Design and Implementation of a Fast Pattern - Reconfigurable Antenna for Single RF Front - end MIMO

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Outline

- Introduction
  - Motivation
  - MIMO transmission with a single RF source

- Antenna design
  - Antenna topology
  - Variable load

- Results
  - Antenna parameters
  - MIMO transmission

- Perspectives
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Introduction: motivation

- Designing a low cost/power and compact and high performance MIMO transceiver seems contradictory using classical MIMO:
  - High antennas spatial correlation for small spacings
  - Multiple RF chains are needed \(\rightarrow\) cost and power consumption
  - Particularly problematic for mobile handsets

- Only partial solutions to the problem exist:
  - Decoupling closely spaced antennas’ ports/patterns by ‘vectorial’ antennas, compensation feed networks, etc:
    \(\rightarrow\) Leverages the spacing problem, but the need for multiple RF chains remains

- A solution enabling a compact and single-RF-chain MIMO transceiver is highly desirable
Introduction: MIMO with a single RF source

- A solution has been proposed using the antenna radiation pattern as a dimension to ‘aerially’ encode information [1,2].

- Imagine a reconfigurable antenna far-field decomposable as follows:

\[
G_T (\theta, \varphi) = \frac{1}{\sqrt{2}} [s_1 B\Sigma (\theta, \varphi) + s_2 B\Delta (\theta, \varphi)]
\]

- Weights, each indep. controllable +1/-1

- Orthogonal basis in rad. pattern domain

- This is a BPSK transmission with two (collocated) uncorrelated antennas
  \(\rightarrow\) In scattering environments the signals \(s_1\) and \(s_2\) can be decoded at the receiver using classical MIMO techniques.


Introduction: MIMO with a single RF source

A switched parasitic antenna (SPA) can implement the required functionality:

1. ‘Objective’ (cf previous slide):

\[ G_T (\vartheta, \varphi) = \frac{1}{\sqrt{2}} [s_1 B_{\Sigma} (\vartheta, \varphi) + s_2 B_{\Delta} (\vartheta, \varphi)] \]

2. It can be shown that the two sym. patterns \( G_1 \) and \( G_2 \) of the SPA can be decomposed into an orthogonal basis:

\[
B_{\Sigma} (\vartheta, \varphi) := \frac{1}{\sqrt{2}} (G_2 (\vartheta, \varphi) + G_1 (\vartheta, \varphi)) \\
B_{\Delta} (\vartheta, \varphi) := \frac{1}{\sqrt{2}} (G_2 (\vartheta, \varphi) - G_1 (\vartheta, \varphi))
\]

3. Change of variable \( s_2 \to S : s_2 = (-1)^S s_1 \)

\[
G_T (\vartheta, \varphi) = \begin{cases} 
 s_1 G_2 (\vartheta, \varphi) & \text{for } S = 0 \\
 s_1 G_1 (\vartheta, \varphi) & \text{for } S = 1
\end{cases}
\]

We are able to implement ‘1.’ by:
- Feeding the antenna port with \( s_1 \)
- Choosing the antenna pattern \( G_1 \) or \( G_2 \) according to \( S \) (fct of \( s_2 \))
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Antenna Design

- Design steps overview:
  
  **Step 1**: Selection of a suitable general antenna topology
  
  **Step 2**: Simulation of the antenna with ports at the variable loads locations
  
  **Step 3**: Determination of the optimal loads (maximize data rate)
  
  **Step 4**: Design of the reconfigurable load
  
  **Step 5**: Implementation and characterization of the reconfigurable load
  
  **Step 6**: Antenna implementation and testing
Antenna Design

**Step 1**: Selection of a suitable general antenna topology

- Based on basic considerations on:
  - operation frequency
  - radiation purity
  - Practical issues on feeding and biasing, etc

- Parasitic dipoles loads still unknown
Antenna Design

**Step 2 : Simulation of the antenna with ports at the variable loads locations:**

- Provides the system scattering matrix and embedded radiation patterns:

\[
S = \begin{bmatrix}
S_{00} & S_{01} & S_{01} \\
S_{01} & S_{11} & S_{12} \\
S_{01} & S_{12} & S_{11}
\end{bmatrix}
\]

\[
E_0(\theta, \varphi) \\
E_1(\theta, \varphi) \\
E_2(\theta, \varphi)
\]

- The real (n.b. ‘actual’) pattern as a function of the unknown parasitic loads are obtained using standard coupled radiators theory

\[
\mathcal{B}_\Sigma(\theta, \varphi) = \sqrt{2} E_0(\theta, \varphi) \mathcal{L}_0 \\
+ \frac{1}{\sqrt{2}} (\mathcal{L}_1 + \mathcal{L}_2) (E_1(\theta, \varphi) + E_2(\theta, \varphi))
\]

\[
\mathcal{B}_\Delta(\theta, \varphi) = \frac{1}{\sqrt{2}} (\mathcal{L}_1 - \mathcal{L}_2) (E_1(\theta, \varphi) - E_2(\theta, \varphi))
\]

\[
\mathcal{L}_0 = \frac{1 - \Gamma_1 S_{11} - \Gamma_2 S_{11} - \Gamma_1 \Gamma_2 S_{12}^2 + \Gamma_1 \Gamma_2 S_{11} S_{12}}{1 + \Gamma_1 \Gamma_2 S_{11}^2 - \Gamma_1 \Gamma_2 S_{12}^2 - \Gamma_1 S_{11} - \Gamma_2 S_{11}},
\]

\[
\mathcal{L}_1 = \frac{S_{01} \Gamma_1 (1 - \Gamma_2 S_{11}) + \Gamma_1 \Gamma_2 S_{01} S_{12}}{1 + \Gamma_1 \Gamma_2 S_{11}^2 - \Gamma_1 \Gamma_2 S_{12}^2 - \Gamma_1 S_{11} - \Gamma_2 S_{11}},
\]

\[
\mathcal{L}_2 = \frac{S_{01} \Gamma_1 (1 - \Gamma_1 S_{11}) + \Gamma_1 \Gamma_2 S_{01} S_{12}}{1 + \Gamma_1 \Gamma_2 S_{11}^2 - \Gamma_1 \Gamma_2 S_{12}^2 - \Gamma_1 S_{11} - \Gamma_2 S_{11}},
\]

\[
\Gamma_k = (j X_k + Z_0)^{-1} (j X_k - Z_0), \quad k \in \{1, 2\}
\]
Step 3: Determination of the optimal loads by computation of the upper bound of the average rate for variable loads values (done at AIT, details available in [1])

\[ [0 + j27 \ \Omega \text{ and } [0 - j100] \ \Omega \]

**Antenna Design**

**Step 4**: Design of the reconfigurable load implementing the target values:
- Choice of suitable layout(s)
- Equivalent circuit including parasitics
- Accurate determination of the parasitics and diode characteristics
- Derivation of the unknown elements ideal target values
- Implementation of the ideal target values with real SMD elements (incl. SMD parasitics compensation)
**Antenna Design**

**Step 5 : Characterization of the reconfigurable load**

– Load implemented as a series impedance in a host transmission line (here microstrip mimicking the dipole)

– TRL calibration for exact extraction and adequate reference planes location

– Extraction of the switchable load impedance

Target loads: [0+j27] Ohm and [0-j100] Ohm

Measured: [3+j38] Ohm and [5-j108] Ohm
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Results

- Fabricated antenna and characterization:

- Return loss:

\[ |S_{11}| \text{[dB]} \]

\[ f \text{[GHz]} \]
Results

- Simulated and measured patterns:
Results

- Note: This antenna has been used for the first experimental validation of multiplexing with a single RF front-end (done at AIT)

Scatter plot of received signal constellation after equalization:

Probability of error versus the transmit signal to noise ratio (per bit):
Perspectives

- First operational antenna optimized for single RF front-end MIMO transmission
- However this is a quite ‘idealized’ demonstration:
  - The antenna design is not compatible with handheld devices
  - The user’s influence on the patterns would in practice be significant
- Other issues:
  - Variable loads require off-chip control element (space, cost, biasing)
  - Use of semiconductor diode:
    - Power consumption
    - Radiation efficiency
    - Non-linearities
  - Conventional MEMS not suitable for bit-rate switching (MEMS switch in the order of 1-50μs)

- Important issues remain at the EM design level from the modeling, design, and technological point of views.
Thank you – Any question ?