**Signal Processing for Antennas: Smart Antennas and MIMO Systems**

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**Outline**

- Smart antennas technology
  - Introduction
  - Type of smart antennas
  - Beamforming techniques
  - Architecture of TX/RX of smart antennas
- MIMO techniques
  - Beamforming vs Spatial Diversity
  - MIMO Characterization
  - Antennas for MIMO Systems
Concepts of smart antennas

• Sectorial antenna

![Sectorial antenna diagram]

Concepts of smart antennas

• Beamforming

![Beamforming diagram]
Concepts of smart antenna

- Space Division Multiple Access (SDMA)

![Diagram showing SDMA concepts]

Concepts of smart antennas

- Radioelectric emissions

![Diagram comparing usual and worst case scenarios]
Key benefits of smart antennas

- Enhanced coverage through range extension
  - By increasing the gain of the base station antenna.
- Reduction of the transmitted power
  - Sensitivity of the base station antenna is increased allowing the mobile station transmitted less power.
- Link quality can be improve though multipath management
  - Smart Antennas mitigate multipath effect (fading, temporal dispersion) or even exploit spatial diversity.
- Smart antennas can improve system capacity
  - By reducing power requirements, frequencies channels can be reused to increase system capacity.

Types of Smart Antenna

- Switched beam antenna
  - The system steers several beams to fixed directions in order to cover an area of interest.
  - An ‘intelligent’ switch is used to select the beam that offers the best service to a desired user.
Types of Smart Antennas

- **Phased arrays**
  - Electronic control of the **feeding phases** at each radiating element for steering the main beam in the desired direction.
  - Need for a **DoA estimation technique** to know the desired steering direction.

- **Adaptive antennas**
  - Beamforming is made by weighting each output signal up to maximize a signal parameter of interest.
  - Beam pattern steers the maximum beam to the desired direction, while nulls are put in interference directions.
Smart antenna types

- Adaptive antennas
  - are able to receive several signals from independent beams.

Application to 3G mobile communications

Sectorial / Switched beam / Adaptive

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Coverage Area Scenario Comparison

Adaptive

- Switched Beam
- Conventional Sectorization
- Low Interference Environment

Adaptive

- Switched Beam
- Conventional Sectorization
- Significant Interference Environment
Beamforming techniques

- Smart antenna system

CONVENTIONAL BEAMFORMING

Objective: Get the feeding weights \( w(t) \) for combining optimally the output array signals

- From ‘antenna’ point of view: the feeding weights are chosen for steering the radiation pattern to the desired direction while nulls are put at the interference directions.
- From the ‘processing’ point of view: the feeding weights are chosen for optimally to maximize (or minimize) some parameter. combining the received signals in order

Examples:
- \textbf{max power}: steer the main beam to the direction of the highest power signal
- \textbf{max SNR}: steer the main beam to the direction of the desired user.
- \textbf{max SINR}: steer the main beam to the direction of the desired user but cancelling signals coming from directions of interferences.
- \textbf{MMSE}: minimize the power of the signal error at the array output after comparing it to a reference signal (pilot bits of UMTS, training sequence in GSM, etc.).
- \textbf{MBER}: Minimize the Bit Error Rate (system point of view)

\textbf{FOR BEAMFORMING IS NEEDED A REFERENCE SIGNAL.}
Type of reference signal

- **Temporal reference**
  - A reference signal is known which is correlated with the desired one (same spread code, training sequence and so on.) and uncorrelated with the interference and noise components.

- **Spatial reference**
  - The Direction-of-arrival (DoA) of the desired signal \((\theta,\phi)\) is known or can be estimated.

- **Blind reference**
  - Some modulation property or signal correlation is known (constant module, ...).

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**Beamforming with temporal reference**

**Case of temporal reference**: a correlated signal with the desired signal and a uncorrelated signal with the interferences (i.e. pilot bit) is known.

- Compare the received signal with the reference one:

\[
e(n) = d(n) - y(n) = d(n) - \mathbf{w}^H \cdot \mathbf{x}(n)
\]

- Compute the Mean Square Error (MSE) of the cost function (function to be minimized)

\[
J(\mathbf{w}) = E[|e(n)|^2] = E[|d(n) - \mathbf{w}^H \cdot \mathbf{x}(n)|^2]
\]
Beamforming with temporal reference

- Look for the weights that minimize the cost function (Mean Square Error), which will be the optimum weights (according to the MMSE criterion)

\[ J(w) = \sigma_d^2 + w^H R_{xx} w - w^H p - p^H w \]

\[ \nabla J(w) = 2 R_{xx} w - 2 p \]

- Equalling to zero:

\[ \nabla J(w) = 0 \Rightarrow w_{opt} = R_{xx}^{-1} p \]

It requires the statistics of \( R_{xx}, p \) de \( x(n) \)!!

- An inverse matrix is needed (more complexity, inestability in the solution)

Optimum weight using Wiener-Hopf

“suboptimal” solutions:
Adaptive algorithms (iterative)

Adaptive algorithms

- Adaptive algorithms are used for obtaining the “suboptimum” weights needed for beamforming in an iterative way.
  - They are updated after each iteration: suitable for changing environments.
  - They offers “suboptimum” solutions (the Wiener-Hopf is a lower bound of the error and it used to be used for comparing simulations).
  - The calculation time and complexity are reduced ⇒ suitable for real applications.

- Conventional adaptive algorithms:
  - **LMS** (Least Mean Squares)
  - **RLS** (Recursive Least Squares)
  - **LPM** (Linearized Power Method)
  - **CG** (Conjugate Gradient)
  - etc…
Least Mean Square (LMS) Algorithm

- Algorithm of stochastic gradient derived from the maximum slope methods: each weight is computed as a function of the last value, moving in the opposite direction of the error gradient.

$$w(n + 1) = w(n) + \frac{1}{2} \cdot \mu \cdot \left[ - \nabla J(n) \right]$$

$$w(n + 1) = w(n) + \mu \cdot \left( p - R_{xx}^{-1} \cdot w(n) \right)$$

where $\mu$ is called the adaptation step. The parameter controls the convergence time as well as the process stability.

$$p(n) \equiv x(n)d^*(n) \quad R_{xx}(n) \equiv \left[ x(n)x^H(n) \right]$$

- The matrix $R$ and the vector $p$ are approximate by its instantaneous values:

$$R(n) \approx \sum_{k=0}^{n} x(k)x^H(k)$$

$$p(n) \approx x(n)d^*(n)$$

- Updating of weights vector:

$$w(n + 1) = w(n) + \mu \cdot \left( x(n)d^*(n) - x(n)x^H(n) \cdot w(n) \right)$$

- If the beamformed array output $y(n) = w^H(n) \cdot x(n)$, the error signal is:

$$e(n) = d(n) - x(n) \cdot w^H(n)$$

- Then, the weights expression with LMS is given by:

$$w(n + 1) = w(n) + \mu \cdot \left( x(n)e^*(n) \right)$$
μ step selection

• The adaptation step \( \mu \) indicated the size of the step over the error surface in each iteration.

• The adaptation step affects:
  – convergence time: \( \uparrow \mu \Rightarrow \uparrow \text{velocity} \)
  – convergence of stability: \( \uparrow \mu \Rightarrow \downarrow \text{robustness} \)
  – final error: \( \uparrow \mu \Rightarrow \uparrow \text{residual error} \)

Compromise between velocity \( \leftrightarrow \) stability

Initial point selection

• It must be chosen an initial weight vector in the adaptive algorithm: \( \mathbf{w}(0) \)

\[
\mathbf{w}(0) \rightarrow \mathbf{w}(n+1) = \mathbf{w}(n) + \mu \cdot (x(n)e(n)^*), \quad n > 0
\]

– As a function of the chosen value, the convergence may be faster or slower. \( \rightarrow \) chose a value near to the optimum solution. If it is known the angular sector from the incident user.

IDEAS FOR ADAPTIVE ANTENNA (linear array):

\begin{itemize}
  \item \( \mathbf{w}(0) = [1 \ 0 \ldots 0]^T \rightarrow \) Omnidirectional initial pattern (any preferred direction)
  \item \( \mathbf{w}(0) = 1/M \cdot [1 \ 1\ldots 1]^T \rightarrow \) Broadside direction of the array
  \item \( \mathbf{w}(0) = 1/M \cdot [\mathbf{a}_{\text{usu.desa}}]^H \rightarrow \) Estimated DoA of the desired user
\end{itemize}
Initial point selection

The evolution to the final solution may be different as a function of the chosen initial point.

i.e.: Two initial points, four antennas

For two different initial point the final solution is the same but for different paths.

NLMS Algorithm

• The amplitude of the received signal $x(n)$ vary due to the propagation channel fading
  – It produces the velocity and robustness of the algorithm evolution changes.
• For avoiding variations in the convergence process, the adaptation step is normalized to the power of the actual received samples.
  – Normalized LMS Algorithm (NLMS)

$$e(n) = d(n) - w^H(n-1)x(n)$$
$$w(n+1) = w^H(n-1) + \frac{\mu_0}{\|x(n)\|^2} x(n)e^*(n)$$
**NLMS Algorithm**

- Advantages of NLMS over LMS algorithm:
  - Convergence is independent of the possible variations of the signal power.
  - The process selection of $\mu_0$ is easier:

\[
\begin{align*}
\text{LMS} & : & 0 < \mu < \frac{2}{\text{tr}(R_{xx})} = \frac{2}{\|x[n]\|^2} \\
\text{NLMS} & : & 0 < \mu_0 < 2
\end{align*}
\]

- Drawback: More intensive processing is required (normalization and signal power computing)

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**LMS conclusions**

- It is derived from maximum slope algorithms
- It is based on the instantaneous estimation of $R$ and $p$.
- Basic features:
  - **Complexity**: low (linear with respect to $M$, $O(M)$).
  - **Convergence**: slow, depending of the signal characteristics ($R_{xx}$, eigenvalues scattering, …) and the chosen parameters ($\mu$, $w_0$, …).

- Important parameters to be chosen:
  - $\mu$: compromise between velocity, stability and final error.
  - $w_0$: affects the convergence time and stability.

- Versions of the algorithm:
  - Normalized LMS (NLMS).
  - LMS with adaptive $\mu$. 

RLS Algorithm

• It is a recursive least square method: the cost function to be minimized is the square error averaged over a time period (or over a several number of samples):

\[ J_{RLS}(n) = \sum_{k=0}^{n} \delta_{0}^{n-k} \cdot |e(k)|^2 \]

where \( \delta \) is the “memory” factor:
- it takes values between 0 and 1
- It allows weighting the averaged values: It emphasizes the samples that are nearer to initial time and reduces weight to samples that are farther to initial time.
  » \( \delta_0 \sim 1 \Rightarrow \) All samples are involved in the process
  » \( \delta_0 < 1 \Rightarrow \) Reduce influence of the past samples.

• The autocorrelation matrix \( R_{xx} \) and weight vector \( p \) are approximate by a temporal average.

\[
R_{RLS}(n) = \frac{1}{n} \sum_{k=1}^{n} \delta_{0}^{n-k} x(k) \cdot x^H(k)
\]

\[
p_{RLS}(n) = \frac{1}{n} \sum_{k=1}^{n} \delta_{0}^{n-k} x(k) \cdot d^*(k)
\]

• From the error function we obtain the “optimum” weights.

\[
J_{RLS}(n) = \sum_{k=0}^{n} \delta_{0}^{n-k} \cdot |e(k)|^2 \quad \nabla J_{RLS}(w) = 0
\]

\[
W_{RLS}(n) = R_{RLS}^{-1}(n) \cdot p_{RLS}(n)
\]
**Iterative equation of RLS**

- The inverse matrix $R_{xx}$ is obtained following the inverse matrix formula:

$$R^{-1}(n) = \frac{1}{\delta} \left[ R^{-1}(n-1) - \frac{R^{-1}(n-1) \cdot x(n) \cdot x^H(n) \cdot R^{-1}(n-1)}{\delta + x^H(n) \cdot R^{-1}(n-1) \cdot x(n)} \right]$$

The inverse matrix is calculated from the last value and the new received snapshot $x(n)$ and it is not necessary to calculate it at each iteration.

- The iterative equation for $w(n)$ is given by:

$$\underline{w}(n) = \underline{w}(n-1) + \epsilon(n/n-1) \cdot R_{RLS}^{-1}(n) \cdot x(n)$$

where: $\epsilon(n/n-1) = d(n) - x^H(n) \cdot \underline{w}(n-1)$

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**Effect of the “memory” factor**

- The greater $\delta$, the bigger algorithm memory factor:
  - For static environments the final error is lower (it means slow temporal fluctuations)...
  - ...but less following-up capacity of the fast temporal fluctuations!!

**Static environment**  
If $\delta$ is increased, the residual error is decreased.

**Dynamic environment**  
$\Delta \theta = 0.015^\circ$/frame  
If $\delta$ is too big, the algorithm does not follow well the temporal signal.
Comparison of LMS vs RLS

- Updating the RLS equation involve to invert the autocorrelation matrix.
  - Complexity is bigger than the LMS algorithm
    Complexity of quadratic order $O(L^2)$
- however:
  - It offers bigger convergence velocity.
  - Higher level of SINR (its improvement depends on the environment).

<table>
<thead>
<tr>
<th>LMS Algorithm</th>
<th>RLS Algorithm</th>
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<tbody>
<tr>
<td>☺ Lineal complexity $O(L)$</td>
<td>☺ Quadratic complexity $O(L^2)$</td>
</tr>
<tr>
<td>☹ Slow convergence</td>
<td>☹ Fast convergence</td>
</tr>
<tr>
<td>☹ Need a high input signal level.</td>
<td>☹ Low adaptive capacity to fast temporal variations.</td>
</tr>
</tbody>
</table>

Tx/Rx architecture of smart antenna systems

- Beamforming: Combining received signals to improve radiation pattern (SNR, SINR, BER …)
- Questions:
  - Which signals to combine?
  - Where to place the beamforming block?
  - How to make the beamforming?
Several aspects must be taken into account when designing a smart-antenna-based system.

• Application type:
  – Cellular telephony, wireless LAN, ...

• Type of signals
  – UMTS, CDMA, type of reference signals,…

• Environment
  – Indoor, outdoor, macrocell, microcell, picocell, line-of-sight (LOS), non-line-of-sight (NLOS), …

Design aspects to be taken into account:

– Link sense for beamforming (uplink, downlink, both) and if it is beamforming weights are different for both sense.

– Signal desired to be beamformed. (shared channels, dedicated channels, …).

– Aspects of the used signal (where the beamforming is done, if it is necessary to introduce another kind of signal processing like space-time processing…)

Design aspects of TX/RX smart antennas
Analogical vs Digital beamforming

- In smart antennas, beamforming process can be made in analogical or digital stage.

**Analogue beamforming**

- Beamforming carried out in the analogical stage
  - Control of the amplitude and phase weights is carried out in the RF or IF stage.
  - Just a sum signal is passed to baseband and to digital form.
    - Less RF or IF chains are needed ⇒ cheaper
    - Less adaptive capacity, less degrees of freedom.

- Beamforming carried out in the digital stage
  - A full receiver for each antenna is needed.
    - It requires one RF-IF chain for each antenna ⇒ expensive system
    - Major processing capacity. ⇒ More flexible.
Smart antennas for W-CDMA base station

CONVENTIONAL ARCHITECTURE:
SMART ANTENNA+ INTELIGENT BASE STATION

- Partial vs Total cancelation
Summary

- There are different aspects to account in Smart Antenna Design: incoming signal, BS or user terminal, etc.
- The “intelligence” of the smart antennas is provided by the beamforming techniques which enhance system performance.
- There is a large list of beamforming algorithms based on temporal, spatial and blind references.
- Discussed adaptive algorithm: LMS (++) and RLS (++).
  - LMS: Step factor ($\mu$), Initial conditions, input signal ($\mathbf{R}$).
  - RLS: Memory factor ($\delta$), Initial conditions, Static or Iterative.
  - RLS is faster than LMS, but expensive in terms of computational resources.

Multiple Antennas: Evolution

- Systems without spatial diversity (1 tx antenna – 1 rx antenna)
- Adaptive antenna systems (array with several elements in one side of the link)
- …Multiple antennas in transmission and reception?
Beamforming Vs Spatial diversity (I)

- Beamforming: combination of the received signals from several antennas with a high level of correlation, mainly to reduce interferences.
  - The spacing between elements must be small.
  - It is assumed that all antennas see a correlated channel respect to the others (minimum effect of multipaths).

\[ d \approx \frac{\lambda}{2} \]

The differences between the received signal by each antenna: only a phase offset!!
\[ \Rightarrow \] it is represented with the steering vector \[ \Rightarrow \] The array factor is applicable.

Beamforming Vs Spatial diversity (II)

- Spatial diversity: several antennas are used to counteract or take advantage of propagation effects.
  - The spacing between elements should be high enough (>Bc)
  - Low-correlated received signals are used to perform data multiplexing or reduce the fading effects.

\[ d \approx 20\lambda \]

The received signals in each antenna can be very different!!
Beamforming Vs Spatial diversity

**Beamforming**

Associated to adaptive antenna.

Basic idea: use an antenna array to combine the signals in order to obtain an optimum and adaptive radiation pattern.

**Space diversity**

Associated to **MIMO** (Multiple Input Multiple Output) systems

Basic idea: use multiple antennas to obtain different channels, which enable to obtain spatial diversity or multiplexing.

**Beamforming Vs Spatial diversity**

**(IV)**

• Distinction according to what we need:
  – Diversity ⇒ all antennas transmit the same, in order to enhance the SNR.
  – Spatial multiplexing ⇒ different data streams are sent by each antenna, to increase the data binary rate.

**SPACE-TIME DIVERSITY**

- Space-Time coding
- Delay diversity.

**SPATIAL MULTIPLEXING**

- Horizontal and vertical coding
- Successive detection schemes (type BLAST).
MIMO systems

The MIMO channel is usually characterized with a matrix, $H$

$$H = \begin{bmatrix}
h_{1,1} & h_{1,2} & \cdots & h_{1,N_T} \\
h_{2,1} & h_{2,2} & \cdots & h_{2,N_T} \\
\vdots & \vdots & \ddots & \vdots \\
h_{N_R,1} & h_{N_R,2} & \cdots & h_{N_R,N_T}
\end{bmatrix}$$

$H$ is time and frequency dependent (in general)

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Mathematical representation (I)

- Narrow-band channel model ($H(t,f) = H(t)$)

$$\mathbf{y} = \mathbf{Hs} + \mathbf{n}$$

where:

$$\mathbf{s} = \begin{bmatrix} s_0 & s_1 & \cdots & s_{N_f-1} \end{bmatrix}$$

$$\mathbf{n} = \begin{bmatrix} n_0 & n_1 & \cdots & n_{N_f-1} \end{bmatrix}$$

$-H$ matrix $(N_R \times N_T)$

$$\mathbf{H} = \begin{bmatrix}
h_{1,1}(t) & h_{1,2}(t) & \cdots & h_{1,N_T}(t) \\
h_{2,1}(t) & h_{2,2}(t) & \cdots & h_{2,N_T}(t) \\
\vdots & \vdots & \ddots & \vdots \\
h_{N_R,1}(t) & h_{N_R,2}(t) & \cdots & h_{N_R,N_T}(t)
\end{bmatrix}$$
Mathematical representation (II)

- Broadband channel model
  - Frequency representation
    \[ Y(t, f) = H(t, f)S(t, f) + N(t, f) \]
    where the channel characterization is done in time and delay domain
  - Time representation \( \Rightarrow \) tapped delay-line model
    \[ y(t) = \sum_{i=0}^{N_{\text{taps}}} h(t, \tau_i) s(t, \tau_i) + n(t) \]

Channel characterization

- Parameters of a propagation radio channel (general case)
  - Narrowband aspects:
    » Long-term fading, short-term fading
    » Coherence time
    » Doppler spectrum
  - Broadband aspects:
    » Power delay profile (PDP)
    » Mean delay, delay spread
    » Coherence bandwidth

- Parameters of a MIMO radio channel
  » Spatial correlation (Tx / Rx), coherence distance
  » Power angular spectrum.
Capacity in MIMO systems (I)

• Capacity of the channel: maximum information rate that can be sent through a channel at a certain bandwidth (bits/sec/Hz)

- SISO (Shannon theorem)

\[ C = \log_2 \left( 1 + \text{SNR} \right) \text{ bps/Hz} \]

- MIMO, narrowband (general case)

\[ C = \log_2 \left| I_{N_R} + HQH^H \right| \text{ bps/Hz} \]

where:
- \( \text{SNR} \): signal to noise ratio
- \( I_{N_R} \): unity matrix (\( N_R \) elements)
- \( H \): MIMO channel matrix
- \( Q \): covariance matrix of the transmitted signal, with normalization so that \( \text{tr}(Q) = \text{SNR} \) (power limitation)

Capacity in MIMO systems (II)

• Specific cases (narrowband):

- MIMO, no channel information (CSI) at TX

Uniform power allocation at transmitter

\[ C = \log_2 \left[ \det \left( I_{N_R} + \frac{\text{SNR}}{N_T} HH^H \right) \right] \]

- MIMO, total channel information (CSI) at TX

Water-filling scheme (power allocation as a function of channel eigenvalues, \( \lambda_i \))

\[ C = \sum_{i=1}^{\min(N_T, N_R)} \log_2 \left( 1 + \frac{\text{SNR}}{N_T} \lambda_i \right) \]

- SISO (Shannon theorem)

\[ C = \log_2 \left( 1 + \text{SNR} \right) \text{ bps / Hz} \]
**Eigenvalue decomposition**

- Eigenvalue decomposition (EVD) of the channel covariance:
  
  It gives information about the distribution of the orthogonal “sub-channels” created when using multiple transmitters and receivers.

  \[
  R = HH^H \quad \Rightarrow \quad \text{Eigenvalue decomposition} \quad R\cdot v = \lambda \cdot v
  \]

  “Subchannels” representation in MIMO

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**Capacity in MIMO systems (III)**

- Cumulative Distribution Function (CDF) shows the probability that the value of the random variable is less or equal than the quantity in the axis X.
MIMO Antennas

Several antenna aspects are significant when considering a MIMO systems…

- Array configuration: elements spacing, type of configuration (linear, circular…)

- Antenna polarization: vertical, horizontal, circular…

- Type of element: omnidirectional vs directive one, conventional antenna vs new compact designs…

- Coupling among elements

Monopole array (omnidireccional, conventional)

Compact antenna array (PIFA elements)

Antennas for BS MIMO

- In WLAN, routers with MIMO technology are being developed

- IEEE 802.11n standard → delivered 2010
  - Enhanced Wireless Consortium (EWC) → consortium among important companies (Apple, Intel, Cisco, Sony, …)
Example of BS antennas: monopoles

- Single-polarized monopoles
  - 4 monopoles in the tx
  - Omnidirectional radiation pattern
  - Frequency: 2.45 GHz
  - $\lambda/4$ antennas
  - Spacing between elements: variable from 0.1 $\lambda$ to $\lambda$

Example of BS antennas: dipoles

- Cross-polarized dipoles
  - 2 dual-polarized antennas
  - Simulated with CST
  - Antenna elements with a slant of 45°
  - Structure with a balum and $\lambda/2$ dipoles
  - Spacing between elements of $\lambda/2$
  - It provides:
    » Polarization diversity
    » Spatial diversity
Antennas for MS MIMO

- External antennas vs internal antennas
  - EXTERNAL:
    » There are different solutions such as monopole, helix or meander lines
      • Monopoles → provides a great bandwidth and an omnidirectional radiation pattern. They present a big size and are mechanically fragile.
      • Helix → has a smaller size and is stronger than the monopole. It also can be used in multiband with combined elements by employing different antennas, multimode or modified multimode antennas.

- INTERNAL:
  » Suitable for small compact designs
  » Very popular solution
  » High efficiency
  » Easy to produce
    • Planar antennas: microstrip, printed
Antennas for MS MIMO

• Internal antennas:
  – Planar Inverted-F Antennas (PIFAs)

\[ L_p \]

\[ \lambda/4 \text{ monopole} \]

Inverted-L Antenna

Inverted-F Antenna

Planar Inverted-F Antenna

Inductive chip

Capacity chip

Short point

Feed point

Circuit board of the mobile terminal
Dual-band PIFA

- Antenna dimensions
  - U-shaped slot introduced to obtain 2 resonant frequencies
    - WLAN 2.4 GHz (2400 – 2483.5 MHz)
    - WLAN 5.2 GHz (5150 – 5725 MHz)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
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<tr>
<td>Xa</td>
<td>6</td>
</tr>
<tr>
<td>Ya</td>
<td>4.5</td>
</tr>
<tr>
<td>Xc</td>
<td>1</td>
</tr>
<tr>
<td>Yc</td>
<td>6</td>
</tr>
<tr>
<td>L1</td>
<td>6</td>
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<tr>
<td>Xs</td>
<td>7</td>
</tr>
<tr>
<td>Ys</td>
<td>5</td>
</tr>
</tbody>
</table>

MIMO application: laptop

- 2 MIMO configurations have been designed with spacing between elements: λ and 2 λ at 2.45 GHz
Tri-band PIFA (I)

- Antenna dimensions
  - 2 U-shaped slots are introduced to obtain 3 resonant frequencies:
    » GSM-1800 (1710 – 1880 MHz)
    » WLAN 2.4 GHz (2400 – 2483.5 MHz)
    » WLAN 5.2 GHz (5150 – 5725 MHz)
  - Simulation of a PDA with the antenna in CST Microwave Studio,

- In order to create an array for MIMO system is necessary to take into account different array configurations → 2 antennas in Rx

Tri-band PIFA (II)

- Results with one antenna
  - Reflection coefficient
  - Radiation pattern
**Tri-band PIFA (III)**

**Configuration 1**

![Graphs and diagrams related to the Tri-band PIFA (III) configuration 1.]

**Tri-band PIFA (IV)**

**Configuration 2**

![Graphs and diagrams related to the Tri-band PIFA (IV) configuration 2.]

**ANTENNA DESIGN AND MEASUREMENT TECHNIQUES - Madrid (UPM) – March 2013**


**Tri-band PIFA (V)**

- Configuration 3

- Graphs showing S parameters (S11, S21, S12, S22)

- Graphs showing E(\(\phi\), \(\theta\)) (dBi) for Antenna 1 and Antenna 2

**Tri-band PIFA (VI)**

- Calculation of MIMO capacity with a spatial channel model of 3GPP

- Cdf of capacity for \(\theta=45^\circ\)

- Graphs showing Cdf of capacity for different configurations (config1, config2, config3)
**Human influence**

- Other aspects need to be considered for mobile terminals in the human influence
- Two points of view:
  - The effect in the user (SAR: Specific Absorption Rate) → the user absorbs a certain energy due to the currents in the mobile
  - The user effect in the antenna → due to the proximity of the head near to the mobile, an effect in the frequency antenna response is produced
Reconfigurable antennas (I)

- Research about the use of reconfigurable antennas in MIMO systems
  - Reconfigurability in function of different parameters

Reconfigurable antennas (II)

- Application example: Different frequencies
  - (a) frequency 1 – 4.1 GHz
  - (b) frequency 2 – 6.4 GHz
Reconfigurable antennas (III)

• Application example: Different polarization
  – (a) polarization X
  – (b) polarization Y

Summary

• Beamforming vs spatial diversity
  – Beamforming: maximize some parameters
  – Spatial diversity: improve the quality of the received signal

• Space-Time diversity vs Spatial multiplexing
  – STBCs: Alamouti
  – HE, VE: BLAST

• MIMO systems
  – Mathematical representation → narrow and wideband
  – Channel characterization → eigenvalues decomposition
  – Capacity depends on the Channel State Information, the channel matrix and the number of antennas in tx and rx.

• MIMO antennas
  – Commercial devices are being developed
  – Monopoles, dipoles, patches, PIFAs, … for MIMO terminals