Adaptive Antenna Systems: Overview

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Presentation Outline

- Overview
- Motivation
- Fundamentals
- System Model
- Adaptation Algorithms
- Conclusions
- References & Exercise

Next . . .

- **Overview**
- Motivation
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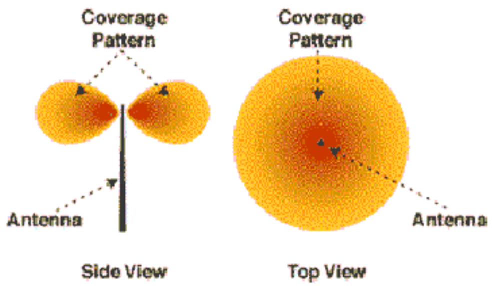
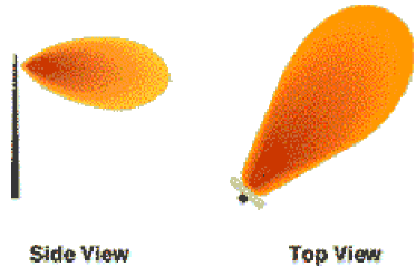
Antennas

- Antenna
  - Couples electromagnetic energy from one medium (space) to another (e.g., wire, coaxial cable, waveguide)
- Omnidirectional Antennas

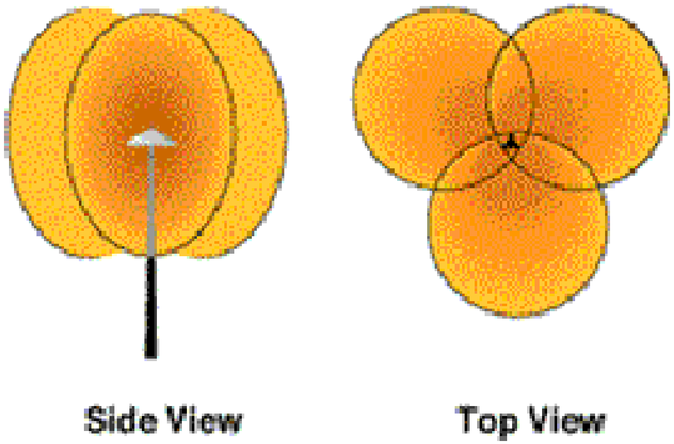


- Directional Antennas



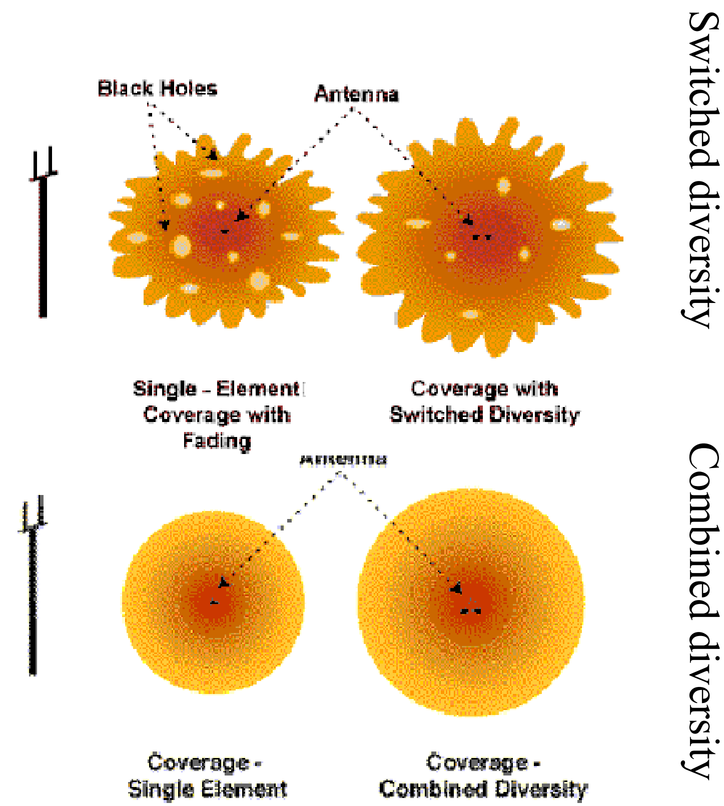
Antenna Systems (1/2)

- Sectorized Systems
  - Subdivide the area into sectors
    - Increases the frequency reuse



Antenna Systems (2/2)

- Diversity Systems
  - Multiple antenna elements
    - Switched Diversity
      - Switch between antennas
    - Diversity combining
      - Combine multipath signals



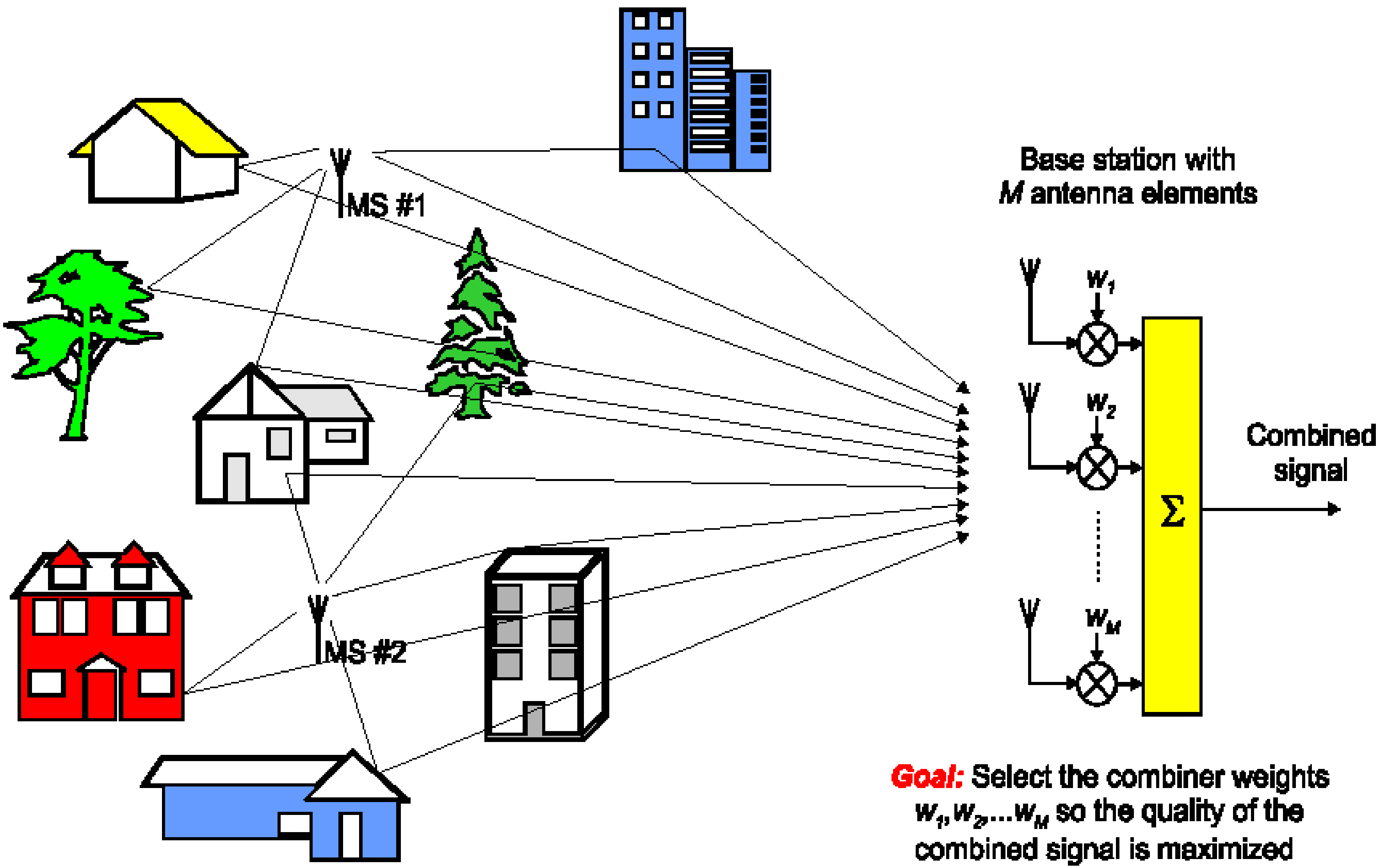
- **Smart Systems ☞ our topic**

Who is Smart?

- Antennas are not smart!
- Antenna *Systems* could be smart!

- Smart Antenna Systems
  - Consists of M antenna elements (*Antenna Array*)
  - Each antenna element signals are processed adaptively
  - Controlled by DSP
  - Adapts to the RF environments

Antenna Array Principle



Goal: Select the combiner weights $w_1, w_2, \ldots w_M$ so the quality of the combined signal is maximized

Smart Antenna System Types

Smart Antennas

Phased Array Antennas (Multibeam Antennas)

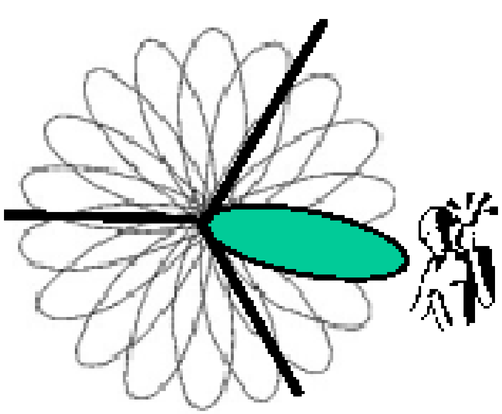
Finite number of fixed, predefined patterns or combining strategies

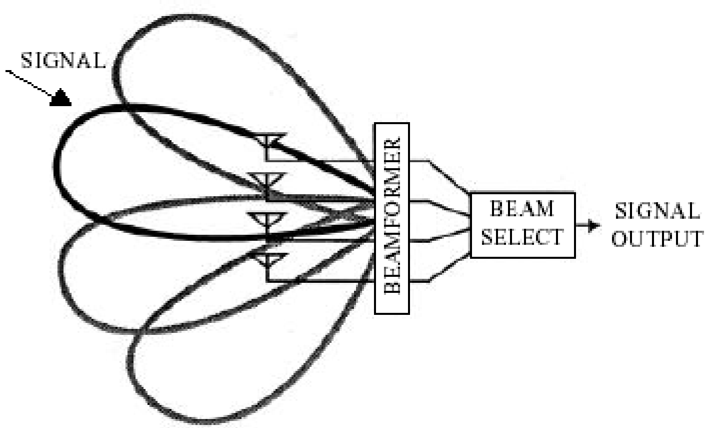
Adaptive Array Antennas (Adaptive Antennas)

Infinite number of patterns (scenario-based) that are adjusted in real time

Multibeam Antenna Systems

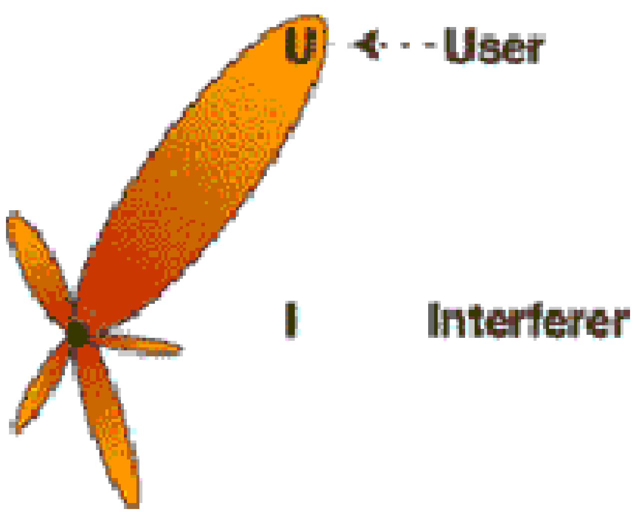
- What
  - Multiple fixed beams with heightened sensitivity in particular direction
- How
  - Detect signal strength
  - Choose from one of several predefined, fixed beams
  - Switch from one beam to another

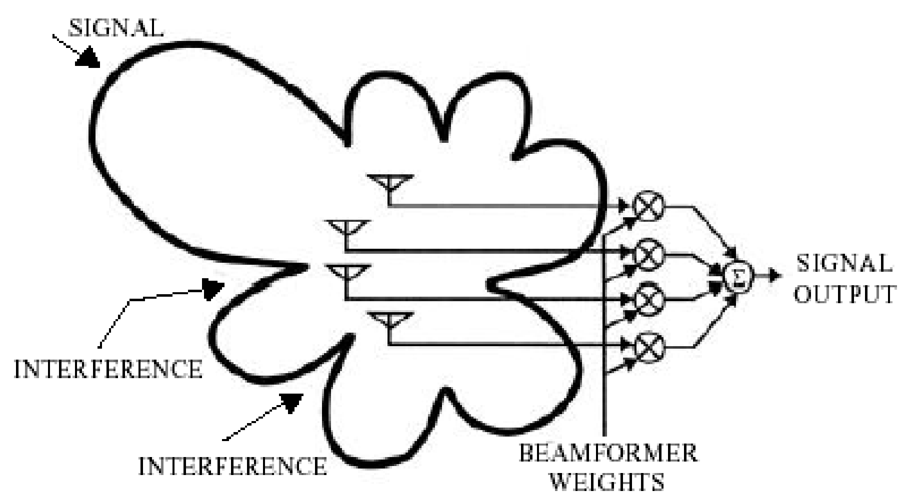




Adaptive Antennas

- The most advanced smart antenna approach
- Uses a variety of DSP algorithms
- Dynamically minimizes interference and maximizes intended signal reception





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Features

- Signal Gain
  - Multipath components are combined (improved SNR)
- Interference Rejection
  - Improved signal to interference ratio (SIR)
- Spatial Diversity
  - Minimizes the multipath fading
- Power Efficiency
  - Improved processing gain

Benefits (1/3)

- **Reduction in co-channel interference**
  - The radiated energy is focused in the form of narrow beams only in the desired direction $\Rightarrow$ Spatial Filtering
- **Mitigating multipath effects**
  - The multipath can be either mitigated as the interference, or it can be constructively exploited to enhance the system performance
- **Capacity Increase**
  - By mitigating the interference, the system capacity improves

Benefits (2/3)

- **Range Improvement (Beamforming gain)**
  - Focusing the cell energy in one direction increases the range
- **Power Efficiency**
  - Energy is radiated in the desired direction only (no waste of energy in other directions)
- **Security**
  - It is more difficult to tap a connection when smart antennas are used
    - To tap a connection, the intruder must be positioned in the same direction as the user seen by the BS

Benefits (3/3)

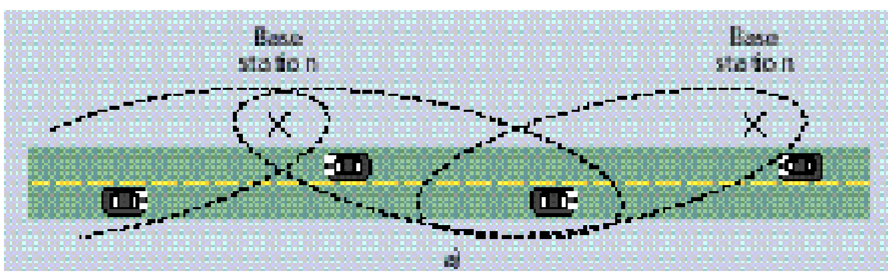
- **Reduction in handoff**
  - No need for splitting the cells for the sake of improved capacity.
- **Spatial information**
  - Spatial information of the users are available on demand
- **Compatibility**
  - This technology can be applied to various multiple access techniques such as TDMA, FDMA, and CDMA.

Drawbacks

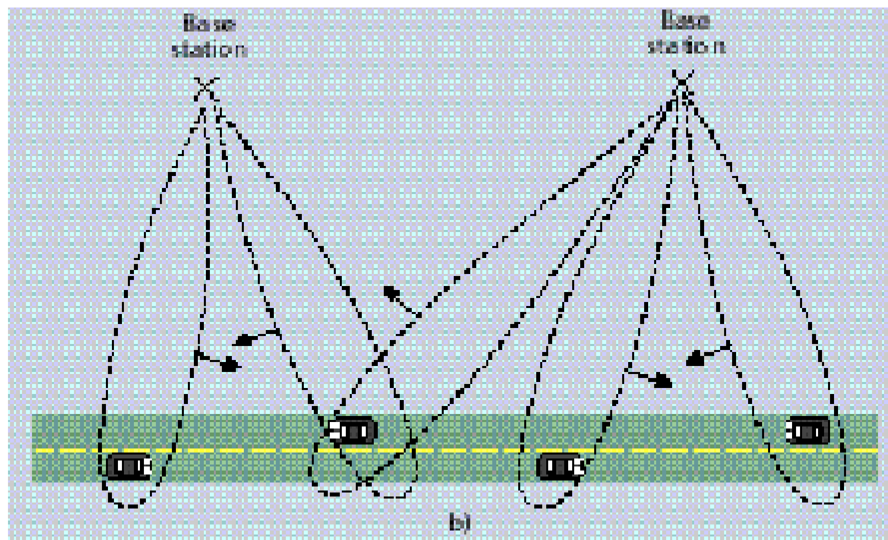
- **Transceiver Complexity**
  - The transceiver is much more complex than the conventional one
- **Resource Management**
  - New demand for mobility management
- **Physical Size**
  - For a reasonable gain, several antenna elements are required. This could provide some problems

Impacts on Radio Planning

- Some of traditional strategies of radio planning has to be modified
  - From adaptive antenna point of view, it is much more efficient to position the BST away from the road or railway
    - This way, the spatial dimension is better exploited



Placing the BST along the roads



Better spatial information is available

Applications

- Key technology for capacity increase in 3G networks
- Potential candidate for next generation Wi-Fi and WiMAX systems
- Electronic Warfare (EWF)

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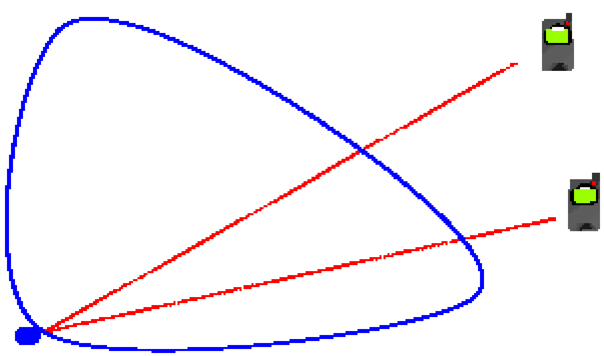
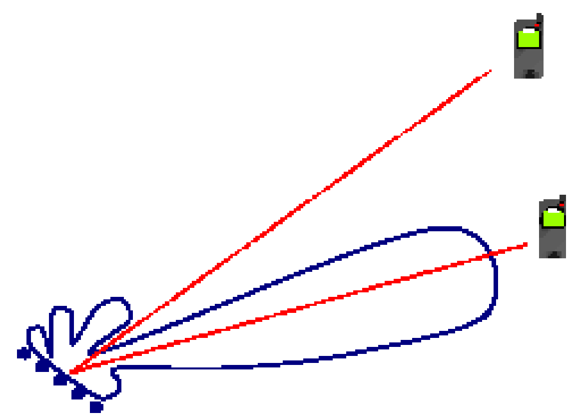
Adaptive Antenna System

- An adaptive antenna system consists of **several antenna elements**, whose signals are processed **adaptively** in order to exploit the **spatial dimension** of the mobile radio channel



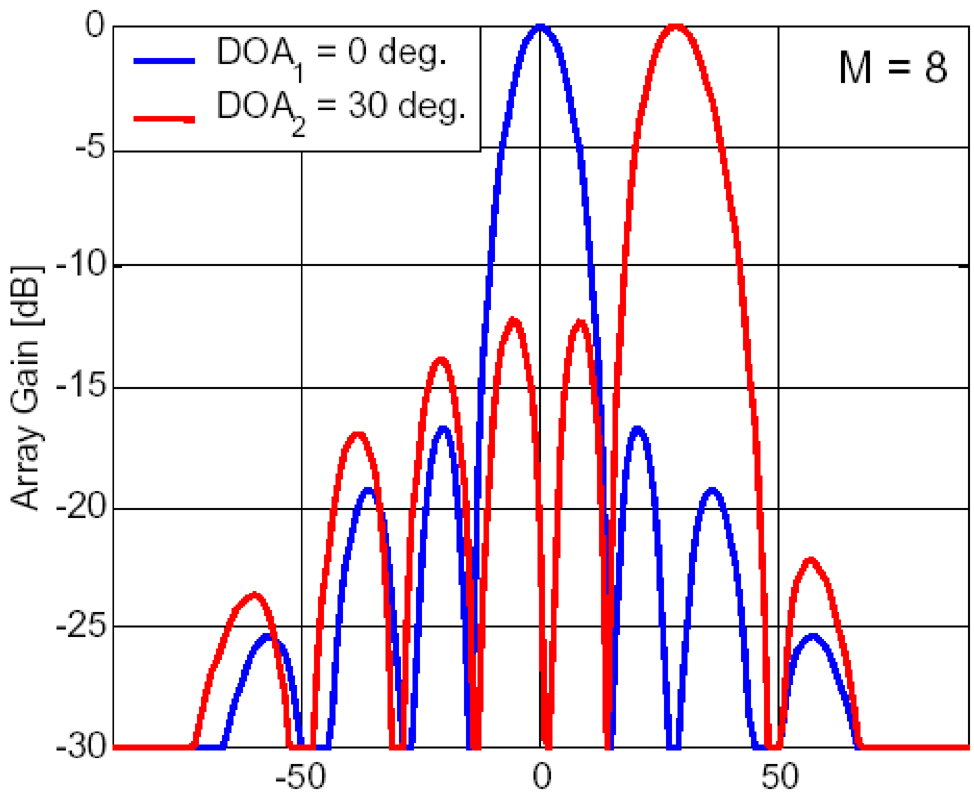
Conventions BTS radiation pattern



Adaptive antenna BTS

Beamforming (beam steering)

- Beamforming = phase the antenna array elements
- Direction-of-Arrival (DoA)
  - The only needed parameter



How Adaptive Antenna Works?

1. The signal processing steers the radiation beam towards a desired mobile user
2. It follows the user as he moves, at the same time,
3. Minimizes the interference arising from other users
   - Interference Nulling

- The smartness comes from the intelligent signal processor that is incorporated in the system
  - Complex, intensive computational algorithms are used

Basic Mechanisms

- The following functions are performed
  - Direction of arrival (DoA) is estimated for all incoming signals, including the interfering and multipath signals
  - The desired user signal is identified
  - The beam is steered in the direction of the desired signal
  - The user is tracked while he moves
  - Nulls are placed in the interfering signal direction

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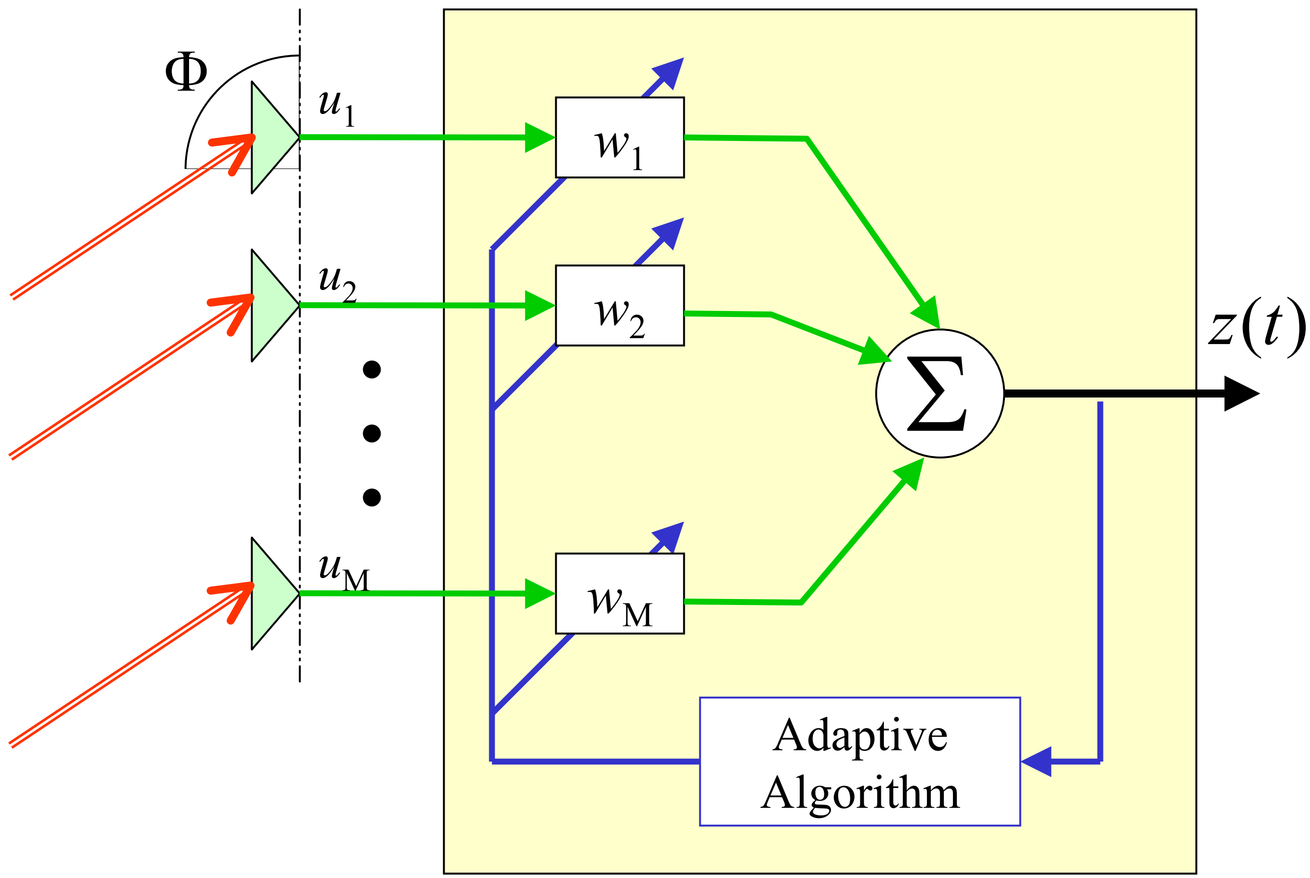
The Mathematical Model (1/10)



The Mathematical Model (2/10)

- The phase difference between the antenna element *m* and a reference element at origin is given by

$$\begin{aligned}\Delta\Psi_m &= \beta\Delta d_m \\ &= \beta\left(x_m\cos(\Phi)\sin(\Theta)+y_m\cos(\Phi)\sin(\Theta)+z_m\cos(\Phi)\sin(\Theta)\right)\end{aligned}$$

  - Where: Φ and Θ are the eve lavation and azimuth angles respectively
    β is the phase propagation factor
    x_m, y_m, z_m are the coordinates of antenna element *m* with with respect to a reference element at origin

The Mathematical Model (3/10)

- The output signal can be represented as

$$z(t) = \sum_{i=1}^{M} u_i(t) w_i$$

The Mathematical Model (4/10)

- If the received at the reference antenna element is $u_1(t)$ the the received signals at the other elements will be a phase shifted replicas of $u_1(t)$

- For one user, the output signal can be represented as

$$z(t)=\sum_{i=1}^{M}u_1(t)e^{-j\beta(x_i\cos(\Phi)\sin(\Theta)+y_i\cos(\Phi)\sin(\Theta)+z_i\cos(\Phi)\sin(\Theta))}w_i$$

- And in more compact form

$$z(t)=\underline{\mathrm{w}}^{\mathrm{H}}\underline{\mathrm{u}}(t)$$

The Mathematical Model (5/10)

- Where

$$\underline{\mathrm{u}}(t) = u_1(t)\begin{bmatrix} e^{-j\Delta\Psi_1} & e^{-j\Delta\Psi_2} & \cdots & e^{-j\Delta\Psi_M} \end{bmatrix}^{\mathrm{T}}$$

$$= u_1(t)\underline{\mathrm{a}}(\Phi,\Theta)$$

- Take the first element as a reference so that $\Delta\Psi_1 = 0$

- The vector _ is called the **Steering Vector**

The Mathematical Model (6/10)

- The input signal at each antenna element is the convolution between the transmitted signal and the channel impulse response

$$u_{ij}(\tau,t) = s_i(t) * h_{ij}(\tau,t)$$

- Where: $s_i(t)$ is the transmitted signal from user i

  $h_{ij}(\tau,t)$ is the channel response between user ***i*** and antenna element ***j***

The Mathematical Model (7/10)

- The channel between the mobile station and the base station can be modeled using the Vector Channel Impulse Response (VCIR) as

$$\underline{\mathrm{h}}_i(\tau,t)=\sum_{k=1}^{B_i}\underline{\mathrm{a}}_i(\phi_k,\theta_k)\alpha_{ik}(t)\delta(t-\tau_k)$$

  - Where: $\underline{\mathrm{a}}_i$ is the steering vector
    $\underline{\mathrm{h}}_i$ is the channel impulse response
    τ_k is the time delay of signal of user *i* to BS through path *k*
    B_i the assumed number of paths of user *i*
    α_{ik} is the complex channel gain

The Mathematical Model (8/10)

- The complex channel gain

$$\alpha_{ik}(t) = \sqrt{\rho_{ik}}\, e^{j\left(2\pi f_{ik} t + \psi_{ik}\right)}$$

- Where ρ_{ik} is the channel gain, given by $\rho_{ik} \approx \frac{A_{ik}}{d_{ik}^{\eta_{ik}}}$
  - Where A_{ik} is the log-normal shadowing effect for path k of user *i*
    d_{ik} is the distance between user *i* and BS through path *k*
    η_{ik} is the path loss exponent of user *i* through path *k*
    f_{ik} is the Doppler Shift
    ψ_{ik} is the phase offset

The Mathematical Model (9/10)

- Hence, we can describe the signal at antenna terminal *j* as

$$u_{ij} = s_i(t) * \sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik}}\, e^{j(2\pi f_{ik} t + \psi_{ik})} \delta(t - \tau_k) + \underline{\mathrm{n}}_i(t)$$

$$= \sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik}}\, e^{j(2\pi f_{ik} t + \psi_{ik})} s_i(t - \tau_k) + \underline{\mathrm{n}}_i(t)$$

  - Where $\underline{\mathrm{n}}_i(t)$ is additive noise at antenna element *j*

The Mathematical Model (10/10)

- In channels where the time difference between paths are small relative to the symbol period $s(t)$ we can approximate the latest equation as

$$u_{ij} = s_i(t-\tau_0)\sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}}\sqrt{\rho_{ik}}\,e^{j(2\pi f_{ik}t+\psi_{ik})} + \underline{\mathrm{n}}_i(t)$$

$$\Rightarrow \underline{\mathrm{u}}_i = s_i(t-\tau_0)\sum_{k=1}^{B_i}\underline{\mathrm{a}}(\phi_{ik})\alpha_{ik}(t) + \underline{\mathrm{n}}_i(t)$$

$$= s_i(t-\tau_0)\underline{\mathrm{b}}(t) + \underline{\mathrm{n}}_i(t)$$

- $\underline{\mathrm{b}}(t)$ is called the spatial signature of the narrowband (flat fading) channel

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1) Conventional Beamformer

- The weights are selected to be the conjugate of the steering vector
  - For one path case, the weights are selected as $\underline{w}^H \underline{a} = c$
    - Where c is a real constant
- Advantages
  - Simple, and provides max. SNR if noise is uncorrelated
- Disadvantage
  - Does not work for mobile communications, since it assumes no directional jamming
  - In WCDMA, there are many users sharing same frequency
    - There are many unintentional jammers

2) Null-Steering Beamformer

- If there are Q users in the cell, and the weights are calculated for user *i*, then the desired weight vector is the solution of the following linear system

$$\underline{\mathrm{w}}_i^{\mathrm{H}}\underline{\mathrm{a}}_i = 1$$

$$\underline{\mathrm{w}}_i^{\mathrm{H}}\underline{\mathrm{a}}_k = 0, \quad \forall k \in [1, Q]\, and\; k \neq i$$

  - The system can be solved if $Q \leq M$
- Generally, the problem could be solved as

$$\underline{\mathrm{w}}_i^{\mathrm{H}} = \underline{\mathrm{D}}^{\mathrm{T}}\left(\underline{\mathrm{A}}^{\mathrm{H}}\underline{\mathrm{A}}\right)^{-1}\underline{\mathrm{A}}^{\mathrm{H}}$$

  - Where

$$\underline{\mathrm{D}} = \begin{bmatrix} 0 & \cdots & 1 & 0 & \cdots & 0 \end{bmatrix}^T, 1 \text{ at the } \mathrm{i}^{\mathrm{th}} \text{ element}, \quad \underline{\mathrm{A}} = \begin{bmatrix} a_1 & \cdots & a_M \end{bmatrix}$$

3) Minimum Variance Distortionless Response Beamformer (MVDR)

- Minimize the average output power, while seeking the unity response in the user direction

$$\min_{\underline{w}} E\left[\left|z(t)\right|^2\right], \quad \text{subject to} \quad \underline{w}_i^{H}\underline{a}_i = 1$$

  - The obtained weights will minimize the total noise, including interferences and uncorrelated noise
  - MVDR maximizes the SINR

- The problem can be solved using Lagrange Multiplier

$$\underline{w}_i = \frac{\underline{R}^{-1}\underline{a}_i}{\underline{a}_i^{H}\underline{R}^{-1}\underline{a}_i}, \qquad \textit{where} \quad \underline{R} = E\left[\underline{u}\,\underline{u}^{H}\right]$$

4) Minimum Square Error Beamformer

- A reference signal is used to calculate the weights
  - This reference signal should be known beforehand
  - Using this signal, the weights can be calculated even without DoA information, or the channel characteristics
- The optimum weights can be found as

$$\hat{\underline{\mathrm{w}}}_i = \arg\min E\left[\left|\underline{\mathrm{w}}_i^H \underline{\mathrm{u}}(k) - d_i(k)\right|^2\right]$$

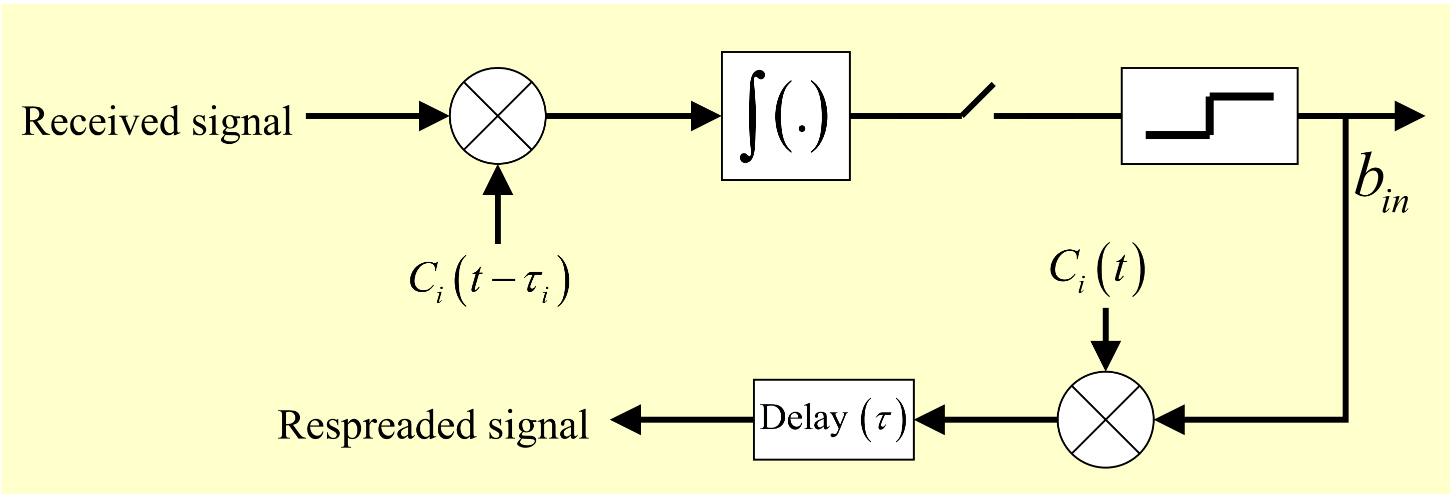
    - Where $d_i(k)$ is the training sequence for user i at time k

- The achieved weight vector is

$$\hat{\underline{\mathrm{w}}}_i = \underline{\mathrm{R}}^{-1}\underline{\mathrm{P}}, \textit{where } \underline{\mathrm{R}} = E\left[\underline{\mathrm{u}}\underline{\mathrm{u}}^{\mathrm{H}}\right] \quad \textit{and} \quad \underline{\mathrm{P}} = E\left[\underline{\mathrm{u}} d_i^*\right]$$

5) Least Square Despread/Respread Multitarget Array (LS-DRMTA) (1/2)

- This algorithm is based on the respreading of the received data bits. The respreaded signal is compared with the received signal (before despreading) and the difference is used as an error signal



$C_i(t)$: spreading code of user i

b_{in} : nth received data for user i

5) Least Square Despread/Respread Multitarget Array (LS-DRMTA) (2/2)

- The respreaded signal is given by

$$r_i(t) = b_{in} C_i(t - \tau_i), \qquad (n-1)T_b \le t \le nT_b$$

- The LS-DRMTA is used to minimize the error function by adjusting the weight vector
  - The cost function is given by

$$F(\underline{w}_i) = \sum_{k=1}^{K} \left| y_i(k) - r_i(k) \right|^2 = \sum_{k=1}^{K} \left| \underline{w}_i^{H} \underline{x}(k) - r_i(k) \right|^2$$

Other Algorithms

- Recursive Mean Square (RMS) algorithm
- The Sample Matrix Inversion (SMI) algorithm
- The Constant Modulus Algorithm (CMA)
- The Cyclostationary algorithm
- The Decision-Directed algorithms

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Conclusions

- Adaptive antenna systems show substantial improvements:
  - **Reduction in co-channel interference**
  - **Mitigating multipath effects**
  - **Capacity Increase**
  - **Range Improvement (Beamforming gain)**
  - **Power Efficiency**
  - **Security**
  - **Reduction in handoff**
  - **Spatial information**
  - **Compatibility**

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References

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- [2] Per H. Lehne, et. al. *"An Overview of smart antenna technology for mobile communication systems"*. IEEE Communications, Surveys
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Exercise

- A base station located at the center of a circular cell. Assume that two users are located at
  - $x = 40$m, $\phi = \pi/8$, and
  - $x = 190$m, $\phi = 3\pi/5$ with respect to base station.

  The carrier frequency is 2 GHz.

1. Find the steering vector $\underline{\mathbf{a}}$ for both users
2. Calculate the weights vector $\underline{\mathbf{w}}_1$ to null the interference of *user 1* with respect to *user 2*.
3. Calculate the weights vector $\underline{\mathbf{w}}_2$ to null the interference of *user 2* with respect to *user 1*.

Thank You!

Q&A