Cost Optimized Antenna Arrays in CDMA Cellular Networks

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CDMA Cellular Networks

- Frequency reuse between cells
- In-cell users distinguished by spreading codes
- Near-far problem: received power differential between near and far users exceeds spread-spectrum processing gain
- Initial cell size is Range Limited
  - Fill in new cells as load increases
  - Cell size becomes interference limited
Goal

Minimize Code Division Multiple Access (CDMA) Wireless Communications Network Cost/User By Trading Off Central Station Complexity Against The Number of Central Stations
Near-Far Problem

- **Closed-Loop Power Control**
  - System capacity very sensitive to power control accuracy
  - Assumes all transmitters in same network
  - Minimal processing cost

- **Multi-User Detection**
  - Adaptively modify code de-spreading to minimize cross-talk
  - Assumes all signals/spreading sequences known (same network)
  - Very high processing cost

- **Smart Antennas**
  - Adaptively set antenna weights to maximize SINR
  - Won’t work against signal with same (equivalent) AOA
  - Moderate to high processing cost
Propagation Model

- Non-Line-Of-Sight Multipath Propagation
  - Rayleigh Fading
  - Decorrelates Rapidly in Space

- Average Signal Power Variable Due to Shadowing
  - Log-Normal Shadowing at Fixed Range
  - Decorrelation Distance Approx. Large Structure Size

- Median Shadowing Loss \( \propto r^{\alpha} \)
  - Observed Range Loss Coefficient \( 2 < \alpha \leq 10 \)
### Assumed Channel Parameters

<table>
<thead>
<tr>
<th>Range-Loss Power</th>
<th>Shadowing Standard Deviation</th>
<th>Environment/Network Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.4 dB</td>
<td>Power-Controlled Cellular Network</td>
</tr>
<tr>
<td>2.25</td>
<td>7.0 dB</td>
<td>Indoor Wireless LAN</td>
</tr>
<tr>
<td>3.0</td>
<td>4.5 dB</td>
<td>Urban Wireless Local Loop</td>
</tr>
<tr>
<td>4.0</td>
<td>8.0 dB</td>
<td>PCS Frequency Cellular Network</td>
</tr>
</tbody>
</table>

**Graphs:**

- **Average Range Loss (dB) vs. Range (Km):**
  - PCS
  - WLL

- **Average Range Loss (dB) vs. Range (m):**
  - Indoor
Range Loss Model

- Median power loss $r^\alpha$
- Mobile locations uniformly distributed on circle of radius $r_o$
- Median power has Pareto Distribution
  - Min. value $\mu_o$
- Median Power in dB has exponential distribution shifted by $\mu_o$
  - Mean value $\mu_o + 5\alpha/\ln(10)$
Performance Model Assumptions

- Co-Channel Interference Limited Performance
  - Large SNR (Signal-to-Noise Ratio)
- Network Capacity Limited By Reverse Link
- Uncorrelated Fading
- Perfect Channel Estimates
  - Performance limit with long adaptation time
- Link Closed if SIR (Signal-to-Interference-Ratio) > 6 dB
  - Average over signal, interference power and fading
Conventional Rake Receiver

- PN Seq.
- Delays
- Weights
- M Taps
- To Demod

Delay/Weight Estimates
3-Tap Rake Receiver Coverage

20 dB Processing Gain, 3–Chip RMS Delay Spread

Probability SIR > 6 dB vs. Number of Signals, K

- Power Control
- Indoor
- WLL
- PCS
Multi-Channel Rake Receiver

Antenna Selection

Delay/Weight Estimates

N x M+1 Switch

PN Seq.

Delays

Weights

To Demod

M Taps

N Antennas

Σ

Σ

Σ

Σ
Multi-Channel Rake Receiver Capacity

\[ K \approx aN^b \]

<table>
<thead>
<tr>
<th></th>
<th>80% Coverage</th>
<th>90% Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Control</td>
<td>5.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Indoor</td>
<td>1.9</td>
<td>0.76</td>
</tr>
<tr>
<td>WLL</td>
<td>2.3</td>
<td>0.73</td>
</tr>
<tr>
<td>PCS</td>
<td>1.3</td>
<td>0.57</td>
</tr>
</tbody>
</table>
Smart Antenna Receiver

\[ \sum \]

\[ \sum \]

\[ W_{11} \]

\[ W_{12} \]

\[ W_{1M} \]

\[ W_{N1} \]

\[ W_{N2} \]

\[ W_{NM} \]

PN Seq.

\[ \prod \]

To Demod

Weights

Weight Estimates

From Antennas

N Antennas

M Taps
Equivalent Smart Antenna Receiver

Frequency Selective Fading

From Antennas

Filter Bank

Filter Bank

Weights

Weight Estimates

Reconstruction Filter Bank

PN Seq.

Σ

Σ

To Demod
Smart Antenna Receiver Capacity

\[ K \approx aN \]

Linear Fit Coefficient

90% Coverage

<table>
<thead>
<tr>
<th></th>
<th>Flat Fading</th>
<th>16-Chip RMS Delay Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Control</td>
<td>9.7</td>
<td>10.2</td>
</tr>
<tr>
<td>Indoor</td>
<td>2.5</td>
<td>2.6</td>
</tr>
<tr>
<td>WLL</td>
<td>3.0</td>
<td>3.2</td>
</tr>
<tr>
<td>PCS</td>
<td>1.9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Indoor Propagation Model

90% Reliability, 20 dB Processing Gain

Number of Antennas, \( N \)

Channels / Cell, \( K \)
Cost Model

\[ C_1 = C_t + \mu (NM)^m C_p + (C_o + NC_a) / K \]

\( C_1 = \) Total Cost / User ($)
\( C_t = \) Incremental Rx Cost / User ($) 
\( C_p = \) Processing Cost / MOPS ($) 
\( C_o = \) Fixed Hub Cost ($) 
\( C_a = \) Cost / Antenna Element ($) 
\( N = \) # Antenna Elements Per Hub 
\( M = \) # Filter Taps Per Antenna Element 
\( \mu (NM)^m = \) Antenna Processing Cost Per Channel (MOPS) 
\( K = \) # Channels Per Hub
Optimized Multi-Channel Rake Receiver

- Capacity \( K = an^b \)

- Design Rule \( \frac{\text{Total Antenna Cost}}{\text{Fixed Hub Cost}} = \frac{b}{1-b} \) if \( b < 1 \)

- Number of Antennas \( N_{opt} = \frac{b}{1-b} \frac{C_o}{C_a} \)
Optimized Smart Antenna Receiver

- Capacity $K = aN$
- Processing Load / Channel = $\mu (NM)^m$ Ops/Sec
  - $m = 2$, RLS
  - $m = 1$, LMS
- Design Rule For Minimum Cost/Channel:
  \[
  \frac{\text{Total Beamforming Cost}}{\text{Fixed Hub Cost}} = \frac{K\mu (NM)^m C_p}{C_0} = \frac{1}{m}
  \]
- Number of Antennas $N_{opt} = \left( \frac{1}{a\mu mM^m} \frac{C_0}{C_p} \right)^{1/(m+1)}$
## Example - Wireless LAN

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost/Hub</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/Hub</td>
<td>$2000</td>
</tr>
<tr>
<td>$C_0$</td>
<td></td>
</tr>
<tr>
<td>Cost/Channel</td>
<td>$200</td>
</tr>
<tr>
<td>$C_t$</td>
<td></td>
</tr>
<tr>
<td>Cost/ Antenna</td>
<td>$500</td>
</tr>
<tr>
<td>$C_a$</td>
<td></td>
</tr>
<tr>
<td>Cost/ MOPS</td>
<td>$1</td>
</tr>
<tr>
<td>$C_p$</td>
<td></td>
</tr>
<tr>
<td>Beam-Forming Coefficient $\mu$</td>
<td>$5.25 \times 10^3$ (RLS)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10.0 \times 10^3$ (LMS)</td>
</tr>
</tbody>
</table>

Indoor Propagation Model, Processing Gain 20 dB, RMS Delay Spread 25 ns

![Graph showing cost per channel versus antennas per hub](image-url)

- MC-Rake
- RLS Array, 1 MBPS
- LMS Array, All Rates
- RLS Array, 10 & 100 KBPS

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Example – 3G Mobile Wireless Cost

<table>
<thead>
<tr>
<th></th>
<th>Cost/Hub</th>
<th>Cost/Channel</th>
<th>Cost/ Antenna</th>
<th>Cost/ MOPS</th>
<th>Beam-Forming Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$100,000</td>
<td>$2000</td>
<td>$2000</td>
<td>$1</td>
<td></td>
</tr>
</tbody>
</table>

- **Data Rate**: 57.6 kbps
- **Processing Gain**: 20 dB
- **RMS Delay Spread**: 2 μs

![Graph showing cost per channel for different algorithms and systems.](image)
Conclusions

- Multi-Channel Rake: Optimal Array Cost = 1 to 4 Times Fixed Hub Cost
- Smart Antennas: Optimal Processor Cost = \( \frac{1}{2} \) to 1 Times Fixed Hub Cost
  - Wider Bandwidths, Higher Data Rates, Drive Up Processing Loads
  - Optimal # Antennas Sometimes High, But RF Electronics and Antennas Are Growing Cheaper
- Smart Antenna Does Not Replace Closed-Loop Power Control
- Interference Canceling Is Cost Effective
  - Makes Non-Power Controlled Network Possible In Severe Propagation
  - Power Controlled Cost Comparable To Rake (Depends on Cost Model, Assumed Propagation, etc.)
  - Smart Antenna Hub Density \( \frac{1}{4} \) Rake Hub Density Or Less