Adaptive Antenna Tutorial: 
*Spectral Efficiency and Spatial Processing*

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Cellular networks divide a coverage area into multiple "cells" each has its own radio infrastructure and users.

- Basis for most two-way wireless services
  - cellular phones (1G, 2G, 3G, ...)
  - MMDS broadband data (Sprint, Worldcom)
  - Wireless LANs
  - LMDS broadband data (Teligent, Winstar, ...)

Cellular Technology

- Switching/Routing
- Data Networks
- Telephony Networks
- Backhaul Network

Base station

Cell

Sector
Motivation For This Talk

- Cellular system design trades off competing requirements
  - service definition
  - service quality
  - capacity
  - capital and operating costs
  - resource requirements including spectrum
  - end-user pricing/affordability
  - coexistence with other radio technologies

- Adaptive antenna technology fundamentally changes the nature of this trade-off
Outline

- Spectral Efficiency and System Economics
- Adaptive Antenna Fundamentals
- Adaptive Antenna Technologies
- Adaptive Antenna Performance Determinants
- Adaptive Antenna Regulatory Issues
- Summary
Spectral Efficiency Defined

- A measure of the amount of information – billable services – that carried by a wireless system per unit of spectrum

- Measured in bits/second/Hertz/cell, includes effects of
  - multiple access method
  - modulation methods
  - channel organization
  - resource reuse (code, timeslot, carrier, …)

- “Per-Cell” is critical
  - fundamental spectral efficiency limitation in most systems is self-generated interference
  - results for isolated base stations are not representative of real-world performance
Why Is Spectral Efficiency Important?

- Spectral efficiency directly affects an operator’s cost structure

- For a given service and grade of service, it determines
  - required amount of spectrum (CapEx)
  - required number of base stations (CapEx, OpEx)
  - required number of sites and associated site maintenance (OpEx)
  - and, ultimately, consumer pricing and affordability

- Quick calculation

\[
\text{number of cells/km}^2 = \frac{\text{offered load (bits/s/km}^2\text{)}}{\text{available spectrum (Hz) x spectral efficiency (bits/s/Hz/cell)}}
\]
Increased Spectral Efficiency

- Improves operator economics
  - reduced equipment CapEx/OpEx per subscriber
  - reduced numbers of sites in capacity limited areas
  - reduced spectrum requirements

- Reduces barriers to new operators and new services

- Makes better use of available spectrum
  - especially important for limited spectrum suitable for mobile applications

- Improves end-user affordability, especially for broadband services
  - cost of service delivery directly reflected in service pricing
  - cost of delivering broadband services higher than cost to deliver voice
    - voice is only 10 kbps of data
    - data quality requirements higher for broadband than voice
Designing For Spectral Efficiency

- **Spectral/Temporal tools**
  - multiple access method and data compression (source coding): TDMA, FDMA, CSMA, CDMA, Vocoding (e.g., CELP), MPEG
    - both optimize efficiency based on traffic characteristics
    - compression/source coding can change service definition
  - modulation, channel coding, equalization: QPSK, OFDM, Trellis Coding…
    - optimize efficiency based on link quality

- **Spatial tools (all to minimize interference)**
  - cellularization
    - mitigate co-channel interference by separating co-channel users
  - sectorization
    - mitigate co-channel interference by more selective downlink patterns and increased uplink sensitivity
  - power control
    - use minimum power necessary for successful communications
Avenues For Further Improvement

- Temporal/Spectral aspects are mature, well understood, well exploited
  - no significant future improvements in spectral efficiency here
  - proper application is important

- Least spectrally efficient aspect of most systems
  - omnidirectional/sectorized distribution and collection of radio energy
  - Why?
    - Most of the energy is wasted.
    - Worse, it creates interference in the system and limits reuse.
Sectorized Transmission/Reception

- Spatially uniform transmission and reception throughout sector
- Causes interference in nearby cells
- Increases sensitivity to interference from nearby cells
- Cellular “reuse” mitigates this effect by separating co-channel users
- Cost: decreased resources per sector and reduced spectral efficiency
- Tradeoff of quality and capacity
How Do Adaptive Antennas Help?

- Adaptive antennas are spatial processing systems
- Combination of
  - antenna arrays
  - sophisticated signal processing
- Adapt the effective pattern to the radio environment
  - users
  - interferers
  - scattering/multipath
- Provide spatially selective transmit and receive patterns
Adaptive Transmission/Reception

- Spatially selective transmission reduces required power for communication
- Reduces interference to nearby cells
- Decreases sensitivity to interference from nearby cells
- Allows reuse distances to be decreased
- Benefits: increased resources per sector, increased spectral efficiency
- Improved tradeoff of capacity and quality
## Comparative Spectral Efficiencies

<table>
<thead>
<tr>
<th>Air Interface</th>
<th>Carrier BW</th>
<th>Peak User Data Rate (kbps)</th>
<th>Average Carrier Throughput (kbps)</th>
<th>Efficiency b/s/Hz/cell</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without Adaptive Antennas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IS95A</td>
<td>1.25 MHz</td>
<td>14.4</td>
<td>100</td>
<td>0.08</td>
<td>Source: Viterbi</td>
</tr>
<tr>
<td>IS95C</td>
<td>1.25 MHz</td>
<td>144</td>
<td>200</td>
<td>0.16</td>
<td>Source: Viterbi</td>
</tr>
<tr>
<td>cdma2000</td>
<td>5 MHz</td>
<td>384</td>
<td>800-1000</td>
<td>0.16-0.20</td>
<td>Source: Viterbi</td>
</tr>
<tr>
<td>GSM</td>
<td>200 kHz</td>
<td>13.3</td>
<td>15.2 (13.3*8/7)</td>
<td>0.08</td>
<td>effective reuse = 7</td>
</tr>
<tr>
<td>PHS</td>
<td>300 kHz</td>
<td>32</td>
<td>12.8 (32*8/20)</td>
<td>0.04</td>
<td>effective reuse = 20</td>
</tr>
<tr>
<td><strong>With Adaptive Antennas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHS</td>
<td>300 kHz</td>
<td>32</td>
<td>64 (32*8/4)</td>
<td>0.21</td>
<td>effective reuse = 4, DDI Pocket</td>
</tr>
<tr>
<td>GSM</td>
<td>200 kHz</td>
<td>13.3</td>
<td>53.2 (13.3*8/2)</td>
<td>0.27</td>
<td>effective reuse = 2, AC/OEM Trials</td>
</tr>
<tr>
<td>IntelliWave FWA</td>
<td>300 kHz</td>
<td>128</td>
<td>640 (128<em>2</em>2.5)</td>
<td>2.1</td>
<td>effective reuse = 1/2.5, Various Operators</td>
</tr>
</tbody>
</table>

- Adaptive antenna gains are significant
- Adaptive antenna benefits vary with air interface and adaptive antenna type (more on this later)
A Word About Reuse

- When talking about spectral efficiency, “reuse” means feasible reuse of traffic resources

- Traffic resource examples
  - AMPS (FDMA): 30 kHz carrier
  - DAMPS/IS-136 (TDMA/FDMA): 30 kHz carrier + time slot
  - GSM (TDMA/FDMA): 200 kHz carrier + time slot
  - IS-95 (CDMA): 1.25 MHz carrier + code

- From previous slide, spectral efficiency of GSM and IS-95 comparable even though IS-95 might use the same carrier in each sector
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  - Adaptive Antenna Fundamentals
- Adaptive Antenna Technologies
- Adaptive Antenna Performance Determinants
- Adaptive Antenna Regulatory Issues
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Adaptive Antennas Defined

- **Systems comprising**
  - multiple antenna elements (antenna arrays)
  - coherent processing
  - signal processing strategies (algorithms) that vary the way in which those elements are used as a function of operational scenario

- **Providing**
  - gain and interference mitigation
  - leading to improved signal quality and spectral efficiency
Adaptive Antenna Concept

- Users’ signals arrive with different relative phases and amplitudes at array
- Processing provides gain and interference mitigation
Protocol Independence

- Fundamental concepts applicable to all access and modulation methods

![Diagram showing antenna, transceivers, channelizers, spatial and temporal processing, and baseband signals/user data.](image-url)
Basic Uplink Gain Calculation

- Signal $s$, $M$ antennas, $M$ receivers with i.i.d. noises $n_i$

\[
\frac{\text{received signal}}{\text{noise}} = \frac{s + \ldots + s}{n_1 + \ldots + n_M}
\]

therefore, Uplink SNR = \[
\frac{(Ms)^2}{M\sigma^2} = M \frac{s^2}{\sigma^2}
\]

= $M \times$ single antenna SNR

- Adaptive antennas improve uplink SNR by factor of $M$

- $M=10$, 10x SNR improvement, examples
  - double data rate if single antenna SNR is 10 dB
  - reduce required subscriber transmit power by 10 dB
  - increase range by 93% with $R^{3.5}$ loss

ArrayComm
Basic Downlink Gain Calculation

- Similar to uplink calculation, except dominant noise is due to (single) receiver at user terminal
- With same total radiated power $P$ in both cases

\[
\frac{\text{Received Power (Adaptive Antenna)}}{\text{Received Power (Single Antenna)}} = \frac{(\sqrt{P/M} \cdot s + \cdots + \sqrt{P/M} \cdot s)^2}{(\sqrt{Ps})^2} = M
\]

- Again, factor of $M$ or $10 \log_{10} M$ dB
- $M=10$, 10 dB gain examples
  - 10 element array with 1 W PA’s, has same EIRP as single element with 100 W PA
  - For given EIRP can reduce total radiated power by 10 dB, 90% interference reduction
Interference Mitigation

- Directive gain term generally results in some passive interference mitigation
- Active interference mitigation independent of and in addition (dB) to gain
- Gain and interference mitigation performance are actually statistical quantities
  - Theoretical gain performance closely approached (within 1 dB) in practice
  - Theoretical interference mitigation, \( \infty \), harder to achieve
    - limited by calibration, environment, number of interferers
    - active mitigation in excess of 20 dB can be reliably achieved for significant interferers
Base Station Architecture

Generic Features
- antenna array
- phase coherent transceiver chains
- automated adaptive techniques to combine (distribute) energy from (to) transceiver chains
- natural application for wideband radios

Architectural Variants
- conventional downlink processing
- analog spatial processing
- narrowband radios
- masthead electronics
- appliqué to conventional system
Antenna Arrays

- Wide variety of geometries and element types possible
  - arrangements of off-the-shelf single elements
  - custom arrays

- Array size
  - vertical extent determined by element gain/pattern as usual
  - horizontal extent, typically 3-5 lambda

- Array of eight 10 dBi elements at 2 GHz is about 0.5 x 0.75 m
  - small!
  - conformal arrays for aesthetics
Comments

- Fundamental concept is coherent processing
- Generally applicable to all air interfaces
- Parallel, independent processing on all traffic resources

Many important issues that are not addressed here
  - estimation/prediction of radio environment (will comment later)
  - processing requirements & architectures (easily > 1Gbps array data rate)
  - performance validation
  - equipment calibration
  - effects of air interface specifics (will comment later)
  - broadcast channel support
  - reliability benefits of redundant radio chains
  - intrinsic diversity of an array (fading immunity)
  - multipath processing
This presentation focuses on adaptive antennas at the base station.

Adaptive antennas can also be incorporated at the user terminal:
- Base station and user terminal can perform independent adaptive antenna processing.
- Base station and user terminal can perform joint adaptive antenna processing, so called “MIMO” systems, with additional benefits.

Fundamental issue is an economic one:
- Incremental costs at base station are amortized over many subscribers.
- Incremental costs at user terminal are amortized over one user, solutions must be inexpensive for consumer electronics applications.
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## Adaptive Antenna Potential

<table>
<thead>
<tr>
<th>Processing Gain</th>
<th>Operational Significance</th>
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</thead>
<tbody>
<tr>
<td>Selective Uplink Gain</td>
<td>Increased Range &amp; Coverage</td>
</tr>
<tr>
<td></td>
<td>Increased Data Rates</td>
</tr>
<tr>
<td></td>
<td>Reduced System – Wide Uplink Noise</td>
</tr>
<tr>
<td></td>
<td>Improved Uplink Multipath Immunity</td>
</tr>
<tr>
<td>Uplink Interference Mitigation</td>
<td>Improved Signal Quality</td>
</tr>
<tr>
<td></td>
<td>Maintained Quality with Tightened Reuse</td>
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<td>Selective Downlink Gain</td>
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</tr>
<tr>
<td></td>
<td>Improved Co–existence Behavior</td>
</tr>
<tr>
<td></td>
<td>Reduced Downlink Multipath</td>
</tr>
<tr>
<td>Downlink Interference Mitigation</td>
<td>Maintained Quality with Tightened Reuse</td>
</tr>
</tbody>
</table>

- **Actual level of benefits depends on implementation details**
Comparing Adaptive Antennas

- Predictability and consistency of performance
- Balance of uplink and downlink performance (key for capacity improvements)
  - downlink is generally most challenging aspect of adaptive antennas
  - base station directly samples environment on uplink; generally must infer the environment on the downlink
- Robustness of performance across propagation and interference scenarios
- Performance in non line-of-sight environments
  - “beams” useful for visualization, but not what happen in practice
Cell Sculpting and Switched Beam

- **Cell Sculpting**
  - load balancing technique
  - sector sizes slowly (e.g., monthly) updated to match offered traffic
  - different from other adaptive antenna techniques mentioned here, doesn’t affect reuse

- **Switched Beam**
  - selects from one of several fixed patterns to maximize received power
  - selection problems for low SINR
  - moderate gain uniformity/predictability
  - less predictable active interference mitigation
Energy Extraction and Fully Adaptive

**Energy Extraction**
- extracts maximum energy from environment ("greedy")
- infinite variety of patterns
- good performance/predictability in high SINR scenarios, poor in low SINR
- no clear downlink strategy
- Examples: maximal ratio, combined diversity

**Fully Adaptive**
- incorporates full model including propagation, users, interferers, air interface
- infinite variety of patterns
- consistent gain/interference performance in wide range of SINR scenarios
- benefits at cost of manageable increase in processing
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Adaptive Antenna Performance

- **Primary determinants**
  - environmental complexity, including mobility
  - air interface support for adaptive antennas (“hooks”)
  - duplexing: frequency-division or time-division (FDD vs. TDD)
    - issue is correlation of uplink and downlink propagation environments

- **Capacity increases in operational systems**

<table>
<thead>
<tr>
<th>Application</th>
<th>Capacity Increase</th>
<th>Deployments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWA, TDD, hooks</td>
<td>20x</td>
<td>1996-present</td>
</tr>
<tr>
<td>Low Mobility PHS, TDD, no hooks</td>
<td>5x</td>
<td>1996-present</td>
</tr>
<tr>
<td>High Mobility AMPS &amp; GSM (900, 1800, 1900), FDD, no hooks</td>
<td>2-6 x</td>
<td>1993-present</td>
</tr>
</tbody>
</table>
Comparing TDD and FDD

- Two-way communications schemes need separate channels for each direction of communication
  - Frequency Division Duplex (FDD): directions separated in frequency
  - Time Division Duplex (TDD): directions separated in time

- **TDD**
  - requires single block of spectrum
  - especially efficient where communications may be asymmetric (e.g., data)
  - leverages maximum benefits from adaptive antennas

- **FDD**
  - requires paired spectrum
  - less efficient with unknown or varying data asymmetry
  - benefits for extreme long-range operation (10’s of km)
  - adaptive antennas provide significant benefits
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Co-Channel Issues

- Recall adaptive antennas’ high ratio of EIRP to total radiated power (TRP)
  - factor of M higher than comparable conventional system
  - result of directivity of adaptive antennas

- Average power radiated in any direction is TRP plus gain of individual array elements
  - EIRP is still worst case directive power

- Regulatory relevance
  - safety/RF exposure considerations
  - coordination of co-channel systems in different markets
Adjacent Channel/Out-Of-Band Issues

- Recall that adaptive antenna gains result from *coherent* processing

- Out-of-band radiation due to intermodulation, phase noise, spurs
  - nonlinear processes
  - reduce/eliminate coherency of signals among PAs’ out-of-bands

- Result
  - ratio of in-band EIRP to out-of-band radiated power is up to a factor of M less than for comparable conventional system

- Regulatory relevance
  - A per-PA “43+10\log P-10\log M rule” would result in comparable operational out-of-bands to single antenna 43+10\log P rule
  - significant positive effect on adaptive antenna power amplifier economics
  - may help to foster adoption
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- Increased spectral efficiency leads to
  - better spectrum conservation
  - diversity of services
  - affordability of services

- Adaptive antennas is the single best technology for increasing spectral efficiency

- Wide range of adaptive antenna technologies
  - same basic principles
  - wide variations in goals and performances
  - intracell reuse (reuse < 1) possible for certain applications

- Proven technology
  - more than 80,000 deployments worldwide