Multiuser Detection for CDMA Systems

Outline

- Overview of DS/CDMA systems
- Concept of multiuser detection (MUD)
- MUD algorithms
- Limitations of MUD
- Conclusion

DS/CDMA Systems

- A conventional DS/CDMA system treats each user separately as a signal, with other users considered as noise or MAI – multiple access interference
- Capacity is *interference-limited*
- Near/far effect: users near the BS are received at higher powers than those far away
  - those far away suffer a degradation in performance
  - Need tight power control

Multiuser Detection

- Multiuser detection considers all users as signals for each other -> joint detection
  - Reduced interference leads to capacity increase
  - Alleviates the near/far problem
- MUD can be implemented in the BS or mobile, or both
- In a cellular system, base station (BS) has knowledge of all the chip sequences
- Size and weight requirement for BS is not stringent
- Therefore MUD is currently being envisioned for the uplink (mobile to BS)

Concept of MUD

- Simplified system model (BPSK)
  - Baseband signal for the k[th] user is:

$$u_k(t) = \sum_{i=0}^{\infty} x_k(i) \cdot c_k(i) \cdot s_k(t - iT - \tau_k)$$

    - $x_k(i)$ is the i^{th} input symbol of the k^{th} user
    - $c_k(i)$ is the real, positive channel gain
    - $s_k(t)$ is the signature waveform containing the PN sequence
    - τ_k is the transmission delay; for synchronous CDMA, $\tau_k=0$ for all users
  - Received signal at baseband

$$y(t) = \sum_{k=1}^{K} u_k(t) + z(t)$$

    - K number of users
    - $z(t)$ is the complex AWGN

Concept of MUD (2)

- Sampled output of the matched filter for the k^th user:

$$y_k = \int_0^T y(t) s_k(t) dt$$

$$= c_k x_k + \sum_{j \neq k}^{K} x_j c_j \int_0^T s_k(t) s_j(t) dt + \int_0^T s_k(t) z(t) dt$$

  - 1^st term - desired information
  - 2^nd term - MAI
  - 3^rd term - noise
- Assume two-user case (K=2), and

$$r = \int_0^T s_1(t) s_2(t) dt$$

Concept of MUD (3)

- Outputs of the matched filters are:

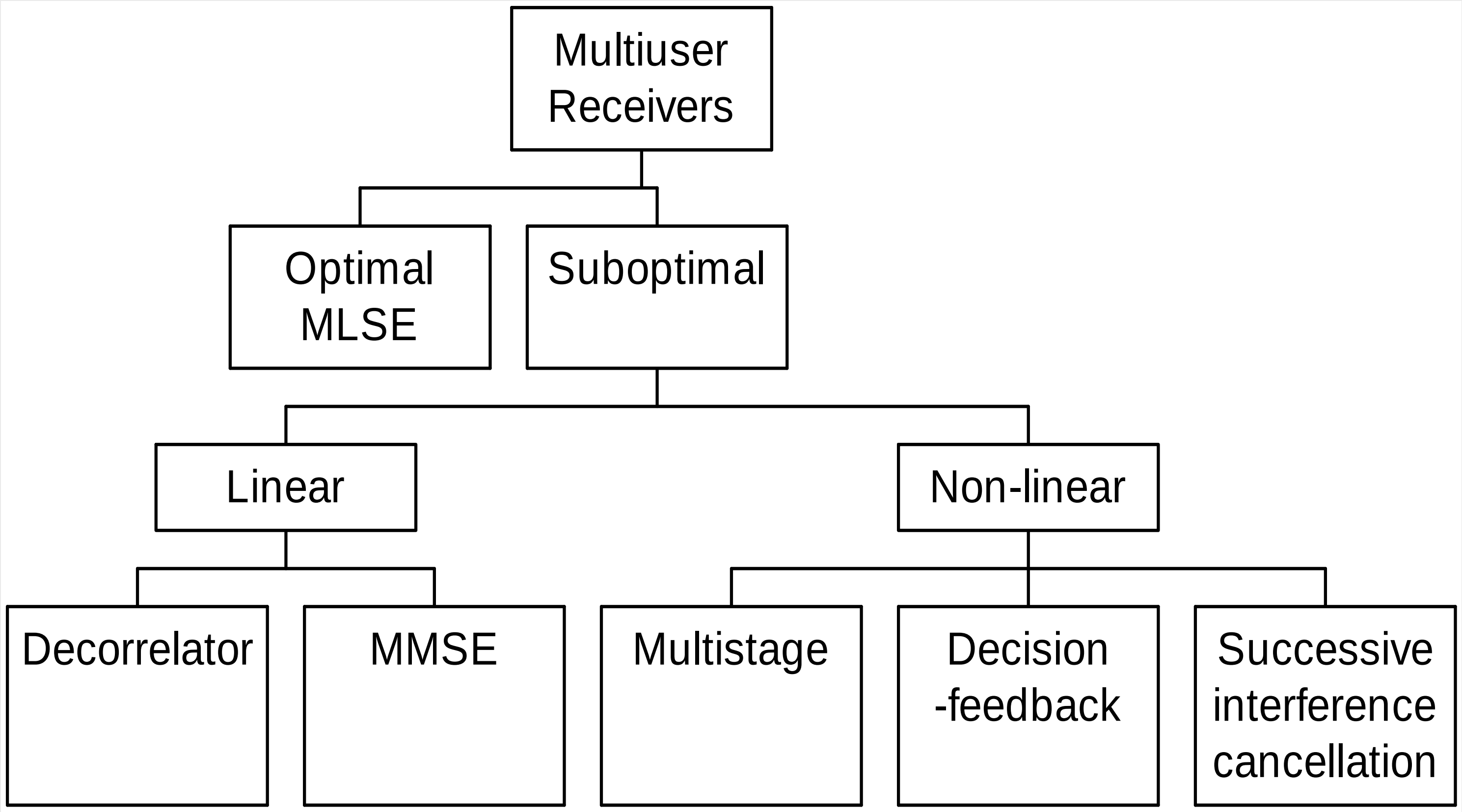
$$y_1 = c_1 x_1 + r c_2 x_2 + z_1 \qquad y_2 = c_2 x_2 + r c_1 x_1 + z_2$$

- Detected symbol for user k: $\hat{x}_k = \operatorname{sgn}(y_k)$
- If user 1 is much stronger than user 2 (the near/far problem), the MAI term rc_1x_1 present in the signal of user 2 is very large
- Successive Interference Cancellation
  - decision is made for the stronger user 1: $\hat{x}_1 = \operatorname{sgn}(y_1)$
  - subtract the estimate of MAI from the signal of the weaker user:

$$\begin{aligned}\hat{x}_2 &= \operatorname{sgn}(y_2 - r c_1 \hat{x}_1) \\ &= \operatorname{sgn}(c_2 x_2 + r c_1 (x_1 - \hat{x}_1) + z_2)\end{aligned}$$

  - all MAI can be subtracted from user 2 signal provided estimate is correct
- MAI is reduced and near/far problem is alleviated

MUD Algorithms



Optimal MLSE Detector

- Maximum-likelihood sequence estimation (MLSE) is the optimal detector (Verdú, 1984)
- For synchronous CDMA, search over 2^K possible combinations of the bits in vector *x*

$$\hat{x} = \arg\left\{ \max_{x \in \{-1,+1\}^K} \left[2y^T W x - b^T W R W b \right] \right\}$$

- For asynchronous CDMA, use Viterbi algorithm with 2^{K-1} states
- Both too complex for practical implementation

Decorrelator

- Matrix representation

$$\underline{y} = RW\underline{x} + \underline{z}$$

  - where $\underline{y}=[y_1,y_2,\ldots,y_K]^T$, R and W are KxK matrices
  - Components of R are given by cross-correlations between signature waveforms $s_k(t)$
  - W is diagonal with component $W_{k,k}$ given by the channel gain c_k of the k^{th} user
  - $\underline{z}$ is a colored Gaussian noise vector
- Solve for $\underline{x}$ by inverting R

$$\underline{\tilde{y}} = R^{-1}\underline{y} = W\underline{x} + R^{-1}\underline{z} \quad \Rightarrow \quad \hat{x}_k = \operatorname{sgn}\left(\tilde{y}_k\right)$$

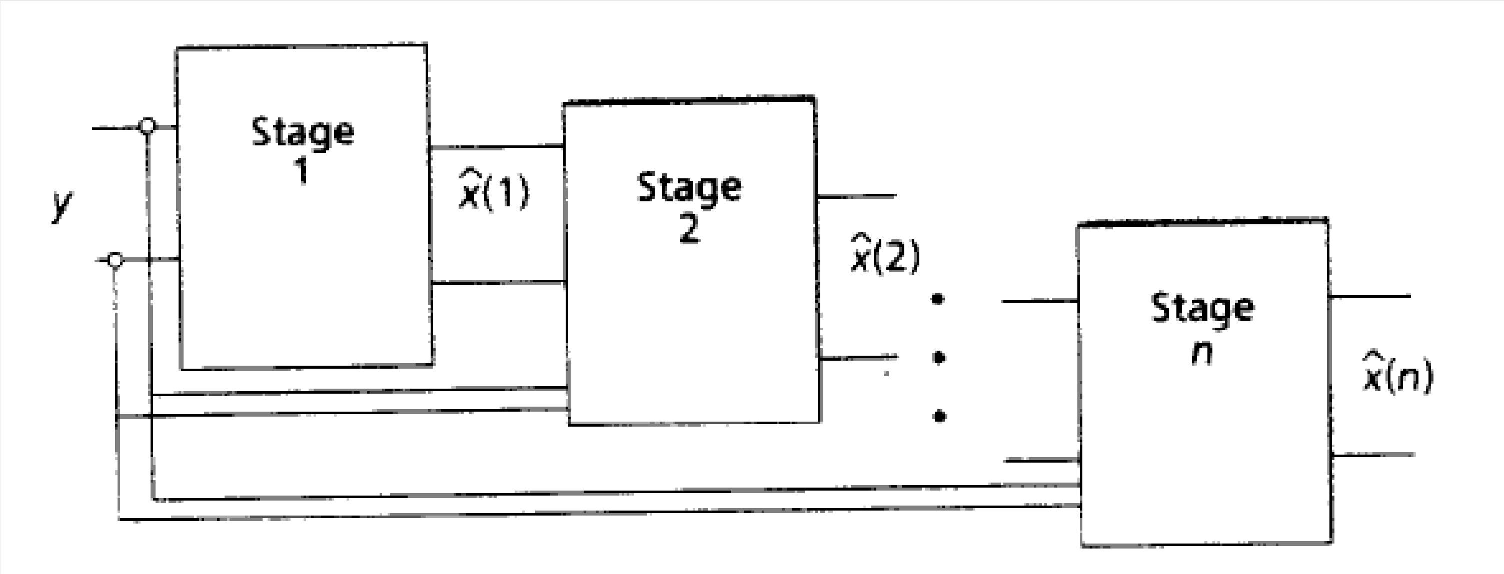
- Analogous to zero-forcing equalizers for ISI channels
- Pros: Does not require knowledge of users' powers
- Cons: Noise enhancement

Multistage Detectors

- Decisions produced by 1st stage are $\hat{x}_1(1), \hat{x}_2(1)$
- 2nd stage:

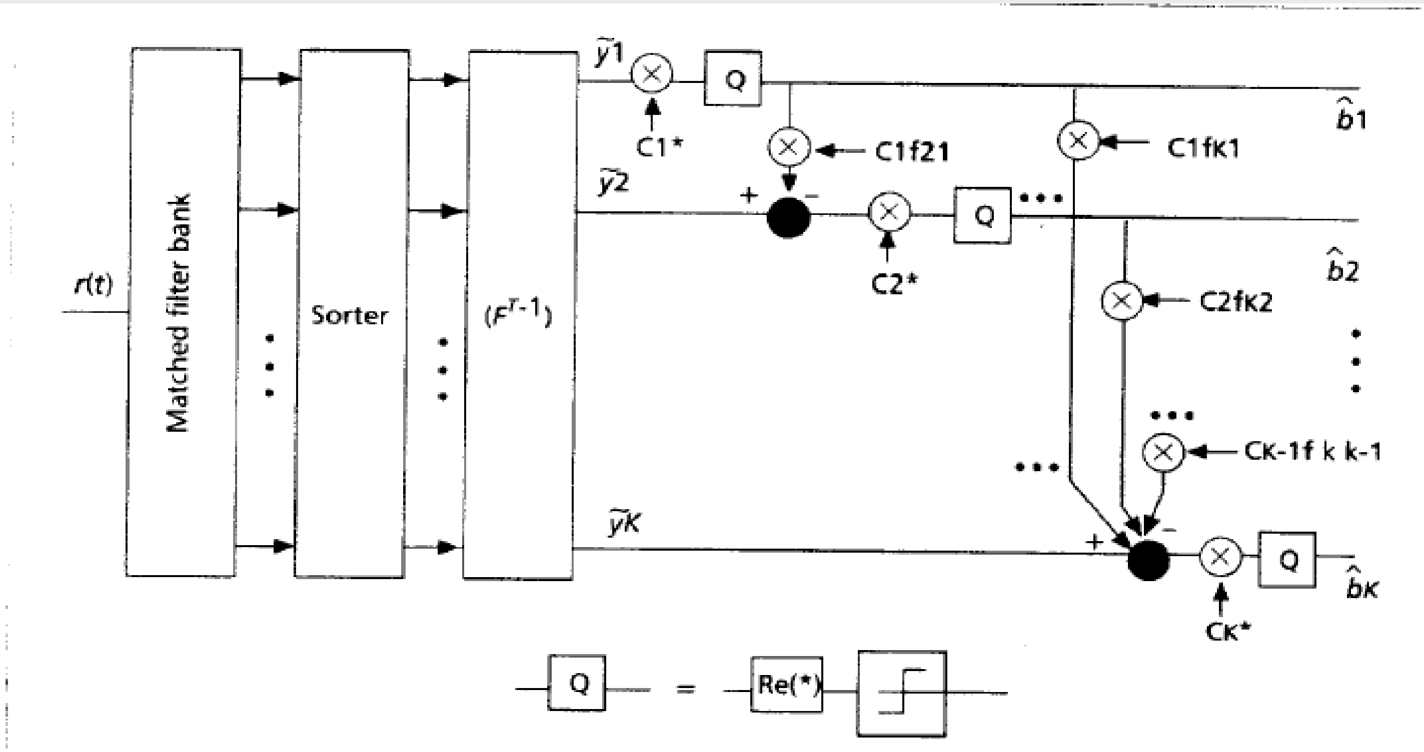
$$\hat{x}_1(2) = \mathrm{sgn}[y_1 - rc_2\hat{x}_2(1)]$$
$$\hat{x}_2(2) = \mathrm{sgn}[y_2 - rc_1\hat{x}_1(1)]$$

- and so on...



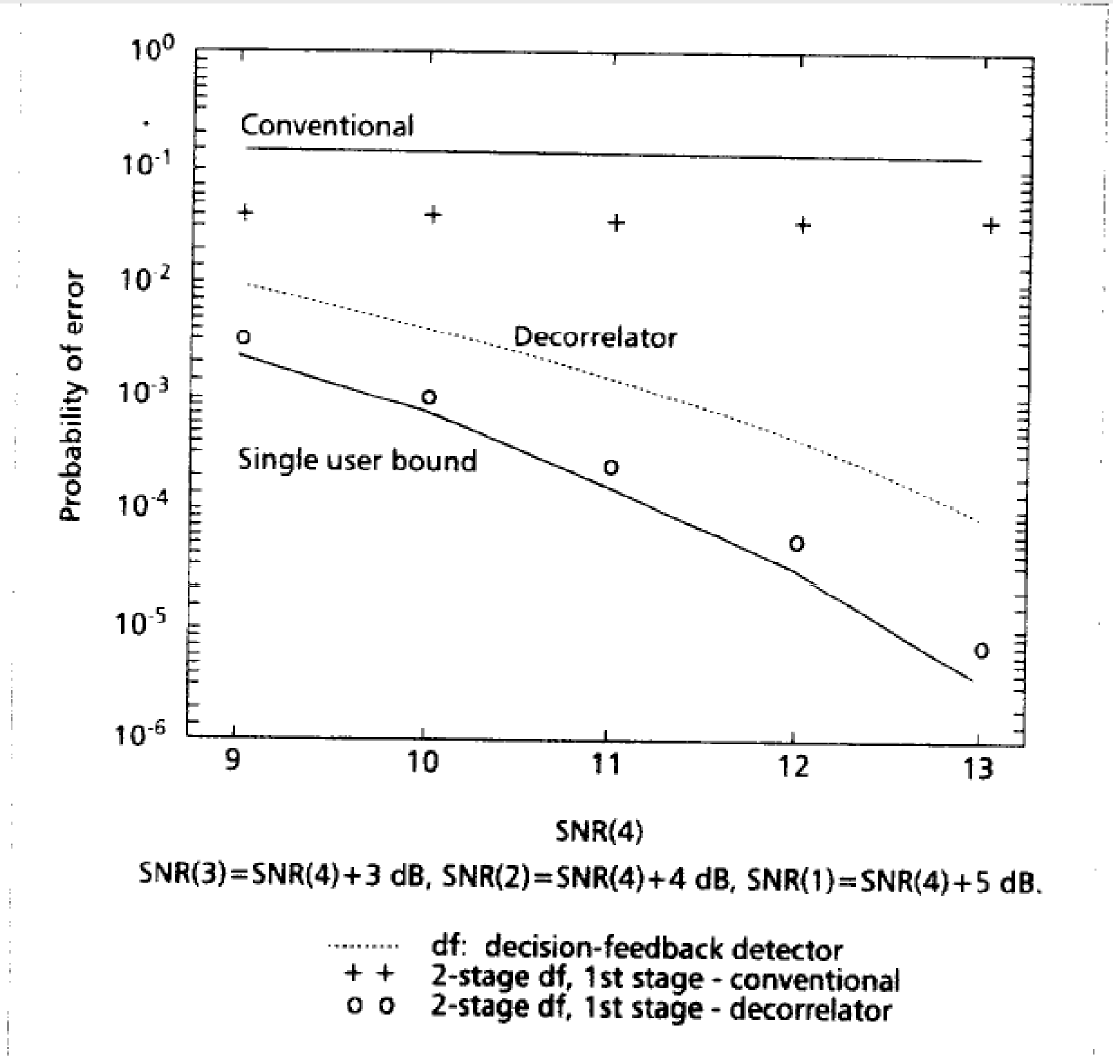
Decision-Feedback Detectors

- Characterized by two matrix transformation: forward filter and feedback filter
- Whitening filter yields a lower triangular MAI matrix
- Performance similar to that of the decorrelator



■ **Figure 4.** *The decorrelating decision-feedback detector for Synchronous CDMA.*

DFD Performance



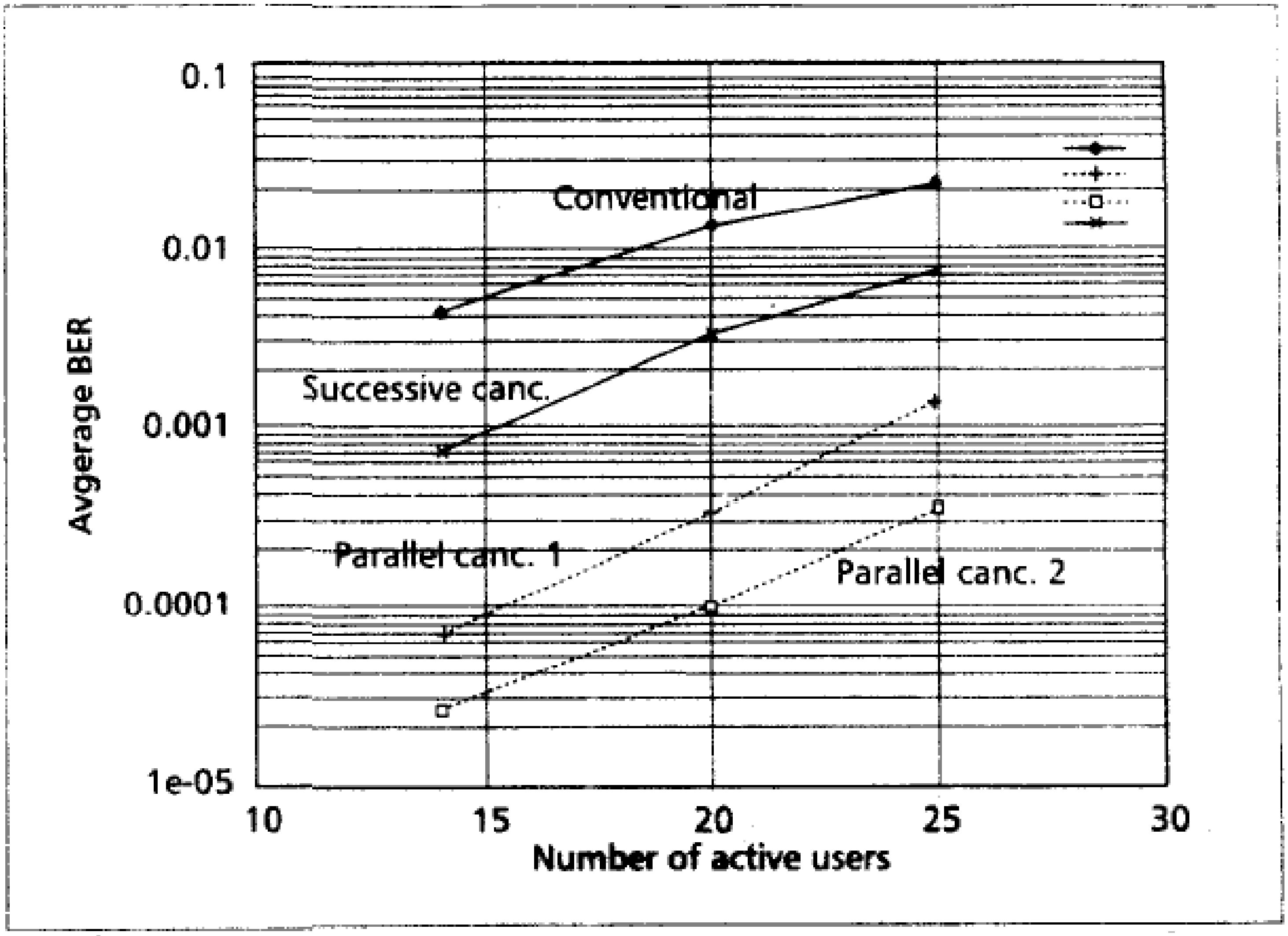
■ **Figure 5.** *Error rates for user 4 in the four-user system of [31].*

Successive Interference Cancellers

- Successively subtracting off the strongest remaining signal
  - Cancelling the strongest signal has the most benefit
  - Cancelling the strongest signal is the most reliable cancellation

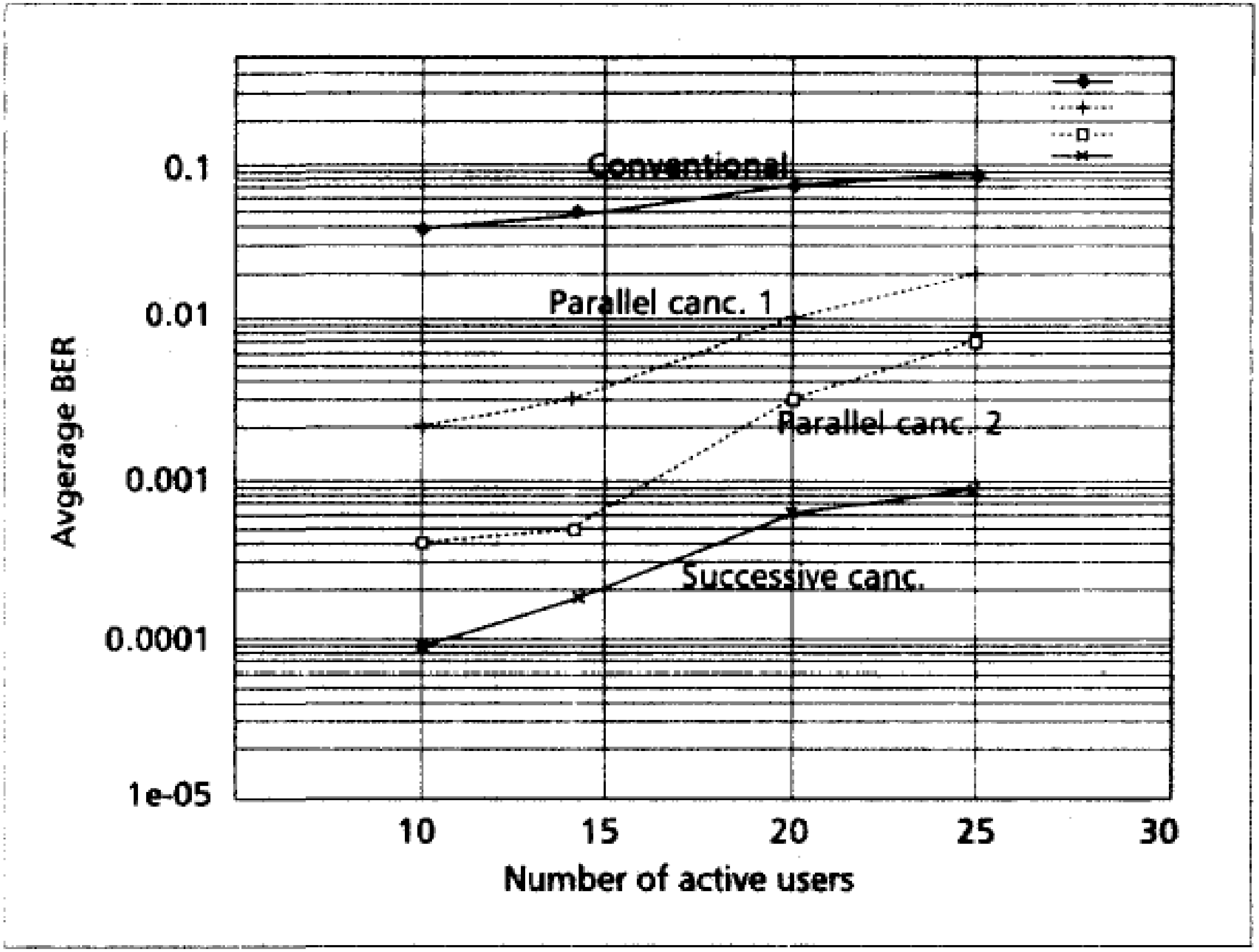
- An alternative called the *Parallel Interference Cancellers* simultaneously subtract off all of the users' signals from all of the others
  - works better than SIC when all of the users are received with equal strength (e.g. under power control)

Performance of MUD



■ **Figure 6.** *BER vs. no. of active users under ideal power control (asynchronous).*

Performance of MUD (2)



■ **Figure 7.** *BER vs. no. of active users under Rayleigh fading (asynchronous).*

Limitations of MUD

- Issues in practical implementation
  - Processing complexity
  - Processing delay
  - Sensitivity and robustness
- Limitations of MUD
  - Potential capacity improvements in cellular systems are not enormous but certainly nontrivial (2.8x upper bound)
  - Capacity improvements only on the uplink would only be partly used anyway in determining overall system capacity
  - Cost of doing MUD must be as low as possible so that there is a performance/cost tradeoff advantage

Conclusion

- There are significant advantages to MUD which are, however, bounded and a simple implementation is needed
- Current investigations involve implementation and robustness issues
- MUD research is still in a phase that would not justify to make it a mandatory feature for 3G WCDMA standards
- Currently other techniques such as smart antenna seem to be more promising