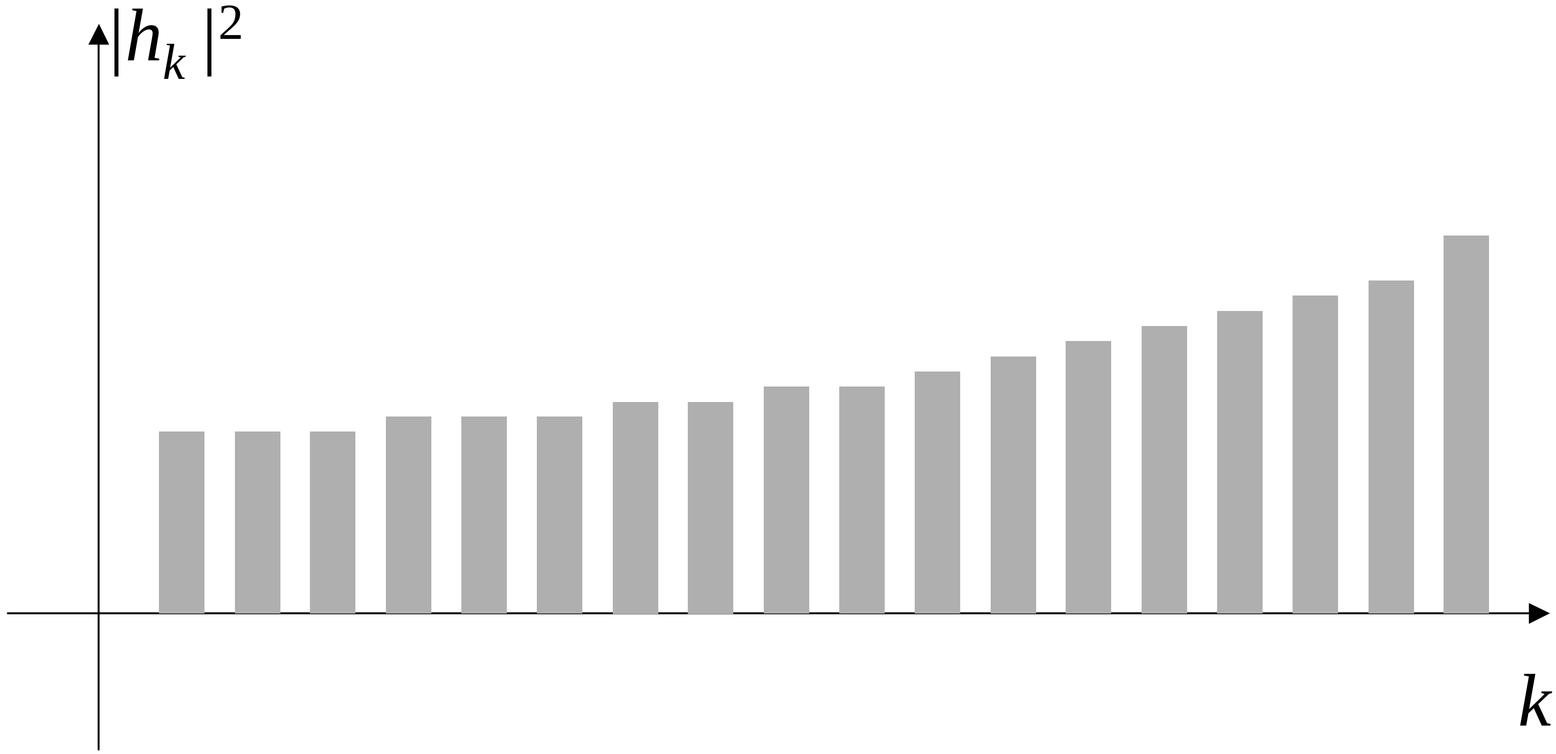
Optimization:

Find $\{h_k\}$ to maximize $\{SNR_k\}$ after certain iterations.

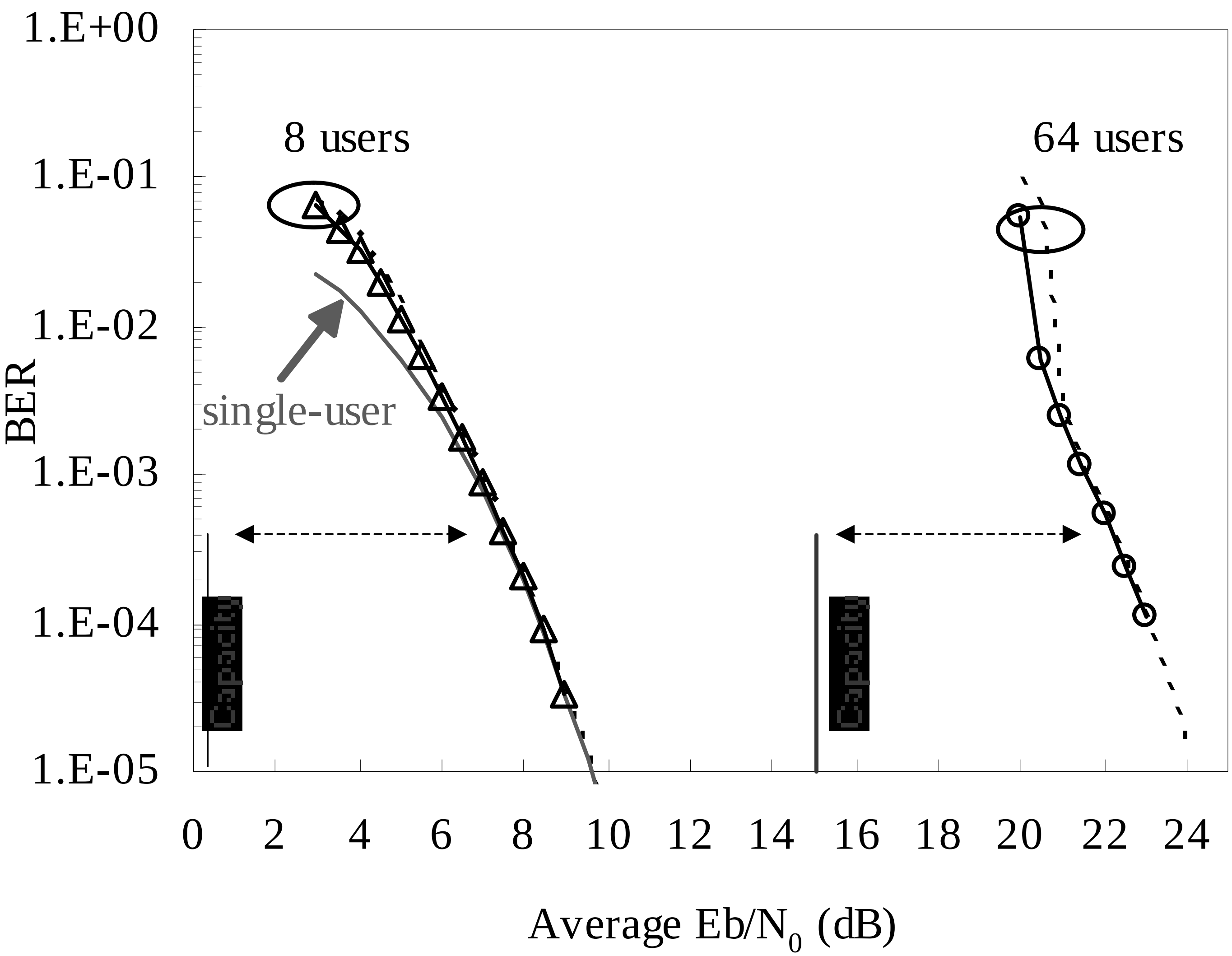
$$SNR_{k\_new} = \frac{|h_k|^2}{\sum_{k' \neq k} |h_{k'}|^2 \, f\left(SNR_{k\_old}\right) + \sigma^2}$$

Constraint: $\sum |h_k|^2 = \text{fixed}$

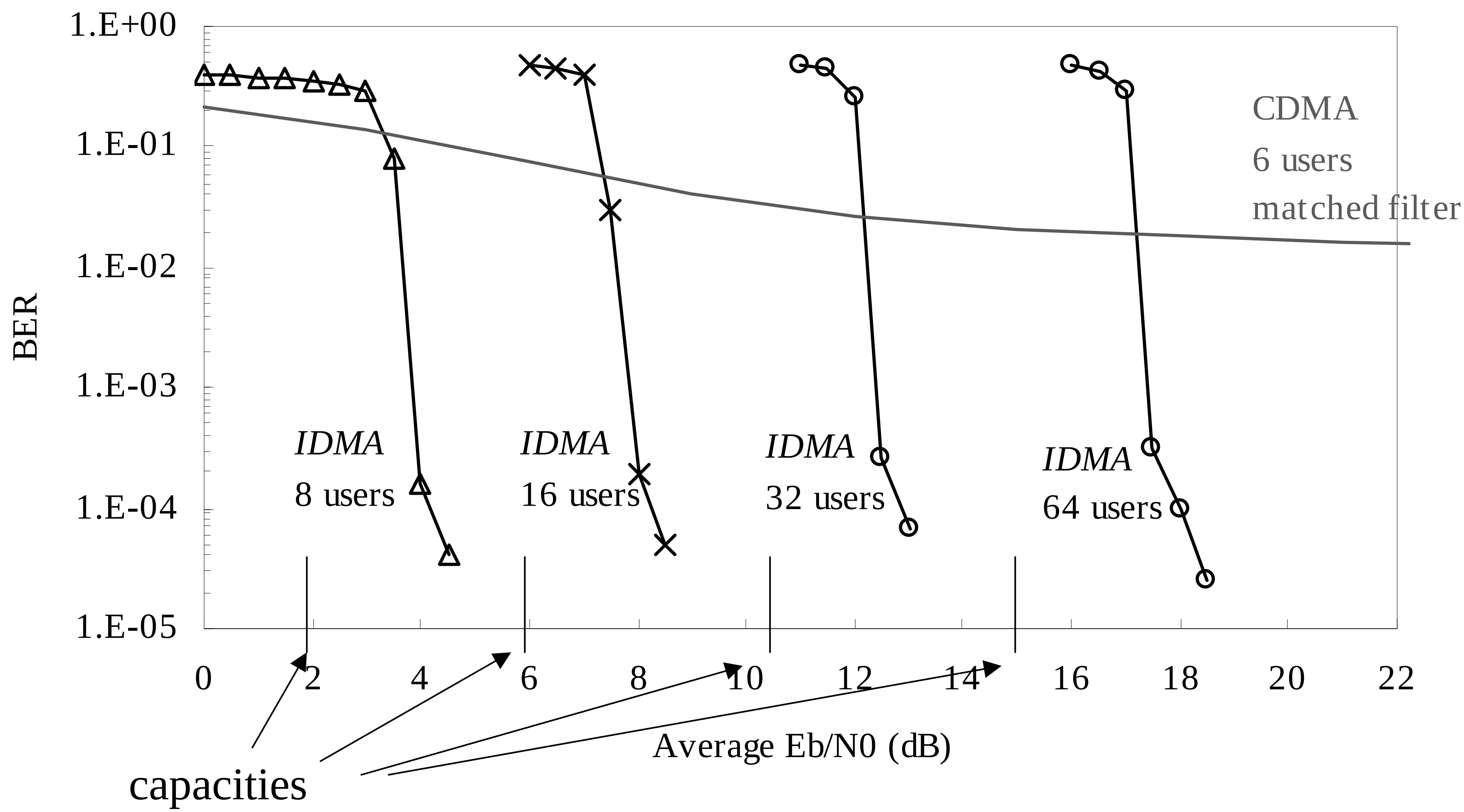
Power Allocation for Different Users



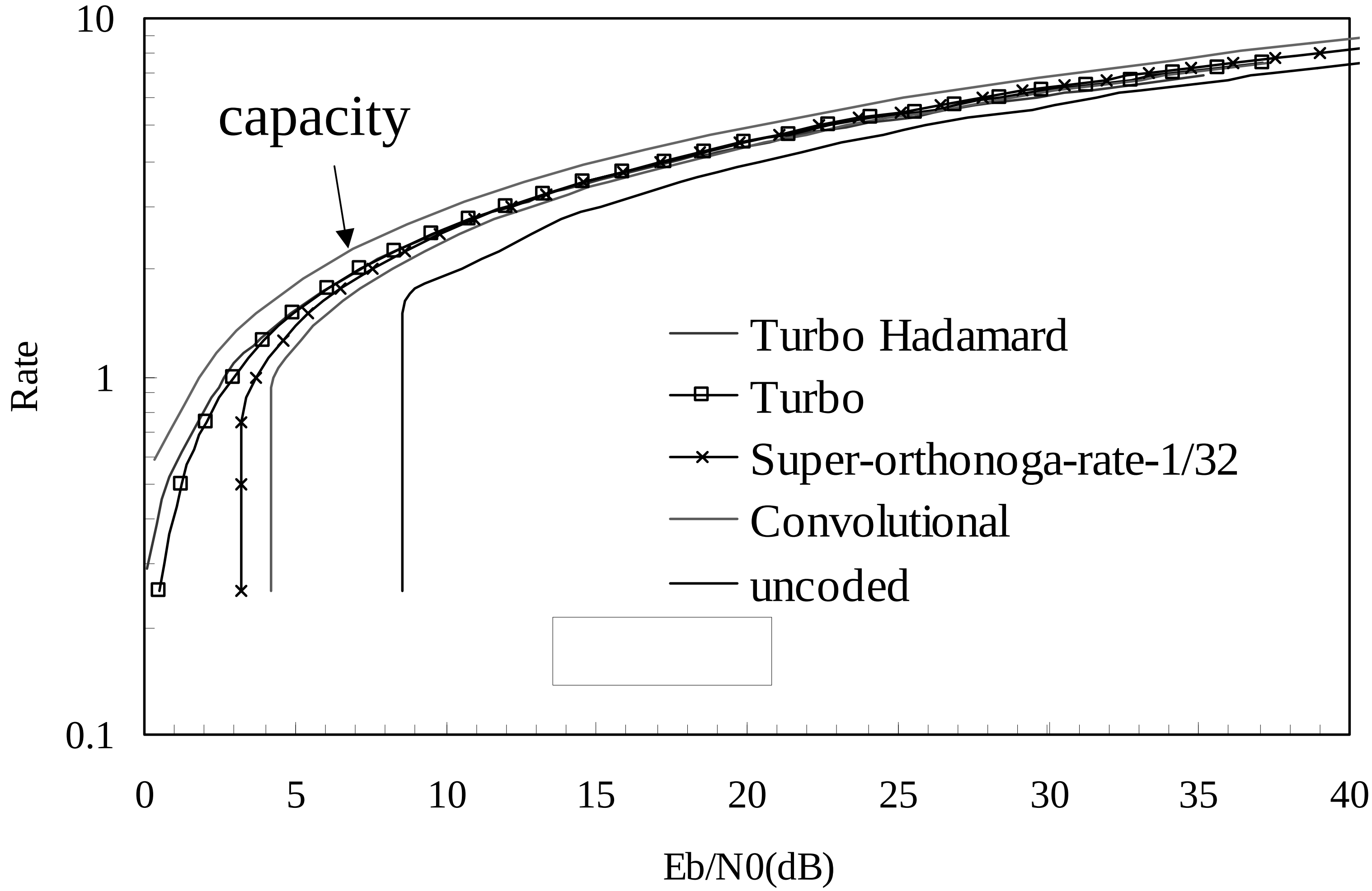
Un-coded IDMA
(with rate-1/8 repetition coding)



Rate 1/8 Convolutional-Repeat Coded IDMA



Impact of FEC Coding on IDMA



Spectral Efficiency

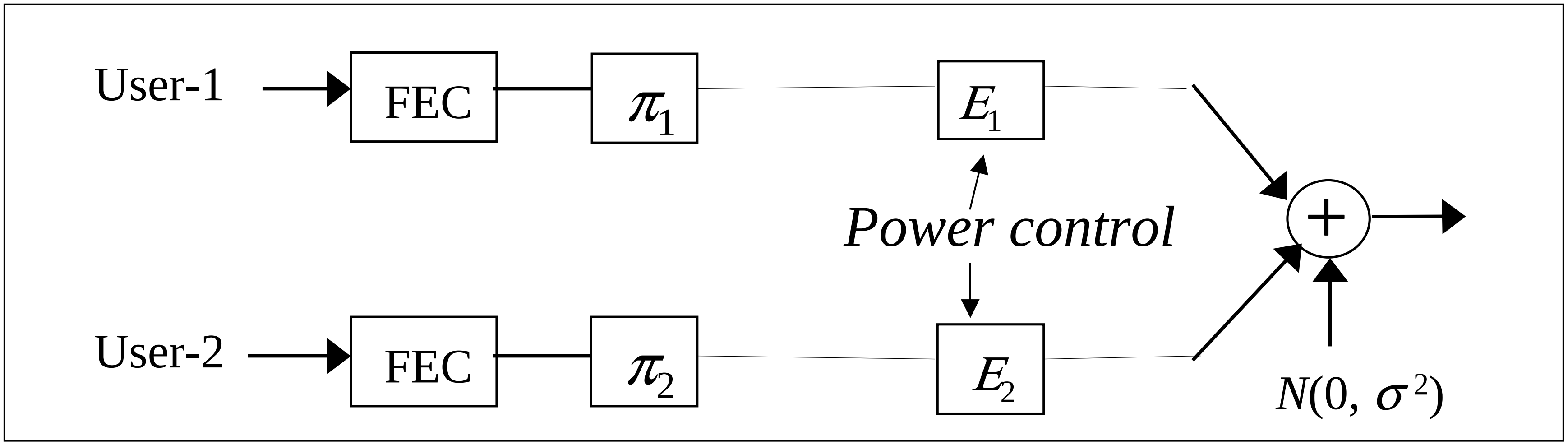
1/8 repeating with 64 users, spectral efficiency = 8bits/chip.

Equivalent to single-user 256-QAM.

Comparison: IS-95 CDMA efficiency ?

with ideal coding

with ideal coding



Achieving overall capacity

Onion-peeling capacity

$$C = \log(1+\frac{E_1+E_2}{\sigma^2}) = \log(1+\frac{E_1}{\sigma^2}) + \log(1+\frac{E_2}{\sigma^2+E_1})$$

Single-user capacity

with ideal coding

$$\log(1+\frac{E_1+E_2+E_3}{\sigma^2})$$

$$=\log(1+\frac{E_3}{\sigma^2+E_1+E_2})+\log(1+\frac{E_2}{\sigma^2+E_1})+\log(1+\frac{E_1}{\sigma^2})$$

We can achieve multi-user capacity provided that an ideal code is used for every user.

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IDMA

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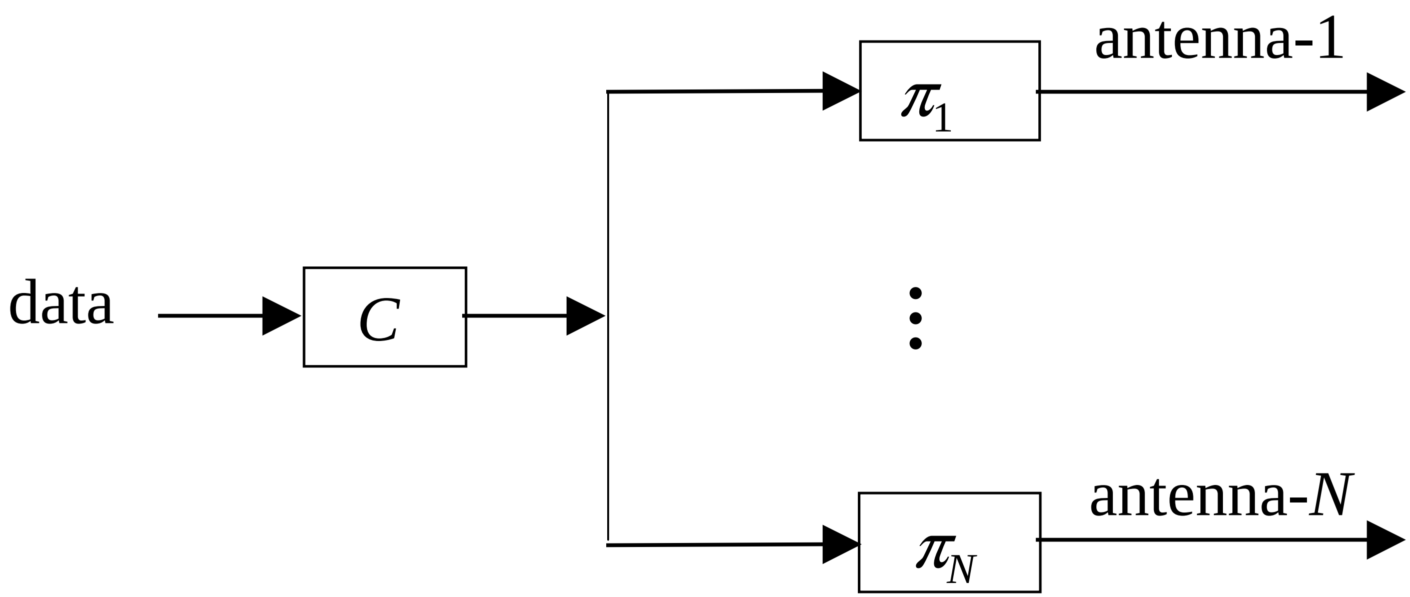
Application 1:

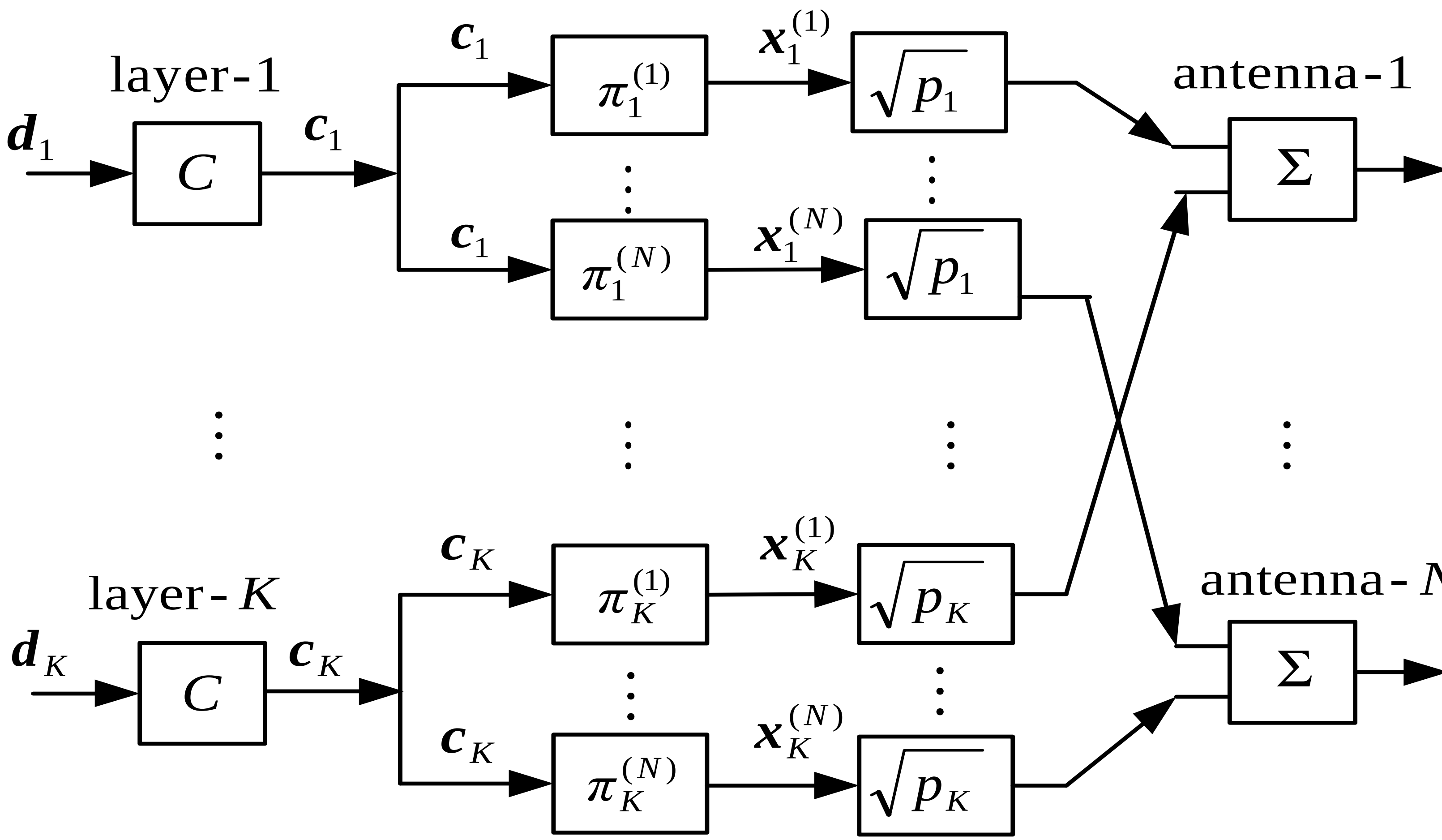
IDM Space-Time Coding

IDM Space-Time Coding

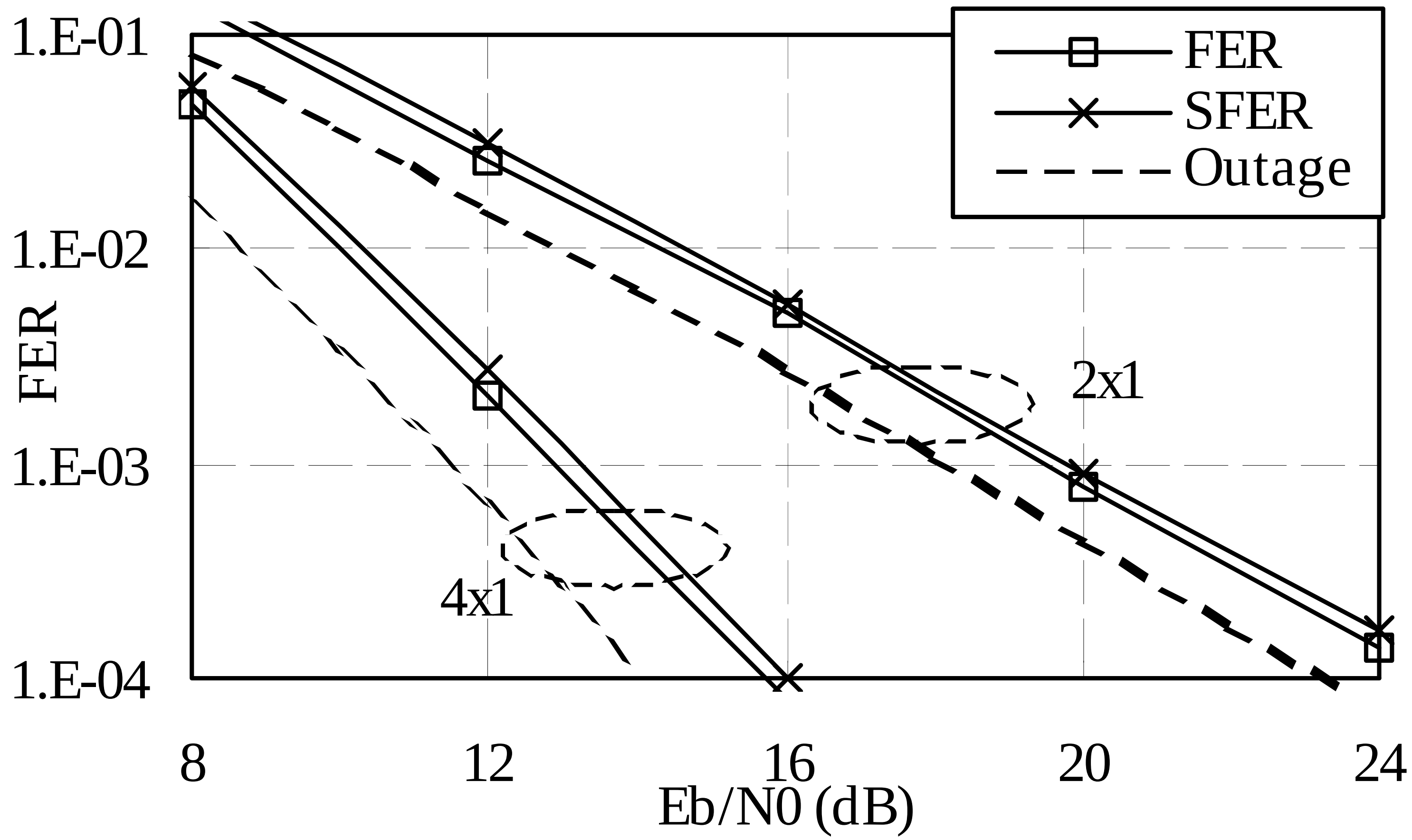


The interleavers $\pi_1, \ldots, \pi_N$ are randomly chosen.

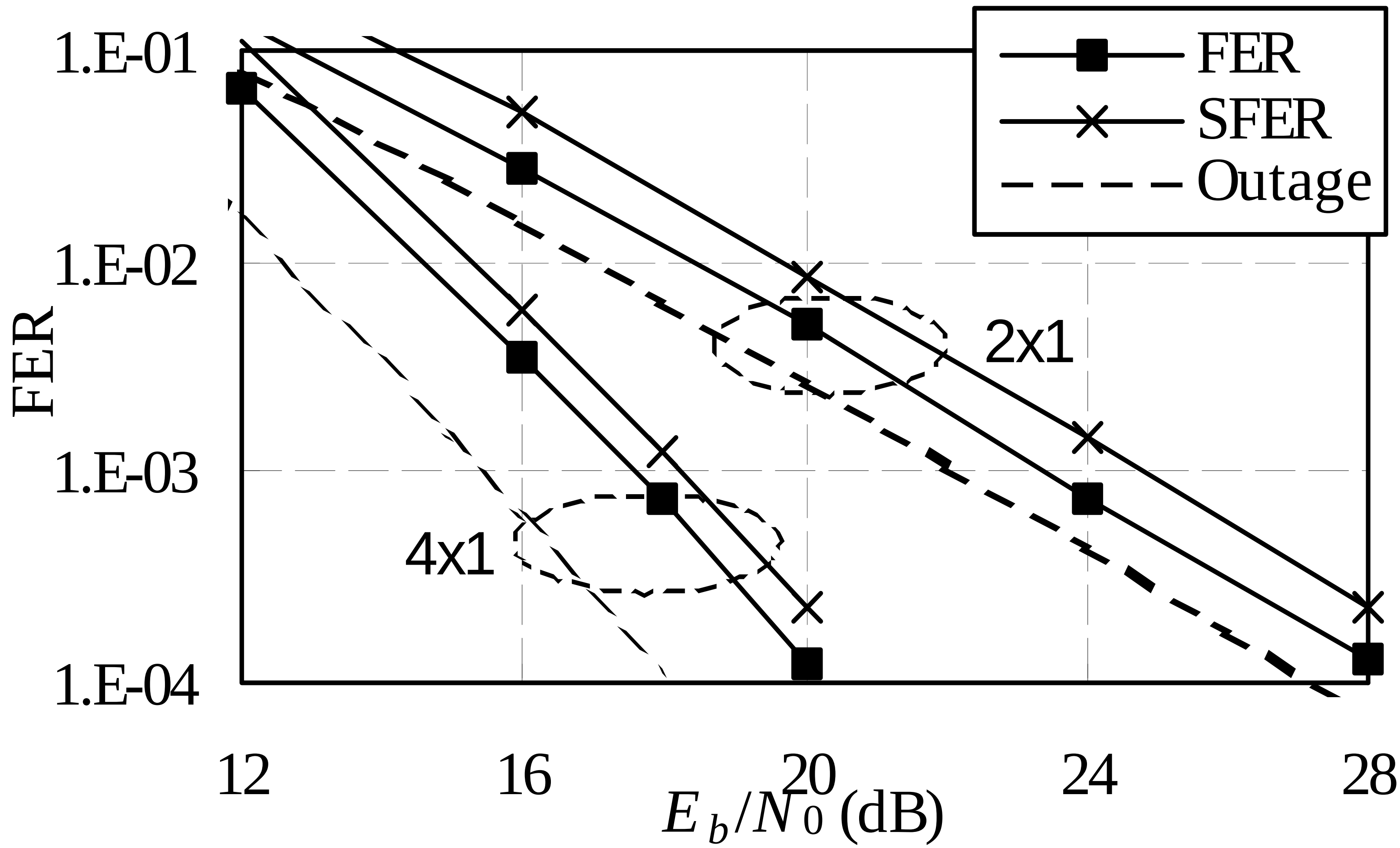
Multi Layer IDM Space-Time Coding



Performance of IDM Space-Time Codes
(overall rate R = 2 bits/symbol)



Performance of IDM Space-Time Codes
(overall rate R = 4 bits/symbol)



Performance Analysis of Space-Time Codes

For performance analysis of space-time codes, we have to consider all possible fading coefficients $\{h_n\}$.

This is usually very difficult, involving multi-dimensional integration over the distribution of $\{h_n\}$.

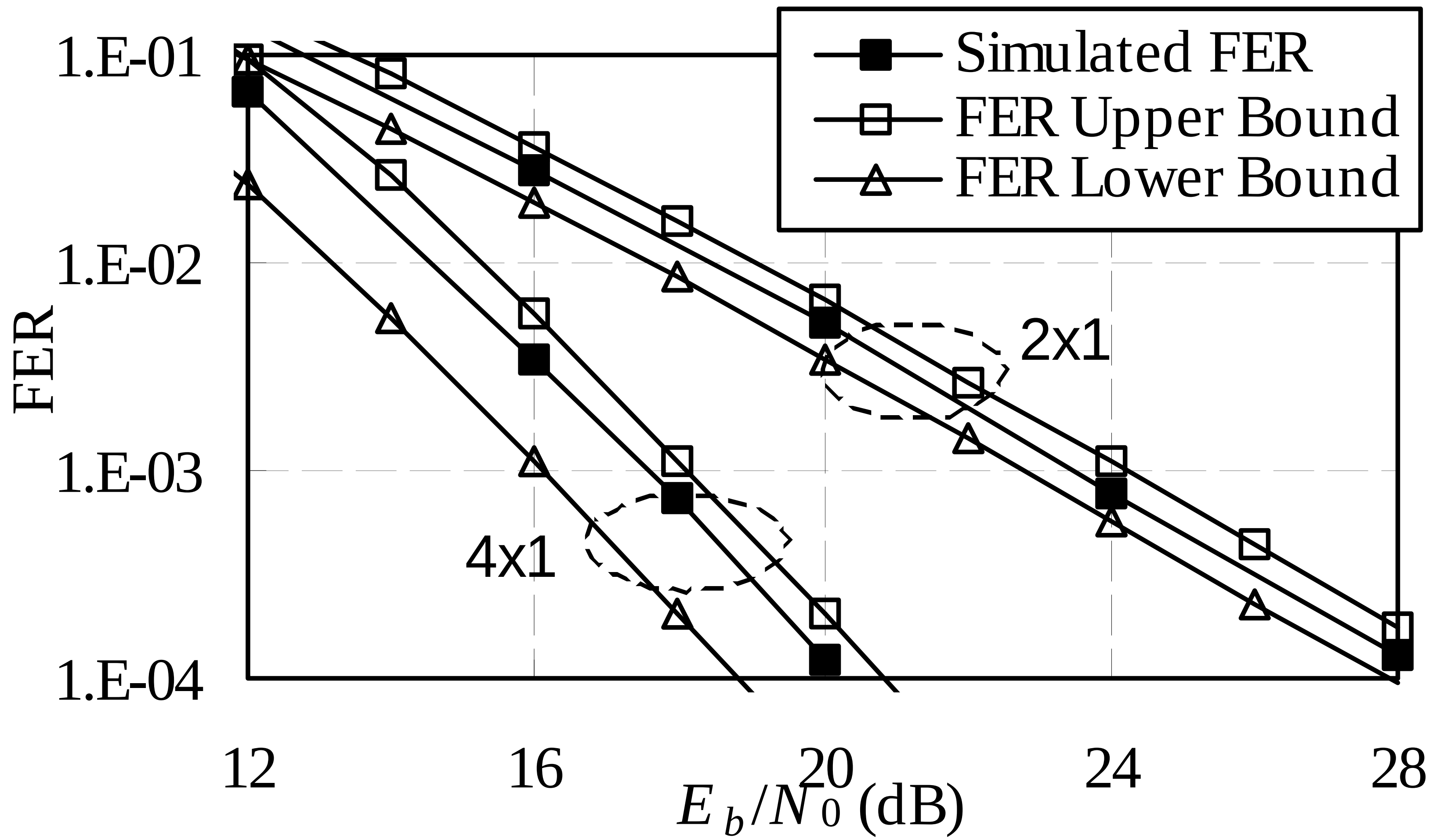
Performance Bounds of IDM Space-Time Codes

Theorem 1: Worst performance at: $h_1 = h_2 = \ldots = h_N$

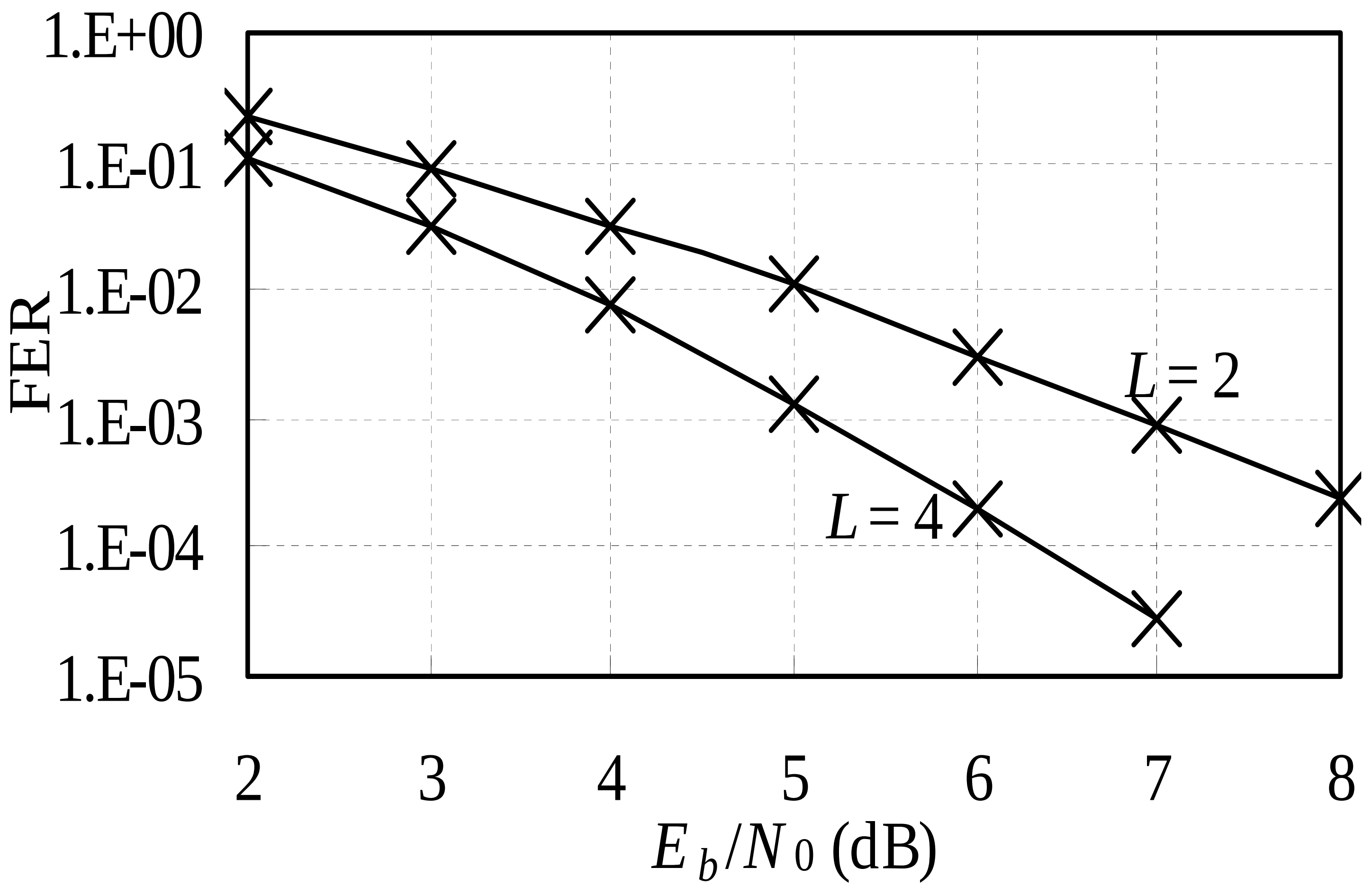
Theorem 2: Best performance at: $h_1 = 1$,

$h_2 = \ldots = h_N = 0$

Performance Bounds
(overall rate R = 4 bits/symbol)



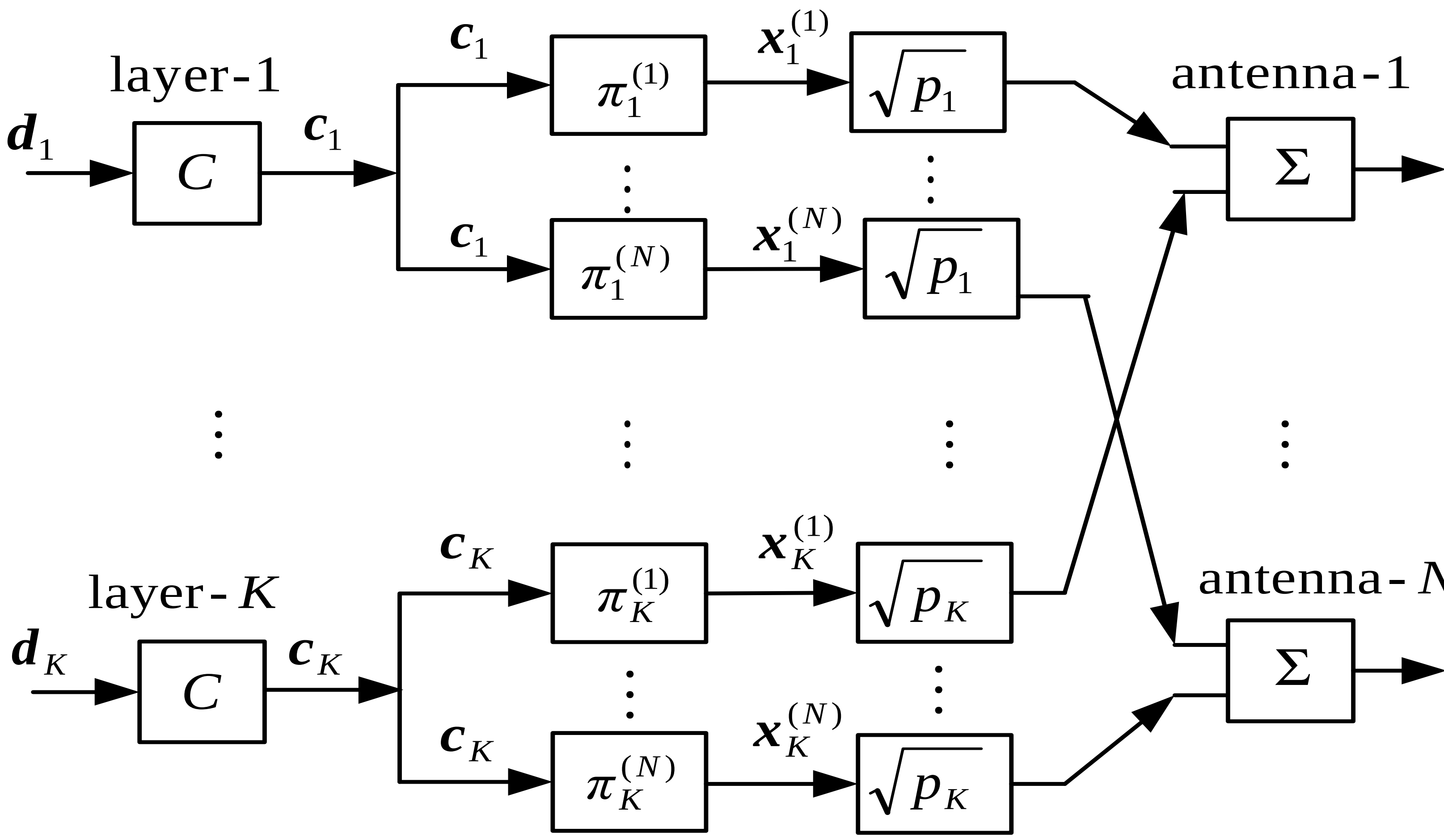
Performance in Multi-Path Channels
(R = 2 bits/symbol, 2×2 system)



The Capacity Achieving Property

An IDM-ST code can achieve capacity
if C is low-rate and achieves capacity in AWGN.

Multi Layer IDM Space-Time Coding



Summary: Properties of IDM ST Codes

Conceptually simple.

Potentially capacity achieving.

Low decoding complexity.

Multi-path resolution.

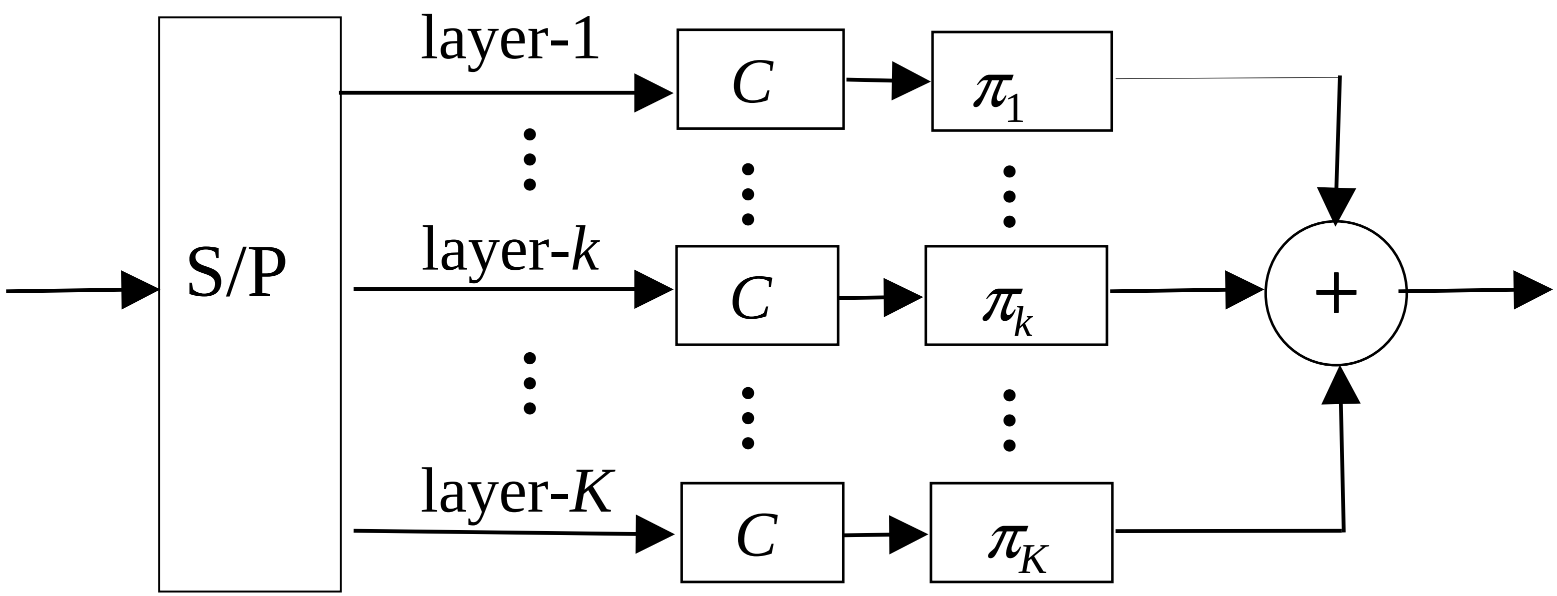
Application 2:

IDM Coded Modulation

IDM Coded Modulation

- Sigma mapping: Duan Rimoldi and Urbanke.
- Multi-level codes: Imai and Hirakawa

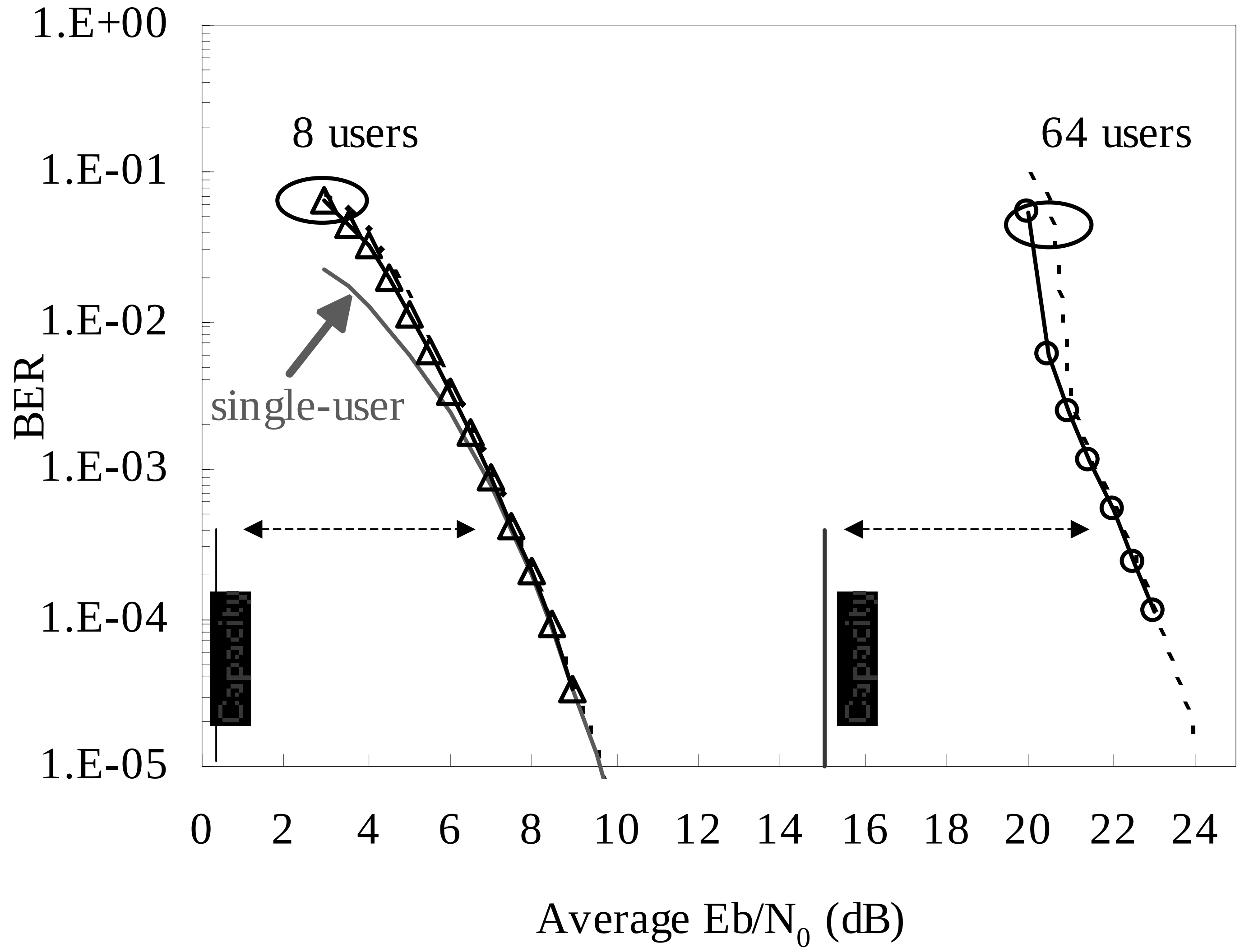
IDM Coded Modulation



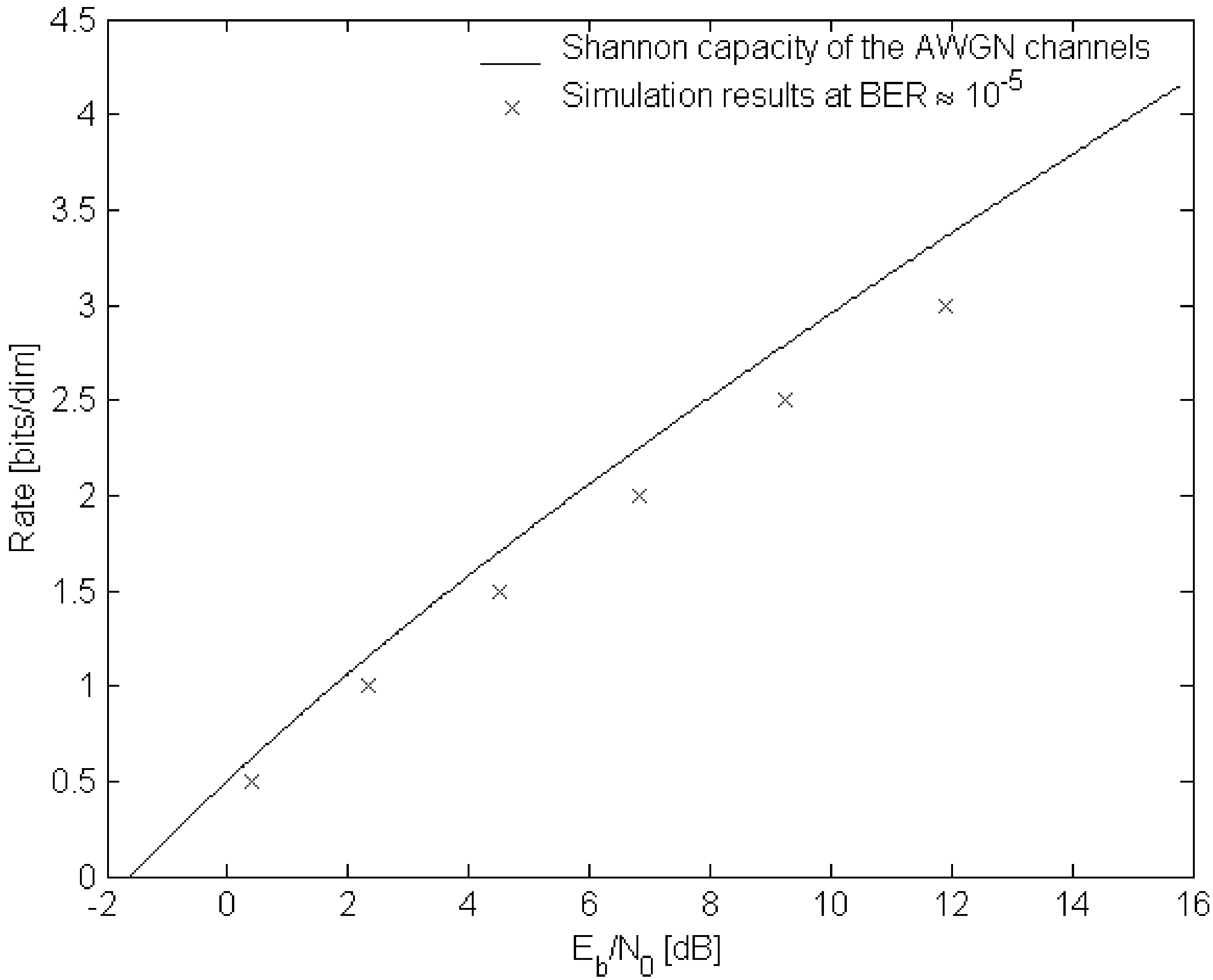
Advantages of IDM Coded Modulation

- Simplicity
- Flexibility
- High performance
- Low-decoding cost
- Easy treatments for ISI

Rate-1/8-Repeating IDMA



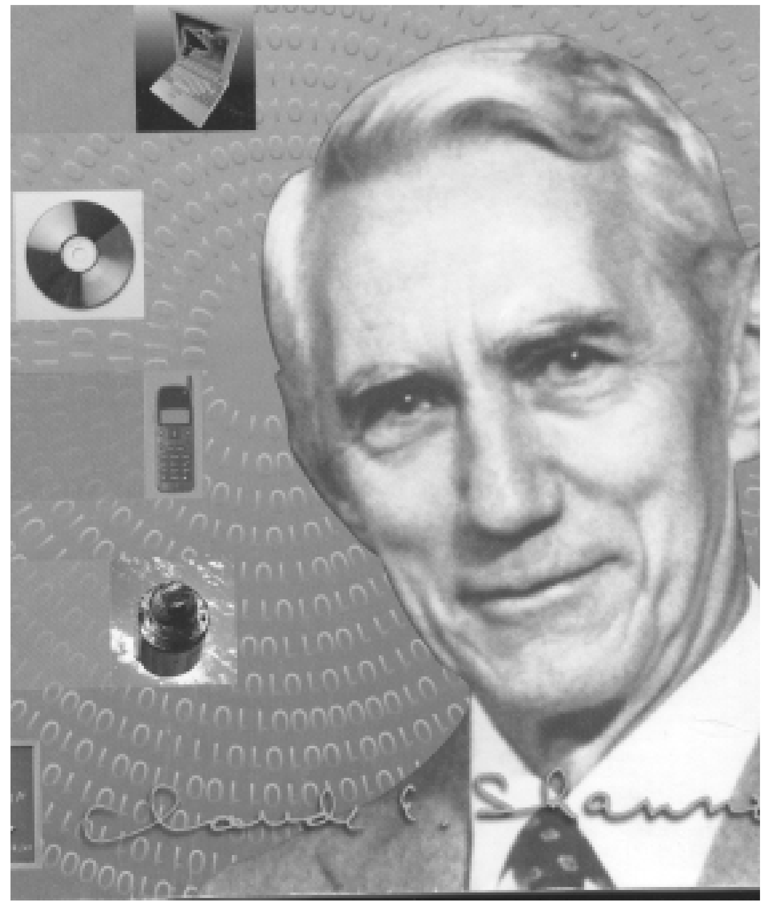
Performance of IDM Coded Modulation (per real dimension)



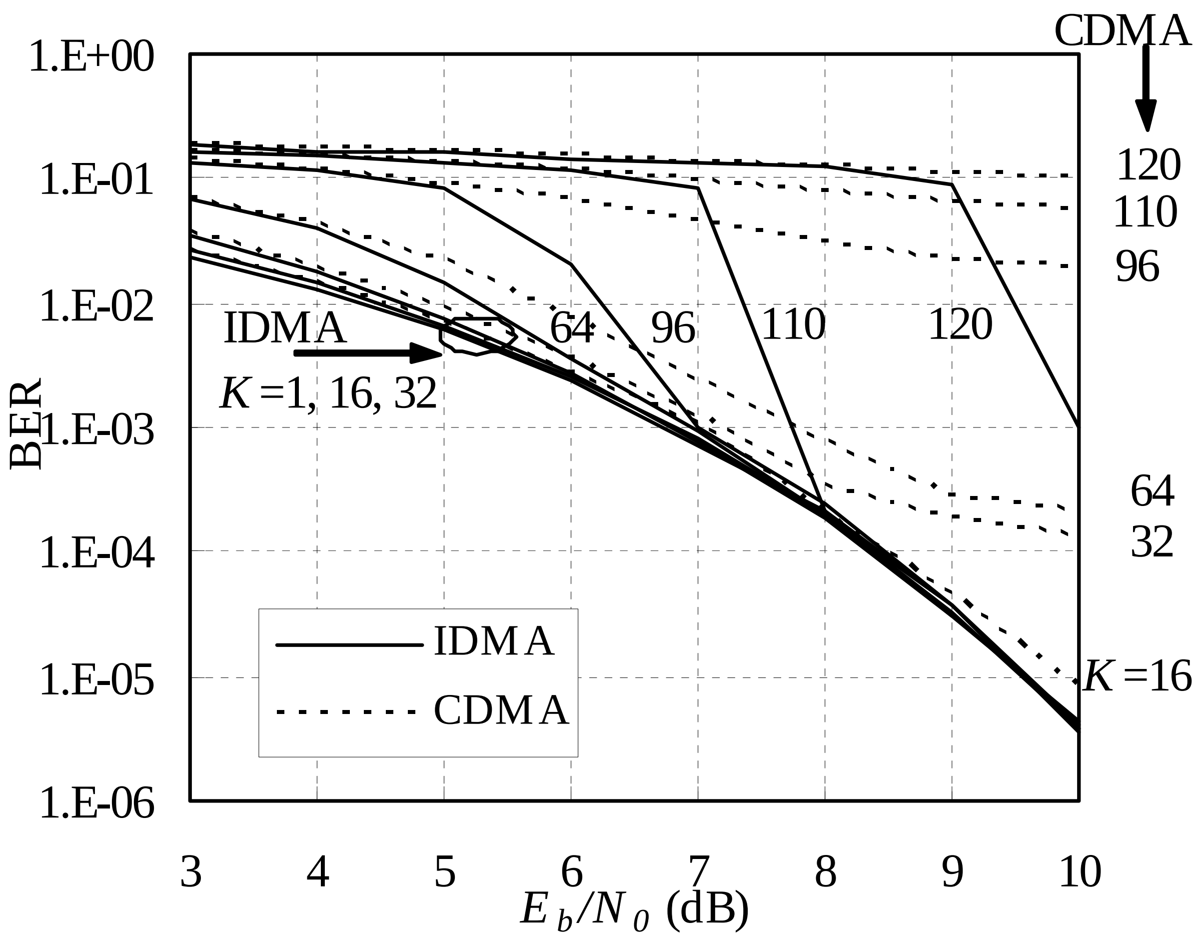
Conclusions Again

What makes IDMA work?

Randomness.



A Comparison between Un-coded IDMA and CDMA



For Details

http://www.ee.cityu.edu.hk/~liping/research/

Chip-by-Chip Detection

Step 1. Chip-level path model: $r(j) = \sum_{k=1}^{K} h_k x_k(j) + n(j)$

Step 2. Gaussian approximation: $r(j) = h_k x_k(j) + \zeta_k(j)$

Gaussian

Step 3. Estimation:

$$e\left(x_k(j)\right) = \frac{2h_k}{\mathrm{Var}(\zeta_k(j))} \cdot \left(r(j) - \mathrm{E}(\zeta_k(j))\right)$$

For a chip, not much can be done. It must be simple.

Analysis of the Chip-by-Chip Algorithm

$$e\left(x_k(j)\right) = \frac{2h_k}{\mathrm{Var}(\zeta_k(j))} \cdot \left(r(j) - \mathrm{E}(\zeta_k(j)) \right)$$

$$= \frac{2h_k}{\mathrm{Var}(\zeta_k(j))} \cdot \left(h_k x_k(j) + \zeta_k(j) - \mathrm{E}(\zeta_k(j)) \right)$$

signal

noise

$$\boxed{SNR_k = \frac{\left|h_k\right|^2}{\sum_{k' \neq k} \left|h_{k'}\right|^2 \mathrm{Var}(x_{k'}(j)) + \sigma^2}}$$