In this tutorial we discuss smart antennas and their use in wireless ad hoc networks. We first describe smart antennas and their application in a wide variety of wireless systems, including cellular and wireless local area networks. We then consider wireless ad hoc networks with smart antennas, including directional antennas, beamforming/adaptive antennas, and/or multiple-input multiple-output (MIMO) techniques. We describe the substantial improvement in performance that these antennas can provide, including collision avoidance, lower latency, higher capacity, and longer battery life. The issues faced when using smart antennas in wireless ad hoc networks will also be addressed, including neighbor discovery, as well as how MAC and routing techniques can be modified to get the maximum benefit from smart antennas.
Outline

- Service Limitations
- Smart Antennas
- Ad Hoc Networks
- Smart Antennas in Ad Hoc Networks
- Conclusions

Service Limitations

- Quality of service for each user is not consistent:
  - Too far away from the access point
  - Behind a wall
  - In a “dead” spot
  - Working off a battery, as with a laptop
  - Suffering from low bandwidth due to range/interference
- Lack of range
  - One AP cannot cover some houses
Solutions

- Smart Antennas
  - Can be implemented today (further improvement with standards in future – 802.11n)

- Ad Hoc Networks
  - Interconnections of multiple clients (standardization in progress for Access Point interconnection – 802.11s)

- Combination of Smart Antennas with Ad Hoc Networks can give greater gains than the sum of the two

Wireless System Impairments

Wireless communication systems are limited in performance and capacity by:

- Delay
- Spread
- CoChannel Interference
- Rayleigh Fading
- Limited Spectrum
A smart antenna is a multi-element antenna where the signals received at each antenna element are intelligently combined to improve the performance of the wireless system. The reverse is performed on transmit.

Smart antennas can:
- Increase signal range
- Suppress interfering signals
- Combat signal fading
- Increase the capacity of wireless systems

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

Switched Multibeam versus Adaptive Array Antenna: Simple beam tracking, but limited interference suppression and diversity gain, particularly in multipath environments.
Smart Antennas

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 antenna technologies can be used to improve most wireless applications, including:
• Wi-Fi a/b/g access points and clients
• In-vehicle DBS entertainment systems, such as:
  – Mobile video
  – Mobile broadband/gaming
• Satellite/digital radio
• GPS
• 3G Wireless
• WiMax
• RFID
• UWB
ANTENNA DIVERSITY

Multiple antenna elements with received signals weighted and combined

With multipath, diversity gain requires independent fading:
- $\lambda/4$ spacing
- Direction
- Polarization

ANTENNA AND DIVERSITY GAIN

**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
- Only $\frac{1}{4}$ wavelength needed at terminal (10 wavelengths on base station)

Polarization: Dual polarization (doubles number of antennas in one location)
- Low correlation
- Horizontal receive 6-10 dB lower than vertical with vertical transmit and LOS

DIVERSITY TYPES (cont.)

Angle: Adjacent narrow beams with switched beam antenna
- Low correlation typical
- 10 dB lower signal in weaker beam, with small angular spread

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

Selection:

- Select antenna with the highest received signal power
- \( P_{0d} = P_{0d}^M \)

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
- \( BER_{sd} = BER^M (M\text{-fold diversity gain}) \)
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
INTERFERENCE NULLING
Multipath Systems

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).

Multiple-Input Multiple-Output (MIMO) Radio

* 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
Practical Issues

Interferers
• # interferers >> M
But:
• Only need to suppress interference into the noise (not eliminate)
• Usually only 1 or 2 dominant interferers
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)

Delay Spread
Channel Model D – 802.11n

Figure 1. Model D delay profile with cluster extension (overlapping clusters).
• Delay spread: Delay spread over \[\frac{(M-1)}{2}T\] or \(M-1\) delayed signals (over any delay) can be eliminated

• Typically use temporal processing with spatial processing for equalization:

```
LE → MLSE/DFE
```

• Spatial processing followed by temporal processing has degradation, but this degradation can be small in many cases

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**Wireless System Enhancements**

<table>
<thead>
<tr>
<th>Peak Data Rate</th>
<th>High performance/price</th>
<th>High ubiquity and mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Mbps</td>
<td>802.11a/g</td>
<td>Enhanced</td>
</tr>
<tr>
<td>10 Mbps</td>
<td>802.11b</td>
<td></td>
</tr>
<tr>
<td>1 Mbps</td>
<td>BlueTooth</td>
<td></td>
</tr>
<tr>
<td>100 kbps</td>
<td>2G/3G Wireless</td>
<td></td>
</tr>
</tbody>
</table>

Usage:
- $\frac{\text{Cell}}{\text{Sub}}$
- $500,000$ $500$
- $1000$ $100$
- $10$ $10$

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**Future Directions**

- Continued research in equalization techniques
- Improved modulation schemes for wireless systems
In 1999, combining at TDMA base stations changed from MRC to MMSE for capacity increase.

Smart Antennas for IS-136

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

Smart Antennas for WLANs

- TDD operation (only need smart antenna at access point or terminal for performance improvement in both directions)
- Higher antenna gain ⇒ Extend range/ Increase data rate/ Extend battery life

Smart Antennas can significantly improve the performance of WLANs
Smart Antennas can significantly improve the performance of WLANs

- Multipath diversity gain ⇒ Improve reliability
- 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)
- Data rate increase ⇒ M-fold increase in data rate with M TX and M Rx antennas (MIMO 802.11n)

Can be implemented Analog (RF) or Digital

Analog Advantages:

- Digital requires M complete RF chains, including M A/D and D/A's, versus 1 A/D and D/A for analog, plus substantial digital signal processing
- The cost is much lower than digital
- An appliqué approach is possible - digital requires a complete baseband

Digital Advantages:

- Slightly higher gain in Rayleigh fading (as more accurate weights can be generated)
- Temporal processing can be added to each antenna branch much easier than with analog, for higher gain with delay spread
- Modification for MIMO (802.11n) possible
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

---

**802.11b Packet Structure**

Time permits weight generation on a packet-by-packet basis

<table>
<thead>
<tr>
<th>Preamble</th>
<th>SFD</th>
<th>PHY H</th>
<th>Data from MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>96 symbol Short Preamble</td>
<td>MPDU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>56 Barker</td>
<td>16 Barker</td>
<td>24 Barker</td>
<td>Barker</td>
</tr>
<tr>
<td>BPSK</td>
<td>BPSK</td>
<td>QPSK</td>
<td>BPSK/QPSK</td>
</tr>
<tr>
<td>CCK 5.5/11Mbps</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Preamble</th>
<th>SFD</th>
<th>PHY H</th>
<th>Data from MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>192 symbol Long Preamble</td>
<td>MPDU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>128 Barker</td>
<td>16 Barker</td>
<td>48 Barker</td>
<td>Barker</td>
</tr>
<tr>
<td>BPSK</td>
<td>BPSK</td>
<td>BPSK</td>
<td>BPSK/QPSK</td>
</tr>
<tr>
<td>(CCK 5.5/11Mbps)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Appliqué**
- Cellular – IS-136
- WLANs – 802.11a/b/g
- WiMAX – 802.16

**Smart Antenna WiFi (PCMCIA Reference Design)**

**Appliqué Architecture Plug-and-Play to legacy designs**
# 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></td>
<td>6.1 dB</td>
<td>12.8 dB</td>
<td>18.0 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22.2 dB</td>
</tr>
</tbody>
</table>

2X to 3X Range + Uniform Coverage
3X to 4X Range + Uniform Coverage

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# 802.11a/g Beamforming Performance Summary with Four Antennas
(Spatial Followed by Temporal Equalization)

<table>
<thead>
<tr>
<th>Beamforming Gain (dB) @ 10% PER</th>
<th>6 Mbps</th>
<th>24 Mbps</th>
<th>54 Mbps</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short Packet</td>
<td>Long Packet</td>
<td>Short Packet</td>
<td>Long Packet</td>
</tr>
<tr>
<td>Flat Rayleigh Fading</td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>500ns Exp Decay Rayleigh Fading</td>
<td>8</td>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>100ns Exp Decay Rayleigh Fading</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>200ns Exp Decay Rayleigh Fading</td>
<td>4</td>
<td>9</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>SUI-2</td>
<td>13</td>
<td>&gt; 13</td>
<td>&gt; 13</td>
<td>&gt; 13</td>
</tr>
</tbody>
</table>
Network Simulation Assumptions

- 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

Network Simulation Results

Performance Comparison - Scenario#1

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

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

Performance Comparison - Scenario#2

- Smart Antenna
  - ReXmit: 15.70%
  - AVG: 9.46 Mbps
  - Pkt drop: 0.46%

- Omni-directional
  - ReXmit: 124.56%
  - AVG: 4.29 Mbps
  - Pkt drop: 19.17%

Gains with 4-Element Smart Antenna in WLANs

- Extends Range by 200% by 300%
- Mitigates Fading for VoIP
- Facilitates Enhanced Radio Resource Management
- Improves Wireless Network Security
- Potentially Reduces Client Transmit Power by 90%
- Increases Data Throughput by 100% - 200%
  (802.11n in future with >600% increase)
802.11n

- Requirements for 802.11n:
  - >100 Mbps in MAC
  - >3 bits/sec/Hz
  - Backward compatible with all 802.11 standards
- Requires MAC changes and MIMO:
  - 2X2, 2X3, up to 4X4 (4TX/RX antennas for >500 Mbps)
- Next standards meeting in Monterey in January

WiMax Smart Antennas

- WiMax operates in unlicensed and licensed bands (more power in licensed bands for up to 70 Mbps over 30 miles)
- WiMax operates with different bandwidths (1.75/3.5/7/14 MHz)

Can use WiFi (802.11b/g) appliqué RFIC in WiMAX (802.16):
- Add to existing systems with little or no modification
- Add at base station or client to provide improvements (in both directions with TDD):
  - >10 dB increase in SNR
  - Compensates for building penetration loss
  - Permits use in buildings (on clients – no truck rolls)
  - Increased interference robustness
  - Improved QoS

MIMO techniques for higher capacity, as well as interference suppression
Smart Antennas

- Adaptive MIMO
  - Adapt among:
    - Antenna gain for range extension/better coverage/battery life increase
    - Interference suppression for capacity (with frequency reuse)
    - MIMO for data rate increase (without any increase in total transmit power), e.g., with 4 antennas at access point and terminal, in 802.11a have the potential to provide >100 Mbps in 20 MHz bandwidth (802.11n)
  - Can be selectively implemented on nodes

Progression for WLAN/WiMAX/Cellular

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

- Network of wireless hosts which may be mobile
- No pre-existing infrastructure
- Multiple hops for routing
- Neighbors and routing changes with time (mobility, environment)

Advantages

- Less transmit power needed (longer battery life)
- Easy/fast to deploy
- Infrastructure is not important
- Possible reuse of frequency for higher capacity
- Applications:
  - Home networking
  - Military/emergency environments
  - Meetings/conventions
Issues

• Mixture of users: equipment/requirements (symmetric/asymmetric)

• MAC/routing
  – Limited transmission range
  – Fading
  – Packet losses
  – Changes in routing/neighbors due to movement
  – Power
  – Broadcast nature of environment
    • Hidden Node
    • Frequency reuse limits

Hidden Node Issue

Nodes A and B, B and C can communicate, but A and C cannot hear each other and potentially collide at B
MAC Solutions

- Many solutions (not covered here)
- On method (802.11) (DCF):
  - Request-to-send
  - Clear-to-send
  - Data
  - Acknowledgement

![Diagram of RTS, CTS, DATA, ACK between A, B, C]

Impact of Smart Antennas

- Most systems today use omni-directional antennas
  - Since this reserves the spectrum over a large area, network capacity is wasted
- Consider smart antenna advantages:
  - Directional antennas (multi-beam and scanning beam)
    - Main emphasis of literature
    - Considered easier/less costly to implement
    - Easier to study/analyze
  - Adaptive arrays
Impact of Smart Antennas

- Since smart antennas are a physical layer technique, existing approaches for MAC/routing in ad hoc networks will work with smart antennas, but these MAC/routing techniques need to be modified to achieve the full benefit (e.g., the 802.11 MAC has inefficiencies with directional antennas).
- Need to add provision to obtain performance data based on smart antenna for coordination:
  - Whether or not other access point has smart antenna is information that needs to be exchanged.
  - The type of smart antenna (switched beam, adaptive array), number of beams/antennas, and type of combining (MRC, MMSE) need to be exchanged.

Directional Antenna Advantages

- Greater gain (M-fold with M beams)
- Greater frequency reuse
- Topology control
- Increased connectivity
Directional Antenna Advantages

- Greater frequency reuse:
  - Use of Directional MAC
  - Transmit RTS with directional beam, receive with omni-directional antenna
  - Send CTS (Data/ACK) with directional beam
- Increases range/reduces battery power
- Increases frequency reuse/network connectivity/link lifetime

Issues for Directional Antennas

- Still have hidden node problem (worsened by asymmetry in gain)
- Loss of RX gain for RTS
- Scanning of RTS
  - Uplink pointing problem: How does AP know which beam to use when client transmits first?
Issues for Directional Antennas

• Association problems with mixed mode Access Points

![Diagram showing AP1, Client, and AP2]

Issues for Directional Antennas

• Movement (increased range can cause association problems)

![Diagram showing AP1, Client, and AP2]
Issues for Directional Antennas

- **Association issue:**
  - If beacon (for association) from base station is omnidirectional, but switched beams used by base station for traffic, then may associate with wrong base station

![Diagram of APs and client](image)

Issues for Directional Antennas

- Many environments are not LOS
  - Fading can dominate over propagation loss
  - DoA not a good indicator of location of user
  - Interference into many/all beams
  - Loss of array gain
Adaptive Arrays

- Still have hidden node problem (worsened by asymmetry in gain)
  - Can suppress up to M-1 interferers with M antennas
    - Independent of environment
    - Can utilize to determine if ok to send even with interference (if #interferers<M-1)

Adaptive Arrays

- Loss of RX gain for RTS
  - Can receive omni-directionally (use just one antenna), but can adapt to maximum gain on preamble (microseconds)
    - 13 dB gain with 4 antennas in 802.11/WiMAX

- Scanning of RTS
  - RTS sent omni-directionally reduces chance of interference
    - Gain on TX is reduced – 5-6 dB loss (13 vs. 18 dB for 802.11)
Adaptive Arrays

- Association problems with mixed mode Access Points
  - Still an issue with adaptive arrays
  - May be even worse as tracking of fading (at Doppler rate) can mean loss of link in milliseconds

- Movement (increased range can cause association problems)
  - Still an issue with adaptive arrays
  - May be even worse as tracking of fading (at Doppler rate) can mean loss of link in milliseconds
Adaptive Arrays

- Association issue:
  - If beacon (for association) from base station is omnidirectional, but switched beams used by base station for traffic, then may associate with wrong base station
  - Not the same issue for adaptive arrays, but lack of diversity for omnidirectional beacon can also be an issue

\[ \text{Client} \quad \text{AP1} \quad \text{AP2} \]

- Many environments are not LOS
  - Adaptive arrays work fine in NLOS
  - Fading can dominate over propagation loss
    - Adaptive arrays provide multipath mitigation as well as full array gain
  - DoA not a good indicator of location of user
    - DoA not used in adaptive arrays
  - Interference into many/all beams
    - Adaptive array can suppress up to M-1 interferers
  - Loss of array gain
    - Full array gain with adaptive arrays
Adaptive Arrays

- **Cost/Complexity:**
  - In 802.11
    - Adaptive arrays can easily be added (e.g., as appliqué) to selected nodes
    - With 802.11n, 2-4 antennas (adaptive array) with MRC, interference suppression, and MIMO will be available
    - TDD – can beamform on transmit based on received signal without DoA information
    - 802.11s to study ad hoc networks among access points
    - 802.11n MAC is to be defined
  - In WiMAX, multiple antennas likely (in standard), and TDD mode most used
  - In UWB, multiple antennas are possible (particularly in OFDM (MBOA) mode along the lines of 802.11)

Adaptive Arrays

- Can use MIMO for increased capacity (shorter transmit time), along with adaptive MIMO (range extension/power reduction and interference suppression)
- Rather than direction for excluded area for transmission, use number of interferers (<M-1) as criteria
Conclusions

• Both smart antennas and ad hoc networks can provide increased capabilities/performance to wireless networks (range, robustness, battery life, capacity)

• Combination of smart antennas and ad hoc networks can provide gains that are greater than the sum of the gains, but only if used properly

• Further research is needed (with standards development), but the potential is substantial