Adaptive Antenna Tutorial:
Spectral Efficiency and Spatial Processing

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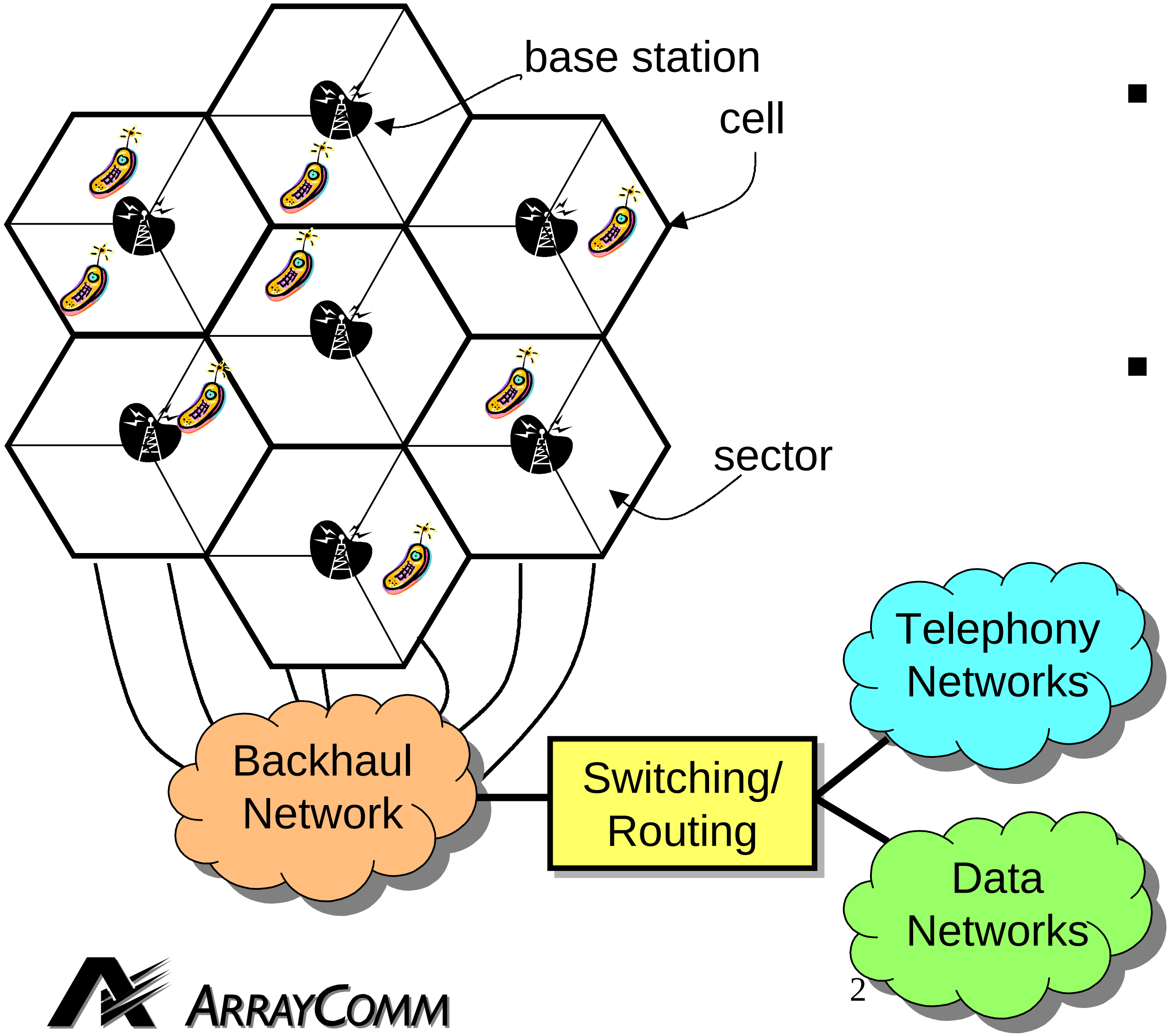
Cellular Technology



- 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, …)

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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**

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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

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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**

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

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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

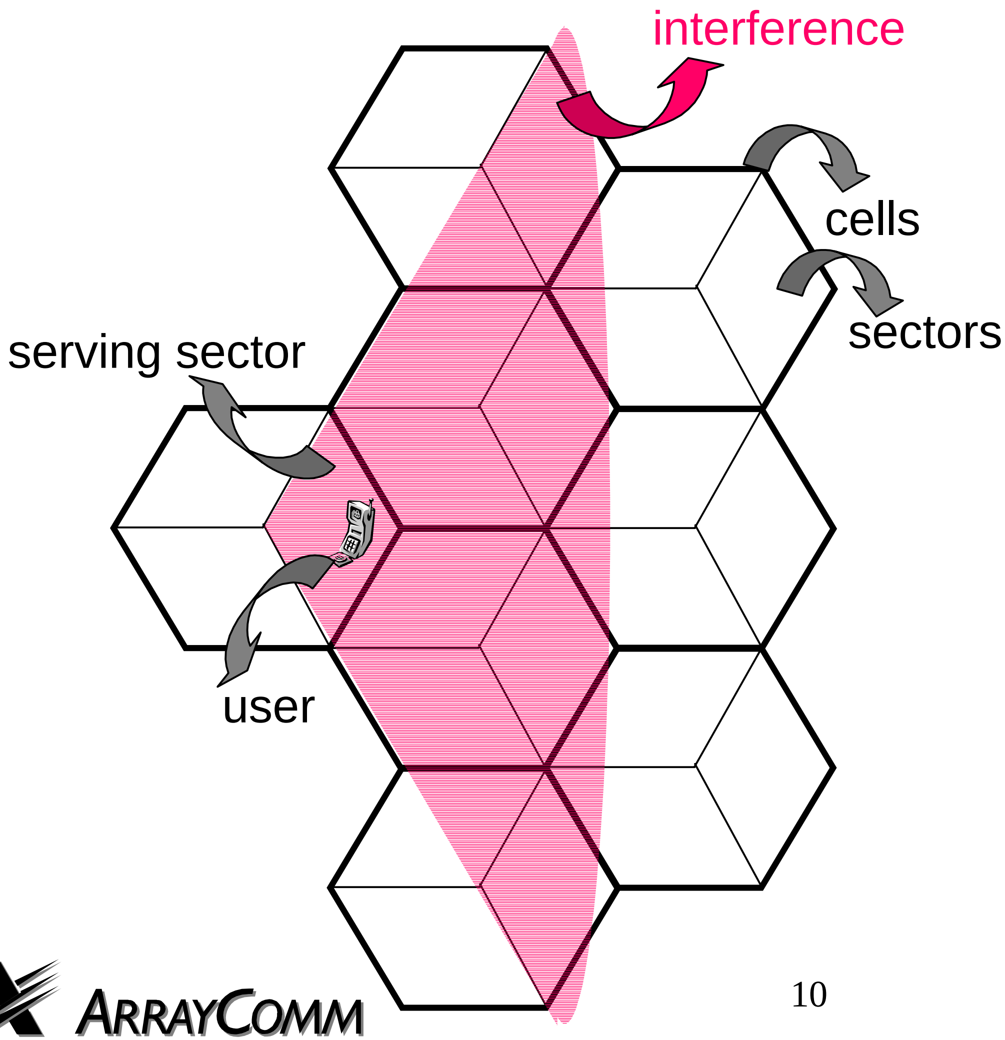
Designing For Spectral Efficiency

- **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

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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**

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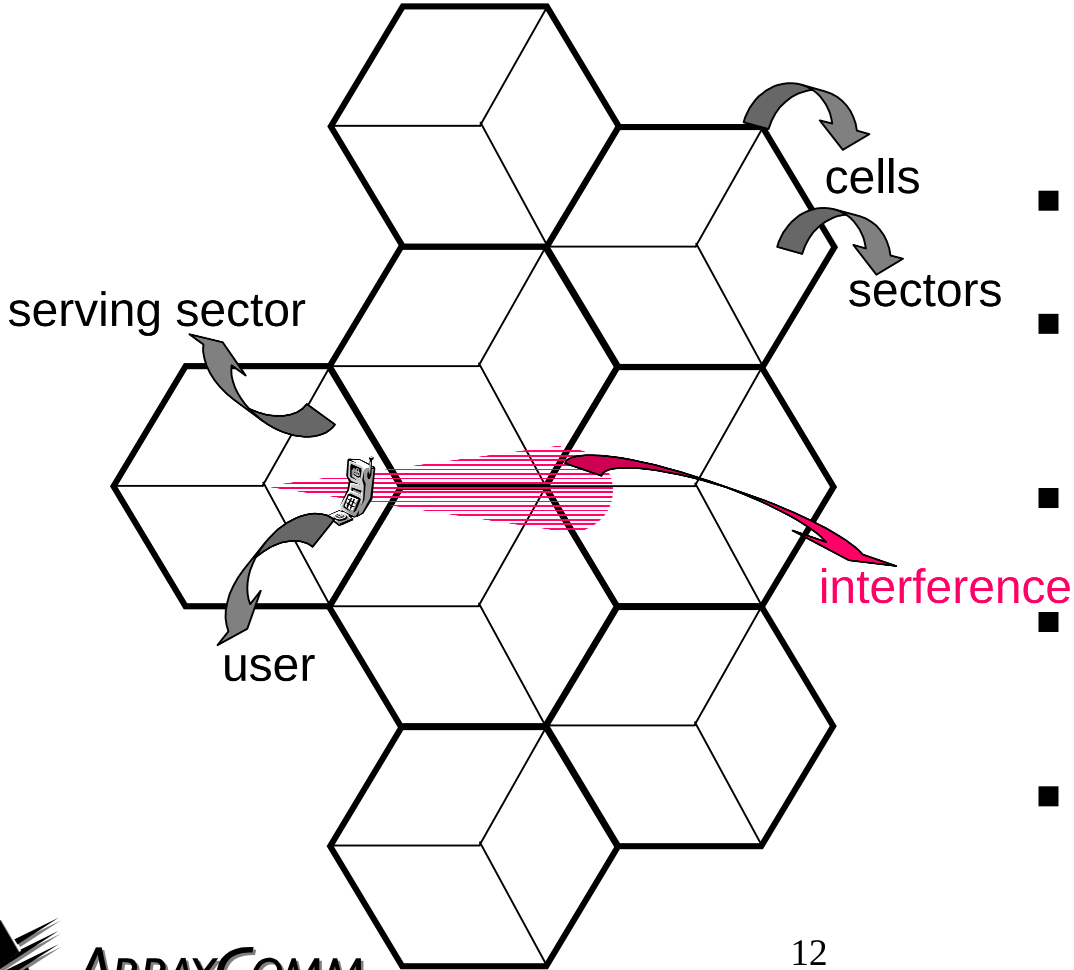
Adaptive Transmission/Reception



- 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

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Comparative Spectral Efficiencies

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

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

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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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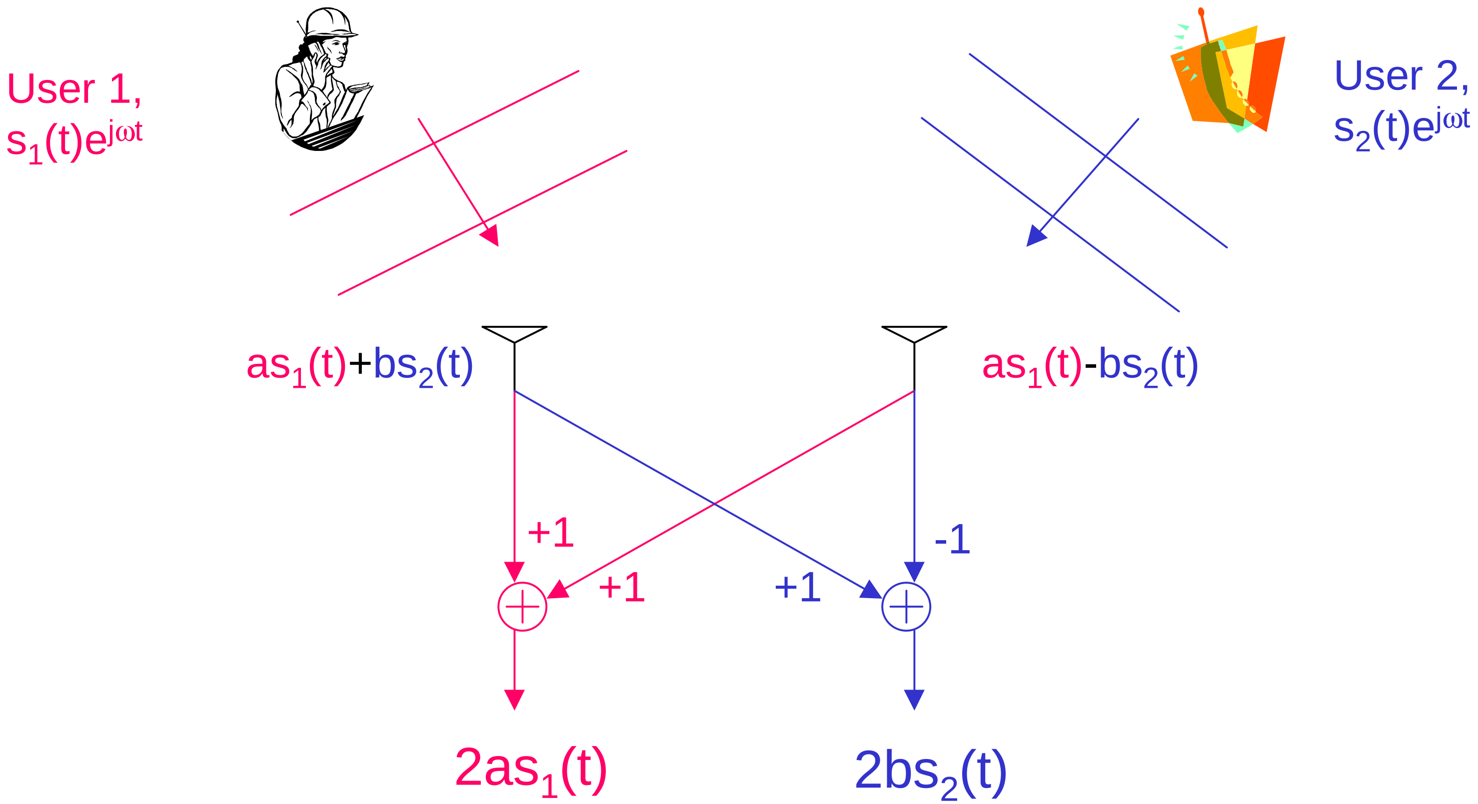
Adaptive Antennas Defined

- **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**

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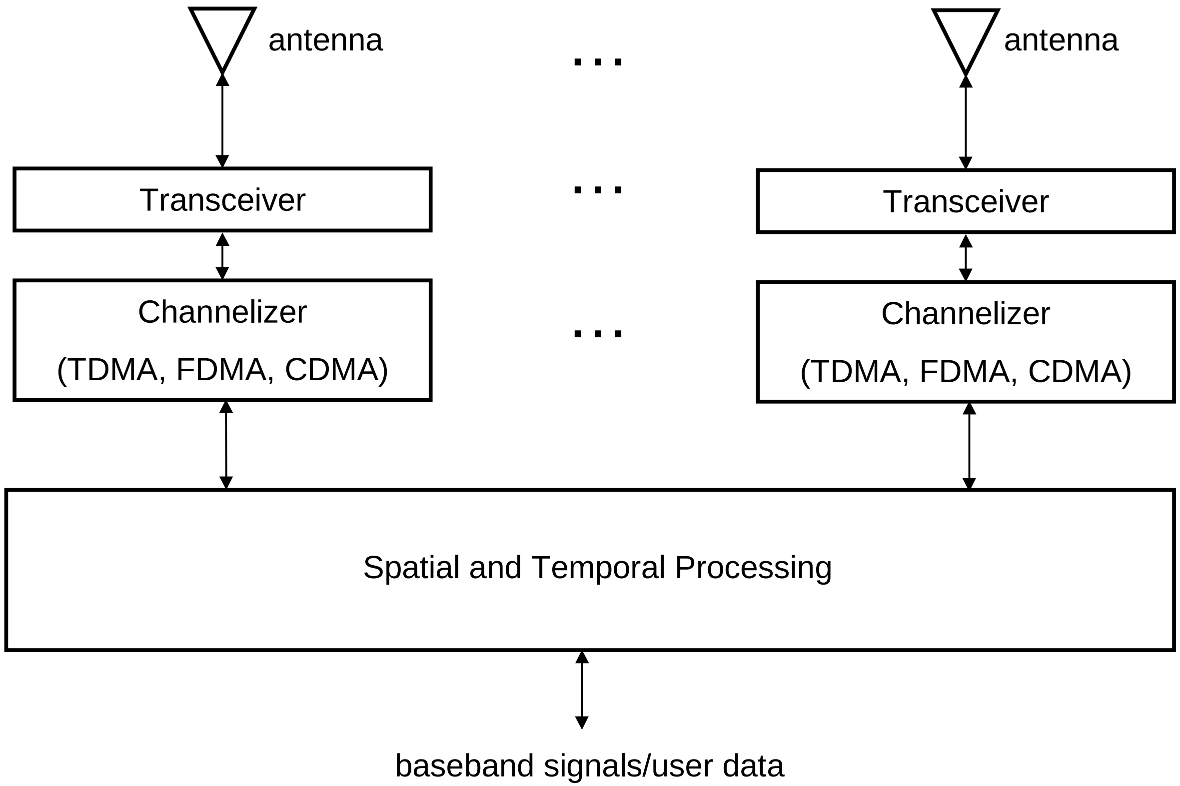
Protocol Independence

- **Fundamental concepts applicable to all access and modulation methods**



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Basic Uplink Gain Calculation

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

$$\frac{\text{received signal}}{\text{noise}} = \frac{s + \dots + s}{n_1 + \dots + n_M}$$

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

$$= \text{M x single antenna SNR}$$

- **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

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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**

$$\frac{\text{Received Power (Adaptive Antenna)}}{\text{Received Power (Single Antenna)}} = \frac{(\sqrt{P/M}\, s + \ldots + \sqrt{P/M}\, s)^2}{(\sqrt{P}s)^2} = M$$

- **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

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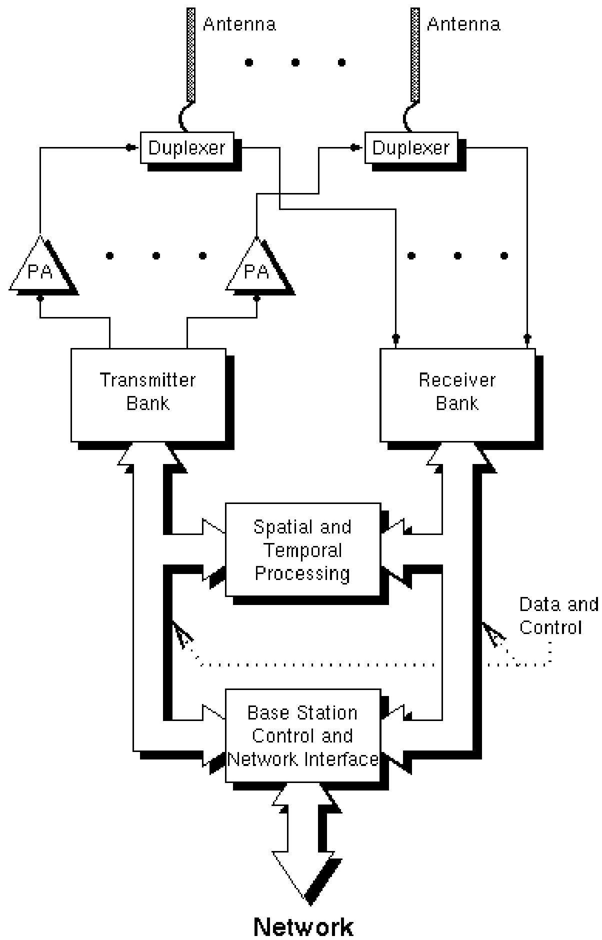
Interference Mitigation

- **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, ∞, 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

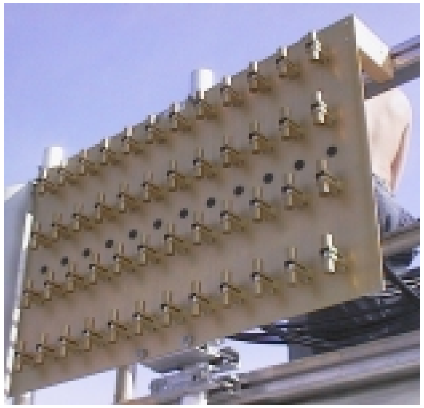
- antenna array
- phase coherent transceiver chains
- automated adaptive techniques to combine (distribute) energy from (to) transceiver chains
- natural application for wideband radios

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

Processing At The User Terminal

- **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

Processing Gain	Operational Significance
Selective Uplink Gain	Increased Range & Coverage Increased Data Rates Reduced System – Wide Uplink Noise Improved Uplink Multipath Immunity
Uplink Interference Mitigation	Improved Signal Quality Maintained Quality with Tightened Reuse
Selective Downlink Gain	Increased Range & Coverage Increased Data Rates Reduced System–Wide Downlink Interference Improved Co–existence Behavior Reduced Downlink Multipath
Downlink Interference Mitigation	Maintained Quality with Tightened Reuse

- **Actual level of benefits depends on implementation details**

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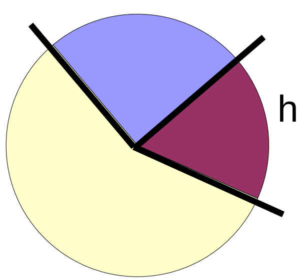
Comparing Adaptive Antennas

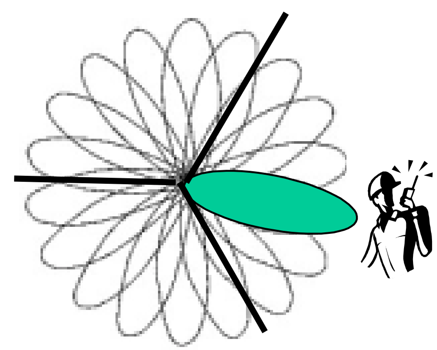
- **Predictability and consistency of performance**
- **Balance of uplink and downlink performance (key for capacity improvements)**
  - downlink is generally most challenging aspect of adaptive antennas
  - base station directly samples environment on uplink; generally must infer the environment on 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

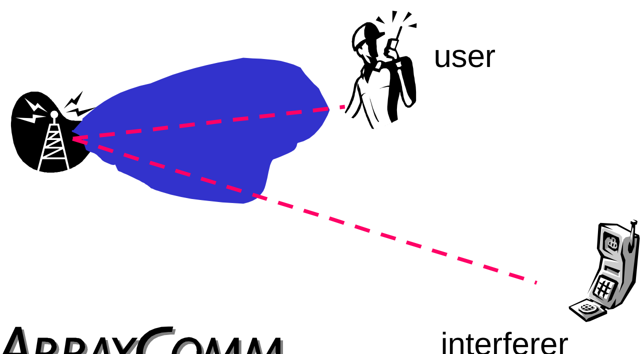


- **Switched Beam**
  - selects from one of several fixed patterns to maximize received power
  - selection problems for low SINR
  - moderate gain uniformity/predictability
  - less predictable active interference mitigation

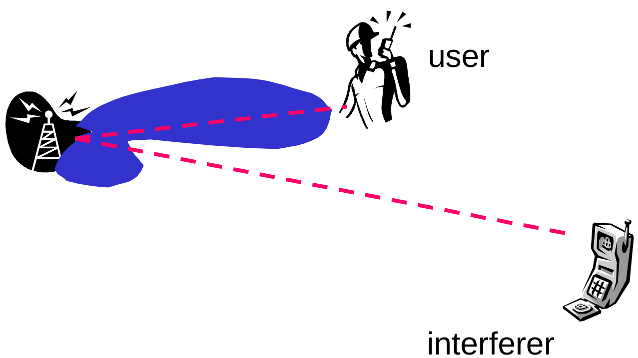


Energy Extraction and Fully Adaptive

- **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**

Application	Capacity Increase	Deployments
FWA, TDD, hooks	20x	1996-present
Low Mobility PHS, TDD, no hooks	5x	1996-present
High Mobility AMPS & GSM (900, 1800, 1900), FDD, no hooks	2-6 x	1993-present

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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+10logP-10logM rule" would result in comparable operational out-of-bands to single antenna 43+10logP rule
  - significant positive effect on adaptive antenna power amplifier economics
  - may help to foster adoption

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Summary

- **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

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