

Adaptive Time-Modulated Arrays in Time-Varying Scenarios

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Abstract

In this report, the use of TMAs is proposed for adaptive antenna systems required to suppress undesired signals whose number and directions vary in time. Toward this purpose, the ON–OFF TMA sequence is optimized with a suitable global optimization technique that requires a limited computational burden and enables real-time reconfigurations.

Formulazione Matematica

Modello SINR

Si consideri un array lineare composto da N elementi spazati uniformemente lungo l'asse x : il segnale desiderato ricevuto all'elemento n -esimo dell'antenna può essere espresso come

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

dove $\beta_n^d = (2\pi/\lambda)(u_d x_n)$, $u_d = \sin \theta_d \cos \phi_d$, x_n è la distanza del n -esimo elemento dal centro dell'array e (θ_d, ϕ_d) rappresentano le coordinate polari che definiscono la direzione di arrivo (DOA) del segnale desiderato caratterizzato dall'involuppo $p_d(t)$. Considerando la possibilità che uno o più (N_I) segnali interferenti vengano ricevuti dall'antenna alla stessa frequenza angolare del segnale desiderato ω_d , si può valutare il contributo di ciascuna interferente all' n -esimo elemento come

$$S_n^i(t) = p_i(t)e^{j\beta_n^i} \quad \begin{cases} n = 1, \dots, N \\ i = 1, \dots, I \end{cases} \quad (2)$$

dove $\beta_n^i = (2\pi/\lambda)(u_i x_n)$, $u_i = \sin \theta_i \cos \phi_i$ e θ_i, ϕ_i rappresentano le coordinate polari che definiscono la direzione di arrivo (DOA) dell' i -esimo segnale interferente caratterizzato dall'involuppo $p_i(t)$. Si considera inoltre nel sistema un contributo del rumore modellato con un processo additivo Gaussiano caratterizzato da potenza \wp_n . Sotto queste ipotesi, la matrice di covarianza di dimensioni $N \times N$ relativa al segnale desiderato si può scrivere come

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

In modo analogo è possibile esprimere la matrice di covarianza associata all' i -esima interferente come

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

mentre la matrice di covarianza del rumore è data da

$$\Phi_n = p_n \mathbf{1}^N \quad (5)$$

dove $\mathbf{1}^N$ rappresenta una matrice identità di dimensioni $N \times N$.

Possiamo esprimere la matrice di covarianza del segnale indesiderato ricevuto nella forma

$$\Phi_u = \sum_{i=1}^I \Phi_i + \Phi_n \quad (6)$$

ed il suo contributo di potenza, utilizzando la time modulation, risulta essere

$$\wp_u = \frac{1}{2} \underline{G}^{T*} \Phi_u \underline{G} \quad (7)$$

dove il vettore \underline{G} è dato da

$$\underline{G} = \{ \omega_n \tau_n e^{j\gamma_n}, \quad n = 1, \dots, N \} \quad (8)$$

dove ω_n è il coefficiente di ampiezza d'eccitazione associato al n -esimo elemento, τ_n è la durata dell'impulso di accensione associata al n -esimo elemento e γ_n è la fase associata all'elemento n -esimo dell'array.

Di conseguenza il contributo di potenza del segnale desiderato al ricevitore è

$$\wp_d = \frac{1}{2} p_d^2(t) |\underline{\mathbf{G}}^T \underline{\mathbf{U}}(\theta_d, \phi_d)|^2 \quad (9)$$

dove

$$\underline{\mathbf{U}}(\theta_d, \phi_d) = \{e^{j\beta_n^d}, n = 1, \dots, N\} \quad (10)$$

Quindi da (6) e (9) il SINR (*Signal to Interference plus Noise Ratio*) si definisce come:

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

Dato che Φ_u e $p_d^2(t)$ non sono direttamente misurabili la (11) non è utilizzabile. E' possibile però riformulare il problema di massimizzazione del SINR con la seguente funzione di costo

$$f(\underline{\mathbf{G}}) = \frac{|\underline{\mathbf{G}}^T \underline{\mathbf{U}}(\theta_d, \phi_d)|^2}{\underline{\mathbf{G}}^{T*} \Phi_t \underline{\mathbf{G}}^T} \quad (12)$$

dove $\Phi_t = \Phi_d + \sum_{i=1}^I \Phi_i + \Phi_n$ è una quantità misurabile al ricevitore.

Modello SINR e Sideband Radiation Minimization

Nel caso specifico si considera una funzione di costo composta da due termini, uno relativo alla funzione di costo definita in (12) (termine direttamente legato al SINR) e l'altro relativo alla Sideband Radiation (Appendice):

$$f_{SR}(\underline{\mathbf{G}}) = f(\underline{\mathbf{G}}) + \frac{P_{SR}}{P_{tot}} \quad (13)$$

Risultati Numerici

TEST CASE - Time-Varying Scenario

Goal

Valutare le prestazioni della tecnica di nulling adattivo mediante time-modulated linear array (*TMLA*) in uno scenario tempo variante.

Test Case Description

- Number of Elements: $N = 20$
- Elements Spacing: $d = 0.5\lambda$
- Static Array Configuration: Uniform Excitations
- Max Gain Pattern Direction : $\theta^d = 90^\circ, \phi^d = 90^\circ$
- Desired Signal Power: 0 dB
- Interference Power: 30 dB
- Noise Power: -30 dB
- Number of Interferences: $N_I \in [1 - 6]$
- Desired Signal Direction Of Arrival: $\theta^d = 90^\circ, \phi^d = 90^\circ$
- Interferences Directions Of Arrival: $\theta^i = 90^\circ, \phi^i \in [0^\circ - 180^\circ]$

Optimization Approach: PSO

- Number of Variables: $X = 20$ ($\tau_n, n = 1, \dots, N$)
- Number of Particles: $S = 20$
- Number of Iterations: $I = 200$
- Inertial Weight: Linearly varying: $0.9 \text{ to } 0.4$

Time Varying Scenario - Poisson Distribution

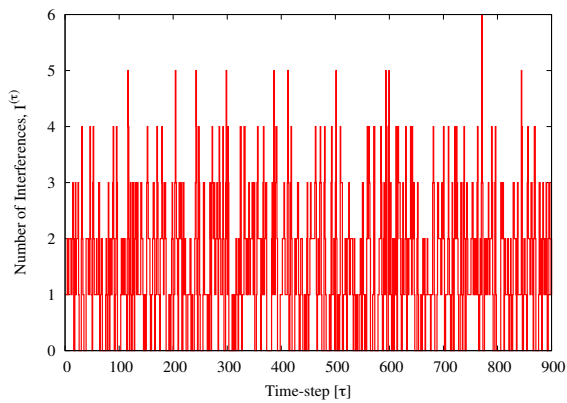


Fig.1 - Number of Interferences

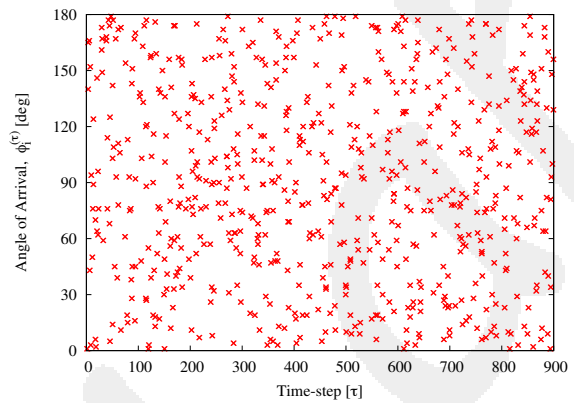


Fig.2 - Directions of Arrival

Time Varying Scenario - Adaptive Nulling in TMLA with PSO - Behavior of SINR and Sideband Radiation

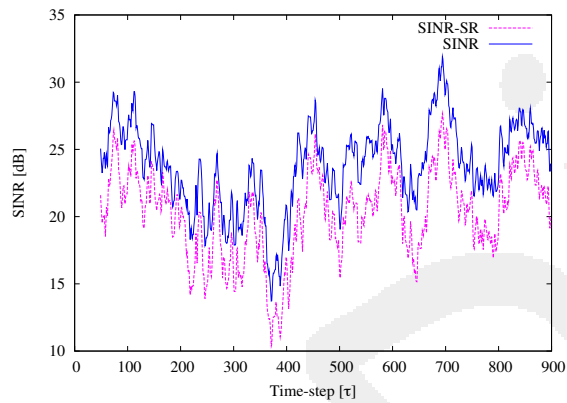


Fig.3 - Time-Varying averaged SINR

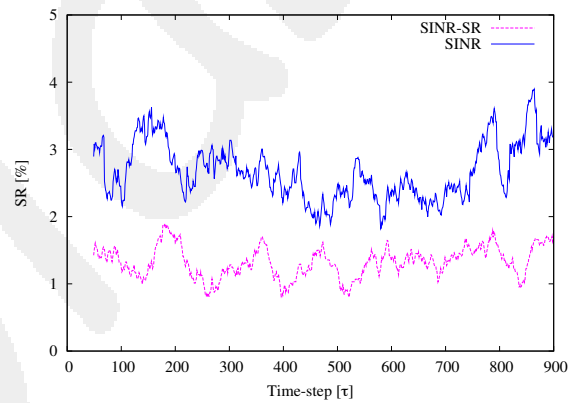


Fig.4 - Time-Varying averaged SR

Note

Fig.3 e Fig.4 riportano rispettivamente l'andamento del signal-to-interferences-plus-noise ratio (*SINR*) e della sideband radiation (*SR*), i cui valori sono mediati sulle precedenti 50 iterazioni. Le due tecniche di ottimizzazione confrontate si basano su due differenti funzioni di costo: (12) e (13).

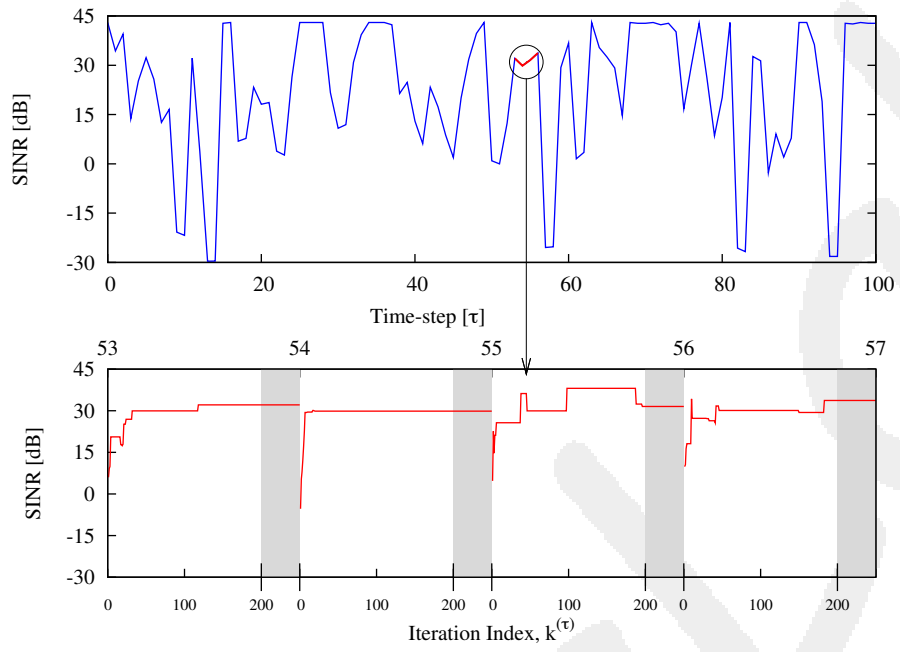


Fig.5 - Time-Varying SINR & Optimization Processes

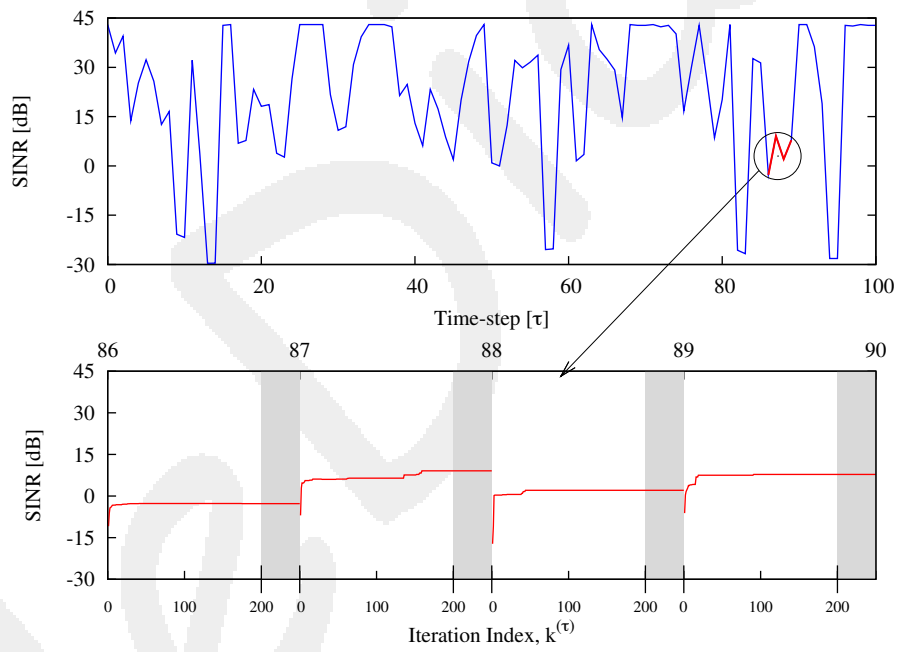


Fig.6 - Time-Varying SINR & Optimization Processes

Timestep 53

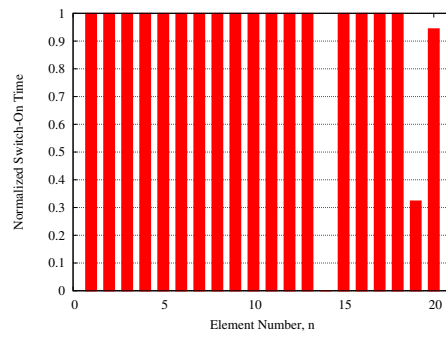


Fig.7 - Pulse Sequence

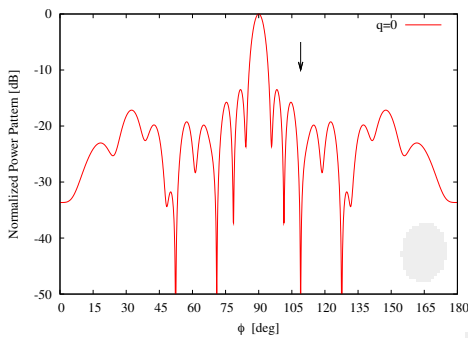


Fig.8 - Beam Pattern - q=0

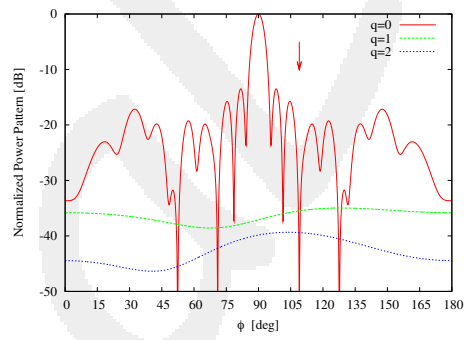


Fig.9 - Beam Patterns - q=0,1,2

Timestep 54

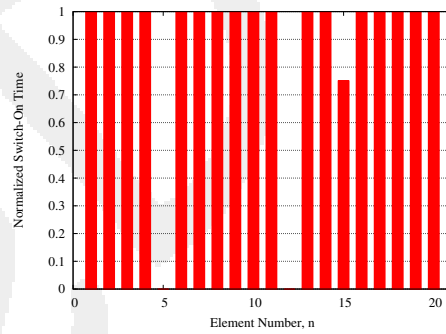


Fig.10 - Pulse Sequence

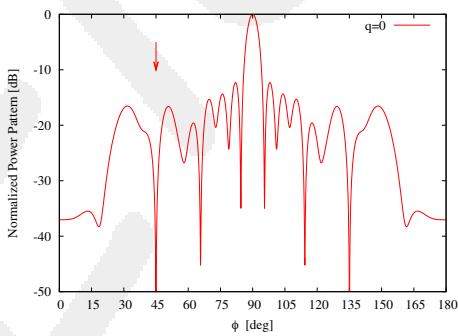


Fig.11 - Beam Pattern - q=0

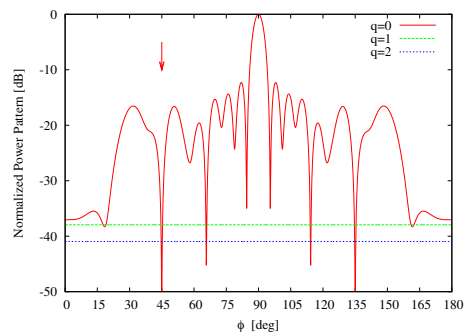


Fig.12 - Beam Patterns - q=0,1,2

Timestep 87

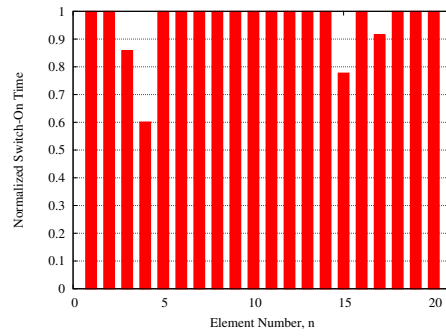


Fig.13 - Pulse Sequence

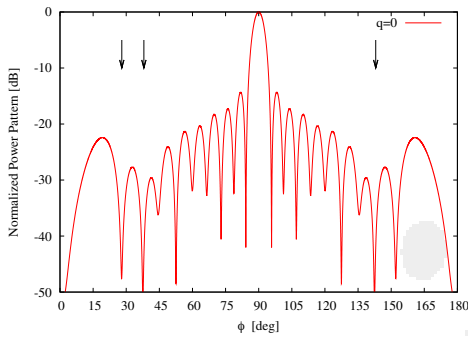


Fig.14 - Beam Pattern - $q=0$

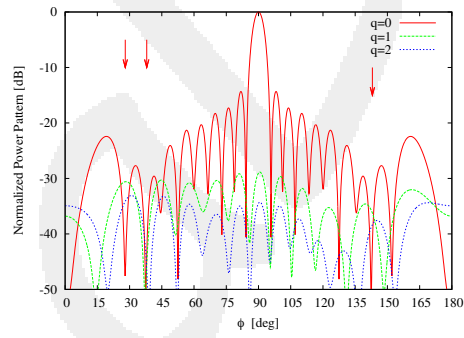


Fig.15 - Beam Patterns - $q=0,1,2$

Timestep 88

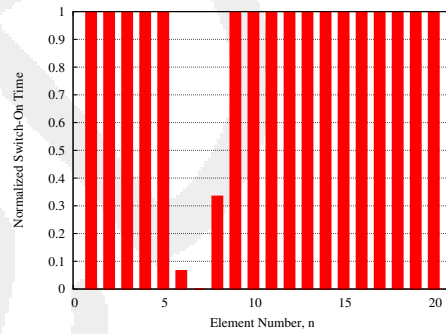


Fig.16 - Pulse Sequence

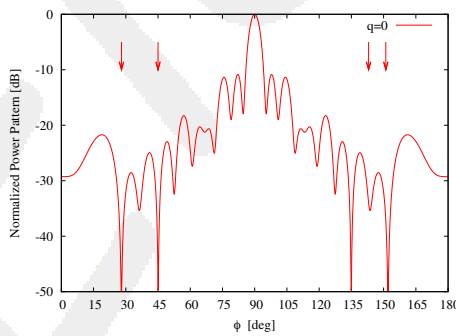


Fig.17 - Beam Pattern - $q=0$

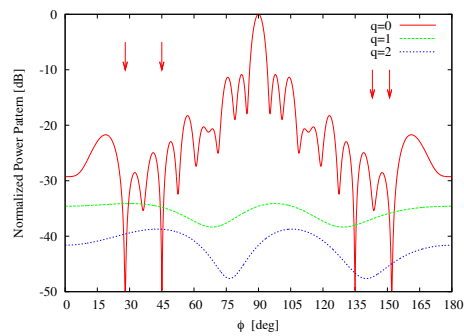


Fig.18 - Beam Patterns - $q=0,1,2$

	$SINR$ [dB]	SR [%]	SBL [dB]	SLL [dB]	BW [deg]	N_I
<i>Timestep 53</i>	39.67	1.23	-36.88	-9.78	5.20	1
<i>Timestep 54</i>	40.29	1.70	-34.68	-13.40	5.06	1
<i>Timestep 55</i>	38.92	1.76	-34.06	-12.58	5.14	1
<i>Timestep 56</i>	41.94	1.72	-34.03	-12.48	5.39	1
<i>Timestep 86</i>	18.08	3.65	-27.11	-6.81	12.25	2
<i>Timestep 87</i>	11.00	3.25	-27.86	-13.55	5.04	3
<i>Timestep 88</i>	5.67	2.63	-30.02	-13.54	5.25	4
<i>Timestep 89</i>	24.15	3.08	-28.37	-15.03	4.56	2

Tab.1 - SINR maximization approach - analysis of the results proposed in Fig.5-6:
signal-to-interferences-plus-noise ratio ($SINR$ [dB]), sideband radiation (SR [%]), sidelobe level (SLL [dB]), sideband level (SBL [dB]), -3 dB beamwidth expressed in degrees (BW [deg]) and number of interferences (N_I).

	$SINR$ [dB]	SR [%]	SBL [dB]	SLL [dB]	BW [deg]	N_I
<i>Timestep 53</i>	32.10	1.49	-34.97	-13.49	5.14	1
<i>Timestep 54</i>	29.85	1.06	-37.94	-12.30	4.92	1
<i>Timestep 55</i>	31.55	1.63	-33.89	-9.83	4.78	1
<i>Timestep 56</i>	33.72	1.26	-36.84	-13.91	5.09	1
<i>Timestep 86</i>	-2.72	2.31	-30.93	-14.37	5.39	2
<i>Timestep 87</i>	9.08	3.19	-28.86	-14.33	5.10	3
<i>Timestep 88</i>	2.06	1.64	-34.12	-10.85	4.88	4
<i>Timestep 89</i>	7.81	2.27	-31.18	-13.05	5.03	2

Tab.2 - SINR maximization and SR minimization approach - analysis of the results proposed in Fig.5-6:
signal-to-interferences-plus-noise ratio ($SINR$ [dB]), sideband radiation (SR [%]), sideband level (SBL [dB]), sidelobe level (SLL [dB]), -3 dB beamwidth expressed in degrees (BW [deg]) and number of interferences (N_I).

Time-Varying Scenario - Adaptive Nulling in TMLA with PSO - Statistical Analysis

	$av \{SINR\}$	$var \{SINR\}$	$min \{SINR\}$	$max \{SINR\}$
<i>SINR max approach</i>	7316.60	74105608	6.19×10^{-4}	20000
<i>SINR max and SR min approach</i>	5890.76	66954948	5.56×10^{-4}	20000

Tab.3 - SINR Statistics: average $av \{ \cdot \}$, variance $var \{ \cdot \}$, minimum $min \{ \cdot \}$ and maximum $max \{ \cdot \}$ of the signal-to-interferences-plus-noise ratio expressed in linear values (*SINR*)

	$av \{SINR [dB]\}$	$var \{SINR [dB]\}$	$min \{SINR [dB]\}$	$max \{SINR [dB]\}$
<i>SINR max approach</i>	23.74	428.37	-32.09	43.01
<i>SINR max and SR min approach</i>	20.20	491.24	-32.55	43.01

Tab.4 - SINR Statistics: average $av \{ \cdot \}$, variance $var \{ \cdot \}$, minimum $min \{ \cdot \}$ and maximum $max \{ \cdot \}$ of the signal-to-interferences-plus-noise ratio expressed in dB (*SINR [dB]*)

	$av \{SLL\}$	$var \{SLL\}$	$min \{SLL\}$	$max \{SLL\}$
<i>SINR max approach</i>	0.2856	2.34×10^{-2}	0.1368	0.9847
<i>SINR max and SR min approach</i>	0.2355	2.34×10^{-3}	0.1476	0.4819

Tab.5 - SLL Statistics: average $av \{ \cdot \}$, variance $var \{ \cdot \}$, minimum $min \{ \cdot \}$ and maximum $max \{ \cdot \}$ of the sidelobe level expressed in linear values (*SLL*)

	$av \{SLL [dB]\}$	$var \{SLL [dB]\}$	$min \{SLL [dB]\}$	$max \{SLL [dB]\}$
<i>SINR max approach</i>	-11.63	10.20	-17.28	-0.13
<i>SINR max and SR min approach</i>	-12.72	2.68	-16.62	-6.34

Tab.6 - SLL Statistics: average $av \{ \cdot \}$, variance $var \{ \cdot \}$, minimum $min \{ \cdot \}$ and maximum $max \{ \cdot \}$ of the sidelobe level expressed in dB (*SLL [dB]*)

	$av \{SBL\}$	$var \{SBL\}$	$min \{SBL\}$	$max \{SBL\}$
<i>SINR max approach</i>	3.08×10^{-2}	9.93×10^{-4}	0.00	0.3125
<i>SINR max and SR min approach</i>	1.61×10^{-2}	3.05×10^{-4}	0.00	0.0767

Tab.7 - SBL Statistics: average $av \{\cdot\}$, variance $var \{\cdot\}$, minimum $min \{\cdot\}$ and maximum $max \{\cdot\}$ of the sideband level expressed in linear values (SBL)

	$av \{SBL [dB]\}$	$var \{SBL [dB]\}$	$min \{SBL [dB]\}$	$max \{SBL [dB]\}$
<i>SINR max approach</i>	–	–	$-\infty$	-10.10
<i>SINR max and SR min approach</i>	–	–	$-\infty$	-22.30

Tab.8 - SBL Statistics: average $av \{\cdot\}$, variance $var \{\cdot\}$, minimum $min \{\cdot\}$ and maximum $max \{\cdot\}$ of the sideband level expressed in dB ($SBL [dB]$)

	$av \{BW [deg]\}$	$var \{BW [deg]\}$	$min \{BW [deg]\}$	$max \{BW [deg]\}$
<i>SINR max approach</i>	5.54	3.82	3.78	36.54
<i>SINR max and SR min approach</i>	5.14	5.30×10^{-2}	4.41	6.52

Tab.9 - BW Statistics: average $av \{\cdot\}$, variance $var \{\cdot\}$, minimum $min \{\cdot\}$ and maximum $max \{\cdot\}$ of the -3 dB beamwidth expressed in degrees ($BW [deg]$)

	$av \{SR\}$	$var \{SR\}$	$min \{SR\}$	$max \{SR\}$
<i>SINR max approach</i>	2.69	8.82	0.00	32.44
<i>SINR max and SR min approach</i>	1.33	2.09	0.00	8.02

Tab.10 - SR Statistics: average $av \{\cdot\}$, variance $var \{\cdot\}$, minimum $min \{\cdot\}$ and maximum $max \{\cdot\}$ of the sideband radiation expressed in percentage [%] on the total power (SR)

Time-Varying Scenario - Adaptive Nulling in TMLA with PSO - Single Timestep Analysis

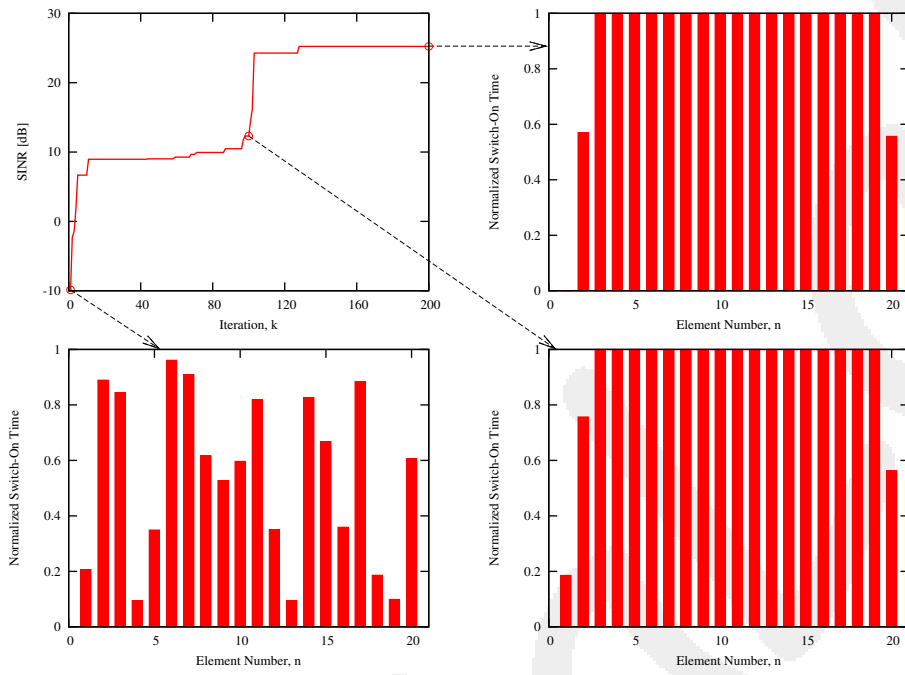


Fig.19 - Intermediate Solutions - Pulse Sequences

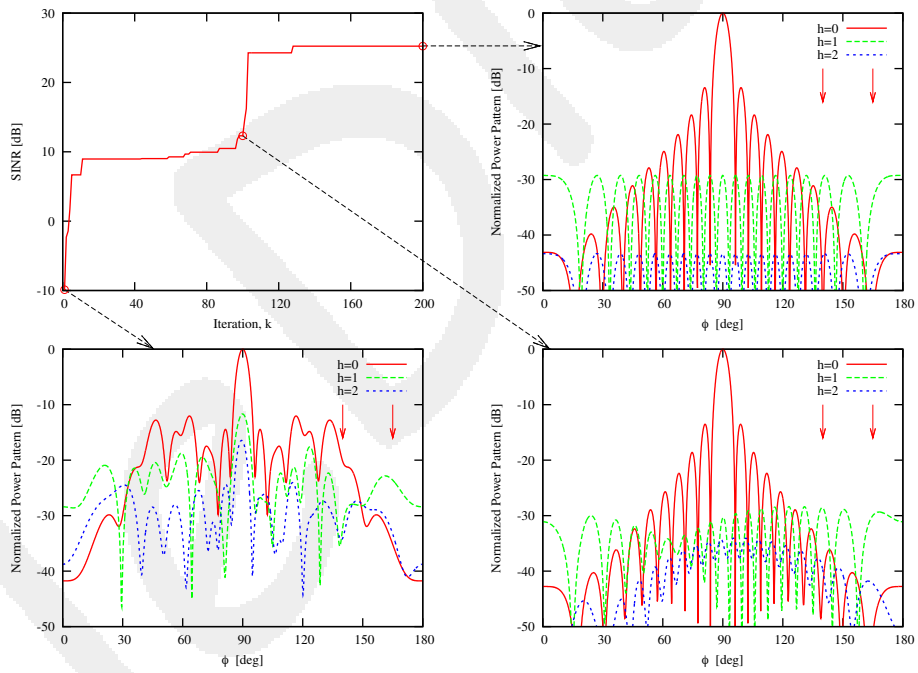


Fig.20 - Intermediate Solutions - Patterns

Appendice

La potenza totale da un array di elementi con eccitazioni sottoposte a Time Modulation è calcolabile come:

$$P_{tot} = \sum_{n=0}^{N-1} \left\{ |\alpha_n|^2 \sum_{h=-\infty}^{\infty} u_{hn}^2 \right\} + 2 \sum_{m,n \in \Omega_{mn}} \left\{ \text{Re} \{ \alpha_m \alpha_n^* \} \text{sinc} [kd(m-n)] \sum_{h=-\infty}^{\infty} u_{hn} u_{hm} \right\} \quad (14)$$

che si può tradurre anche in una sommatoria di infiniti termini rappresentanti la potenza associata alle varie frequenze, centrale ed armoniche:

$$P_{tot} = \sum_{h=-\infty}^{\infty} P_h \quad (15)$$

La Sideband Radiation rappresenta la quantità di potenza radiata dall'array alle frequenze spurie: sarà in seguito espressa in percentuale rispetto alla potenza totale radiata.

E' possibile ricavare la potenza associata alle frequenze spurie grazie alla seguente equazione:

$$P_{SR} = \sum_{n=1}^N \left\{ |\alpha_n|^2 \tau_n (1 - \tau_n) \right\} + \sum_{m,n \in \Upsilon_{mn}} \left\{ \text{Re} \{ \alpha_m \alpha_n^* \} \text{sinc} [k(z_m - z_n)] (\tau_{\{m,n\}MinVal} - \tau_m \tau_n) \right\} \quad (16)$$

dove

$$\tau_{\{m,n\}MinVal} = \begin{cases} \tau_n & \text{if } \tau_n \leq \tau_m \\ \tau_m & \text{altrimenti} \end{cases} \quad (17)$$

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