IMPROVING WIRELESS NETWORKS WITH ANTENNAS – WND-845

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Goal

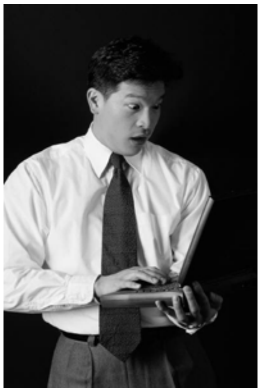
This class discusses the use of smart antennas in wireless local area networks, WLANs. We will first discuss the issue of analog versus digital implementation of smart antennas and how smart antenna technology can be added to existing WLAN systems without modifying those systems. This presentation will examine current technologies for wireless networking in the home or enterprise, and will make a case for why smart antenna technology is needed. Performance results and extensions will be described, and future applications (beyond Wi-Fi to areas such as WiMax) of smart antenna technology will also be discussed.

Outline

- Service Limitations
- Smart Antennas
- Antenna Diversity/Combining Techniques
- Implementation Issues
- Examples
- 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**

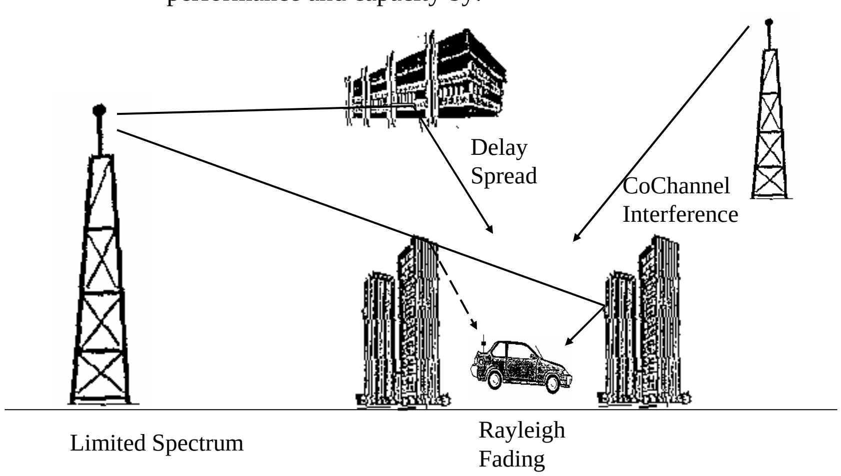


Solutions

- **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:



Smart Antennas

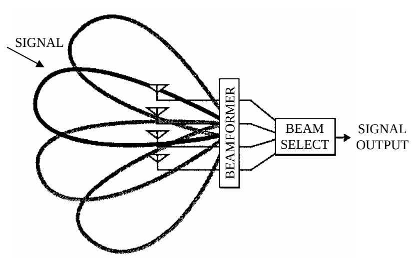
A smart antenna is a multi-element antenna where the signals received at each antenna element are intelligently combined to improve the performance of the wireless system. The reverse is performed on transmit.

Smart antennas can:

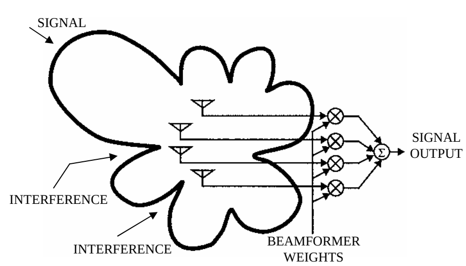
- **Increase signal range**
- **Suppress interfering signals**
- **Combat signal fading**
- **Increase the capacity of wireless systems**

Smart Antennas

Switched Multibeam Antenna



Adaptive Antenna Array

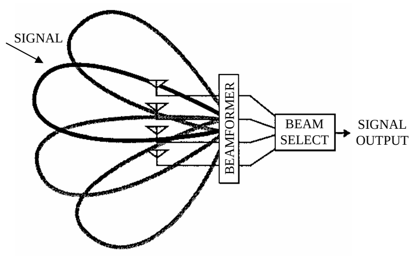


Smart antenna is a multibeam or adaptive antenna array that tracks the wireless environment to significantly improve the performance of wireless systems.

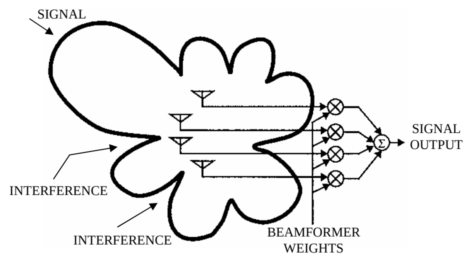
Switched Multibeam versus Adaptive Array Antenna: Simple beam tracking, but limited interference suppression and diversity gain, particularly in multipath environments

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

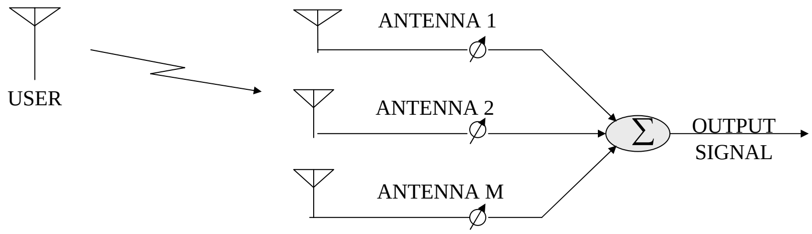
Smart Antennas

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*=∞

- 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

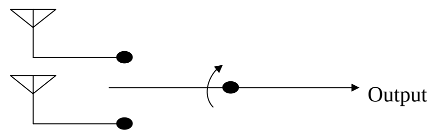
⇒ 4 or more antennas on a PCMCIA card

⇒ 16 on a handset

⇒ Even more on a laptop

Combining Techniques

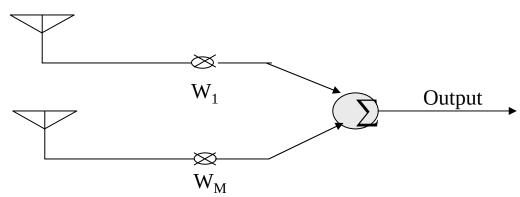
Selection:



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

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
- $\mathrm{BER}_M \approx \mathrm{BER}^M$ (M-fold diversity gain)

Optimum Combining (Adaptive Arrays)

• Weight and combine signals to maximize signal-to-interference-plus-noise ratio (SINR)

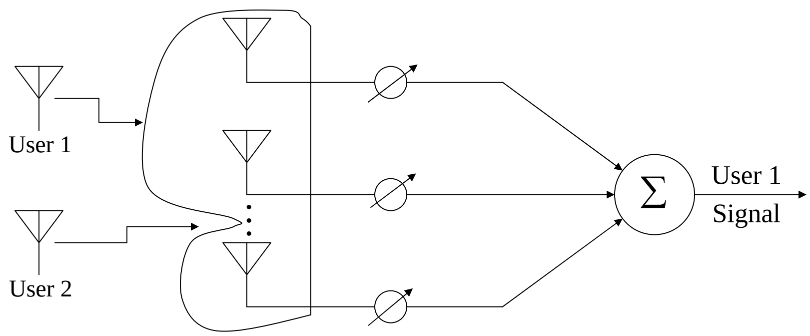
- Usually minimize mean squared error (MMSE)

• 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:

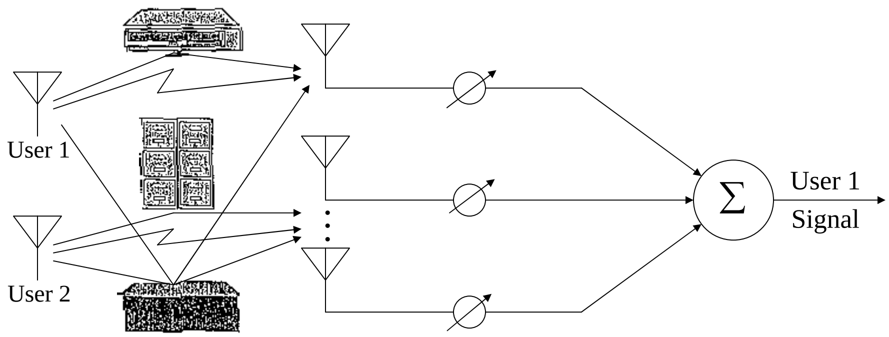
• Maximize signal-to-interference-plus-noise ratio

• Increase gain towards desired signal

• Null interference: M-1 interferers with M antennas

Interference Nulling

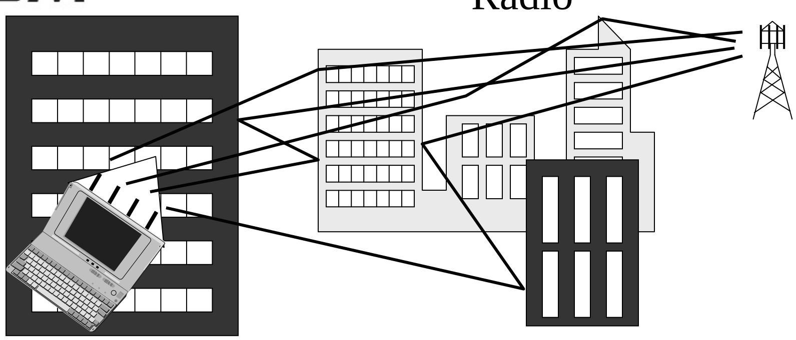
Multipath Systems



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

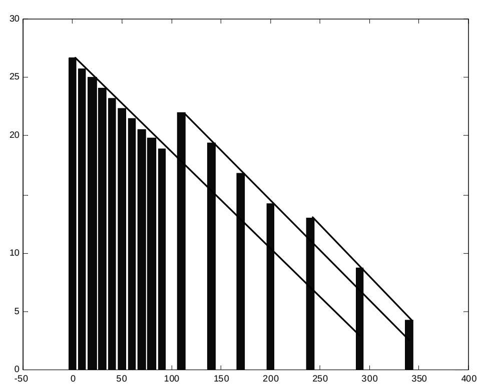
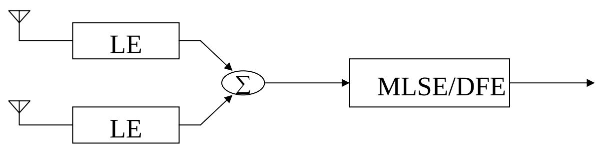


Figure 1. Model D delay profile with cluster extension (overlapping clusters).

Equalization

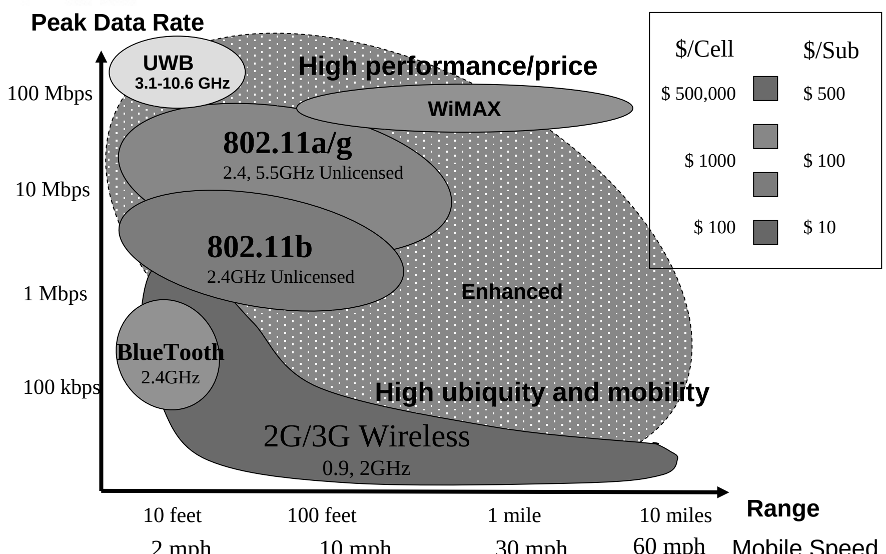
• Delay spread: Delay spread over [(*M*-1) / 2]*T* or *M*-1 delayed signals (over any delay) can be eliminated

• Typically use temporal processing with spatial processing for equalization:



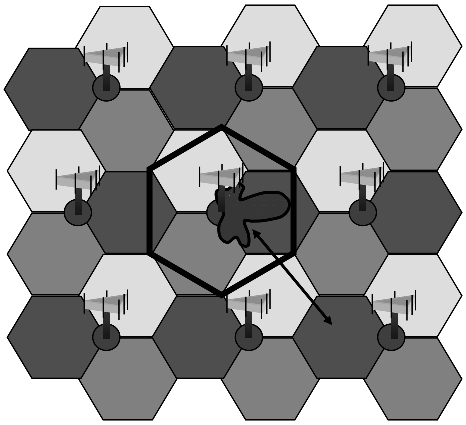
• Spatial processing followed by temporal processing has degradation, but this degradation can be small in many cases

Wireless System Enhancements



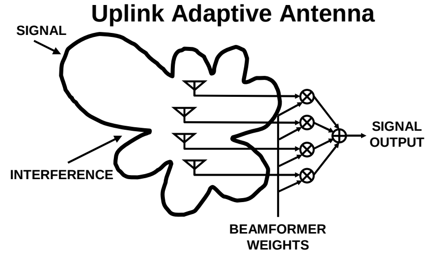
Smart Antennas for IS-136

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

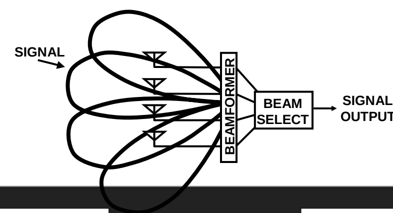


In 1999, combining at TDMA base stations changed from MRC to MMSE for capacity increase

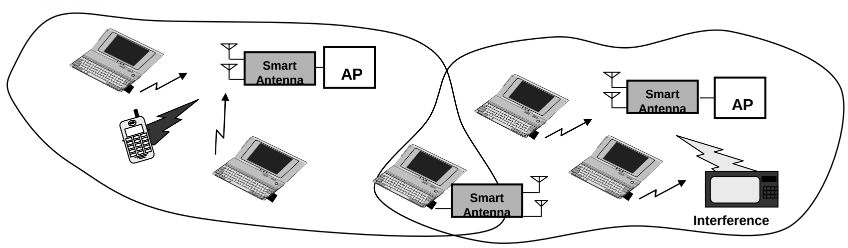
Uplink Adaptive Antenna



Downlink Switched Beam Antenna



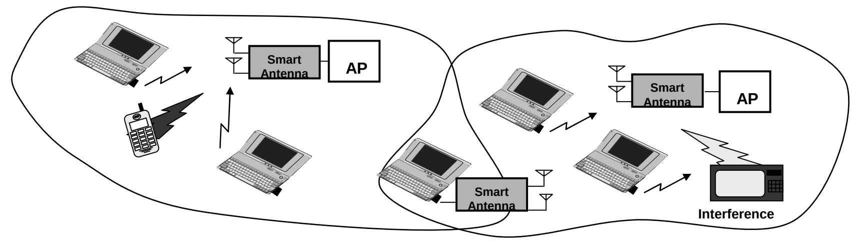
Smart Antennas for WLANs



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:

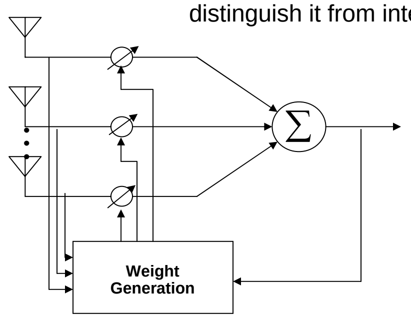
- Digital requires M complete RF chains, including M A/D and D/A's, versus 1 A/D and D/A for analog, plus substantial digital signal processing
- The cost is much lower than digital
- An appliqué approach is possible - digital requires a complete baseband

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

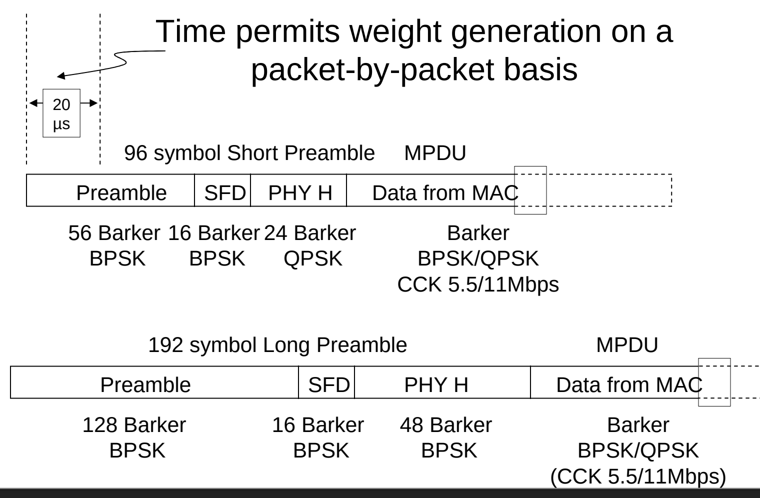


Blind (no demod): MRC – Maximize output power
Interference suppression – CMA, power inversion, power out-of-band

Non-Blind (demod): Training sequence/decision directed reference signal
MIMO needs non-blind, with additional sequences

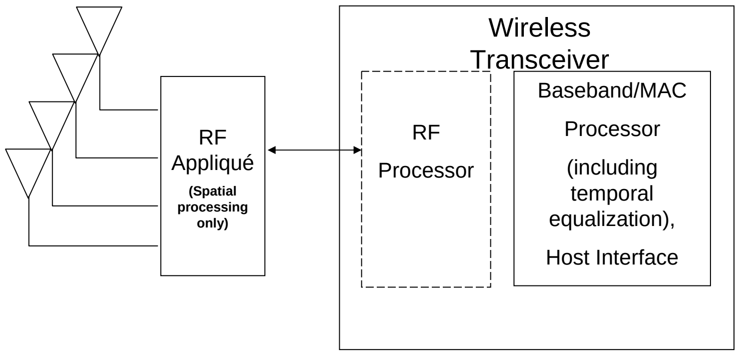
802.11b Packet Structure

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



Appliqué

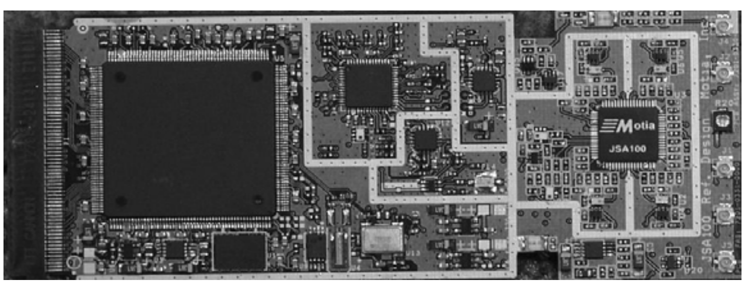
- Cellular – IS-136
- WLANs – 802.11a/b/g
- WiMAX – 802.16

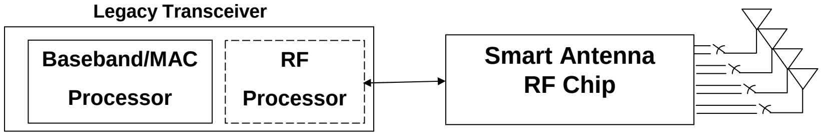


Smart Antenna WiFi (PCMCIA Reference Design)

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 (12.8 dB)

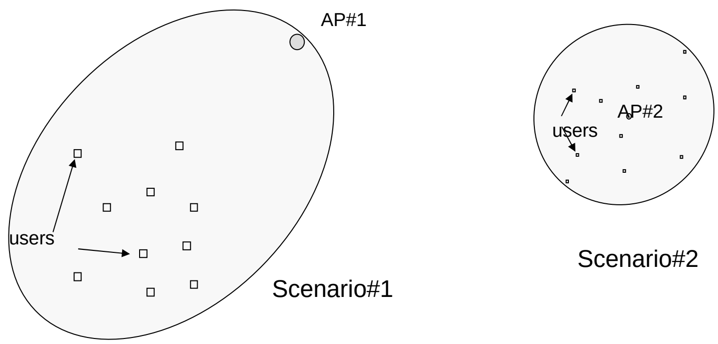
3X to 4X Range + Uniform Coverage (18.0 dB)

802.11a/g Beamforming Performance

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 +

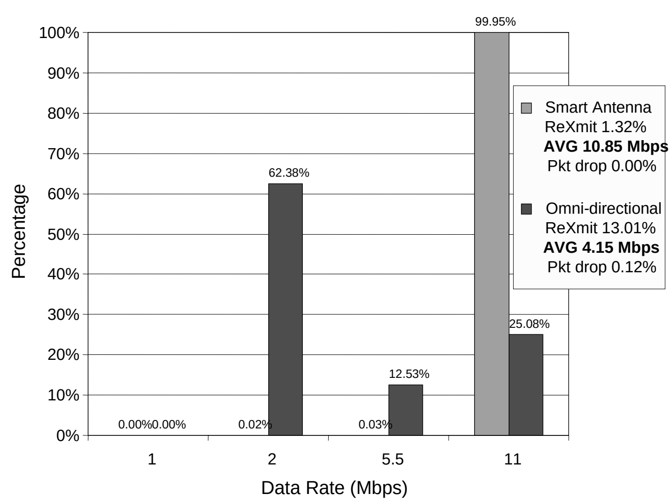
Network Simulation Assumptions



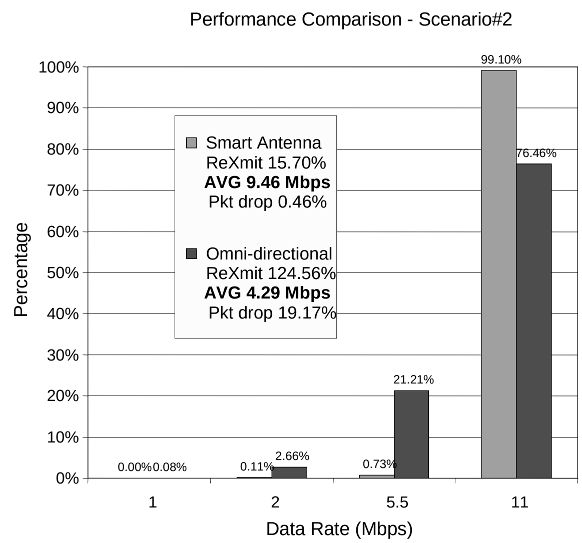
- One AP, 10 users in random locations
- Poisson traffic with fixed data length (1.5Kbytes)
- RTS/CTS operation
- TCP/IP default transmission
- Smart antenna used at AP only

Network Simulation Results

Performance Comparison - Scenario#1



Network Simulation Results



Gains with 4-Element Smart Antenna (Analog) 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)
- Requires digital beamforming with N complete RF chains with N-fold spatial multiplexing
- Next standards meeting in Atlanta next week

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

Cellular Smart Antennas

- Operates at 900 MHz and 1.9 GHz
- Bandwidths of 200 kHz and 5 MHz with GSM and WCDMA, respectively.

- Can use appliqué, but only on receive, as transmit weights can be different (since FDD)
- 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)**

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**
  - **In WiMAX, multiple antennas likely (in standard), and TDD mode most used**
  - **In cellular, smart antennas possible and MIMO may be added to the standard**
  - **In UWB, multiple antennas are possible (particularly in OFDM (MBOA) mode along the lines of 802.11)**

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Smart Antennas for Wireless Systems

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