Multiple Antennas in the Downlink: A System View

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Downlink of a wireless communication system

Fading Channel

Base Station

Mobile
User 1

User 2

User K

User K
System Design: Two Key Features

- Resource Allocation
- Interference Management
System Design: Two Key Features

- **Resource Allocation**: Orthogonalization
  - IS-136: separation in frequency and time
  - IS-95: M-ary orthogonal signaling

- **Interference Management**
System Design: Technology Examples

- **Resource Allocation**: Orthogonalization
  - IS-136/GSM: separation in frequency and time
  - IS-95: M-ary orthogonal signaling

- **Interference Management**
  - IS-136/GSM: frequency planning - high SNR
  - IS-95: full reuse - low SNR
Information Theory

- Performance: total throughput (Tse '97)

At any time transmit full power only to user with best SIR
Information Theory

- Performance: total throughput (Tse '97)

At any time transmit full power only to user with best SIR

- Assumptions:
  - channel tracked by users and SIR fed back to BS
  - peak transmit power constraint
  - Implemented in IS-856 (HDR)
Fading Channel: Rayleigh with average SNR = 0 dB
A Real System Implementation

- Multiuser diversity gain
  - significant improvement in overall throughput
  - system wide benefit
  - different from traditional diversity forms

- Real System Constraints
  - Fairness to Users
  - Scheduling within time scale of interest
Multiuser Diversity Harnessing Scheduler

• Over desired time scale,
  – Resource Fair
    • Equal resources (bandwidth and power) to users
    – Users scheduled at (or around) their peak SIR

• Example: Proportional Fair Scheduling (Tse ’99)
A Simulation Example

Mobile environment: independent Rayleigh Fading, SNR = 0 dB
Fixed environment: 2Hz Ricean Fading, SNR = 0 dB, $\kappa = 5$
Proportional Fair Scheduling: $t_c = 1.6s, 1.25$MHz.
Channel Fluctuation: Mobile Environment

Mobile Environment

Supportable Rate vs. Time Slots

$tc = 1.6s$
Channel Fluctuation: Fixed Environment

Fixed Environment

- Supportable Rate
- Time Slots

$t_c = 1.6s$
Summary: Limitations of Multiuser Diversity Gain

Amount of diversity gain depends mainly on

- range of SIR fluctuation
Summary: Limitations of Multiuser Diversity Gain

Amount of diversity gain depends mainly on

- range of SIR fluctuation

- rate of SIR fluctuation in the time scale $t_c$
Summary: Limitations of Multiuser Diversity Gain

Amount of diversity gain depends mainly on

- range of SIR fluctuation
- rate of SIR fluctuation in the time scale $t_c$
- number of active users
- ability to track and predict the SIR fluctuations.
A Question and an Idea

Question:

Is it possible to dictate nature to have more channel fluctuations?

Idea:

Artificially induce channel SIR fluctuations that have

- larger range and

- faster time scale fluctuations
Inducing Channel Variations

\[ h(t) = \sqrt{\alpha(t)} \]  
\[ x(t) \]

\[ \sqrt{1 - \alpha(t)e^{j\theta(t)}} \]  

User \( k \)
Inducing Channel Fluctuations

- **Same signal** transmitted over both antennas

- **Different Power and Phases** of the signals

- Power and Phase **changing in time**
  
  \[ \alpha \in [0, 1] \text{ and } \theta \in [0, 2\pi] \].

- **Overall Channel:**
  
  \[ \sqrt{\alpha(t)h_{1k}(t)} + \sqrt{1 - \alpha(t)e^{j\theta(t)}} h_{2k}(t) \]
Slow Fading Environment

Before

Supportable Rate

User 1

User 2

Time Slots

Supportable Rate

Time Slots
Slow Fading Environment

After

Time Slots
Supportable Rate
User 1
User 2

Time Slots
Opportunistic Beamforming

- With phase and amplitude feedback, optimal strategy is Transmit Beamforming.

- With independent power and phase fluctuations, some user $k$ is in beamforming configuration.

- Overall Channel SIR is $|h_{1k}|^2 + |h_{2k}|^2$: 3dB beamforming gain.
Mobile environment: independent Rayleigh Fading, SNR = 0 dB
Fixed environment: 2Hz Ricean Fading, SNR = 0 dB, $\kappa = 5$
Proportional Fair Scheduling: $t_c = 1.6s$. 
A Comparison

Number of Users

Throughput in kbps

Coherent Beamforming, Equal time sched.

Opp. Beamforming

Prop. Fair sched.

Alamouti scheme, Equal time sched.

1 antenna, Equal time sched.
# The Return of the Dumb Antennas

<table>
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<tr>
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<th>Opp. Beamforming</th>
<th>Space Time Codes</th>
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<tbody>
<tr>
<td><strong>Design Perspective</strong></td>
<td>multiuser</td>
<td>point to point</td>
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<tr>
<td><strong>Average SIR</strong></td>
<td>$</td>
<td>h_1</td>
</tr>
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<td><strong>Outage decay</strong></td>
<td>$\frac{1}{2SNR^2}$</td>
<td>$\frac{1}{SNR^2}$</td>
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<td><strong>System Requirement</strong></td>
<td>Track and Feedback of overall SIR</td>
<td>Track channel from each antenna</td>
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<td>Tight feedback loop</td>
<td>No tight feedback</td>
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<td></td>
<td>Changes BS specific</td>
<td>Receivers redesigned</td>
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<td><strong>Summary</strong></td>
<td>Truly Dumb Antennas</td>
<td>Smart Antennas but poorer performance</td>
</tr>
</tbody>
</table>
Cellular Environment

- Distributed Cellular Environment: no coordination between base stations

- Multiuser diversity scheduling exploits time varying interference

- Transmit to user with **good channel AND very low interference**.

- Opportunistic Beamforming combined with **Opportunistic Nulling**.
System Design Contrast

Traditional wireless communication design principles:

- **Make individual** point-point links close to AWGN
  - Multiple path combining
  - Time interleaving

- **Average the interference**
  - Spreading techniques
System Design Revised

• Modern design principle:
  
  Large and Rapid channel fluctuations are preferable

• Proactive Stance:
  
  Induce Larger and Faster Channel fluctuations

• Caveat:
  
  – Sufficient number of users in the system
  
  – Need to have some flexibility to schedule packets
Return to Information Theory

- Single transmit antenna: transmit to one user only

- **Question:**

  What does information theory say with multiple transmit antennas at base station?

- Again focus on **total throughput**

- Assume **full channel feedback**, not just overall SIR.
Linear Strategies

- High SNR: \( \min(N, K) \) log SNR (degrees of freedom)

- Low SNR: \( N \) SNR (beamforming or power gain)
Precoding

- Base station knows signal for user 2 when designing signal for user 1

- Precode signal of user 1 based on this information
  - precoding for ISI channels (V.34 telephone modem)
Costa Precoding

- Users' data modulated onto spatial signatures $u_1, u_2$
Stage 1: Costa Precoding

- Encoding for user 1 treating signal from user 2 as known interference at transmitter
- Encode user 2 treating signal for user 1 as noise
Is Precoding the Best?

Upper Bound

Broadcast channel

Cooperating Receivers

\( z \sim \mathcal{N}(0, K) \)
Is Precoding the Best?

Upper Bound

Broadcast channel

Cooperating Receivers

\( z \sim \mathcal{N}(0, K) \)

\( K \) is covariance of coloring among the noises at the users
Upper Bound is Tight

\[ z \sim \mathcal{N}(0, K) \]

\[ H \]

\[ \text{Broadcast} \]

\[ \text{Cooperating Receivers} \]

\[ \text{Reciprocity} \]

\[ \text{Convex Duality} \]

\[ E \left[ x^t K x \right] \leq P \]

\[ H^* \]

\[ x_1, x_2 \text{ independent} \]

\[ \text{Multiple Access} \]

\[ \text{Cooperating Transmitters} \]
With Full Feedback

High SNR

• Throughput again: $\sim \min (N, K) \log \text{SNR}$

• Compare with only $\log \text{SNR}$ with one user at a time

• An extension of opportunistic beamforming can also get this
  - Limited feedback
With Full Feedback

- **High SNR**
  - Throughput: $\sim \min(N, K) \log \text{SNR}$
  - An extension of opportunistic beamforming gets this

- **Low SNR**
  - Now only beamforming power gain
  - Can also be obtained by opportunistic beamforming
    - *limited feedback*
System Design Implications

- At high SNR, multiple antennas provide degrees of freedom
- At low SNR, beamforming (power) gain
- Both can be obtained by opportunistic communication
  - limited feedback
A Question for the System Designer

- We moved from narrowband systems (IS-136/GSM) to full frequency reuse (IS-95)
  - improved spectral efficiency (degrees of freedom)
  - but low SNR operation

- Multiple transmit antennas provide spatial degrees of freedom at high SNR

Should we go back to narrowband systems and work at high SNR?