EE360: Lecture 6 Outline

MUD/MIMO in Cellular Systems

• Announcements
  • Project proposals due today
  • Makeup lecture tomorrow Feb 2, 5-6:15, Gates 100

• Multiuser Detection in cellular

• MIMO in Cellular
  • Multiuser MIMO/OFDM
  • Multiplexing/diversity/IC tradeoffs
  • Distributed antenna systems
  • Virtual MIMO
  • Brian’s presentation
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.

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.
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: $b_1 = c_1x_1 + rc_2x_2 + z_1 \quad b_2 = c_2x_2 + rc_1x_1 + z_2$
- Decision made for strongest user: $\hat{x}_1 = \text{sgn}(b_1)$
- Subtract this MAI from the weaker user:
  \[
  \hat{x}_2 = \text{sgn}(y_2 - rc_1\hat{x}_1) \\
  = \text{sgn}(c_2x_2 + rc_1(x_1 - \hat{x}_1) + z_2)
  \]
  - 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

![Graph showing the performance of MUD in AWGN with three different methods: Conventional, Successive canc., Parallel canc. 1, Parallel canc. 2. The x-axis represents the number of active users, and the y-axis represents the average BER. The graph illustrates how the performance of MUD varies with the number of active users.]
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 fashion

$$s_1(t) + s_2(t) + s_3(t)$$

VF 1

$$y_1 + I_1$$

VF 2

$$y_2 + I_2$$

VF 3

$$y_3 + I_3$$

Viterbi Algorithm

Searches for ML bit sequence
## Tradeoffs

<table>
<thead>
<tr>
<th>MUD type</th>
<th>Complexity order</th>
<th>Latency</th>
<th>ECCs?</th>
<th>$K &gt; N$ allowed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal max. likelihood</td>
<td>$2^K$</td>
<td>1</td>
<td>Separate</td>
<td>Yes</td>
</tr>
<tr>
<td>Linear</td>
<td>$K$ to $K^3$</td>
<td>1</td>
<td>Separate$^1$</td>
<td>No (ZF), Yes (MMSE)</td>
</tr>
<tr>
<td>Turbo</td>
<td>$PK$ to $2^K$</td>
<td>$2P$</td>
<td>Integrated</td>
<td>Yes</td>
</tr>
<tr>
<td>Parallel IC</td>
<td>$PK$</td>
<td>$P$</td>
<td>Integrated</td>
<td>Yes</td>
</tr>
<tr>
<td>Successive IC</td>
<td>$K$</td>
<td>$K$</td>
<td>Integrated</td>
<td>Yes</td>
</tr>
<tr>
<td>Nonorth. matched filter</td>
<td>$K$</td>
<td>1</td>
<td>Separate</td>
<td>Yes$^2$</td>
</tr>
<tr>
<td>Orth. matched filter</td>
<td>$K$</td>
<td>1</td>
<td>Separate</td>
<td>No</td>
</tr>
</tbody>
</table>

$^1$ 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.
MIMO Techniques in Cellular

- How should MIMO be fully used in cellular systems?
- Shannon capacity requires dirty paper coding or IC (Thur)
- 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
Multiuser OFDM with Multiple Antennas

- MIMO greatly increases 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

- Use similar optimization formulation for resource allocation

“Spatial Multiuser Access OFDM With Antenna Diversity and Power Control”
J. Kim and J. Cioffi, VTC 2000
Resulting Power Control Algorithm

- **Waterfill for all K users if:**
  - Perfect interference cancellation, or
  - BER constraint is satisfied

- **When interference kicks in:**
  - Do not assign further energy, instead, use it on other channels.
Performance Results

• Pe < 0.01 on all active subchannels
Comparison to Other Methods:

- Has path diversity versus beamforming

- Space Time Equalizer:

\[ W(f) = [H^*(f)H(f)]^{-1}H^*(f) \]

- Noise enhancement when signal fades
- Since channel gain (\( \Lambda \)) not present in SVD, channel model updates less frequently, and is less prone to channel estimation errors
- SVD less prone to near/far because of spatial isolation.
Summary of OFDM/MIMO

- OFDM compensates for ISI
  - Flat fading can be exploited
- One spatial mode per user per frequency
- Receiver spatially separates multiple users on a frequency
- Traditional detection methods used
- Power control similar to other systems
Spatial multiplexing provides for multiple data streams

TX beamforming and RX diversity provide robustness to fading

TX beamforming and RX nulling cancel interference
- Can also use DSP techniques to remove interference post-detection

Optimal use of antennas in wireless networks unknown
Antenna Techniques

• Switched Beam or Phased Array
  • Antenna points in a desired direction
  • Other directions have (same) lower gain
  • No diversity benefits

• Smart Antennas (Adaptive Array)
  • Signals at each antenna optimally weighted
  • Weights optimize tradeoff between diversity and interference mitigation
  • Channel tracking required
Adaptive Array Benefits

- Can provide array/diversity gain of $M$
- Can suppress $M-1$ interferers
- Provides diversity gain of $M-J$ for nulling of $J$ interferers
- Can obtain multiplexing gain $\min(M,N)$ if transmitter has multiple antennas

Diversity/Multiplexing/Interference Mitigation Tradeoff
Performance Benefits

- Antenna gain $\Rightarrow$ extended battery life, extended range, and higher throughput
- Diversity gain $\Rightarrow$ improved reliability, more robust operation of services
- Interference suppression $\Rightarrow$ improved link quality, reliability, and robustness
- Multiplexing gain $\Rightarrow$ higher data rates
- Reduced interference to other systems
Analysis

- We have derived closed-form expressions for outage probability and error probability under optimal MRC.

- Analysis based on SINR MGF.

- Can be used to determine the impact on performance of adding antennas.
$P_{out}$ versus average normalized SINR/$\gamma_{th}$
interferer configuration
(fixed total power)
different interferers + noise configurations

Fixed I+N power

![Graph showing outage probability versus average normalized SINR in dB with different interferer and noise configurations. The graph includes curves for equal power in noise and interferers, no noise, dominant interferer, and dominant noise.]
Distributed Antennas (DAS) in Cellular

- **Basic Premise:**
  - Distribute BS antennas throughout cell
    - Rather than just at the center
  - Antennas connect to BS through wireless/wireline links

- **Performance benefits**
  - Capacity
  - Coverage
  - Power consumption
Average Ergodic Rate

- Assume full CSIT at BS of gains for all antenna ports
- Downlink is a MIMO broadcast channel with full CSIR
- Expected rate is

\[
C_{csit}(P) = E_u E_{sh} \left[ \log_2 \left( 1 + \bar{S} \left( \sum_{i=1}^{N} \sqrt{\frac{f_i}{D(p_i, u)\alpha}} \right)^2 \right) \right]
\]

- Average over user location and shadowing
- DAS optimization
  - Where to place antennas
  - Goal: maximize ergodic rate
Solve via Stochastic Gradients

- Stochastic gradient method to find optimal placement
  1. Initialize the location of the ports randomly inside the coverage region and set $t=0$.
  2. Generate one realization of the shadowing vector $f(t)$ based on the probabilistic model that we have for shadowing.
  3. Generate a random location $u(t)$, based on the geographical distribution of the users inside the cell.
  4. Update the location vector as $P_{t+1} = P_t + \left. \frac{\partial}{\partial P} C(u(t), f(t), P) \right|_{P_t}$.
  5. Let $t = t + 1$ and repeat from step 2 until convergence.
Gradient Trajectory

- $N = 3$ (three nodes)
- Circular cell size of radius $R = 1000\text{m}$
- Independent log-Normal shadow fading
- Path-loss exponent: $\alpha=4$
- Objective to maximize: average ergodic rate with CSIT
Power efficiency gains

- Power gain for optimal placement versus central placement
- Three antennas

![Graph showing power efficiency gain vs. path-loss exponent.](image-url)
Non-circular layout

- For typical path-loss exponents $2 < \alpha < 6$, and for $N > 5$, optimal antenna deployment layout is not circular.
Interference Effect

- Impact of intercell interference

\[
SINR = \frac{\sum_{i=1}^{N} f_i D(p_i, u)^{\alpha}}{\sum_{j=1}^{6} \sum_{i=1}^{N} \gamma_j \frac{f_i}{D(p_i^j, u)^{\alpha}} + \sigma^2}
\]

- \( \gamma_j \) is the interference coefficient from cell \( j \)
  - Autocorrelation of neighboring cell codes for CDMA systems
  - Set to 1 for LTE(OFDM) systems with frequency reuse of one.
Interference Effect

The optimal layout shrinks towards the center of the cell as the interference coefficient increases.
Power Allocation

- Prior results used same fixed power for all nodes
- Can jointly optimize power allocation and node placement
- Given a sum power constraint on the nodes within a cell, the primal-dual algorithm solves the joint optimization
- For N=7 the optimal layout is the same: one node in the center and six nodes in a circle around it.
  - Optimal power of nodes around the central node unchanged
For larger interference and in high path-loss, central node transmits at much higher power than distributed nodes.
Area Spectral Efficiency

- Average user rate/unit bandwidth/unit area (bps/Hz/Km$^2$)
  - Captures effect of cell size on spectral efficiency and interference

- ASE typically increases as cell size decreases

- Optimal placement leads to much higher gains as cell size shrinks vs. random placement
MIMO in Cellular: Performance Benefits

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

*Optimal use of MIMO in cellular systems, especially given practical constraints, remains an open problem*
Virtual/Network MIMO in Cellular

• Network MIMO: Cooperating BSs form a MIMO array
  • Downlink is a MIMO BC, uplink is a MIMO MAC
  • Can treat “interference” as known signal (DPC) or noise
  • Can cluster cells and cooperate between clusters

• Mobiles can cooperate via relaying, virtual MIMO, conferencing, analog network coding, …

• Design Issues: CSI, delay, backhaul, complexity

Many open problems for next-gen systems

Will gains in practice be big or incremental; in capacity or coverage?
Open design questions

• Single Cluster
  • Effect of impairments (finite capacity, delay) on the backbone connecting APs:
  • Effects of reduced feedback (imperfect CSI) at the APs.
  • Performance improvement from cooperation among mobile terminals
  • Optimal degrees of freedom allocation

• Multiple Clusters
  • How many cells should form a cluster?
  • How should interference be treated? Cancelled spatially or via DSP?
  • How should MIMO and virtual MIMO be utilized: capacity vs. diversity vs interference cancellation tradeoffs
Cooperative Multipoint (CoMP)

Part of LTE Standard - not yet implemented

Figure 1. Base station cooperation: intersite and intrasite COMP.

- "Coordinated multipoint: Concepts, performance, and field trial results"
<table>
<thead>
<tr>
<th>Environment</th>
<th>Dresden testbed</th>
<th>Berlin testbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial setup</td>
<td>10 sites with up to a total of 28 sectors</td>
<td>4 sites with up to 10 sectors</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.68 GHz DL, 2.53 GHz UL</td>
<td></td>
</tr>
<tr>
<td>Baseline technology</td>
<td>OFDMA in DL and UL, scalable bandwidth 5–20 MHz, transmissions limited to a maximum of 40 resource blocks (PRBs) in UL and 10 PRBs in DL.</td>
<td>DL: 2 x 2 MIMO-OFDMA, UL: 1 x 2 SC-FDMA, scalable bandwidth 1.5–20 MHz, full bandwidth can be used in both up- and downlink</td>
</tr>
<tr>
<td>Processing</td>
<td>Real-time DL transmission. For uplink COMP offline processing. Scheduling is investigated in quasi-realtime.</td>
<td>Real-time PHY, adaptive MIMO multiple access and network layer. PHY is extended for DL CoMP.</td>
</tr>
<tr>
<td>Backhaul and interconnects</td>
<td>5.4/5.8 GHz microwave with a net data rate of 100 Mb/s and 1 ms delay</td>
<td>1 Gb/s Ethernet over optical fiber and free-space-optical links.</td>
</tr>
<tr>
<td>Testbed scope</td>
<td>UL and DL MU-MIMO COMP, relaying, practical issues</td>
<td>DL MU-MIMO, COMP, relaying, real-time demos such as high-definition mobile video conference</td>
</tr>
</tbody>
</table>

Table 1. COMP testbeds developed within the EASY-C project.

![Graph](image)

Figure 2. Performance of selected uplink COMP schemes: 1) inter-site interference prediction, 2) inter-site joint detection, 3) intra-site joint detection, 4) combining inter-site interference prediction with intra-site joint detection.
Summary

- Multiuser detection reduces interference, and thus allows greater spectral efficiency in cellular
  - Techniques too complex for practical implementations in mobiles
  - Recently have some implementations in BSs

- MIMO/OFDM slices system resources in time, frequency, and space
  - Can adapt optimally across one or more dimensions

- MIMO introduces diversity – multiplexing-interference cancellation tradeoffs

- Distributed antennas (DAS) and cooperative multipoint leads to large performance gains
Presentation

“Asynchronous Interference Mitigation in Cooperative Base Station Systems”

Presentation by Brian Jungman