Smart Antennas for Wireless Systems

Jack H. Winters

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jwinters@motia.com
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GOAL

In this tutorial, we will discuss current and future antenna technology for wireless systems and the improvement that smart and adaptive antenna arrays can provide. We will describe standard cellular antennas, smart antennas using fixed beams, and adaptive antennas for base stations, as well as antenna technologies for handsets and other wireless devices. We will show the potential improvement that these antennas can provide, including range extension, multipath diversity, interference suppression, and capacity increase.

The issues involved in incorporating these antennas into wireless systems, including 2nd generation (CDMA, GSM, and IS-136), 3rd generation (WCDMA and EDGE), and future cellular systems, as well as other wireless systems, such as wireless local area networks (WLAN’s) in different environments, such as rural, suburban, and urban areas, as well as indoors, will be described in detail. Theoretical, computer simulation, experimental, and field trial results will be presented. This tutorial should provide a basic understanding of the antenna technology options and their potential in wireless systems.
WIRELESS SYSTEM IMPAIRMENTS

Wireless communication systems are limited in performance and capacity by:

- Delay Spread
- CoChannel Interference
- Rayleigh Fading
- Limited Spectrum

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MULTIPATH

- Many paths ⇒ Rayleigh fading (complex Gaussian channel)
- Flat fading (negligible ISI) if $\Delta \tau < 10\% \ T$ (symbol period)
- Fading is independent with distance ($> \lambda/4$), direction, and polarization
- Distribution of bit error rate (BER) ⇒ outage probability $P_0 = Pr(BER > BER_0)$
DELAY SPREAD

\[ \Delta \tau > 10\% T \]

- Time domain
- Delay spectrum
- Frequency domain
- Intersymbol interference (ISI)

Double Spike
Exponential

Power

|\( H(f) |}

\( f \)
CO-CHANNEL INTERFERENCE (CCI)

- Cellular systems use frequency reuse for capacity increase

  \[
  \begin{array}{c}
  F_1 \quad N = 3 \\
  F_2 \\
  F_3 
  \end{array}
  \]

- To increase capacity further: shrink cell size, increase reuse
- \( N = 7 \) frequency reuse currently
- Six closest interferers (S/I set by \( N \) only)
- One interferer usually dominates
- CCI assumed Gaussian noise in most studies
Multiple antenna elements with received signals weighted and combined

With multipath, diversity gain requires independent fading:

- $\lambda/4$ spacing
- Direction
- Polarization
**Antenna Gain**: Increased average output signal-to-noise ratio
- Gain of $M$ with $M$ antennas
- Narrower beam with $\lambda/2$-spaced antenna elements

**Diversity Gain**: Decreased required receive signal-to-noise ratio for a given BER averaged over fading
- Depends on BER - Gain for $M=2$ vs. 1:
  - $5.2$ dB at $10^{-2}$ BER
  - $14.7$ dB at $10^{-4}$ BER
- Decreasing gain increase with increasing $M$ - $10^{-2}$ BER:
  - $5.2$ dB for $M=2$
  - $7.6$ dB for $M=4$
  - $9.5$ dB for $M=\infty$
- Depends on fading correlation
  - Antenna diversity gain may be smaller with RAKE receiver in CDMA
DIVERSITY TYPES

Spatial: Horizontal separation
  - Correlation depends on angular spread

Polarization: Dual polarization
  - Low correlation
  - Horizontal receive 6-10 dB lower than vertical with vertical transmit and LOS

Angle: Adjacent narrow beams
  - Low correlation typical
  - 10 dB lower signal in weaker beam, with small angular spread
Field trial results for 4 receive antennas on the uplink:

- Range extension: 40% reduction in the number of base stations can be obtained 4 to 5 dB greater margin ⇒ 30% greater range

- Interference suppression: potential to more than double capacity
  Operation with S/I close to 0 dB at high speeds ⇒ greater capacity and quality
DIVERSITY TYPES
(wireless devices)

Spatial: Separation – only $\frac{1}{4}$ wavelength needed at terminal (10 wavelengths on basestation)

Polarization: Dual polarization (doubles number of antennas in one location)

Angle: Adjacent narrow beams with switched beam antenna

Pattern: Allows even closer than $\frac{1}{4}$ wavelength
  $\Rightarrow$ 4 or more antennas on a PCMCIA card
  $\Rightarrow$ 16 on a handset
  $\Rightarrow$ Even more on a laptop
Diversity Antennas

Base Station Antennas

- Antennas mounted on 60 foot tower on 5 story office building
- Dual-polarized slant 45° 1900 MHz sector antennas and fixed multibeam antenna with 4 - 30° beams

Laptop Prototype

- 4 patch antennas at 1900 MHz separated by 3 inches (\text{\lambda}/2 wavelengths)
- Laptop prototype made of brass with adjustable PCB lid

Friday, December 5, 2003
COMBINING TECHNIQUES

Selection:

• Select antenna with the highest received signal power

• $P_{0M} = P_0^M$
COMBINING TECHNIQUES (CONT.)

Maximal ratio combining:

- Weight and combine signals to maximize signal-to-noise ratio (Weights are complex conjugate of the channel transfer characteristic)
- Optimum technique with noise only
- $\text{BER}_M \approx \text{BER}^M$ ($M$-fold diversity gain)
OPTIMUM COMBINING (ADAPTIVE ANTENNAS)

• Weight and combine signals to maximize signal-to-interference-plus-noise ratio (SINR)
  - Usually minimize mean squared error (MMSE)

• Utilizes correlation of interference at the antennas to reduce interference power

• Same as maximal ratio combining when interference is not present
INTERFERENCE NULLING
Line-Of-Sight Systems

Utilizes spatial dimension of radio environment to:
• Maximize signal-to-interference-plus-noise ratio
• Increase gain towards desired signal
• Null interference: M-1 interferers with M antennas
Antenna pattern is meaningless, but performance is based on the number of signals, not number of paths (without delay spread).

=> A receiver using adaptive array combining with $M$ antennas and $N-1$ interferers can have the same performance as a receiver with $M-N+1$ antennas and no interference, i.e., can null $N-1$ interferers with $M-N+1$ diversity improvement ($N$-fold capacity increase).
SPATIAL VS. ANGULAR DOMAIN

• Number of rays < number of antennas ⇒ angular domain (LOS)

• Number of rays > number of antennas ⇒ spatial domain (multipath)
THEORY

Model:

• $N$ transmitters, 1 to $N$ outputs

• At each output, 1 desired signal and $N$-1 interferers

• $M$ receiving antennas, with channel matrix $C=[C_{ij}]$, where $C_{ij}$ is the channel coefficient between transmitter $i$ and antenna $j$
THEORY (CONT’D)

Assumptions:

• Flat Rayleigh fading

• Antennas spaced far enough for independent fading
  - $C_i = [C_{i1} \cdots C_{iM}]$ are linearly independent
  - $C_{ij}$ are complex i.i.d. zero-mean Gaussian random variables

• Noise is additive, zero-mean i.i.d. Gaussian

Goal: Linear receiver cancels $N-1$ interferers and maximizes desired signal SNR
Solution for $N = 1$ (no interferers):

- $W = C_1^*$

- $P_e \leq E_C \exp \left\{-\rho \sum_{j=1}^{M} |C_{1j}|^2 \right\} = (1 + \rho)^{-M}$

- Maximal ratio combining
Solution for \( N \geq 2 \) \((N-1 \text{ interferers})\):

- To cancel interferers \( W \) must be orthogonal to \( C_2 \cdots C_N \)
- \( W \) is the projection of \( C_1^* \) onto the \( M-N+1 \) dimensional space orthogonal to \( C_2 \cdots C_N \)
- Since the elements of \( C_1^* \) are i.i.d. Gaussian random variables, \( W \) has \( M-N+1 \) dimensions, with the same statistics as \( C_1 \), independent of \( C_2 \cdots C_N \)

\[
P_e \leq E_z \exp \left\{ -\rho \sum_{i=1}^{M-N+1} |Z_i|^2 \right\} = (1 + \rho)^{(M-N+1)}
\]
RESULT

A receiver using linear (optimum) combining with $M$ antennas and $N-1$ interferers has the same performance as a receiver with $M-N+1$ antennas and no interference.

• Null $N-1$ interferers with $M-N+1$ diversity improvement ($N$-fold capacity increase)
EQUALIZATION

• Delay spread: Delay spread over \([(M-1) / 2]T\) or \(M-1\) delayed signals (over any delay) can be eliminated

• Typically use temporal processing with spatial processing for equalization:

  - Spatial processing followed by temporal processing has degradation, but this degradation can be small in many cases
MIMO CAPACITY INCREASE

• With $M$ antennas at both the base station and mobiles, $M$ independent channels can be provided in the same bandwidth if the multipath environment is rich enough.

  • 1.2 Mbps in a 30 kHz bandwidth using 8 transmit and 12 receive antennas demonstrated by Lucent (indoors).

  • Separation of signals from two closely-spaced antennas 5 miles from the base station demonstrated by AT&T/Lucent.
• With M transmit and M receive antennas, can provide M independent channels, to increase data rate M-fold with no increase in total transmit power (with sufficient multipath) – only an increase in DSP
  - Indoors – up to 150-fold increase in theory
  - Outdoors – 8-12-fold increase typical
• Measurements (e.g., AT&T) show 4x data rate & capacity increase in all mobile & indoor/outdoor environments (4 Tx and 4 Rx antennas)
  - 216 Mbps 802.11a (4X 54 Mbps)
  - 1.5 Mbps EDGE
  - 19 Mbps WCDMA
OPTIMUM COMBINING
THEORETICAL (ZERO-FORCING) RESULT

- A receiver using linear (optimum) combining with $M$ antennas and $N-1$ interferers has the same performance as a receiver with $M-N+1$ antennas and no interference
- Multipath: $M$-fold diversity gain
- CCI only: $N$ interferers eliminated ($M$-fold capacity increase
- Delay spread: Delay spread over $[(M-1)/2]T$ or $M-1$ delayed signals (over any delay) eliminated
- CCI and multipath: $N$ interferers eliminated with $M-N$-fold diversity gain
- CCI, delay spread, and multipath: $N$ interferers with delay spread over $D$ symbols with $M+1-(N+1)(2D+1)$-fold diversity gain
OPTIMUM COMBINING - MMSE RESULT

Practical systems (typically):

• # interferers >> M
• D >> (M-1)/2

But:

• Only need to suppress interference (and ISI) into the noise (not eliminate)
• Usually only 1 or 2 dominant interferers and delayed paths

Result:

• Substantial increase in performance and capacity even with a few (even 2) antennas

Note:

• Optimum combining yields interference suppression under all conditions (e.g., line-of-sight, Rician fading)
EXAMPLE - MULTIPATH AND CCI WITH 2 ANTENNAS

Theory (zero-forcing):

- Dual diversity against multipath (maximal ratio combining)

or

- Elimination of one interferer (gain = INR - 12.8 dB) without diversity gain \{INR - interference to noise ratio, BER = 10^{-3}\}

MMSE result:

- Gain over maximal ratio combining \(\approx\) INR/2 (in dB) with one interferer

- Gain of 1 to 2 dB with 2 to 6 equal-strength interferers
EXAMPLE - MULTIPATH AND CCI WITH ADAPTIVE ANTENNAS

Ber = 10^{-3}
Coherent detection of BPSK
Two antennas

Gain over maximal ratio combining (dB)

Interference-to-Noise Ratio (dB)

BER = 10^{-3}
Coherent detection of BPSK
Two antennas
SMART ANTENNAS

Today: Cellular systems with sectorization (120°) ⇒ handoffs between sectors

For higher performance ⇒ Narrower sectors ⇒ Too many handoffs

Smart Antenna: Multibeam antenna or adaptive array without handoffs between beams
Smart Antennas

Smart antenna is a multibeam or adaptive antenna array that tracks the wireless environment to significantly improve the performance of wireless systems.

Adaptive arrays in any environment provide:

- Antenna gain of $M$
- Suppression of $M-1$ interferers

**In a multipath environment, they also provide:**

- $M$-fold multipath diversity gain
- With $M$ Tx antennas (MIMO), $M$-fold data rate increase in same channel with same total transmit power
Smart Antennas can significantly improve the performance of wireless systems

- Higher antenna gain / diversity gain \(\Rightarrow\) Range extension and multipath mitigation
- Interference suppression \(\Rightarrow\) Quality and capacity improvement
- Suppression of delayed signals \(\Rightarrow\) Equalization of ISI for higher data rates
- Multiple signals in the same bandwidth \(\Rightarrow\) Higher data rates

Switched Multibeam versus Adaptive Array Antenna: Simple beam tracking, but limited interference suppression and diversity gain
SMART/ADAPTIVE ANTENNA ARRAY TECHNOLOGY

Military
- high resolution direction-finding
- jammer cancellation
- interference reduction
- signal classification
- directional transmission
- custom VLSI implementations

Commercial
- mobile, indoor, wireless local loop
- range extension
- interference reduction with fast fading
- signal acquisition and tracking
- delay spread equalization
- propagation characterization
- adaptive retransmission
- antenna design and implementations

Research

Applications
- long range surveillance radars
- military communication systems
- sonar
- geophysical exploration
- imaging

• Nortel SmartBTS - GSM
• MetaWave SpotLight
• ArrayComm IntelliCell
• Celwave Smart System - AMPS
• Hazeltine IAS - AMPS
• Ericsson and Lucent - IS-136

1980
1990
2000

• 3G
• WLAN
• WiMAX
• UWB
• 802.20
• Satellite radio/TV

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CELLULAR APPLICATIONS

IS-136
GSM
EDGE
CDMA

• Range increase (2 GHz versus 900 MHz ⇒ 9 dB)
• Capacity increase (higher reuse)
• Data rate increase (wireless Internet access)
IS-136

- TDMA with 3 users per channel
- $\pi/4$ DQPSK at 48.6 kbps
- 162 symbols/slot
- 14 symbol synchronization sequence
- Two receive antennas at base (Tracking over slot, but spatial processing before equalization is adequate)

**IS-136 Timing Structure**

**Digital Traffic Channel**

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDMA FRAME 40 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TIME SLOT 6.687 ms (162 symbols)**

<table>
<thead>
<tr>
<th>G</th>
<th>R</th>
<th>DATA</th>
<th>SYNC</th>
<th>DATA</th>
<th>SACCH</th>
<th>CDVCC</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>8</td>
<td>14</td>
<td>61</td>
<td>6</td>
<td>6</td>
<td>61</td>
</tr>
</tbody>
</table>

**MOBILE TO BASE**

<table>
<thead>
<tr>
<th>14</th>
<th>6</th>
<th>65</th>
<th>6</th>
<th>65</th>
<th>1</th>
<th>5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYNC</td>
<td>SACCH</td>
<td>DATA</td>
<td>CDVCC</td>
<td>DATA</td>
<td>RSVD</td>
<td>CDL</td>
</tr>
</tbody>
</table>

**BASE TO MOBILE**

Symbol duration 41 $\mu$s (48.6 kb/s)
Smart Antennas for IS-136

- Key enhancement technique to increase system capacity, extend coverage, and improve user experience in cellular (IS-136)

In 1999, combining at TDMA base stations changed from MRC to MMSE for capacity increase
GSM

- TDMA with 8 users per channel
- Gaussian MSK at 270.833 kbps
- 156.25 bits/slot
- 26 bit synchronization sequence
- Two receive antennas at base (weights fixed over slot, but S-T processing is needed)

Frame

```
1  2  3  4  5  6  7  8
```

Frame duration: 4.615 ms

```
T  Data  F  Train  F  Data  T  Guard
3   57 b  1   26   1    57   3    8.25
```

Slot duration: 577 µs

Key:
T: Tail Bit
F: Flag
Train: Equalizer Training Sequence
SMART ANTENNAS IN THIRD GENERATION SYSTEMS: EDGE

- High data rate (384 kbps) service based on GSM, for both Europe and North America
- 8PSK at 270.833 kbps
- 26 symbol training sequence
- 1/3, 3/9 or 4/12 reuse

<table>
<thead>
<tr>
<th>3</th>
<th>58</th>
<th>26</th>
<th>58</th>
<th>3</th>
<th>8.25</th>
</tr>
</thead>
</table>

576.92 µs
Spatial-Temporal processing using DDFSE for interference suppression

Issues: tracking, dual antenna terminals
CDMA

IS-95 (2G)

- 1.25 MHz channel
- 9.6 (13) kbps per user
- Spreading gain = 128
- Two receive antennas at base with RAKE receiver
- Common downlink pilot - Multibeam downlink difficult
- M-fold increase in gain/capacity with M-beam antenna
- Many interferers - Limited additional gain with adaptive arrays
WCDMA (3G)

- 5 MHZ channels at 4.096 Mchips/sec
- FDD & TDD duplexing
- Coherent pilot detection
- Pilot signal per user - Smart antenna downlink
- Pilot channel available on uplink
- Multirate traffic => Adaptive array can be useful
- Large numbers of interferers on uplink (but could have near-far problem, nonuniform traffic or user distribution)
- A few interferers on downlink (other base stations) => interference suppression at mobile may be useful
WCDMA with Adaptive Antennas

- Techniques
  - S-T MMSE
  - S-T RAKE
  - Beamforming
Space-Time MMSE

- Utilizes knowledge of desired signal and interference covariance
- Selects L out of N available fingers, with received signals combined for each finger and then finger output combined, to minimize MSE (maximize SINR)
S-T MMSE

- RAKE receiver - resolves multipath at chip duration

\[
\sum \text{Fractional chip rate transversal filter}
\]

\[
\sum \text{Fractional chip rate transversal filter}
\]
Selects L out of N available fingers, based on largest SNR (SINR) after the received signals are combined, and then output signals combined to maximize SNR or SINR.
Beamforming with RAKE

• Closely-spaced antennas
• Adaptive beamforming based on
  – Nonuniform traffic
    • Adaptive sectorization
  – Few high data rate users (many voice users)
    • Null steering
• Can be used on uplink and downlink
RANGE INCREASE

• Fixed beam versus adaptive array
• TDMA versus CDMA
PHASED ARRAYS

- Fixed (or steerable) beams

- Consider cylindrical array with $M$ elements ($\lambda/2$ spacing)
  - Diameter $\approx (M / 4\pi)$ feet at 2 GHz

- With small scattering angle ($\gamma = 4$):
  - Margin = $10\log_{10}M$ (dB)
  - Number of base stations = $M^{1/2}$
  - Range = $M^{1/4}$

- Disadvantages:
  - No diversity gain (unless use separate antenna)
  - With large scattering angle $\alpha$, gain is limited for beamwidths $\approx \alpha$
• Circular array of $M$ cardioid-pattern antennas
• Uniformly-distributed, equal-power scatterers (20)
• $\gamma = 4$, no shadow fading
• For a $10^{-2}$ BER (averaged over 10,000 cases) with an omnidirectional antenna, and fixed transmit power and $r$, range is increased with $M$-element array until BER = $10^{-2}$.
• $\lambda/2$ antenna spacing
• No delay spread
Range Increase for IS-136

- **Fixed Multibeam Antenna**
  - Increases gain for better coverage
  - Range increase is limited by angular spread
  - No spatial diversity gain
  - Can be used on downlink or uplink

- **Adaptive Array**
  - Range increase independent of angular spread
  - Diversity gain increases with antenna spacing
  - Can be used on uplink with fixed multibeam downlink
CDMA

- 3-finger RAKE
- Phased or adaptive array combining of RAKE outputs at each delay
- Maximal ratio combining of (summed over antennas) delayed RAKE outputs
- $r$ set for 3-symbol delay spread (e.g. $r = 300\text{ft}$ at 5 Mbps)
- IS-95 picks different beams for each finger ⇒ Less sensitive to scattering angle, and diversity gain with wider spacing not significant
CDMA with Adaptive Array

![CDMA with Adaptive Array Diagram]
Range Increase with CDMA Signals

Single beam for all RAKE fingers results in range limitation with angular spread for multibeam antenna (phased array)
Range Increase with CDMA Signals - Different Beams per Finger

- Adaptive Array
- Phased Array
- Theory

Normalized Range

log_{10} (M)

3M-fold Diversity

5\lambda \text{ Spacing}

FIXED SECTORS, \alpha_0=60^\circ

3\text{-fold Diversity}
CONCLUSIONS FOR RANGE INCREASE

Phased Arrays:
- Range increase limitation determined by $\alpha$, (with TDMA, rural areas with $M > 100$, urban areas with smaller $M$)
- With CDMA and RAKE, range increase degradation is much less

Adaptive Arrays:
- No range limitation
- Diversity gain with $\lambda/2$ spacing
- Full diversity gain with large $M$ and a few $\lambda$ spacing for $\alpha > 1^\circ$

TDMA: Adaptive array with wide spacing (> $M$-fold increase in gain), but
  - Downlink requires fixed beam approach (transmit diversity)
  - Tracking at fading rate (184 Hz at 2 GHz)

CDMA: Fixed beam ($M$-fold increase in gain)
CAPACITY

CDMA

Phased Arrays:

• $M$-fold increase in capacity with $M$ antennas through sectorization, with loss compared to $M$-fold increase only with large scattering angles and $>3$ dominant rays

• Tracking at beam switching rate (every few seconds)/same beam for transmission as reception

• Multiuser detection for greater capacity

Adaptive Arrays:

• Provide limited increase in capacity since number of interferers $\gg$ number of antennas (except for near-far problem/narrowband interferers)

⇒ Fixed beams
CAPACITY

TDMA

• Capacity is limited by a few dominant interferers

Phased Arrays: Some capacity increase - 2-fold with 4 beams

Adaptive Arrays: Large capacity increase on uplink with just a few antennas, but need fixed beams on the downlink ⇒ adaptive array
SMART ANTENNAS IN 2G TDMA SYSTEMS

• IS-136 TDMA:
  – On uplink, with two receive antennas, in 1999 changed from maximal ratio combining to optimum combining
    • Software change only - provided 3-4 dB gain in interference-limited environments
    • Combined with power control on downlink (software change only) - increased capacity through frequency reuse reduction
  – Use of 4 antennas (adaptive array uplink/multibeam, with power control, downlink) extends range and/or doubles capacity (N=7 to 4 or 3)
ADAPTIVE ARRAYS IN EDGE

Block Error Rate vs. SIR (dB)

- Typical Urban
- Hilly Terrain
- 1-branch
- 2-br. MMSE
CONCLUSIONS FOR CAPACITY INCREASE

TDMA: Adaptive arrays provide $> M$-fold capacity increase

CDMA: Fixed beams provide $\approx M$-fold capacity increase
• With M transmit and M receive antennas, can provide M independent channels, to increase data rate M-fold with no increase in total transmit power (with sufficient multipath) – only an increase in DSP
  – Indoors – up to 150-fold increase in theory
  – Outdoors – 8-12-fold increase typical
• Measurements (e.g., AT&T) show 4x data rate & capacity increase in all mobile & indoor/outdoor environments (4 Tx and 4 Rx antennas)
  – 216 Mbps 802.11a (4X 54 Mbps)
  – 1.5 Mbps EDGE
  – 19 Mbps WCDMA
MIMO-EDGE

- **Goal:** 4 transmit / 4 receive antennas in EDGE can theoretically increase capacity 4-fold with the same total transmit power (3.77X384 kbps = 1.45 Mbps is actual theoretical increase)

- **Issues:**
  - Joint spatial-temporal equalization
  - Weight adaptation
  - Mobile channel characteristics to support MIMO-EDGE

- **AT&T approach:**
  - Development of multi-antenna EDGE testbed
  - Development of 2X2 and 4X4 DDFSE architecture with MMSE combining using successive interference cancellation
  - Mobile channel measurements
MIMO Channel Testing

Transmit Antenna Configurations

- Space diversity
- Space / polarization diversity
- Space / pattern diversity
- Space / polarization / pattern diversity

Mobile Transmitter

W1 → Tx → Rx

W2 → Tx → Rx

W3 → Tx → Rx

W4 → Tx → Rx

Synchronous test sequences

LO

Test Bed Receiver with Rooftop Antennas

- Record complex correlation of each transmit waveform on each receive antenna, $C_{4x4}$
- Compute $C^HC$ correlation matrix to determine potential capacity and predict performance
- Compute fading correlation across receive array

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MIMO Channel Measurement System

Transmitter
- 4 antennas mounted on a laptop
- 4 coherent 1 Watt 1900 MHz transmitters with synchronous waveform generator

Receive System
- Dual-polarized slant 45° PCS antennas separated by 10 feet and fixed multibeam antenna with 4 - 30° beams
- 4 coherent 1900 MHz receivers with real-time baseband processing using 4 TI TMS320C40 DSPs
ISSUES

• Equalization
• Correlation
• Downlink/Portable Antennas
• Multipath Distribution
Linear equalization (LE)

* Inverts the channel

\[ H_R(f) = H_c^{-1}(f) \]

* Delay may be less than \( T \) for FSE if \( BW > 1/T \)

* Advantages:
  - Easy to implement and analyze

* Disadvantages:
  - Noise enhancement
  - May require many taps (e.g. \( K = \infty \) with double spike)

* Poor performance compared to nonlinear techniques
DECISION FEEDBACK EQUALIZER (DFE)

- Advantages:
  - Easy to implement
  - No noise enhancement
  - # taps $\approx D$

- Disadvantages:
  - Error propagation
  - Subtracts ISI portion (loss in signal power)
MAXIMUM LIKELIHOOD SEQUENCE ESTIMATION (MLSE)

• Chooses sequence of symbols with MMSE

Typically implemented by Viterbi algorithm

• Advantages:
  - Optimum technique
  - Utilizes all received signal power

• Disadvantages:
  - Complex to implement (# states in trellis grows exponentially with delay and # signal levels) and analyze
Spatial-Temporal processing using DDFSE for interference suppression

Issues: tracking, dual antenna terminals
CORRELATION

- Degradation due to fading correlation with adaptive array that combats fading, suppresses interference, and equalizes delay spread is only slightly larger than that for combating fading alone:

  - Small degradation with correlation less than 0.5
1) If same channel is used for transmitting and receiving (TDMA/TDD or FDD within coherence bandwidth

   • Adaptive retransmission
   
   • Selection diversity: transmit with best receive antenna
   
   • Maximal ratio combining: transmit with same antenna pattern as receive to maximize receive signal power
   
   • Optimum combining: transmit with receive antenna pattern to increase receive signal power while reducing interference to other users

2) If feedback from receiver is possible:

   • Switched diversity with feedback - single bit feedback with propagation delay
3) Create ISI and then equalize

- With MLSE, two transmit antennas give 2-fold diversity
  [Seshadri and Winters, JWIN ‘94]
Can use transmit diversity to obtain adaptive antenna improvement with transmit antennas:

- Create ISI with time delay between transmit antennas and equalize at receiver
- Diversity gain is (transmit antennas) x (receive antennas) - multiple remote antennas may not be needed
- Interference suppression is also possible (if interferers use same method)

Example - QPSK with $N$ Transmit Antennas
CDMA

- RAKE receiver - resolves multipath at chip duration

- Transmit diversity creates frequency selective fading even without delay spread (e.g. indoors) [Viterbi and Padovani, Communications Magazine, 1992]
4) Create fast fading with frequency offset between transmit antennas ($M$-fold diversity gain with interleaving and coding)
MULTIPATH DISTRIBUTION

Distribution of multipath around antennas significantly impacts fixed beam and adaptive array approaches for

• Range increase in TDMA on downlink
• Capacity increase in CDMA
• Delay spread reduction
• Multipath fading tracking methods

If multipath is uniformly distributed in angle-of-arrival for both strength and delay, these gains are not possible

But:

• Generally, there are only a few dominant paths
  ⇒ Large impact of model on performance
  ⇒ Multipath can be beneficial for MIMO techniques
WEIGHT GENERATION TECHNIQUES

For Smart Antenna: Need to identify desired signal and distinguish it from interference

- **Blind (no demod):** MRC – Maximize output power
  - Interference suppression – CMA, power inversion, power out-of-band

- **Non-Blind (demod):** Training sequence/decision directed reference signal
  - MIMO needs non-blind, with additional sequences
• Smart antennas for WCDMA can provide significant gains (>7 dB at handset)
  – But not justified today (Innovics, Metawave) (Qualcomm is implementing, though)
• MIMO for WCDMA may be implemented in 2-5 years
- Dual-polarized slant 45° PCS antennas separated by 10 feet and fixed multibeam antenna with 4 - 30° beams
- 4 coherent 1900 MHz receivers with real-time baseband processing using 4 TI TMS320C40 DSPs
IS-136 Smart Antenna System

- 4 Branch adaptive antenna uplink for range extension and interference suppression
- Fixed switched beam downlink with power control for increased coverage and capacity
- Uplink and downlink are independent
- Shared linear power amplifiers reduce amplifier requirements to handle maximum traffic load
Applique Architecture

Existing 900 MHz Dual-Diversity Base Station
ANT 1
ANT 2
To MTSO

Existing 900 MHz Dual-Diversity Base Station Timing Signals
ANT 1
ANT 2
To MTSO

AAA Applique
2 GHz → Baseboard downconversion
Array Processing (baseband)
Baseband → 900 MHz upconversion
Array Output

Original Antenna Feeds

Additional Antenna Feeds
EXPERIMENTAL TESTBED

- 1.9 GHz PCS band, IS-136
- 4 antennas (adaptive array uplink / multibeam downlink)
- Baseband processing: 4 ‘C40 DSP’s
- DMI - realtime (symbol-by-symbol) processing with sliding window and symbol synchronization (uplink)
- RF channel emulator (independent Rayleigh fading)
- Ideal (theoretical) performance at $10^{-2}$ BER (versus 2 antenna system with selection diversity):
  - 6 dB gain in noise alone ($S/I = \infty$)
  - 4 dB gain with $S/I = 0$ dB
- Experimental Results:
  - Noise alone ($S/I = \infty$): < 0.5 dB implementation loss up to 60 mph
  - $S/I = 0$ dB: 1dB implementation loss for speeds < 8 mph, close to $10^{-2}$ BER at high S/N at 60 mph
RANGE EXTENSION
Spatial Diversity: AAA with 4 antennas vs. REF with 2 antennas

BER (log)

SNR (dB)
### RANGE EXTENSION RESULTS

<table>
<thead>
<tr>
<th>Diversity Type</th>
<th>Adaptive Array</th>
<th>Gain at $10^{-2}$ BER over Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>4 equally-spaced ($12'$)</td>
<td>4.2 dB</td>
</tr>
<tr>
<td>Pol./Space</td>
<td>2 ($12'$) dual pol (45)</td>
<td>4.4 dB</td>
</tr>
<tr>
<td>Pol./Angle</td>
<td>2 ($18''$) dual pol (45)</td>
<td>2.9 dB</td>
</tr>
<tr>
<td>Angle</td>
<td>4 (before Butler matrix)</td>
<td>1.1 dB</td>
</tr>
</tbody>
</table>
INTERFERENCE SUPPRESSION
- OFFSET INTERFERER

Spatial Diversity: S/I = 0dB, AAA with 4 antennas vs. REF with 2 antennas

-BER vs. SNR (dB) graph showing performance comparison between AAA and REF configurations.
INTERFERENCE SUPPRESSION
- ADJACENT INTERFERER

Spatial Diversity: S/I = 0dB, AAA with 4 antennas vs. REF with 2 antennas

SNR (dB)

BER

0 10 20 30

0 0.5 1 1.5 2 2.5 3 3.5 4

AAA(avg.)
REF (avg.)
AAA (data)
REF (data)
Theory
Laboratory Results

0 mph
8 mph
60 mph
30 mph

Friday, December 5, 2003
## Interference Suppression Results for Required SNR

<table>
<thead>
<tr>
<th>Case</th>
<th>Diversity Type</th>
<th>S/N (dB) @ BER = 0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>REF</td>
</tr>
<tr>
<td>Adj., S/I=0dB</td>
<td>Spatial</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pol./Spatial</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pol./Angle</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Angle</td>
<td>*</td>
</tr>
<tr>
<td>Offset, S/I=0dB</td>
<td>Spatial</td>
<td>28.5</td>
</tr>
<tr>
<td></td>
<td>Pol./Spatial</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pol./Angle</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Angle</td>
<td>*</td>
</tr>
</tbody>
</table>

- Can’t be achieved for SNR < 30dB

* Not determined
## Interference Suppression Results for Required S/I Offset Interferer Only

<table>
<thead>
<tr>
<th>Diversity Type</th>
<th>S/I (dB) @ BER = 0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>REF</td>
</tr>
<tr>
<td>Spatial</td>
<td>17.5</td>
</tr>
<tr>
<td>Pol./Spatial</td>
<td>18.0</td>
</tr>
<tr>
<td>Pol./Angle</td>
<td>19.5</td>
</tr>
<tr>
<td>Angle</td>
<td>*</td>
</tr>
</tbody>
</table>

* Not determined
Field Test Drive Route

- 60° drive route within coverage of two center beams and 65° dual pol antennas
- Non line-of-sight conditions along route
- Suburban environment with gently rolling terrain
- Sense residential area with 2 story houses and tall trees
- Open area with office parks
- Maximum downrange distance of 2.5 miles
- Peak speed of 45 mph, average speed of 30 mph
FIELD TEST CONCLUSIONS

Experimental results with 4 antennas and real-time implementation show low implementation loss for

- 6 dB gain increase for 40% greater range

- Operation with an equal power interferer with potential to more than double capacity with rapid fading
OTHER WIRELESS APPLICATIONS

Peak Data Rate

100 Mbps

10 Mbps

1 Mbps

100 kbps

BlueTooth 2.4GHz

802.11b 2.4GHz Unlicensed

802.11g/a 2.4, 5.5GHz Unlicensed

WiMAX

UWB 3.1-10.6 GHz

2G/3G Wireless 0.9, 2 GHz

2 mph 10 mph 30 mph 60 mph

$500,000 $1000 $100 $10

$/Cell $/Sub

High performance/price

High ubiquity and mobility

Range
### Key 802.11b Physical Layer Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>1, 2, 5.5, 11 Mbps  (adaptation to our needs for 1 Mbps only)</td>
</tr>
<tr>
<td>Modulation/Spreading</td>
<td>Direct Sequence Spread Spectrum (DSSS)</td>
</tr>
<tr>
<td>Transmission modes</td>
<td>• DBPSK, DQPSK with 11-chip Barker code (1, 2 Mbps) (this mode stems from the original 802.11 standard)</td>
</tr>
<tr>
<td></td>
<td>• 8-chip complementary code keying (CCK) (5.5, 11 Mbps)</td>
</tr>
<tr>
<td></td>
<td>• optional: packet binary convolutional coding (PBCC), 64 state, rate 1/2 CC (BPSK 5.5 Mbps, QPSK 11 Mbps)</td>
</tr>
<tr>
<td>Chip rate</td>
<td>11 MHz</td>
</tr>
<tr>
<td>Frequency band</td>
<td>Industrial, Scientific and Medical (ISM, unlicensed) 2.4 - 2.4835 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>22 MHz - TDD</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Number of channels</td>
<td>Total of 14 (but only the first 11 are used in the US)</td>
</tr>
<tr>
<td>Carrier accuracy</td>
<td>±25 ppm</td>
</tr>
</tbody>
</table>
Key 802.11a Physical Layer Parameters:

- Data rate: 6, 9*, 12, 18*, 24, 36*, 48*, 54* Mbps
- Modulation: BPSK, QPSK, 16QAM, 64QAM*
- Coding rate: 1/2, 2/3, 3/4*
- Subcarriers: 52
- Pilot subcarriers: 4
- FFT size: 64
- Symbol duration: 4 μs
- Guard interval: 800 ns
- Subcarrier spacing: 312.5 kHz
- Bandwidth: 16.56 MHz - TDD
- Channel spacing: 20 MHz
- Frequency band: Unlicensed national infrastructure (U-NII)
- Number of channels: Total of 12 in three blocks between 5 and 6 GHz
- Carrier accuracy: 20 ppm
- Carrier accuracy @5.8GHz: 114 kHz

* optional
Wireless System Enhancements

Peak Data Rate

- **UWB**
  - 3.1-10.6 GHz
  - High performance/price

- **WiMAX**
  - High ubiquity and mobility

- **802.11a/g**
  - 2.4, 5.5GHz Unlicensed

- **802.11b**
  - 2.4GHz Unlicensed

- **BlueTooth**
  - 2.4GHz

- **2G/3G Wireless**
  - 0.9, 2GHz

- **Enhanced**

$/Cell$/Sub

- $500,000
- $1000
- $100
- $10

Range

- 10 feet
- 100 feet
- 1 mile
- 10 miles

Mobile Speed

- 2 mph
- 10 mph
- 30 mph
- 60 mph
Smart Antennas can significantly improve the performance of WLANs

- TDD operation (only need smart antenna at access point or terminal for performance improvement in both directions)
- Interference suppression ⇒ Improve system capacity and throughput
  - Supports aggressive frequency re-use for higher spectrum efficiency, robustness in the ISM band (microwave ovens, outdoor lights)
- Higher antenna gain ⇒ Extend range (outdoor coverage) and lower cost (gain limits)
- Multipath diversity gain ⇒ Improve reliability
- MIMO (multiple antennas at AP and laptop) ⇒ Increase data rates
RF Appliqué
(Spatial processing only)

Wireless Transceiver

RF Processor

Baseband/MAC Processor, Host Interface
802.11b Packet Structure

Time permits weight generation

96 symbol Short Preamble | MPDU
---|---
Preamble | SFD | PHY H | Data from MAC

56 Barker 16 Barker 24 Barker Barker
BPSK BPSK QPSK BPSK/QPSK
CCK 5.5/11Mbps

192 symbol Long Preamble | MPDU
---|---
Preamble | SFD | PHY H | Data from MAC

128 Barker 16 Barker 48 Barker Barker
BPSK BPSK BPSK BPSK/QPSK
(CCK 5.5/11Mbps)
802.11b Performance with Fading

Achieves a 12 to 14 dB gain over a single antenna

Performance Comparison - All four data rates

Theoretical for short packet

SNR (dB)

FER

y = 4.1054e^{0.1845x}
**802.11b Beamforming Gains with 4 Antennas**

Performance Gain over a Single Antenna in a Rayleigh Fading Channel

<table>
<thead>
<tr>
<th>2 Antenna Selection</th>
<th>Adaptive One Side</th>
<th>Adaptive Both Sides</th>
<th>Theoretical Bound Both Sides</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 dB</td>
<td>12.8 dB</td>
<td>18.0 dB</td>
<td>22.2 dB</td>
</tr>
</tbody>
</table>

2X to 3X Range + Uniform Coverage

3X to 4X Range + Uniform Coverage
802.11a/g
Flat Rayleigh Fading
24Mbps, Short Packet

8 symbols/packet
802.11a/g
50ns Exp Decay Rayleigh Fading
24Mbps, Short Packet

- 1 Ant
- 2 Ant, Selective
- 4 Ant, Selective
- 4 Ant, Motia RF Beamforming
- 2 Ant, Motia BB Beamforming
- 2 Ant, Motia BB Beamforming w/ Ideal Weight
- 4 Ant, Motia BB Beamforming
- 4 Ant, Motia BB Beamforming w/ Ideal Weight

SNR (dB) vs. PER

8 symbols/packet
802.11a/g
200ns Exp Decay Rayleigh Fading
24Mbps, Short Packet

8 symbols/packet
802.11a/g
SUI-2 Channel Model
24Mbps, Short Packet

8 symbols/packet

SNR (dB)

PER

1

0.1

0.01

3 5 7 9 11 13 15 17 19 21 23 25 27 29 31

1 Ant

2 Ant, Selective

4 Ant, Selective

4 Ant, Motia RF Beamforming

2 Ant, Motia BB Beamforming

4 Ant, Motia BB Beamforming
Network Simulation Assumptions

Scenario#1

- One AP, 10 users in random locations
- Poisson traffic with fixed data length (1.5Kbytes)
- RTS/CTS operation
- TCP/IP default transmission
- Smart antenna used at AP only

Scenario#2

- Two APs, multiple users in random locations
- Similar network conditions as Scenario#1

Table: Network Simulation Assumptions

<table>
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<th>Scenario#2</th>
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</thead>
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<td></td>
</tr>
<tr>
<td>Smart antenna used at AP only</td>
<td></td>
</tr>
</tbody>
</table>
Network Simulation Results

Performance Comparison - Scenario#1

- Smart Antenna
  - ReXmit: 1.32%
  - AVG: 10.85 Mbps
  - Pkg drop: 0.00%

- Omni-directional
  - ReXmit: 13.01%
  - AVG: 4.15 Mbps
  - Pkg drop: 0.12%
Network Simulation Results

Performance Comparison - Scenario#2

Data Rate (Mbps) vs. Percentage

- **Smart Antenna**
  - ReXmit 15.70%
  - AVG 9.46 Mbps
  - Pkg drop 0.46%

- **Omni-directional**
  - ReXmit 124.56%
  - AVG 4.29 Mbps
  - Pkg drop 19.17%
Smart Antennas

• Adaptive MIMO
  – Adapt among:
    • antenna gain for range extension
    • interference suppression for capacity (with frequency reuse)
    • MIMO for data rate increase

• With 4 antennas at access point and terminal, in 802.11a have the potential to provide up to 216 Mbps in 20 MHz bandwidth within the standard

• In EDGE/GPRS, 4 antennas provide 4-fold data rate increase (to 1.5 Mbps in EDGE)

• In WCDMA, BLAST techniques proposed by Lucent
“We don’t believe in dumb access points,” says William Rossi, vice president and general manager for Cisco’s wireless business unit. “The access points will eventually become smart antennas.”

Network World 06/02/03

Communications Design Conference:

• Craig Barratt (Atheros) - expects the technology (smart antennas) to first appear before the end of next year in silicon for access points supporting multiple antennas linking to single-antenna PC chip sets to provide greater range or capacity - followed by support for multiple antennas on both client and access-point chip sets. (Airgo - MIMO)

• Craig Mathias (Farpoint Group) - expects to see cellphones with WiFi emerge at the Consumer Electronics Show in January and to be in production by June - we will see the logical convergence of cellular and WiFi networks next year
Progression

• Smart antennas for 802.11 APs/clients
• Cellphones, PDAs, laptops with integrated WLAN/cellular
• Smart antennas for both WLANs and cellular in these devices
• MIMO in WLANs (802.11n), with MIMO in cellular (base stations)
• Seamless roaming with WLANs/cellular (WiMAX, 802.20)
Conclusions

• Smart antennas can improve user experience and system capacity by reducing interference, extending range, increasing data rates, and improving quality.

• Smart antennas can be implemented in the physical layer with little or no impact on standards.

• Expertise and experience in the development and deployment of smart antennas for cellular can be applied to develop smart antennas for WLANs, and many other wireless applications.