Smart Antenna Techniques and Their Application to Wireless Ad Hoc Networks

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Goal

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.

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Outline

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

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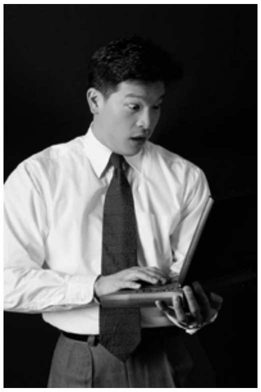
Service Limitations

- **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**

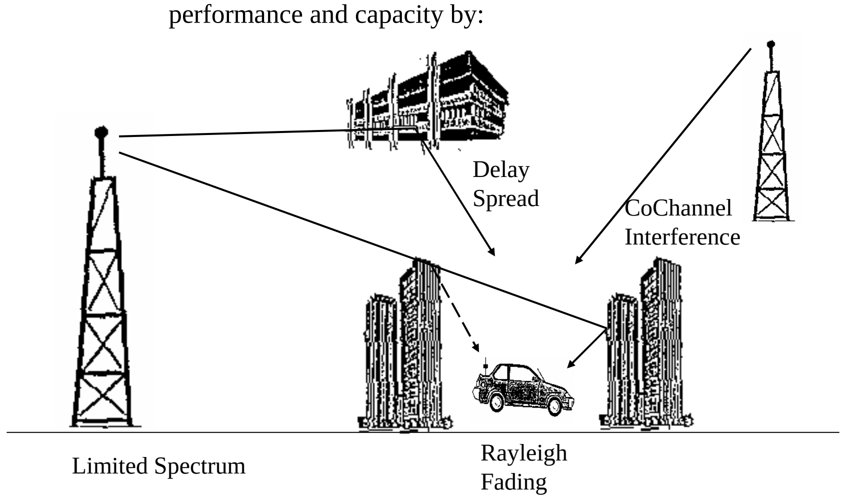


Solutions

- **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:



Smart Antennas

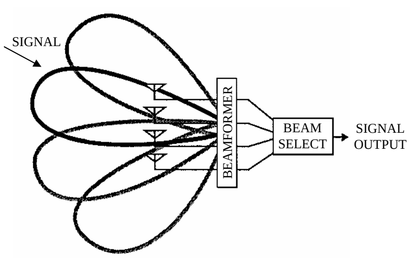
A smart antenna is a multi-element antenna where the signals received at each antenna element are intelligently combined to improve the performance of the wireless system. The reverse is performed on transmit.

Smart antennas can:

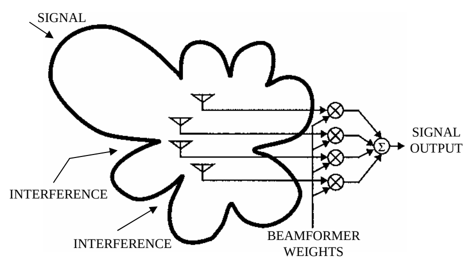
- **Increase signal range**
- **Suppress interfering signals**
- **Combat signal fading**
- **Increase the capacity of wireless systems**

Smart Antennas

Switched Multibeam Antenna



Adaptive Antenna Array

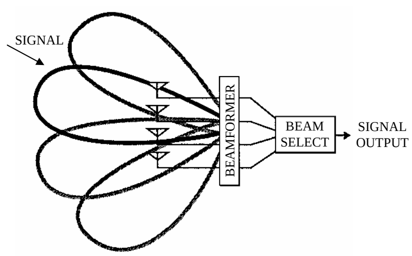


Smart antenna is a multibeam or adaptive antenna array that tracks the wireless environment to significantly improve the performance of wireless systems.

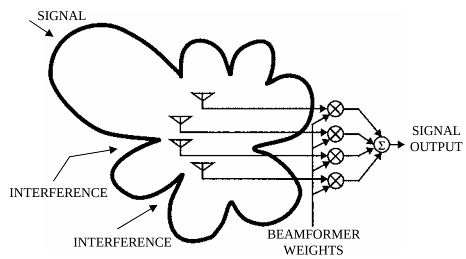
Switched Multibeam versus Adaptive Array Antenna: Simple beam tracking, but limited interference suppression and diversity gain, particularly in multipath environments

Smart Antennas

Switched Multibeam Antenna



Adaptive Antenna Array



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

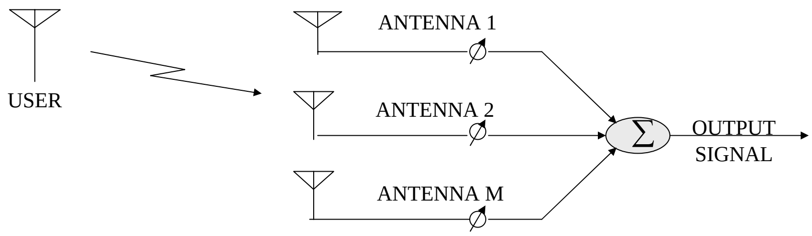
Smart Antennas

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 ¼ 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 ¼ wavelength

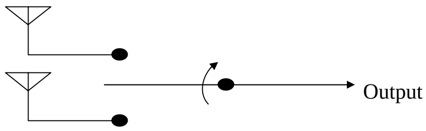
$\Rightarrow$ 4 or more antennas on a PCMCIA card

$\Rightarrow$ 16 on a handset

$\Rightarrow$ Even more on a laptop

COMBINING TECHNIQUES

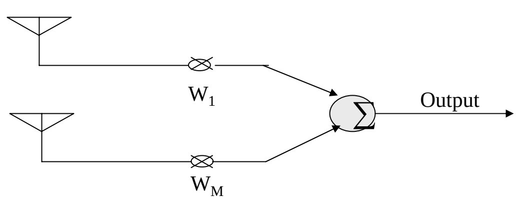
Selection:



- Select antenna with the highest received signal power
- $P_{0M} = P_0^M$

COMBINING TECHNIQUES (CONT.)

Maximal ratio combining:



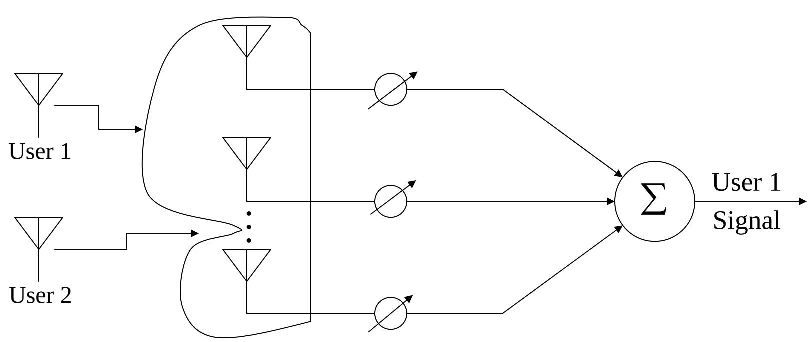
- Weight and combine signals to maximize signal-to-noise ratio (Weights are complex conjugate of the channel transfer characteristic)
- Optimum technique with noise only
- $BER_M \approx BER^M$ (M-fold diversity gain)

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

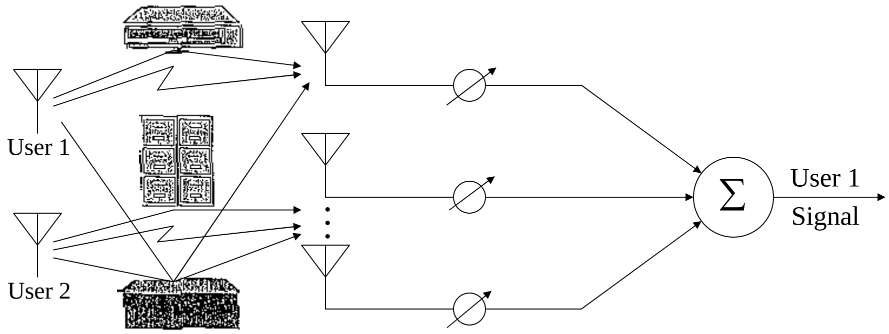
INTERFERENCE NULLING

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

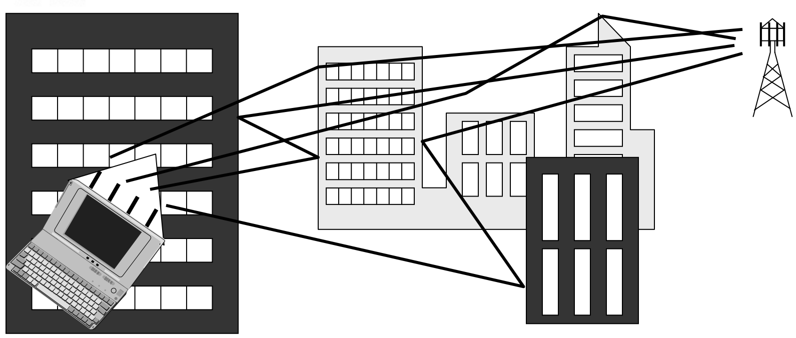
INTERFERENCE NULLING
Multipath Systems



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

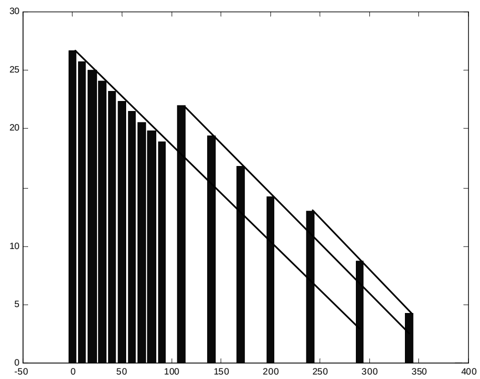
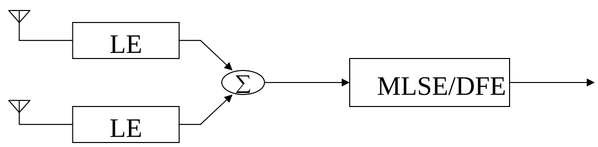


Figure 1. Model D delay profile with cluster extension (overlapping clusters).

EQUALIZATION

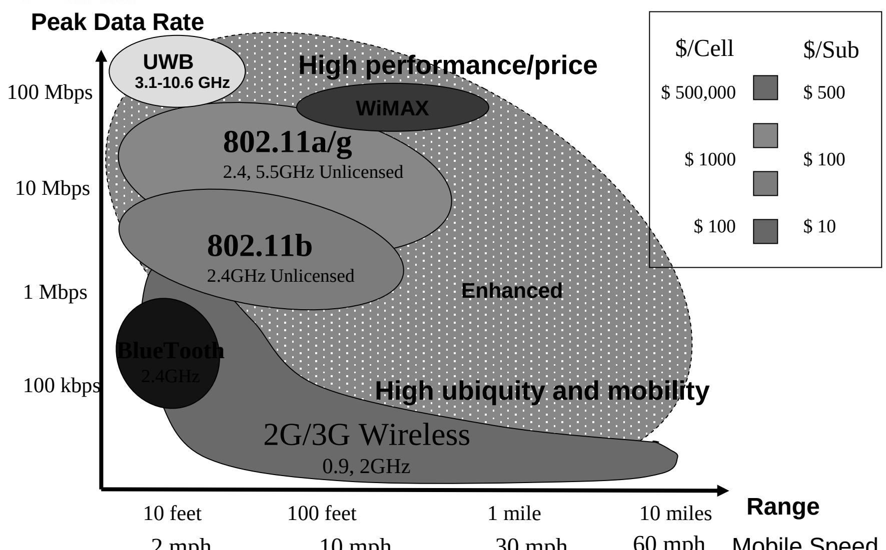
• Delay spread: Delay spread over [(*M*-1) / 2]*T* or *M*-1 delayed signals (over any delay) can be eliminated

• Typically use temporal processing with spatial processing for equalization:



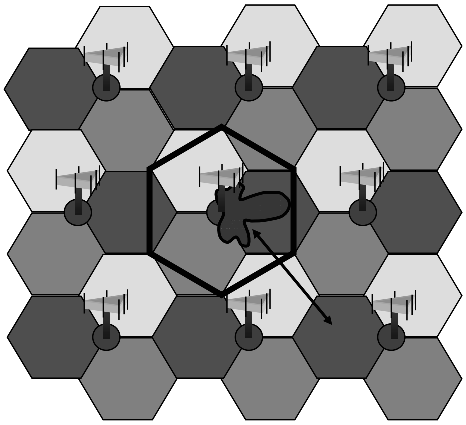
• Spatial processing followed by temporal processing has degradation, but this degradation can be small in many cases

Wireless System Enhancements



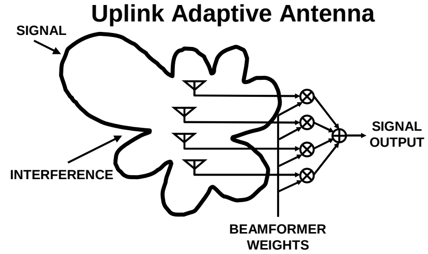
Smart Antennas for IS-136

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

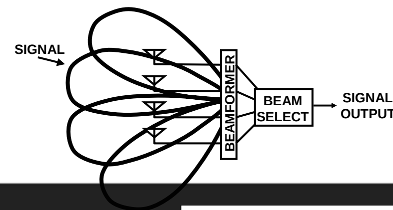


In 1999, combining at TDMA base stations changed from MRC to MMSE for capacity increase

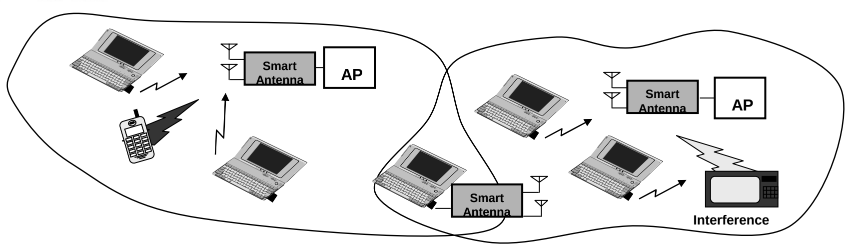
Uplink Adaptive Antenna



Downlink Switched Beam Antenna



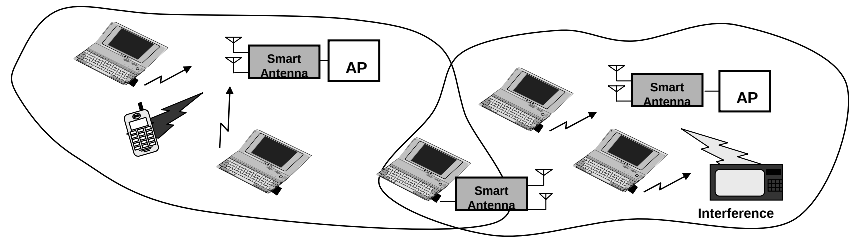
Smart Antennas for WLANs



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)
- Higher antenna gain ⇒ Extend range/ Increase data rate/ Extend battery life

Smart Antennas for 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:

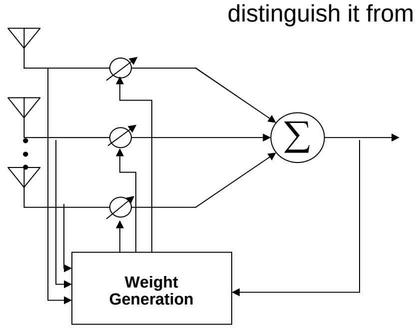
- Digital requires M complete RF chains, including M A/D and D/A's, versus 1 A/D and D/A for analog, plus substantial digital signal processing
- The cost is much lower than digital
- An appliqué approach is possible - digital requires a complete baseband

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

20 µs

96 symbol Short Preamble — MPDU

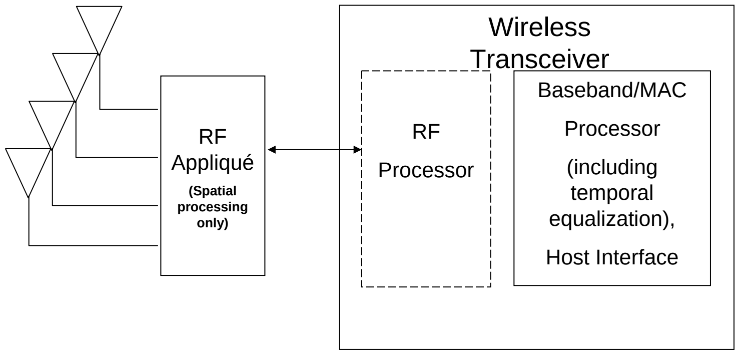
Preamble	SFD	PHY H	Data from MAC
56 Barker BPSK	16 Barker BPSK	24 Barker QPSK	Barker BPSK/QPSK CCK 5.5/11Mbps

192 symbol Long Preamble — MPDU

Preamble	SFD	PHY H	Data from MAC
128 Barker BPSK	16 Barker BPSK	48 Barker BPSK	Barker BPSK/QPSK (CCK 5.5/11Mbps)

Appliqué

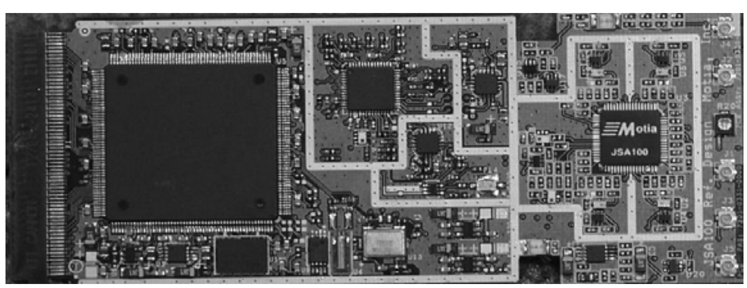
- Cellular – IS-136
- WLANs – 802.11a/b/g
- WiMAX – 802.16

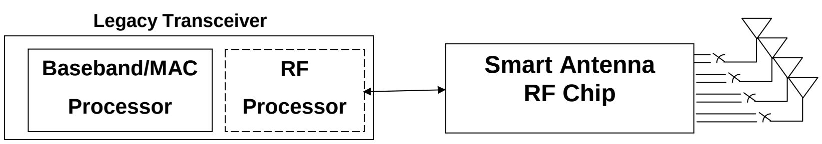


Smart Antenna WiFi (PCMCIA Reference Design)

Appliqué Architecture Plug-and-Play to legacy designs

PCMCIA - CARDBUS Interface





802.11b Beamforming Gains with 4 Antennas

Performance Gain over a Single Antenna in a Rayleigh Fading Channel

2 Antenna Selection	Adaptive One Side	Adaptive Both Sides	Theoretical Bound Both Sides
6.1 dB	12.8 dB	18.0 dB	22.2 dB

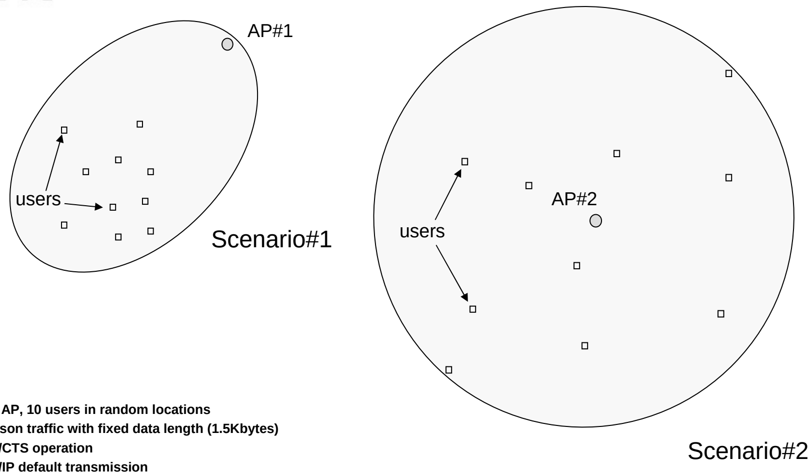
2X to 3X Range + Uniform Coverage

3X to 4X Range + Uniform Coverage

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

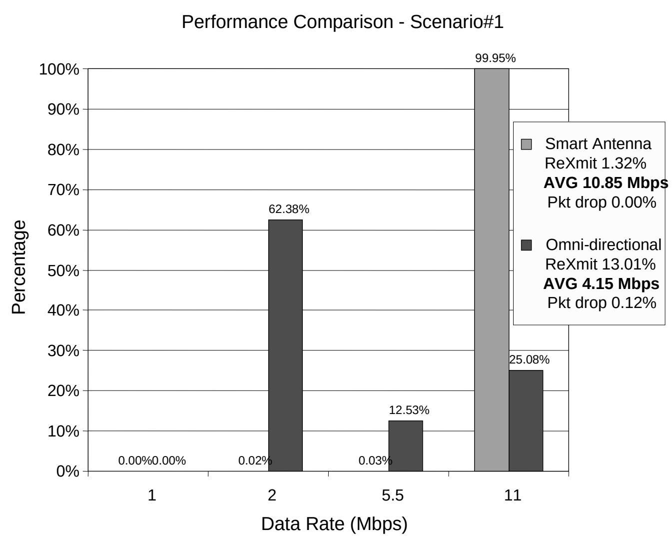
Beamforming Gain (dB) @ 10% PER							
	6 Mbps		24 Mbps		54 Mbps		Summary
	Short Packet	Long Packet	Short Packet	Long Packet	Short Packet	Long Packet	
Flat Rayleigh Fading	11	11	12	12	12	12	11 ~ 12
50ns Exp Decay Rayleigh Fading	8	10	7	7	8	9	7 ~ 10
100ns Exp Decay Rayleigh Fading	6	6	5	5	6	7	5 ~ 7
200ns Exp Decay Rayleigh Fading	4	9	5	6	Very High Error Floor	Very High Error Floor	4 ~ 9
SUI-2	13	> 13	> 13	> 13	Very High Error Floor	Very High Error Floor	13 +

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



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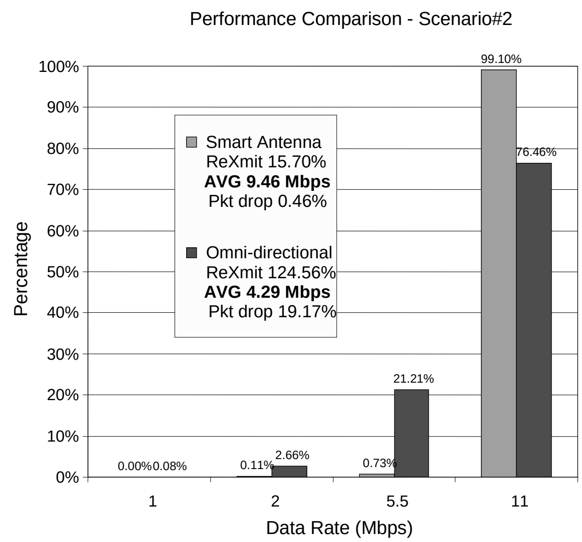
Network Simulation Results



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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

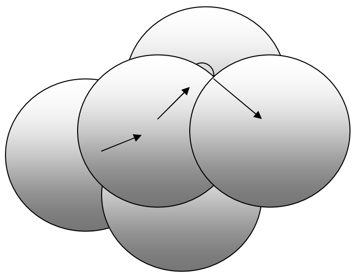
- Adaptive MIMO
  - Adapt among:
    - Antenna gain for range extension/better coverage/battery life increase
    - Interference suppression for capacity (with frequency reuse)
    - MIMO for data rate increase (without any increase in total transmit power), e.g., with 4 antennas at access point and 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)

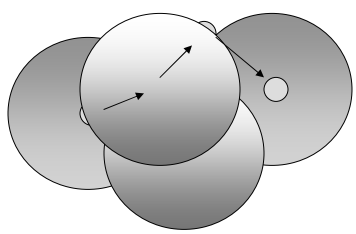
Mobile Ad Hoc Networks

- 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

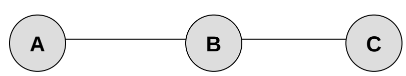
- Less transmit power needed (longer battery life)
- Easy/fast to deploy
- Infrastructure is not important
- Possible reuse of frequency for higher capacity
- Applications:
  - Home networking
  - Military/emergency environments
  - Meetings/conventions



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

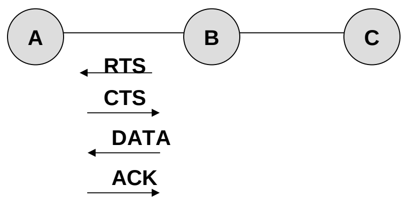
Hidden Node Issue



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



Impact of Smart Antennas

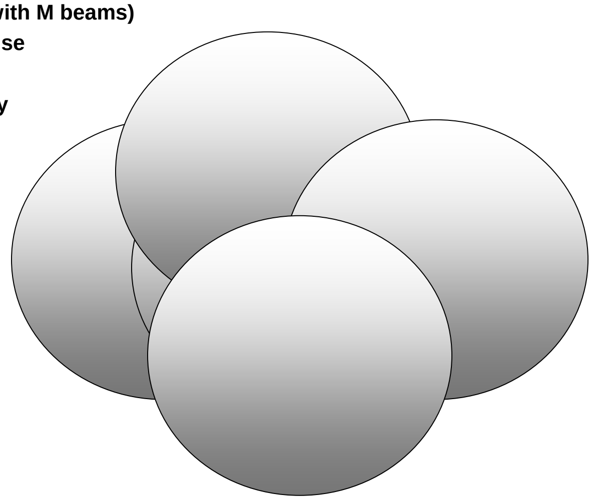
- Most systems today use omni-directional antennas
  - Since this reserves the spectrum over a large area, network capacity is wasted
- Consider smart antenna advantages:
  - Directional antennas (multi-beam and scanning beam)
    - Main emphasis of literature
    - Considered easier/less costly to implement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

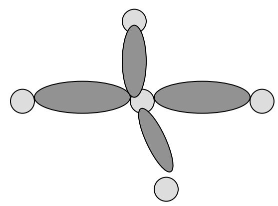
Directional Antenna Advantages

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



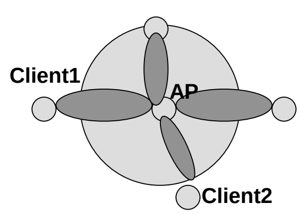
Directional Antenna Advantages

- 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



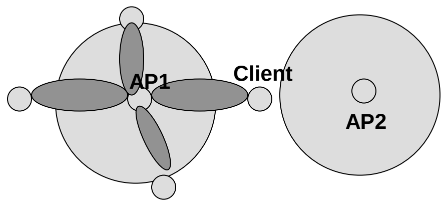
Issues for Directional Antennas

- 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?



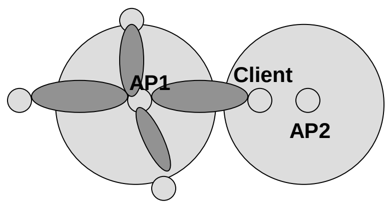
Issues for Directional Antennas

- Association problems with mixed mode Access Points



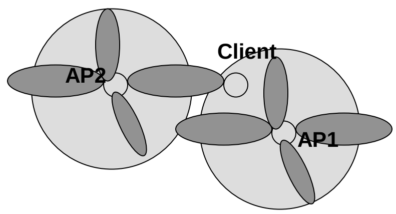
Issues for Directional Antennas

- Movement (increased range can cause association problems)



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



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

Motia

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)*

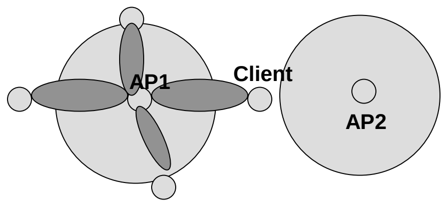
Motia

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)*

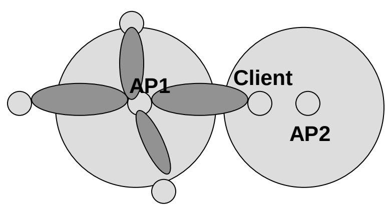
Adaptive Arrays

- 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*



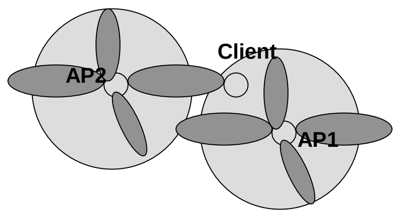
Adaptive Arrays

- 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*



Adaptive Arrays

- 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

Motia

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