An Emerging Technology: Load-Modulated Antenna Arrays for Small & Large Scale MIMO Systems

Dr. Constantinos B. Papadias
Dean
Athens Information Technology (AIT)
Head
AIT’s Broadband Wireless & Sensor Networks Research Group (B-WiSE)
papadias@ait.edu.gr

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Outline

Motivation: the role of antennas in 5G networks

- Compact MIMO for small access points / handsets
- Massive arrays for large base stations and wireless backhauling
- Distributed arrays & other applications: relays, satellite, sensing, etc.

MIMO systems

- Early prototypes
- Commercial adoption & main challenges for next-G wireless networks

Parasitic Antenna Arrays

- Historical perspective / Basic theory / Adaptive beamforming & diversity
- Spatial multiplexing: theory & over-the-air validation
- Other applications

A new perspective for load-modulated arrays

- A new signal model that encompasses a variety of arrays
- A new design methodology
Starting point: the growth of wireless data traffic

![Graph showing the growth of wireless data traffic from 2010 to 2020.](image)

Source: Goldman Sachs Research estimates.

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Key approaches to satisfy the projected wireless data needs

- Cell densification
- More antennas
- More aggressive spectrum sharing
- More coordination / cloud radio
Multiple antennas: key trends for use in future wireless nets

- Massive MIMO
- Remote radio heads
- Network MIMO
- Compact MIMO
Original Experimental Indoor MIMO ("BLAST") Setup
RF circuitry.
15 years later: MIMO in 3G & LTE

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MIMO arrays at the terminal: challenges

• Designing low cost, high performance compact multi-antenna transceivers seems challenging within the conventional MIMO paradigm

Problems:

i. High cost due to expensive RF components

ii. High spatial correlation for spacing less than $\lambda/2$

iii. Reduced antenna efficiency due to strong mutual coupling

iv. Interference among the parallel RF chains

v. High consumption of DC power as multiple IF/RF front-ends are used

A New (?) Multi-Antenna Paradigm: Parasitic Antenna Arrays
The Ladder Antenna

**Yagi-Uda Antenna : Single Step Design**

- Passive Reflector
- Driven Dipole
- Passive Directors

Used for fixed beamforming

Excitation can be an incident plane wave as in TV Rx or a voltage source.

Harrington's Reactively Controlled Array

A Single Active Dipole Surrounded by Six Parasitic Dipoles Loaded with Reactances.

Switched Parasitic Arrays (SPA)

After 1978


**Electronically steerable passive array radiators (ESPAR)**

**ESPAR** is a modified version of the Harrington Array in the sense that monopoles rather than dipoles are used, and the variable reactive loads are integrated in the ground plane.

Analog Adaptive Beamforming via ESPAR

Beam-shaping using stochastic algorithms

Cost function:

\[ r(X) = 1 - \rho, \quad \rho = \frac{p_{\text{des}}^H \cdot p_{\text{rad}}}{\|p_{\text{des}}^H\|_F \|p_{\text{rad}}\|_F} \]

\( p_{\text{des}}, p_{\text{rad}} \): Angular samples of the patterns


Key point: the radiation pattern mechanism is the same regardless of the current generation mechanism.

By approximating the H-Plane to omnidirectional, the radiated field is the linear combination of the currents induced on the dipoles/monopoles:

\[ G(\varphi) = \sum_{i} I_i e^{-jkd \cos \varphi} \]
Planar ESPAR for Diversity

A 3-element planar ESPAR was mainly introduced for Pattern Diversity

Inter-element spacing of $\lambda/4$ and $\lambda/20$ was used

The configuration is quite attractive for mobile terminals, for mitigating the fading effect


Coordinated T/R Beamforming: A Simple MIMO Approach

But could we use parasitic arrays for spatial multiplexing?

Conventional MIMO Transmission

Future MIMO Transmission
A Beam Space Approach
BS-MIMO formulation for conventional arrays

\[ G(\theta) = g_{isol}(\theta) \left[ 1 - e^{-jkd\cos(\theta)} \right] \begin{bmatrix} Z_{L1} & 0 \\ 0 & Z_{L2} \end{bmatrix}^{-1} + \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{12} & Z_{11} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \]

\[ = g_{isol}(\theta) \left[ 1 - e^{-jkd\cos(\theta)} \right] \frac{1}{D} \begin{bmatrix} Z_{L1}+Z_{11} & Z_{12} \\ Z_{12} & Z_{L2}+Z_{11} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \]

\[ = g_{isol}(\theta) \left[ 1 - e^{-jkd\cos(\theta)} \right] \begin{bmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \]

\[ = \underbrace{g_{isol}(\theta) \left[ M_{11} + M_{12} e^{-jkd\cos(\theta)} \right]}_{G_1(\theta)} s_1 + \underbrace{g_{isol}(\theta) \left[ M_{12} + M_{22} e^{-jkd\cos(\theta)} \right]}_{G_2(\theta)} s_2 \]
Conventional arrays: continued

\[ G(\theta) = G_1(\theta) \ s_1 + G_2(\theta) \ s_2 \]

\[ R_s := \frac{s_1}{s_2} = e^{j \frac{2\pi}{M} m}, \ m = \{0, 1, \ldots, M - 1\}. \]

<table>
<thead>
<tr>
<th>(s_1, s_2)</th>
<th>s_1</th>
<th>R_s</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 1)</td>
<td>1</td>
<td>1</td>
<td>G_1 + G_2</td>
</tr>
<tr>
<td>(1, -1)</td>
<td>1</td>
<td>-1</td>
<td>G_1 - G_2</td>
</tr>
<tr>
<td>(1, j)</td>
<td>1</td>
<td>j</td>
<td>G_1 + jG_2</td>
</tr>
<tr>
<td>(1, -j)</td>
<td>1</td>
<td>-j</td>
<td>G_1 - jG_2</td>
</tr>
</tbody>
</table>

\[ d = \lambda/16 \]

\[ R_s = e^{j \frac{\pi}{4}} \]

\[ R_s = j \]
The next step

- In classical MIMO systems we map symbols on orthonormal functions in the **antenna domain** (on antenna elements).

- This is equivalent to mapping symbols on the **wave vector (radiation field) domain**.

- We call this is a **Beam space** model for MIMO transmission.

- The next step is to use the Beam space model for parasitic arrays, in order to transmit **different symbol pairs simultaneously towards different AoD at the transmitter**, hence achieving spatial multiplexing with a single active element.
BS-MIMO using Parasitic Arrays
The beam-space approach

- We can map symbols directly on any orthogonal basis patterns as:

\[ G = \sum_i s_i B_i \]

- We can choose the bases to our convenience.
Circuit Relations of a 3-element ESPAR

\[ \mathbf{i} = \frac{\mathbf{v}_s}{2Z_s} \mathbf{w} \]

\[ \mathbf{w} := [\mathbf{Z} + \mathbf{X}]^{-1} \mathbf{u}_0 \]

\[ \mathbf{Z} = \begin{pmatrix} Z_{00} & Z_{01} & Z_{01} \\ Z_{01} & Z_{11} & Z_{12} \\ Z_{01} & Z_{12} & Z_{22} \end{pmatrix} \]

\[ \mathbf{X} := \text{diag} ([Z_0 \ jX_{L1} \ jX_{L2}]) \]

\[ v_s = I_0 Z_{00} + I_1 Z_{01} + I_2 Z_{01} \]
\[ -I_1 \cdot jX_{L1} = I_0 Z_{01} + I_1 Z_{11} + I_2 Z_{12} \]
\[ -I_2 \cdot jX_{L2} = I_0 Z_{01} + I_1 Z_{12} + I_2 Z_{11} \]


Three-Element ESPAR Far-Field

\[
AF = i^T a(\theta)
\]

\[
i = \begin{bmatrix} I_0 & I_1 & I_2 \end{bmatrix}
\]

\[
a(\theta) = \begin{bmatrix} 1 & e^{-jkd \cos(\theta-\phi)} & e^{-jkd \cos(\theta-\pi)} \end{bmatrix}
\]

\[
AF = I_0 + I_1 e^{-jkd \cos(\theta-\phi)} + I_2 e^{-jkd \cos(\theta-\pi)}
\]

\[
= I_0 \left( 1 + \alpha_{10} e^{-jkd \cos(\theta-\phi)} + \alpha_{20} e^{-jkd \cos(\theta-\pi)} \right)
\]

\[
\alpha_{10} = \left( \frac{I_1}{I_0} \right) = \frac{Z_{12}Z_{01} - Z_{01}(Z_{11} + jX_{L2})}{(Z_{11} + jX_{L1})(Z_{11} + jX_{L2}) - Z_{12}^2},
\]

\[
\alpha_{20} = \left( \frac{I_2}{I_0} \right) = \frac{Z_{12}Z_{01} - Z_{01}(Z_{11} + jX_{L1})}{(Z_{11} + jX_{L1})(Z_{11} + jX_{L2}) - Z_{12}^2}.
\]

A Basis of Two Angular Functions

\[ AF_n = 1 + \alpha_{12} e^{-jkd \cos(\theta - \phi)} + \alpha_{13} e^{-jkd \cos(\theta - \pi)} \]

\[ = 1 + \left( \alpha_{12} + \alpha_{13} \right) \cos(kd \cos(\theta)) \]

\[ - j \left( \alpha_{12} - \alpha_{13} \right) \sin(kd \cos(\theta)) \]

\[ = s_1 B_1(\theta) + s_2 B_2(\theta) \]

\[ B_1(\theta) + B_2(\theta) \]

\[ \left[ X_{L1} \quad X_{L2} \right] \]

\[ B_1(\theta) - B_2(\theta) \]

\[ \left[ X_{L2} \quad X_{L1} \right] \]
All PSK Modulation Schemes

\[ AF_n \approx 1 + \frac{-j (\alpha_{12} - \alpha_{13})}{1 + \alpha_{12} + \alpha_{13}} \sin(kd \cos(\theta)) \]

\[ AF = 1 + \left( \frac{I_1}{I_0} \right) e^{-jkd \cos(\theta)} + \left( \frac{I_2}{I_0} \right) e^{jkd \cos(\theta)} \]

\[ = 1 + \left( \frac{I_2 + I_1}{I_0} \right) \cos(kd \cos(\theta)) + \left( -j \frac{I_2 - I_1}{I_0} \right) \sin(kd \cos(\theta)) \]

\[ = B_0(\theta) + \left( \frac{I_2 + I_1}{I_0} \right) B_1(\theta) + \left( -j \frac{I_2 - I_1}{I_0} \right) B_2(\theta). \]

Mutual information

Gaussian Signaling is assumed rather than PSK
Average Mutual Information for Discrete PSK Input

![Average Mutual Information Graph](image)

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Over-the-air performance
Over the air tests with AIT’s MIMO Testbed

SPA+Switch

RX

TX

Osc.
MIMO Testbed Overview

- Transmitter RF modules – 2
- Receiver RF modules – 2
- Carrier frequency – (2.5-2.7) GHz
- BB Signal bandwidth – up to 1 MHz
- 'Innovative DSP’ (TMS320C6201) CLK – 200 MHz
- GPS Synchronization feature
- RS232 Serial Interface
- 10BaseT Ethernet Interface
The Parasitic Antenna Array

- Uses only one RF front end and two or more parasitic elements
- Can form different beams in each symbol period by controlling the parasitic elements
- Compact, cheap and less power-hungry
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Antenna Design & Measurements

Photograph of the fully operational SPA, optimized for the proposed aerial MIMO approach.
Simulated and measured co- and cross-polarization components of the beampattern $S_1(\vartheta, \varphi)$ in the H-plane i.e. $S_1(\vartheta = \frac{\pi}{2}, \varphi)$, at $f = 2.6$ GHz.
Return Loss (dB) of the SPA for both loading states i.e. $S := 1$ and $S := 2$. 
First ESPAR Spatial Multiplexing Over-the-Air Proof-of-Concept Validation

A 5-element prototype for LTE
Elevation Pattern
Azimuth Pattern

Crown, f=1.905(GHz), E-total, theta=95 (deg)
3D Radiation Pattern
Anechoic chamber setup
Array setup
Measurement setup
Measured Azimuth Pattern
Comparison of Simulation and measurements
Other applications: Rx beam selection combined with OBF


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Other applications (2): tunable & steerable arrays


Other applications (3): directional sensing for cognitive radio

Other applications (4): energy efficiency in WSNs

A new approach
Starting point: the current design methodology

In the existing model, the following methodology is used for spatial multiplexing:

1. Given a certain parasitic array, determine the set of basis patterns

2. For a given constellation, determine the set of all possible radiation patterns

\[ P(\varphi) = \sum_{n=0}^{M_{\text{esp}}-1} w_n \Phi_n(\varphi) = w_e^T \Phi(\varphi) \]

3. Apply a stochastic optimization algorithm or an exhaustive search and obtain the sets of loading values that correspond to these radiation patterns
Weaknesses of the approach

• In the current approach, the computation of loads must take into account explicitly the antenna characteristics.

• The use of orthogonal beam patterns does not guarantee orthogonality at the receiver.

• It is not possible to have arbitrary channel-dependent precoding.

• Moreover, the radiating modes cannot be computed accurately for an arbitrary parasitic array.

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A new view of the signal model

Given an arbitrary antenna array...

The currents at all ports are given by

\[ i = (Z_T + Z_G)^{-1} v_T \]

Where

\[ Z_G = \text{diag}(Z_{G1}, Z_{G2}, \ldots, Z_{GN}) \]

\[ v_T = [v_{T1} \quad v_{T2} \quad \ldots \quad v_{TN}]^T \]
A new signal model for Parasitic arrays

In case of a parasitic array....

The currents at all ports are given by

\[ i = \left( Z_T + Z_G \right)^{-1} v_T \]

\[ v_T = \begin{bmatrix} v_{T1} & 0 & \ldots & 0 \end{bmatrix}^T \]
A new signal model for load-modulated arrays

The well-known baseband model can be adopted as:

\[ y = Hi + n \]

\( y: (M_R \times 1) \) Contains the open-circuit voltages of the Rx antennas

\( H: (M_R \times M_T) \) Is the channel matrix. The \((m,n)\) entry represents the complex gain between the \(m\)-th Tx current and the \(n\)-th Rx antenna element voltage

\( i_T: (M_T \times 1) \) holds the ESPAR’s currents \( i_T = (Z_T + Z_G)^{-1} v_T \)

\( n: (M_R \times 1) \) Gaussian noise vector

Benefits of the new model

- It allows to obtain the desired loads from pre-coding matrices that are computed in baseband.
- It allows arbitrary channel-dependent pre-coding (e.g. needed for closed-loop techniques).

\[ y = Hi + n \]
Arbitrary Linear Precoding

The currents at the ports of the radiating elements should be adjusted so that: \( i = V Gs \)

\[
y = H i + n
\]

\( V \): is the required precoding matrix

\( G = diag(g_1, g_2, \ldots, g_r) \): is the required power loading matrix

\( s \): is the Tx symbol vector

\( n \): is the AWGN noise vector

The loads are linked to the currents via:

\[
i = \left( Z_T + Z_G \right)^{-1} v_T
\]

\[
v_T = \begin{bmatrix} v_{T1} & 0 & \ldots & 0 \end{bmatrix}^T
\]

Then link the loading values to the triggering voltage

Example: Waterfilling Precoding with single-fed parasitic arrays

- Consider a communication pair with 2 antenna arrays each
- Procedure:
  1) The Rx estimates the channel, executes the SVD and the Waterfilling algorithm:

\[ H = U \Sigma V^H \] : SVD to estimate the Tx and Rx filters

\[ G = \text{diag}(g_1, g_2) \] : Power allocation obtained via Waterfilling

2) The Tx applies the loading values that correspond to the vector of currents that implement the desired precoding:

\[ i = V D_s, D = \sqrt{G} \]
Example: waterfilling with 1 active / 1 passive element

- The shape is adjusted to give an appropriate coupling matrix.
- Substrate
  - Active element
  - Parasitic element

Complex voltage

Tunable matching

Input

Output
Prototyping and experimentation

Early designs and prototyping

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A novel load-modulated design for large arrays

No RF Chain needed – just an oscillator

Generated 16-QAM constellation


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Load modulated designs for large arrays: A closer look

- A single carrier signal is assumed
- The antennas are far enough from each other to avoid mutual coupling
- To protect the power amplifier, the circulator grounds any reflected power through the resistor.
- Cheap and less power-hungry
Input impedance distribution

- The input impedance is a function of the analog loads
- Large number of elements:
  - The variance of the input impedance reduces as the number of elements increases
  - The mean value of the voltage standing wave ratio (VSWR) reduces to one: Perfect matching (VSWR<2 indicates adequate matching anyway)
Single RF Load Massive Arrays (3/3)

- Peak-to-average power ratio (PAPR) converges to one as the number of elements increases.
- Highly efficient power amplifiers can be used (e.g. class F with 70% - 80% efficiency).
- Angry bird: current at the ports of the radiating elements: Almost any complex constellation is achievable by tuning the loads.
MIMO transmission architectures: an overall view

Conventional MIMO

Close MIMO

ESPAR MIMO

New Load-Modulated MIMO

Some recent experiments
Prototype array for channel measurements

- Simulation Tool: IE3D
  - It uses the Method of Moments (MoM) or Boundary Element Method (BEM).

- Main parameters for simulation:
  - Element Length: \(~\lambda_0 / 2~\)
  - Inter-element spacing: \(~\lambda_0 / 12~\)

- Fabrication Imposed Parameters
  - Dielectric: FR4 (\(er = 4.45, \tan\delta = 0.017\))
  - Substrate thickness: 1.6 mm
  - Copper trace thickness 35 \(\mu\)m
IE3D vs. Matlab: Comparison of radiation patterns for indicative loading values

X1 = [50; j10; -j20; j25; -j5]

X2 = [50; j20; j20; j20; j20]

X3 = [50; -j100; j9; j100; j15]

X4 = [50; j5; j8; -j100; -j100]
Indicative Reflection Coefficient curves vs. frequency

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Measurement setup

ESPAR top view

Omni antennas

MIMO Testbed Tx

H: \((2 \times 5)\)

MIMO Testbed Rx

A parasitic design with 5 SMA connectors

Goal: to estimate the channel matrix
Training

- The signal is composed of 2048 samples with a baseband sampling frequency of 500 kHz.
- The number of transmitted symbols is 128 and consists of 100 zeros and 28 BPSK symbols.
- Raised cosine pulse shaping was used, with 16 samples per symbol.

Frame Size: 128 symbols

| 0 0 0 ... 0 | 1 -1 ... 1 |

100 zero symbols   28 BPSK symbols
Measurement setup

The two Rx were moved around the room in random positions. Not every realization involved LoS and they were always around the same height level with the Tx.

The Tx was moved only in the azimuthal plane and was kept at the same height level throughout all the realizations of the experiment.
Channel estimation

- 76 different configurations were measured (380 measurements in total, 5 for each configuration) and for each one of them a channel matrix $H$ was calculated.

- Least squares estimate:

$$H = YX^T(X^TX)^{-1}$$

$X$: (1x28) BPSK training symbols
$Y$: (1x28) Received symbols

The spatial scenario involved scatterers (whiteboard, chairs, meeting table, drawers) and in most occasions there was no LoS component.
Received signal

- Received signal in RX1 (top) and constellation diagrams before and after the channel estimation (bottom), for one out of the 380 measurements in total.
Spatial modes

Empirical CDFs of the Eigenvalues of $H^*(H^H)$

- CDF
- Value for Eigenvalues

Spatial modes

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Closed loop capacity

- CDF of the closed-loop capacity for different SNRs
- Reasonable results
Summary

- **Multi-antenna technology** is poised to remain an important technology component of 5G wireless networks & beyond

- In particular:
  - **Compact arrays** will play an important role in mobile handsets, remote radio heads, sensors, relays etc.
  - **Massive arrays** will be important in allowing a better handling of interference without the need for base station cooperation, both on the access and backhaul side of the network

- Load modulated arrays can be seen as a MIMO array super-architecture that encompasses a large variety of designs that may be suitable in each case
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Thank you!
For a closer look..