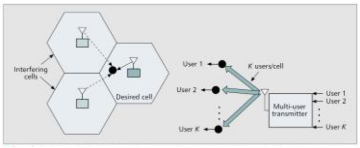
EE360: Lecture 6 Outline
MUD/MIMO in Cellular Systems

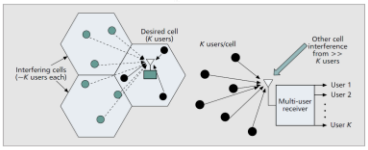
- Announcements
  - Project proposals due today
  - Makeup lecture tomorrow Feb 2, 5-6:15, Gates 100
- Multiuser Detection in cellular
- MIMO in Cellular
  - Multiuser MIMO/OFDM
  - Multiplexing/diversity/IC tradeoffs
  - Distributed antenna systems
  - Virtual MIMO
  - Brian’s presentation

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 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

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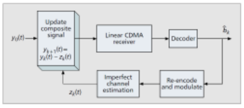
Successive Interference Cancellers

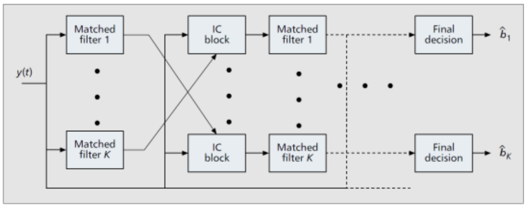


- Successively subtract off strongest detected bits
- MF output: $b_1 = c_1x_1 + rc_2x_2 + z_1$ $\qquad b_2 = c_2x_2 + rc_1x_1 + z_2$
- Decision made for strongest user: $\hat{x}_1 = \operatorname{sgn}(b_1)$
- Subtract this MAI from the weaker user:

$$\begin{aligned}\hat{x}_2 &= \operatorname{sgn}(y_2 - rc_1\hat{x}_1)\\ &= \operatorname{sgn}(c_2x_2 + rc_1(x_1 - \hat{x}_1) + z_2)\end{aligned}$$

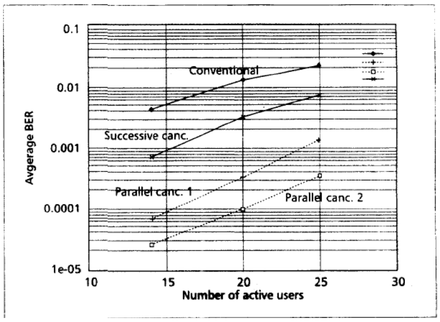
  - all MAI can be subtracted is user 1 decoded correctly
- MAI is reduced and near/far problem alleviated
  - Cancelling the strongest signal has the most benefit
  - Cancelling the strongest signal is the most reliable cancellation

Parallel Interference Cancellation



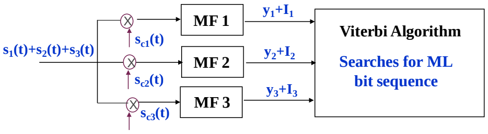
- Similarly uses all MF outputs
- Simultaneously subtracts off all of the users’ signals from all of the others
- works better than SIC when all of the users are received with equal strength (e.g. under power control)

Performance of MUD: AWGN

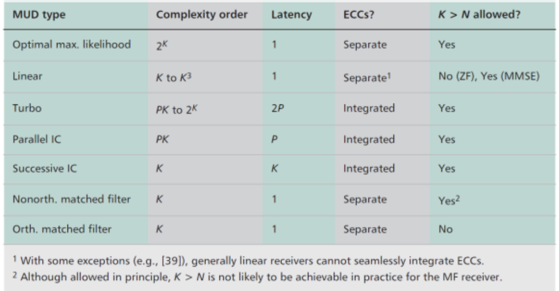


Optimal Multiuser Detection

- 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



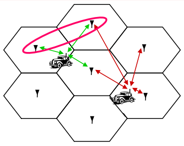
MUD type	Complexity order	Latency	ECCs?	$K > N$ allowed?
Optimal max. likelihood	2^K	1	Separate	Yes
Linear	K to K^3	1	Separate[1]	No (ZF), Yes (MMSE)
Turbo	PK to 2^K	$2P$	Integrated	Yes
Parallel IC	PK	P	Integrated	Yes
Successive IC	K	K	Integrated	Yes
Nonorth. matched filter	K	1	Separate	Yes[2]
Orth.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

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

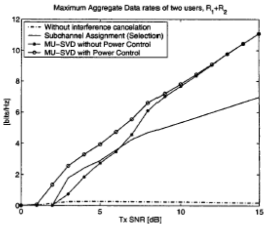
- MIMO greatly increases channel capacity
- Multiple antennas also used for spatial multiple access:
  - Users separated by spatial signatures (versus CDMA time signatures)
  - Spatial signatures are typically not orthogonal
  - May require interference reduction (MUD, cancellation, etc.)
- Methods of spatial multiple access
  - Singular value decomposition
  - Space-time equalization
  - Beamsteering
- Use similar optimization formulation for resource allocation

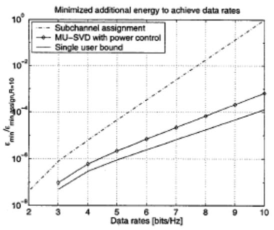
"Spatial Multiuser Access OFDM With Antenna Diversity and Power Control"
J. Kim and J. Cioffi, VTC 2000

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:

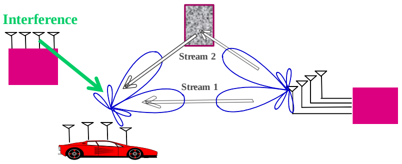
- Has path diversity versus beamforming
- Space Time Equalizer:

  $W(f) = [H^*(f)H(f)]^{-1}H^*(f)$
  - Noise enhancement when signal fades
  - Since channel gain (Λ) 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

Multiplexing/diversity/interference cancellation tradeoffs



- 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

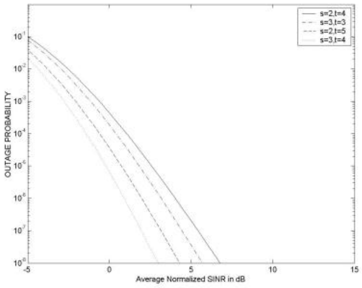
Performance Benefits

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

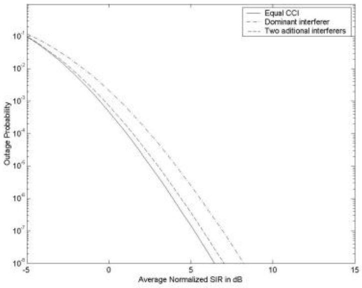
Analysis

- 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/γ_{th}

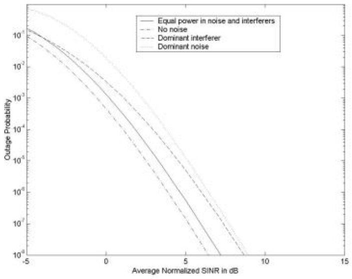


interferer configuration (fixed total power)

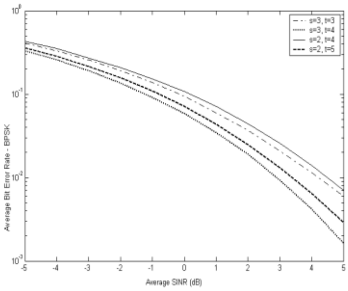


different interferers + noise configurations

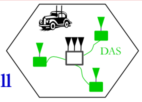
Fixed I+N power



BER vs. Average SNR



Distributed Antennas (DAS) in Cellular



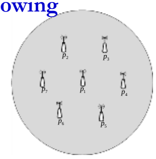
- Basic Premise:
  - Distribute BS antennas throughout cell
    - Rather than just at the center
  - Antennas connect to BS through wireless/wireline links
- Performance benefits
  - Capacity
  - Coverage
  - Power consumption

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**

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

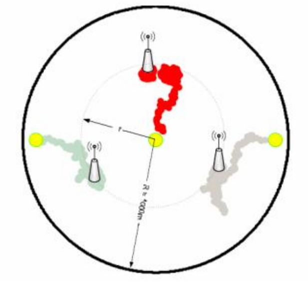
  - Average over user location and shadowing
- DAS optimization
  - Where to place antennas
  - Goal: maximize ergodic rate



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 $P_{t+1} = P_t + \frac{\partial}{\partial P} C(u(t), f(t), P)\Big|_{P_t}$
  5. Let t = t +1 and repeat from step 2 until convergence.

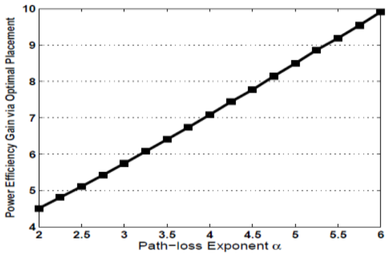
Gradient Trajectory



- N = 3 (three nodes)
- Circular cell size of radius R = 1000m
- Independent log-Normal shadow fading
- Path-loss exponent: α=4
- Objective to maximize : average ergodic rate with CSIT

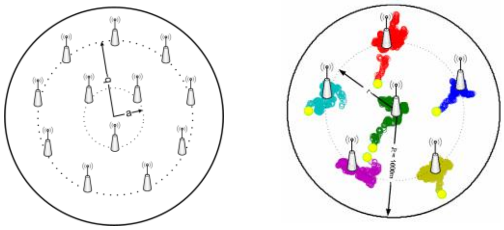
Power efficiency gains

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



Non-circular layout

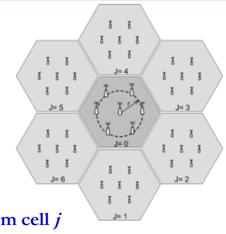
- For typical path-loss exponents 2<α<6, and for N>5, optimal antenna deployment layout is not circular



Interference Effect

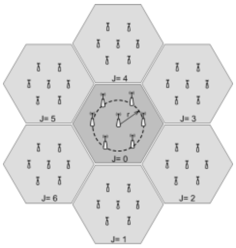
- Impact of intercell interference

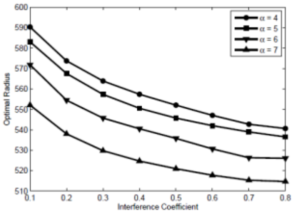
$$SINR = \frac{\sum_{i=1}^{N}\frac{f_i}{D(p_i,u)^{\alpha}}}{\sum_{j=1}^{6}\sum_{i=1}^{N}\gamma_j\frac{f_i}{D(p_i^j,u)^{\alpha}}+\sigma^2}$$



- γ_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

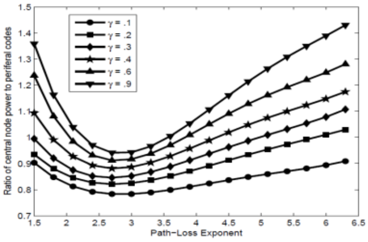




Power Allocation

- **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**

Power Allocation Results

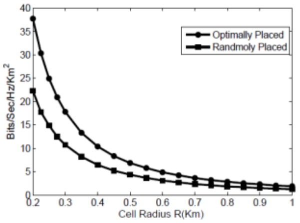


- **For larger interference and in high path-loss, central node transmits at much higher power than distributed nodes**

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

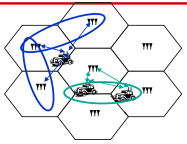


MIMO in Cellular: *Performance Benefits*

- **Antenna gain ⇒ 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

Virtual/Network MIMO in Cellular

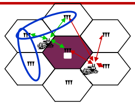


Many open problems for next-gen systems

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

- **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**

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

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Cooperative Multipoint (CoMP)

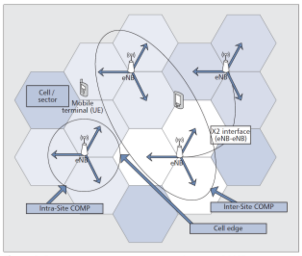
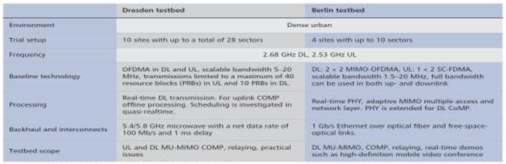


Figure 1. *Base station cooperation: intersite and intrasite COMP.*

Part of LTE Standard
- not yet implemented

- **"Coordinated multipoint: Concepts, performance, and field trial results"** ***Communications Magazine, IEEE*** **, vol.49, no.2, pp.102-111, February 2011**



	Dresden testbed	**Berlin testbed**
Environment	Dense urban	
Trial setup	10 sites with up to a total of 28 sectors	4 sites with up to 10 sectors
Frequency	2.68 GHz DL, 2.53 GHz UL	
Baseline technology	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	DL: 2 × 2 MIMO-OFDMA, UL: 1 × 2 SC-FDMA, scalable bandwidth 1.5–20 MHz, full bandwidth can be used in both up- and downlink
Processing	Real-time DL transmission. For uplink COMP offline processing. Scheduling is investigated in quasi-realtime.	Real-time PHY, adaptive MIMO multiple access and network layer. PHY is extended for DL CoMP.
Backhaul and interconnects	5.4/5.8 GHz microwave with a net data rate of 100 Mb/s and 1 ms delay	1 Gb/s Ethernet over optical fiber and free-space-optical links.
Testbed scope	UL and DL MU-MIMO COMP, relaying, practical issues	DL MU-MIMO, COMP, relaying, real-time demos such as high-definition mobile video conference

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

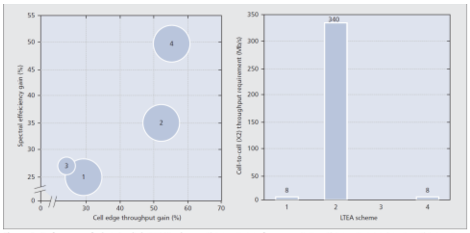


Figure 2. *Performance of selected uplink COMP schemes: 1) inter-site interference prediction, 2) inter-site joint detection, 3) intra-site joint detection, 4) combining inter-site interference prediction with intra-site joint detection.*

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

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Presentation

- "Asynchronous Interference Mitigation in Cooperative Base Station Systems" by H. Zhang , N. Mehta , A. Molisch , J. Zhang and H. Dai, IEEE Trans. Wireless Commun., Jan 2008.
- *Presentation by Brian Jungman*