Smart Antenna Techniques and Their Application to Wireless Ad Hoc Networks

Plenary Talk at:

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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/base station
  - 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 – e.g., IEEE802.11n)
- Ad Hoc Networks
  - Interconnections of multiple clients (e.g., standardization in progress for Access Point interconnection – IEEE802.11s)
- Combination of Smart Antennas with Ad Hoc Networks can give greater gains than the sum of the two

Smart Antennas

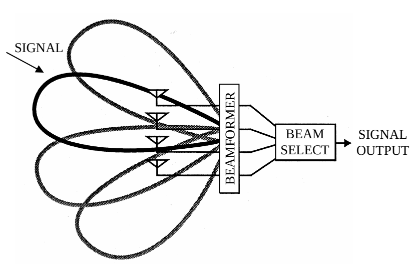
A smart antenna is a multi-element antenna where the signals received at each antenna element are intelligently combined to improve the performance of the wireless system. The reverse is performed on transmit.

Smart antennas can:

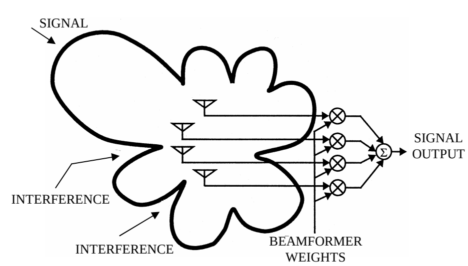
- **Increase signal range**
- **Suppress interfering signals**
- **Combat signal fading**
- **Increase the capacity of wireless systems (MIMO)**

Smart Antennas

Switched Multibeam Antenna



Adaptive Antenna Array

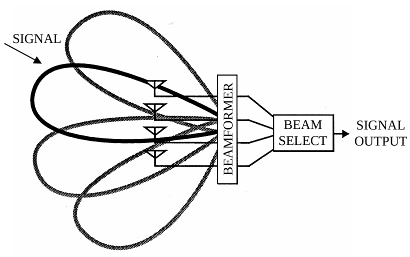


Smart antenna is a multibeam (directional) or adaptive antenna array that tracks the wireless environment to significantly improve the performance of wireless systems.

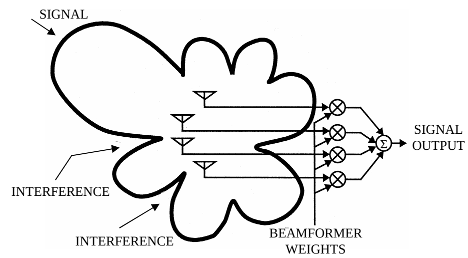
Switched Multibeam versus Adaptive Array Antenna: Simple beam tracking, but limited interference suppression and diversity gain, particularly in multipath environments

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 (4 antennas -> 13 dB gain, 802.11n)**
- **In-vehicle DBS entertainment systems, such as:**
  - **Mobile video**
  - **Mobile broadband/gaming**
- **Satellite/digital radio**
- **GPS**
- **3G Wireless**
- **WiMax (4 antennas -> 12-15 dB gain for indoor CPE)**
- **RFID**
- **UWB**

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Wireless System Enhancements

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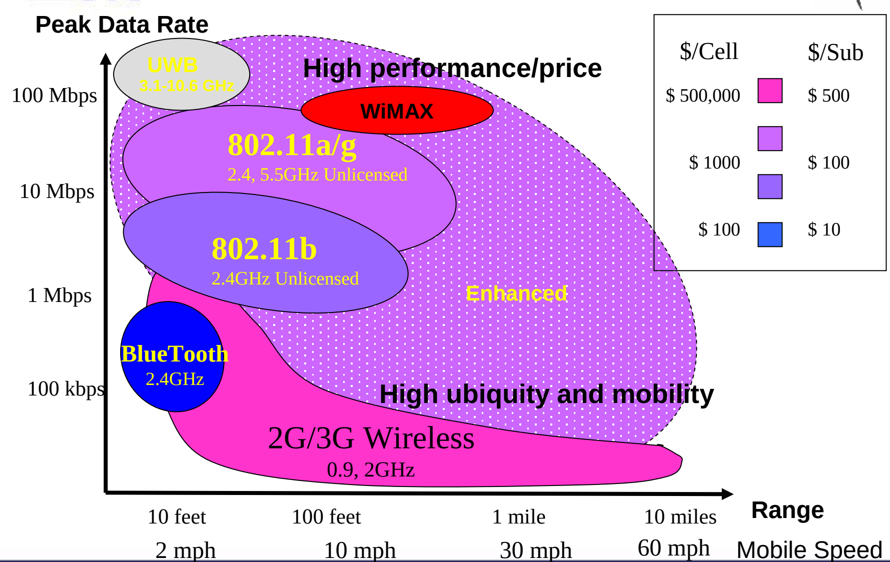

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Smart Antennas for WLANs

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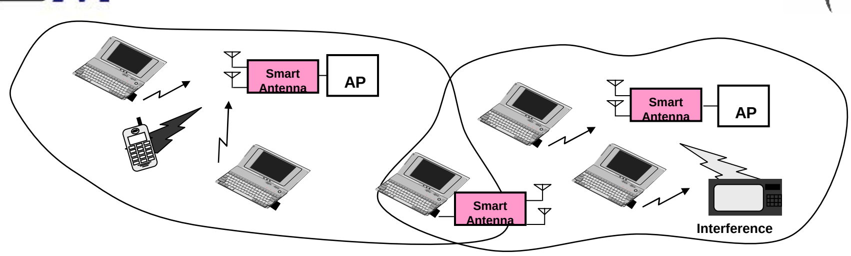
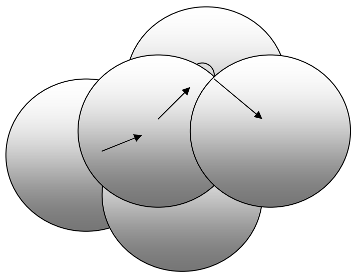


•TDD operation (only need smart antenna at access point or terminal for performance improvement in both directions)

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

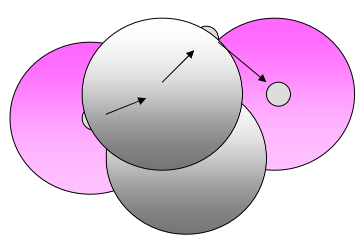
Mobile Ad Hoc Networks

- 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

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 antennas for greater range and capacity:
  - Directional antennas (multi-beam and scanning beam)
    - Main emphasis of literature - considered easier/less costly to implement and 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

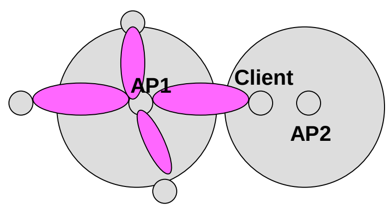
Issues for Directional Antennas

- Need to scan antenna if transmitter location not known
- 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
- MAC algorithm complexity can be much larger (location, number of beams, etc., need to be considered)

- These problems are overcome with adaptive arrays
  - Can look ominidirectionally, but adapt when packet is received
  - Provides both array gain and diversity gain in multipath environments, as well as uses multipath for spatial multiplexing gain
  - Can limit MAC complexity by only considering number of antennas and spatially multiplexed channels)

Issues for Smart Antennas

- Hidden node problem can be increased (although mitigated by interference suppression)
- Association problems with mixed-mode systems

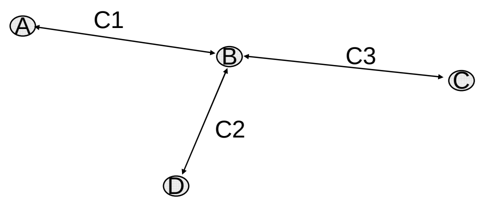


Example: IEEE802.11s

- IEEE802.11s: Mesh networks of APs using IEEE802.11
- Issue: When IEEE802.11s becomes a standard (in 2 years?) the dominant AP's will most likely use 802.11n and/or other smart antenna techniques
  - Many AP vendors already have products with MIMO
  - A primary application of IEEE802.11s is residential systems which may include multimedia distribution, a main area of application of 802.11n
- IEEE802.11s may not work well with 802.11n AP's or AP's with smart antennas:
  - Addition of smart antenna AP's into mesh networks designed without smart antenna considerations can actually degrade performance (Even though the link performance is higher, the network performance can be worse).

Example of Degradation Due to Smart Antenna

2.4 GHz ISM band with 3 channels



- **Without smart antenna:**
  - **AB, BD, and BC can communicate using different channels (up to 54 Mbps per link)**
- **With smart antenna using spatial multiplexing (802.11n):**
  - **If AB uses spatial multiplexing (to double its data rate) adjacent channel interference tolerance can be much lower, such that BC and BD cannot use adjacent channel, resulting in substantial loss in overall system capacity**

Issues (cont.)

- **The ability to have higher spatial reuse greatly increases the capacity of a mesh network:**
  - **Smart antennas can suppress co-channel interference (up to *M-1* co-channel interferers with *M* antennas), allowing for spatial reuse in the adjacent cell**
  - **Spatial multiplexing (as proposed for IEEE802.11n) with MIMO permits multiple channels in the same frequency band**
- **The ability to have spatial reuse greatly increases the capacity of a mesh network (cont.):**
  - **These techniques can increase the link capacity by a factor of *M* or more (2, 4, or even 8 times capacity of networks without smart antennas – with 2 or 4 antennas at the AP)**
  - **These gains can dwarf the variation of performance of various routing techniques/protocols, but these gains can be lost if IEEE802.11s techniques do not accommodate smart antenna capabilities**

Implementation

- Hooks that need to be included in a standard:
  - Hooks for frequency assignment techniques to include reusing a frequency (up to M-1 times) if AP's have M antennas. That is, with a contention-based protocol allow reuse of channel by an adjacent AP.
  - Hooks for the inclusion of multiple radio capability to include multiple radios in the same channel. This includes the ability to limit adjacent channel interference, i.e., forbid the reuse of a channel by the adjacent AP, if spatial multiplexing is used.
- This can be done in such a way to actually reduce the complexity of the MAC/routing algorithms.

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