EE360: Multiuser Wireless Systems and Networks

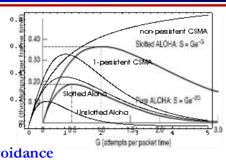
Lecture 4 Outline

- 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



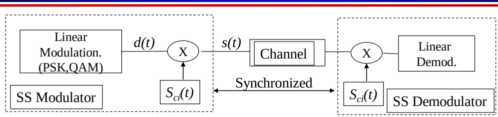
- Dedicated channels wasteful
  - Use statistical multiplexing
- Random Access Techniques
  - Aloha (Pure and Slotted)
  - Carrier sensing
    - Can include collision detection/avoidance
    - If channel busy, deterministic or random delay (non-persistent)
  - Poor performance in heavy loading
- Reservation 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

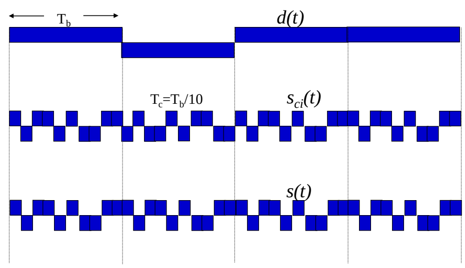
Note: spreading is 2nd modulation (after bits encoded into digital waveform, e.g. BPSK). DS spreading codes are inherently digital.

Direct Sequence

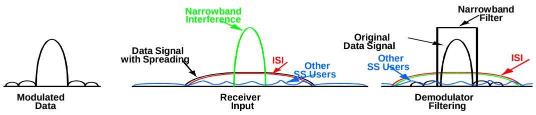


- Chip time T_c is N times the symbol time T_s.
- Bandwidth of $s(t)$ is $N+1$ times that of $d(t)$.
- Channel introduces noise, ISI, narrowband and multiple access interference.
  - Spreading has no effect on AWGN noise
  - ISI delayed by more than T_c reduced by code autocorrelation
  - narrowband 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 τ.
  - $\rho(\tau)=\delta(\tau)$ 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:

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

- 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 τ 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)

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

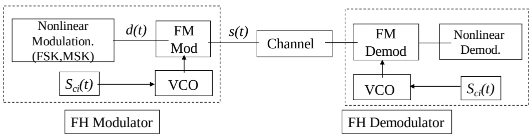
CDMA vs. TD/FD

- 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

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

- 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

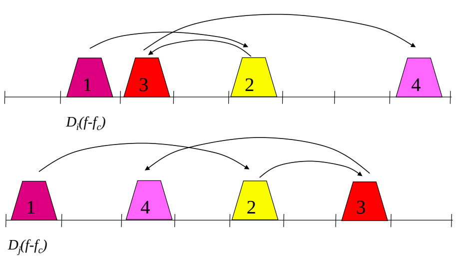


- Spreading codes used to generate a (slow or fast) "hopping" carrier frequency for *d(t).*
- Channel BW determined by hopping range.
  - Need not be continuous.
- Channel introduces ISI, narrowband, and MAC interference

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).

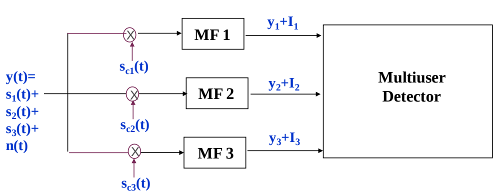
spread spectrum lost out to OFDM in 4G

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

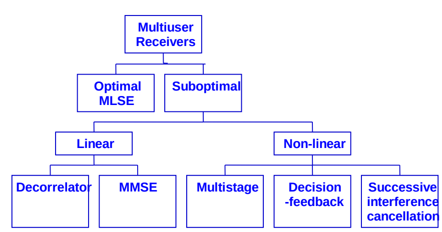
MUD System Model

Synchronous Case



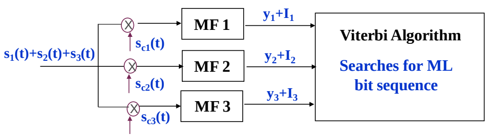
Matched filter integrates over a symbol time and samples

MUD Algorithms



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

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

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

Matched Filter Output

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

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

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

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

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

Symbol Detection

- Outputs of the matched filters are:

$$y_1=c_1x_1+rc_2x_2+z_1 \qquad y_2=c_2x_2+rc_1x_1+z_2$$

- Detected symbol for user k: $\hat{x}_k=\mathrm{sgn}(y_k)$
- 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

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

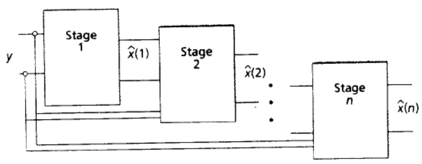
  - where $\underline{y}=[y_1,y_2,\ldots,y_K]^T$, R and W are KxK matrices
  - Components of R are cross-correlations between codes
  - W is diagonal with $W_{k,k}$ given by the channel gain c_k
  - $\underline{z}$ is a colored Gaussian noise vector
- Solve for $\underline{x}$ by inverting R

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

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



Successive Interference Cancellers

- Successively subtract off strongest detected bits
- MF output: $b_1 = c_1x_1 + rc_2x_2 + z_1 \qquad b_2 = c_2x_2 + rc_1x_1 + z_2$
- Decision made for strongest user: $\hat{x}_1 = \mathrm{sgn}(b_1)$
- Subtract this MAI from the weaker user:

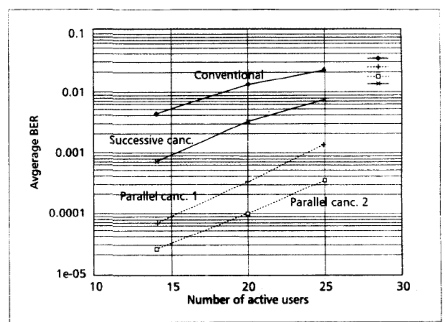
$$\hat{x}_2 = \mathrm{sgn}(y_2 - rc_1\hat{x}_1)$$
$$= \mathrm{sgn}(c_2x_2 + rc_1(x_1 - \hat{x}_1) + z_2)$$

  - 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

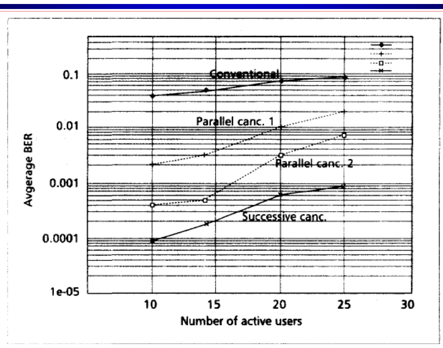
Parallel Interference Cancellation

- 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

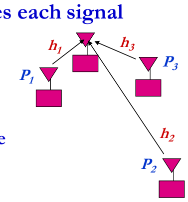


Performance of MUD Rayleigh Fading



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

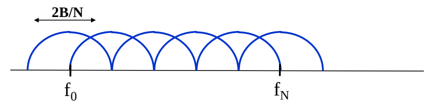
- MUD a powerful technique to reduce interference
  - Optimal under ideal conditions
  - High complexity: hard to implement
  - Processing delay a problem for delay-constrained apps
  - Degrades in real operating conditions
- Much research focused on complexity reduction, practical constraints, and real 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

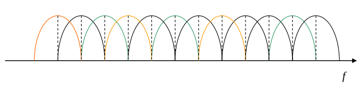
- OFDM overlaps substreams
  - Substreams separated in receiver
  - Minimum substream separation is B/N, total BW is B



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

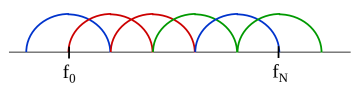
OFDM-FDMA (a.k.a. OFDMA)

- 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

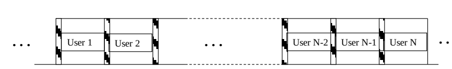
Adaptive Resource Allocation

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)

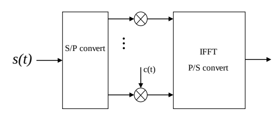
*Stephan's talk

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.