# EE360: Multiuser Wireless Systems and Networks

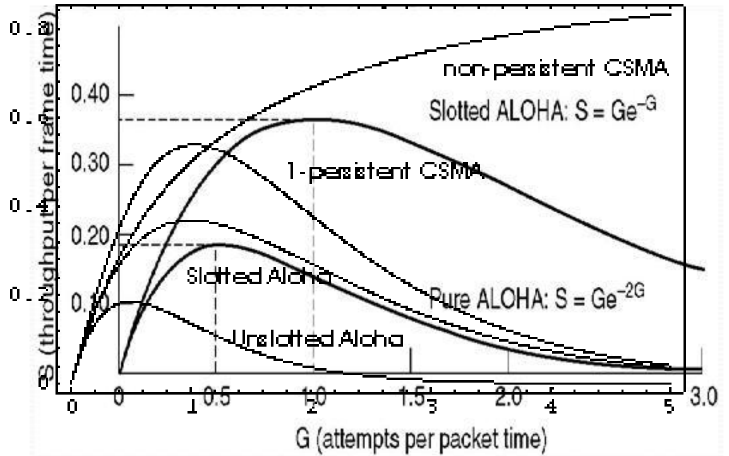
# Lecture 4 Outline

- Announcements
  - Project proposals due Feb. 1 (1 week)
  - Makeup lecture Feb 2, 5-6:15, Gates
  - Presentation schedule finalizes
- Random vs. Multiple Access
- Random Access and Scheduling
- Spread Spectrum
- Multiuser Detection
- Multiuser OFDM and OFDM/CDMA

# Multiple vs. Random Access

- Multiple Access Techniques
  - Used to create a dedicated channel for each user
  - Orthogonal (TD/FD with no interference) or semi-orthogonal (CD with interference reduced by the code spreading gain) techniques may be used
- Random Access
  - No dedicated channel assigned to each user
  - Users contend for channel when they have data to send
  - Very efficient when users rarely active; very inefficient when users have continuous data to send
  - Scheduling and hybrid scheduling used to combine benefits of multiple and random access

# Random Access and Scheduling



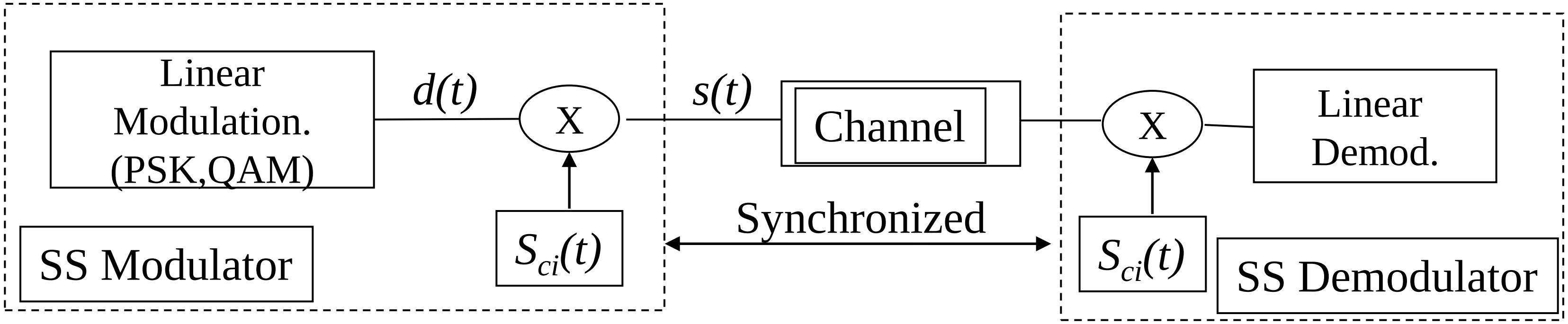
- Dedicated channels wasteful
  - Use statistical multiplexing
- Random Access Techniques
  - Aloha (Pure and Slotted)
  - Carrier sensing
    - Can include collision detection/avoidance
    - If channel busy, deterministic or random delay (non-persistent)
  - Poor performance in heavy loading
- Reservation protocols
  - Resources reserved for short transmissions (overhead)
  - Hybrid Methods: Packet-Reservation Multiple Access
- Retransmissions used for corrupted data (ARQ)
  - Hybrid ARQ – partial retransmission: more coded bits

# Spread Spectrum MAC

- Basic Features
  - signal spread by a code
  - synchronization between pairs of users
  - compensation for near-far problem (in MAC channel)
  - compression and channel coding
- Spreading Mechanisms
  - direct sequence multiplication
  - frequency hopping

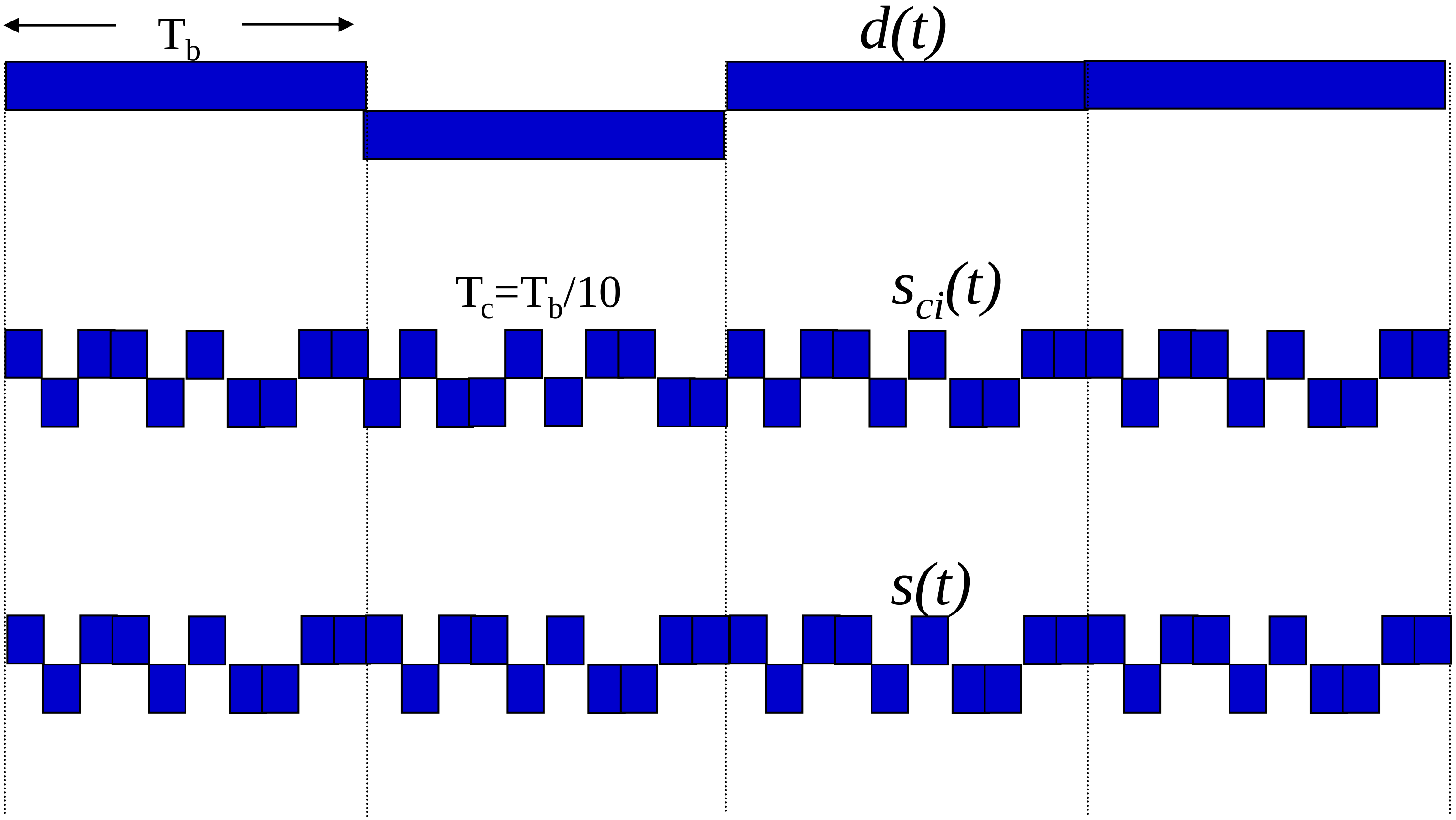
*Note: spreading is 2nd modulation (after bits encoded into digital waveform, e.g. BPSK). DS spreading codes are inherently digital.*

# Direct Sequence

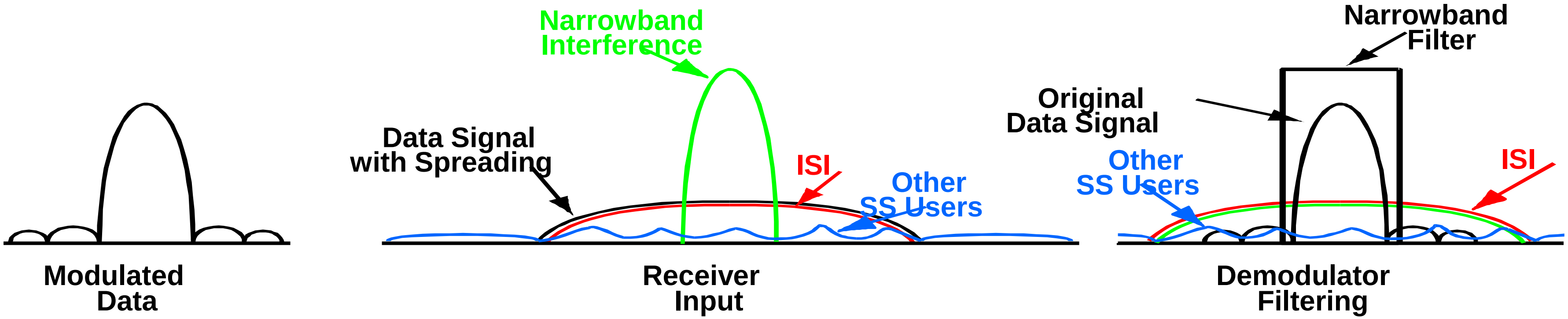


- Chip time $T_c$ is $N$ times the symbol time $T_s$.
- Bandwidth of *s(t)* is *N+1* times that of *d(t).*
- Channel introduces noise, ISI, narrowband and multiple access interference.
  - Spreading has no effect on AWGN noise
  - ISI delayed by more than $T_c$ reduced by code autocorrelation
  - narrowband interference reduced by spreading gain.
  - MAC interference reduced by code cross correlation.

# BPSK Example



# Spectral Properties



# Code Properties

**Autocorrelation:**

$$\rho(\tau) = \frac{1}{T_s}\int_0^{T_s} s_{ci}(t)s_{ci}(t-\tau)dt$$

**Cross Correlation**

$$\rho_{ij}(\tau) = \frac{1}{T_s}\int_0^{T_s} s_{ci}(t)s_{cj}(t-\tau)dt$$

- Good codes have $\rho(\tau)=\delta(\tau)$ and $\rho_{ij}(\tau)=0$ for all $\tau$.
  - $\rho(\tau)=\delta(\tau)$ removes ISI
  - $\rho_{ij}(\tau)=0$ removes interference between users
  - Hard to get these properties simultaneously.

# ISI Rejection

- Transmitted signal: $s(t)=d(t)s_{ci}(t)$.
- Channel: $h(t)=\delta(t)+\delta(t-\tau)$.
- Received signal: $s(t)+s(t-\tau)$
- Received signal after despreading:

$$\begin{aligned} r(t)s_{ci}(t) &= d(t)s_{ci}{}^{2}(t)+d(t-\tau)s_{ci}(t-\tau)s_{ci}(t) \\ &= d(t)+d(t-\tau)s_{ci}(t-\tau)s_{ci}(t) \end{aligned}$$

- In the demodulator this signal is integrated over a symbol time, so the second term becomes $d(t-\tau)\rho(\tau)$.
  - *For $\rho(\tau)=\delta(\tau)$, all ISI is rejected.*

# MAC Interference Rejection

- Received signal from all users (no multipath):

$$r(t)=\sum_{j=1}^{M} s_j(t-\tau_j)=\sum_{j=1}^{M} d_j(t-\tau_j)s_{cj}(t-\tau_j)$$

- Received signal after despreading

$$r(t)s_{ci}(t)=d_i(t)s_{ci}{}^2(t)+\sum_{j=1,\, j\neq i}^{M} d_j(t-\tau_j)s_{cj}(t-\tau_j)s_{ci}(t)$$

- In the demodulator this signal is integrated over a symbol time, so the second term becomes

$$\sum_{j=1,\, j\neq i}^{M} d_j(t-\tau_j)\rho_{ij}(\tau_j)$$

  - For $\rho_{ij}(\tau)=0$, all MAC interference is rejected.

# Walsh-Hadamard Codes

- For N chips/bit, can get N orthogonal codes
- Bandwidth expansion factor is roughly N.
- Roughly equivalent to TD or FD from a capacity standpoint
- Multipath destroys code orthogonality.

# Semi-Orthogonal Codes

- Maximal length feedback shift register sequences have good properties
  - In a long sequence, equal # of 1s and 0s.
    - No DC component
  - A run of length $r$ chips of the same sign will occur $2^{-r}l$ times in $l$ chips.
    - Transitions at chip rate occur often.
  - The autocorrelation is small except when $\tau$ is approximately zero
    - ISI rejection.
  - The cross correlation between any two sequences is small (roughly $\rho_{ij}=G^{-1/2}$ , where $G=B_{ss}/B_s$)
    - Maximizes MAC interference rejection

# SINR analysis

- **SINR (for K users, N chips per symbol)**

$$SINR = \left( \frac{K-1}{3N} + \frac{N_0}{E_s} \right)^{-1}$$

Assumes random spreading codes

- **Interference limited systems (same gains)**

$$\boxed{SIR = \frac{3N}{K-1} \approx \frac{3G}{K-1}}$$

Random spreading codes

$$SIR = \frac{3N}{\xi(K-1)} \approx \frac{3G}{\xi(K-1)}$$

Nonrandom spreading codes

- **Interference limited systems (near-far)**

$$SIR_k = \frac{\alpha_k^2 3N}{\alpha^2 \xi(K-1)} << \frac{3G}{\xi(K-1)}; \quad \alpha_k << \alpha$$

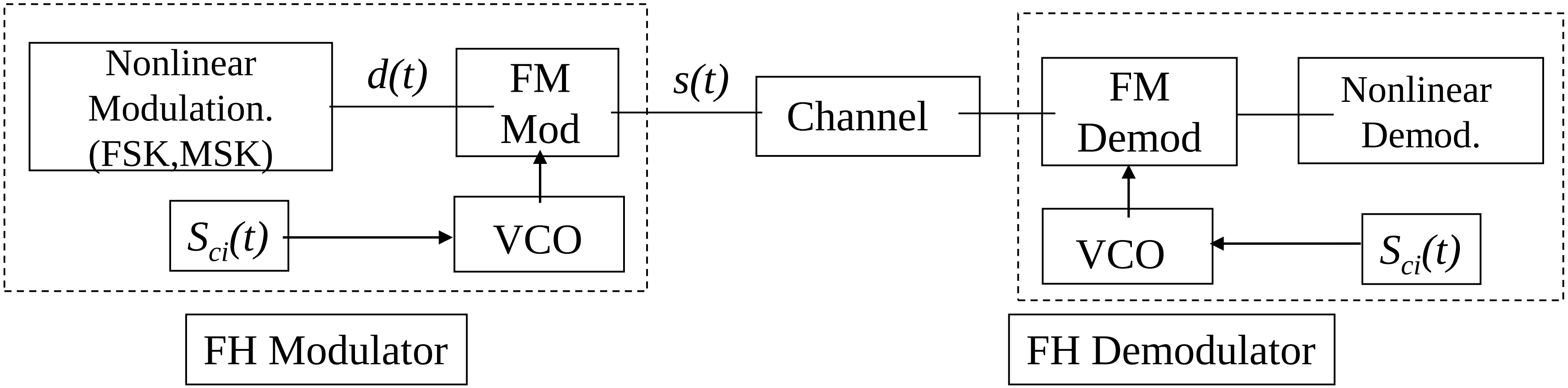
# CDMA vs. TD/FD

- For a spreading gain of *G*, can accommodate *G* TD/FD users in the same bandwidth
  - SNR depends on transmit power
- In CDMA, number of users is SIR-limited

$$SIR = \frac{3G}{\xi(K-1)} \quad \Rightarrow \quad K = 1 + \frac{3G}{\xi \cdot SIR}$$

- For SIR≈3/ξ, same number of users in TD/FD as in CDMA
  - Fewer users if larger SIR is required
  - Different analysis in cellular (Gilhousen et. Al.)

# Frequency Hopping

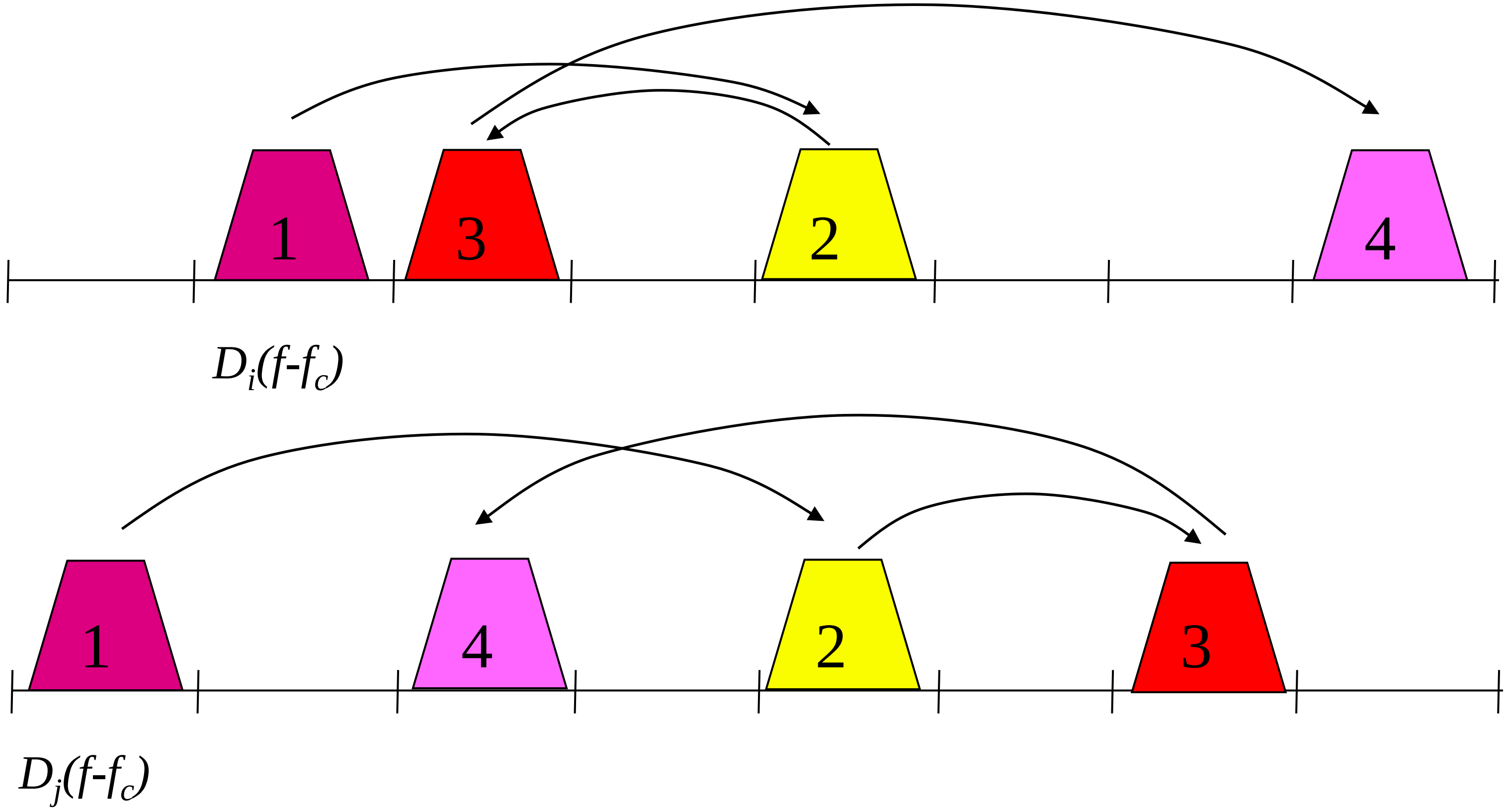


- **Spreading codes used to generate a (slow or fast) “hopping” carrier frequency for *d(t).***
- **Channel BW determined by hopping range.**
  - **Need not be continuous.**
- **Channel introduces ISI, narrowband, and MAC interference**

# Tradeoffs

- Hopping has no effect on AWGN
- No ISI if *d(t)* narrowband, but channel nulls affect certain hops.
- Narrowband interference affects certain hops.
- MAC users collide on some hops.

# Spectral Properties



# Slow vs. Fast Hopping

- Fast Hopping - hop on every symbol
  - NB interference, MAC interference, and channel nulls affect just one symbol.
  - Correct using coding
- Slow Hopping - hop after several symbols
  - NB interference, MAC interference, and channel nulls affect many symbols.
  - Correct using coding and interleaving if # symbols is small.
  - Slow hopping used in cellular to average interference from other cells

# FH vs. DS

- Linear vs. Nonlinear
  - DS is a linear modulation (spectrally efficient) while FH is nonlinear
- Wideband interference/jamming
  - Raises noise spectral density, affects both techniques equally.
- Narrowband interference/jamming
  - DS: interfering signal spread over spread BW, power reduced by spreading gain in demodulator
  - FH: interference affects certain hops, compensate by coding (fast hopping) or coding and interleaving (slow hopping).

# FH vs. DS

- Tone interference
  - DS: tone is wideband, raises noise floor for duration of the tone. Compensate by coding (tone duration=symbol time) or coding and interleaving (tone duration>symbol time). Similar affect as NB interference in FH.
  - FH: Tone affects certain hops. Compensate by coding or coding and interleaving.
- ISI Rejection
  - DS: ISI reduced by code autocorrelation.
  - FH: ISI mostly eliminated.

# FH vs. DS

- MAC interference
  - DS: MAC interference reduced by cross correlation of spreading codes. Each additional user raises noise floor.
    - Overall SNR reduced
  - FH: MAC interference affects certain hops. Each additional user causes more hops to be affected.
    - More bits likely to be received in error.

- Overlay systems: high-power NB interferers
  - Similar impact as with regular interferers
  - DS: Noise floor raised significantly
  - FH: Hops colliding with interferers are lost
  - Can notch out interfering signals

# Evolution of a Scientist turned Entrepreneur

- "Spread spectrum communications - myths and realities," A.J. Viterbi, IEEE Comm. Magazine, May '79 (Linkabit 5 years old - TDMA company).

- "When not to spread spectrum - a sequel," A.J. Viterbi, IEEE Comm. Magazine, April 1985 (Linkabit sold to M/A-Com in 1982)

- "Wireless digital communications: a view based on three lessons learned," A.J. Viterbi, IEEE Comm. Magazine, Sept.'91. (Qualcomm CDMA adopted as standard).

# Myths and Realities

- Myth 1: Redundancy in error correction codes spreads signal bandwidth and thereby reduces processing gain
  - Reality: Effective processing gain increased by coding by considering symbol rate and energy
  - Reality today: coded modulation more efficient even without symbol argument. But tradeoffs between coding and spreading an open issue.

- Myth 2: Error correction codes only good against uniform interference
  - Reality: Not true when coding combined with spread spectrum, since SS averages interference.
  - Reality today: Unchanged.

- Myth 3: Interleaving destroys memory which can be used to correct errors, hence interleaving is bad
  - Reality: Memory preserved by soft-decisions even with an interleaver
  - Reality today: Unchanged, but interleavers may require excessive delays for some applications.

- Myth 4: Direct sequence twice as efficient as frequency hopping
  - Myth=Reality. Argument is that DS is coherent and that accounts for 3dB difference. Analysis shows that higher level signaling alphabets does not help FH performance with partial band jammer.
  - Reality today: A true efficiency tradeoff of FH versus DS has not been done under more general assumptions. FH typically used to average interference. Appealing when continuous spreading BW not available.

# When not to Spread Spectrum - A Sequel ('85)

- **Conclusion 1:** When power is limited, don't contribute to the noise by having users jam one another.

- **Conclusion 2:** Network control is a small price to pay for the efficiency afforded by TDMA or FDMA
  - Power control is a big control requirement.

- **Conclusion 3:** Interference from adjacent cells affects the efficiency of TDMA or FDMA less severely than in CDMA.

- **Conclusion 4:** Treating bandwidth as an inexpensive commodity and processing as an expensive commodity is bucking current technology trends.

- *Application was small earth terminals for commercial satellites.*

# Three Lessons Learned ('91)

- **Never discard information prematurely**
- **Compression can be separated from channel transmission with no loss of optimality**
- **Gaussian noise is worst case. Optimal signal in presence of Gaussian noise has Gaussian distribution. So self-interference should be designed as Gaussian.**

*i.e. spread spectrum optimal* → *Standard for 2G/3G*

# Realities (2011)

- *Never discard information prematurely*
  - Use soft-decisions and sequence detectors
  - Compression can be separated from channel transmission
  - For time-invariant single-user channels only.
- *Self-interference should be Gaussian*
  - Based on Viterbi's argument, this represents a saddle (not optimal) point.
  - If the self-interference is treated as noise, not interference, then Gaussian signaling is suboptimal (by Shannon theory).

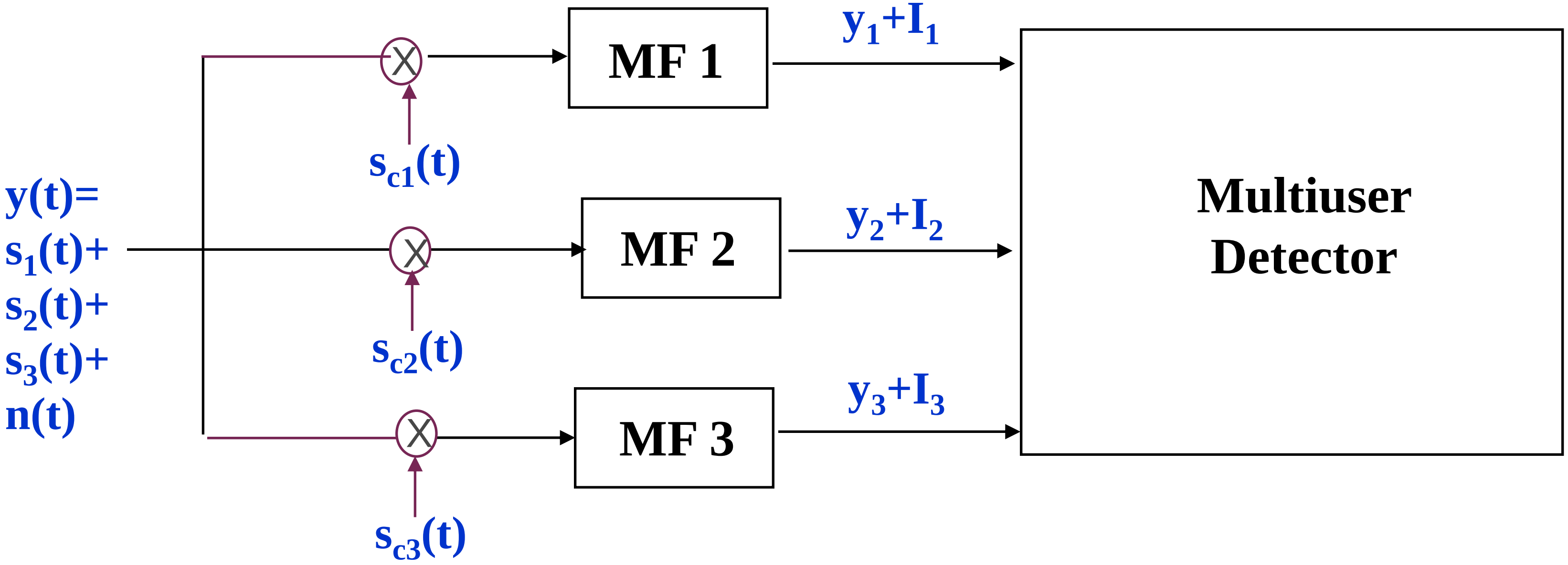
*spread spectrum lost out to OFDM in 4G*

# Multiuser Detection

- In all CDMA systems and in TD/FD/CD cellular systems, users interfere with each other.
- In most of these systems the interference is treated as noise.
  - Systems become interference-limited
  - Often uses complex mechanisms to minimize impact of interference (power control, smart antennas, etc.)
- Multiuser detection exploits the fact that the structure of the interference is known
  - Interference can be detected and subtracted out
  - Better have a darn good estimate of the interference

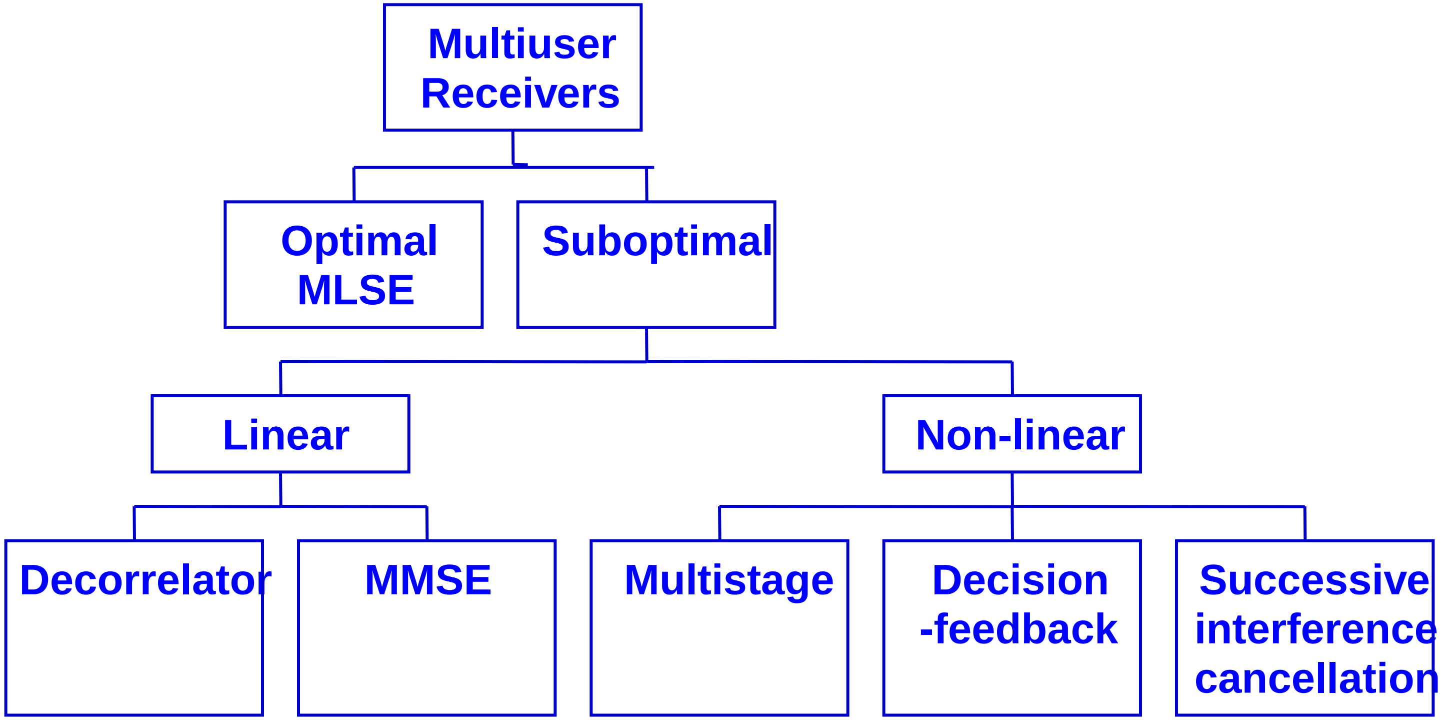
# MUD System Model

*Synchronous Case*



***Matched filter integrates over a symbol time and samples***

# MUD Algorithms



Multiuser Receivers

Optimal MLSE

Suboptimal

Linear

Non-linear

Decorrelator

MMSE

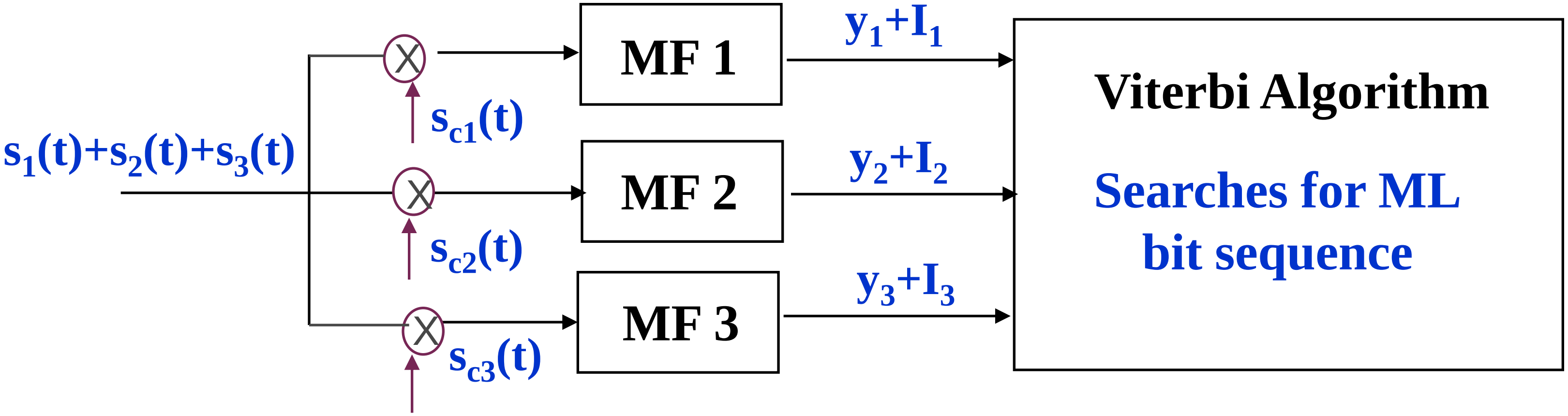
Multistage

Decision-feedback

Successive interference cancellation

# Optimal Multiuser Detection

- Maximum Likelihood Sequence Estimation
  - Detect bits of all users simultaneously ($2^M$ possibilities)
- Matched filter bank followed by the VA (Verdu'86)
  - VA uses fact that $I_i=f(b_j, j\neq i)$
  - Complexity still high: ($2^{M-1}$ states)
  - In asynchronous case, algorithm extends over 3 bit times
    - VA samples MFs in round robin fasion



# Suboptimal Detectors

- Main goal: reduced complexity
- Design tradeoffs
    - Near far resistance
    - Asynchronous versus synchronous
    - Linear versus nonlinear
    - Performance versus complexity
    - Limitations under practical operating conditions
- Common methods
    - Decorrelator
    - MMSE
    - Multistage
    - Decision Feedback
    - Successive Interference Cancellation

# Mathematical Model

- Simplified system model (BPSK)
  - Baseband signal for the $k^{th}$ user is:

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

    - $s_k(i)$ 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
    - $\tau_k$ is the transmission delay; for synchronous CDMA, $\tau_k=0$ for all users
  - Received signal at baseband

$$y(t) = \sum_{k=1}^{K} s_k(t) + n(t)$$

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

# Matched Filter Output

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

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

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

  - 1st term - desired information
  - 2nd term - MAI
  - 3rd term - noise

- Assume two-user case (K=2), and

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

# Symbol Detection

- 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 much stronger than user 2 (near/far problem), the MAI $rc_1x_1$ of user 2 is very large

# Decorrelator

- Matrix representation

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

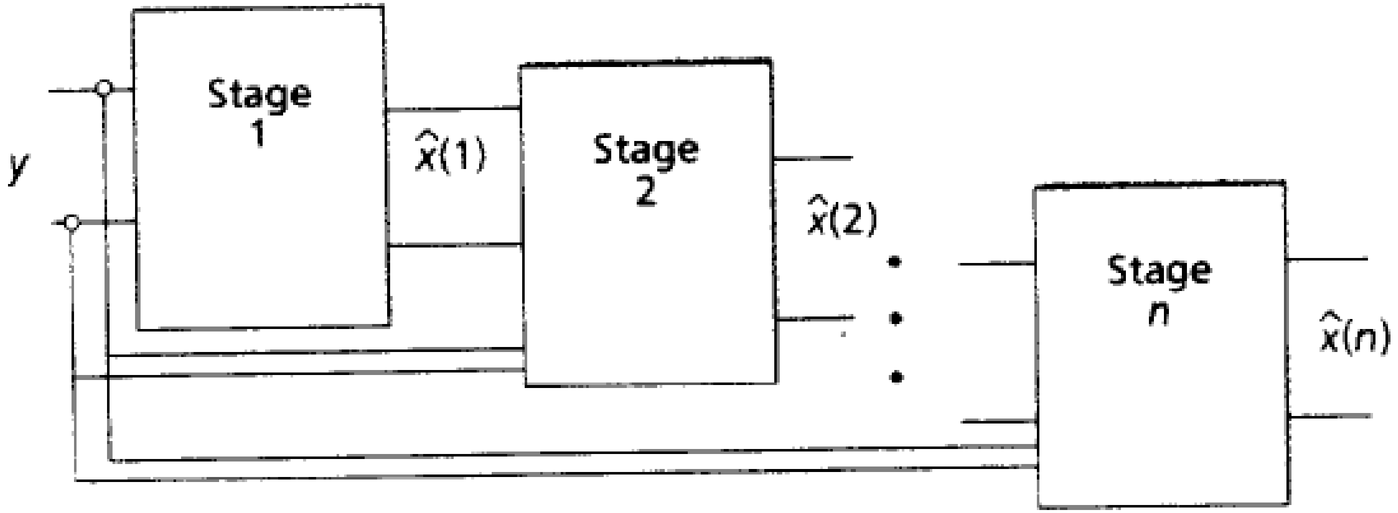
  - where $\underline{y}=[y_1,y_2,\ldots,y_K]^T$, $\boldsymbol{R}$ and $\boldsymbol{W}$ are $\boldsymbol{K}$x$\boldsymbol{K}$ matrices
  - Components of $\boldsymbol{R}$ are cross-correlations between codes
  - $\boldsymbol{W}$ is diagonal with $\boldsymbol{W}_{k,k}$ given by the channel gain $\boldsymbol{c}_k$
  - $\underline{z}$ is a colored Gaussian noise vector
- Solve for $\underline{x}$ by inverting $\boldsymbol{R}$

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

- Analogous to zero-forcing equalizers for ISI
  - 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:** $$\hat{x}_1(2) = \operatorname{sgn}\left[y_1 - rc_2\hat{x}_2(1)\right]$$ $$\hat{x}_2(2) = \operatorname{sgn}\left[y_2 - rc_1\hat{x}_1(1)\right]$$
- **and so on…**



# Successive Interference Cancellers

- Successively subtract off strongest detected bits
- MF output: $b_1 = c_1 x_1 + r c_2 x_2 + z_1$  $b_2 = c_2 x_2 + r c_1 x_1 + z_2$
- Decision made for strongest user: $\hat{x}_1 = \operatorname{sgn}(b_1)$
- Subtract this MAI from the weaker user:

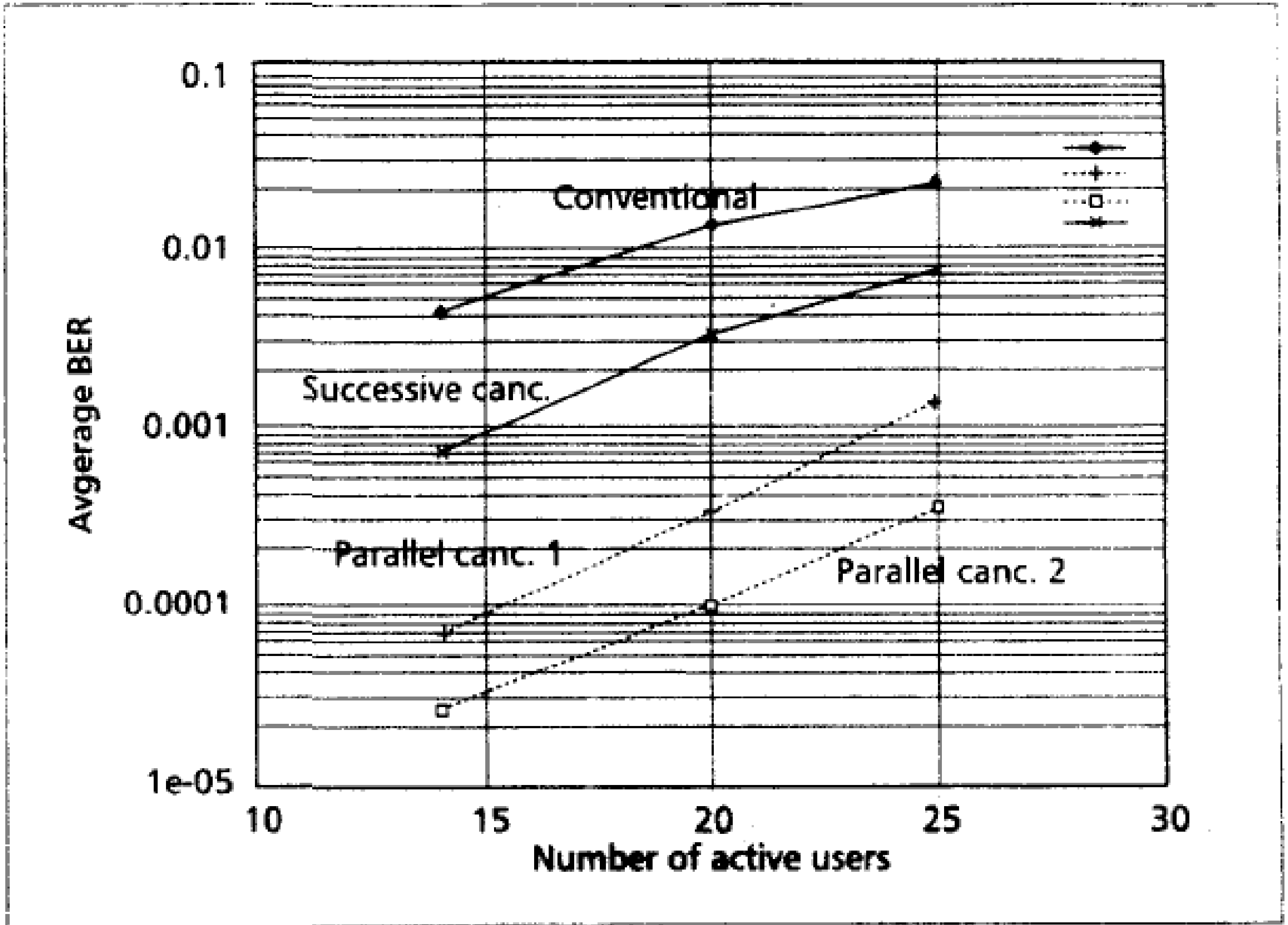
$$\begin{aligned}\hat{x}_2 &= \operatorname{sgn}\left(y_2 - r c_1 \hat{x}_1\right)\\ &= \operatorname{sgn}\left(c_2 x_2 + r c_1\left(x_1 - \hat{x}_1\right) + z_2\right)\end{aligned}$$

  - all MAI can be subtracted is user 1 decoded correctly
- MAI is reduced and near/far problem alleviated
  - Cancelling the strongest signal has the most benefit
  - Cancelling the strongest signal is the most reliable cancellation

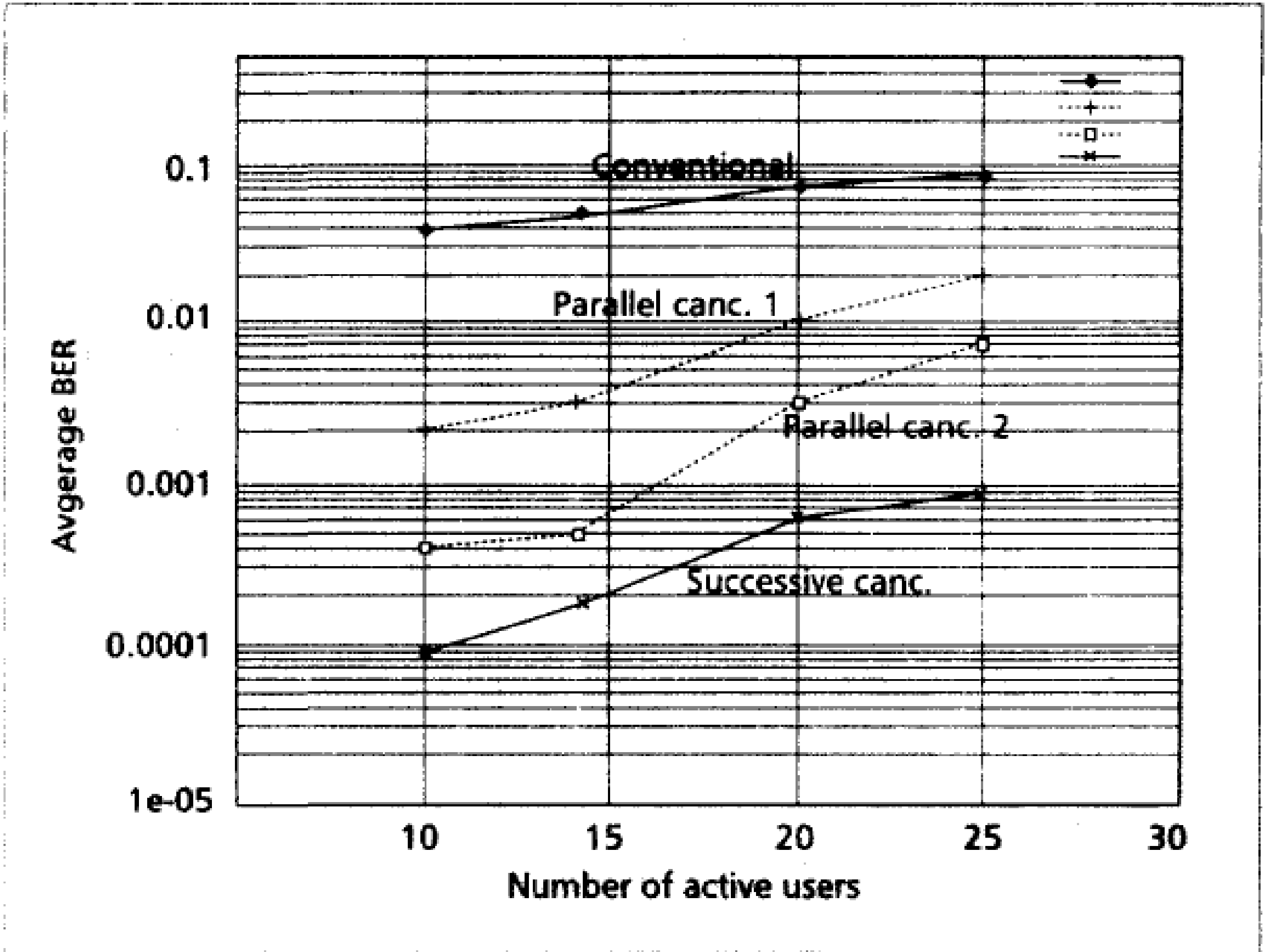
# Parallel Interference Cancellation

- Similarly uses all MF outputs
- Simultaneously subtracts 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: AWGN

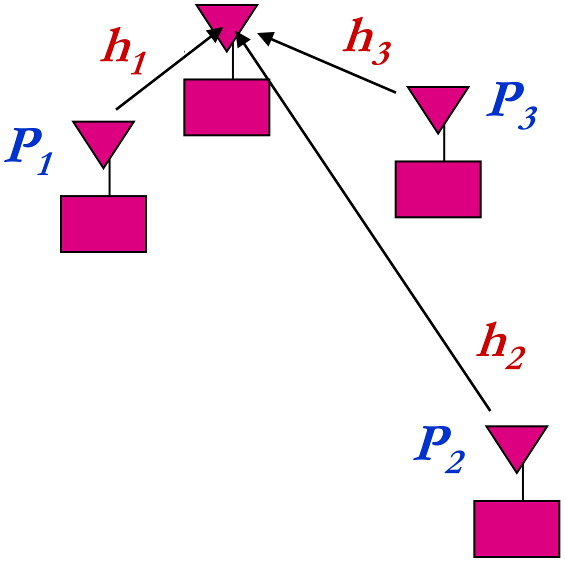


# Performance of MUD Rayleigh Fading



# Near-Far Problem and Traditional Power Control

- On uplink, users have different channel gains
- If all users transmit at same power ($P_i = P$), interference from near user drowns out far user
- "Traditional" power control forces each signal to have the same *received* power
  - Channel inversion: $P_i = P/h_i$
  - Increases interference to other cells
  - Decreases capacity
  - Degrades performance of successive interference cancellation and MUD
    - Can't get a good estimate of any signal



# Near Far Resistance

- Received signals are received at different powers
- MUDs should be insensitive to near-far problem
- Linear receivers typically near-far resistant
  - Disparate power in received signal doesn't affect performance
- Nonlinear MUDs must typically take into account the received power of each user
  - Optimal power spread for some detectors (Viterbi'92)

# Synchronous vs. Asynchronous

- Linear MUDs don't need synchronization
  - Basically project received vector onto state space orthogonal to the interferers
  - Timing of interference irrelevant
- Nonlinear MUDs typically detect interference to subtract it out
  - If only detect over a one bit time, users must be synchronous
  - Can detect over multiple bit times for asynch. users
    - Significantly increases complexity

# Channel Estimation (Flat Fading)

- Nonlinear MUDs typically require the channel gains of each user

- Channel estimates difficult to obtain:
  - Channel changing over time
  - Must determine channel before MUD, so estimate is made in presence of interferers

- Imperfect estimates can significantly degrade detector performance
  - Much recent work addressing this issue
  - Blind multiuser detectors
    - Simultaneously estimate channel and signals

# State Space Methods

- Antenna techniques can also be used to remove interference (smart antennas)
- Combining antennas and MUD in a powerful technique for interference rejection
- Optimal joint design remains an open problem, especially in practical scenarios

# Multipath Channels

- In channels with N multipath components, each interferer creates N interfering signals
  - Multipath signals typically asynchronous
  - MUD must detect and subtract out N(M-1) signals
- Desired signal also has N components, which should be combined via a RAKE.
- MUD in multipath greatly increased
- Channel estimation a nightmare
- Current work focused on complexity reduction and blind MUD in multipath channels (Wang/Poor'99)

# Summary

- MUD a powerful technique to reduce interference
  - Optimal under ideal conditions
  - High complexity: hard to implement
  - Processing delay a problem for delay-constrained apps
  - Degrades in real operating conditions

- Much research focused on complexity reduction, practical constraints, and real channels

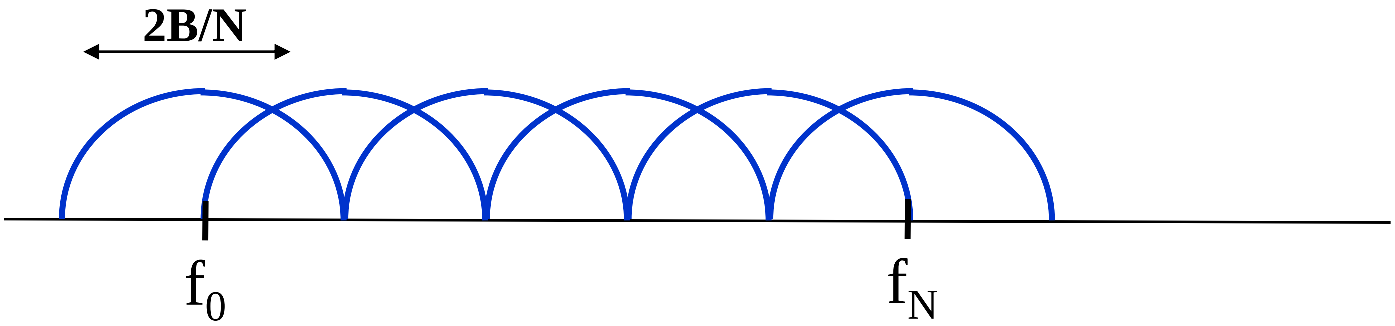
- Smart antennas seem to be more practical and provide greater capacity increase for real systems

# Multiuser OFDM

- MCM/OFDM divides a wideband channel into narrowband subchannels to mitigate ISI
- In multiuser systems these subchannels can be allocated among different users
  - Orthogonal allocation: Multiuser OFDM
  - Semiorthogonal allocation: Multicarrier CDMA
- Adaptive techniques increase the spectral efficiency of the subchannels.
- Spatial techniques help to mitigate interference between users

# OFDM

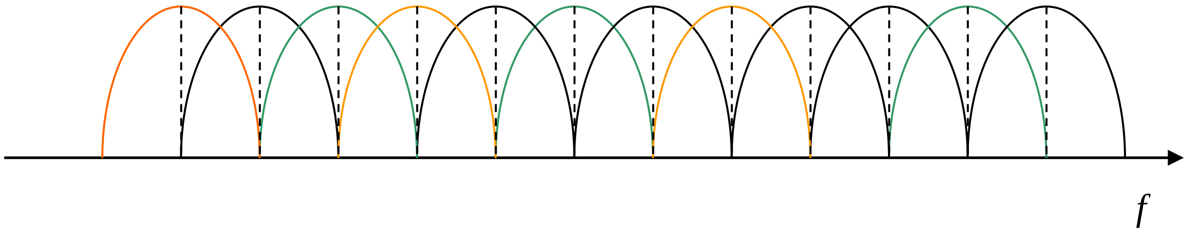
- OFDM overlaps substreams
  - Substreams separated in receiver
  - Minimum substream separation is B/N, total BW is B



- Efficient IFFT structure at transmitter
  - Similar FFT structure at receiver
- Subcarrier orthogonality must be preserved
  - Impaired by timing jitter, frequency offset, and fading.

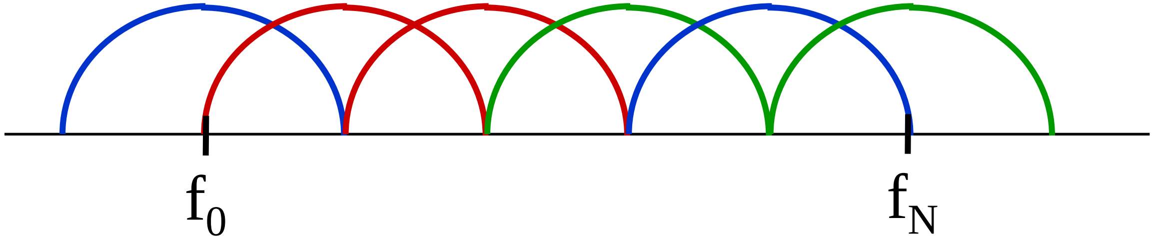
# OFDM-FDMA (a.k.a. OFDMA)

- **Used by the CATV community**
  - **Used to send upstream data from subscriber to cable head-end.**
- **Assigns a subset of available carriers to each user**



# Adaptive OFDM-FDMA

- Different subcarriers assigned to different users
  - Assignment can be orthogonal or semiorthogonal



- The fading on each individual subchannel is independent from user to user
- Adaptive resource allocation gives each their “best” subchannels and adapts optimally to these channels
- Multiple antennas reduces interference when multiple users are assigned the same subchannels

# Adaptive Resource Allocation

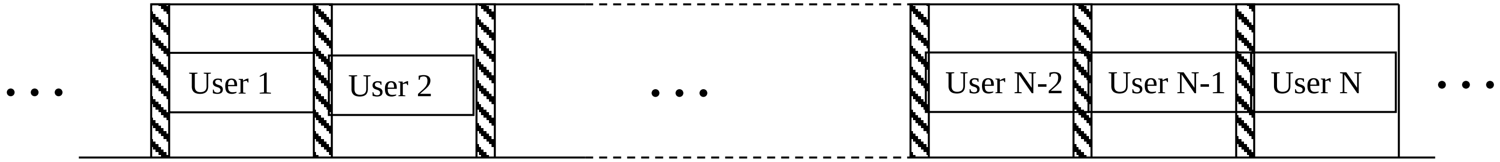
## Orthogonal Subcarrier Allocation

- Degrees of freedom
  - Subcarrier allocation
  - Power
  - Rate
  - Coding
  - BER
- Optimization goals (subject to power constraint):
  - Maximize the sum of average user rates
  - Find all possible average rate vectors (“capacity” region)
  - Find average rate vectors with minimum rate constraints
  - Minimize power for some average rate vector
  - Minimize outage probability for some constant rate vector.

# OFDM-TDMA

- **Each user sequentially sends one or more OFDM symbols per frame**

- **A single OFDM-TDMA frame:**



# Multiuser OFDM with Multiple Antennas

- Multiple antennas at the transmitter and receiver can greatly increase channel capacity

- Multiple antennas also used for spatial multiple access:
  - Users separated by spatial signatures (versus CDMA time signatures)
  - Spatial signatures are typically not orthogonal
  - May require interference reduction (MUD, cancellation, etc.)

- Methods of spatial multiple access
  - Singular value decomposition
  - Space-time equalization
  - Beamsteering

- OFDM required to remove ISI
  - ISI degrades spatial signatures and interference mitigation

# CDMA-based schemes

- **Can combine concepts of CDMA and OFDM**
- **Reap the benefits of both techniques**
- **In 1993, three slightly different schemes were independently proposed:**
  - **MC-CDMA (Yee, Linnartz, Fettweis, and others)***
  - **Multicarrier DS-CDMA (DaSilva and Sousa)***
  - **MT-CDMA (Vandendorpe)**

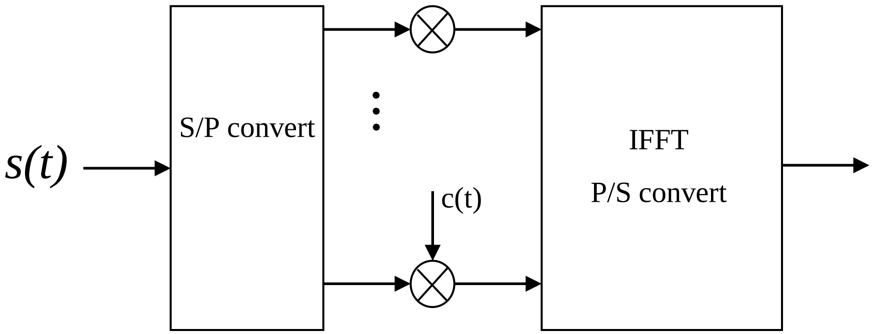
*Stephan's talk

# Multicarrier CDMA

- Multicarrier CDMA combines OFDM and CDMA
- Idea is to use DSSS to spread a narrowband signal and then send each chip over a different subcarrier
  - DSSS time operations converted to frequency domain
- Greatly reduces complexity of SS system
  - FFT/IFFT replace synchronization and despreading
- More spectrally efficient than CDMA due to the overlapped subcarriers in OFDM
- Multiple users assigned different spreading codes
  - Similar interference properties as in CDMA

# Multicarrier DS-CDMA

- The data is serial-to-parallel converted.
- Symbols on each branch spread in time.
- Spread signals transmitted via OFDM
- Get spreading in both time and frequency



# Summary

- OFDM is a well-known technique to combat ISI
- Also very powerful in a multiuser setting
- Some forms of multiuser OFDM lend themselves well to adaptive techniques
- Many high-performance multiuser wireless systems today are based on OFDM techniques.