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ESPAR Antennas – A New Beamforming Scheme and the Applications

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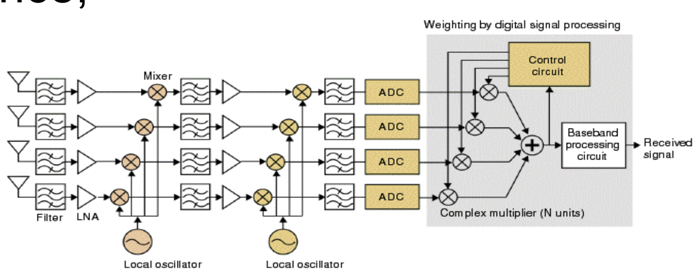
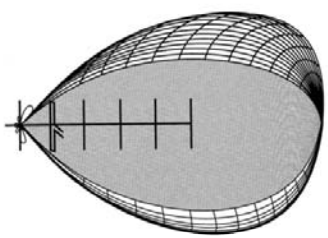
Introduction

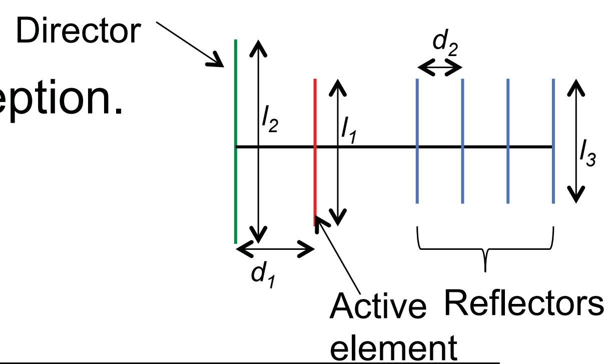
- Key trends to the next−generation networks: Smart antennas
- A smart antenna can be employed in a variety of ways: beamforming, direction finding, MIMO [1], etc.
- Challenges in the employment of multi-active antennas:
  - RF hardware complexity and cost,
  - power consumption,
  - antenna system efficiency,
  - inter-chain interference,
  - spatial correlation.



Parasitic Antennas

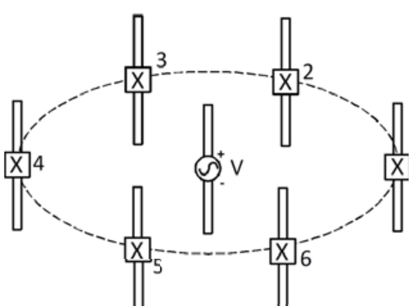
- Parasitic antennas use non-driven (parasitic) elements to achieve beamforming, where a parasitic element is connected to a simple control circuit rather than an expensive RF chain.
- The first parasitic antenna is the Yagi-Uda antenna [2]
  - Beamforming is achieved by changing the dimension (l_1,l_2,l_3 and d_1,d_2).
  - Extensively used for TV reception.



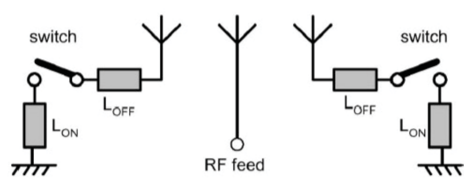


Parasitic Antennas

- Harrington's "reactively controlled array" [3]
  - A single dipole is surrounded by 6 parasitic elements each of which is loaded to reactive loads.

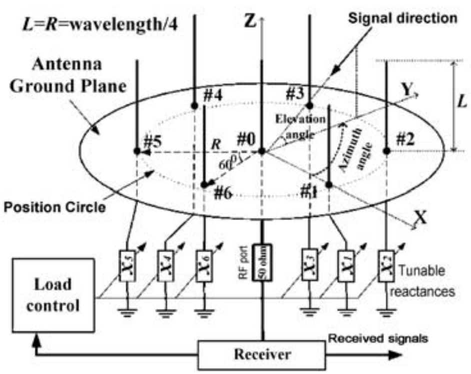


- Switched parasitic antenna [4]
  - A parasitic element becomes a reflector when shorted to the ground plane by the electronic switch, when not shorted, it has little effect on the beampattern response.

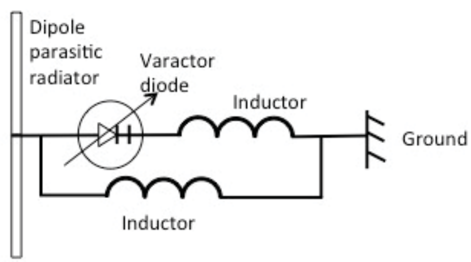


ESPAR Antennas

- ESPAR antenna is developed by Ohira *et al*. (2000) [5], which is a modified version of the Harrington Array in the sense that monopoles are mounted on a ground plane.



Classical 7-element ESPAR with a λ/4 spacing



Reactance load control circuit to a parasitic element

ESPAR Antennas

- Multi-active antennas vs. ESPARs

Multi-active antennas	ESPARs
x *M* RF chains	✓ 1 RF chain
x Large inter-element spacing >λ/2	✓ Small inter-element spacing ≤λ/4
x Mutual coupling is a problem	✓ Mutual coupling is required
✓ Less frequency dependent	x Characteristics change with frequency
✓ Wideband operation possible	x Only narrowband operation
✓ Concurrent signal sampling	x Sequential signal sampling

Applications: Adaptive beamforming

- The ESPAR produces a beampattern:

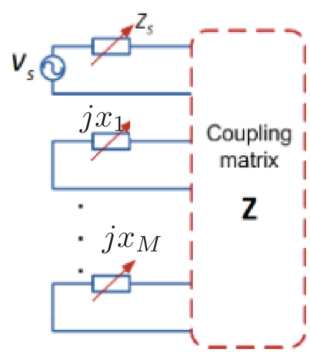
$$B(\theta) = \mathbf{w}^T \mathbf{a}(\theta),$$

where $\mathbf{a}(\theta)$ is the steering vector. $\mathbf{w} \in \mathbb{C}^{(M+1)}$ is the equivalent weight vector given by

$$\mathbf{w} = (\mathbf{Z} + \mathbf{X})^{-1} \mathbf{u}_0,$$

and the loading matrix is

$$\mathbf{X} = diag([Z_s \quad jx_1 \quad \cdots \quad jx_M]).$$



- ESPAR's beampattern $B(\theta)$ is a function of the reactance loads $jx_m, m = \{1, \cdots, M\}$.

Applications: Adaptive Beamforming

- Modify the MVDR algorithm as an iterative algorithm for ESPARs [6]:
  1) The estimate correlation matrix is obtained by measuring the signal via different beampatterns;
  2) Reformulate the MVDR optimization problem as a convex problem and introduce a projector for feasible reactance loads.

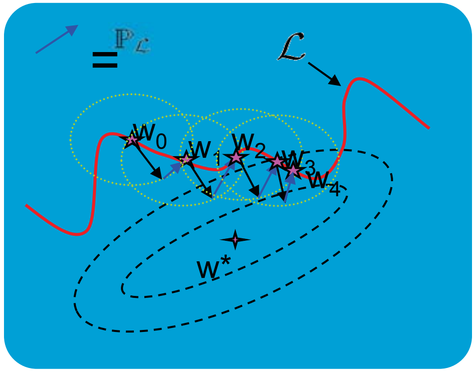
$$\min_{\mu_1,\mu_2,\tilde{\boldsymbol{v}}} \quad \beta_1\mu_1 + \beta_2\mu_2,$$

$$s.t. \quad \|\hat{\boldsymbol{U}}\tilde{\boldsymbol{v}}\|^2 \le \mu_1, \longrightarrow$$ Minimize output power

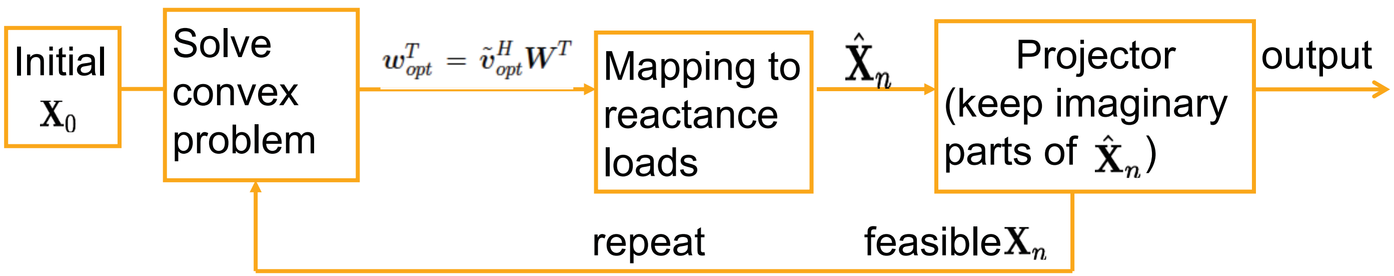
$$|\tilde{\boldsymbol{v}}^H \boldsymbol{a}_{rd}(\theta_d) - 1|^2 \le \mu_2, \longrightarrow$$ Distortionless response

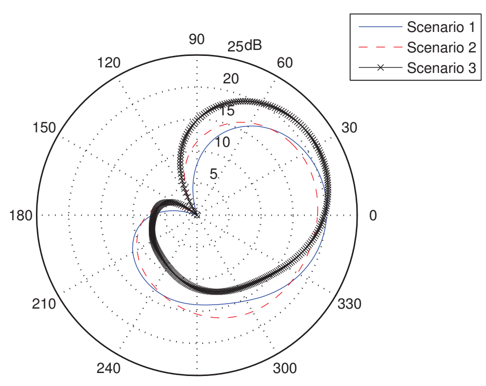
$$\|\bar{\boldsymbol{Z}}_L(\tilde{\boldsymbol{v}}^H \boldsymbol{W}^T)^T\|^2 \le \epsilon, \longrightarrow$$ Stay close to feasible set

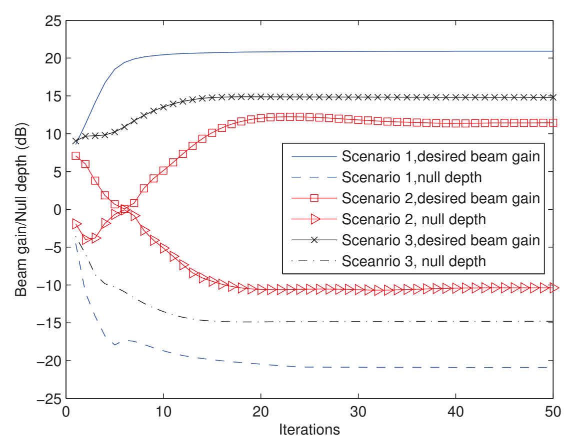
$$[\boldsymbol{Z}(\tilde{\boldsymbol{v}}^H \boldsymbol{W}^T)^T](1) + Z_s[(\tilde{\boldsymbol{v}}^H \boldsymbol{W}^T)^T](1) = 1. \longrightarrow$$ Constraint to Zs



Applications: Adaptive Beamforming







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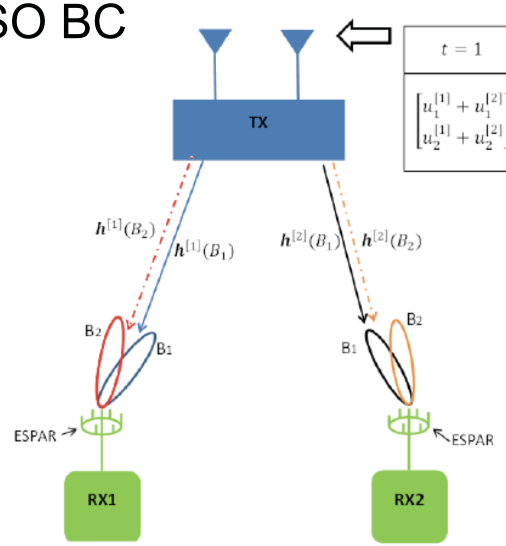
Applications: Blind Interference Alignment

- Blind interference alignment (BIA) [7] is a promising technique providing an optimal DoF in the multi-user MISO BC without knowledge of CSIT (channel state information at the transmitter).
- The key to BIA is antenna mode switching (e.g., frequency, polarization and beampattern) at the receiving end.
- Compared to frequency switching and polarization switching, the beampattern switching is an easier operating manner. Thus, the ESPAR antenna can be employed as the solution to beampattern switching for BIA [8-10].

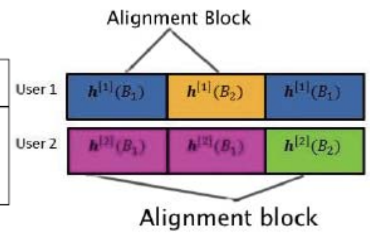
Applications: Blind Interference Alignment

Example: 2-User 2x1 MISO BC



Transmit signals

$t=1$	$t=2$	$t=3$
$\begin{bmatrix} u_1^{[1]}+u_1^{[2]} \\ u_2^{[1]}+u_2^{[2]} \end{bmatrix}$	$\begin{bmatrix} u_1^{[1]} \\ u_2^{[1]} \end{bmatrix}$	$\begin{bmatrix} u_1^{[2]} \\ u_2^{[2]} \end{bmatrix}$



Precoding Matrix

$$\begin{array}{cc} \begin{pmatrix} I_2 & I_2 \\ 0_2 & I_2 \\ I_2 & 0_2 \end{pmatrix} \\ \text{User 1} \quad \text{User 2} \end{array}$$

Supersymbol

$$\begin{bmatrix} y^{[1]}(1) \\ y^{[1]}(2) \\ y^{[1]}(3) \end{bmatrix} = \underbrace{\begin{bmatrix} \boldsymbol{h}^{[1]}(B_1) \\ \boldsymbol{h}^{[1]}(B_2) \\ \mathbf{0} \end{bmatrix} \begin{bmatrix} u_1^{[1]} \\ u_2^{[1]} \end{bmatrix}}_{\text{desired signal}} + \underbrace{\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \boldsymbol{h}^{[1]}(B_1) \begin{bmatrix} u_1^{[2]} \\ u_2^{[2]} \end{bmatrix}}_{\text{interference}} + \begin{bmatrix} z^{[1]}(1) \\ z^{[1]}(2) \\ z^{[1]}(3) \end{bmatrix}$$

$$\underbrace{\begin{bmatrix} y^{[1]}(1) - y^{[1]}(3) \\ y^{[1]}(2) \end{bmatrix}}_{\tilde{\boldsymbol{y}}^{[1]}} = \underbrace{\begin{bmatrix} \boldsymbol{h}^{[1]}(B_1) \\ \boldsymbol{h}^{[1]}(B_2) \end{bmatrix}}_{\tilde{\boldsymbol{H}}^{[1]}} \begin{bmatrix} u_1^{[1]} \\ u_2^{[1]} \end{bmatrix} + \begin{bmatrix} z^{[1]}(1) - z^{[1]}(3) \\ z^{[1]}(2) \end{bmatrix}$$

$t=1$	$t=2$	$t=3$
B_1	B_2	B_1

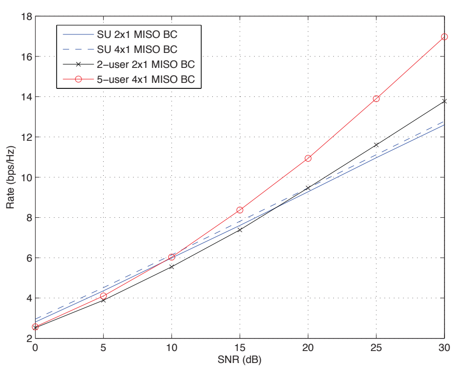
$t=1$	$t=2$	$t=3$
B_1	B_1	B_2

Antenna switching patterns

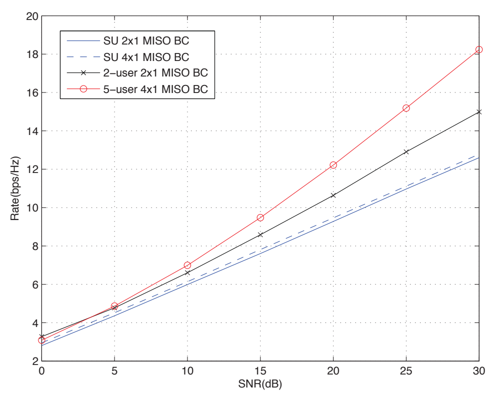
Applications: Blind Interference Alignment

- Three ESPAR beamforming methods for BIA:

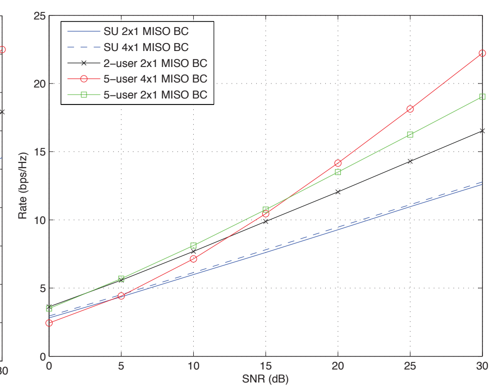
1) Random beamforming



2) Sector beam selection



3) SVD beamforming



Applications: DoA Estimation

- Compressive sensing based DoA estimation is with high resolution, reduced sampling numbers, robust to noise and correlated signals [11].
- **Overcomplete dictionary**: discretize the azimuth plane $\tilde{\theta} = [\tilde{\theta}_1, \tilde{\theta}_2, \cdots, \tilde{\theta}_{N_\theta}]$, $N_\theta \gg P$ (the number of source signals),

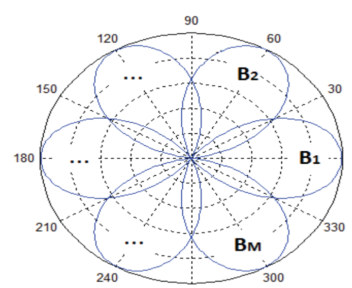
therefore the overcomplete dictionary is $\tilde{A} = [a(\tilde{\theta}_1), a(\tilde{\theta}_2), \cdots, a(\tilde{\theta}_{N_\theta})]$.

- **Projection matrix**: introduce a projection matrix $W = [w_1, w_2, \cdots, w_M]^T$ to project the spare signal into measures in beamspace.

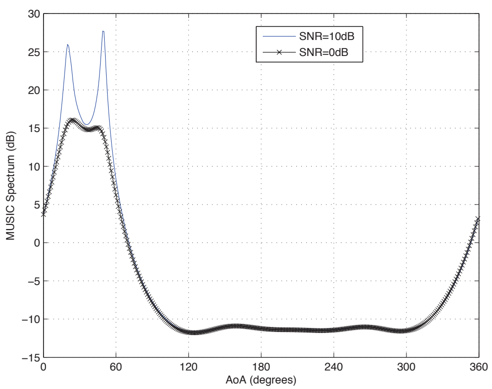
  Sparse representation problem:

$$y = r + e = W\tilde{A}\tilde{s} + e,$$

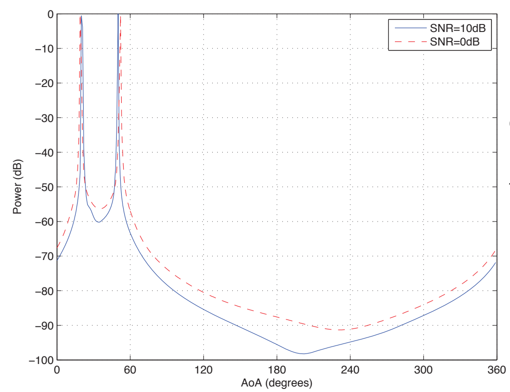
$$\tilde{s}_n(t) = \begin{cases} s_p(t) & \tilde{\theta}_n = \theta_p, \\ 0 & otherwise \end{cases}$$



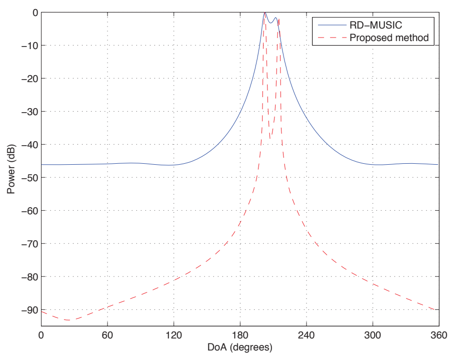
Applications: DoA Estimation



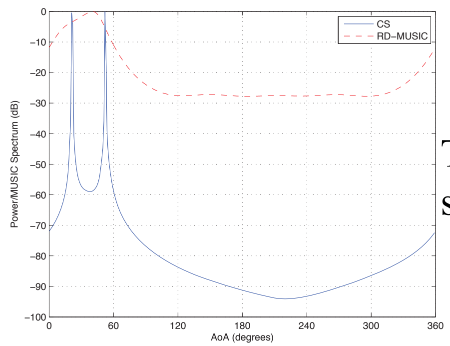
RD-MUSIC
200 samples



CS
200 samples



Two incident signals with 15° separation



Two correlated source signals

Conclusions

- ESPAR antennas, using a single RF chain, is suitable for applications of the small terminals.
- A fast adaptive beamforming is modified from the MVDR algorithm.
- ESPAR antennas can be employed as the beam switching solution for the implementation of BIA. Moreover, the directional beampattern helps to improve the BIA performance by enhancing receive SNR.
- The compressive sensing has been studied for the DoA estimation with the ESPAR antenna, and showed the superiority to the MUSIC algorithm.

Acknowledgements

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