Handling Sideband Radiations in Compromise Sum-Difference Pattern Synthesis through Time-Modulation

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Abstract

The synthesis of time-modulated planar arrays for the design of monopulse antennas is addressed in this report. The sum beam is generated through an optimal set of static excitations and the difference beam is yielded by aggregating the array elements into sub-arrays suitably modulated in time by means of a set of radio-frequency (RF) switches. Towards this aim, iterative deterministic and hybrid approaches are proposed for the joint definition of the sub-array configuration and the pulse sequence controlling the RF switches to reproduce an optimal difference pattern at the working frequency, whereas minimizing the power losses in the harmonic radiation caused by the on-off switch commutations.

Mathematical Formulation

[1.a] Approach: Pulse Matching

The method is a 2D-extension of the *Coutiguous Partition Method* (*CPM*) used for linear arrays.

- Cost Function:

$$\Psi^{i_k}(\underline{C},\underline{T}) = \frac{1}{N_{tot}} \sum_{n=1}^{N_{tot}} \left\| \alpha_n \left(\frac{\beta_n}{\alpha_n} - \sum_{q=1}^{Q} \delta_{c_n q} \tau_q \right) \right\| \tag{1}$$

where N_{tot} is the total number of elements, $\delta_{c_n q}$ stands for the Kronecker delta function, $\underline{A} = \{\alpha_n;\, n = 1, ..., N_{tot}\}$ is the vector with the static excitations of the array elements, $\underline{B} = \{\beta_n;\, n = 1, ..., N_{tot}\}$ is the vector with the optimal excitations of the array elements to generate a desired reference difference pattern, $\underline{C} = \{c_n \in [0,\, Q]\,;\, n = 1, ..., N\}$ is the integer vector describing the sub-array configuration and $\underline{T} = \{\tau_q;\, q = 1, ..., Q\}$ is the vector with the *duty-cycles* of the pulse waveforms exciting the aggregated elements.

[1.b] Approach: Pulse Matching & SR Minimization

The method is a 2D-extension of the *Coutiguous Partition Method* (*CPM*) used for linear arrays, with an improvement concerning the cost function to minimize the power losses in sideband radiation by using a closed form equation.

- Cost Function:

$$\Psi^{i_k}(\underline{C},\underline{T}) = w_{PM}^{CPM} \cdot \frac{1}{N_{tot}} \sum_{n=1}^{N_{tot}} \left\| \alpha_n \left(\frac{\beta_n}{\alpha_n} - \sum_{q=1}^{Q} \delta_{c_n q} \tau_q \right) \right\| + w_{SR}^{CPM} \cdot \frac{\mathcal{P}_{SR}(\underline{C},\underline{T})}{\mathcal{P}_{TOT}(\underline{C},\underline{T})} \tag{2}$$

[1.c] Approach: Pulse Matching + Partcle Swarm Optimization (Two Stage Approach)

The method is based on two steps:

1. The 2D-extension of the *Coutiguous Partition Method* (*CPM*) for linear arrays is applied to calculate the aggregation of the elements (Approach [1.a]);

2. The *Particle Swarm Optimizer* algorithm is applied to calculate the optimal *duty-cycles* of the pulse waveforms exciting the aggregated elements;

- Cost Function:

$$\Psi^{i_k}(\underline{T}) = w_{SLL}^{PSO} \cdot \frac{\left\| SLL^{i_k}(\underline{T}) - SLL^{trg} \right\|^2}{\left\| SLL^{trg} \right\|^2} + w_{PM}^{PSO} \cdot \frac{\mathcal{P}_{SR}(\underline{T})}{\mathcal{P}_{TOT}(\underline{T})} \tag{3}$$

Sideband Radiation in TMPA

The sideband radiation in a time-modulated planar array can be calculated using the following closed-form equation:

$$\mathcal{P}_{SR} = 2\pi \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} \sum_{r=1}^{N_x} \sum_{s=1}^{N_y} \left[\mathrm{Re}\left\{\alpha_{mn}\alpha_{rs}^*\right\} \mathrm{sinc}\left(k\sqrt{(x_m - x_r)^2 + (y_n - y_s)^2} \right) \left(\tau_{(m,n),(r,s)_{MinVal}} - \tau_{mn}\tau_{rs} \right) \right] \tag{4}$$

where

$$\tau_{(m,n),(r,s)_{MinVal}} = \begin{cases} \tau_{mn} & \text{if} \quad \tau_{mn} \leq \tau_{rs} \\ \tau_{rs} & \text{elsewhere} \end{cases} \tag{5}$$

Optimal Configuration

Having a static set of excitations $\underline{A} = \{\alpha_n; n = 1, ..., N_{tot}\}$, the optimal pulse-sequence to generate a desired pattern at the central frequency can be calculated using:

$$\tau_n^{opt} = \frac{\beta_n}{\alpha_n} \qquad n = 1, ..., N_{tot} \tag{6}$$

Numerical Results

Taylor -25dB switched to Bayliss -20dB

Goal

Design of a sub-arrayed monopulse planar antenna array using time-modulation technique to synthesize a compromise difference pattern at the central frequency minimizing the power losses in sideband radiation.

Test Case Description

- Number of Elements along the x-axis: $N_x = 20$
- Number of Elements along the y-axis: $N_y = 20$
- Total Number of Elements: $N_{tot} = 400$
- Elements Spacing along the x-axis: $d_x = 0.5\lambda$
- Elements Spacing along the y-axis: $d_y = 0.5\lambda$
- Static Array Configuration: $\underline{A} = \{\alpha_n;\, n = 1, ..., N_{tot}\}$ - $Taylor$, $SLL = -25dB$, $\overline{n} = 3$
- Reference Difference Time-Modulated Pattern at Central Frequency: $\underline{B} = \{\beta_n;\, n = 1, ..., N_{tot}\}$ - $Bayliss$, $SLL = -25\,dB$, $\overline{n} = 4$
- Array Aperture Radius: $r = 5\lambda$
- Total Active Elements: $N_{tot} = 316$

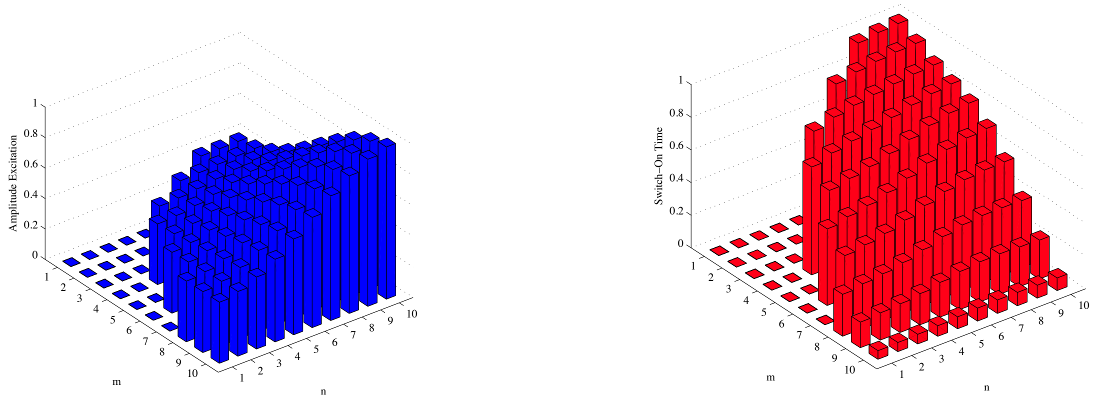
[1.a] Approach: Pulse Matching (PM)

- Number of Iterations: $I = 20$
- Number of Subarrays: $Q = 6$
- Pulse Matching Weight: $w_{PM}^{CPM} = 1$
- SR Minimization Weight: $w_{SR}^{CPM} = 0$

[1.b] Approach: Pulse Matching & SR Minimization (PM - minSR)

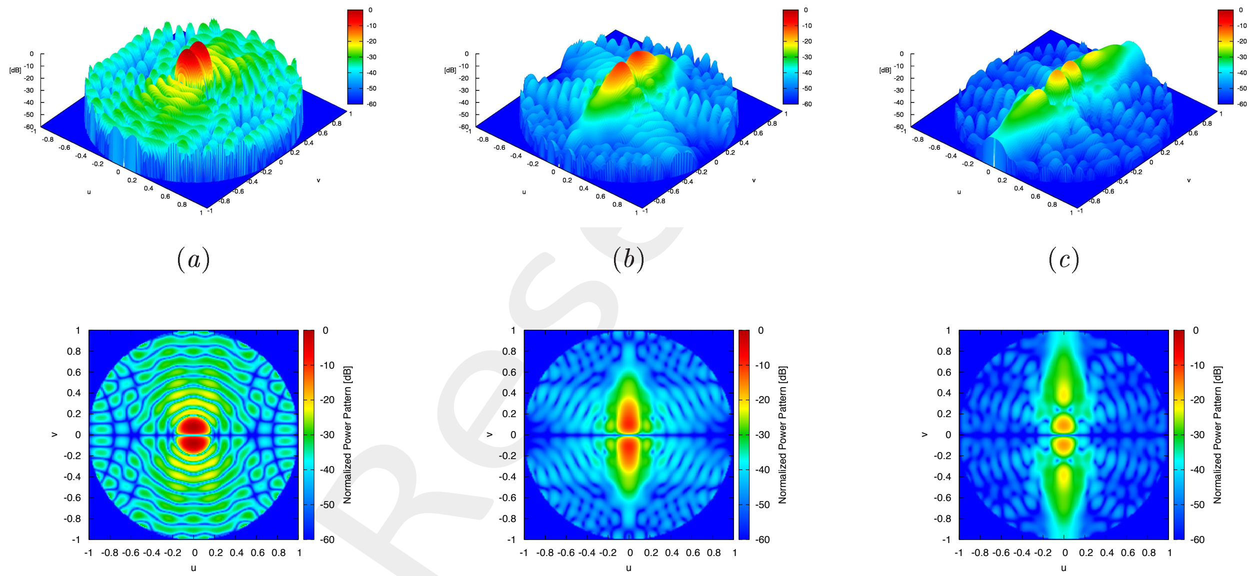
- Number of Iterations: $I = 20$
- Number of Subarrays: $Q = 6$
- Pulse Matching Weight: $w_{PM}^{CPM} = 1$
- SR Minimization Weight: $w_{SR}^{CPM} = Q$

Taylor SLL=-25dB switched to Bayliss SLL=-20 dB, Optimal



(a) (b)

Fig.25 - Taylor Static Amplitude Excitations (a) and Optimal Pulse Sequence (b).

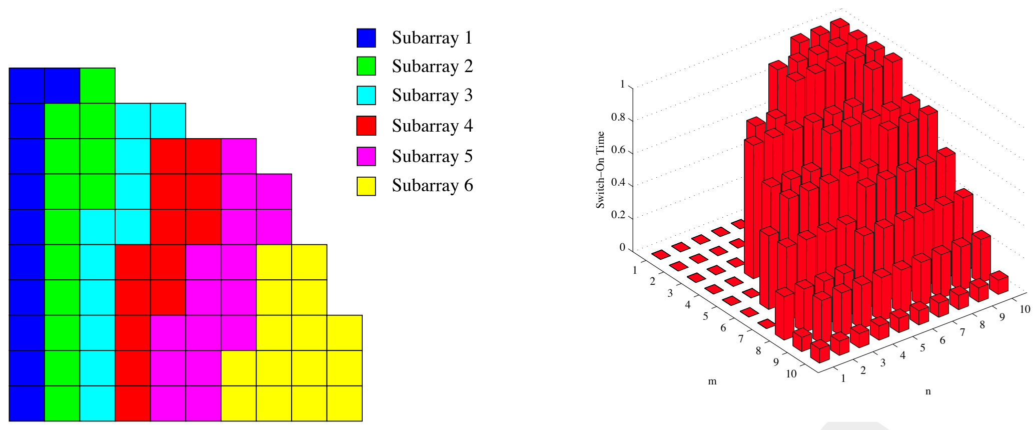


(a) (b) (c)

(d) (e) (f)

Fig.26 - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

Taylor SLL=-25dB switched to Bayliss SLL=-20 dB, Pulse Matching



(a) (b)

Fig.27 - PM - Subarray Configuration (a) and Pulse Sequence (b).

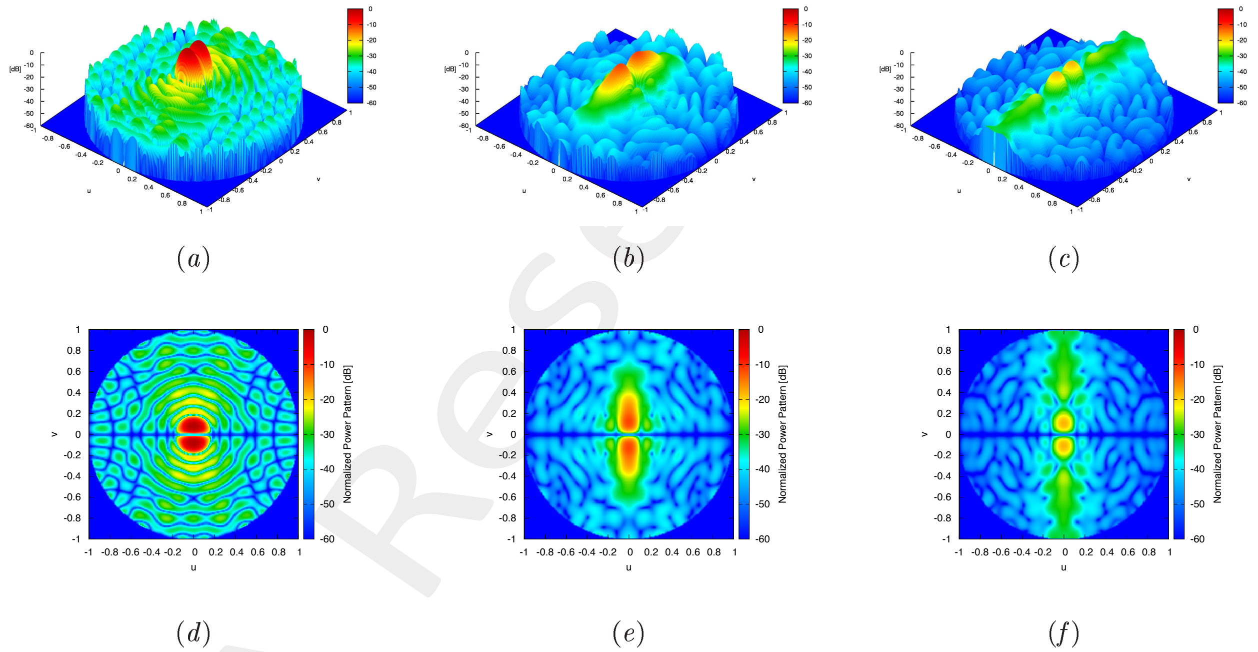
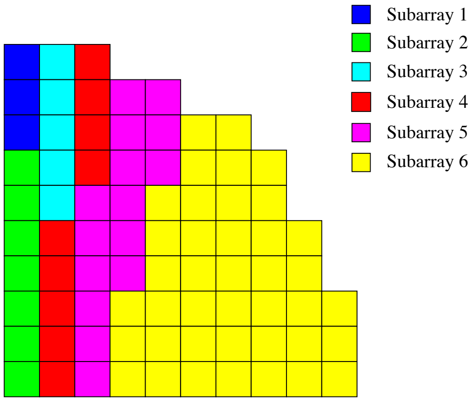
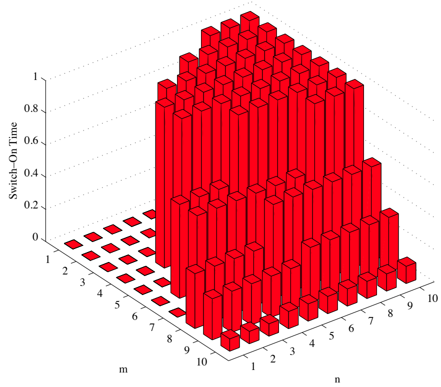


Fig.28 - PM - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

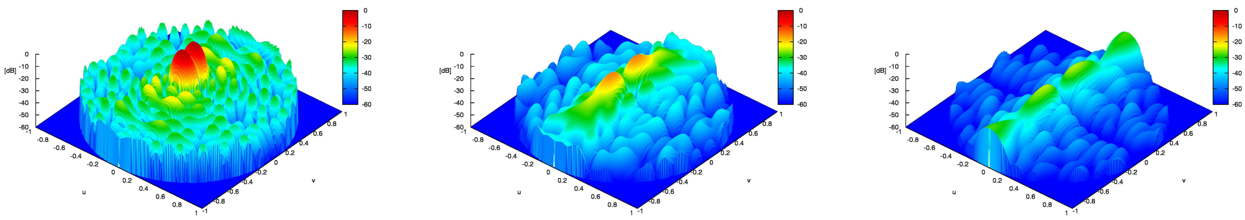
Taylor SLL=-25dB switched to Bayliss SLL=-20 dB, Pulse Matching & SR Minimization, $Q = 6$ ($w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = Q$)



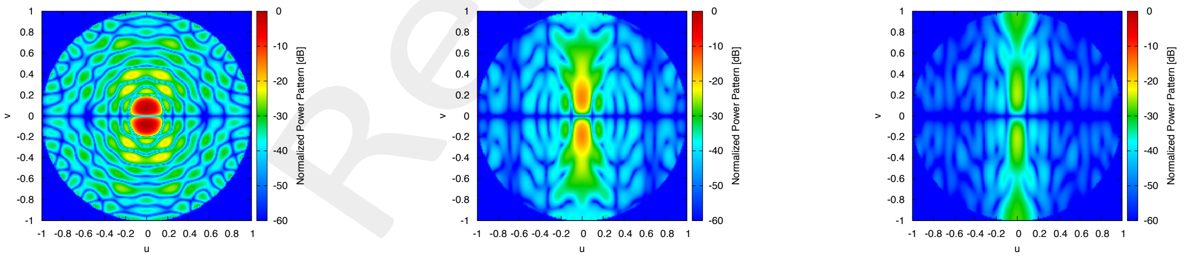


(a) (b)

Fig.29 - PM - minSR - Subarray Configuration (a) and Pulse Sequence (b).

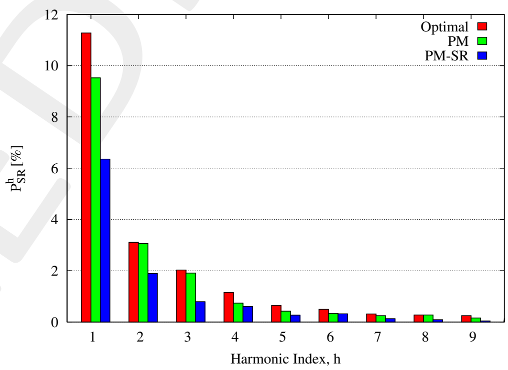


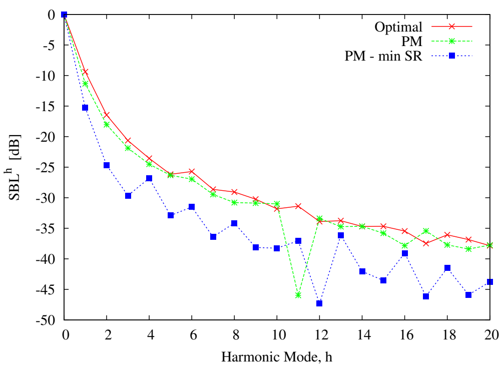
(a) (b) (c)



(d) (e) (f)

Fig.30 - PM - minSR - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).





(a) (b)

Fig.31 - SR (a) and SBL (b) Comparison.

	$SLL\,[dB]$	$P_{SR}\,[\%]$	Δ	$BW\,[deg]$	$FNBW$	$SBL\,[dB]$
$Optimal$	-20.42	42.03	$-$	4.87	0.192	-9.38
PM	-20.41	35.56	6.55	4.90	0.193	-11.33
$PM - min\,SR$, $w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = Q$	-20.75	22.44	13.41	5.11	0.206	-15.29

Tab.1 - Pattern Parameters Comparison: Sidelobe Level (SLL), Sideband Radiation (P_{SR}), Pattern Matching Error (Δ), -3dB Beamwidth (BW), First Null Beamwidth ($FNBW$) and Sideband Level (SBL).

Observations:

- Osservando l'andamento di Fig.4(c) si può notare che le soluzioni ricavate dalle tecniche PM e PM-minSR si differenziano tra loro di poco dal punto di vista della sideband radiation P_{SR}: aumentando però il peso del termine relativo alla sideband radiation nella funzione di costo definita in (3) (agendo quindi su w_{SR}^{CPM}) è possibile ridurre sensibilmente l'ammontare di tale potenza sprecata (Fig.13(c)) a discapito però di un peggioramento in termini di pattern matching, ma non per quanto riguarda il SLL che rimande circa invariato. Fig.29,30 e 31 mostrano una soluzione ricavata per $Q = 6$ considerando $w_{SR}^{CPM} = Q$.

Taylor -30dB switched to Bayliss -20dB

Goal

Design of a sub-arrayed monopulse planar antenna array using time-modulation technique to synthesize a compromise difference pattern at the central frequency minimizing the power losses in sideband radiation.

Test Case Description

- Number of Elements along the x-axis: $N_x = 20$
- Number of Elements along the y-axis: $N_y = 20$
- Total Number of Elements: $N_{tot} = 400$
- Elements Spacing along the x-axis: $d_x = 0.5\lambda$
- Elements Spacing along the y-axis: $d_y = 0.5\lambda$
- Static Array Configuration: $\underline{A} = \{\alpha_n; n = 1, ..., N_{tot}\}$ - $Taylor$, $SLL = -30dB$, $\overline{n} = 5$
- Reference Difference Time-Modulated Pattern at Central Frequency: $\underline{B} = \{\beta_n; n = 1, ..., N_{tot}\}$ - $Bayliss$, $SLL = -20\,dB$, $\overline{n} = 4$
- Array Aperture Radius: $r = 5\lambda$
- Total Active Elements: $N_{tot} = 316$

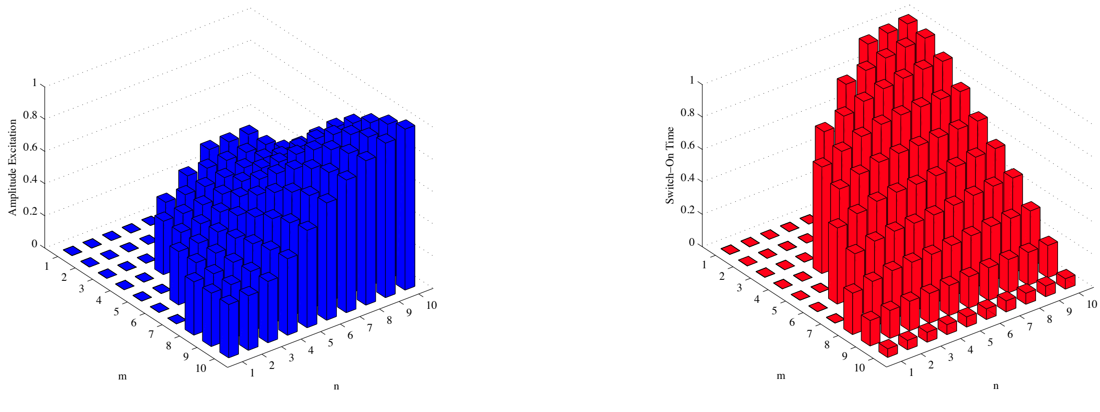
[1.a] Approach: Pulse Matching (PM)

- Number of Iterations: $I = 20$
- Number of Subarrays: $Q = 6$
- Pulse Matching Weight: $w_{PM}^{CPM} = 1$
- SR Minimization Weight: $w_{SR}^{CPM} = 0$

[1.b] Approach: Pulse Matching & SR Minimization (PM - minSR)

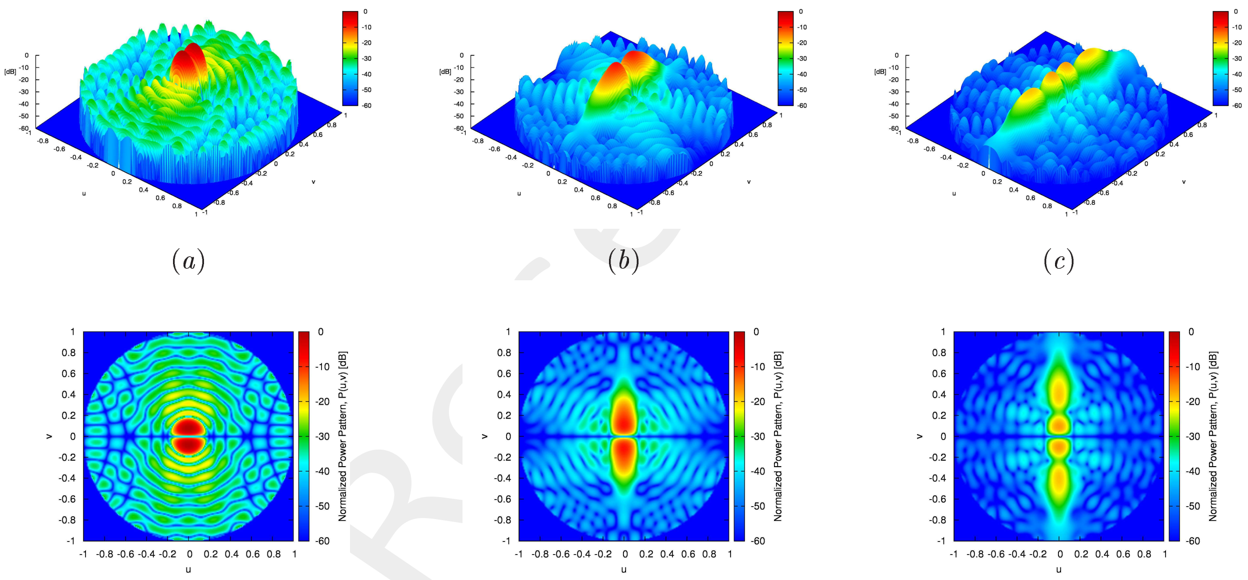
- Number of Iterations: $I = 20$
- Number of Subarrays: $Q = 6$
- Pulse Matching Weight: $w_{PM}^{CPM} = 1$
- SR Minimization Weight: $w_{SR}^{CPM} = Q$

Taylor SLL=-30dB switched to Bayliss SLL=-20 dB, Optimal



(a) (b)

Fig.32 - Taylor Static Amplitude Excitations (a) and Optimal Pulse Sequence (b).



(a) (b) (c)

(d) (e) (f)

Fig.33 - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

Taylor SLL=-30dB switched to Bayliss SLL=-20 dB, Pulse Matching

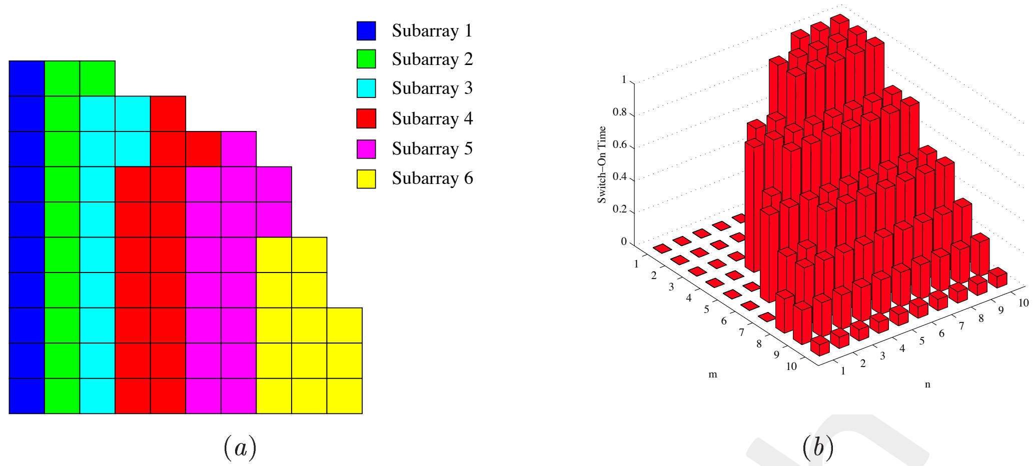


Fig.34 - PM - Subarray Configuration (*a*) and Pulse Sequence (*b*).

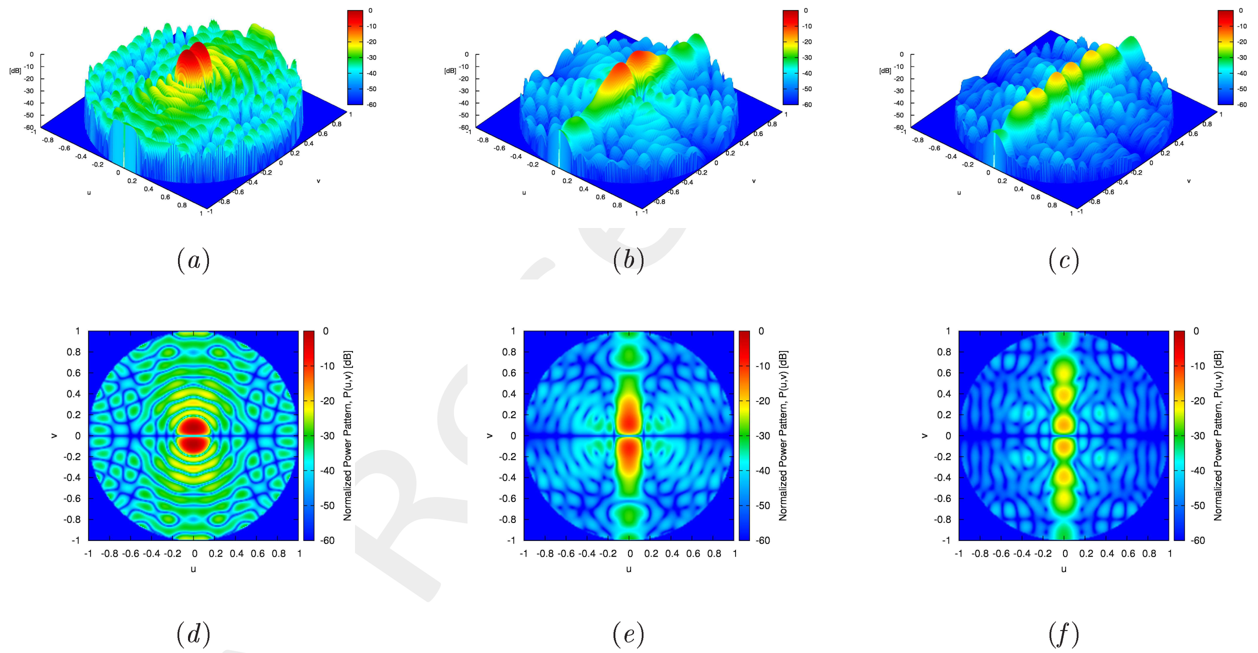
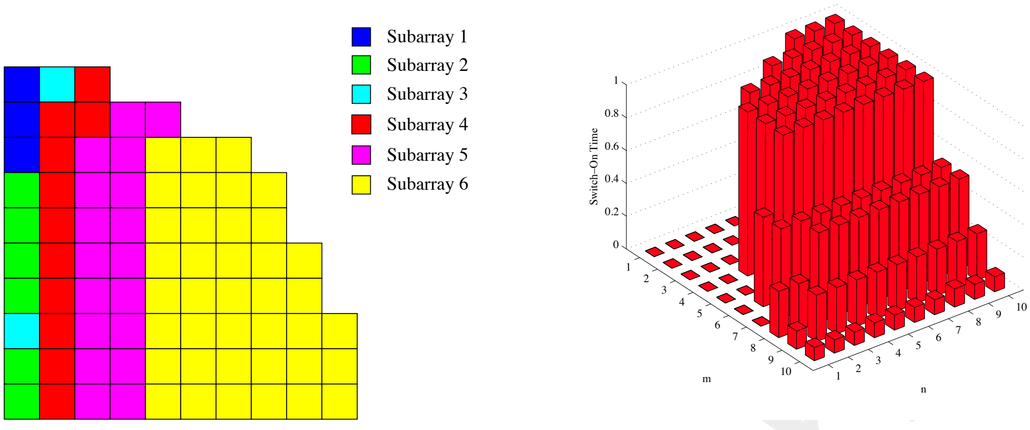


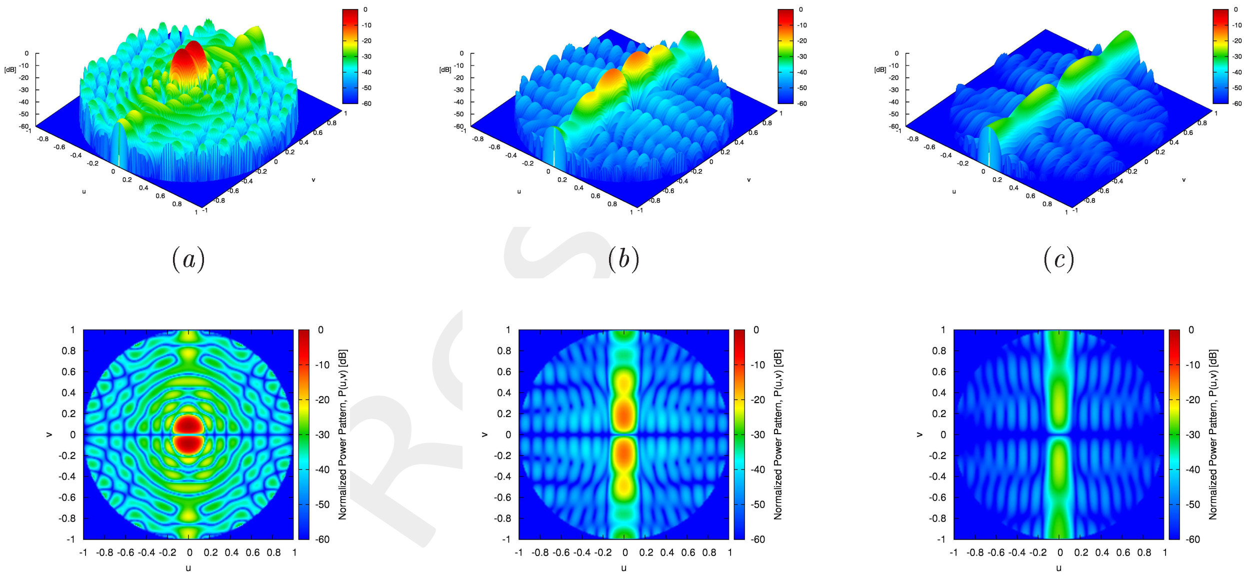
Fig.35 - PM - Time-Modulated Patterns: $h = 0$ (*a*)-(*d*), $h = 1$ (*b*)-(*e*) and $h = 2$ (*c*)-(*f*).

Taylor SLL=-30dB switched to Bayliss SLL=-20 dB, Pulse Matching & SR Minimization, $Q = 6$ ($w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = Q$)



(a) (b)

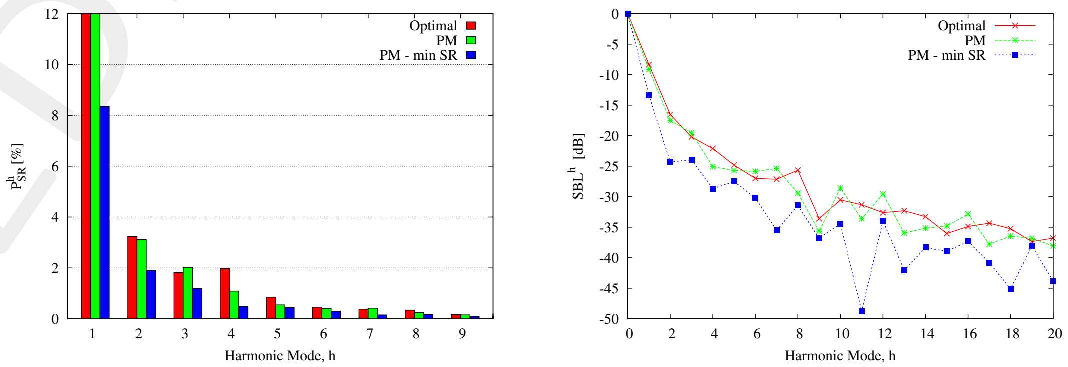
Fig.36 - PM - minSR - Subarray Configuration (a) and Pulse Sequence (b).



(a) (b) (c)

(d) (e) (f)

Fig.37 - PM - minSR - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).



(a) (b)

Fig.38 - SR (a) and SBL (b) Comparison.

	$SLL\,[dB]$	$P_{SR}\,[\%]$	Δ	$BW\,[deg]$	$FNBW$	$SBL\,[dB]$
$Optimal$	-20.42	47.66	$-$	4.87	0.192	-8.34
PM	-20.67	43.44	6.93	4.90	0.195	-9.15
$PM - min\,SR$, $w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = Q$	-21.78	27.66	14.24	5.15	0.207	-13.37

Tab.2 - Pattern Parameters Comparison: Sidelobe Level (SLL), Sideband Radiation (P_{SR}), Pattern Matching Error (Δ), -3dB Beamwidth (BW), First Null Beamwidth ($FNBW$) and Sideband Level (SBL).

Observations:

- Osservando l'andamento di Fig.7(c) si può notare che le soluzioni ricavate dalle tecniche PM e PM-minSR si differenziano tra loro di poco dal punto di vista della sideband radiation P_{SR}: aumentando però il peso del termine relativo alla sideband radiation nella funzione di costo definita in (3) (agendo quindi su w_{SR}^{CPM}) è possibile ridurre sensibilmente l'ammontare di tale potenza sprecata (Fig.16(c)) a discapito però di un peggioramento in termini di pattern matching, ma non per quanto riguarda il SLL che rimande circa invariato. Fig.36,37 e 38 mostrano una soluzione ricavata per $Q = 6$ considerando $w_{SR}^{CPM} = Q$.

Taylor -25dB switched to Bayliss -25dB

Goal

Design of a sub-arrayed monopulse planar antenna array using time-modulation technique to synthesize a compromise difference pattern at the central frequency minimizing the power losses in sideband radiation.

Test Case Description

- Number of Elements along the x-axis: $N_x = 20$
- Number of Elements along the y-axis: $N_y = 20$
- Total Number of Elements: $N_{tot} = 400$
- Elements Spacing along the x-axis: $d_x = 0.5\lambda$
- Elements Spacing along the y-axis: $d_y = 0.5\lambda$
- Static Array Configuration: $\underline{A} = \{\alpha_n; n = 1, ..., N_{tot}\}$ - $Taylor$, $SLL = -25dB$, $\overline{n} = 3$
- Reference Difference Time-Modulated Pattern at Central Frequency: $\underline{B} = \{\beta_n; n = 1, ..., N_{tot}\}$ - $Bayliss$, $SLL = -25\,dB$, $\overline{n} = 5$
- Array Aperture Radius: $r = 5\lambda$
- Total Active Elements: $N_{tot} = 316$

[1.a] Approach: Pulse Matching

- Number of Iterations: $I = 20$
- Number of Subarrays: $Q = 6$
- Pulse Matching Weight: $w_{PM}^{CPM} = 1$
- SR Minimization Weight: $w_{SR}^{CPM} = 0$

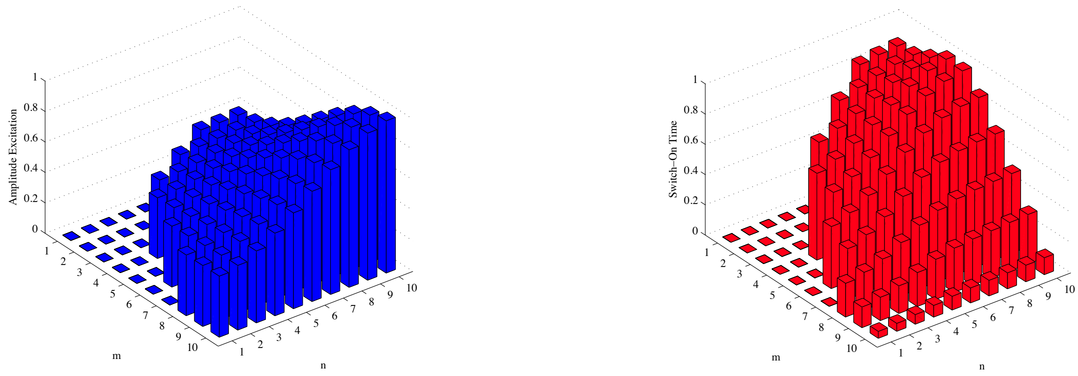
[1.b] Approach: Pulse Matching & SR Minimization

- Number of Iterations: $I = 20$
- Number of Subarrays: $Q = 6$
- Pulse Matching Weight: $w_{PM}^{CPM} = 1$
- SR Minimization Weight: $w_{SR}^{CPM} = 1$

[1.b] Approach: Pulse Matching + Particle Swarm Optimization

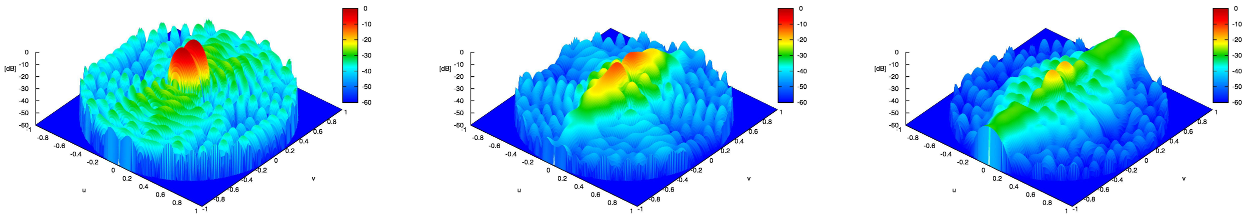
- Number of Iterations: $I = 100$
- Number of Subarrays: $Q = 6$
- Number of Particles: $P = 2Q$
- Inertial Weight: 0.4
- Sidelobe Level Matching Weight: $w_{SLL}^{PSO} = 1$
- SR Minimization Weight: $w_{SR}^{PSO} = 1$

Taylor SLL=-25dB switched to Bayliss SLL=-25 dB, Optimal

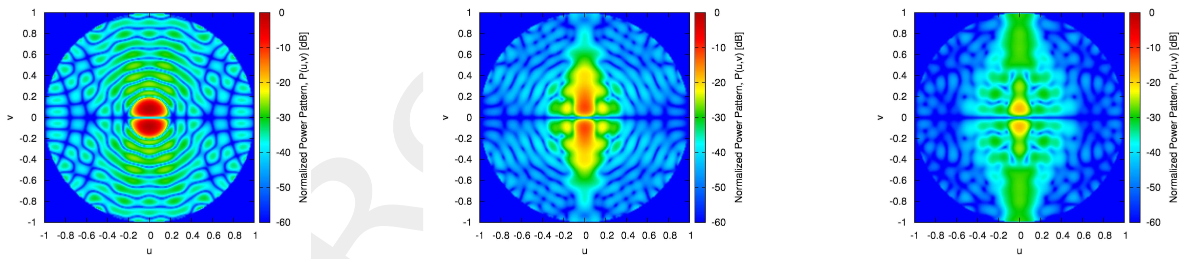


(a) (b)

Fig.39 - Taylor Static Amplitude Excitations (a) and Optimal Pulse Sequence (b).



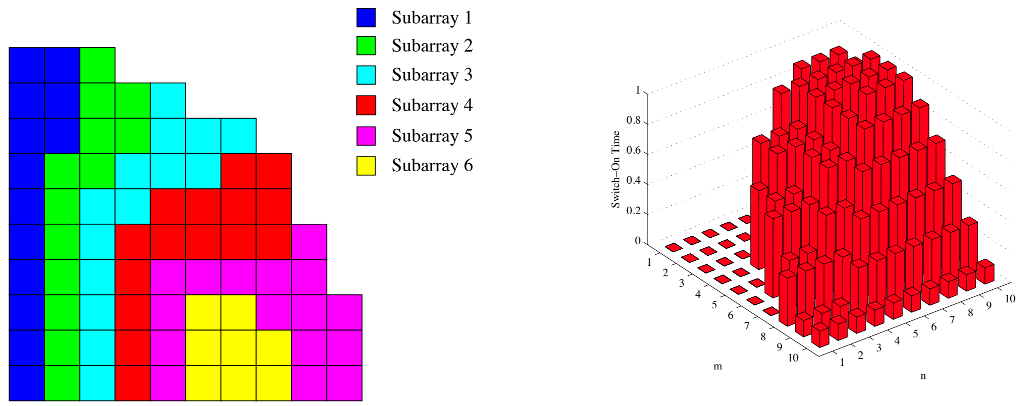
(a) (b) (c)



(d) (e) (f)

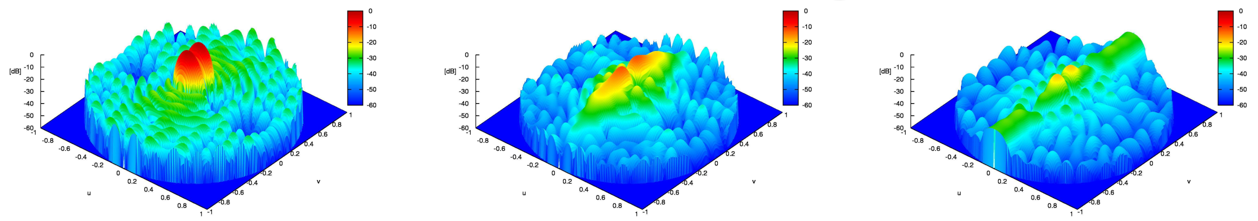
Fig.40 - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

Taylor SLL=-25dB switched to Bayliss SLL=-25 dB, Pulse Matching

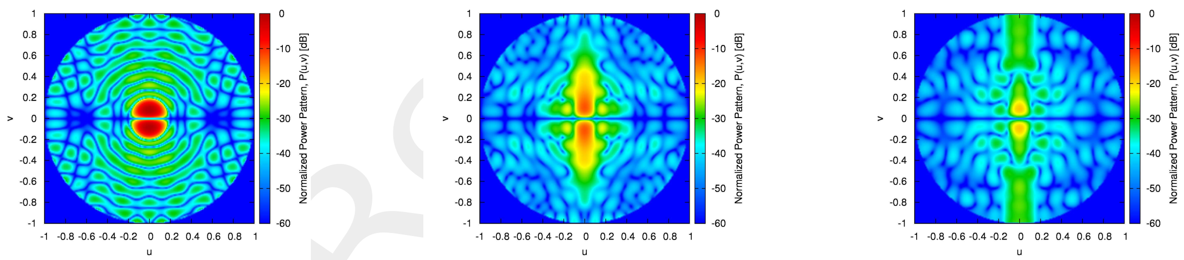


(a) (b)

Fig.41 - PM - Subarray Configuration (a) and Pulse Sequence (b).



(a) (b) (c)



(d) (e) (f)

Fig.42 - PM - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

Taylor SLL=-25dB switched to Bayliss SLL=-25 dB, Pulse Matching & SR Minimization ($w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = 1$)

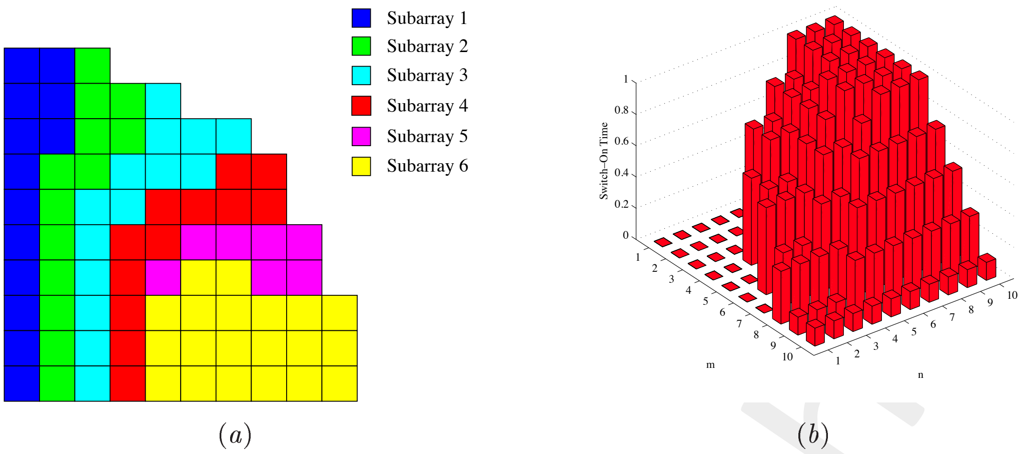


Fig.43 - PM - minSR - Subarray Configuration (a) and Pulse Sequence (b).

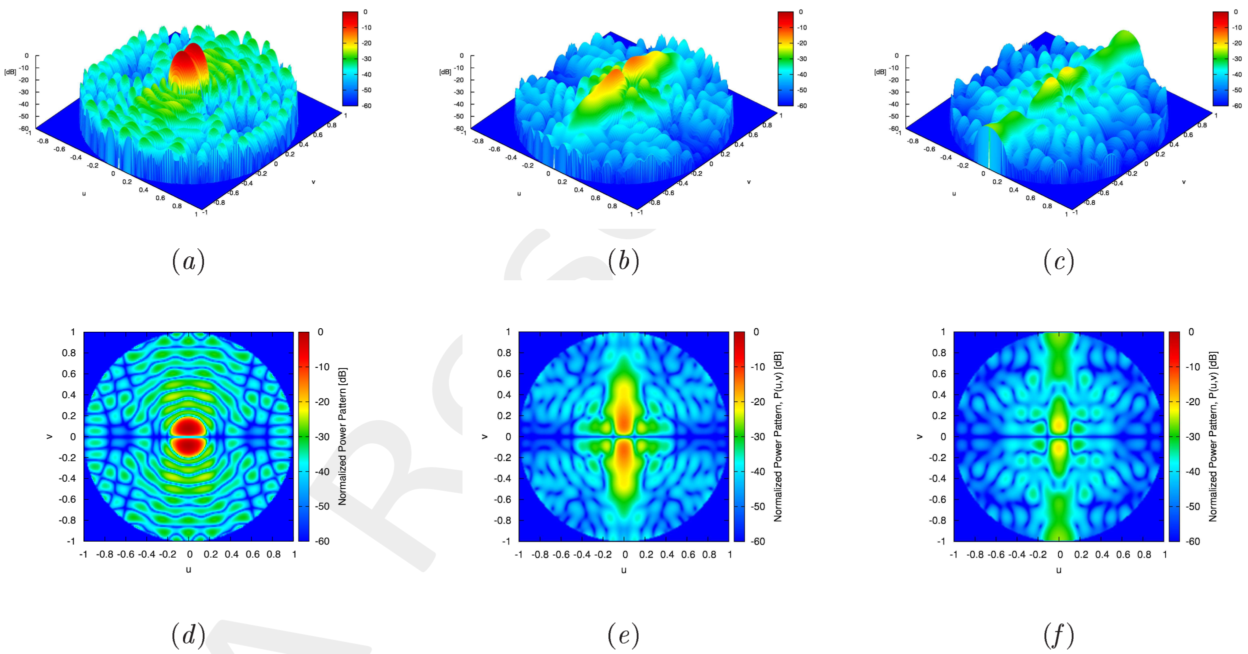


Fig.44 - PM - minSR - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

Taylor SLL=-25dB switched to Bayliss SLL=-25 dB, Pulse Matching & SR Minimization ($w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = 2$)

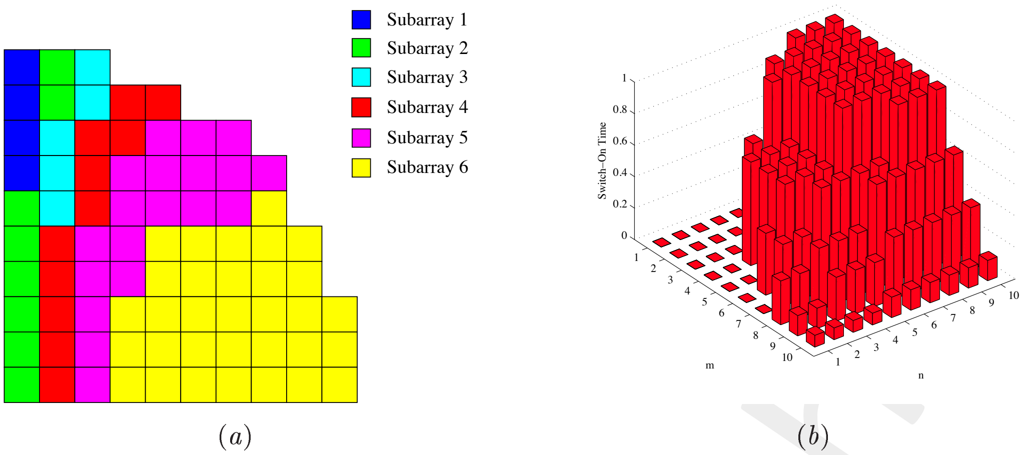


Fig.45 - PM - minSR - Subarray Configuration (a) and Pulse Sequence (b).

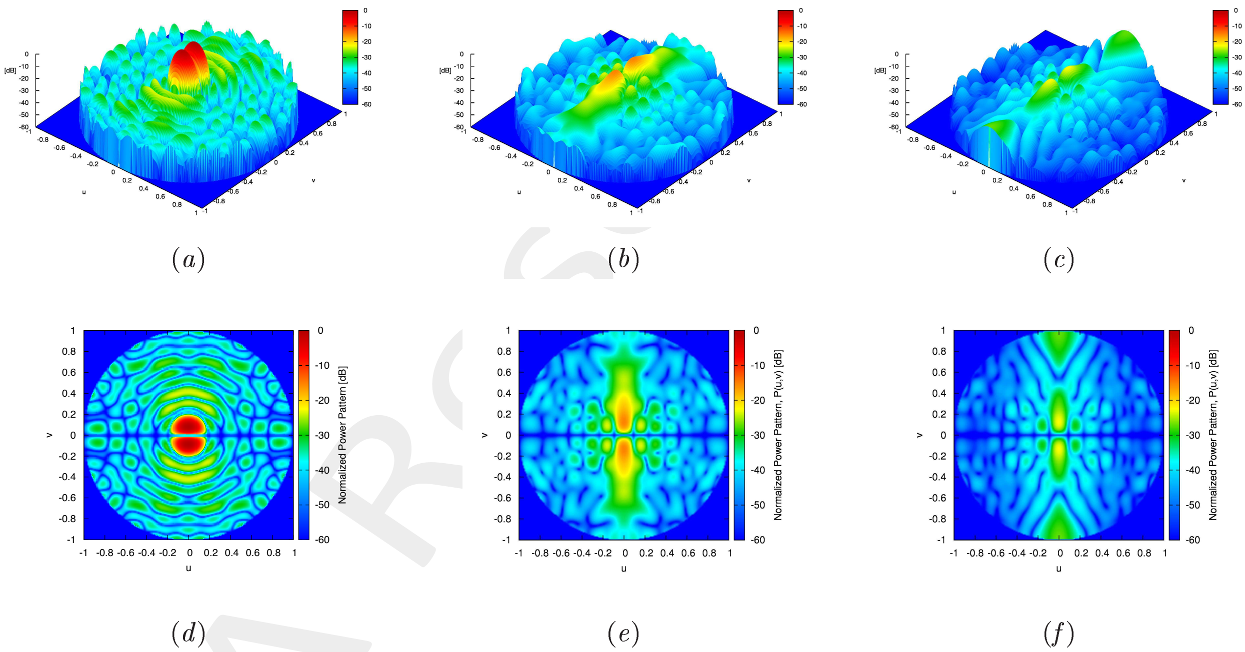


Fig.46 - PM - minSR - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

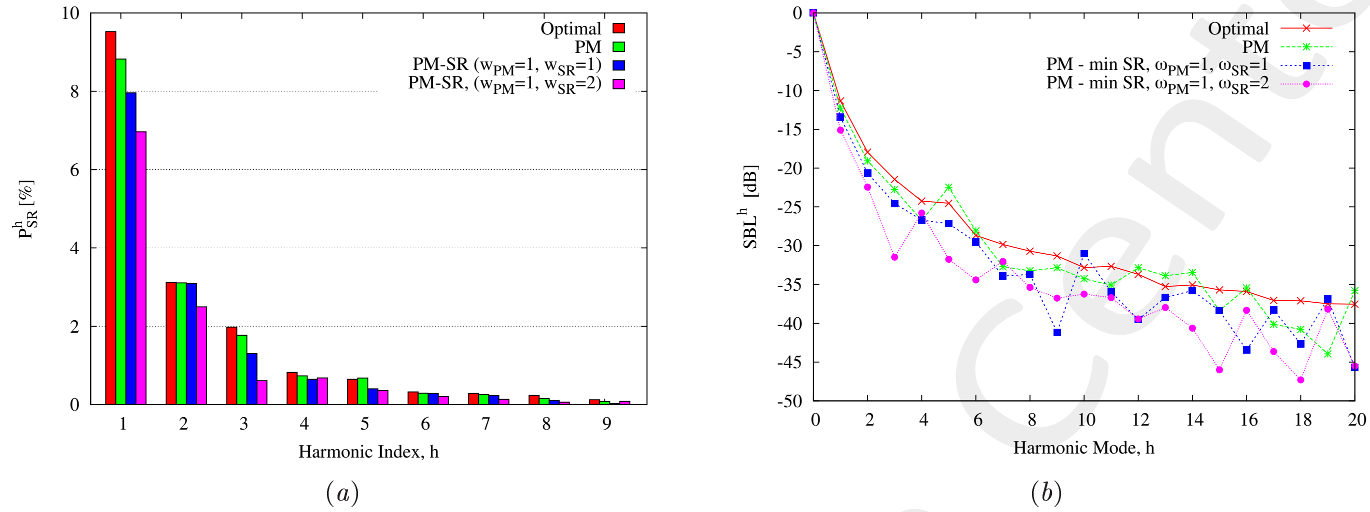
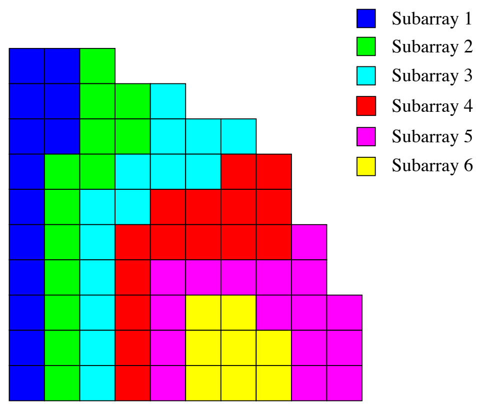
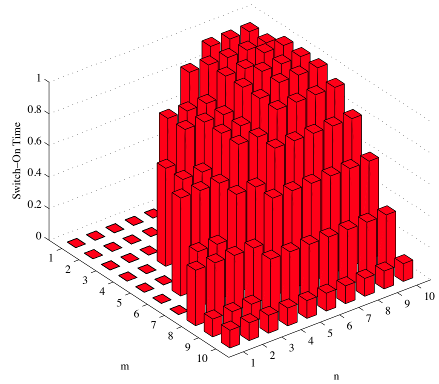


Fig.47 - SR (a) and SBL (b) Comparison.

Taylor SLL=-25dB switched to Bayliss SLL=-25 dB, Pulse Matching + Particle Swarm Optimization (Two Steps Approach) ($w_{SLL}^{PSO} = 1$, $w_{SR}^{PSO} = 1$)

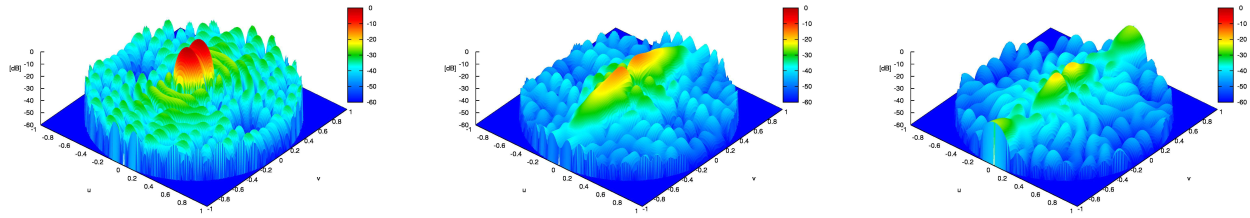


(a)

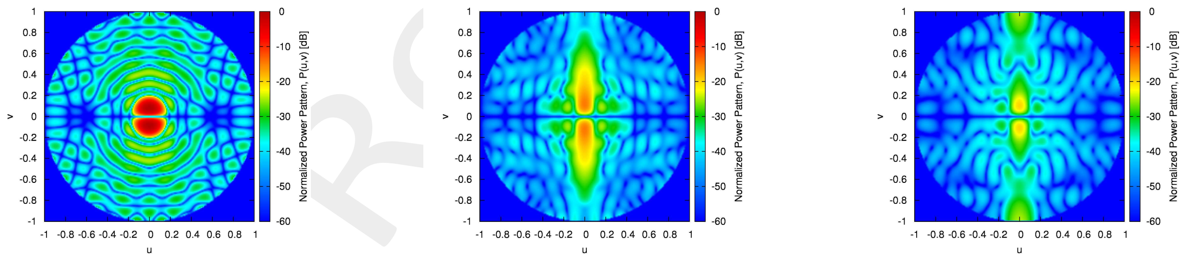


(b)

Fig.48 - PM+PSO - Subarray Configuration (a) and Pulse Sequence (b).



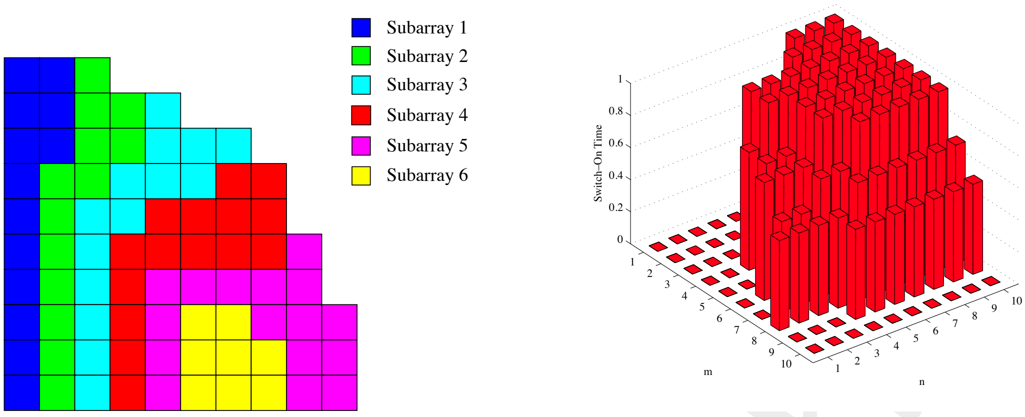
(a) (b) (c)



(d) (e) (f)

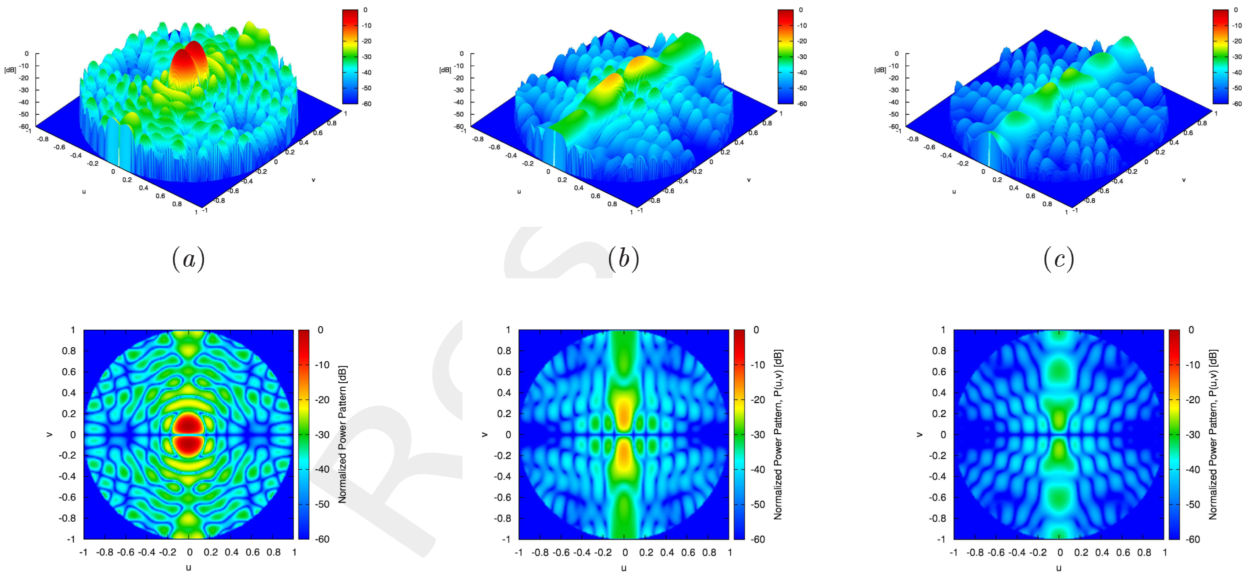
Fig.49 - PM+PSO - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).

Taylor SLL=-25dB switched to Bayliss SLL=-25 dB, Pulse Matching + Particle Swarm Optimization (Two Steps Approach) ($w_{SLL}^{PSO} = 1$, $w_{SR}^{PSO} = 2$)



(a) (b)

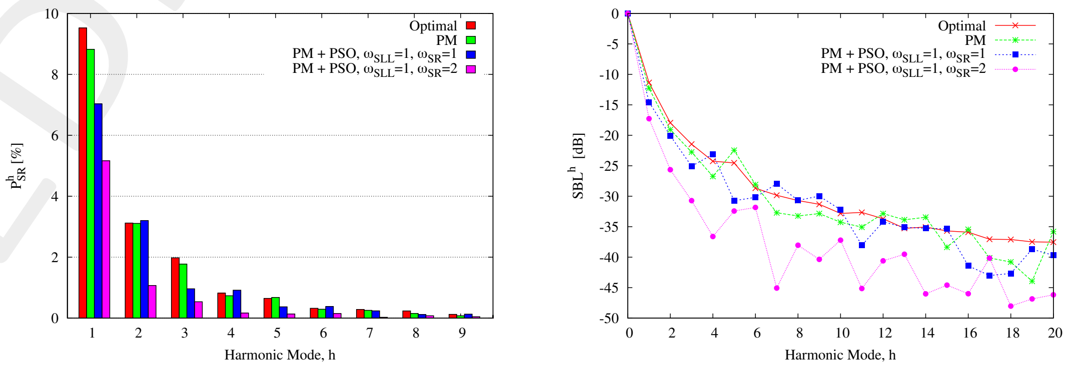
Fig.50 - PM+PSO - Subarray Configuration (a) and Pulse Sequence (b).



(a) (b) (c)

(d) (e) (f)

Fig.51 - PM+PSO - Time-Modulated Patterns: $h = 0$ (a)-(d), $h = 1$ (b)-(e) and $h = 2$ (c)-(f).



(a) (b)

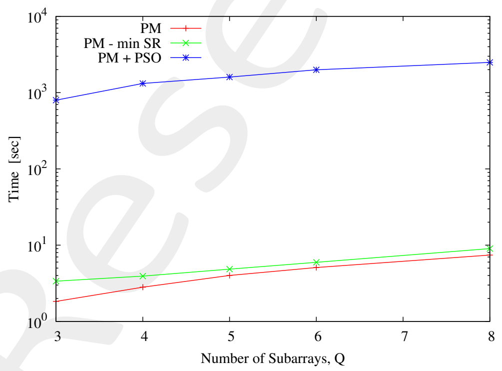
Fig.52 - SR (a) and SBL (b) Comparison.

	$SLL\,[dB]$	$P_{SR}\,[\%]$	Δ	$BW\,[deg]$	$FNBW$	$SBL\,[dB]$
$Optimal$	-25.44	36.68	$-$	5.10	0.208	-11.35
PM	-25.07	34.08	7.18	5.10	0.209	-12.27
$PM - min\,SR$, $w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = 1$	-23.94	30.10	7.70	5.09	0.209	-13.44
$PM - min\,SR$, $w_{PM}^{CPM} = 1$, $w_{SR}^{CPM} = 2$	-23.57	24.76	13.60	5.16	0.220	-15.10
$PM + PSO$, $w_{SLL}^{PSO} = 1$, $w_{SR}^{PSO} = 1$	-24.86	28.86	9.07	5.16	0.217	-14.56
$PM + PSO$, $w_{SLL}^{PSO} = 1$, $w_{SR}^{PSO} = 2$	-22.49	15.66	16.69	5.31	0.244	-17.27

Tab.3 - Pattern Parameters Comparison: Sidelobe Level (SLL), Sideband Radiation (P_{SR}), Pattern Matching Error (Δ), -3dB Beamwidth (BW), First Null Beamwidth ($FNBW$) and Sideband Level (SBL).

	$Q = 3$	$Q = 4$	$Q = 5$	$Q = 6$	$Q = 8$
PM	1.83	2.81	4.01	5.09	7.41
$PM - min\,SR$	3.37	3.93	4.85	5.96	9.01
$PM + PSO$	795.70	1318.76	1989.94	1989.94	2490.20

Tab.4 - Computational Times Comparison [sec].



(a)

Fig.53 - (a) Computational Times Comparison.

Observations:

- Osservando anche in questo caso l'andamento di Fig.5(c) si può notare che le soluzioni ricavate dalle tecniche PM e PM-minSR si differenziano tra loro di poco dal punto di vista della sideband radiation P_{SR}: aumentando però il peso del termine relativo alla sideband radiation nella funzione di costo definita in (3) (agendo quindi su w_{SR}^{CPM}) è possibile ridurre sensibilmente l'ammontare di tale potenza sprecata (Fig.14(c)) a discapito però di un peggioramento in termini di pattern matching ed in questo caso anche per quanto riguarda il SLL (il cui valore di riferimento è posto a $25\,dB$ invece di $20\,dB$ come nei casi precedenti). Osservando Fig.19-24 che riportano un'analisi delle prestazioni della tecnica PM-minSR al variare del peso w_{SR}^{CPM}, considerando il caso $Q = 6$ è possibile determinare la migliore soluzione "compromesso" tra pattern-matching e minimizzazione della P_{SR}, ricavata in questo caso ponendo $w_{SR}^{CPM} = 2$ (tale soluzione può essere considerata come miglior compromesso in quanto l'aumento del peso $w_{SR}^{CPM} = 3$ porta ad un abbassamento della P_{SR} piuttosto irrilevante a discapito di un innalzamento del SLL);

- E' possibile osservare dalla Tab.3 che l'approccio two-stage [1.c] non porta ad un considerevole miglioramento delle prestazioni rispetto alla tecnica PM-minSR: tuttavia l'utilizzo dell'ottimizzatore permette di ridurre maggiormente la quantità di P_{SR} a fronte però di un notevole peggioramento in termini di pattern-matching e di un innalzamento del SLL.

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