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

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2014 Smart Antennas Workshop

Stanford, CA, USA, August 1, 2014

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

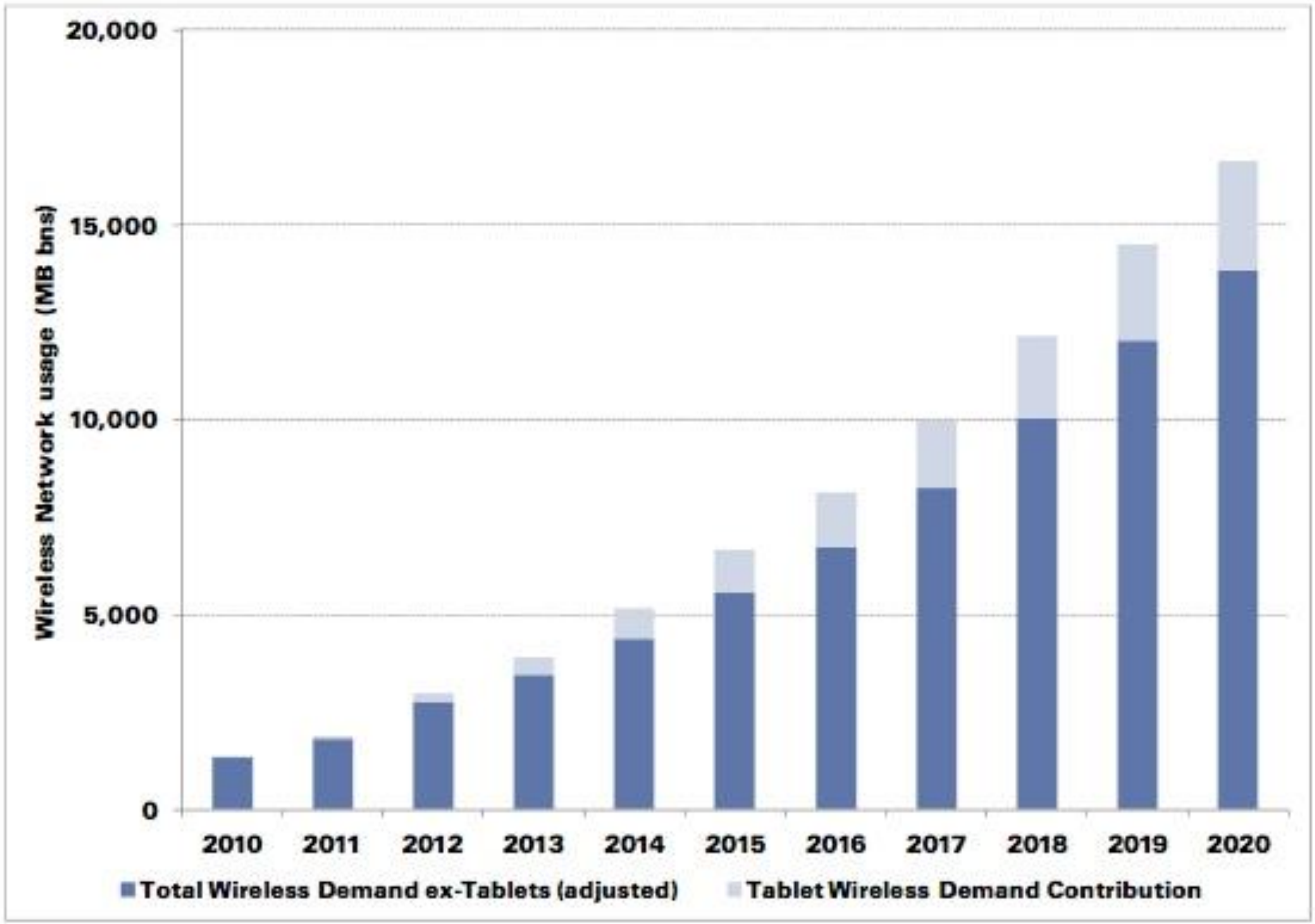
Parasitic Antenna Arrays

- 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

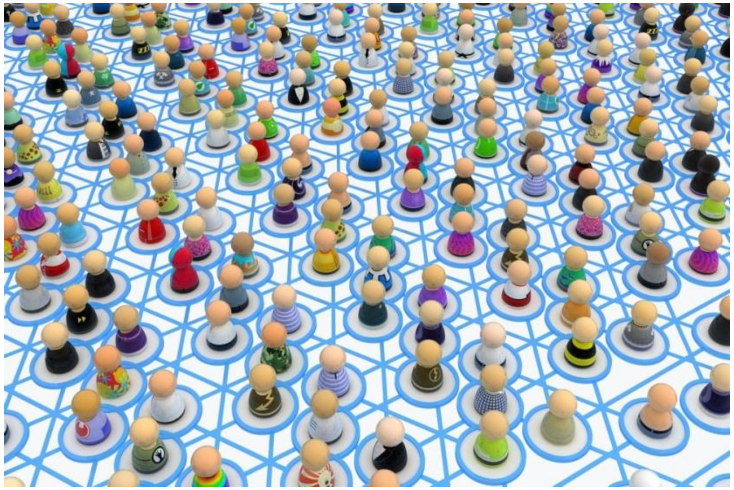
Starting point: the growth of wireless data traffic



Source: Goldman Sachs Research estimates.

Key approaches to satisfy the projected wireless data needs

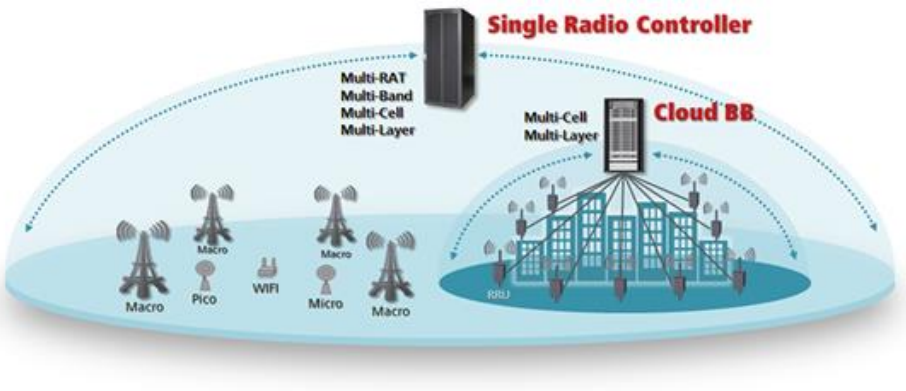
- Cell densification



- More antennas

- More aggressive spectrum sharing

- More coordination / cloud radio

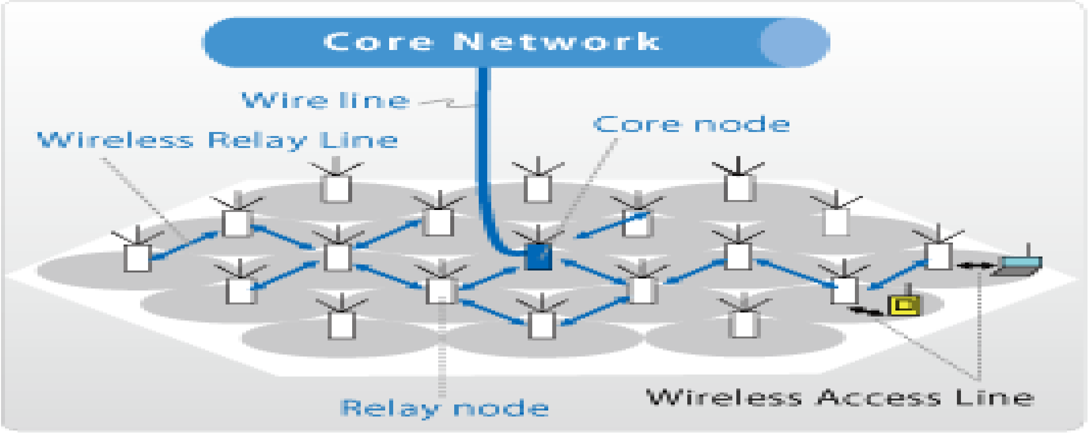


Multiple antennas: key trends for use in future wireless nets

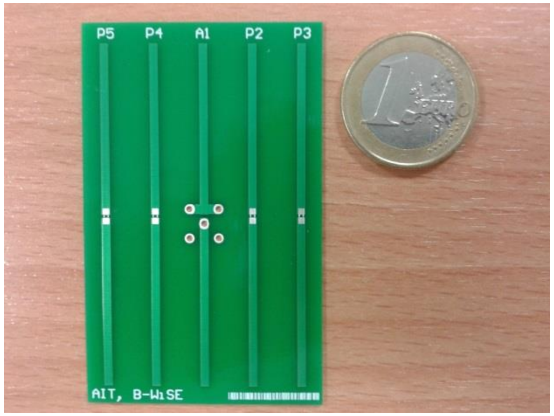
- Massive MIMO

- Remote radio heads

- Network MIMO

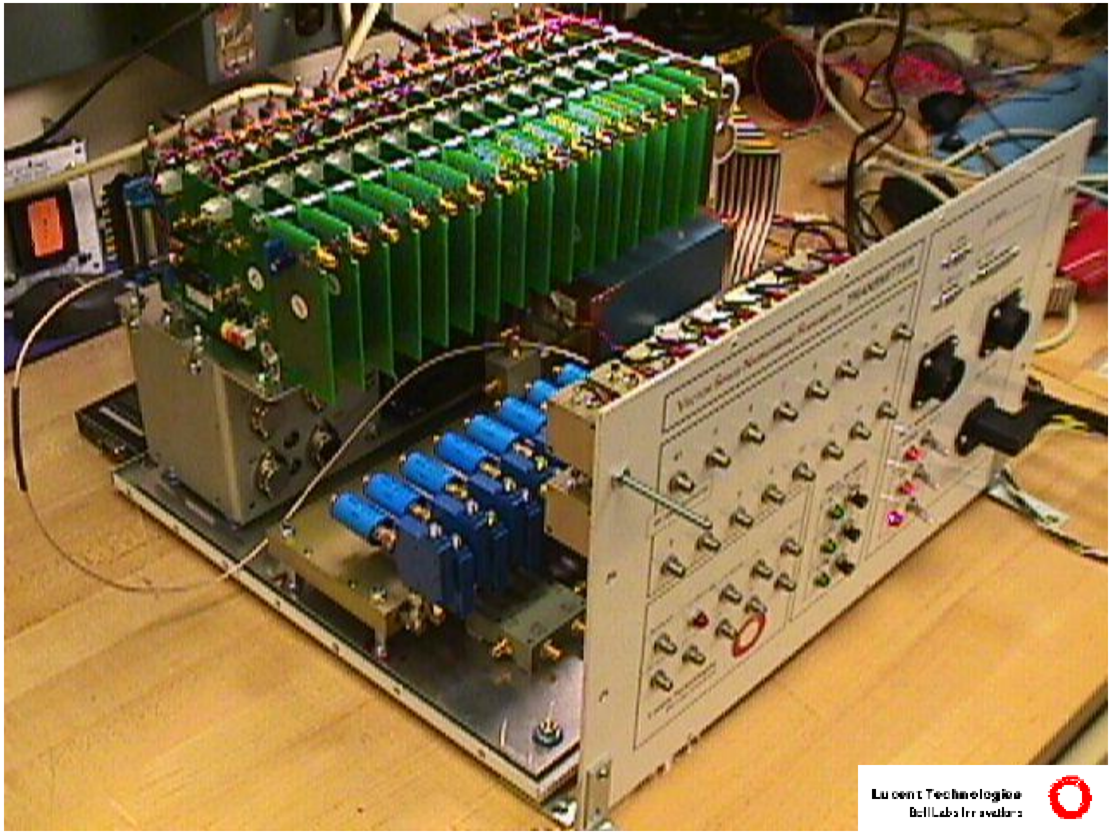


- Compact MIMO

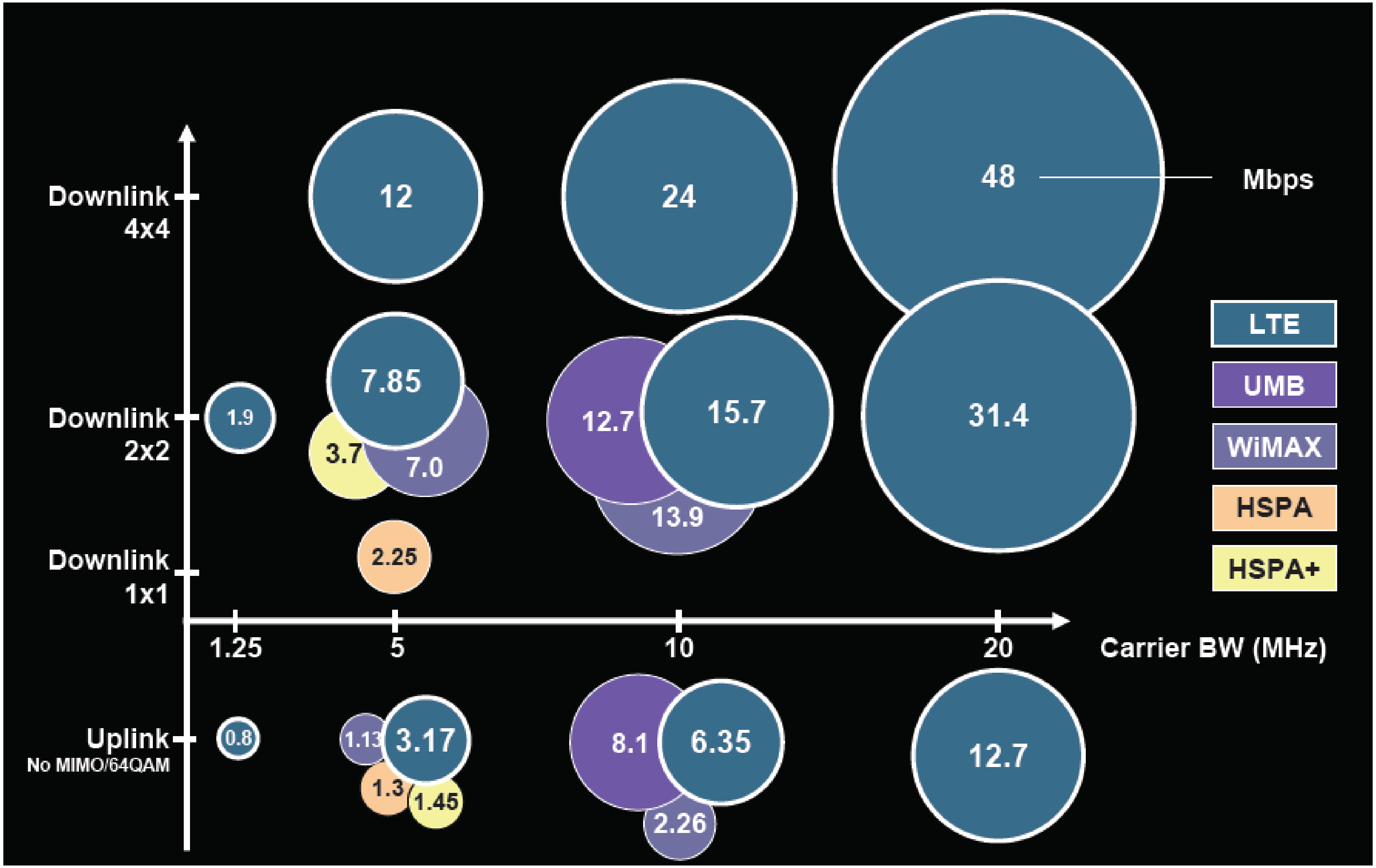


Original Experimental Indoor MIMO (“BLAST”) Setup

RF circuitry..



15 years later: MIMO in 3G & LTE



MIMO arrays at the terminal: challenges

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

Problems:

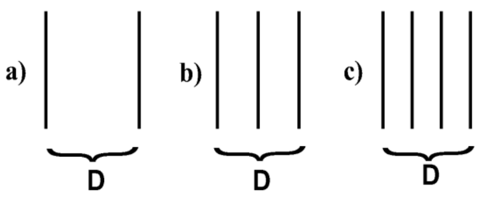
i. **High cost due to expensive RF components**

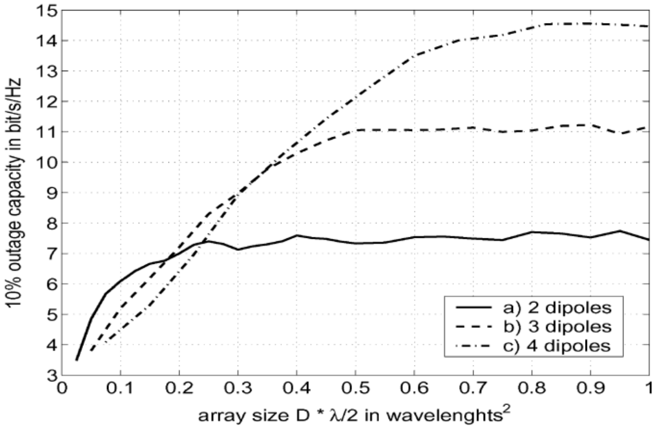
ii. **High spatial correlation for spacing less than λ/2**

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**



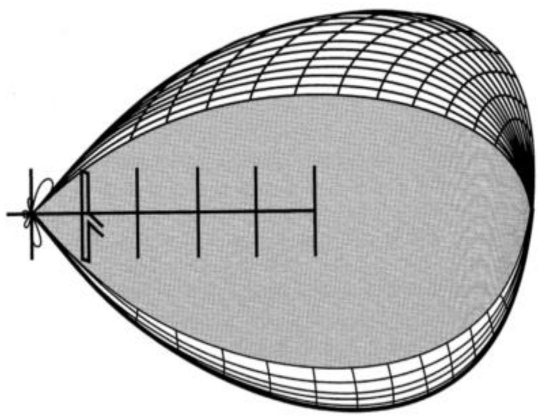


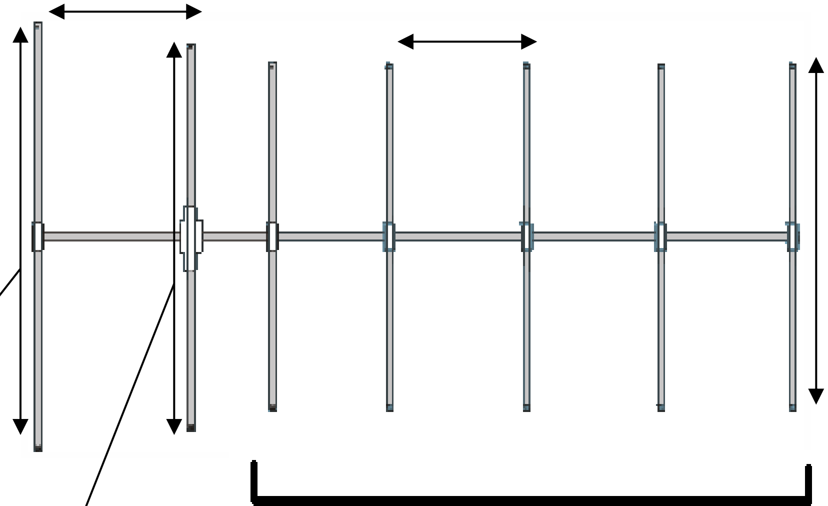
C. Waldschmidt,, S. Schulteis, and W. Wiesbeck, "Complete RF System Model for Analysis of Compact MIMO Arrays", IEEE Trans. Vehicular Technology, vol. 53, No. 3, May 2004.

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

The Ladder Antenna

Yagi-Uda Antenna : Single Step Design





Used for fixed beamforming

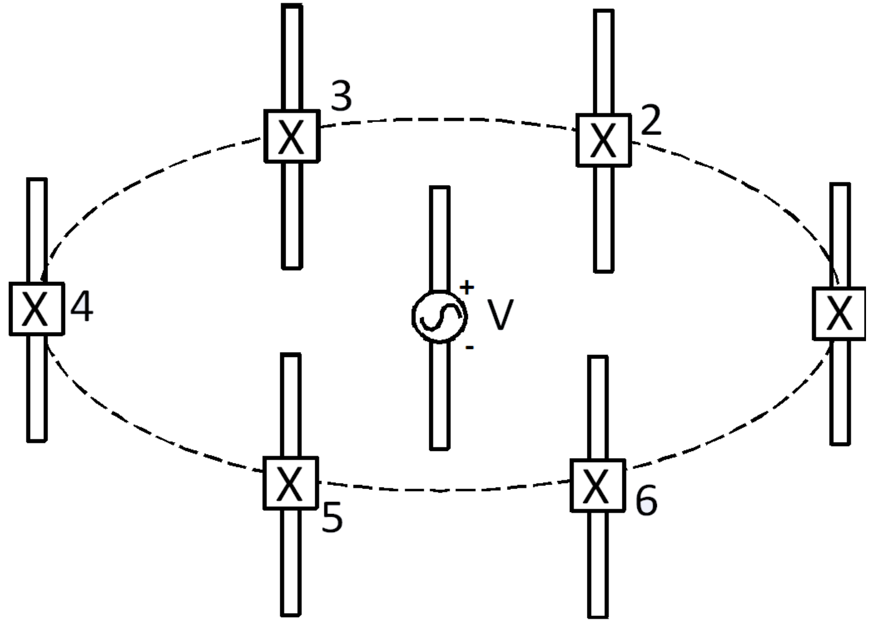
Excitation can be an incident plane wave as in TV Rx or a voltage source.

S. Uda "On the Wireless Beam of Short Electric Waves", Journal of the institute of Electrical Engineers of Japan", March 1926-July 1929.

Harrington Array

Harrington's Reactively Controlled Array

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

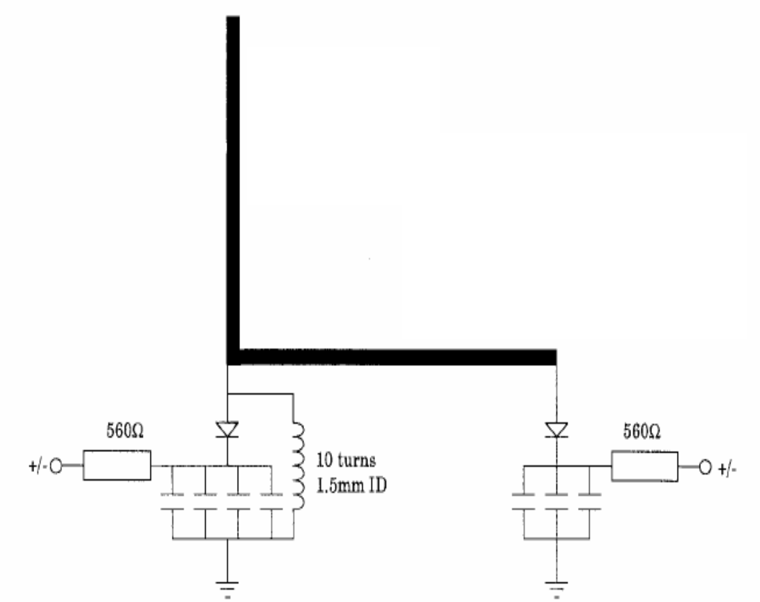


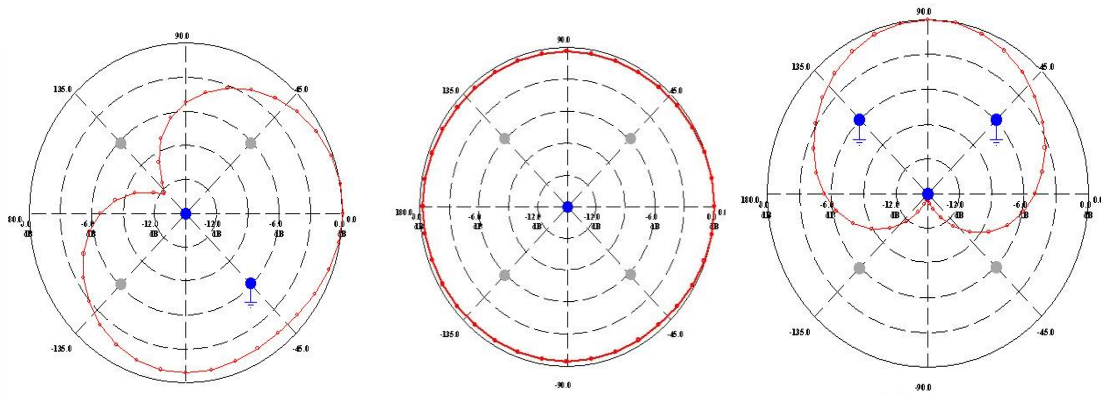
Harrington, R. Reactively controlled directive arrays. IEEE Trans Antennas Propag 1978; 26(3): 390-395.

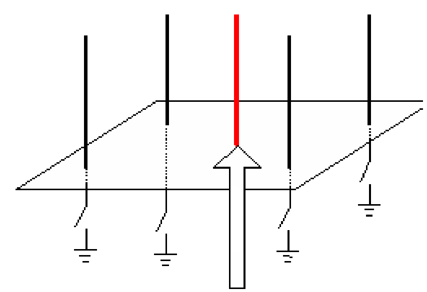
Switched Parasitic Arrays (SPA)

After 1978

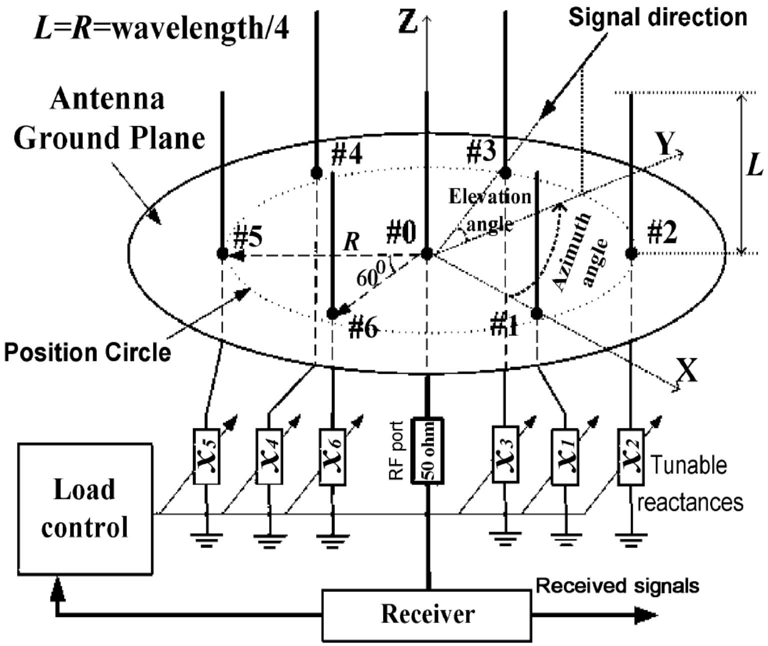
Dinger, R. Reactively steered adaptive array using microstrip patch elements at 4 GHz. IEEE Trans Antennas Propag 1984; 32(8): 848-856.
Dinger, R. A planar version of a 4.0 GHz reactively steered adaptive array. IEEE Trans Antennas Propag 1986; 34(3): 427-431.
Preston, S. L., Thiel, D. V., Smith, T. A., O'Keefe, S. G., Lu, J. W. Base-station tracking in mobile communications using a switched parasitic antenna array. IEEE Trans Antennas Propag 1998; 46(6): 841-844.
Vaughan, R. Switched parasitic elements for antenna diversity. IEEE Trans Antennas Propag 1999; 47(2): 399-405.

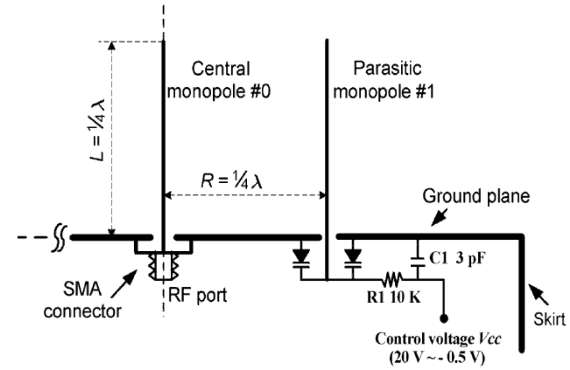


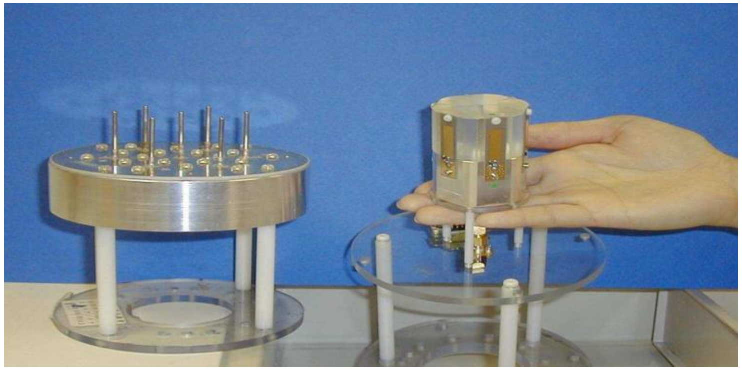




Electronically steerable passive array radiators (ESPAR)



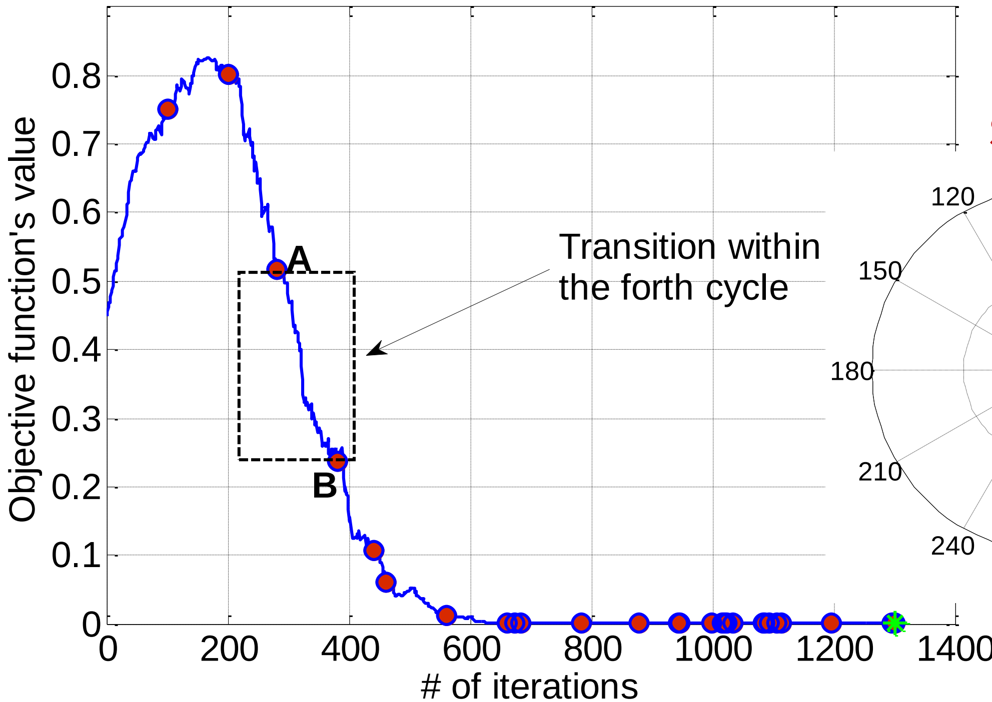




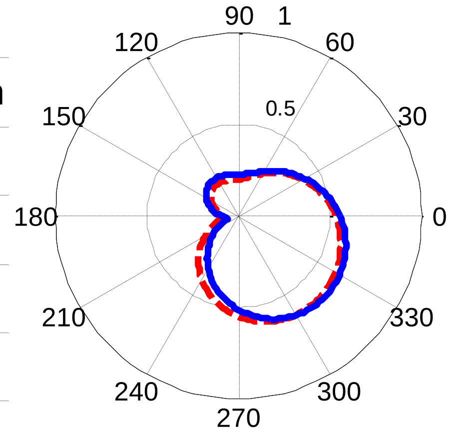
ESPAR is a modified version of the Harrington Array in the sense that monopoles rather than dipoles are used, and the variable reactive loads are integrated in the ground plane.

Gyoda, K., Ohira, T. Design of electronically steerable pasive array radiator (ESPAR) antennas. *Proc.* IEEE Antennas Propag Soc Int Symp, 2000, 922-955.

Analog Adaptive Beamforming via ESPAR



Beam-shaping using stochastic algorithms



Cost function:

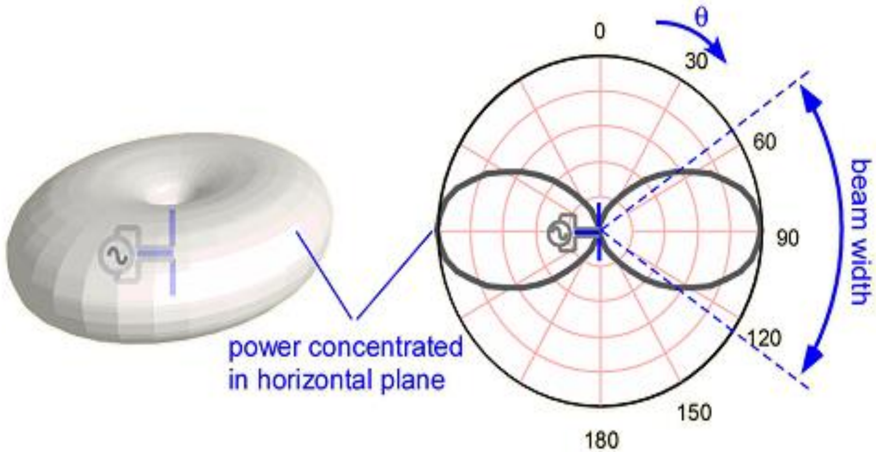
$$r(\mathbf{X}) = 1 - \rho, \quad \rho = \frac{\left|\mathbf{p}_{des}^{H}\mathbf{p}_{rad}\right|}{\left\|\mathbf{p}_{des}^{H}\right\|_F \left\|\mathbf{p}_{rad}\right\|_F}$$

$\mathbf{p}_{des}, \mathbf{p}_{rad}$: Angular samples of the patterns

S. Chen, A. Hirata, T.Ohira and N.C. Karmakar, "Fast beamforming of electronically steerable parasitic array radiator antennas: theory and experiment," IEEE Trans. on Antennas and Propagation, vol.52, no.7, pp.1819,1832, July 2004.

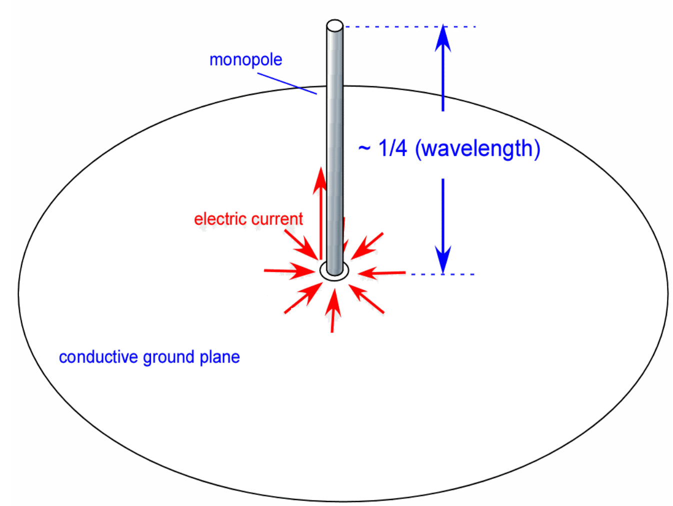
V. Barousis, A.G. Kanatas, A. Kalis, and C. Papadias, "A Stochastic Beamforming Algorithm for ESPAR Antennas," IEEE Antennas and Wireless Prop. Letters, vol.7, pp.745-748, 2008.

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



3D Pattern

E-Plane



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

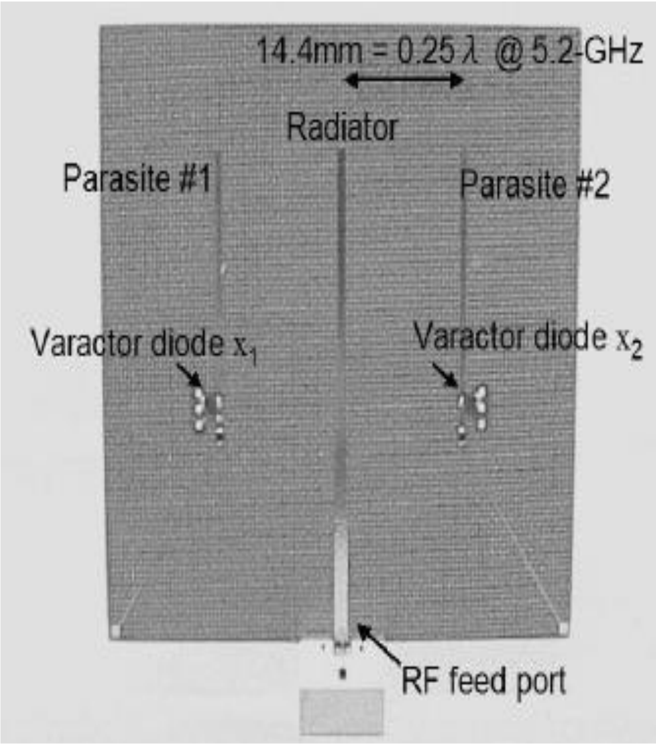
$$G(\varphi) = \sum_i I_i e^{-jkd\cos\varphi}$$

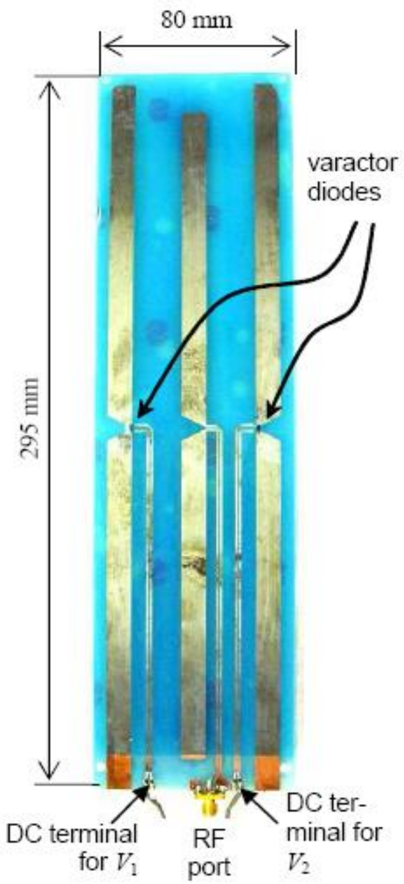
Planar ESPAR for Diversity

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

Inter-element spacing of λ/4 and λ/20 was used

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

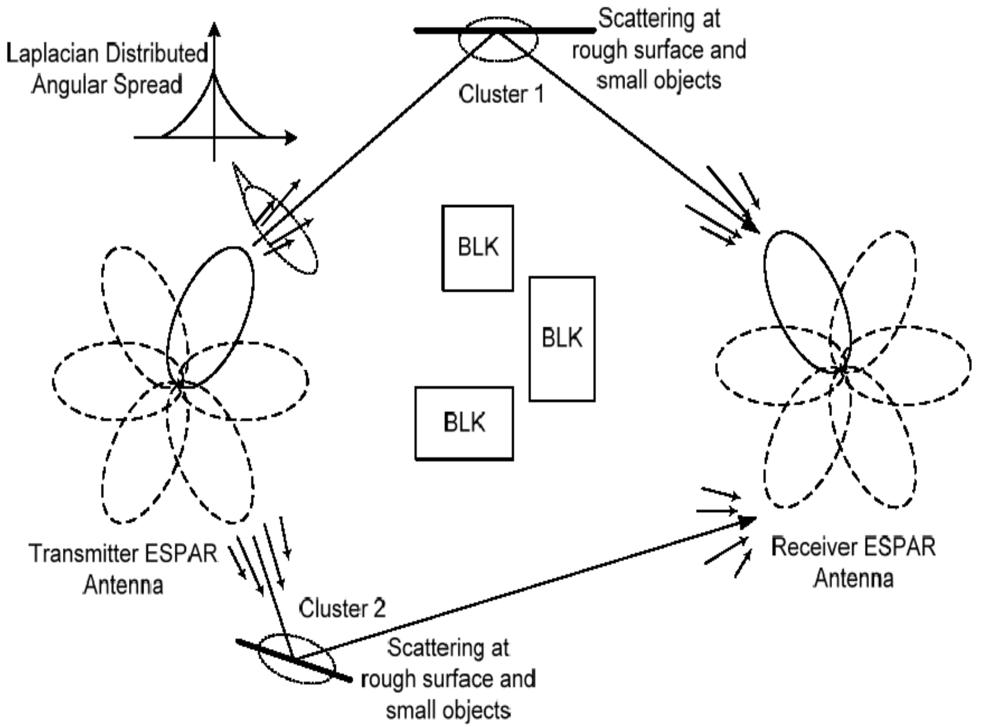


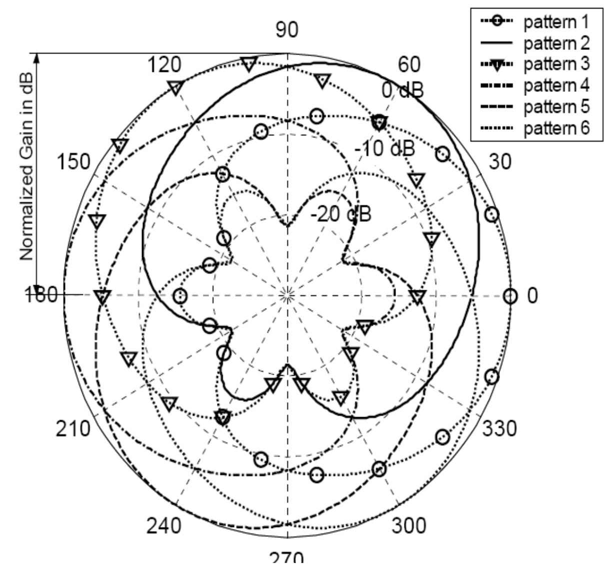


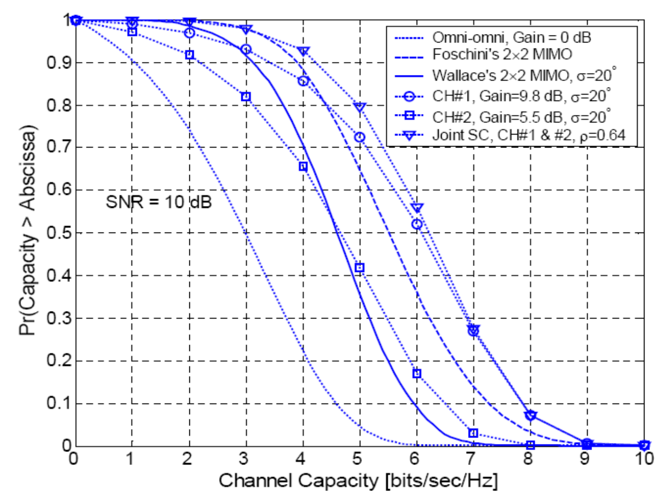
T. Sawaya, K. Iigusa, M. Taromaru, and T. Ohira, "Reactance Diversity: Proof-of-Concept Experiments in an Indoor Multipath-Fading Environment with a 5-GHz Prototype Planar Espar Antenna", Consumer Communications and Networking Conference, 5-8 Jan. 2004, pp. 678 – 680.

M. Taromaru and T. Ohira, "Electronically Steerable Parasitic Array Radiator Antenna – Principle, Control Theory and its Applications –", 28th General Assembly of International Union of Radio Science (URSI GA 2005).

Coordinated T/R Beamforming: A Simple MIMO Approach



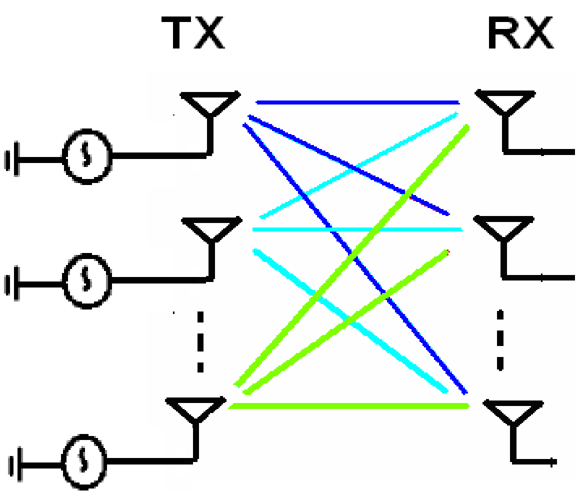




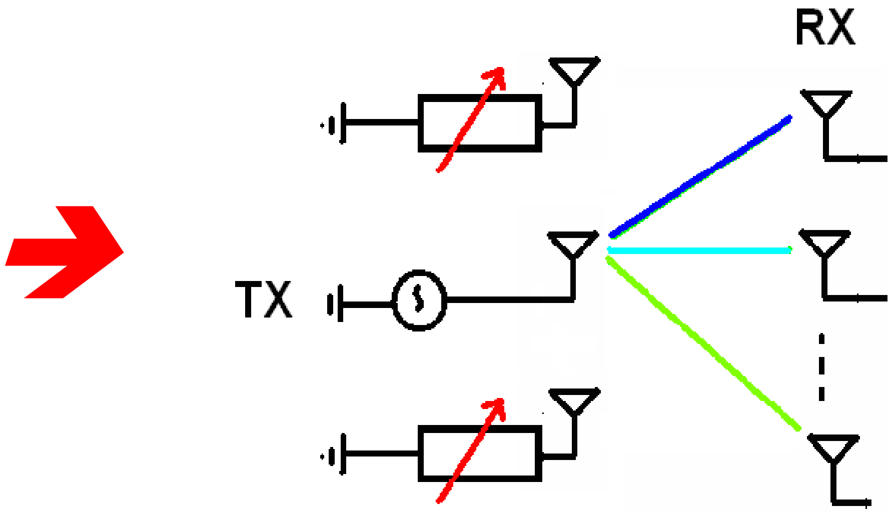
Chen Sun; Hunziker, T.; Taromaru, M. "Wireless Communication Systems", 2005. 2nd International Symposium on 7-7 Sept. 2005 Page(s):581 - 585

But could we use parasitic arrays for spatial multiplexing?

Conventional MIMO Transmission



Future MIMO Transmission



A Beam Space Approach

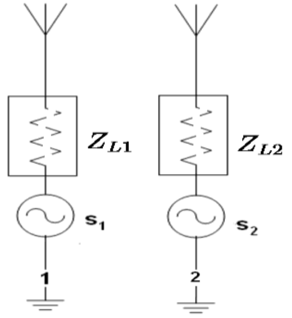
BS-MIMO formulation for conventional arrays

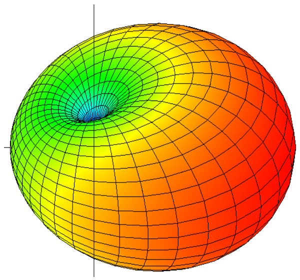
$$G(\theta) = g_{isol}(\theta)\begin{bmatrix}1 & e^{-jkd\cos(\theta)}\end{bmatrix}\left[\begin{bmatrix}Z_{L1} & 0\\ 0 & Z_{L2}\end{bmatrix} + \begin{bmatrix}Z_{11} & Z_{12}\\ Z_{12} & Z_{11}\end{bmatrix}\right]^{-1}\begin{bmatrix}s_1\\ s_2\end{bmatrix}$$

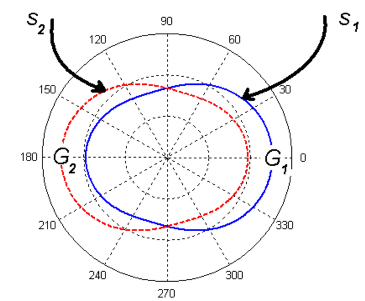
$$= g_{isol}(\theta)\begin{bmatrix}1 & e^{-jkd\cos(\theta)}\end{bmatrix}\frac{1}{D}\begin{bmatrix}Z_{L1}+Z_{11} & Z_{12}\\ Z_{12} & Z_{L2}+Z_{11}\end{bmatrix}\begin{bmatrix}s_1\\ s_2\end{bmatrix}$$

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

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





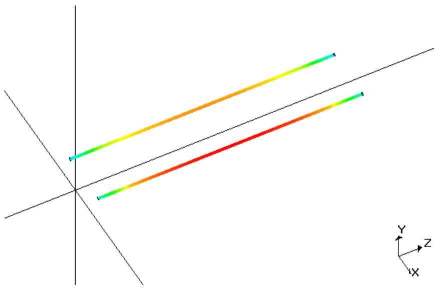


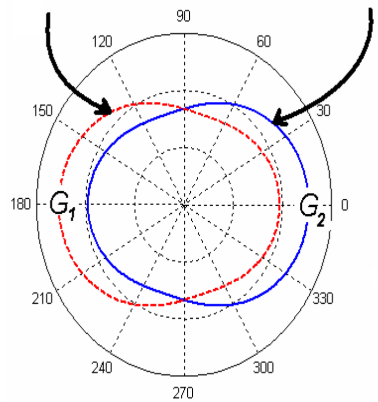
Basis Functions of a 2-Element λ/10 ULA

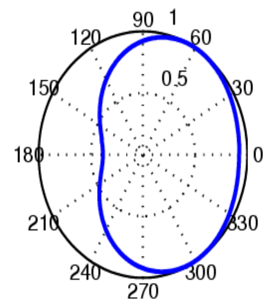
Conventional arrays: continued

$$G(\theta) = G_1(\theta)\, s_1 + G_2(\theta)\, s_2$$

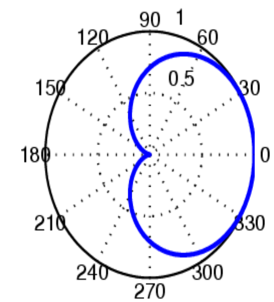
$d = \lambda/16$







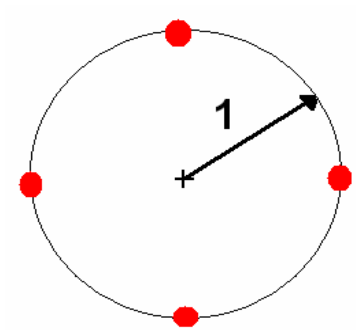
$\Re_s = e^{j\frac{\pi}{4}}$



$\Re_s = j$

$$\Re_s := \frac{s_1}{s_2} = e^{j\frac{2\pi}{M}m} \quad , m = \{0, 1, \ldots, M-1\}.$$

(s_1, s_2)	s_1	$\Re_s$	G
$(1, 1)$	1	1	$G_1 + G_2$
$(1, -1)$	1	-1	$G_1 - G_2$
$(1, j)$	1	j	$G_1 + jG_2$
$(1, -j)$	1	$-j$	$G_1 - jG_2$



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 Beamspace model for MIMO transmission
- The next step is to use the Beampsace 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

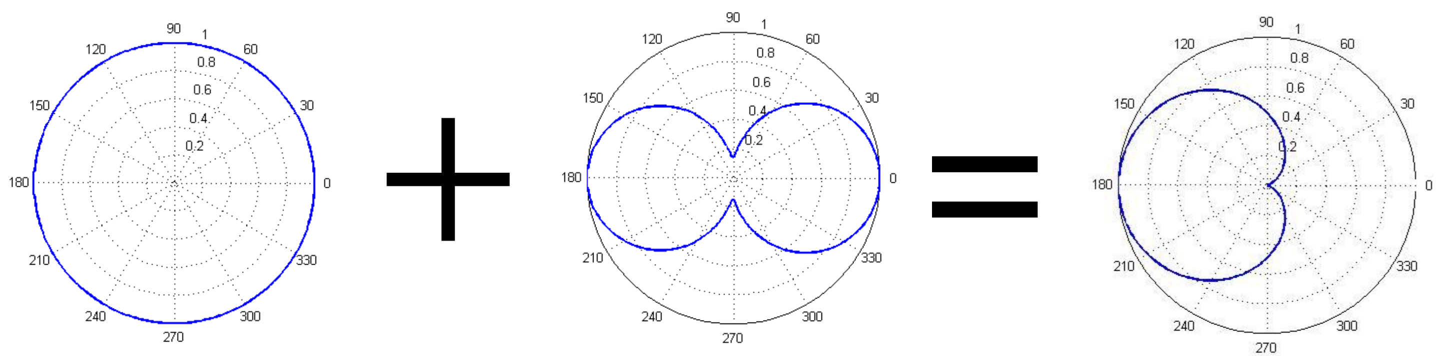
BS-MIMO using Parasitic Arrays

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.



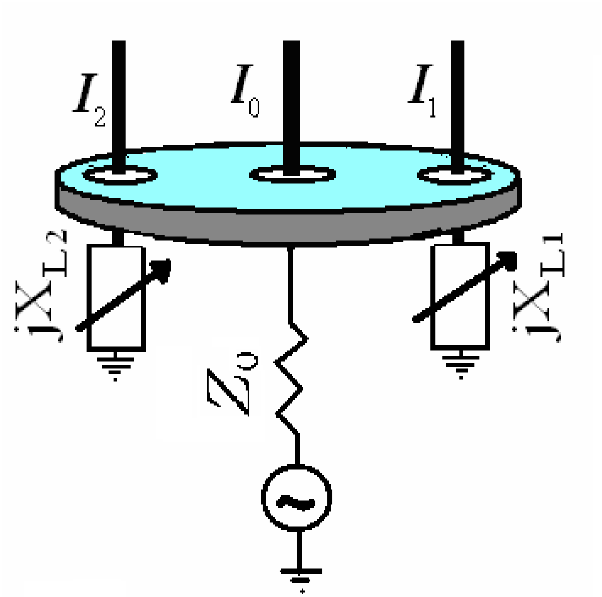
Circuit Relations of a 3-element ESPAR

$$\mathbf{i} = \frac{v_s}{2Z_s}\mathbf{w}$$

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

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

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



$$v_s = I_0 Z_{00} + I_1 Z_{01} + I_2 Z_{01}$$

$$-I_1 \cdot jX_{L1} = I_0 Z_{01} + I_1 Z_{11} + I_2 Z_{12}$$

$$-I_2 \cdot jX_{L2} = I_0 Z_{01} + I_1 Z_{12} + I_2 Z_{11}$$

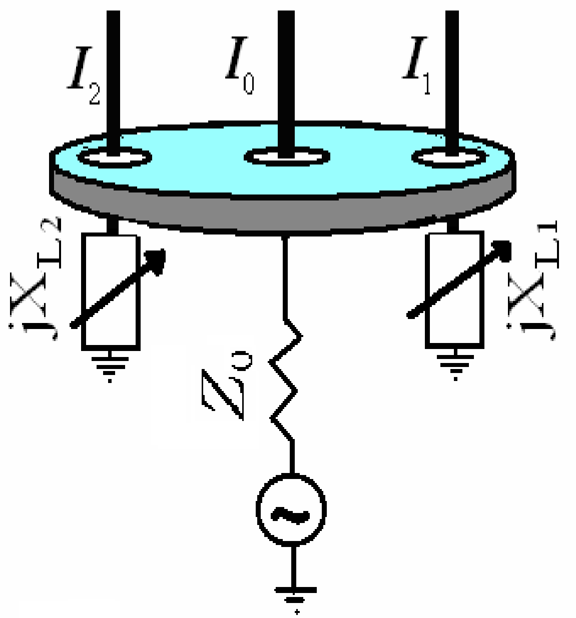
O. N. Alrabadi, A. Kalis, C. Papadias and A. Kanatas, ``Spatial Multiplexing by decomposing the far-field of a compact ESPAR antenna," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 15-18 Sept 2008.

Three-Element ESPAR Far-Field

$$AF = \mathbf{i}^T a(\theta)$$

$$\mathbf{i} = \begin{bmatrix} I_0 & I_1 & I_2 \end{bmatrix}$$

$$a(\theta) = \begin{bmatrix} 1 & e^{-jkd\cos(\theta-0)} & e^{-jkd\cos(\theta-\pi)} \end{bmatrix}$$



$$AF = I_0 + I_1 e^{-jkd\cos(\theta-0)} + I_2 e^{-jkd\cos(\theta-\pi)}$$

$$= I_0 \left(1 + \alpha_{10} e^{-jkd\cos(\theta-0)} + \alpha_{20} e^{-jkd\cos(\theta-\pi)}\right)$$

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

$$\alpha_{10} = \left(\frac{I_2}{I_0}\right) = \frac{Z_{12}Z_{01} - Z_{01}(Z_{11} + jX_{L1})}{(Z_{11} + jX_{L1})(Z_{11} + jX_{L2}) - Z_{12}^2}.$$

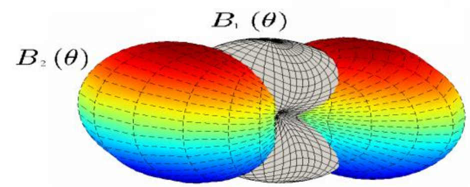
O. N. Alrabadi, C. B. Papadias, A. Kalis, N. Marchetti and R. Prasad ``MIMO Transmission and Reception Techniques Using Three-Element ESPAR Antennas," IEEE Communications Letters, Vol.13, No. 4, April 2009, pp. 236-238.

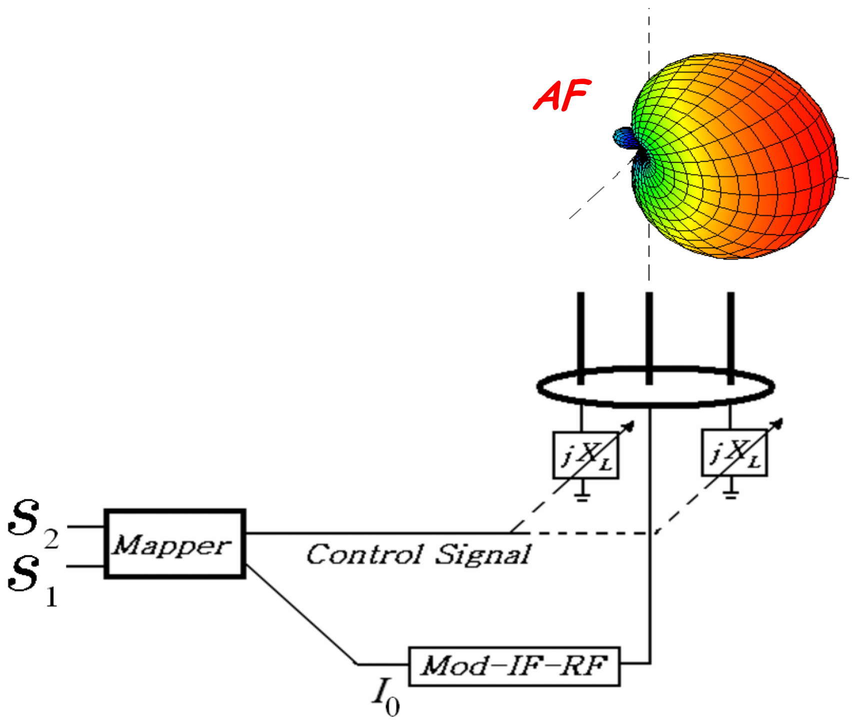
A Basis of Two Angular Functions

$$
\begin{aligned}
AF_n &= 1 + \alpha_{12} e^{-jkd\cos(\theta - 0)} + \alpha_{13} e^{-jkd\cos(\theta - \pi)} \\
&= \underbrace{1 + (\alpha_{12} + \alpha_{13})\cos(kd\cos(\theta))}_{B_1(\theta)} \\
&\quad - \underbrace{j(\alpha_{12} - \alpha_{13})\sin(kd\cos(\theta))}_{B_2(\theta)} \\
&= s_1 B_1(\theta) + s_2 B_2(\theta)
\end{aligned}
$$

$$
B_1(\theta) + B_2(\theta)\Big|_{[X_{L1} \quad X_{L2}]}
$$

$$
B_1(\theta) - B_2(\theta)\Big|_{[X_{L2} \quad X_{L1}]}
$$

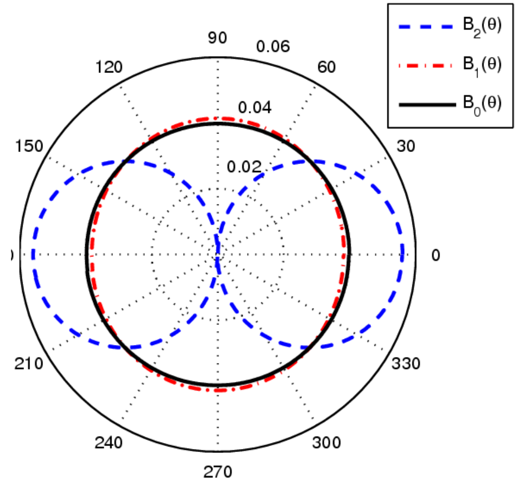


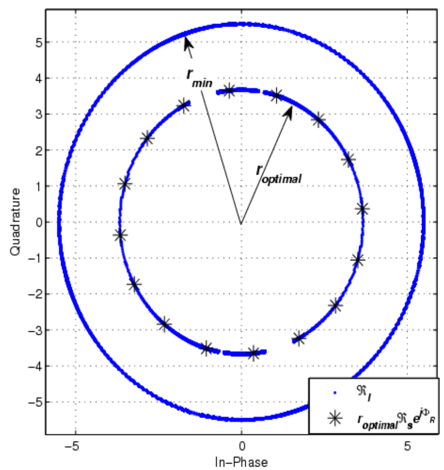


All PSK Modulation Schemes

$$AF_n \approx 1 + \frac{-j\left(\alpha_{12} - \alpha_{13}\right)}{1 + \alpha_{12} + \alpha_{13}} \sin(kd\cos(\theta))$$

$$\begin{aligned} AF &= 1 + \left(\frac{I_1}{I_0}\right) e^{-jkd\cos(\theta)} + \left(\frac{I_2}{I_0}\right) e^{jkd\cos(\theta)} \\ &= 1 + \left(\frac{I_2 + I_1}{I_0}\right) \cos\left(kd\cos(\theta)\right) + \left(-j\frac{I_2 - I_1}{I_0}\right) \sin\left(kd\cos(\theta)\right) \\ &= B_0(\theta) + \left(\frac{I_2 + I_1}{I_0}\right) B_1(\theta) + \left(-j\frac{I_2 - I_1}{I_0}\right) B_2(\theta). \end{aligned}$$



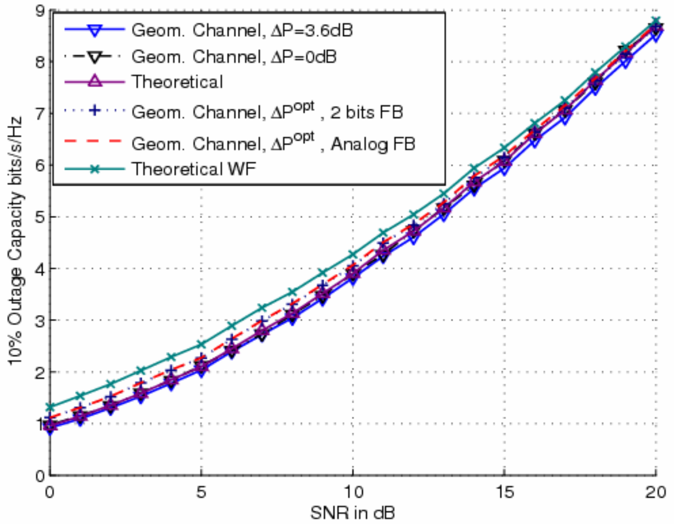


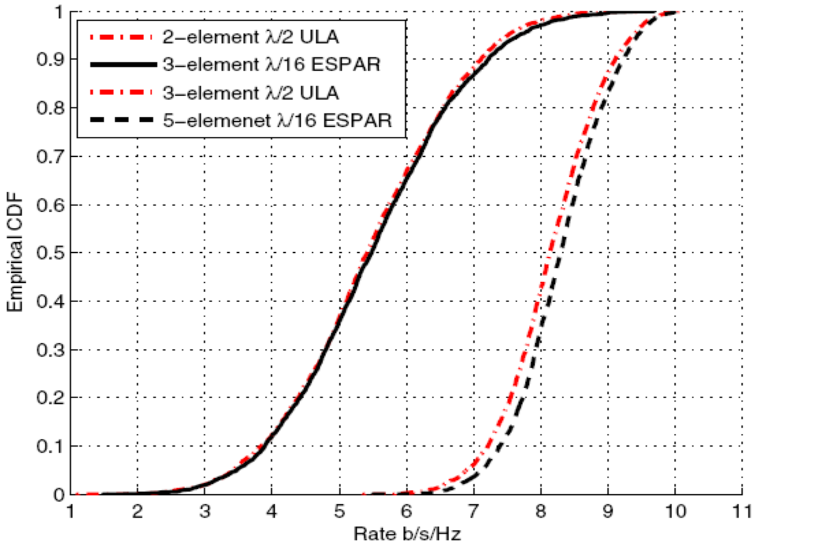
Reactive Loadings for Different PSK Modulation Orders (M)

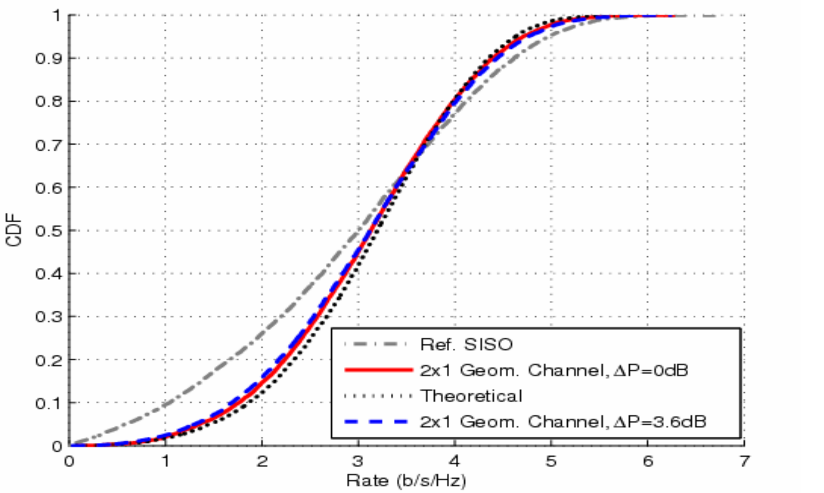
	$jX_{L1}(\Omega)$	$jX_{L2}(\Omega)$	M	E_1	E_2
$e^{j0\frac{2\pi}{16}}$	$j15.2$	$j5.5$	2, 4, 8, 16	0.42%	0.39%
$e^{j1\frac{2\pi}{16}}$	$j13.1$	$j0.8$	16	0.05%	0.1%
$e^{j2\frac{2\pi}{16}}$	$j10.9$	$-j9.5$	8, 16	0.16%	0.07%
$e^{j3\frac{2\pi}{16}}$	$j7.7$	$-j78$	16	0.13%	0.12%
$e^{j4\frac{2\pi}{16}}$	$-j10.5$	$j53.7$	4, 8, 16	0.01%	0%
$e^{j5\frac{2\pi}{16}}$	$j30$	$j34.4$	16	0.01%	0.03%
$e^{j6\frac{2\pi}{16}}$	$j11.9$	$j21.6$	8, 16	0.35%	0.09%
$e^{j7\frac{2\pi}{16}}$	$j8.7$	$j17.8$	16	0.15%	0.17%
$e^{j8\frac{2\pi}{16}}$	$j5.5$	$j15.2$	2, 4, 8, 16	0.42%	0.39%
$e^{j9\frac{2\pi}{16}}$	$j11.7$	$j13.1$	16	0.05%	0.1%
$e^{j10\frac{2\pi}{16}}$	$j0.8$	$j10.9$	8, 16	0.16%	0.07%
$e^{j11\frac{2\pi}{16}}$	$-j78$	$j7.7$	16	0.13%	0.12%
$e^{j12\frac{2\pi}{16}}$	$j53.7$	$-j10.5$	4, 8, 16	0.01%	0%
$e^{j13\frac{2\pi}{16}}$	$j34.4$	$j30$	16	0.01%	0.03%
$e^{j14\frac{2\pi}{16}}$	$j21.6$	$j11.9$	8, 16	0.35%	0.09%
$e^{j15\frac{2\pi}{16}}$	$j17.8$	$j8.7$	16	0.15%	0.17%

O. Alrabadi, C. B. Papadias, A. Kalis and R. Prasad, "A Universal Encoding Scheme for MIMO Transmission Using a Single RF-Fronted", IEEE Transactions on Wireless Communications, vol. 8, No. 10, pp. 5133-5143, Oct. 2010.

Mutual information

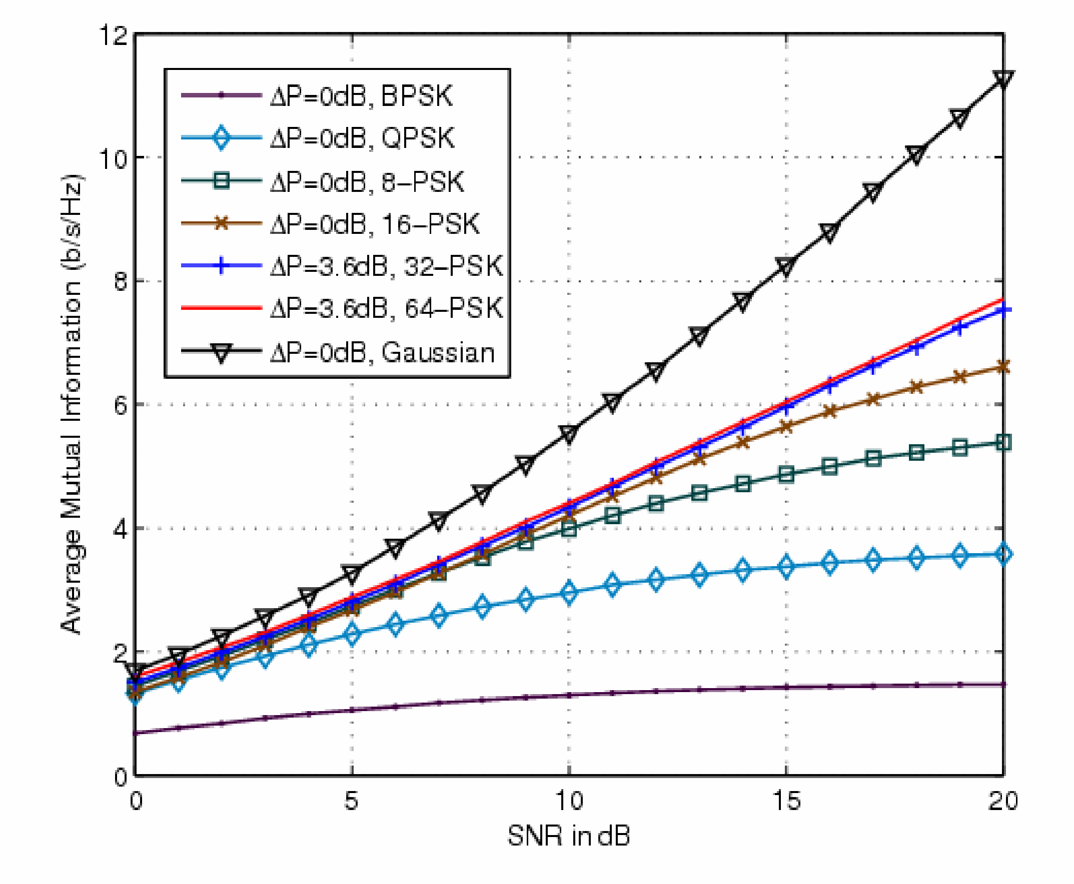






Gaussian Signaling is assumed rather than PSK

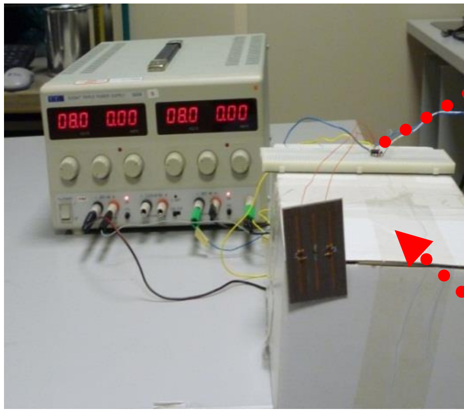
Average Mutual Information for Discrete PSK Input

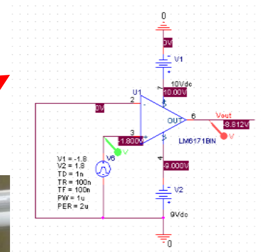


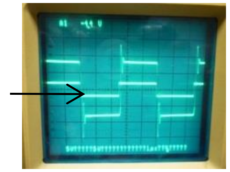
Over-the air performance

Over the air tests with AIT's MIMO Testbed

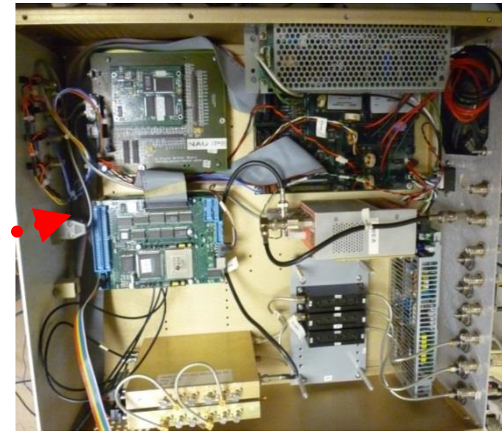
SPA+Switch

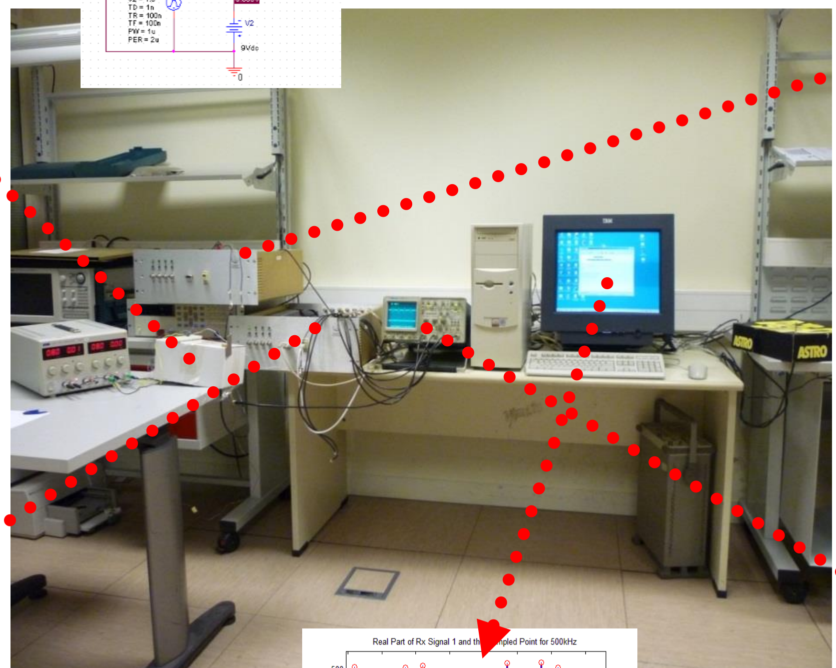




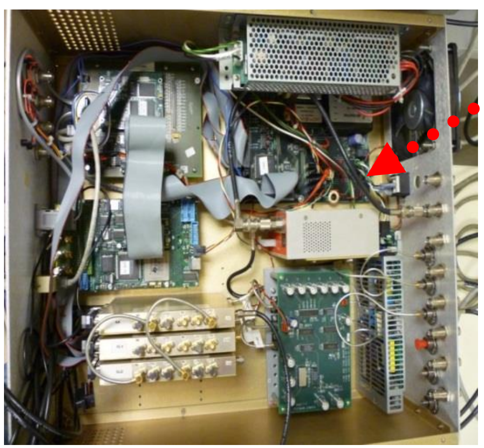


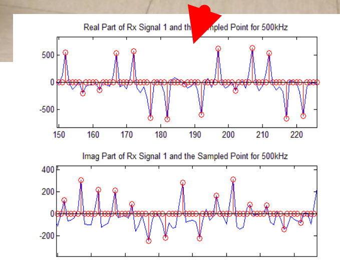
TX



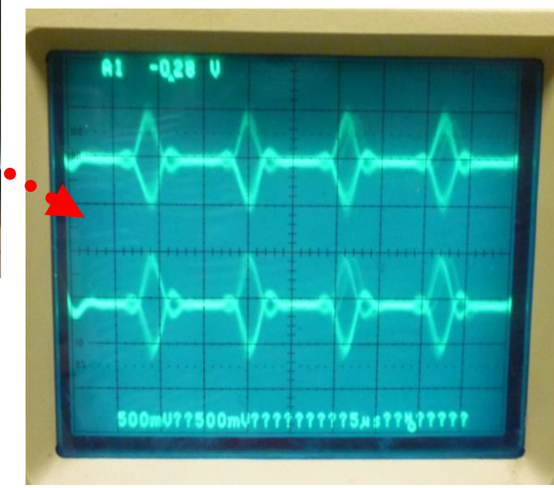


RX





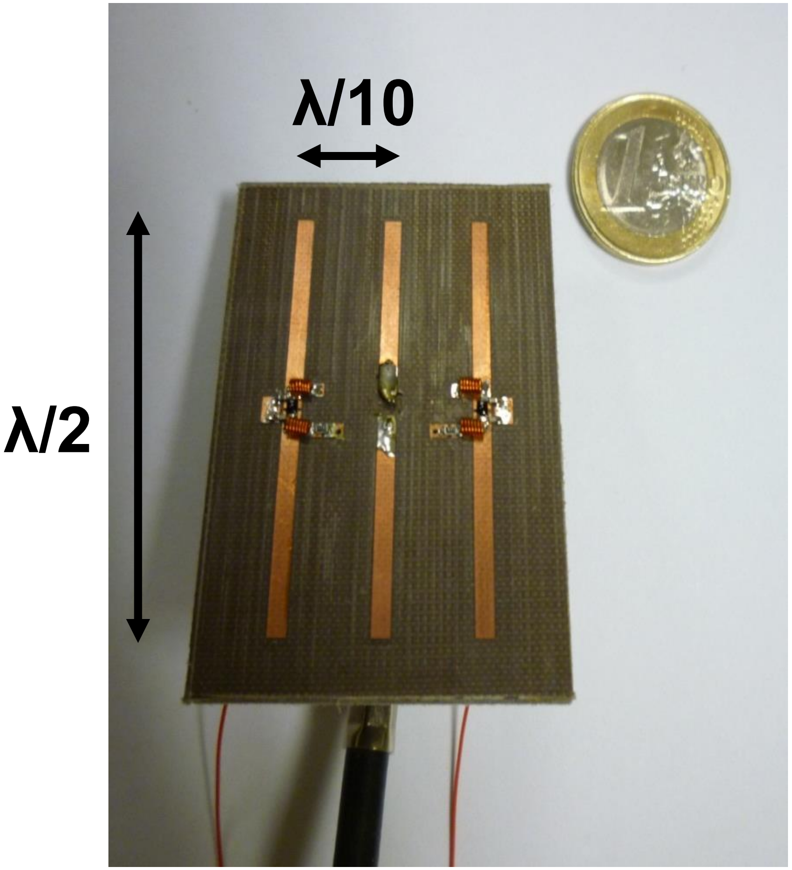
Osc.



MIMO Testbed Overview

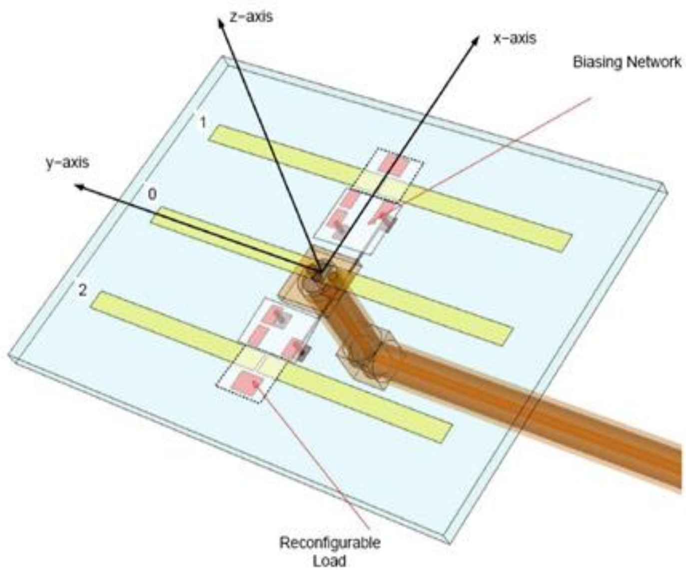
• Transmitter RF modules	– 2
• Receiver RF modules	– 2
• Carrier frequency	– (2.5-2.7) GHz
• BB Signal bandwidth	– up to 1 MHz
• 'Innovative DSP' (TMS320C6201) CLK	– 200 MHz
• GPS Synchronization feature	
• RS232 Serial Interface	
• 10BaseT Ethernet Interface	

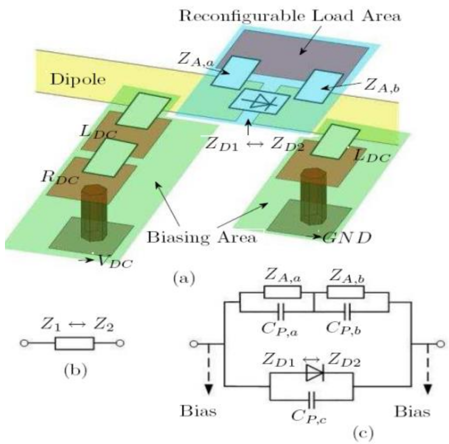
The Parasitic Antenna Array

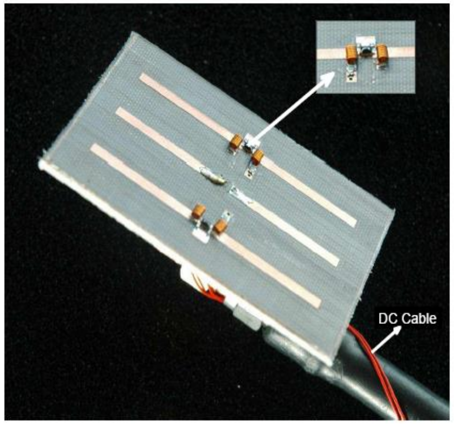


- Uses only one RF front end and two or more parasitic elements
- Can form different beams in each symbol period by controlling the parasitic elements
- Compact, cheap and less power-hungry

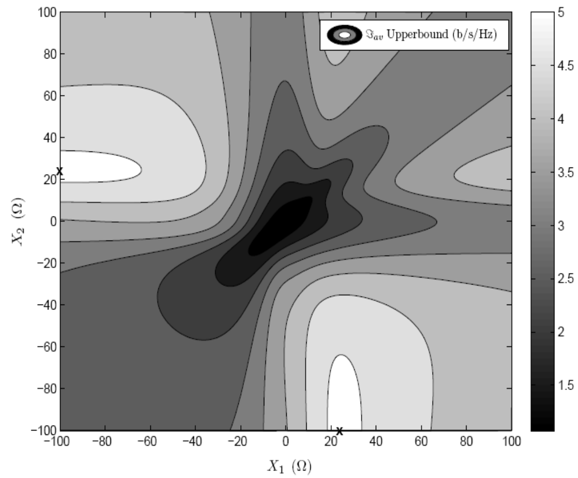
Antenna Design & Measurements



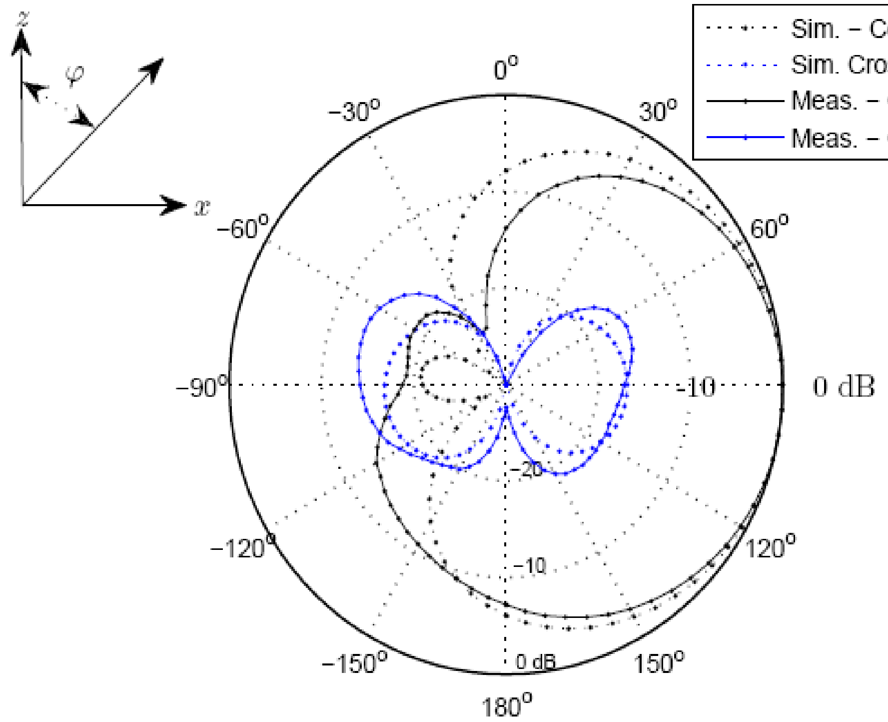




Photograph of the fully operational SPA, optimized for the proposed aerial MIMO approach.

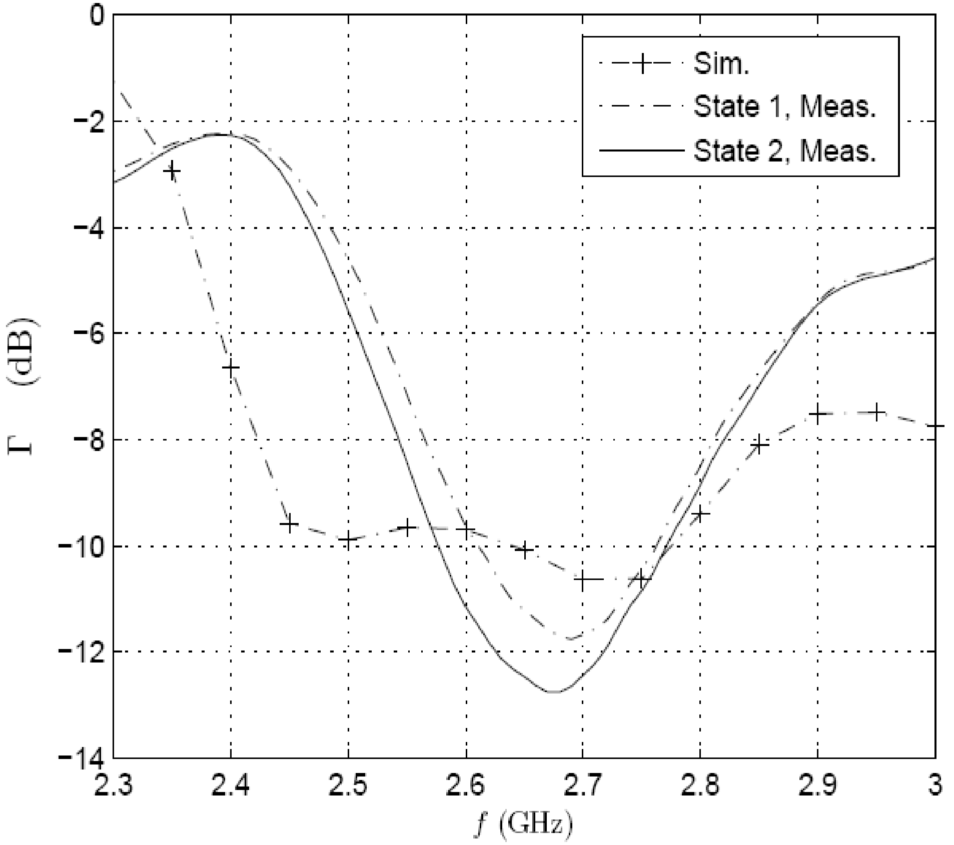


Antenna Design & Measurements



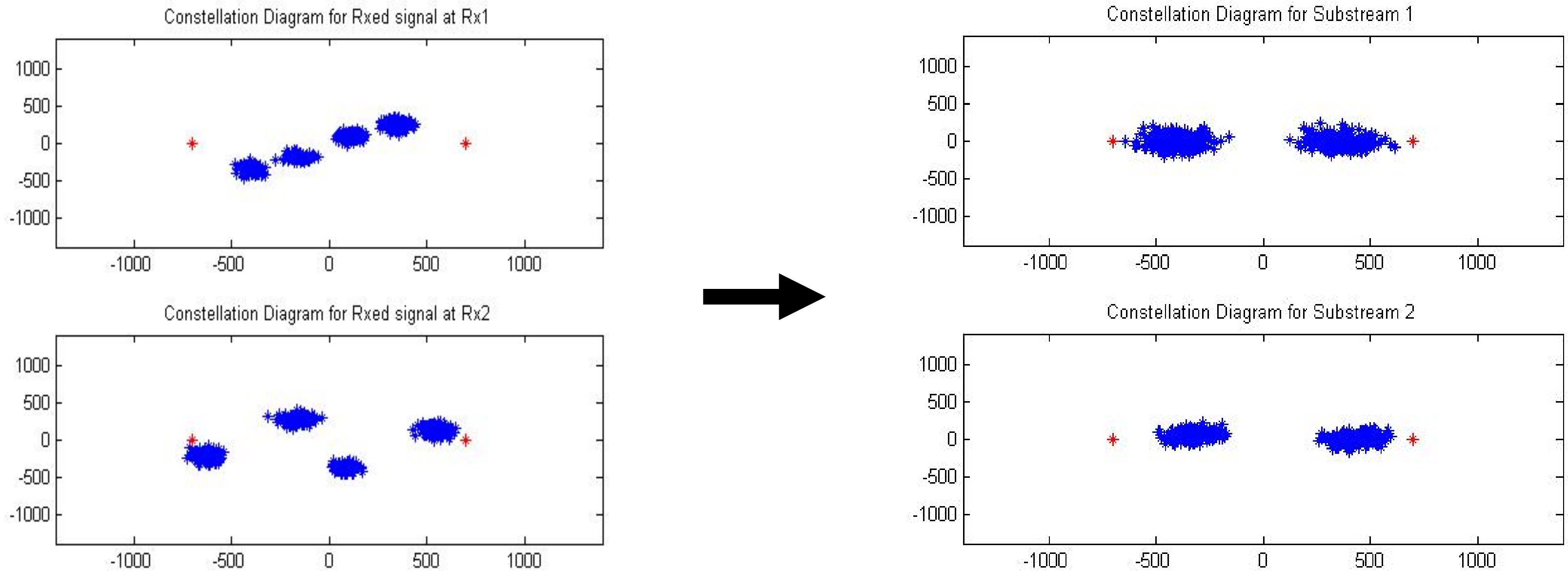
Simulated and measured co- and cross- polarization components of the beampattern $\mathcal{G}_1(\vartheta, \varphi)$ in the H-plane i.e. $\mathcal{G}_1(\vartheta = \frac{\pi}{2}, \varphi)$, at $f = 2.6$ GHz.

Antenna Design & Measurements



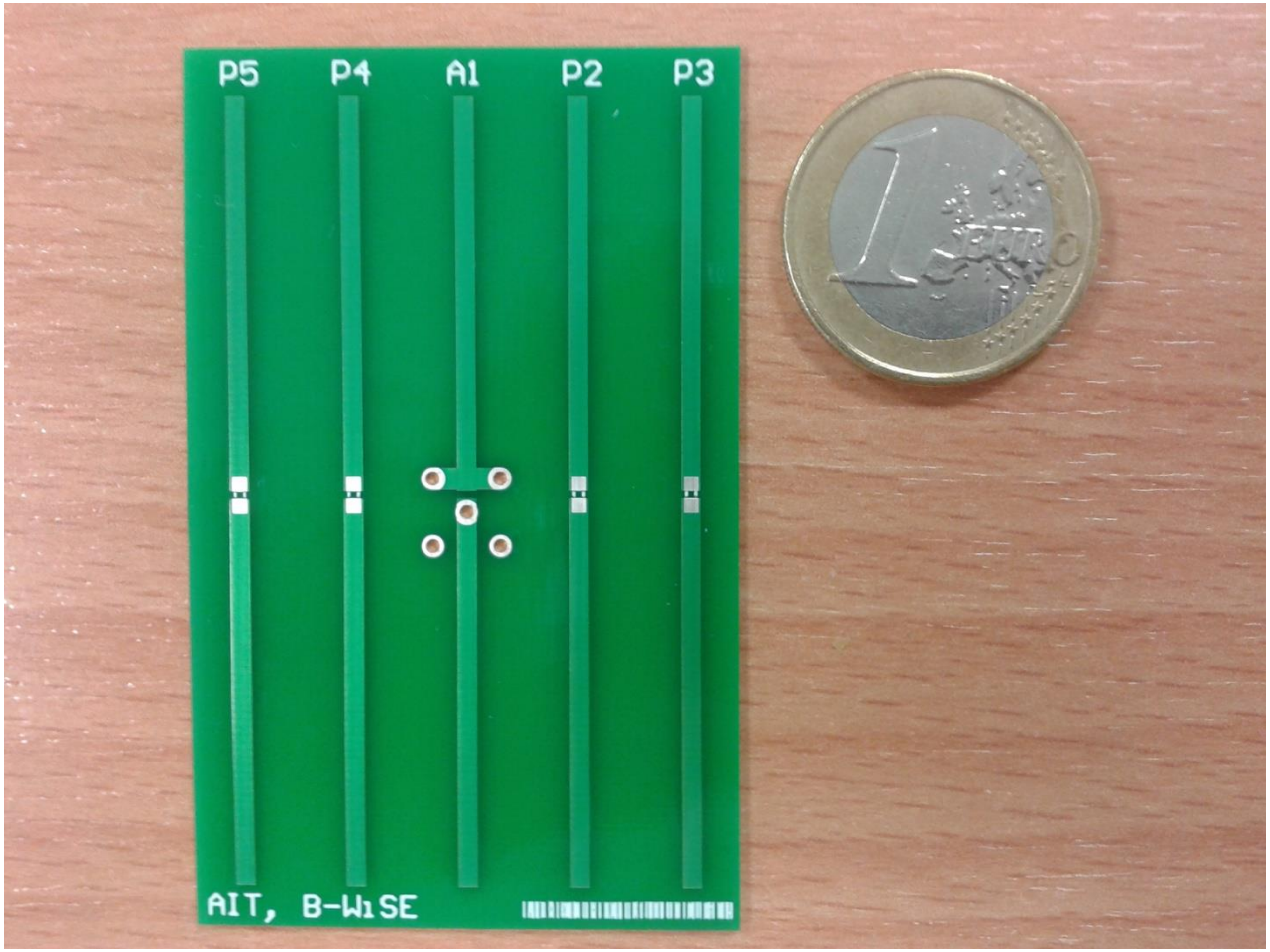
Return Loss (dB) of the SPA for both loading states i.e. $S := 1$ and $S := 2$.

First ESPAR Spatial Multiplexing Over-the-Air Proof-of-Concept Validation

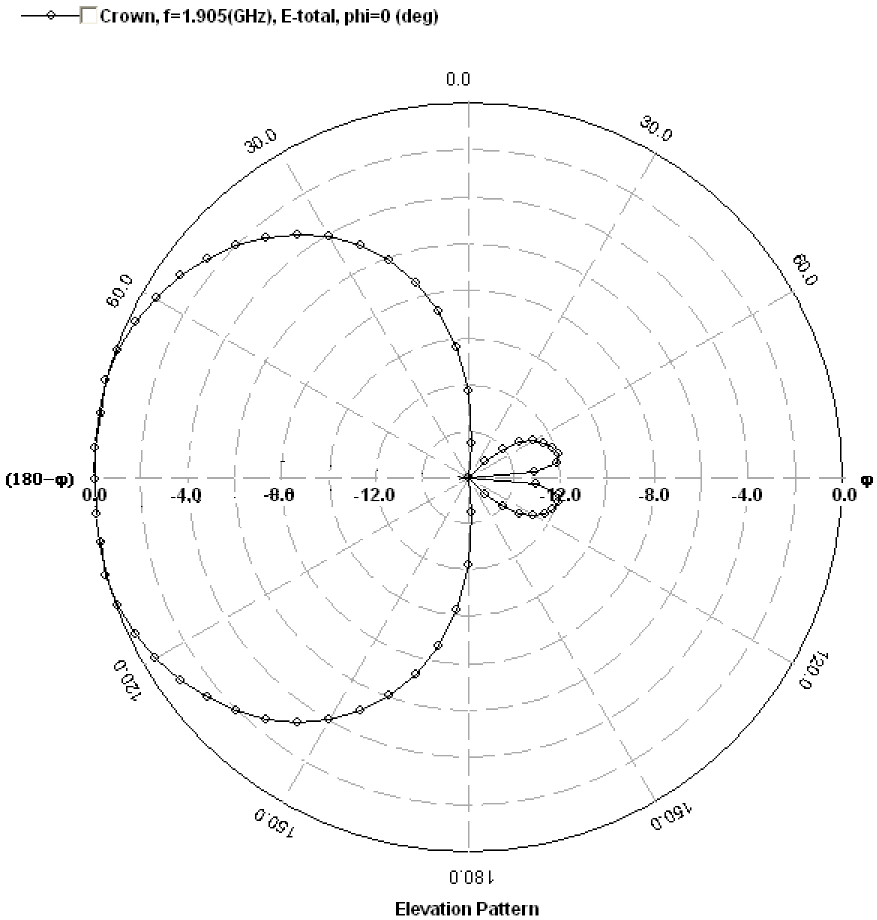


O. N. Alrabadi, C. Divarathne, P. Tragas, A. Kalis, N. Marchetti, C. B. Papadias, R. Prasad, "Spatial Multiplexing with a Single Radio: Proof-of-Concept Experiments in an Indoor Environment with a 2.6 GHz Prototype," IEEE Comm. Letters, vol. 15, No. 2, pp. 178-180, Feb. 2011.

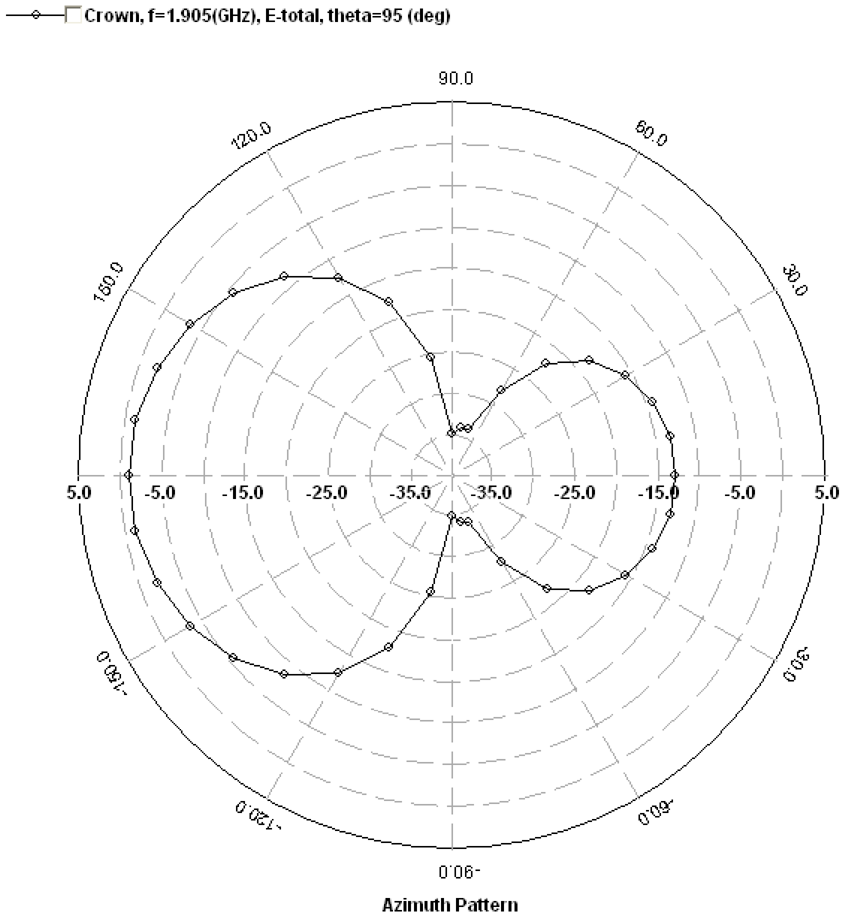
A 5-element prototype for LTE



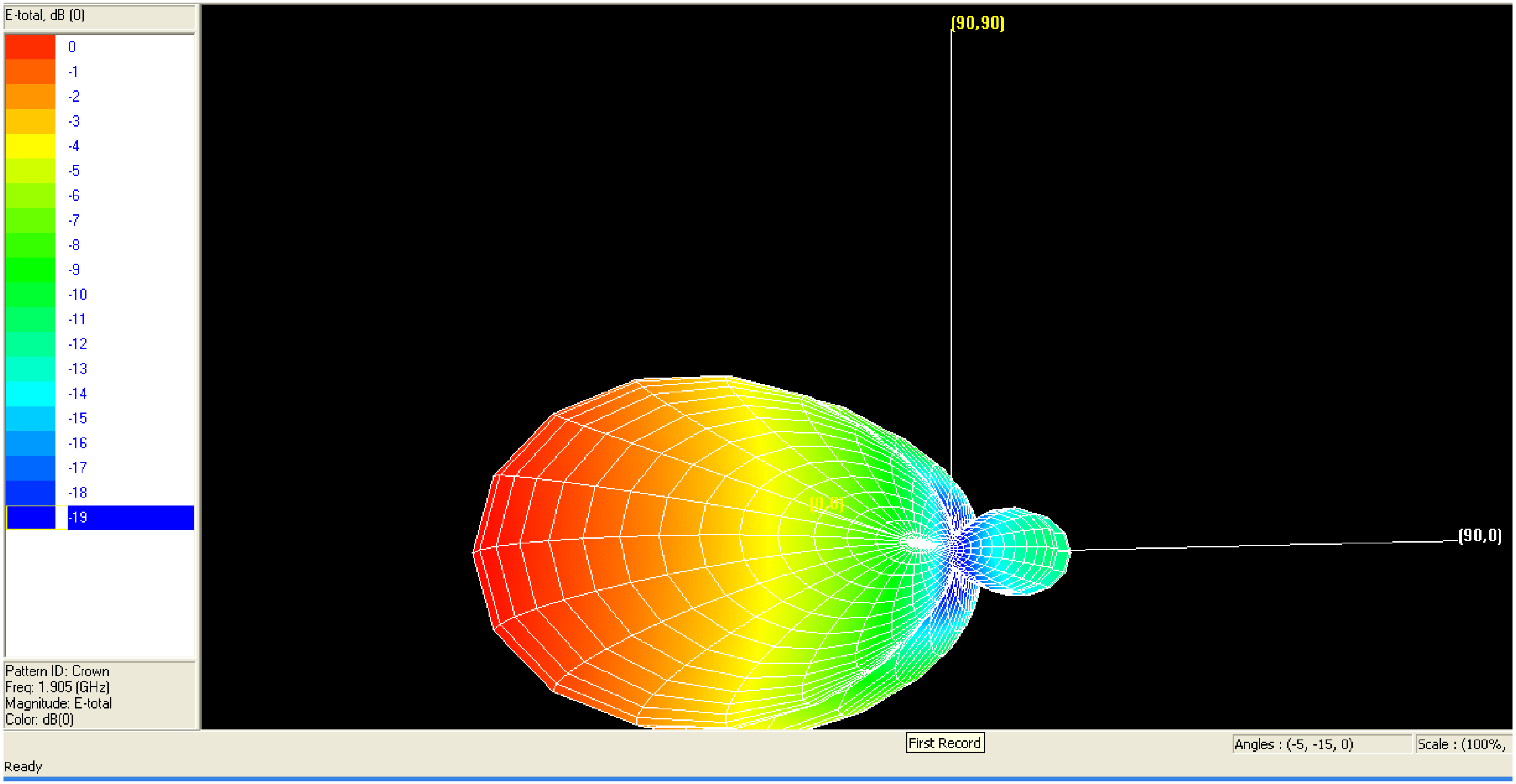
Elevation Pattern



Azimuth Pattern

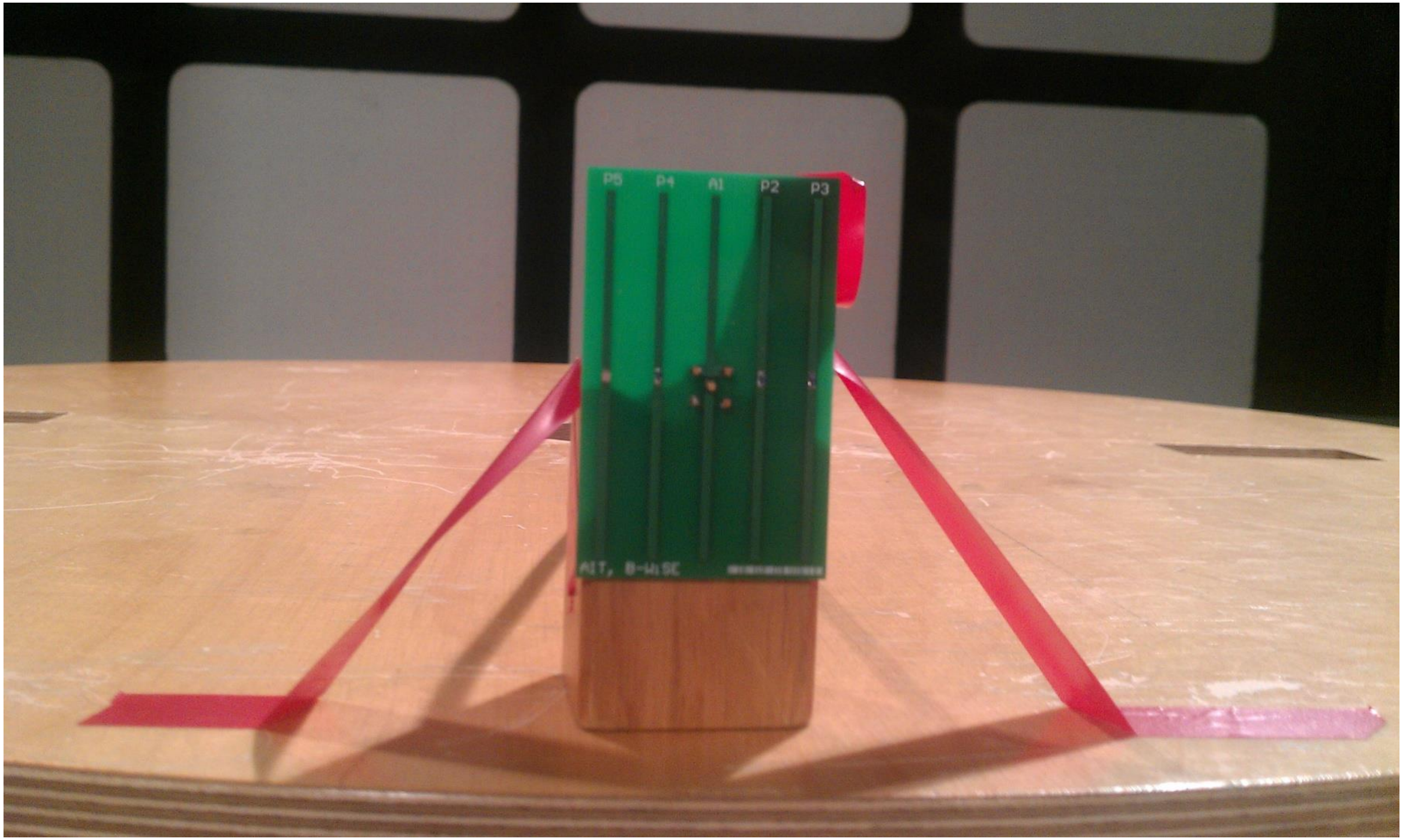


3D Radiation Pattern



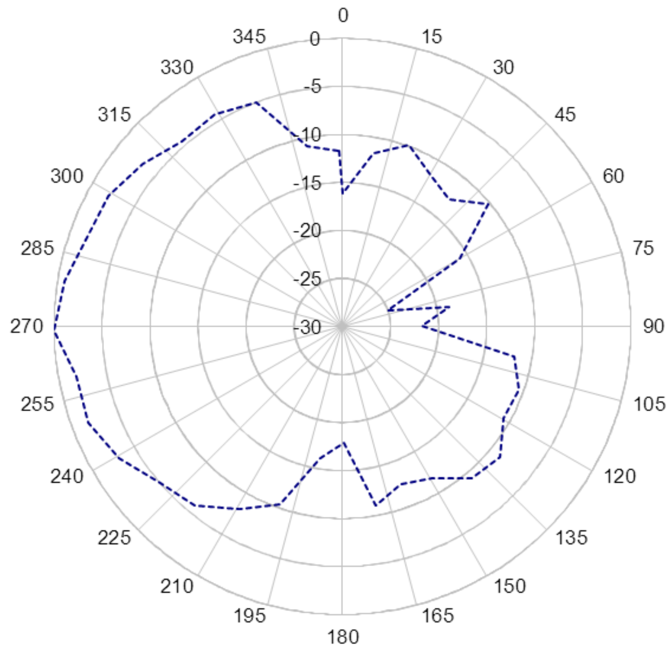
Anechoic chamber setup

Array setup

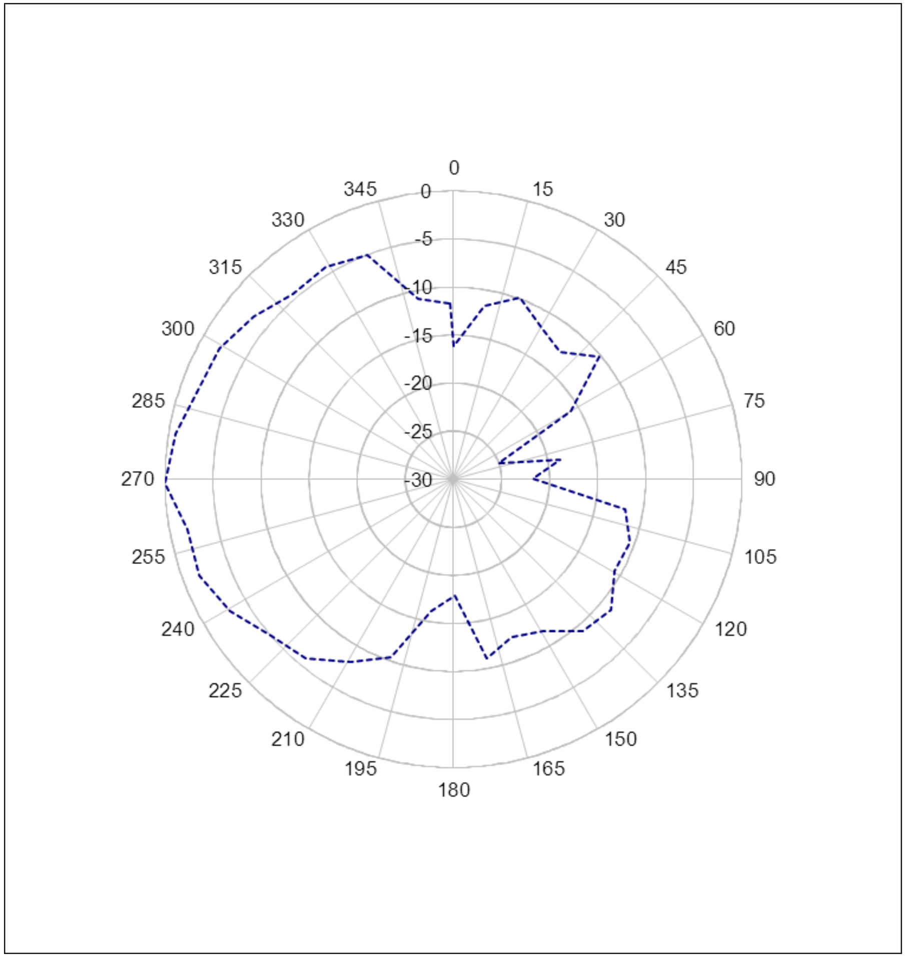


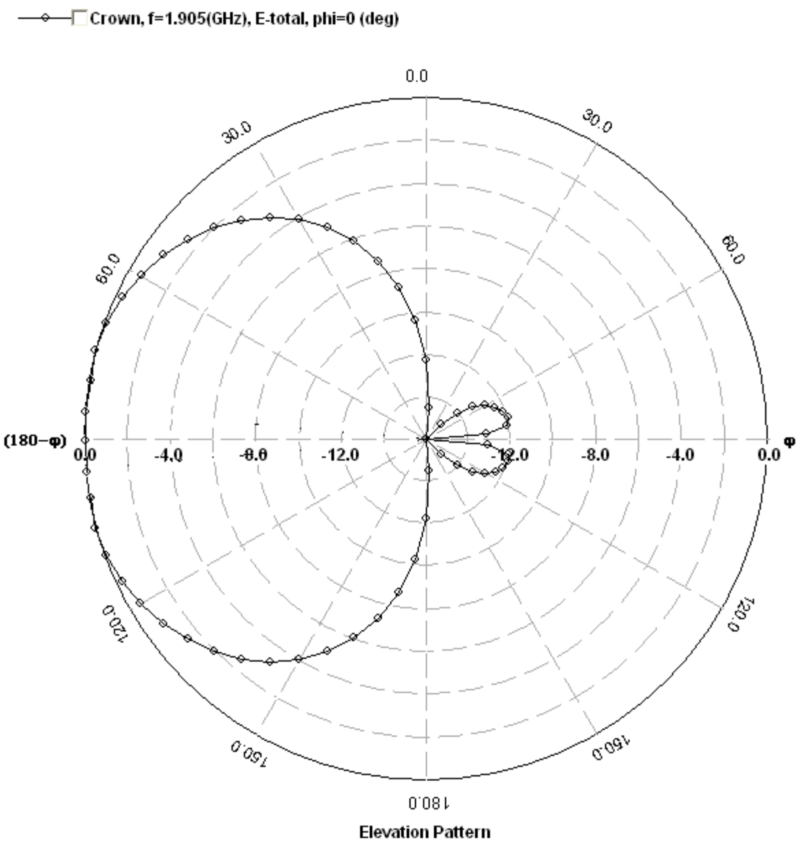
Measurement setup

Measured Azimuth Pattern

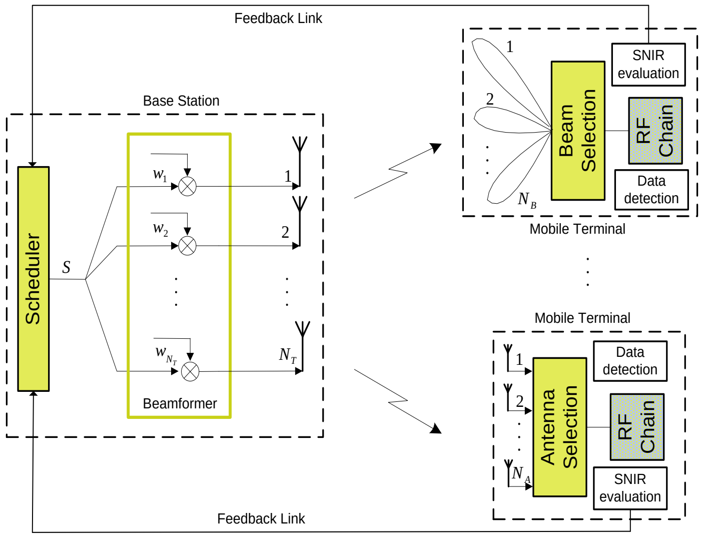


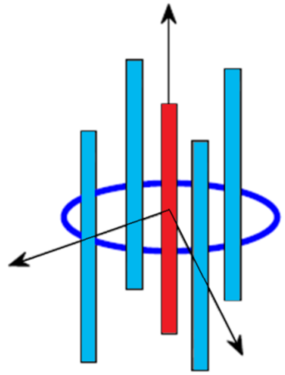
Comparison of Simulation and measurements

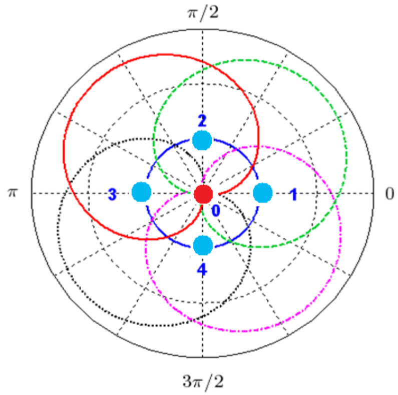


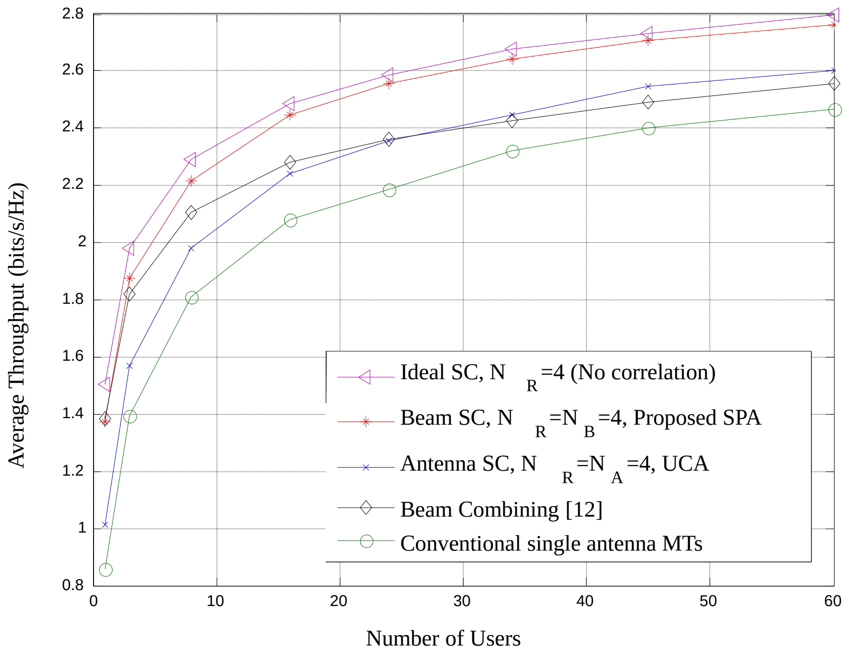


Other applications: Rx beam selection combined with OBF



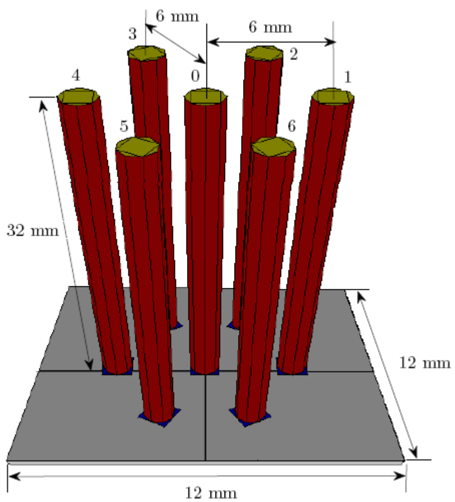


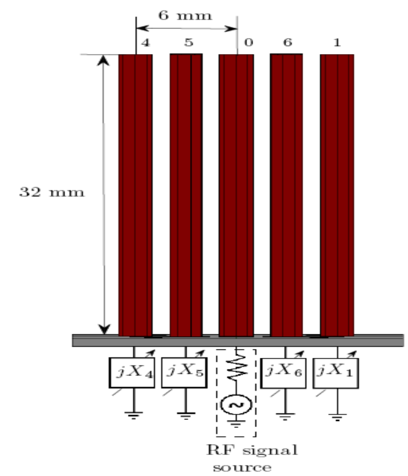


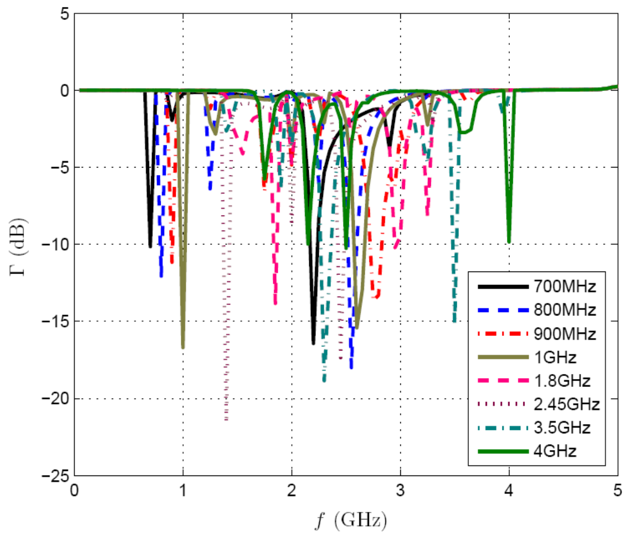


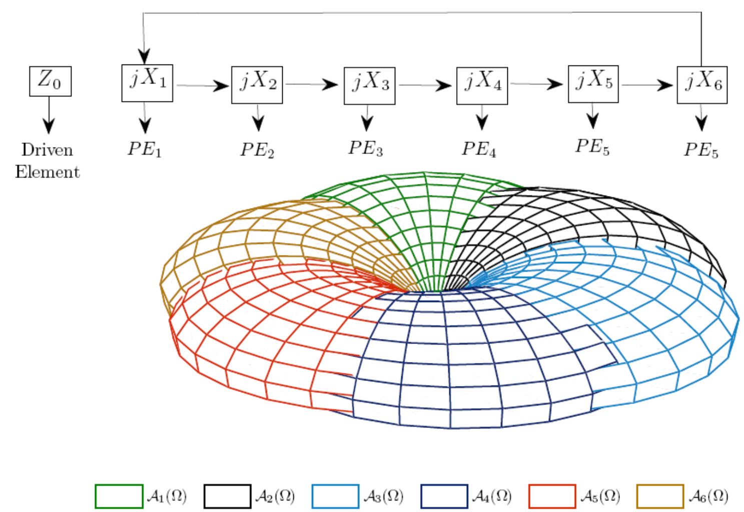
E. P. Tsakalaki, O. N. Alrabadi, C. B. Papadias, R. Prasad, "Reduced complexity radio architectures for enhanced receive selection combining in multiuser diversity systems," International Journal of Antennas and Propagation, Special Issue on MIMO Antenna Design and Channel Modeling, vol. 2012, Article ID 454210, 2012.

Other applications (2): tunable & steerable arrays



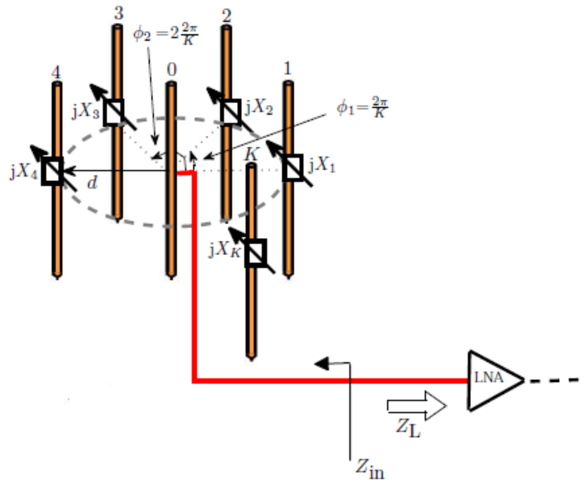


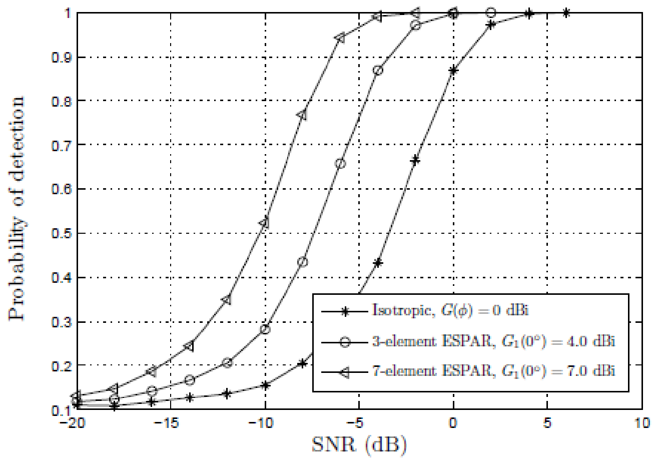


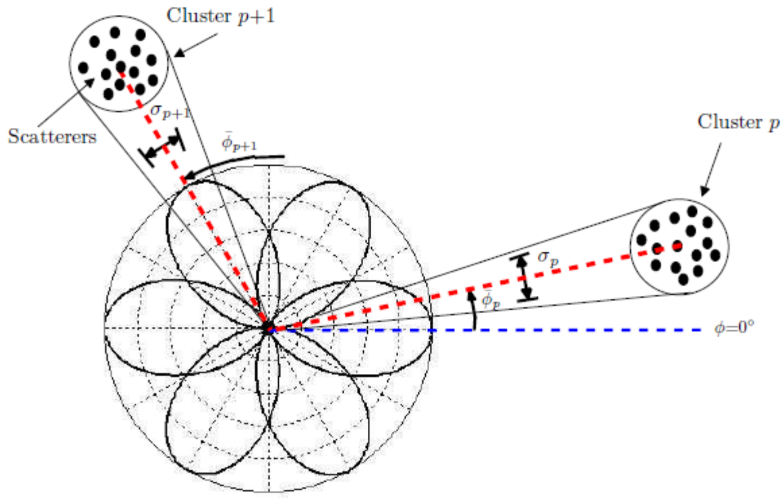


E. P. Tsakalaki, O. N. Alrabadi, C. B. Papadias, R. Prasad, "Spatial spectrum sensing for wireless handheld terminals: design challenges and novel solutions based on tunable parasitic antennas, " IEEE Wireless Comm. Magazine, Dynamic Spectrum Management in Wireless Networks, vol. 17, no. 4, pp. 33-40, Aug. 2010.

Other applications (3): directional sensing for cognitive radio

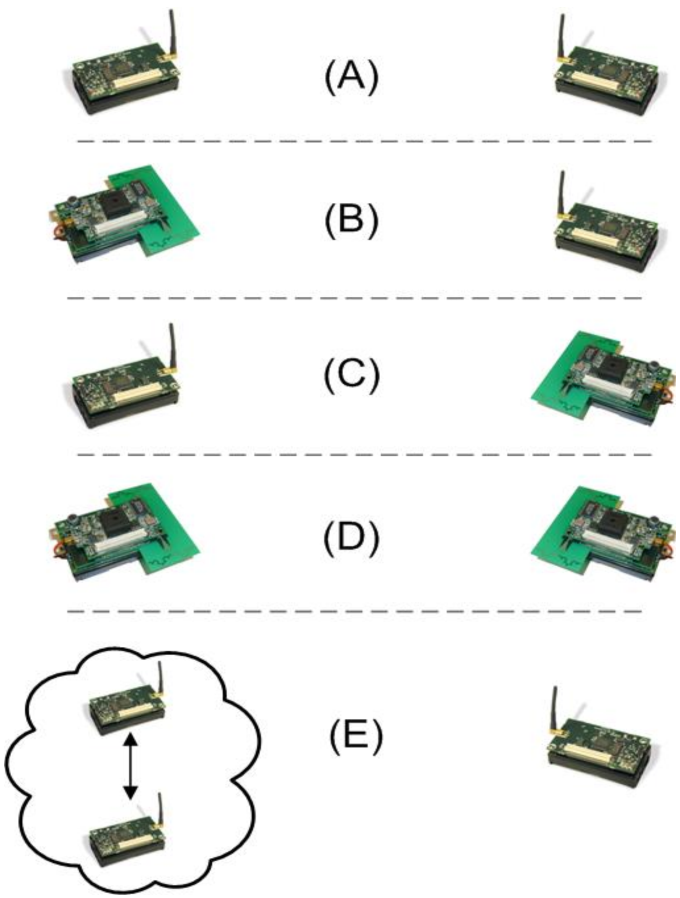


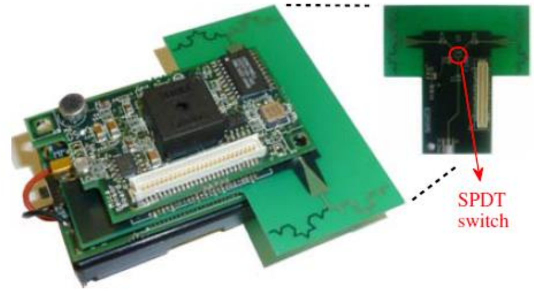


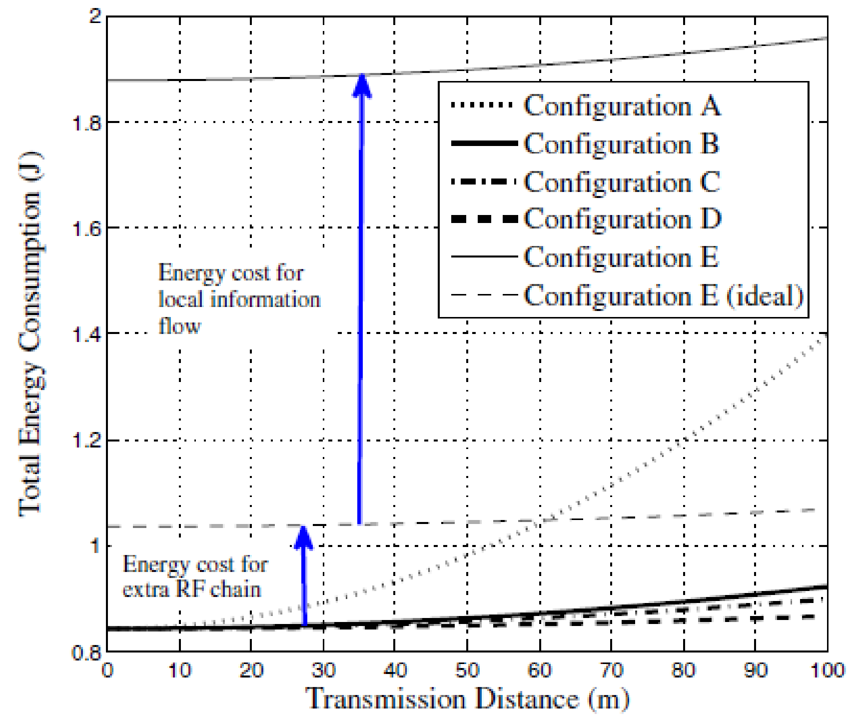


D. Wilcox, E. P. Tsakalaki, A. Kortun, T. Ratnarajah, C. B. Papadias, M. Sellathurai, "On spatial domain cognitive radio using single-radio parasitic antenna arrays," IEEE Journal on Selected Areas in Communications (J-SAC), vol. 31, No. 3, pp. 571-580, March 2013.

Other applications (4): energy efficiency in WSNs







E. P. Tsakalaki, O. N. Alrabadi, A. Kalis, C. B. Papadias, R. Prasad, "Non cooperative space time communication for energy efficiency in sensor networks," IEEE Trans. on Communications, vol. 60, No. 1, pp. 48-54, Jan. 2012.

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

$$P(\varphi) = \sum_{n=0}^{M_{esp}-1} w_n \Phi_n(\varphi) = \mathbf{w}_e^T \boldsymbol{\Phi}(\varphi)$$

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

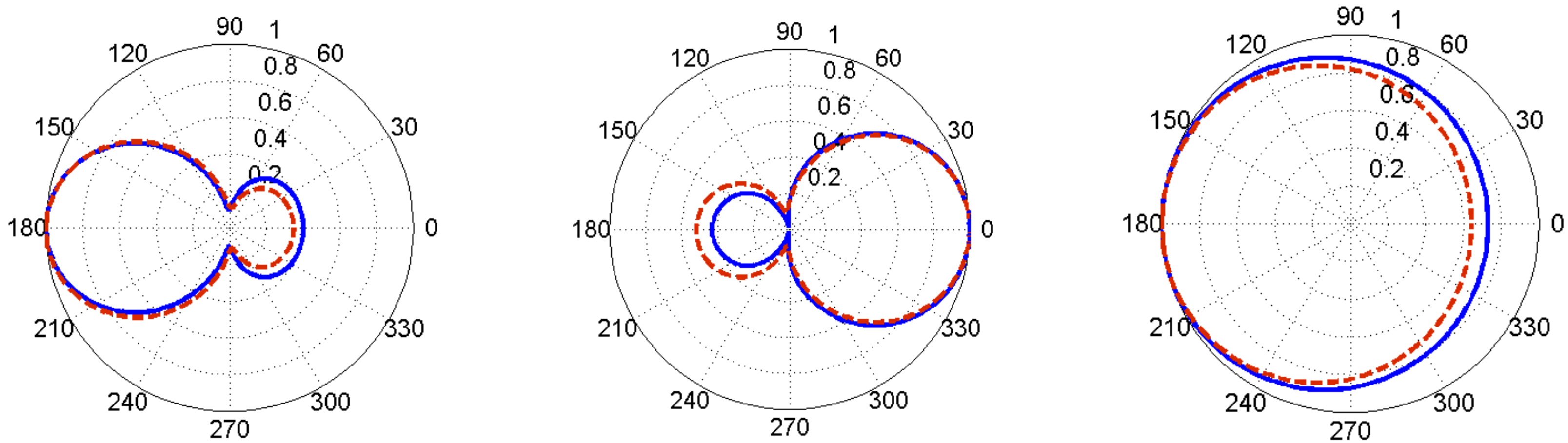
ATHENS INFORMATION TECHNOLOGY

- 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



A new view of the signal model

Given an arbitrary antenna array…

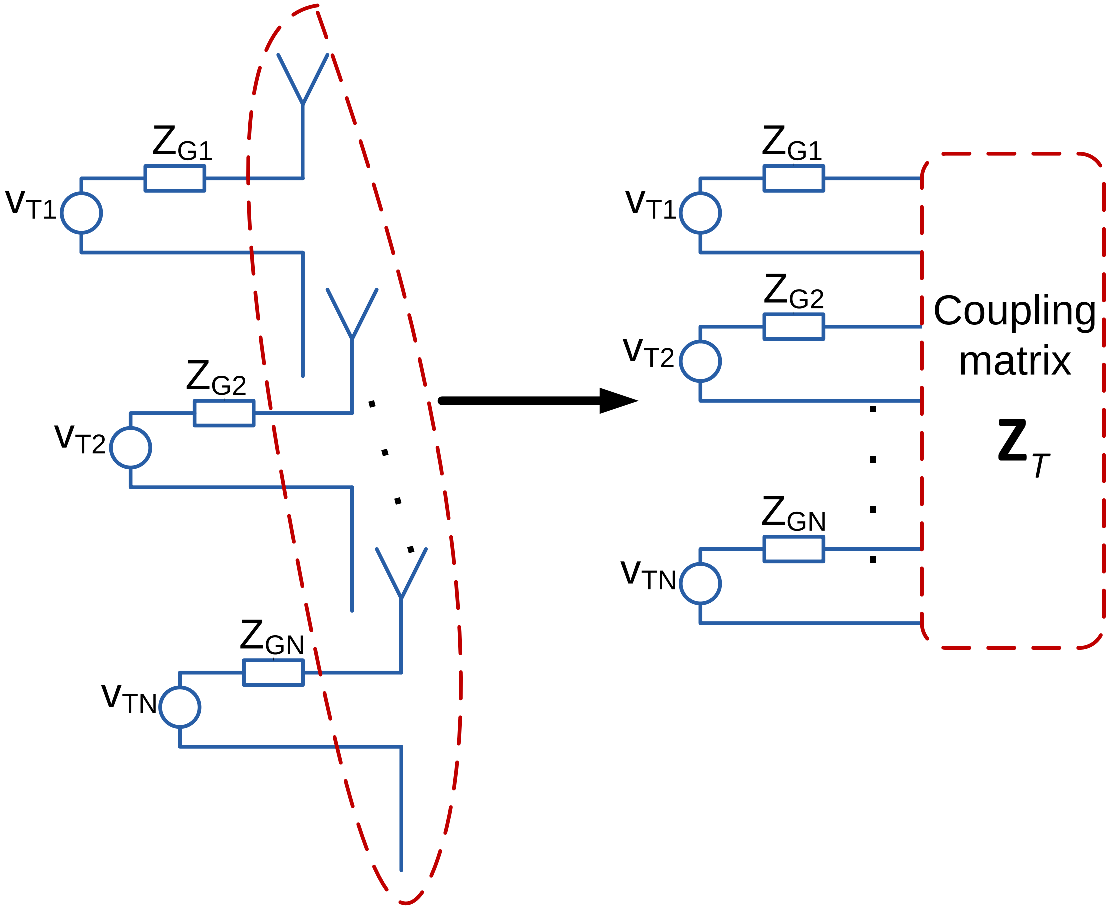
The currents at all ports are given by

$$\mathbf{i} = \left(\mathbf{Z}_T + \mathbf{Z}_G\right)^{-1} \mathbf{v}_T$$

Where

$$\mathbf{Z}_G = diag\left(Z_{G1}, Z_{G2}, \ldots, Z_{GN}\right)$$

$$\mathbf{v}_T = \begin{bmatrix} v_{T1} & v_{T2} & \ldots & v_{TN} \end{bmatrix}^T$$



Z_{Gi}: Output resistance

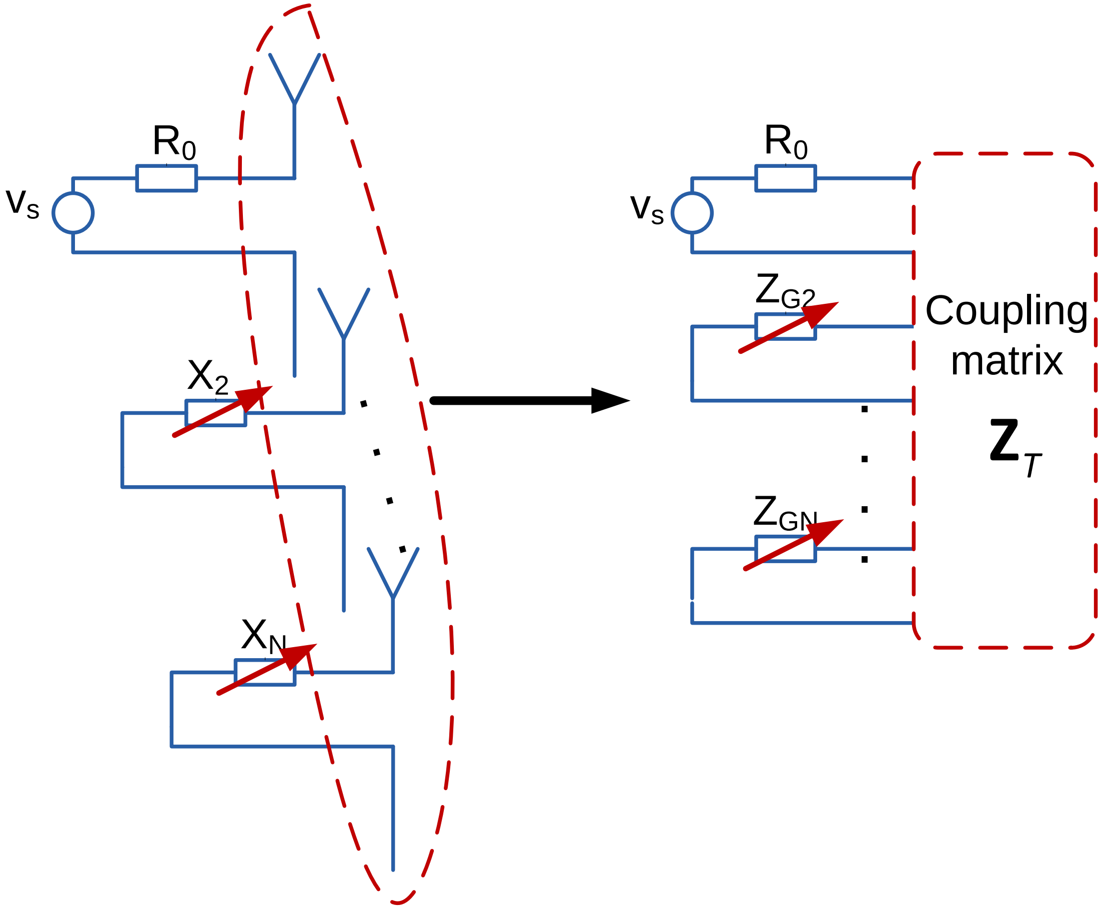
A new signal model for Parasitic arrays

In case of a parasitic array….

The currents at all ports are given by

$$\mathbf{i} = \left(\mathbf{Z}_T + \mathbf{Z}_G\right)^{-1} \mathbf{v}_T$$

$$\mathbf{v}_T = \left[v_{T1} \quad 0 \quad \dots \quad 0\right]^T$$



A new signal model for load-modulated arrays

The well-known baseband model can be adopted as:

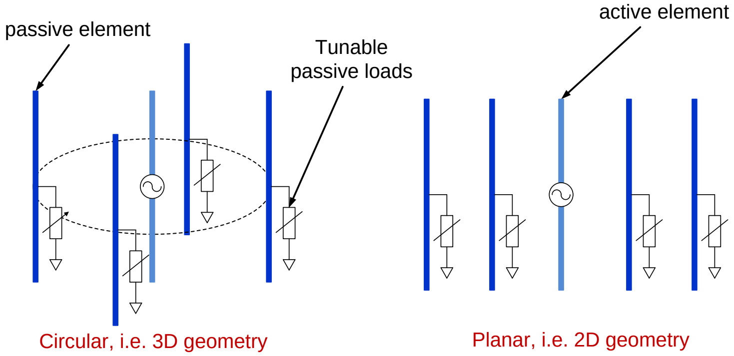
$$\mathbf{y} = \mathbf{H}\mathbf{i} + \mathbf{n}$$

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

$\mathbf{H}: (M_R \times M_T)$ 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

$\mathbf{i}_T: (M_T \times 1)$ holds the ESPAR's currents $\quad \mathbf{i}_T = (\mathbf{Z}_T + \mathbf{Z}_G)^{-1} \mathbf{v}_T$

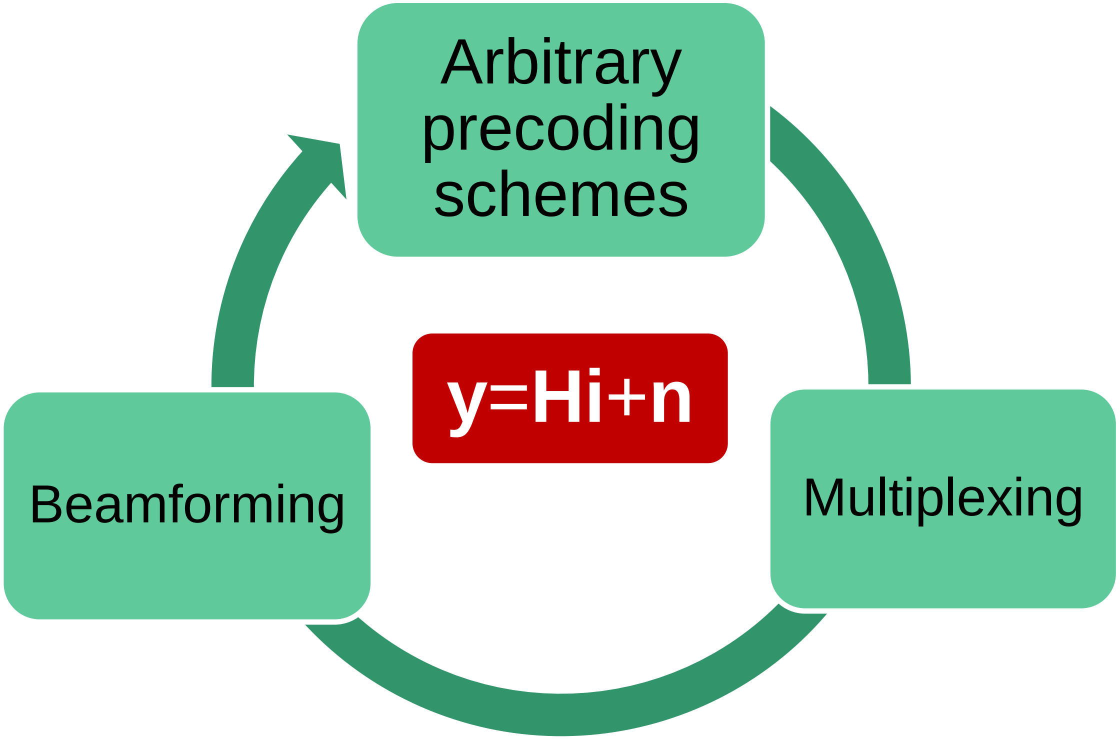
$\mathbf{n}: (M_R \times 1)$ Gaussian noise vector



V. Barousis, C. B. Papadias and R. R. Müller, "A new signal model for MIMO communication with compact parasitic arrays," In Proc. International Symposium on Communications, Control and Signal Processing, Athens, Greece, May 21-23, 2014.

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)



Arbitrary Linear Precoding

The currents at the ports of the radiating elements should be adjusted so that: $\mathbf{i} = \mathbf{VGs}$

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

$\mathbf{V}$: is the required precoding matrix

$\mathbf{G} = diag\begin{pmatrix} g_1 & g_2 & \dots & g_r \end{pmatrix}$: is the required power loading matrix

$\mathbf{s}$: is the Tx symbol vector

$\mathbf{n}$: is the AWGN noise vector

The loads are linked to the currents via:

$$\mathbf{i} = \left(\mathbf{Z}_T + \mathbf{Z}_G\right)^{-1} \mathbf{v}_T$$

$$\mathbf{v}_T = \begin{bmatrix} v_{T1} & 0 & \dots & 0 \end{bmatrix}^T$$

Then link the loading values to the triggering voltage

V. I. Barousis and C. B. Papadias, "Arbitrary precoding with single-fed Parasitic arrays: Closed-form expressions and design guidelines," IEEE Wireless Communications Letters, vol. PP, no. 99, Feb. 2014.

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:

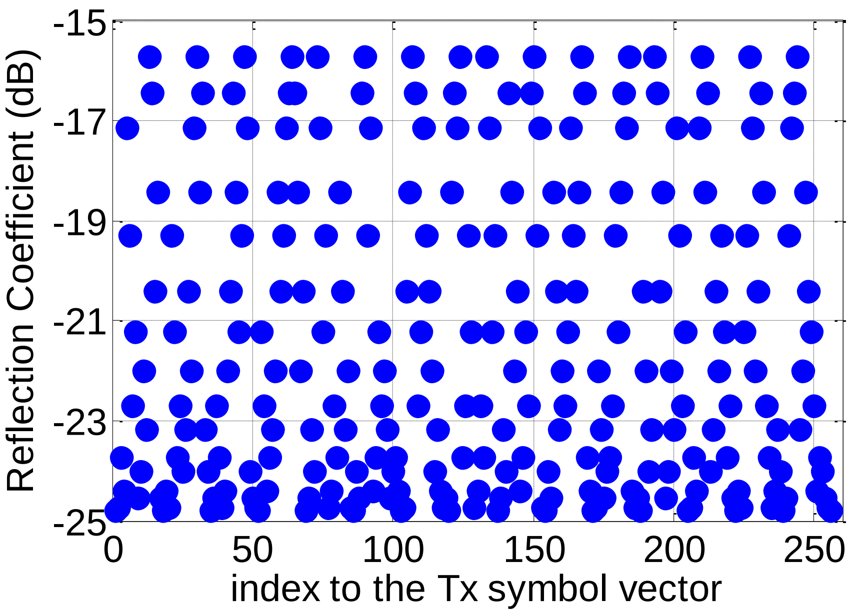
     $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$: SVD to estimate the Tx and Rx filters

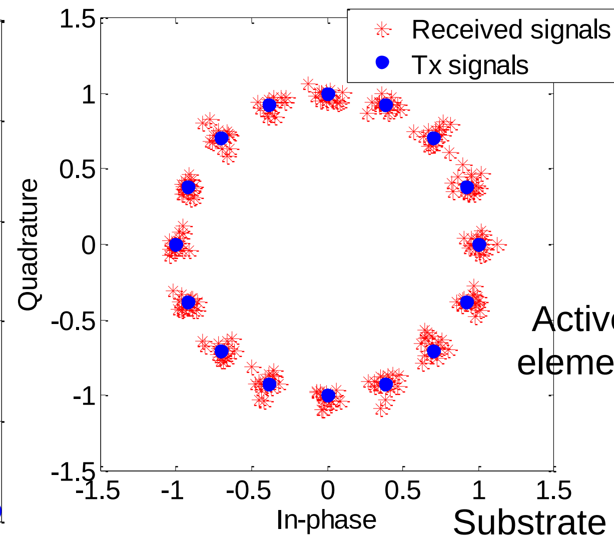
     $\mathbf{G} = diag\left(g_1 \; g_2\right)$: Power allocation obtained via Waterfilling

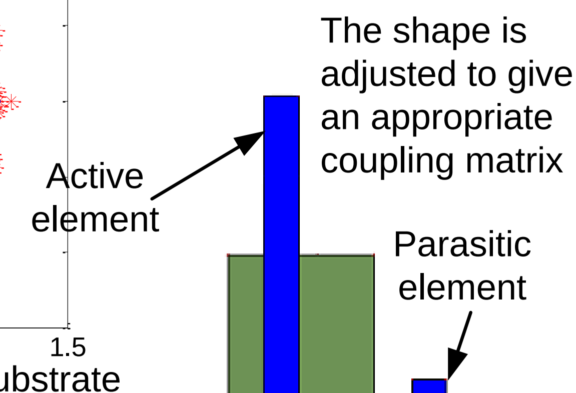
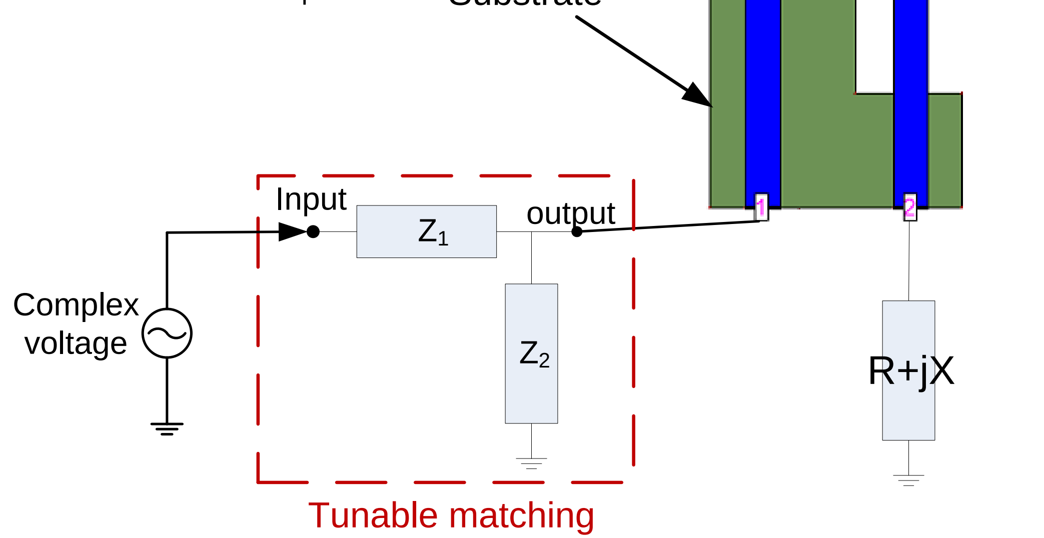
  2) The Tx applies the loading values that correspond to the vector of currents that implement the desired precoding:

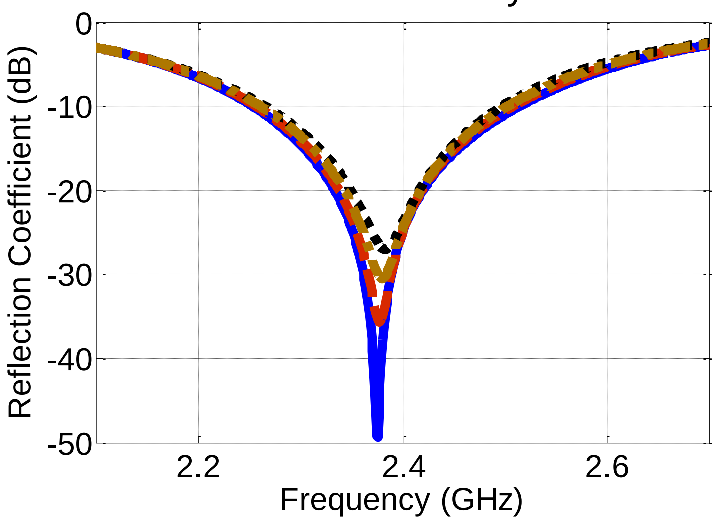
$$\mathbf{i} = \mathbf{VDs}, \mathbf{D} = \sqrt{\mathbf{G}}$$

Example: waterfilling with 1 active / 1 passive element



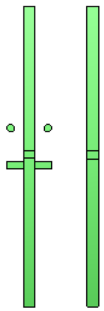


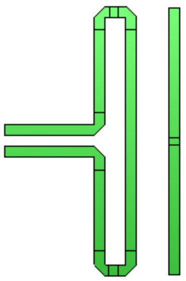



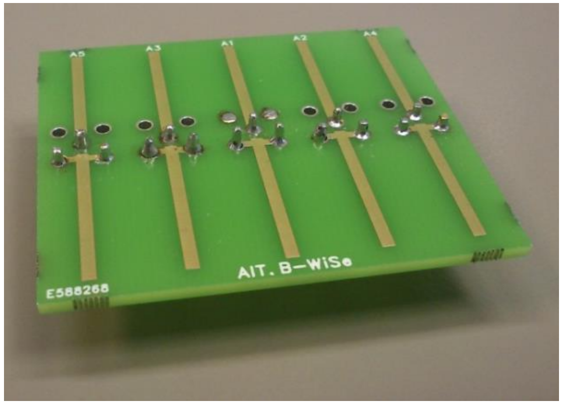


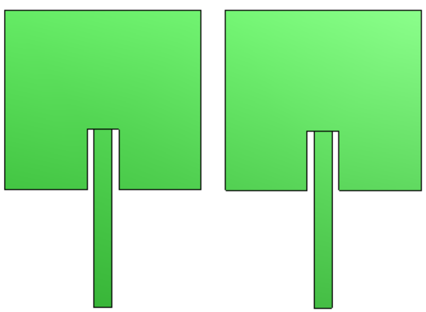
Prototyping and experimentation

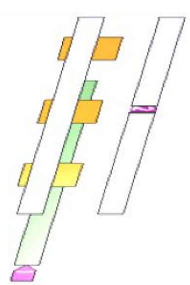
Early designs and prototyping

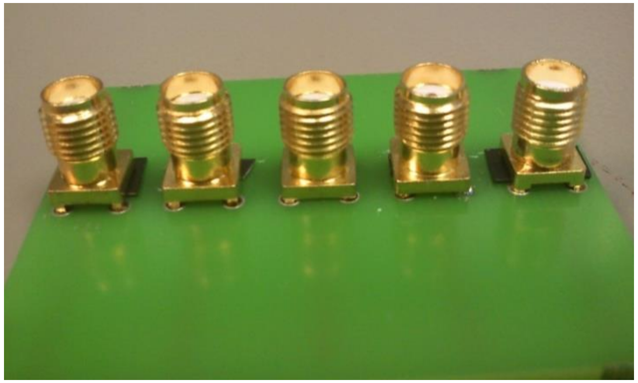






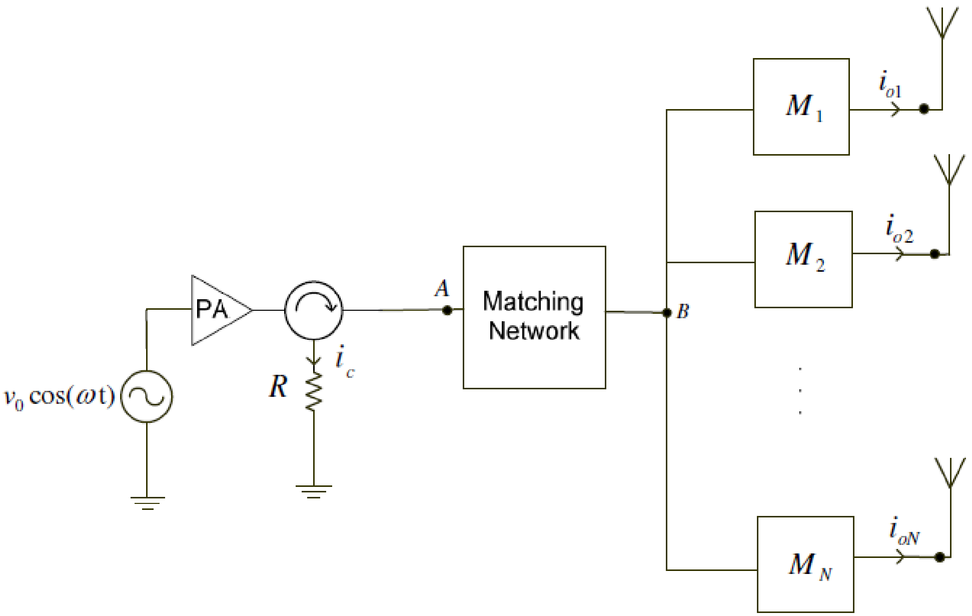




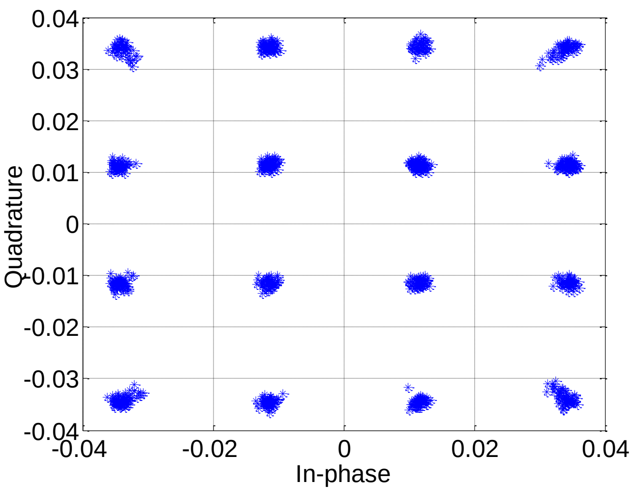


A novel load-modulated design for large arrays

No RF Chain needed – just an oscillator

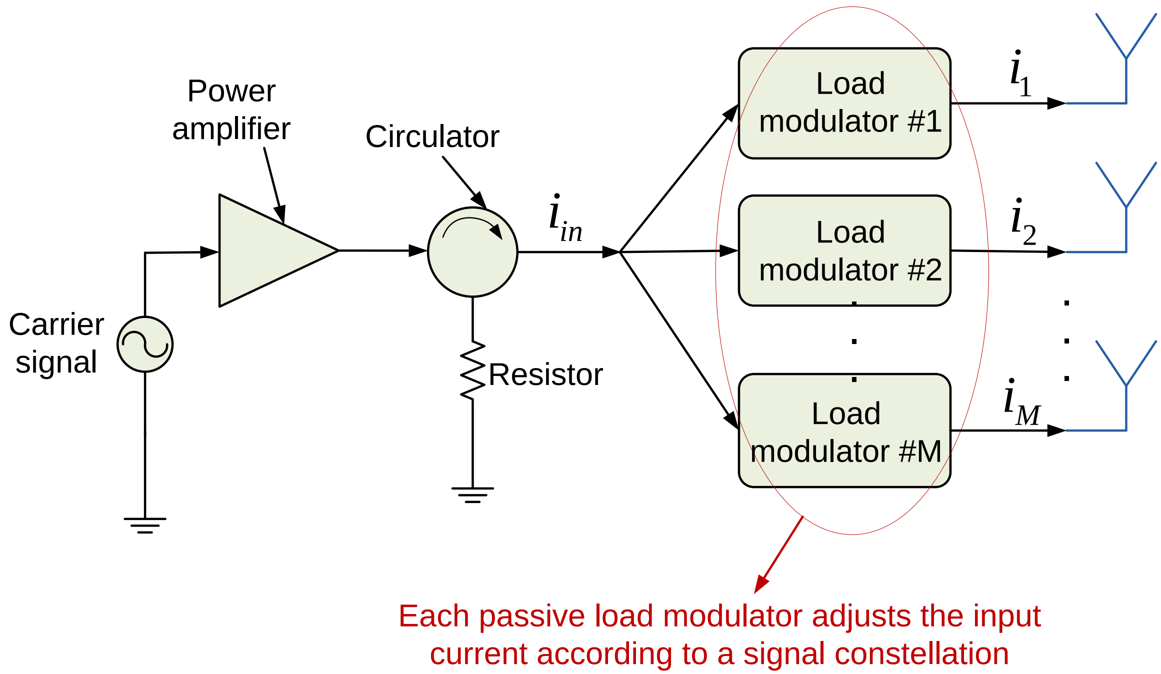


Generated 16-QAM constellation



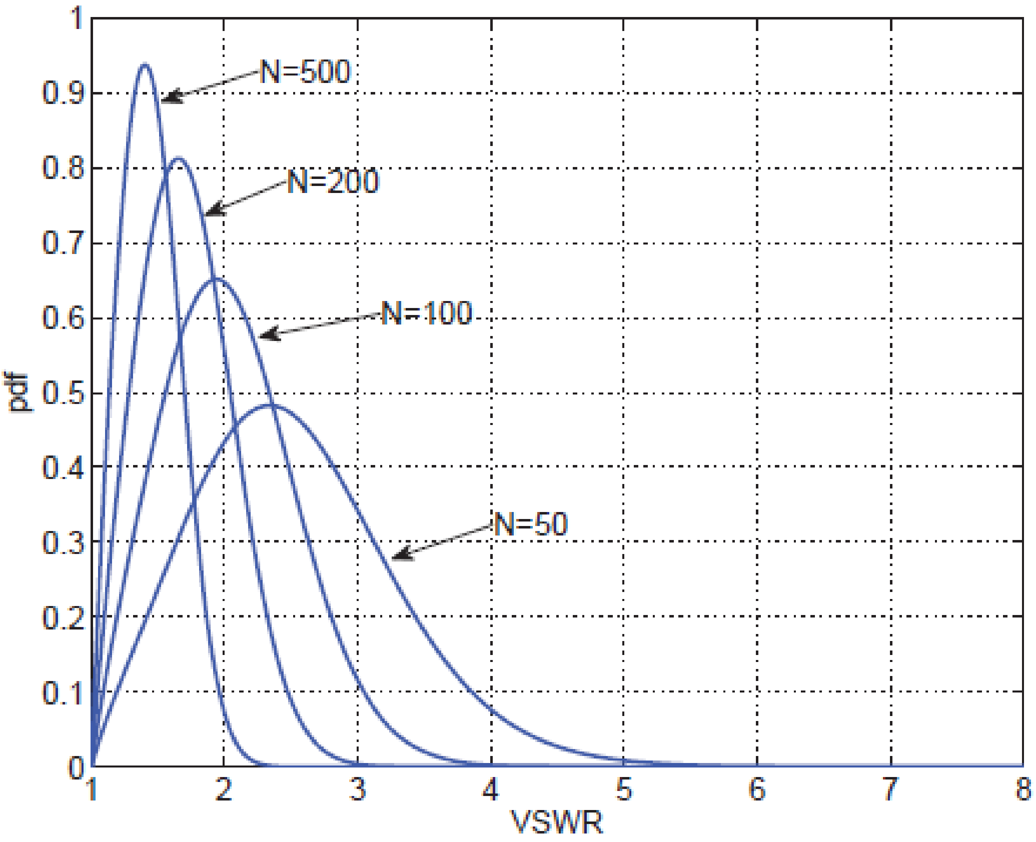
M. A. Sedaghat, R. R. Mueller, G. Fischer, "A Novel Single-RF Transmitter for Massive MIMO," In Proc. 18th International ITG Workshop on Smart Antennas (WSA), pp.1-8, 12-13 March 2014, Erlangen, Germany.

Load modulated designs for large arrays: A closer look



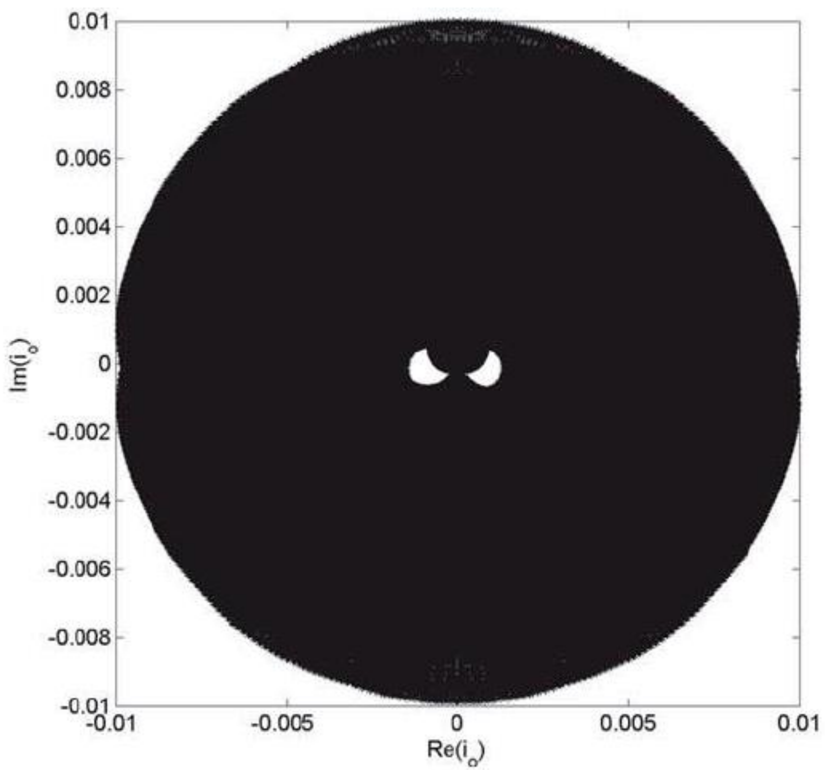
- A single carrier signal is assumed
- The antennas are far enough from each other to avoid mutual coupling
- To protect the power amplifier, the circulator grounds any reflected power through the resistor.
- Cheap and less power-hungry

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)

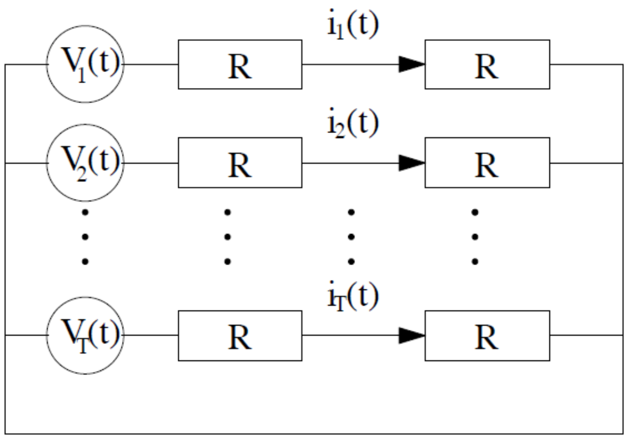
Single RF Load Massive Arrays (3/3)



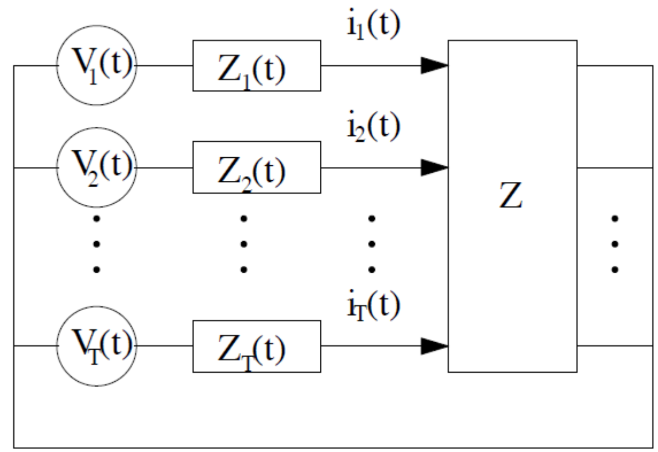
- Peak-to-average power ratio (PAPR) converges to one as the number of elements increases
- Highly efficient power amplifiers can be used (e.g. class F with 70% - 80% efficiency)
- Angry bird: current at the ports of the radiating elements: Almost any complex constellation is achievable by tuning the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

MIMO transmission architectures: an overall view

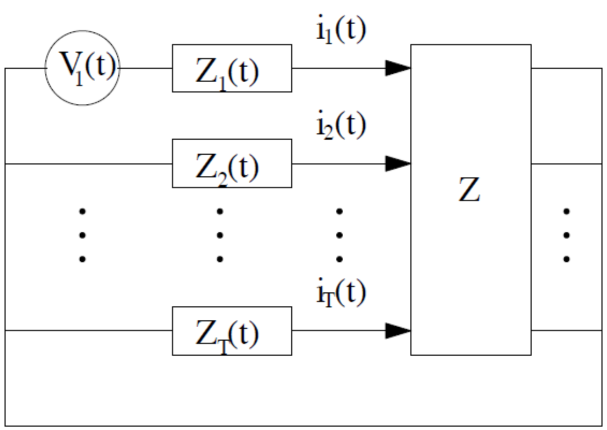
Conventional MIMO



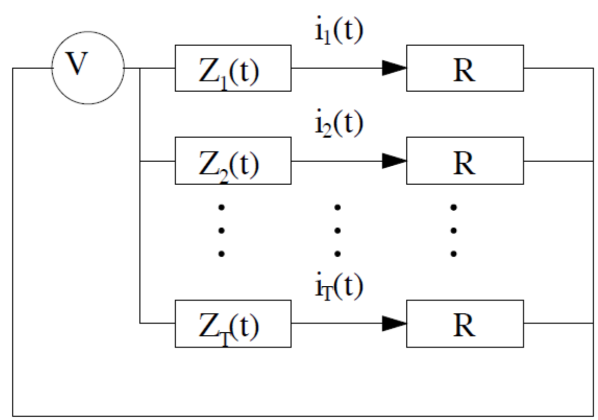
Close MIMO



ESPAR MIMO



New Load-Modulated MIMO

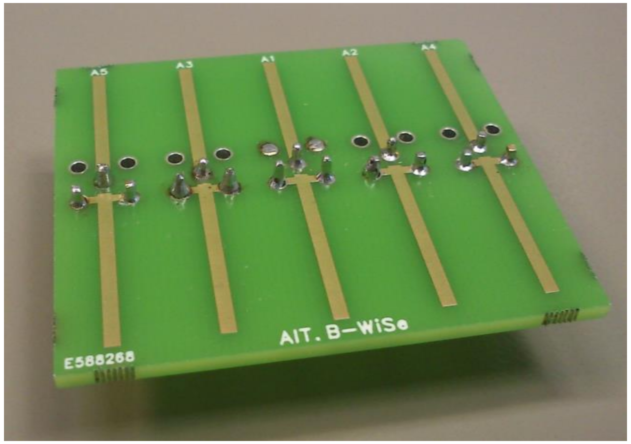


V. I. Barousis, M. Sedaghat, R. Muller and C. B. Papadias, "Massive Antenna Arrays with Low Front-End Hardware Complexity: An Enabling Technology for the Emerging Small Cell and Distributed Network Architectures ," arxiv.org, July 30, 2014.

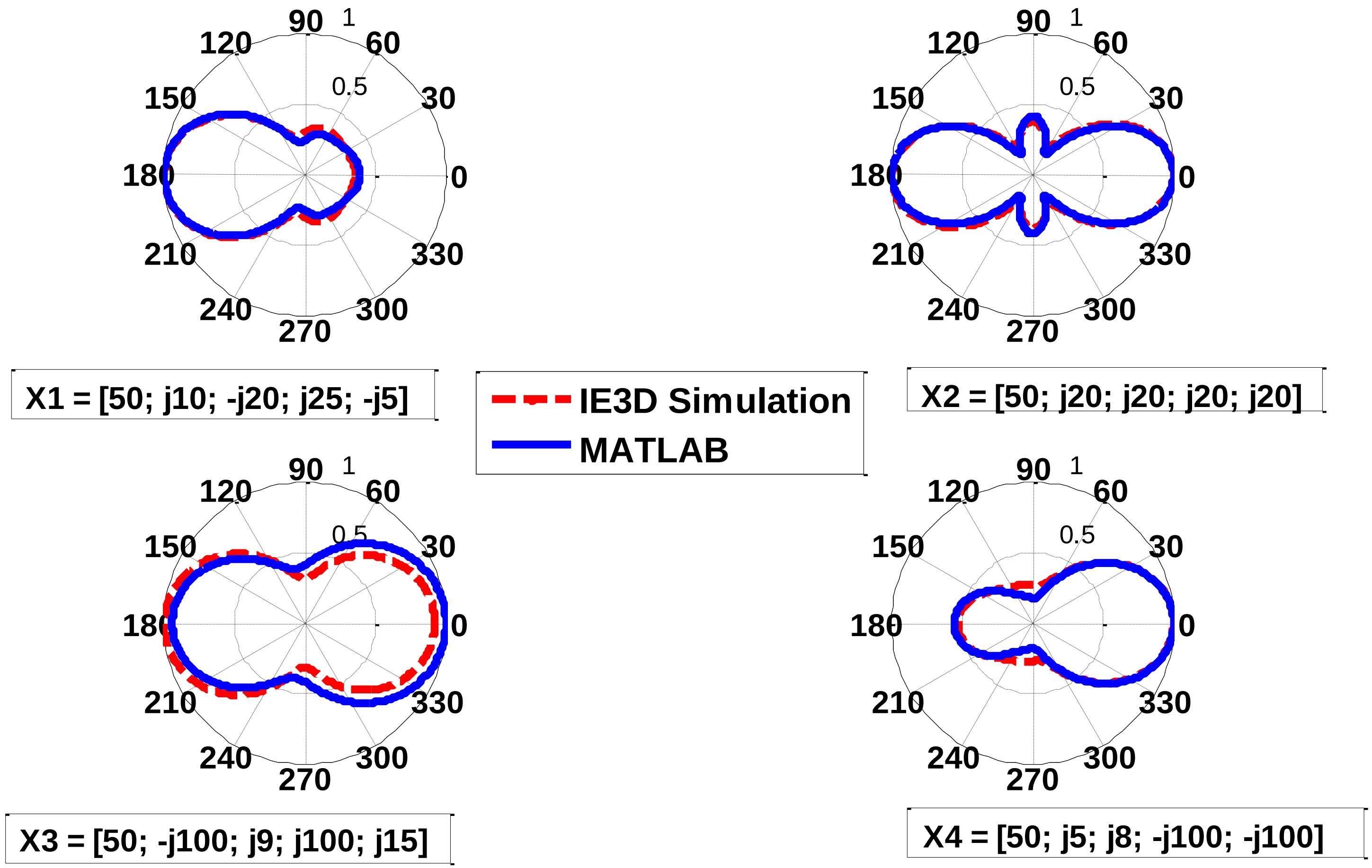
Some recent experiments

Prototype array for channel measurements

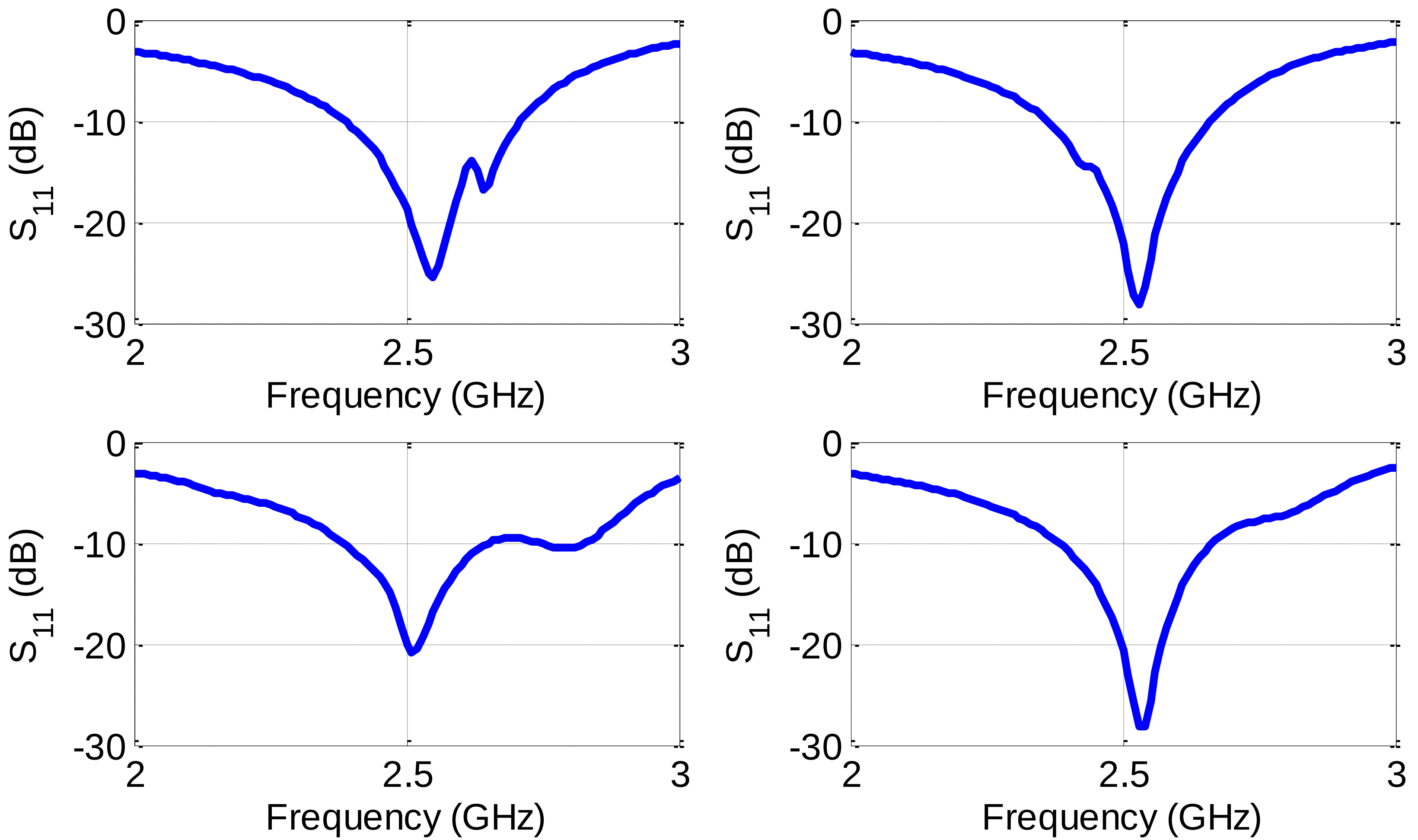
- **Simulation Tool: IE3D**
  - **It uses the Method of Moments (MoM) or Boundary Element Method (BEM).**
- **Main parameters for simulation:**
  - **Element Length: ~λ_0 / 2**
  - **Inter-element spacing: ~ λ_0 / 12**
- **Fabrication Imposed Parameters**
  - **Dielectric: FR4 (er = 4.45, tanδ = 0.017)**
  - **Substrate thickness: 1.6 mm**
  - **Copper trace thickness 35 μm**



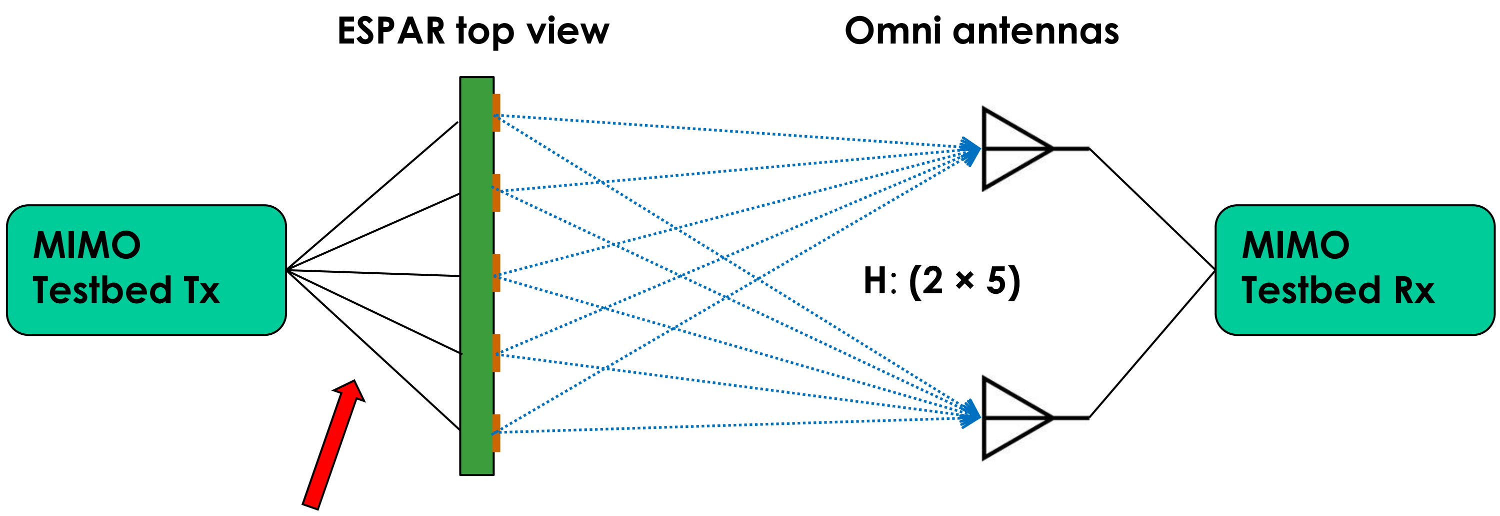
IE3D vs. Matlab: Comparison of radiation patterns for indicative loading values



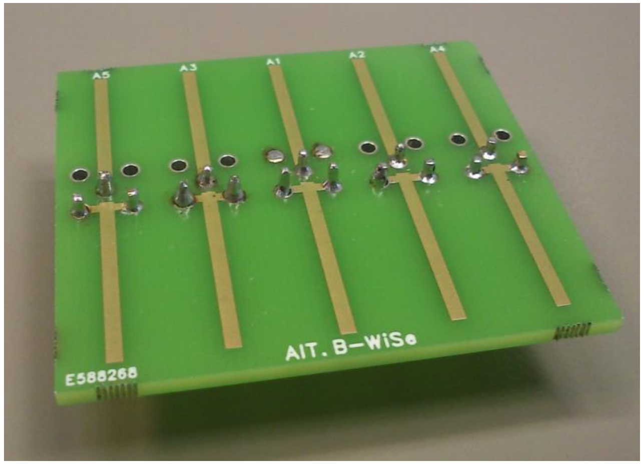
Indicative Reflection Coefficient curves vs. frequency



Measurement setup



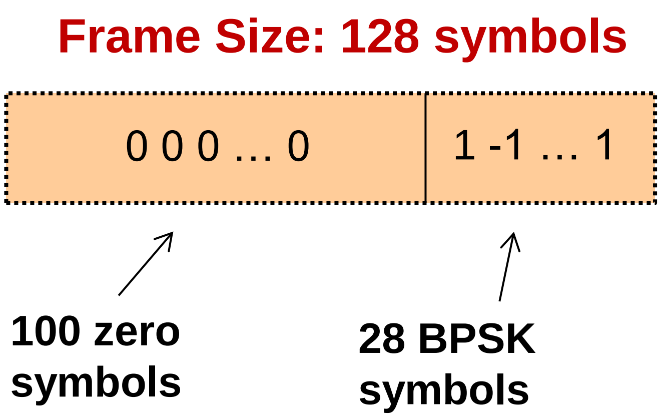
A parasitic design with 5 SMA connectors

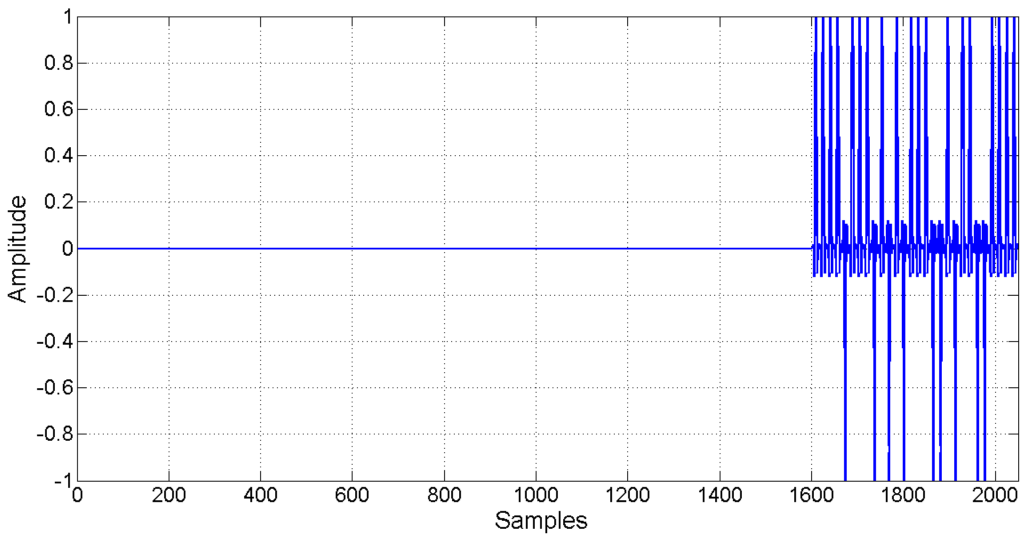


Goal: to estimate the channel matrix

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.**

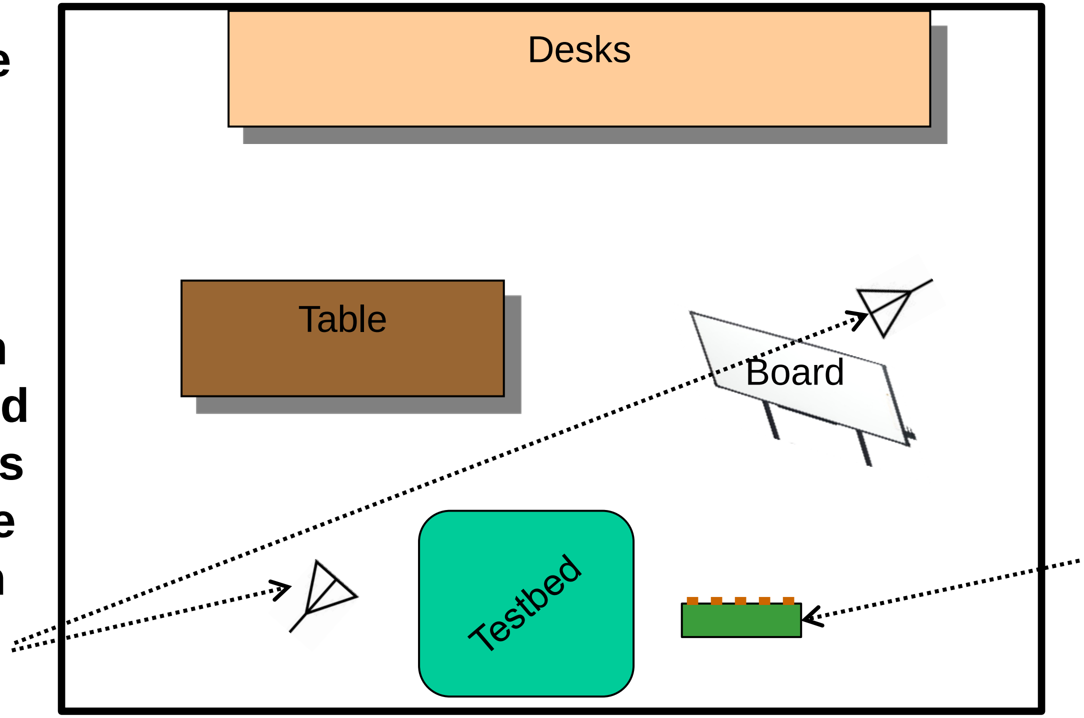




Measurement setup

Top View Configuration

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.

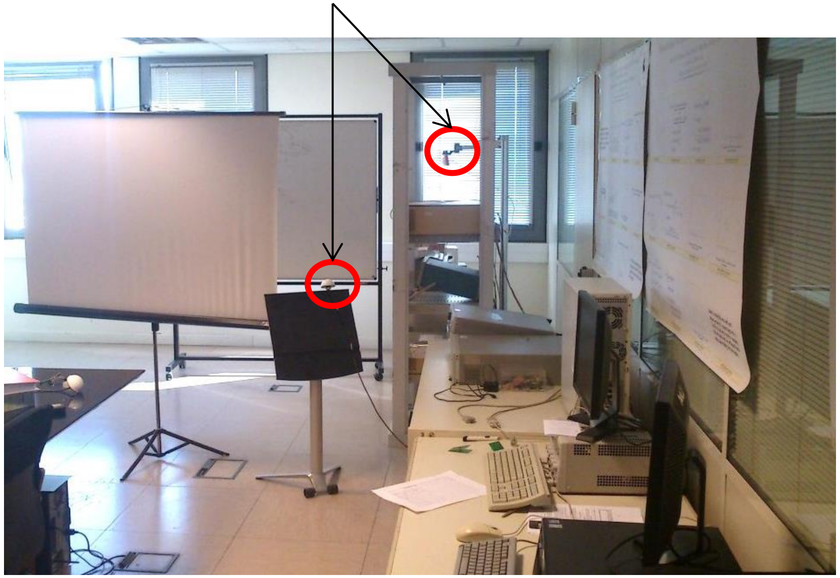
Channel estimation

- 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: $\mathbf{H = Y*X^T*(X*X^T)^{-1}}$

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

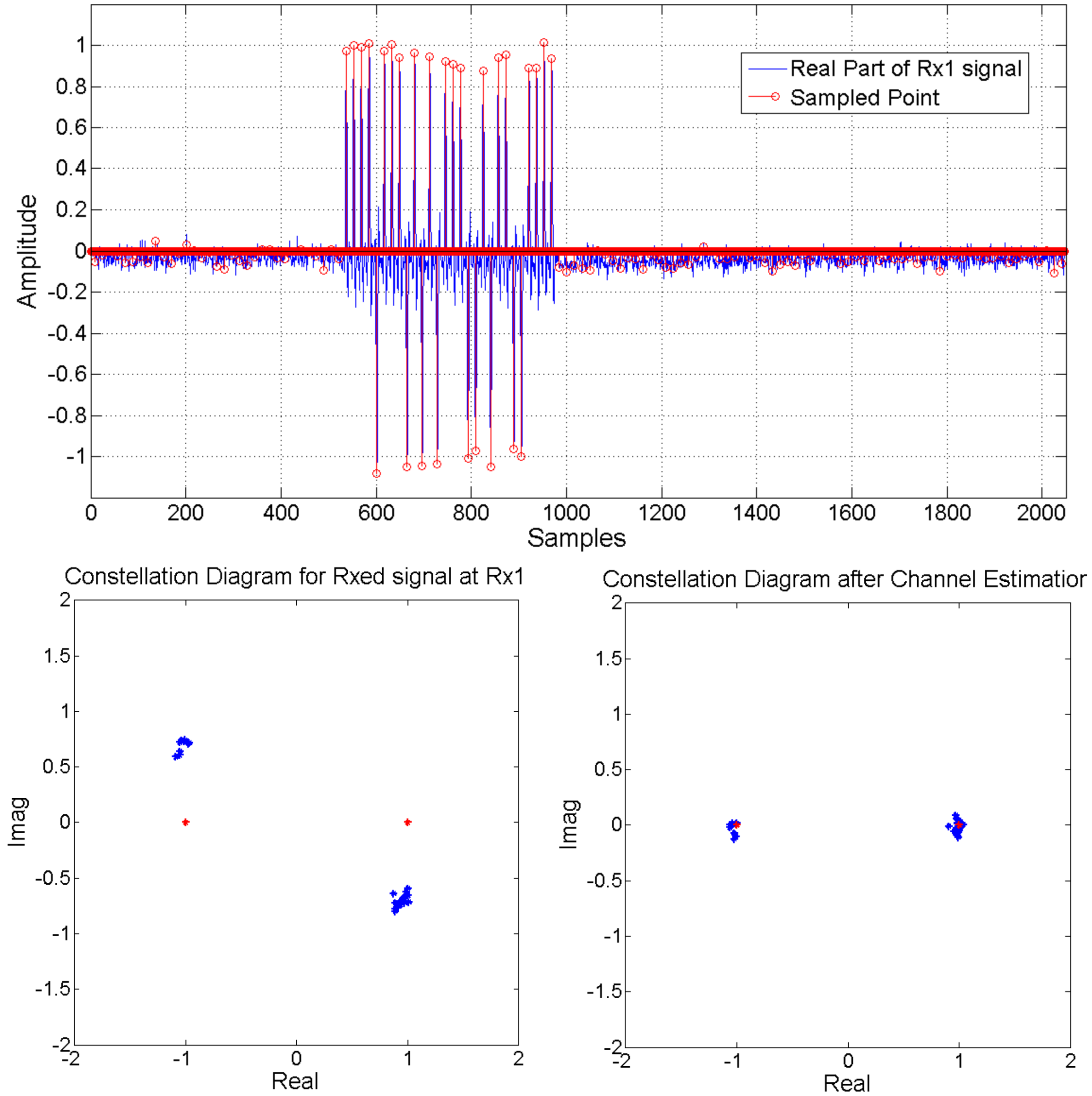
Rx Antennas



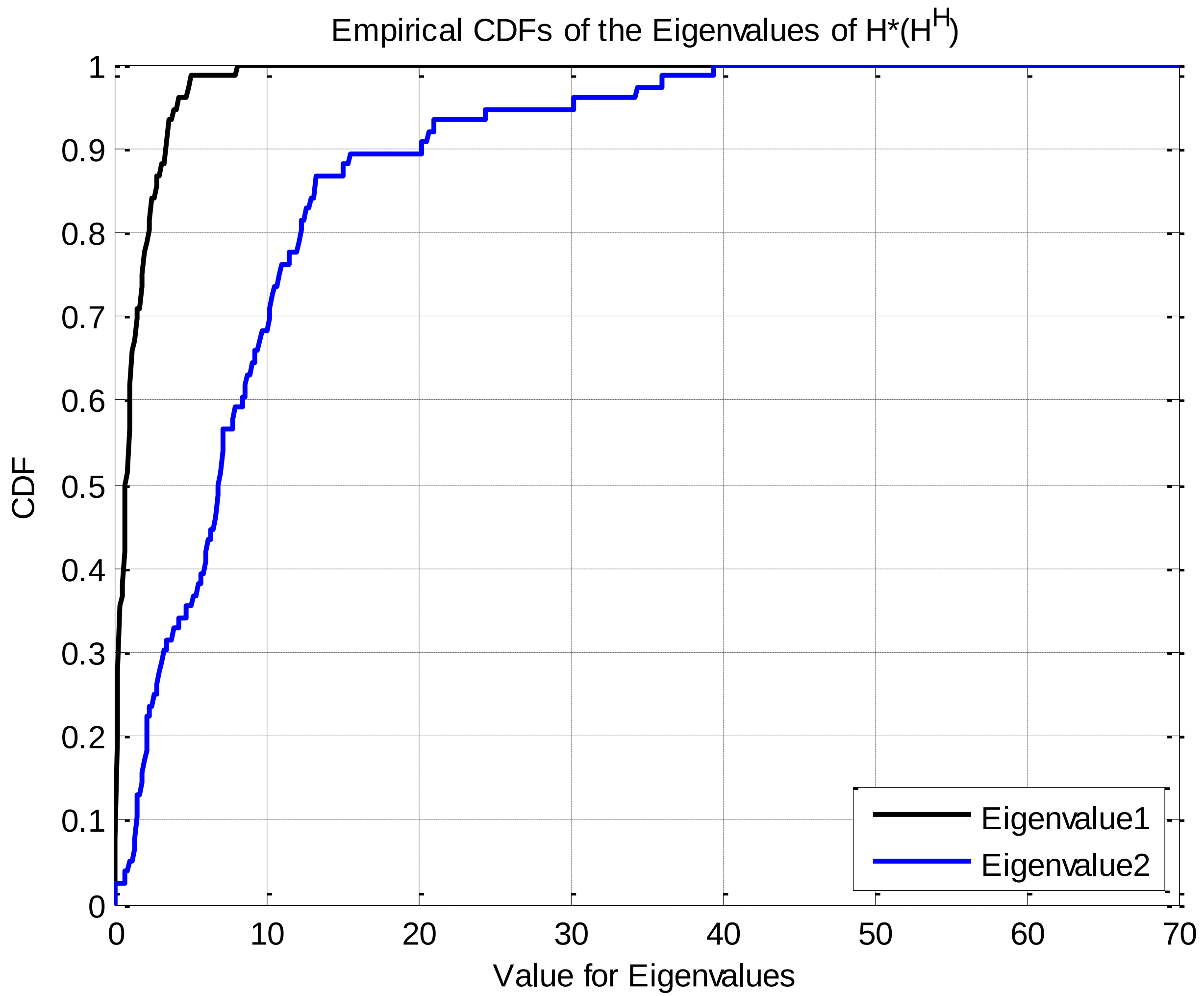
The spatial scenario involved scatterers (whiteboard, chairs, meeting table, drawers) and in most occasions there was no LoS component.

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.

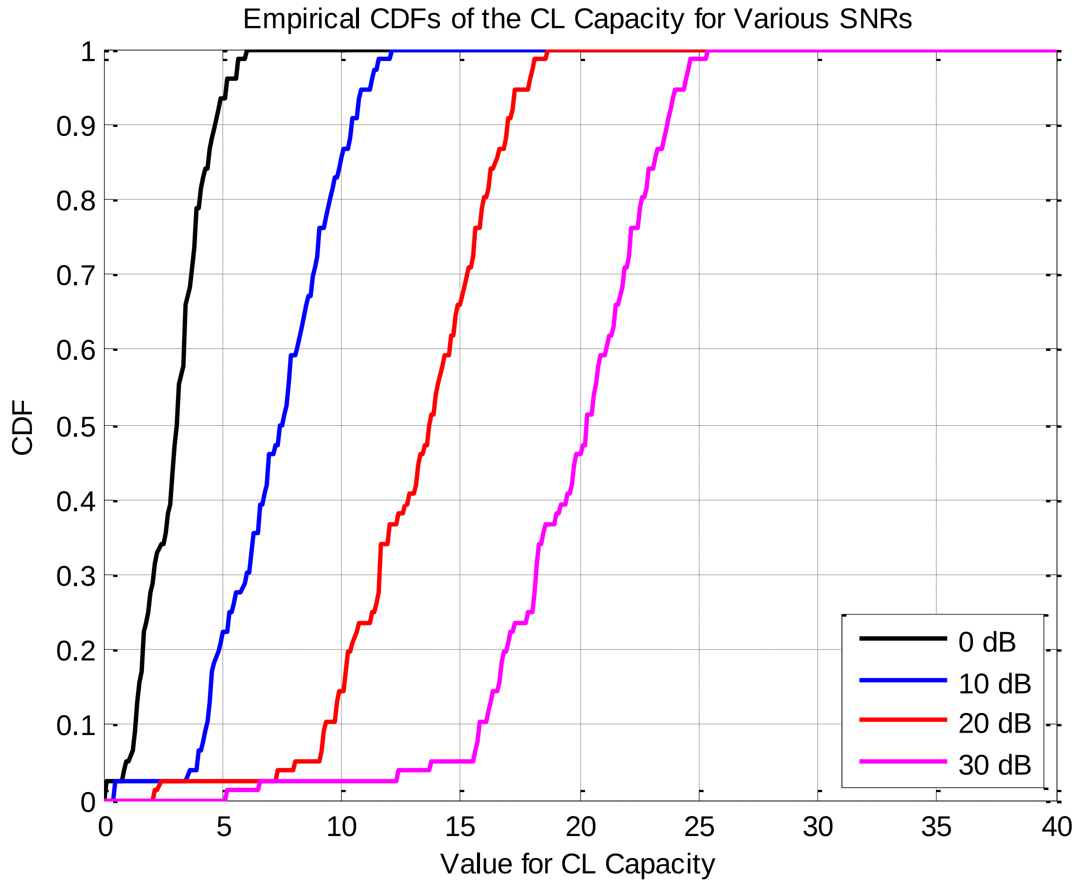


Spatial modes



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**

Acknowledgments

❖ **Research Grants:**

FP7 FET-Open grant CROWN-233843, www.fp7-crown.eu

FP7 PEOPLE-ITN-2008 SMARTEN- 238726, www.smarten-itn.eu

WISESPOT: Novel wireless sensor nodes with smart Antennas – Research Promotion Foundation Cyprus, http://www.wisespot.signalgenerix.com

FP7 FET-Open grant HIATUS-265578, http://www.fp7-hiatus.eu

FP7 Future Networks grant HARP-318489 http://www.fp7-harp.eu

❖ **My colleagues V. Barousis, L. Roumpakias, G. Alexandropoulos**

❖ **Our collaborators A. Kalis, A. Kanatas, P. Tragas, R. Mueller, M. Sedaghat**

❖ **Our former PhD students Osama Alrabadi, Elpiniki Tsakalaki & Bo Han**

Thank you!

For a closer look..