Reconfigurable thinning for the maximization of the SINR in adaptive linear arrays

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Abstract

In this report, an easily-reconfigurable and low-complexity antenna architecture is considered where a set of radio-frequency switches is exploited to either connect or disconnect the array elements for controlling the radiation pattern and generating deep nulls along the directions-of-arrival of the undesired signals. The mathematical formulation together with a preliminary validation of the adaptive nulling strategy are proposed.

Part I

Mathematical Formulation

Mathematical Formulation

Multiple Interferences at the Central Frequency - SINR Maximization

Consider a linear array of N isotropic elements equally spaced along the x axis: the desired signal received by the n-th element of the antenna array can be defined as

$$S_n^d(t) = p_d(t)e^{j\beta_n^d} \quad n = 1, ..., N \tag{1}$$

where $\beta_n^d = (2\pi/\lambda)(u_d x_n)$, $u_d = \sin\theta_d \cos\phi_d$, x_n is the distance between the n-th element and the center of the array e θ_d, ϕ_d are the polar coordinates defining the direction of arrival (DOA) of the desired signal characterized by envelope $p_d(t)$. Assuming that one or more (I) interfering signals can be received by the antenna at the same angular frequency ω_d of the desired signal, it is possible to evaluate the contribution of each interference at the n-th element:

$$S_n^i(t) = p_i(t)e^{j\beta_n^i} \quad \left\{ \begin{array}{c} n = 1, ..., N \\ i = 1, ..., I \end{array} \right. \tag{2}$$

where $\beta_n^i = (2\pi/\lambda)(u_i x_n)$, $u_i = \sin\theta_i \cos\phi_i$ e θ_i, ϕ_i are the polar coordinates defining the direction of arrival (DOA) of the i-th interfering signal characterized by envelope $p_i(t)$. Moreover, let assume the presence of the noise modelled with an additive gaussian process with power $\wp_n$.

Hence, the coefficients of the covariance matrix $(N \times N)$ of the desired signal Φ_d are

$$\Phi_d^{mn} = E\left\{S_m^{d*}(t)S_n^d(t)\right\} \quad m, n = 1, ..., N \tag{3}$$

Similarly, it is possible to write the coefficients of the covariance matrix Φ_i of the i-th interfering signal ($i = 1, ..., I$) as

$$\Phi_i^{mn} = E\left\{S_m^{i*}(t)S_n^i(t)\right\} \quad m, n = 1, ..., N \tag{4}$$

while the covariance matrix of the noise is defined

$$\Phi_n = p_n 1^N \tag{5}$$

where 1^N is an identity matrix with dimension $N \times N$.

Let us write the covariance matrix of the undesired signal with the form

$$\Phi_u = \sum_{i=1}^{I} \Phi_i + \Phi_n \tag{6}$$

The power of the undesired signal received at the central frequency is

$$\wp_u = \frac{1}{2}\underline{W}^{T*}\Phi_u\underline{W} \tag{7}$$

where $\underline{W}$ is defined as

$$\underline{W} = \left\{\alpha_n e^{j\gamma_n}, \;\; n = 1, ..., N\right\} \tag{8}$$

where α_n amplitude excitation coefficients of the n-th element and γ_n is the phase excitation coefficient of the n-th element of the array. Using a thinning technique, the possible solutions of α_n are just two values: $\alpha_n \in \Upsilon, \;\; n = 1, ..., N$, where $\Upsilon = [\{0\}, \{1\}]$. We consider $\gamma_n = 0, \;\; n = 1, ..., N$.

The power contribution of the desired signal at the receiver is

$$\wp_d = \frac{1}{2} p_d^2(t) \left| W^T \underline{U}(\theta_d, \phi_d) \right|^2 \tag{9}$$

where

$$\underline{U}(\theta_d, \phi_d) = \left\{ e^{j\beta_n^d}, \;\; n = 1, ..., N \right\} \tag{10}$$

Considering (7) and (9) the SINR (*Signal to Interferience plus Noise Ratio)* can be defined as:

$$\Psi(\underline{G}) \triangleq \frac{\wp_d}{\wp_u} = \frac{p_d^2(t) \left| W^T \underline{U}(\theta_d, \phi_d) \right|^2}{\underline{W}^{T*} \Phi_u \underline{W}} \tag{11}$$

Since Φ_u and $p_d^2(t)$ are not directly misurable, (11) is not useful. But, it is possible to reformulate the SINR maximization problem through the following cost function

$$f(\underline{G}) = \frac{\left| W^T \underline{U}(\theta_d, \phi_d) \right|^2}{\underline{W}^{T*} \Phi_t \underline{W}} \tag{12}$$

where $\Phi_t = \Phi_d + \sum_{i=1}^{I} \Phi_i + \Phi_n$ is a quantity that can be measured at the receiver.

Part II

Preliminary Results - Unconstrained Directivity Cases

TEST CASE 1 - 40 Elements - Fixed Scenario, Single Interference

Goal

Maximization of the SINR using genetic algorithms (GA) to determine the optimal thinned array configuration, considering a static scenario with a single interference.

Test Case Description

- Number of Elements $N = 40$
- Elements Spacing: $d = 0.5\lambda$
- Max Gain Pattern Direction : $\theta^d = 90°$, $\phi^d = 90°$
- Desired Signal Power: $0\,dB$
- Interference Power: $30\,dB$
- Noise Power: $-30\,dB$
- Number of Interferences: $N_I = 1$
- Interference Direction Of Arrival: $\theta_1^i = 90°$, $\phi_1^i = 42°$

Optimization Approach: GA

- Number of Variables: $X = 40$ $(\alpha_n,\, n = 1, ..., N)$
- Population: 40
- Crossover Probability: 0.9
- Mutation Probability: 0.01
- Number of Generations: 50

GA - Single Interference: $\theta_1^i = 90°$, $\phi_1^i = 42°$

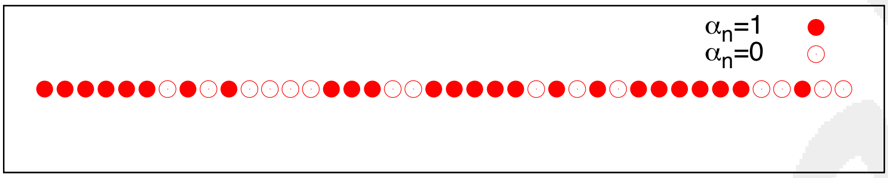

Fig.1 - Thinning Configuration

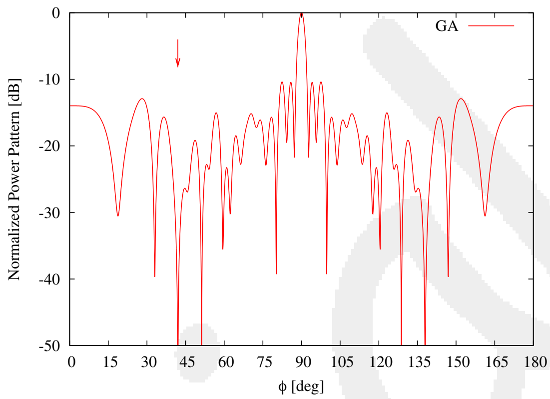

Fig.2 - Pattern

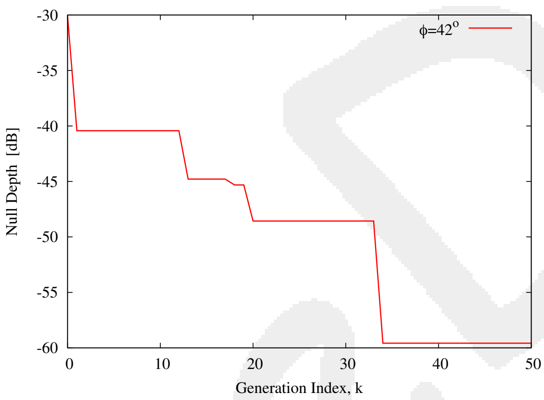

Fig.3 - Nulls Depth

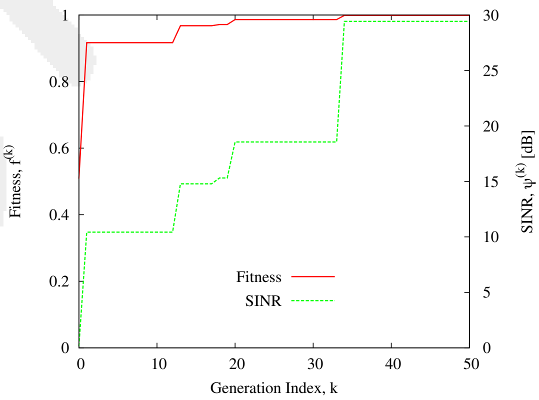

Fig.4 - Fitness - SINR

	$AF(\theta_1^i, \phi_1^i)$	$Nr. Active\ Elements$	$SINR\,[dB]$
GA	-59.58	25	29.42

Tab.1 - GA Simulation Results Analysis

TEST CASE 2 - 40 Elements - Fixed Scenario, Double Interference

Goal

Maximization of the SINR using genetic algorithms (GA) to determine the optimal thinned array configuration, considering a static scenario with a double interference.

Test Case Description

- Number of Elements $N = 40$
- Elements Spacing: $d = 0.5\lambda$
- Max Gain Pattern Direction : $\theta^d = 90°$, $\phi^d = 90°$
- Desired Signal Power: $0\,dB$
- Interference Power: $30\,dB$
- Noise Power: $-30\,dB$
- Number of Interferences: $N_I = 2$
- Interference Direction Of Arrival: $\theta_1^i = 90°$, $\phi_1^i = 42°$, $\theta_2^i = 90°$, $\phi_2^i = 113°$

Optimization Approach: GA

- Number of Variables: $X = 40$ (α_n, $n = 1, ..., N$)
- Population: 40
- Crossover Probability: 0.9
- Mutation Probability: 0.01
- Number of Generations: 100

GA - Double Intereference: $\theta_1^i = 90°$, $\phi_1^i = 42°$, $\theta_2^i = 90°$, $\phi_2^i = 113°$

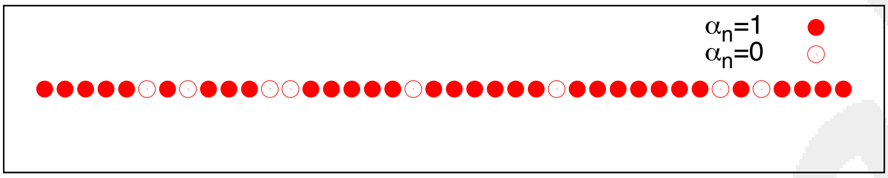

Fig.5 - Thinning Configuration

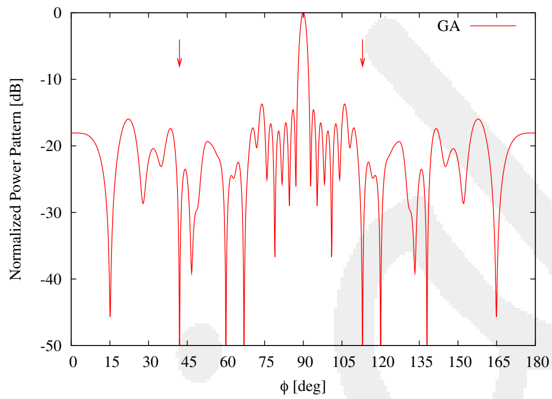

Fig.6 - Pattern

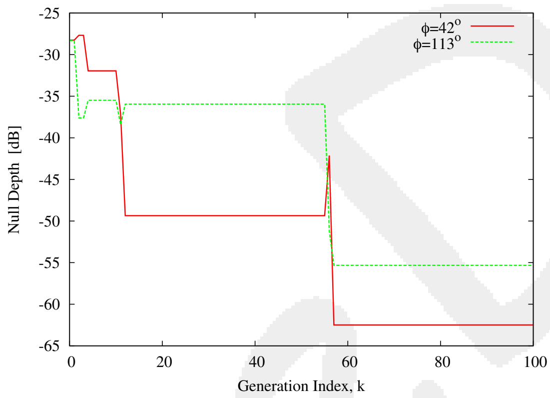

Fig.7 - Null Depth

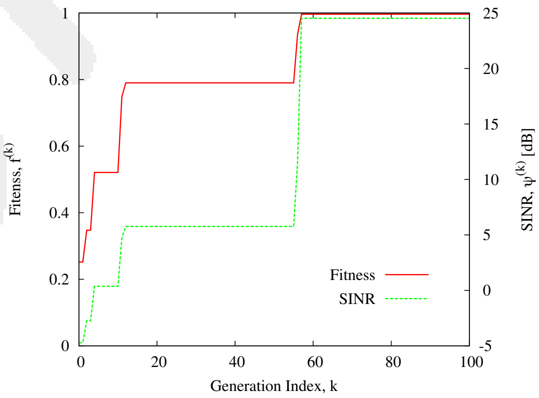

Fig.8 - Fitness - SINR

	$AF(\theta_1^i, \phi_1^i)$	$AF(\theta_2^i, \phi_2^i)$	*Nr. Active Elements*	$SINR\,[dB]$
GA	-62.49	-55.32	32	24.52

Tab.2 - GA Simulation Results Analysis

TEST CASE 3 - 40 Elements - Fixed Scenario, Triple Interference

Goal

Maximization of the SINR using genetic algorithms (GA) to determine the optimal thinned array configuration, considering a static scenario with a triple interference.

Test Case Description

- Number of Elements $N = 40$
- Elements Spacing: $d = 0.5\lambda$
- Max Gain Pattern Direction : $\theta^d = 90°$, $\phi^d = 90°$
- Desired Signal Power: $0\,dB$
- Interference Power: $30\,dB$
- Noise Power: $-30\,dB$
- Number of Interferences: $N_I = 3$
- Interference Direction Of Arrival: $\theta_1^i = 90°$, $\phi_1^i = 42°$, $\theta_2^i = 90°$, $\phi_2^i = 113°$, $\theta_3^i = 90°$, $\phi_3^i = 175°$

Optimization Approach: GA

- Number of Variables: $X = 40$ (α_n, $n = 1, ..., N$)
- Population: 40
- Crossover Probability: 0.9
- Mutation Probability: 0.01
- Number of Generations: 100

GA - Triple Interference: $\theta_1^i = 90°$, $\phi_1^i = 42°$, $\theta_2^i = 90°$, $\phi_2^i = 113°$, $\theta_3^i = 90°$, $\phi_3^i = 175°$

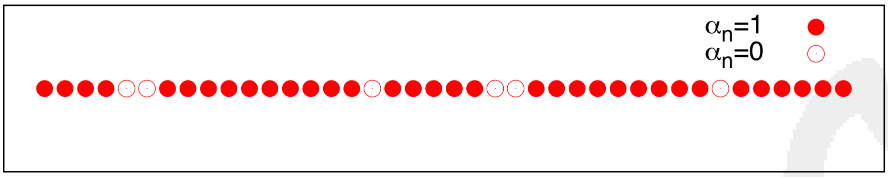

Fig.9 - Thinning Configuration

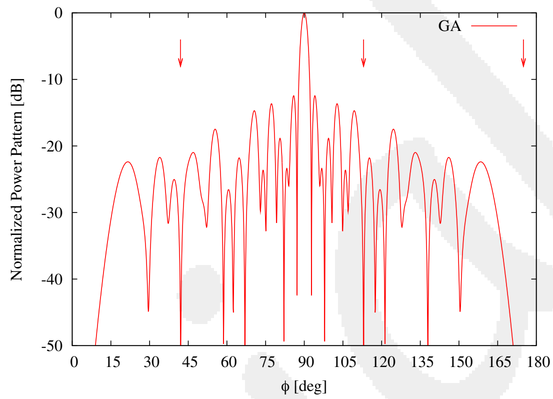

Fig.10 - Pattern

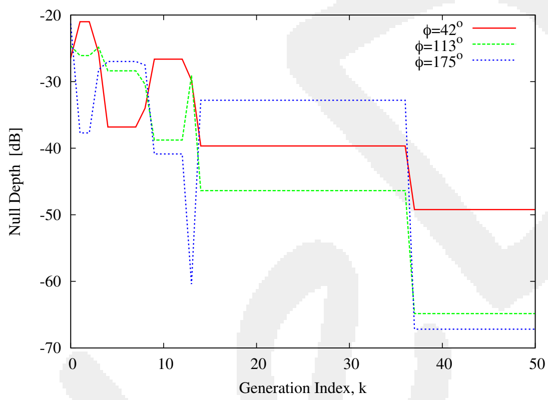

Fig.11 - Nulls Depth

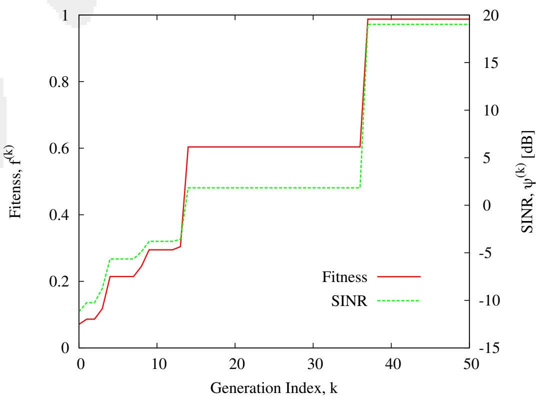

Fig.12 - Fitness - SINR

	$AF(\theta_1^i, \phi_1^i)$	$AF(\theta_2^i, \phi_2^i)$	$AF(\theta_3^i, \phi_3^i)$	$Nr. Active\ Elements$	$SINR\,[dB]$
GA	-49.21	-64.83	-67.19	34	19.02

Tab.3 - GA Simulation Results Analysis

TEST CASE 4 - 40 Elements - Time-Varying Scenario

Goal

Maximization of the SINR using genetic algorithms (GA) to determine the optimal thinned array configuration, considering a time-varying scenario.

Test Case Description

- Number of Elements $N = 40$
- Elements Spacing: $d = 0.5\lambda$
- Max Gain Pattern Direction : $\theta^d = 90°$, $\phi^d = 90°$
- Desired Signal Power: $0\,dB$
- Interference Power: $30\,dB$
- Noise Power: $-30\,dB$
- Number of Interferences: variable
- Timesteps: $T = 900$

Optimization Approach: GA

- Number of Variables: $X = 40$ (α_n, $n = 1, ..., N$)
- Population: 40
- Crossover Probability: 0.9
- Mutation Probability: 0.01
- Number of Generations (for each iteration of the time-varying scenario): 200

GA - Time-Varying Scenario

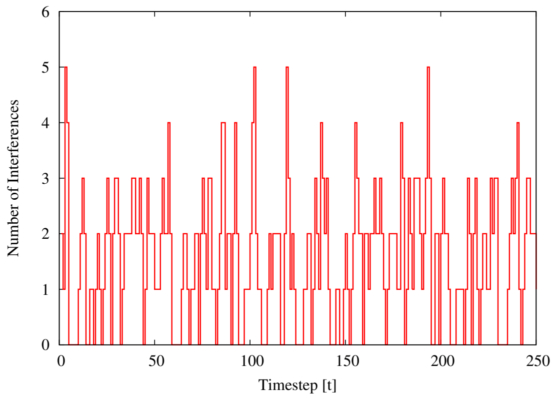

Fig.13 - Number of Interferences

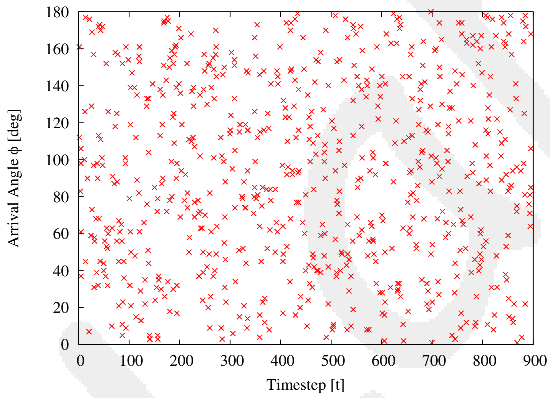

Fig.14 - Arrival Angle

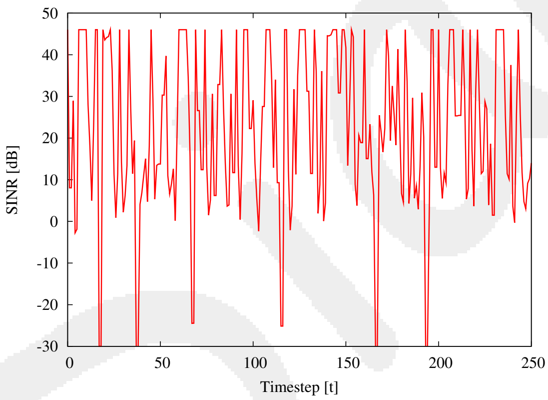

Fig.15 - Time-Varying SINR

	$Min\{SINR\}$ $[dB]$	$Max\{SINR\}$ $[dB]$	$Average\{SINR\}$ $[dB]$	$Variance\{SINR\}$ $[dB]$
GA	-30.00	46.02	23.38	351.85

Tab.4 - SINR statistics

	$Min\{N_{ON}\}$	$Max\{N_{ON}\}$	$Average\{N_{ON}\}$	$Variance\{N_{ON}\}$
GA	4	40	31.10	41.46

Tab.5 - Number of Active Elements (N_{ON}) statistics

References

[1] P. Rocca, M. Benedetti, M. Donelli, D. Franceschini, and A. Massa, "Evolutionary optimization as applied to inverse problems," Inverse Problems - 25 th Year Special Issue of Inverse Problems, Invited Topical Review, vol. 25, pp. 1-41, Dec. 2009.

[2] P. Rocca, G. Oliveri, and A. Massa, "Differential Evolution as applied to electromagnetics," IEEE Antennas Propag. Mag., vol. 53, no. 1, pp. 38-49, Feb. 2011.

[3] P. Rocca, L. Poli, G. Oliveri, and A. Massa, "Adaptive nulling in time-varying scenarios through time-modulated linear arrays," IEEE Antennas Wireless Propag. Lett., vol. 11, pp. 101-104, 2012.

[4] M. Benedetti, G. Oliveri, P. Rocca, and A. Massa, "A fully-adaptive smart antenna prototype: ideal model and experimental validation in complex interference scenarios," Progress in Electromagnetic Research, PIER 96, pp. 173-191, 2009.

[5] M. Benedetti, R. Azaro, and A. Massa, "Memory enhanced PSO-based optimization approach for smart antennas control in complex interference scenarios," IEEE Trans. Antennas Propag., vol. 56, no. 7, pp. 1939-1947, Jul. 2008.

[6] M. Benedetti, R. Azaro, and A. Massa, "Experimental validation of a fully-adaptive smart antenna prototype," Electronics Letters, vol. 44, no. 11, pp. 661-662, May 2008.

[7] R. Azaro, L. Ioriatti, M. Martinelli, M. Benedetti, and A. Massa, "An experimental realization of a fully-adaptive smart antenna," Microwave Opt. Technol. Lett., vol. 50, no. 6, pp. 1715-1716, Jun. 2008.

[8] M. Donelli, R. Azaro, L. Fimognari, and A. Massa, "A planar electronically reconfigurable Wi-Fi band antenna based on a parasitic microstrip structure," IEEE Antennas Wireless Propag. Lett., vol. 6, pp. 623-626, 2007.

[9] M. Benedetti, R. Azaro, D. Franceschini, and A. Massa, "PSO-based real-time control of planar uniform circular arrays," IEEE Antennas Wireless Propag. Lett., vol. 5, pp. 545-548, 2006.

[10] F. Viani, L. Lizzi, M. Donelli, D. Pregnolato, G. Oliveri, and A. Massa, "Exploitation of smart antennas in wireless sensor networks," Journal of Electromagnetic Waves and Applications, vol. 24, no. 5/6, pp. 993-1003, 2010.

[11] L. Poli, P. Rocca, M. Salucci, and A. Massa, "Reconfigurable thinning for the adaptive control of linear arrays," IEEE Transactions on Antennas and Propagation, vol. 61, no. 10, pp. 5068-5077, October 2013.

[12] P. Rocca, R. L. Haupt, and A. Massa, "Interference suppression in uniform linear array through a dynamic thinning strategy," IEEE Trans. Antennas Propag., vol. 59, no. 12, pp. 4525-4533, Dec. 2011.

[13] G. Oliveri, F. Viani, and A. Massa, "Synthesis of linear multi-beam arrays through hierarchical ADS-based interleaving, " IET Microw. Antennas Propag., vol. 8, no. 10, pp. 794-808, Jul. 2014.