EE360: Lecture 5 Outline
Cellular Systems

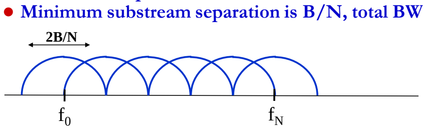
- Announcements
  - Project proposals due Feb. 1 (1 week)
  - Makeup lecture Feb 2, 5-6:15, Gates
- Multiuser OFDM and OFDM/CDMA
- Cellular System Overview
- Design Considerations
- Standards
- Cellular System Capacity
- MIMO in Cellular
- Multiuser Detection in Cellular

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

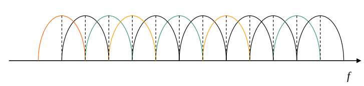
- OFDM overlaps substreams
  - Substreams separated in receiver
  - Minimum substream separation is B/N, total BW is B



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

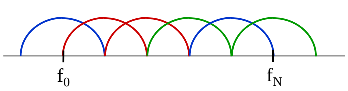
OFDM-FDMA
(a.k.a. OFDMA)

- 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



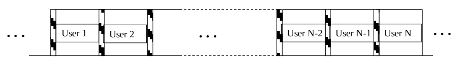
- The fading on each individual subchannel is independent from user to user
- Adaptive resource allocation gives each their "best" subchannels and adapts optimally to these channels
- Multiple antennas reduces interference when multiple users are assigned the same subchannels

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

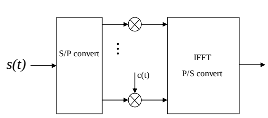
- Can combine concepts of CDMA and OFDM
- Reap the benefits of both techniques
- In 1993, three slightly different schemes were independently proposed:
  - MC-CDMA (Yee, Linnartz, Fettweis, and others)
  - Multicarrier DS-CDMA (DaSilva and Sousa)
  - MT-CDMA (Vandendorpe)

Multicarrier CDMA

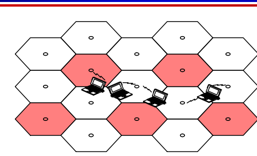
- Multicarrier CDMA combines OFDM and CDMA
- Idea is to use DSSS to spread a narrowband signal and then send each chip over a different subcarrier
  - DSSS time operations converted to frequency domain
- Greatly reduces complexity of SS system
  - FFT/IFFT replace synchronization and despreading
- More 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



Cellular System Overview



- Frequencies (or time slots or codes) are reused at spatially-separated locations ⇒ exploits power falloff with distance.
- Base stations perform centralized control functions (call setup, handoff, routing, etc.)
- Best efficiency obtained with minimum reuse distance
  - System capacity is interference-limited.

Basic Design Considerations

- Spectral Sharing
  - TD,CD or hybrid (TD/FD)
  - Frequency reuse
- Reuse Distance
  - Distance between cells using the same frequency, timeslot, or code
  - Smaller reuse distance packs more users into a given area, but also increases co-channel interference
- Cell radius
  - Decreasing the cell size increases system capacity, but complicates routing and handoff
- Resource allocation: power, BW, etc.

1-2 G Cellular Design:
Voice Centric

- Cellular *coverage* is designed for voice service
  - Area outage, e.g. < 10% or < 5%.
  - Minimal, but equal, service everywhere.
- Cellular *systems* are designed for voice
  - 20 ms framing structure
  - Strong FEC, interleaving and decoding delays.
- Spectral Efficiency
  - around 0.04-0.07 bps/Hz/sector
  - comparable for TDMA and CDMA

IS-54/IS-136 (TD)

- FDD separates uplink and downlink.
- Timeslots allocated between different cells.
  - FDD separates uplink and downlink.
- One of the US standards for digital cellular
  - IS-54 in 900 MHz (cellular) band.
  - IS-136 in 2 GHz (PCS) band.
- IS-54 compatible with US analog system.
  - Same frequencies and reuse plan.

GSM (TD with FH)

- FDD separates uplink and downlink.
- Access is combination of FD,TD, and slow FH
  - Total BW divided into 200Khz channels.
  - Channels reused in cells based on signal and interference measurements.
  - All signals modulated with a FH code.
    - FH codes within a cell are orthogonal.
    - FH codes in different cells are semi-orthgonal
  - FH mitigates frequency-selective fading via coding.
  - FH averages interference via the pseudorandom hop pattern

IS-95 (CDMA)

- Each user assigned a unique DS spreading code
  - Orthogonal codes on the downlink
  - Semiorthogonal codes on the uplink
- Code is reused in every cell
  - No frequency planning needed
  - Allows for soft handoff is code not in use in neighboring cell
- Power control required due to near-far problem
  - Increases interference power of boundary mobiles.

3G Cellular Design:
Voice and Data

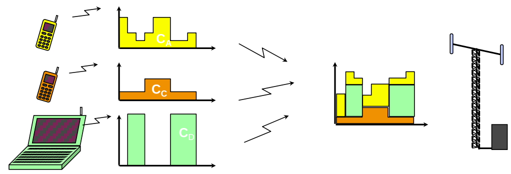
- Goal (early 90s): A single worldwide air interface
  - Yeah, right
- Bursty Data => Packet Transmission
  - Simultaneous with circuit voice transmisison
- Need to "widen the data pipe":
  - 384 Kbps outdoors, 1 Mbps indoors.
- Need to provide QOS
  - Evolve from best effort to statistical or "guaranteed"
- Adaptive Techniques
  - Rate (spreading, modulation/coding), power, resources, signature sequences, space-time processing, MIMO

3G GSM-Based Systems

- EDGE: Packet data with adaptive modulation and coding
- 8-PSK/GMSK at 271 ksps supports 9.02 to 59.2 kbps per time slot with up to 8 time-slots
- Supports peak rates over 384 kbps
- IP centric for both voice and data

3G CDMA Approaches
W-CDMA and cdma2000

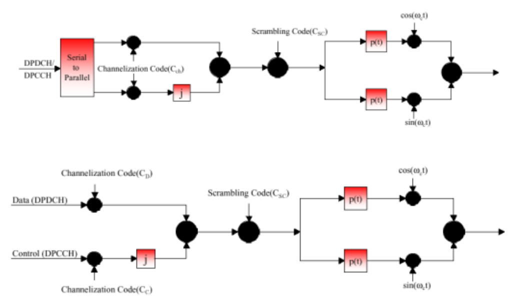
- cdma2000 uses a multicarrier overlay for IS-95 compatibility
- WCDMA designed for evolution of GSM systems
  - Current 3G services based on WCDMA
  - Voice, streaming, high-speed data
  - Multirate service via variable *power* and *spreading*
  - Different services can be mixed on a single code for a user



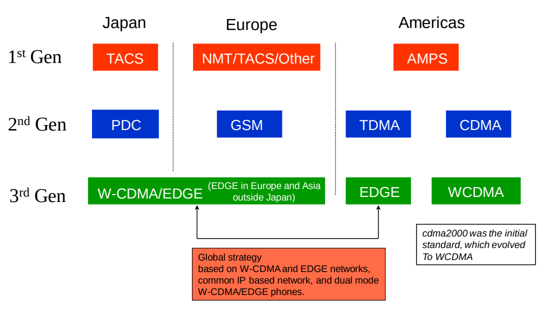
Features of WCDMA

Bandwidth	5, 10, 20 MHz
Spreading codes	Orthogonal variable spreading factor (OVSF) SF: 4-256
Scrambling codes	DL- Gold sequences. (len-18) UL- Gold/Kasami sequences (len-41)
Data Modulation	DL - QPSK UL - BPSK
Data rates	144 kbps, 384 kbps, 2 Mbps
Duplexing	FDD

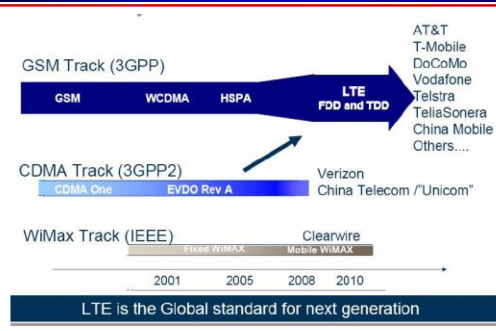
UL and DL Spreading



Cellular Evolution: 1G-3G



4G Evolution



Long-Term Evolution (LTE)

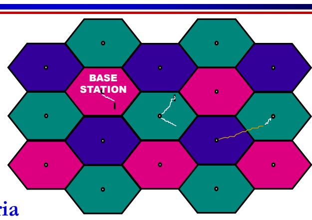
- OFDM/MIMO
- Much higher data rates (50-100 Mbps)
- Greater spectral efficiency (bits/s/Hz)
- Flexible use of up to 100 MHz of spectrum
- Low packet latency (<5ms).
- Increased system capacity
- Reduced cost-per-bit
- Support for multimedia

Improving Performance

- Dynamic resource allocation
  - Dynamic time/freq/code allocation
  - Power control
- Antenna and MIMO techniques
  - Sectorization and smart antennas
  - Space-time processing
  - Diversity/interference cancellation tradeoffs
- Interference cancellation
  - Multiuser detection

Dynamic Resource Allocation

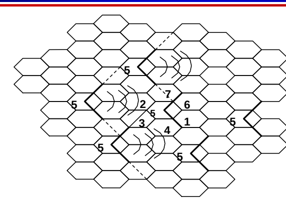
Allocate resources as user and network conditions change



- Resources:
  - Channels
  - Bandwidth
  - Power
  - Rate
  - Base stations
  - Access
- Optimization criteria
  - Minimize blocking (voice only systems)
  - Maximize number of users (multiple classes)
  - Maximize "revenue"
    - Subject to some minimum performance for each user

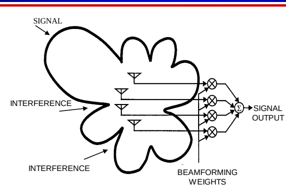
More on Wednesday

Sectorization and Smart Antennas



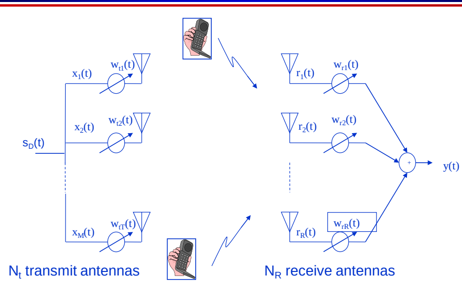
- 120^0 sectoring reduces interference by one third
- Requires base station handoff between sectors
- Capacity increase commensurate with shrinking cell size
- Smart antennas typically combine sectorization with an intelligent choice of sectors

Beam Steering



- Beamforming weights used to place nulls in up to N_R directions
  - Can also enhance gain in direction of desired signal
  - Requires AOA information for signal and interferers

Diversity vs. Interference Cancellation



Romero and Goldsmith: Performance comparison of MRC and IC Under transmit diversity, IEEE Trans. Wireless Comm., May 2009

Diversity/IC Tradeoffs

- N_R antennas at the RX provide N_R-fold diversity gain in fading
  - Get $N_T N_R$ diversity gain in MIMO system
- Can also be used to null out N_R interferers via beam-steering
  - Beam steering at TX reduces interference at RX
- Antennas can be divided between diversity combining and interference cancellation
- Can determine optimal antenna array processing to minimize outage probability

Diversity Combining Techniques

- MRC diversity achieves maximum SNR in fading channels.
- MRC is suboptimal for maximizing SINR in channels with fading and interference
- Optimal Combining (OC) maximizes SINR in both fading and interference
  - Requires knowledge of all desired and interferer channel gains at each antenna

SIR Distribution and P_{out}

- Distribution of γ obtained using similar analysis as MRC based on MGF techniques.
- Leads to closed-form expression for P_{out}.
  - Similar in form to that for MRC
- Fo L>N, OC with equal average interference powers achieves the same performance as MRC with $N-1$ fewer interferers.

Performance Analysis for IC

- Assume that N antennas perfectly cancel N-1 strongest interferers
  - General fading assumed for desired signal
  - Rayleigh fading assumed for interferers
- Performance impacted by remaining interferers and noise
  - Distribution of the residual interference dictated by order statistics

SINR and Outage Probability

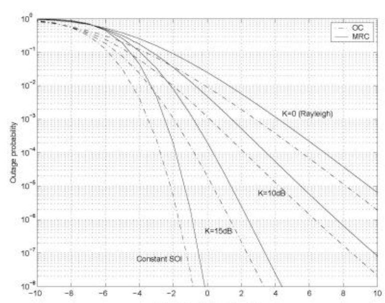
- The MGF for the interference can be computed in closed form
  - pdf is obtained from MGF by differentiation
- Can express outage probability in terms of desired signal and interference as

$$P_{out}|_{Y=y} = P(X < \beta(y+\sigma^2)) = 1 - e^{-\beta(y+\sigma^2)/P_s}$$

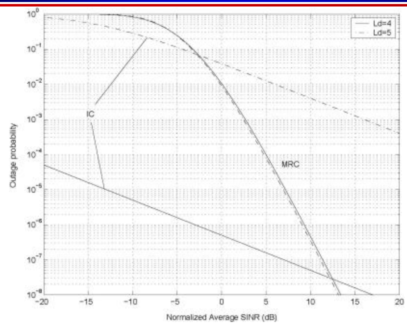
- Unconditional P_{out} obtained as

$$P_{out} = 1 - e^{-\beta(y+\sigma^2)/P_s} \int_0^\infty e^{-\beta y/P_s} f_Y(y)dy$$

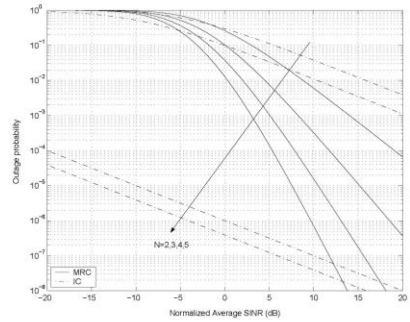
OC vs. MRC for Rician fading



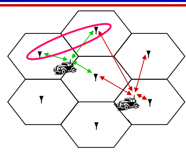
IC vs MRC as function of No. Ints



Diversity/IC Tradeoffs



MIMO Techniques in Cellular



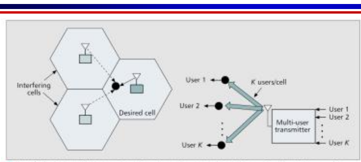
- How should MIMO be *fully* used in cellular systems?
- Shannon capacity requires dirty paper coding or IC
- Network MIMO: Cooperating BSs form an antenna array
  - Downlink is a MIMO BC, uplink is a MIMO MAC
  - Can treat “interference” as known signal (DPC) or noise
  - Shannon capacity will be covered later this week
- Multiplexing/diversity/interference cancellation tradeoffs
  - Can optimize receiver algorithm to maximize SINR

MIMO in Cellular: *Performance Benefits*

- Antenna gain ⇒ extended battery life, extended range, and higher throughput
- Diversity gain ⇒ improved reliability, more robust operation of services
- Interference suppression (TXBF) ⇒ improved quality, reliability, and robustness
- Multiplexing gain ⇒ higher data rates
- Reduced interference to other systems

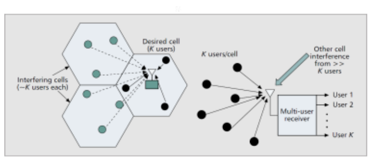
Optimal use of MIMO in cellular systems, especially given practical constraints, remains an open problem

MUD in Cellular



*In the **downlink scenario**, each RX only needs to decode its own signal, while suppressing other-cell interference from just a few dominant neighboring cells. Because all K users’ signals originate at the base station, the link is synchronous and the K – 1 intracell interferers can be orthogonalized at the base station transmitter. Typically, though, some orthogonality is lost in the channel.*

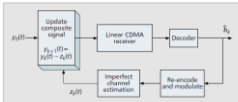
*In **the uplink scenario**, the BS RX must decode all K desired users, while suppressing other-cell interference from many independent users. Because it is challenging to dynamically synchronize all K desired users, they generally transmit asynchronously with respect to each other, making orthogonal spreading codes unviable.*



MUD in Cellular

- Goal: decode interfering signals to remove them from desired signal
- Interference cancellation
  - – decode strongest signal first; subtract it from the remaining signals
  - – repeat cancellation process on remaining signals
  - – works best when signals received at very different power levels
- Optimal multiuser detector (Verdu Algorithm)
  - – cancels interference between users in parallel
  - – complexity increases exponentially with the number of users
- Other techniques trade off performance and complexity
  - – decorrelating detector
  - – decision-feedback detector
  - – multistage detector
- MUD often requires channel information; can be hard to obtain

Successive Interference Cancellers

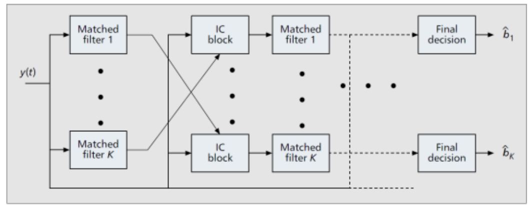


- Successively subtract off strongest detected bits
- MF output: $b_1 = c_1 x_1 + r c_2 x_2 + z_1 \qquad b_2 = c_2 x_2 + r c_1 x_1 + z_2$
- Decision made for strongest user: $\hat{x}_1 = \text{sgn}(b_1)$
- Subtract this MAI from the weaker user:

$$\hat{x}_2 = \text{sgn}(y_2 - r c_1 \hat{x}_1) = \text{sgn}(c_2 x_2 + r c_1 (x_1 - \hat{x}_1) + z_2)$$

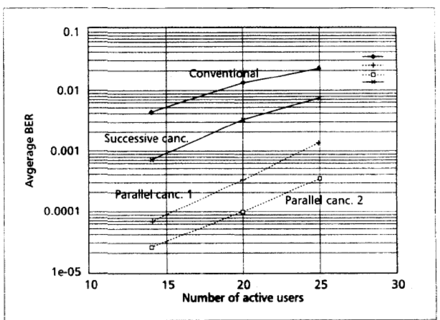
  - all MAI can be subtracted is user 1 decoded correctly
- MAI is reduced and near/far problem alleviated
  - Cancelling the strongest signal has the most benefit
  - Cancelling the strongest signal is the most reliable cancellation

Parallel Interference Cancellation



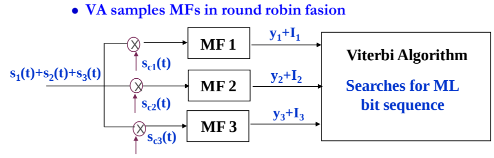
- Similarly uses all MF outputs
- Simultaneously subtracts off all of the users' signals from all of the others
- works better than SIC when all of the users are received with equal strength (e.g. under power control)

Performance of MUD: AWGN



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



Tradeoffs

MUD type	Complexity order	Latency	ECCs?	$K > N$ allowed?
Optimal max. likelihood	2^K	1	Separate	Yes
Linear	K to K^3	1	Separate[1]	No (ZF), Yes (MMSE)
Turbo	PK to 2^K	$2P$	Integrated	Yes
Parallel IC	PK	P	Integrated	Yes
Successive IC	K	K	Integrated	Yes
Nonorth. matched filter	K	1	Separate	Yes[2]
Orth. matched filter	K	1	Separate	No

[1] With some exceptions (e.g., [39]), generally linear receivers cannot seamlessly integrate ECCs.
[2] Although allowed in principle, $K > N$ is not likely to be achievable in practice for the MF receiver.

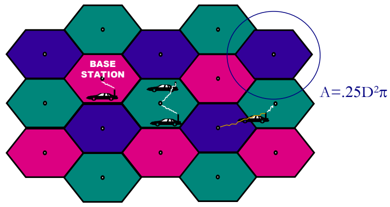
Table 1. *Key general trends of different multiuser receivers, with spreading factor N, number of users K, and P receiver stages.*

Cellular System Capacity

- Shannon Capacity
  - Shannon capacity does no incorporate reuse distance.
  - Some results for TDMA systems with joint base station processing (more later this week).
- User Capacity
  - Calculates how many users can be supported for a given performance specification.
  - Results highly dependent on traffic, voice activity, and propagation models.
  - Can be improved through interference reduction techniques. (Gilhousen et. al.)
- Area Spectral Efficiency
  - Capacity per unit area

In practice, all techniques have roughly the same capacity

Area Spectral Efficiency



- S/I increases with reuse distance.
- For BER fixed, tradeoff between reuse distance and link spectral efficiency (bps/Hz).
- Area Spectral Efficiency: $A_e=\Sigma R_i/(.25D^2\pi)$ bps/Hz/Km^2.

ASE with Adaptive Modulation

- Users adapt their rates (and powers) relative to S/I variation.
- S/I distribution for each user based on propagation and interference models.

$$\gamma_d = S_d / \sum S_i$$

  - Computed for extreme interference conditions.
  - Simulated for average interference conditions.
- The maximum rate R_i for each user in a cell is computed from its S/I distribution.
  - For narrowband system use adaptive MQAM analysis

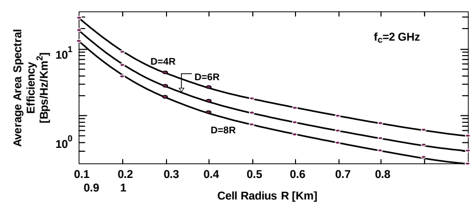
Propagation Model

- Two-slope path loss model:

$$\bar{S}_r(d) = \frac{K}{d^a(1+d/g)^b}\bar{S}_t,$$

- Slow fading model: log-normal shadowing
- Fast fading model: Nakagami-m
  - Models Rayleigh and approximates Ricean.
- *ASE maximized with reuse distance of one!*
  - Adaptive modulation compensate for interference

ASE vs. Cell Radius



Summary

- Wireless data/multimedia are main drivers for future generations of cellular systems.
  - Killer application unknown; how will cellular users access the Internet; will cellular or WLANs prevail.
- Efficient systems are interference-limited
  - Interference reduction key to high system capacity
- Adaptive techniques in cellular can improve significantly performance and capacity
- MIMO a powerful technique, but impact on out-of-cell interference and implementation unknown.

Presentation

- "On the capacity of a cellular CDMA system" by S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, C. E. Wheatley