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:

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 \( \Rightarrow \) 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.

### 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.

### 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.

### 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

### 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-orthogonal
  - FH mitigates frequency-selective fading via coding.
  - FH averages interference via the pseudorandom hop pattern

### 3G Cellular Design: Voice and Data

- **Goal** (early 90s): A single worldwide air interface
  - Yeah, right
- **Bursty Data => Packet Transmission**
  - Simultaneous with circuit voice transmission
- **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 kbps 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

1st Gen
- Japan: TACS
- Europe: NMT/TACS/Other
- Americas: AMPS

2nd Gen
- Japan: PDC
- Europe: GSM
- Americas: TDMA, CDMA

3rd Gen
- Japan: W-CDMA/EDGE
- Europe/Asia: EDGE/WCDMA
- Americas: EDGE/WCDMA

4G Evolution

- GSM (3GPP), WCDMA (3GPP2), TDMA, CDMA One, WiMax (IEEE)
- LTE (FDD and TDD)
- AT&T, T-Mobile, DoCoMo, Vodafone, Telsis, China Mobile, Others...

LTE is the global standard for next generation
**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° 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
**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 $\gamma$ 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.
- For $L>N$, 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
  \[ P_{out|\gamma} = P(X < \beta(y + \sigma^2)) = 1 - e^{-\beta(y + \sigma^2)/P} \]
- Unconditional $P_{out}$ obtained as
  \[ P_{out} = 1 - e^{-\beta(y + \sigma^2)/P} \int_0^\infty e^{-\beta(y + \sigma^2)/P} f_y(y)\,dy \]

**OC vs. MRC for Rician fading**

![Image showing OC vs. MRC for Rician fading](image_url)
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

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 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 users’ signals originating at the base station, the link is asynchronous and the K – 1 intracell interferers can be orthogonalized at the base station transmitter. Typically, though, some orthogonality is lost in the channel.

• 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

MUD in Cellular

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

- Successively subtract off strongest detected bits
- MF output: \( h_i = c_i x_i + r c_i x_i + z_i \)  
- Decision made for strongest user:  
  \[ \hat{x}_i = \text{sgn}(h_i) \]
- Subtract this MAI from the weaker user:
  \[ \hat{x}_j = \text{sgn}(y_j - r c_j \hat{x}_i) \]
- All MAI can be subtracted if 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

- 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 fashion

Optimal Multiuser Detection

- Shannon Capacity
  - Shannon capacity does not 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

Cellular System Capacity

- 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: \( A_e = \sum R_i / (0.25D^2p) \) bps/Hz/Km².

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.
  \( \gamma_r = S_r / \sum S_i \)
  - 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

ASE vs. Cell Radius

- Two-slope path loss model:
  \( S(d) = K d^{-\alpha} (d + g)^{-\beta} \).
- 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

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