# A Pulse-Shifting Strategy applied to the Synthesis of Directive Time-modulated Linear Arrays

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**Abstract**

This report deals with the minimization of the amount of sideband radiation on time-modulated linear arrays by taking advantage of the directive nature of radiating elements. An innovative approach is exploited to synthesis harmonic patterns with high sideband level within the 'blind' directions of the element factor. A set of representative numerical results is reported to illustrate the potentialities and the limitations of the proposed approach considering both sum and difference patterns.

# Numerical Validation

## TEST CASE 2 - $0.5\lambda$ Elements Spacing - Short Dipoles - Dolph Pattern

### Goal

Sideband radiation minimization of a TMLA composed by real radiating elements (short dipoles considered in this test case) adopting the pulse shifting technique.

### Test Case Description

- Number of Elements: $N = 16$
- Elements Spacing: $d = 0.5\lambda$
- Static Array Configuration: $\alpha_n = 1,\ n = 0, ..., N-1$
- Pattern at Central Frequency: $Dolph - Chebyshev\,,\, SLL = -30\,dB$
- Max Gain Pattern Direction : $\theta^{max} = 90°$

### 1.b) Optimization Approach: PS-PSO, SR Min.

The optimization process though the PSO algorithm acts just on the temporal shift of the pulses;

- Number of Variables: $X = 16$
- Number of Particles: $S = 15 - 30$
- Number of Iterations: $I = 500$
- Inertial Weight: Linearly varying: $0.9\, to\, 0.4$
- Cost Function:

$$\Psi^{PSO}\left[\tau_n'(i_k)\right] = P_{SR}^{act,(i_k)} \tag{1}$$

**Dolph-Chebyshev Pattern, SLL=-30 dB - Original - Short Dipole Elements Array**

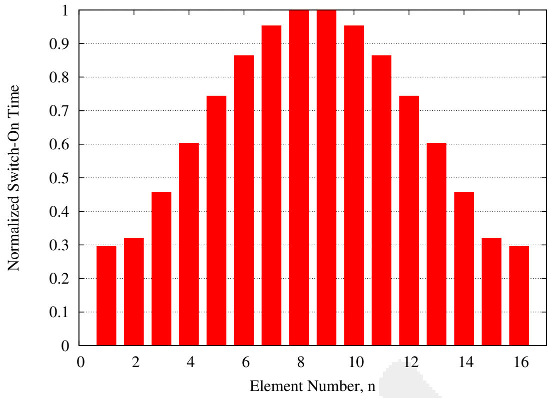


**Fig.17 - Pulse Sequence**

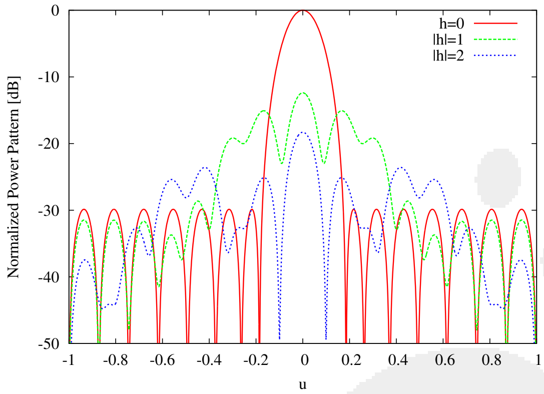


**Fig.18 - Isotropic - Pattern(u)**

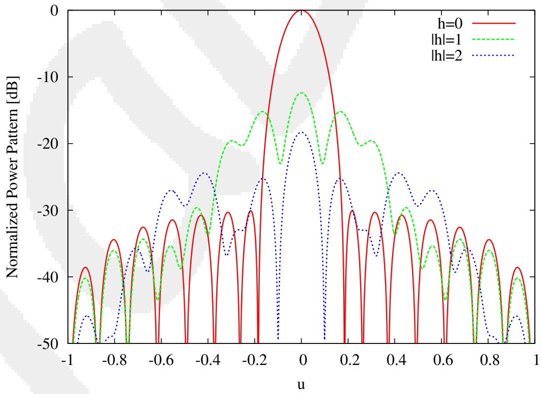


**Fig.19 - Short Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - End-Fire h=1 - Short Dipole Elements Array

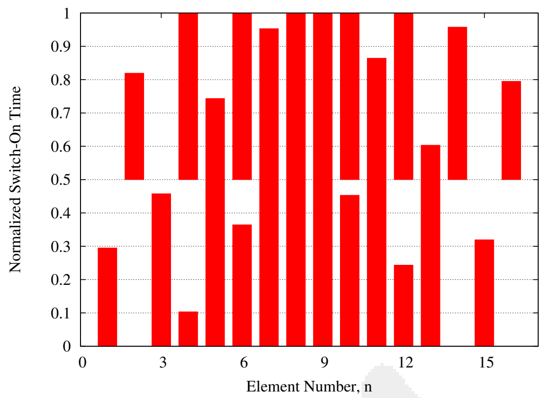


**Fig.20 - Pulse Sequence**

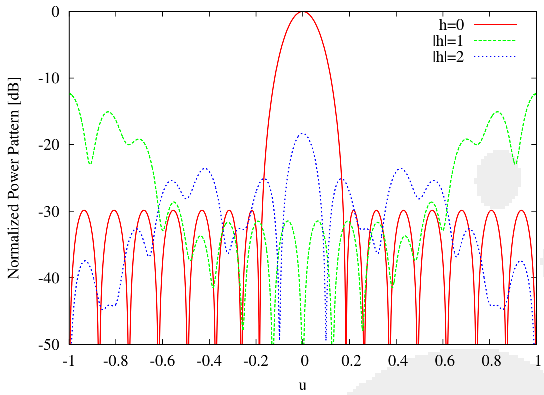


**Fig.21 - Isotropic - Pattern(u)**

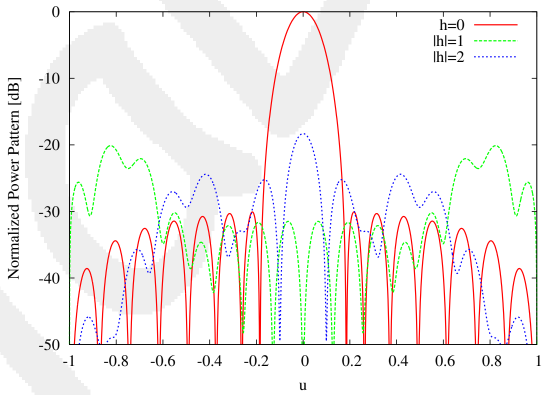


**Fig.22 - Short Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=1 - Short Dipole Elements Array

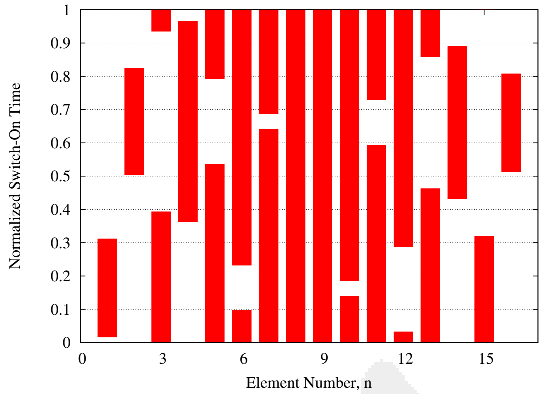


**Fig.23 - Pulse Sequence**

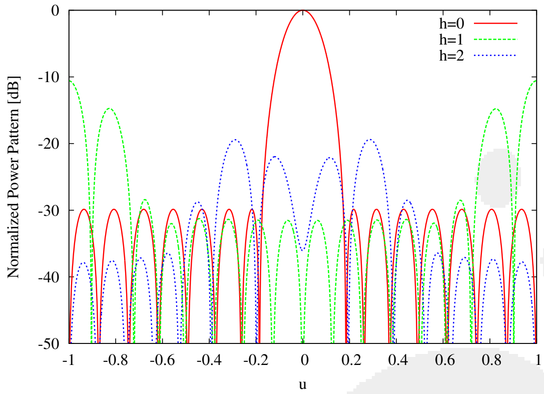


**Fig.24 - Isotropic - Pattern(u)**

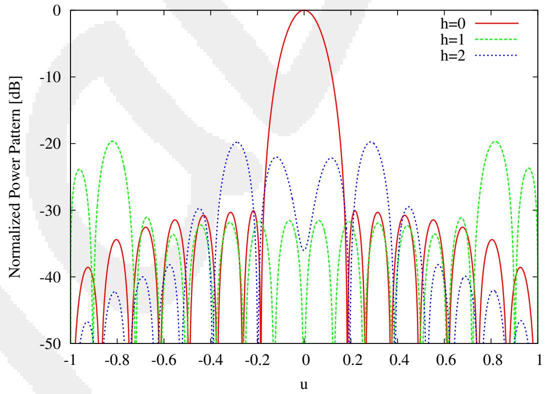


**Fig.25 - Short Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=2 - Short Dipole Elements Array

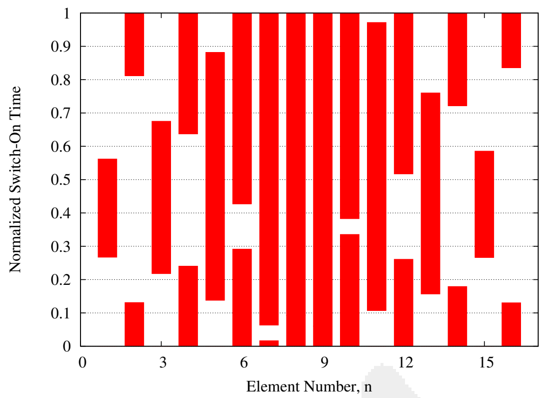


**Fig.26 - Pulse Sequence**

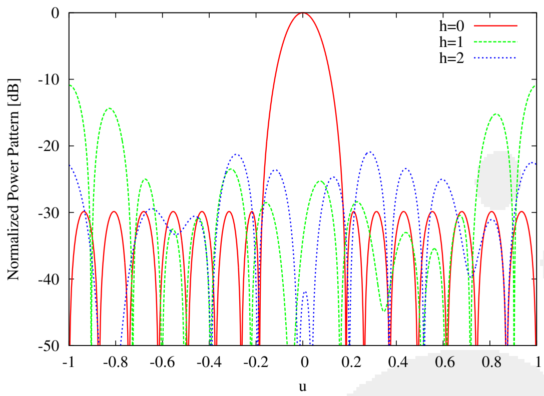


**Fig.27 - Isotropic - Pattern(u)**

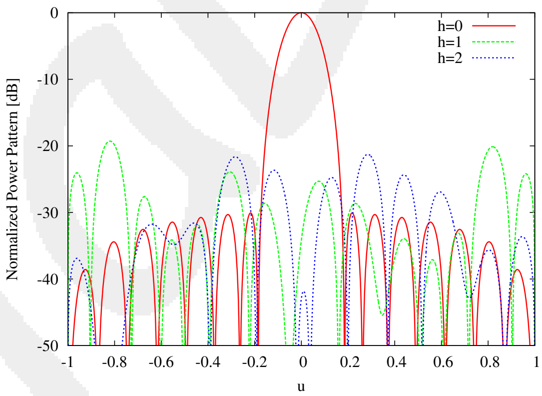


**Fig.28 - Short Dipole - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=100 - Short Dipole Elements Array**

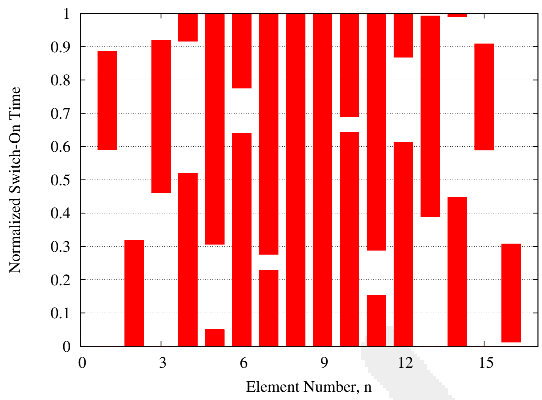


**Fig.29 - Pulse Sequence**

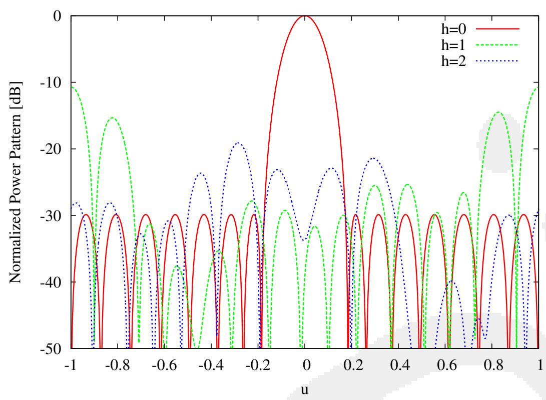


**Fig.30 - Isotropic - Pattern(u)**

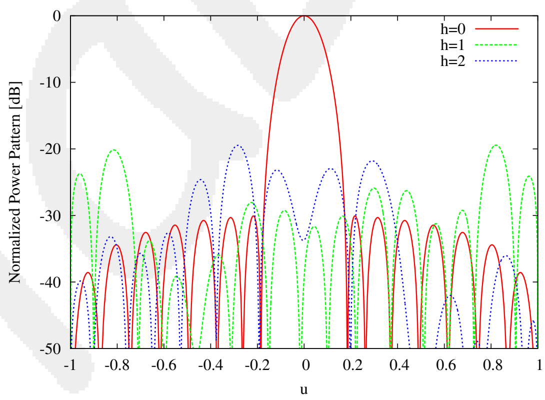


**Fig.31 - Short Dipole - Pattern(u)**

| | $SLL\,[dB]$ | $SBL\,[dB]$ | $SBL_1\,[dB]$ | $SBL_2\,[dB]$ | $BW\,[deg]$ | $SR\,[\%]$ |
|---|---|---|---|---|---|---|
| $Dolph-Chebyshev$ | $-30.08$ | $-12.39$ | $-12.39$ | $-18.30$ | 15.85 | 22.50 |
| $End\,Fire\,h=1\,Pattern$ | $-30.08$ | $-18.30$ | $-20.12$ | $-18.30$ | 15.85 | 12.18 |
| $PS-PSO,\,SR\,Min.\,H=1$ | $-30.08$ | $-19.65$ | $-19.65$ | $-19.75$ | 15.85 | 11.45 |
| $PS-PSO,\,SR\,Min.\,H=2$ | $-30.08$ | $-19.29$ | $-19.29$ | $-21.28$ | 15.85 | 11.45 |
| $PS-PSO,\,SR\,Min.\,H=100$ | $-30.08$ | $-19.44$ | $-19.44$ | $-19.47$ | 15.85 | 11.45 |

**Tab.2 - Sidelobe Lebel ($SLL$), Sideband Level ($SBL$), -3 dB Beamwidth ($BW$), Sideband Radiation ($SR$).**

# TEST CASE 3 - $0.7\lambda$ Elements Spacing - Dipoles - Dolph Pattern

### Goal

Sideband radiation minimization of a TMLA composed by real radiating elements (dipoles considered in this test case) adopting the pulse shifting technique.

### Test Case Description

- Number of Elements: $N = 16$
- Elements Spacing: $d = 0.7\lambda$
- Static Array Configuration: $\alpha_n = 1,\ n = 0, ..., N-1$
- Pattern at Central Frequency: $Dolph - Chebyshev\,,\, SLL = -30\,dB$
- Max Gain Pattern Direction : $\theta^{max} = 90°$

### 1.b) Optimization Approach: PS-PSO, SR Min.

The optimization process though the PSO algorithm acts just on the temporal shift of the pulses;

- Number of Variables: $X = 16$
- Number of Particles: $S = 15 - 30$
- Number of Iterations: $I = 500$
- Inertial Weight: Linearly varying: $0.9\, to\, 0.4$
- Cost Function:

$$\Psi^{PSO}\left[\tau_n'(i_k)\right] = P_{SR}^{act,(i_k)} \tag{2}$$

**Dolph-Chebyshev Pattern, SLL=-30 dB - Original - Dipole Elements Array**

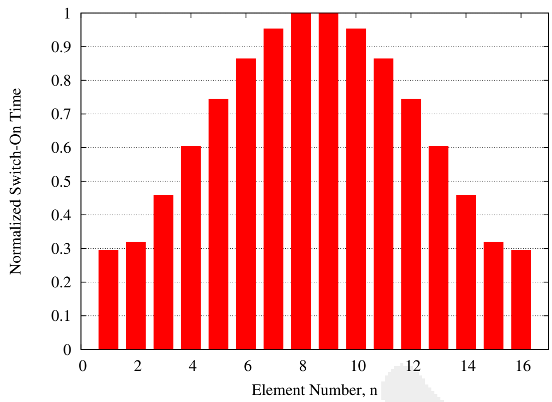


**Fig.32 - Pulse Sequence**

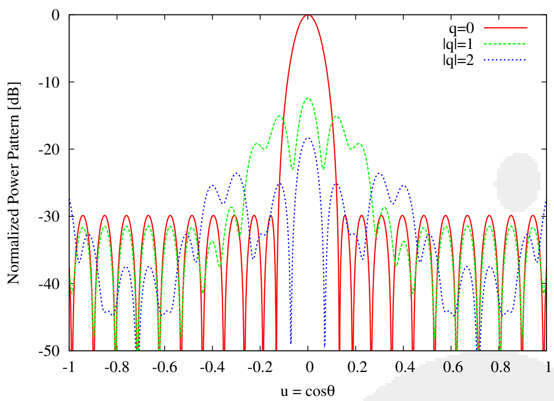


**Fig.33 - Isotropic - Pattern(u)**

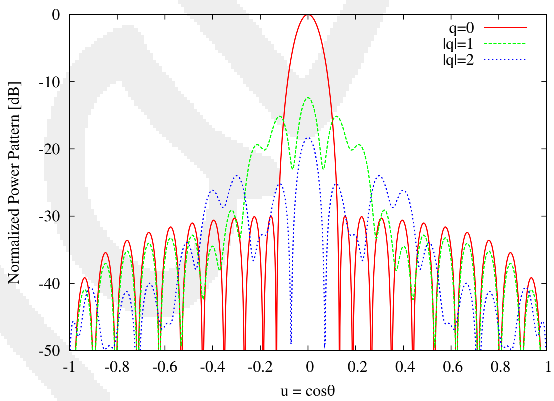


**Fig.34 - Dipole - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - End-Fire h=1 - Dipole Elements Array**

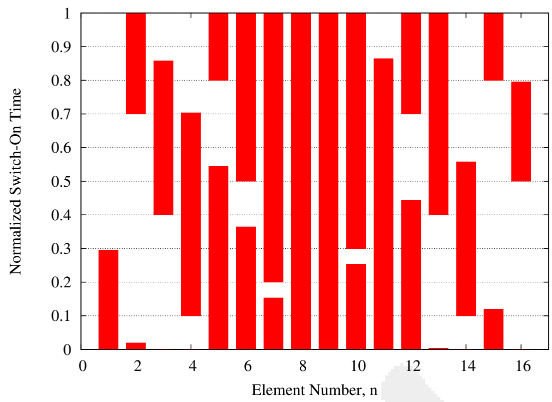


**Fig.35 - Pulse Sequence**

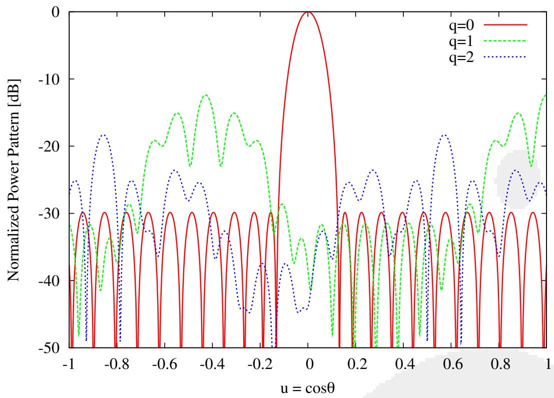


**Fig.36 - Isotropic - Pattern(u)**

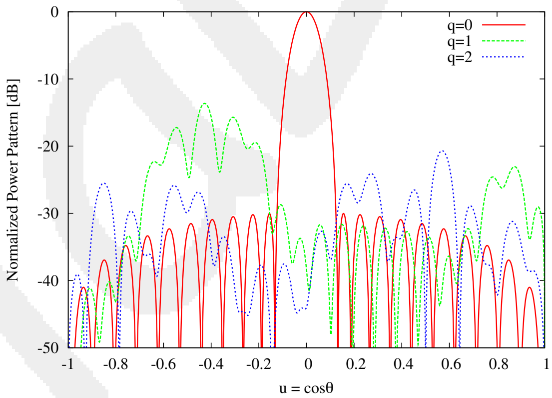


**Fig.37 - Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=1 - Dipole Elements Array

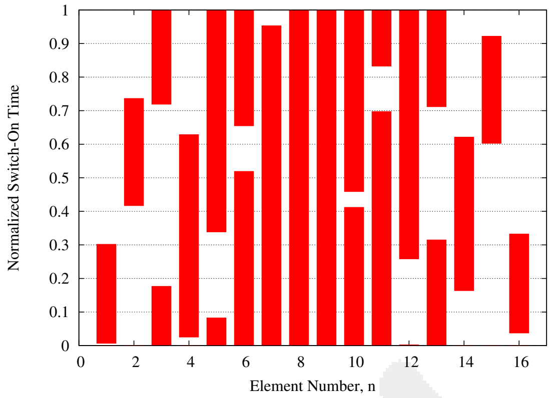


**Fig.38 - Pulse Sequence**

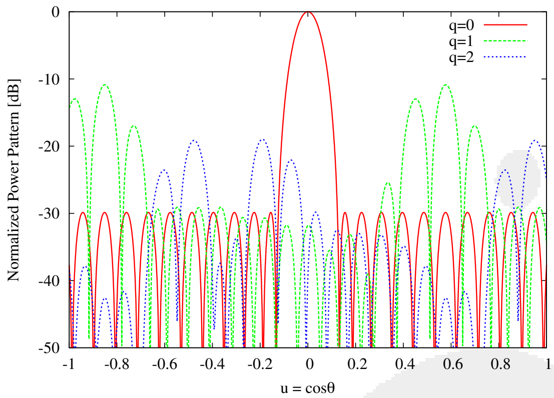


**Fig.39 - Isotropic - Pattern(u)**

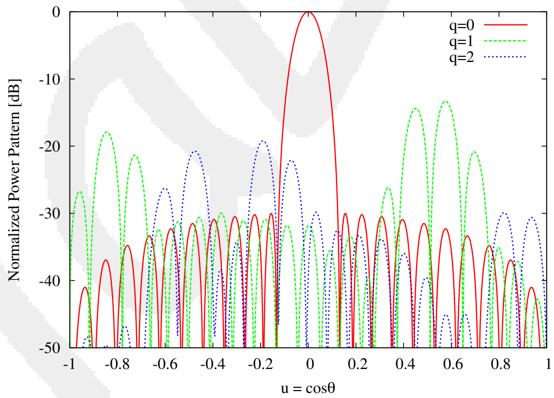


**Fig.40 - Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=2 - Dipole Elements Array

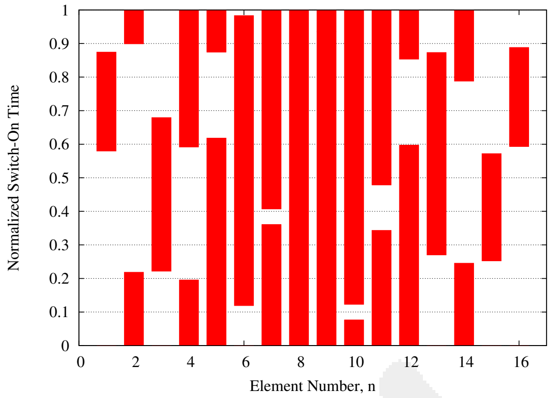


**Fig.41 - Pulse Sequence**

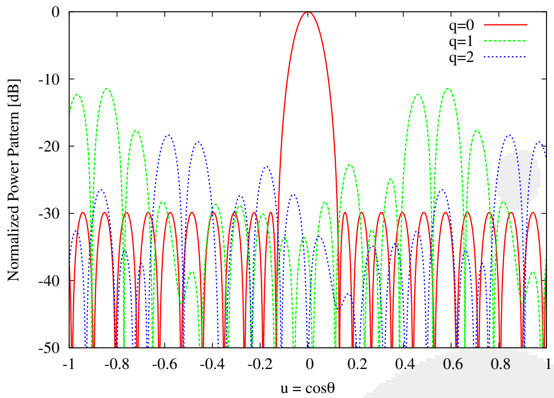


**Fig.42 - Isotropic - Pattern(u)**

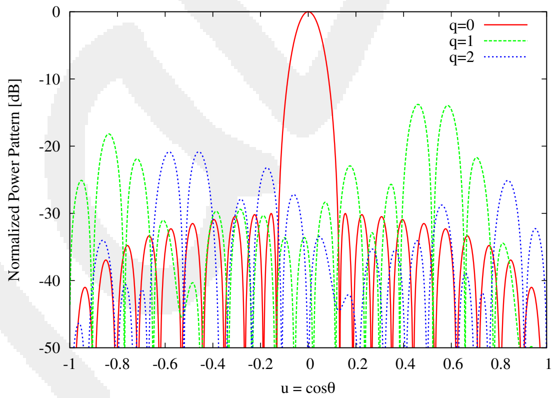


**Fig.43 - Dipole - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=100 - Dipole Elements Array**

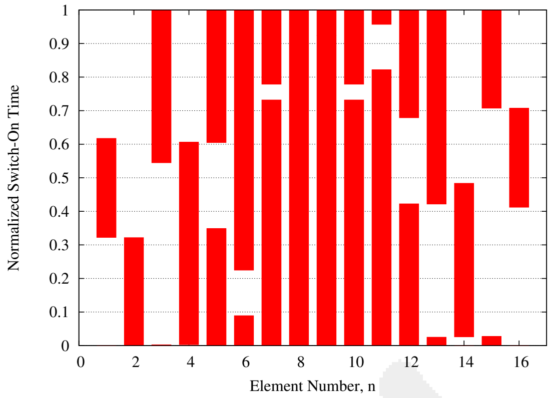


**Fig.44 - Pulse Sequence**

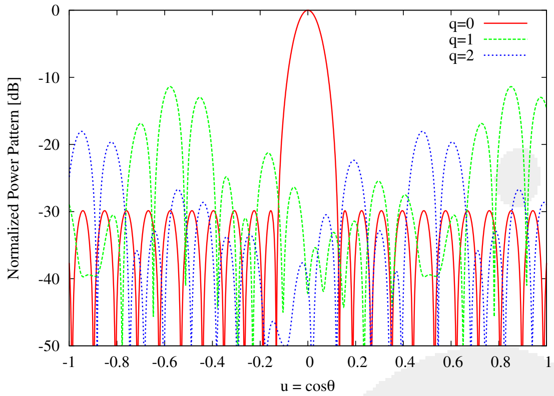


**Fig.45 - Isotropic - Pattern(u)**

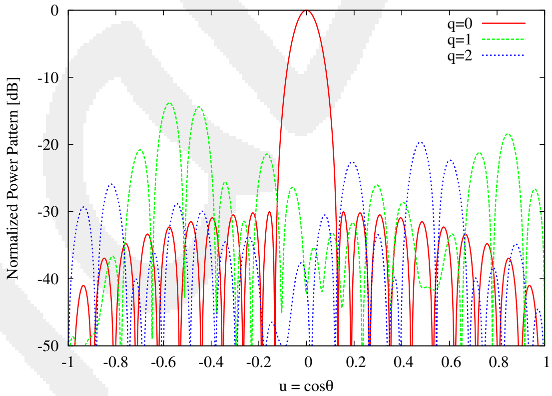


**Fig.46 - Dipole - Pattern(u)**

| | $SLL\,[dB]$ | $SBL\,[dB]$ | $SBL_1\,[dB]$ | $SBL_2\,[dB]$ | $BW\,[deg]$ | $SR\,[\%]$ |
|---|---|---|---|---|---|---|
| $Dolph-Chebyshev$ | $-30.02$ | $-12.39$ | $-12.39$ | $-18.30$ | $11.33$ | $23.28$ |
| $End\,Fire\,h=1\,Pattern$ | $-30.02$ | $-13.64$ | $-13.64$ | $-20.68$ | $11.33$ | $20.63$ |
| $PS-PSO,\,SR\,Min.\,H=1$ | $-30.02$ | $-13.31$ | $-13.31$ | $-19.21$ | $11.33$ | $20.37$ |
| $PS-PSO,\,SR\,Min.\,H=2$ | $-30.02$ | $-13.78$ | $-13.78$ | $-20.82$ | $11.33$ | $20.22$ |
| $PS-PSO,\,SR\,Min.\,H=100$ | $-30.02$ | $-13.82$ | $-13.82$ | $-19.64$ | $11.33$ | $20.16$ |

**Tab.3 - Sidelobe Lebel ($SLL$), Sideband Level ($SBL$), -3 dB Beamwidth ($BW$), Sideband Radiation ($SR$).**

# TEST CASE 4 - $0.4\lambda$ Elements Spacing - Short Dipoles - Dolph Pattern

### Goal

Sideband radiation minimization of a TMLA composed by real radiating elements (short dipoles considered in this test case) adopting the pulse shifting technique.

### Test Case Description

- Number of Elements: $N = 16$
- Elements Spacing: $d = 0.4\lambda$
- Static Array Configuration: $\alpha_n = 1,\ n = 0, ..., N-1$
- Pattern at Central Frequency: $Dolph - Chebyshev\,,\, SLL = -30\,dB$
- Max Gain Pattern Direction : $\theta^{max} = 90°$

### 1.b) Optimization Approach: PS-PSO, SR Min.

The optimization process though the PSO algorithm acts just on the temporal shift of the pulses;

- Number of Variables: $X = 16$
- Number of Particles: $S = 15 - 30$
- Number of Iterations: $I = 500$
- Inertial Weight: Linearly varying: $0.9\,to\,0.4$
- Cost Function:

$$\Psi^{PSO}\left[\tau_n'(i_k)\right] = P_{SR}^{act,(i_k)} \tag{3}$$

## Dolph-Chebyshev Pattern, SLL=-30 dB - Original - Short Dipole Elements Array

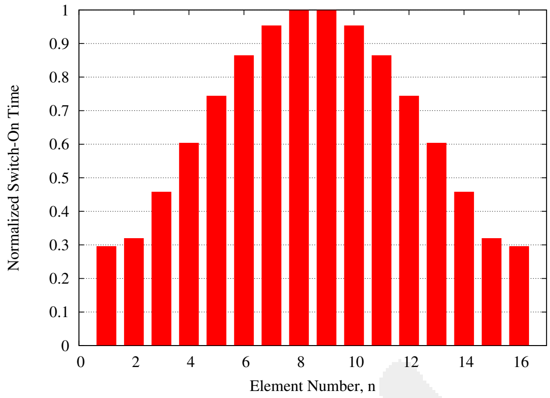


**Fig.47 - Pulse Sequence**

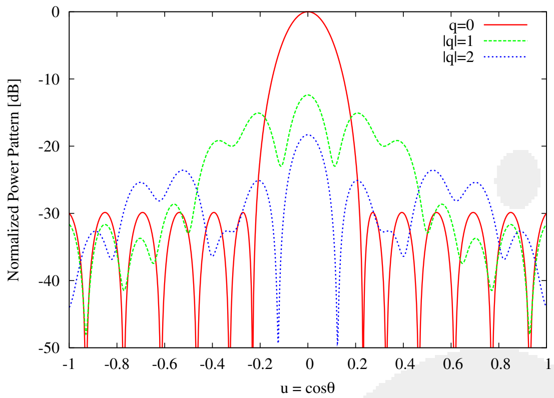


**Fig.48 - Isotropic - Pattern(u)**

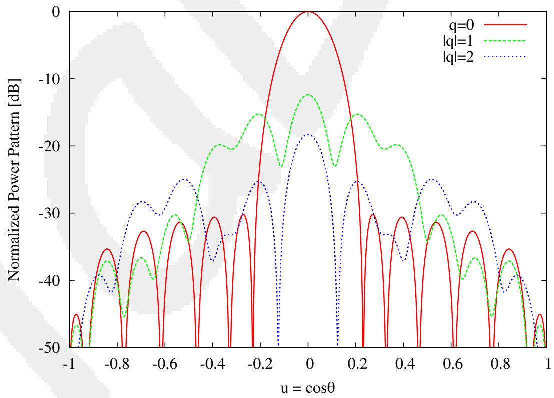


**Fig.49 - Short Dipole - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - End-Fire h=1 - Short Dipole Elements Array**

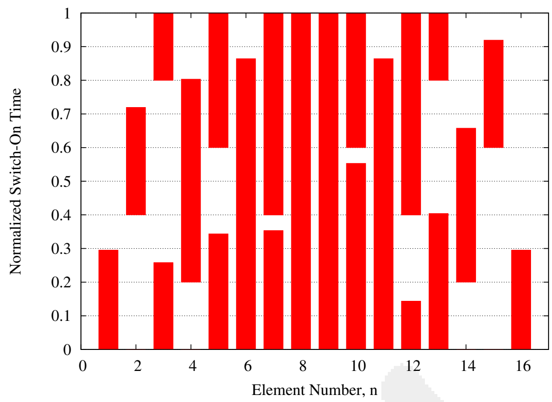


**Fig.50 - Pulse Sequence**

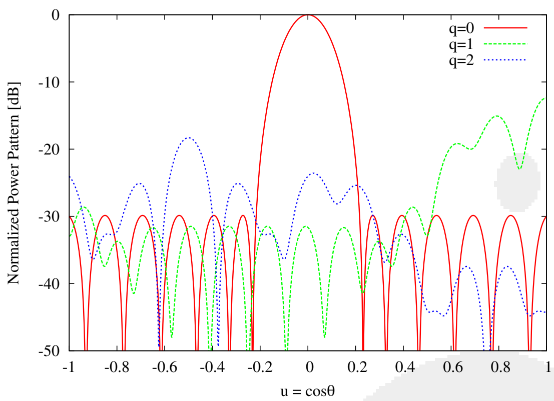


**Fig.51 - Isotropic - Pattern(u)**

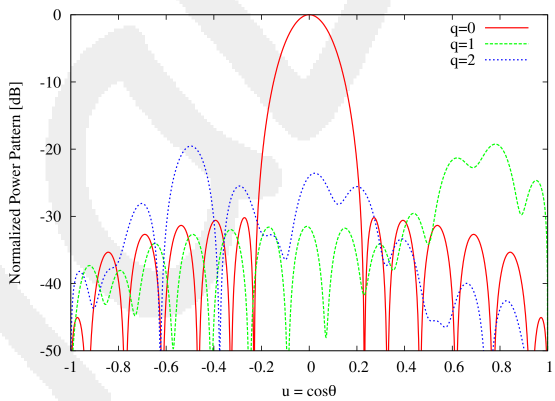


**Fig.52 - Short Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=1 - Short Dipole Elements Array

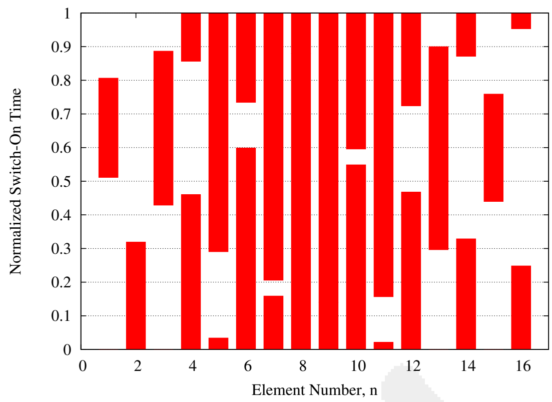


**Fig.53 - Pulse Sequence**

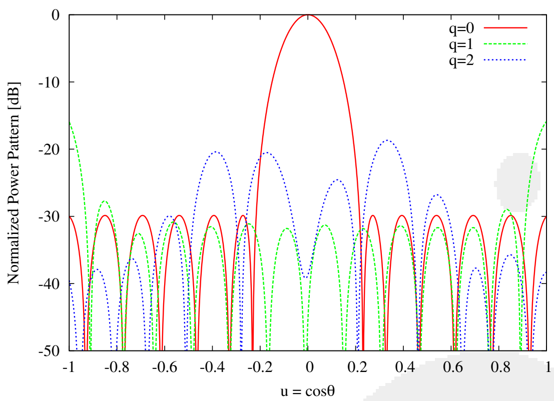


**Fig.54 - Isotropic - Pattern(u)**

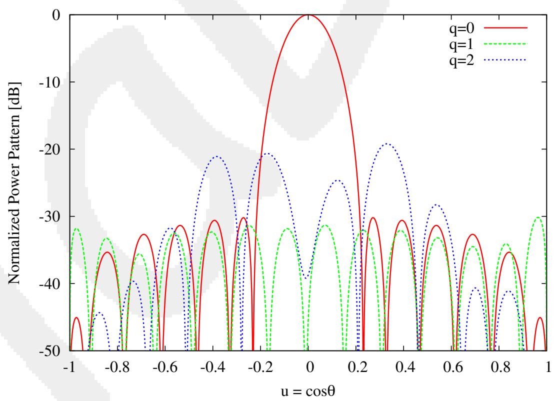


**Fig.55 - Short Dipole - Pattern(u)**

## Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=2 - Short Dipole Elements Array

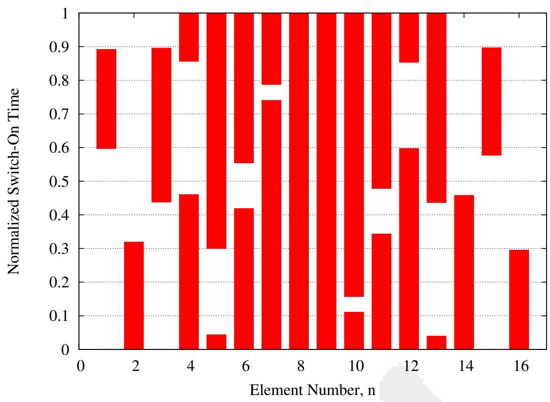


**Fig.56 - Pulse Sequence**

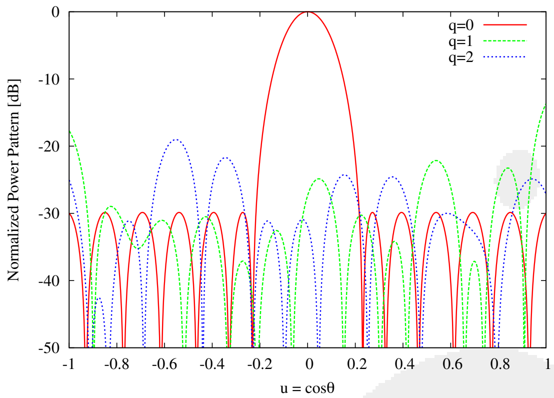


**Fig.57 - Isotropic - Pattern(u)**

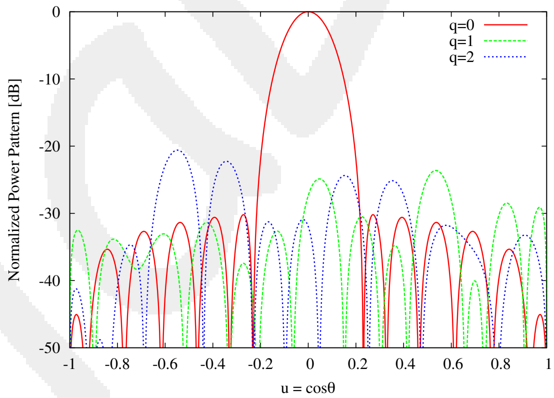


**Fig.58 - Short Dipole - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=100 - Short Dipole Elements Array**

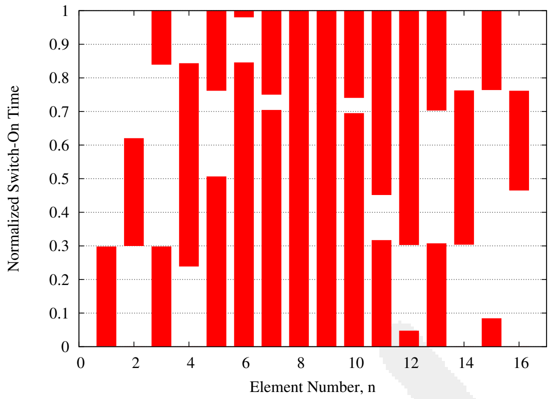


**Fig.59 - Pulse Sequence**

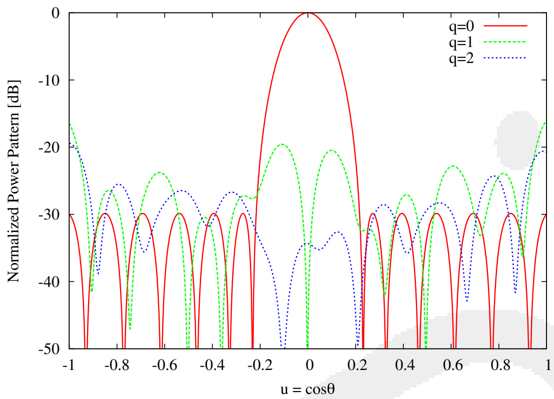


**Fig.60 - Isotropic - Pattern(u)**

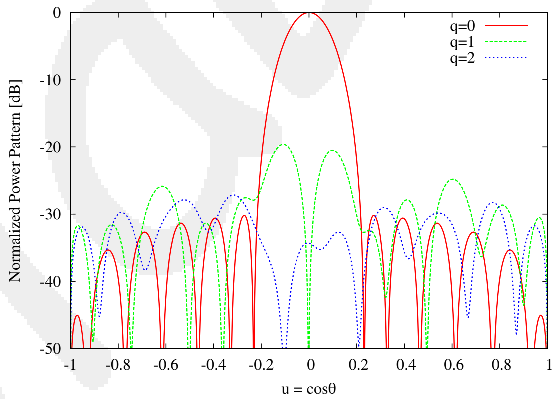


**Fig.61 - Dipole - Pattern(u)**

| | $SLL\,[dB]$ | $SBL\,[dB]$ | $SBL_1\,[dB]$ | $SBL_2\,[dB]$ | $BW\,[deg]$ | $SR\,[\%]$ |
|---|---|---|---|---|---|---|
| $Dolph-Chebyshev$ | $-30.20$ | $-12.38$ | $-12.38$ | $-18.30$ | 19.78 | 21.69 |
| $End\,Fire\,h=1\,Pattern$ | $-30.20$ | $-19.26$ | $-19.26$ | $-19.54$ | 19.78 | 9.17 |
| $PS-PSO,\,SR\,Min.\,H=1$ | $-30.20$ | $-19.20$ | $-30.15$ | $-19.20$ | 19.78 | 7.81 |
| $PS-PSO,\,SR\,Min.\,H=2$ | $-30.20$ | $-20.59$ | $-23.62$ | $-20.59$ | 19.78 | 7.73 |
| $PS-PSO,\,SR\,Min.\,H=100$ | $-30.20$ | $-19.63$ | $-19.63$ | $-27.15$ | 19.78 | 7.62 |

**Tab.4 - Sidelobe Lebel ($SLL$), Sideband Level ($SBL$), -3 dB Beamwidth ($BW$), Sideband Radiation ($SR$).**

# TEST CASE 5 - $0.7\lambda$ Elements Spacing - Dipoles on Ground Plane - Dolph Pattern

**Goal**

Sideband radiation minimization of a TMLA composed by real radiating elements (short dipoles considered in this test case) adopting the pulse shifting technique.

**Test Case Description**

- Number of Elements: $N = 16$
- Elements Spacing: $d = 0.7\lambda$
- Static Array Configuration: $\alpha_n = 1,\ n = 0, ..., N-1$
- Pattern at Central Frequency: $Dolph - Chebyshev\,,\, SLL = -30\,dB$
- Max Gain Pattern Direction : $\theta^{max} = 90°$
- Dipole Length: $l = 0.5\lambda$
- Dipole Distance from Ground Plane: $h = 0.75\lambda$
- Ground Plane Dimension: $8\lambda \times 8\lambda$

**1.b) Optimization Approach: PS-PSO, SR Min.**

The optimization process though the PSO algorithm acts just on the temporal shift of the pulses;

- Number of Variables: $X = 16$
- Number of Particles: $S = 15$
- Number of Iterations: $I = 500$
- Inertial Weight: Linearly varying: $0.9\,to\,0.4$
- Cost Function:

$$\Psi^{PSO}\left[\tau'_n(i_k)\right] = P_{SR}^{act,(i_k)} \tag{4}$$

### Element Factor - Dipoles on a Ground Plane

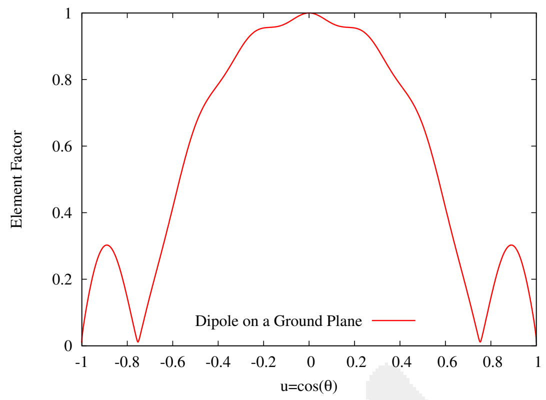


**Fig.62 - Element Factor**

### Dolph-Chebyshev Pattern, SLL=-30 dB - Original - Dipoles on a Ground Plane

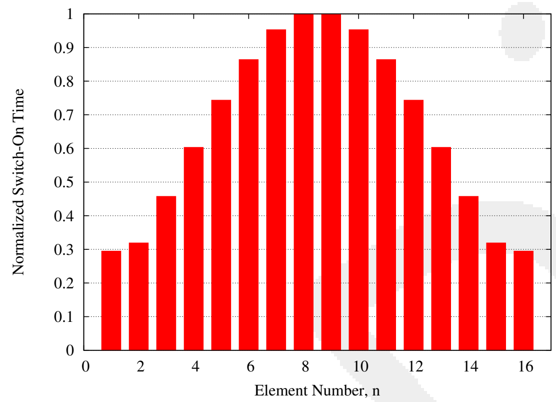


**Fig.63 - Pulse Sequence**

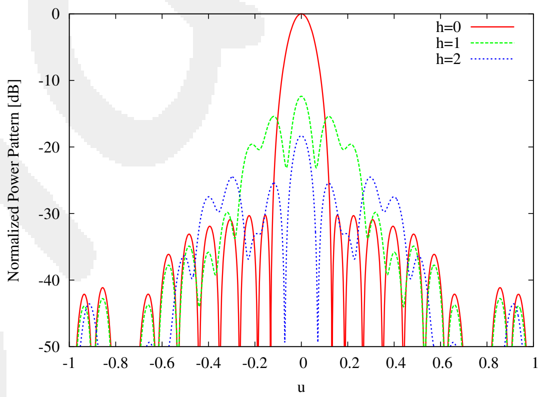


**Fig.64 - Pattern(u)**

### Dolph-Chebyshev Pattern, SLL=-30 dB - End-Fire h=1 - Dipoles on a Ground Plane

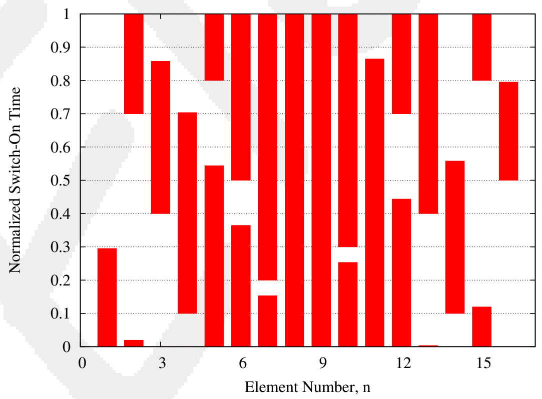


**Fig.65 - Pulse Sequence**

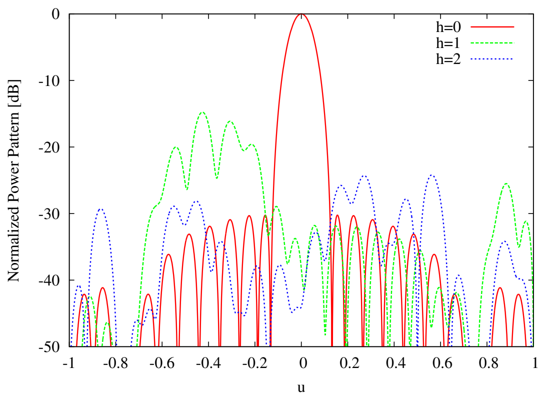


**Fig.66 - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=1 - Dipoles on a Ground Plane**

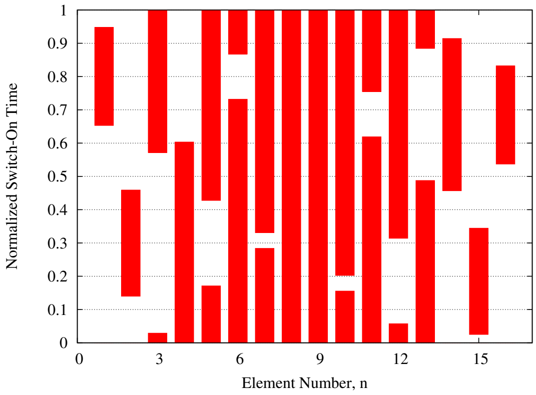


**Fig.67 - Pulse Sequence**

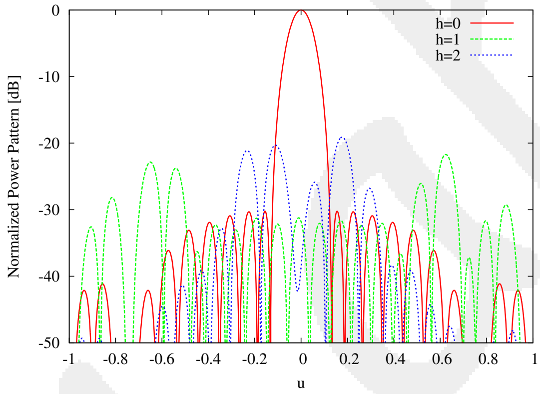


**Fig.68 - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=2 - Dipoles on a Ground Plane**

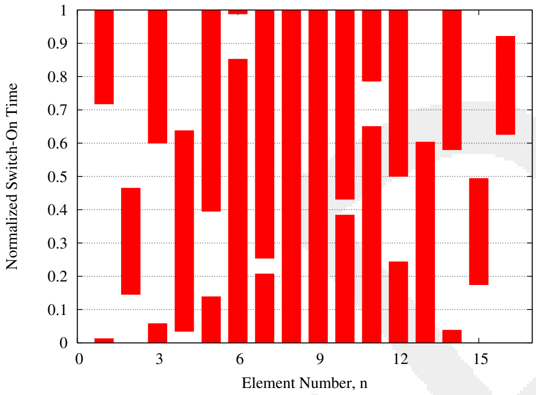


**Fig.69 - Pulse Sequence**

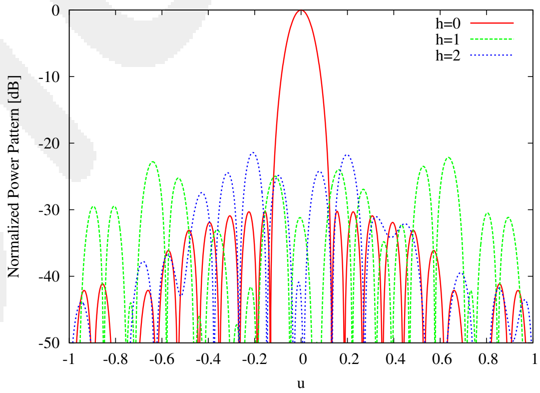


**Fig.70 - Pattern(u)**

**Dolph-Chebyshev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=100 - Dipoles on a Ground Plane**

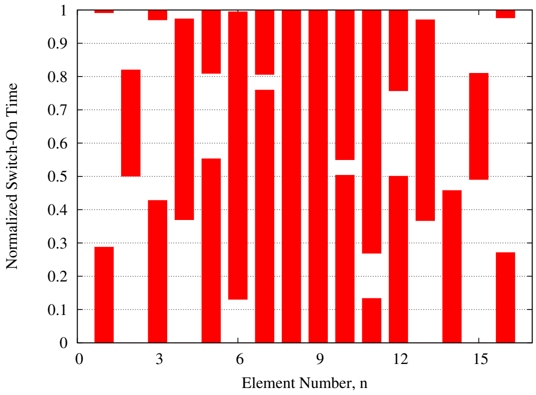


**Fig.71 - Pulse Sequence**

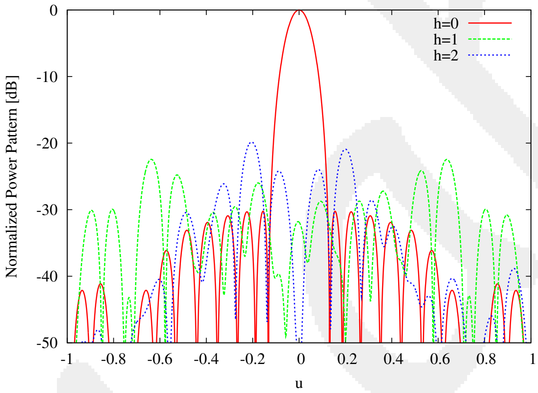


**Fig.72 - Dipole - Pattern(u)**

| | $SLL\,[dB]$ | $SBL\,[dB]$ | $SBL_1\,[dB]$ | $SBL_2\,[dB]$ | $BW\,[deg]$ | $SR\,[\%]$ |
|---|---|---|---|---|---|---|
| $Dolph-Chebyshev$ | $-30.24$ | $-12.38$ | $-12.38$ | $-18.30$ | 19.78 | 22.23 |
| $End\,Fire\,h=1\,Pattern$ | $-30.24$ | $-14.77$ | $-14.77$ | $-24.20$ | 19.78 | 15.58 |
| $PS-PSO,\,SR\,Min.\,H=1$ | $-30.24$ | $-19.11$ | $-21.70$ | $-19.11$ | 19.78 | 10.62 |
| $PS-PSO,\,SR\,Min.\,H=2$ | $-30.24$ | $-21.41$ | $-22.14$ | $-21.41$ | 19.78 | 10.61 |
| $PS-PSO,\,SR\,Min.\,H=100$ | $-30.24$ | $-20.09$ | $-22.19$ | $-20.09$ | 19.78 | 10.59 |

**Tab.5 - Sidelobe Lebel ($SLL$), Sideband Level ($SBL$), -3 dB Beamwidth ($BW$), Sideband Radiation ($SR$).**

## TEST CASE 6 - $0.5\lambda$ Elements Spacing - Short Dipoles - Zolotarev Pattern

### Goal

Sideband radiation minimization of a TMLA composed by real radiating elements (short dipoles considered in this test case) adopting the pulse shifting technique.

### Test Case Description

- Number of Elements: $N = 16$
- Elements Spacing: $d = 0.5\lambda$
- Static Array Configuration: $\alpha_n = 1,\ n = 0, ..., N-1$
- Pattern at Central Frequency: $Zolotarev\,,\, SLL = -30\,dB$
- Dipole Length: $l = 0.5\lambda$

### 1.b) Optimization Approach: PS-PSO, SR Min.

The optimization process though the PSO algorithm acts just on the temporal shift of the pulses;

- Number of Variables: $X = 16$
- Number of Particles: $S = 15$
- Number of Iterations: $I = 500$
- Inertial Weight: Linearly varying: $0.9\,to\,0.4$
- Cost Function:

$$\Psi^{PSO}\left[\tau_n'(i_k)\right] = P_{SR}^{act,(i_k)} \tag{5}$$

## Zolotarev Pattern, SLL=-30 dB - Original - Short Dipole Elements Array

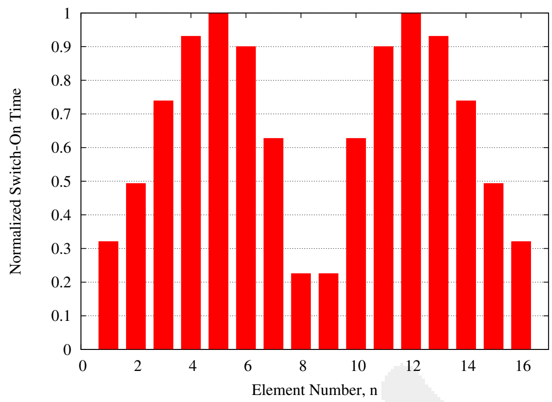


**Fig.75 - Pulse Sequence**

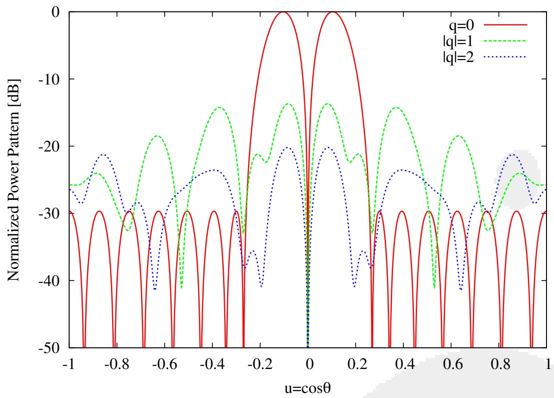


**Fig.76 - Isotropic - Pattern(u)**

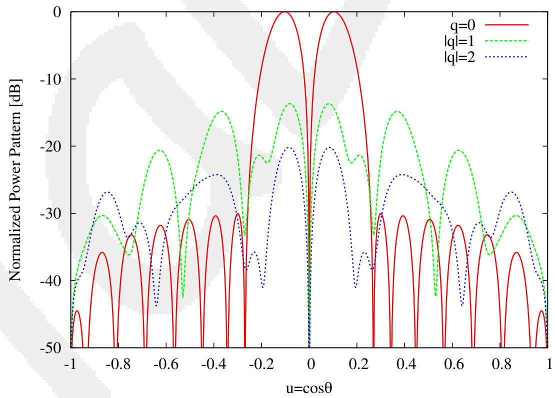


**Fig.77 - Short Dipole - Pattern(u)**

## Zolotarev Pattern, SLL=-30 dB - End-Fire h=1 - Short Dipole Elements Array

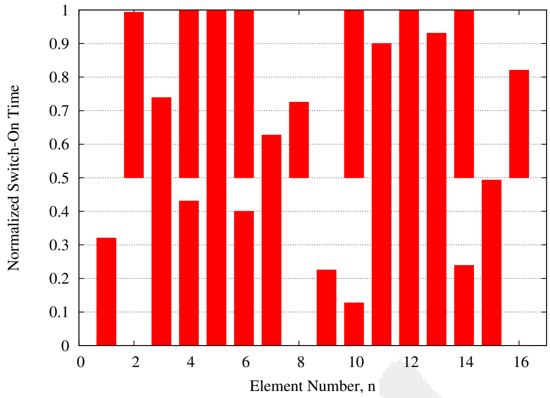


**Fig.78 - Pulse Sequence**

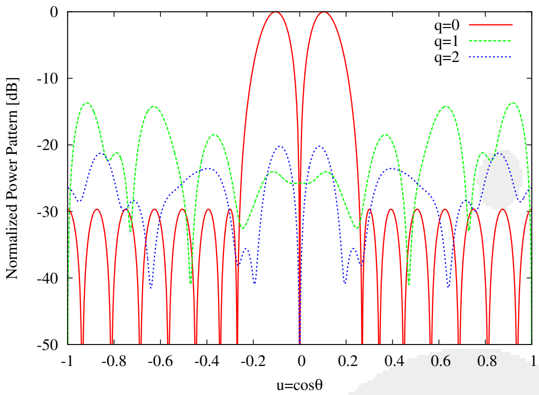


**Fig.79 - Isotropic - Pattern(u)**

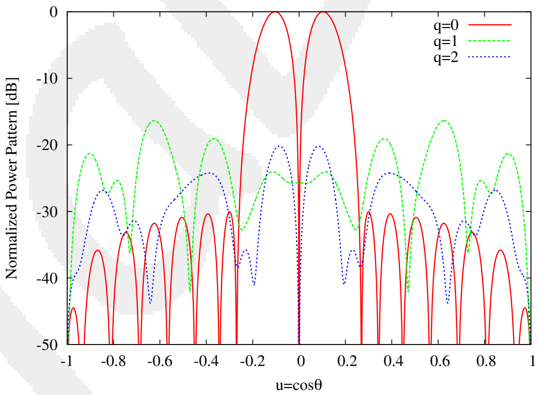


**Fig.80 - Short Dipole - Pattern(u)**

**Zolotarev Pattern, SLL=-30 dB - Analytic Steering (Maximum of h=1 harmonic pattern in End-Fire) - Short Dipole Elements Array**

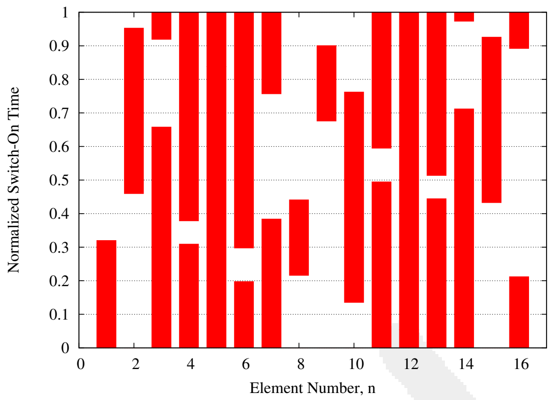


Fig.81 - Pulse Sequence

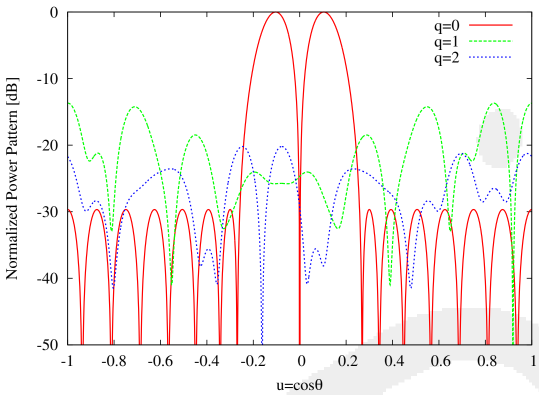


Fig.82 - Isotropic - Pattern(u)

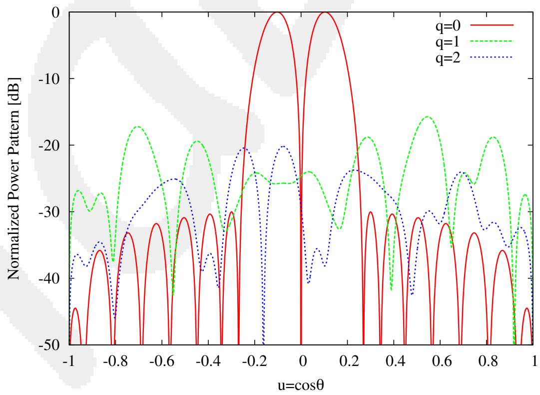


Fig.83 - Short Dipole - Pattern(u)

## Zolotarev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=1 - Short Dipole Elements Array

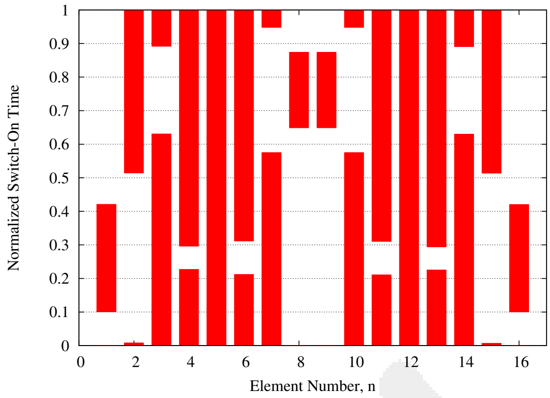


**Fig.84 - Pulse Sequence**

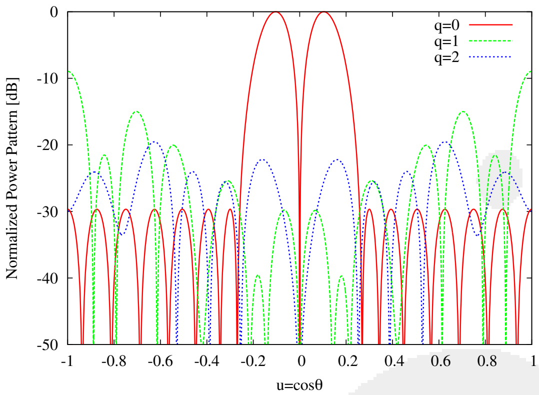


**Fig.85 - Isotropic - Pattern(u)**

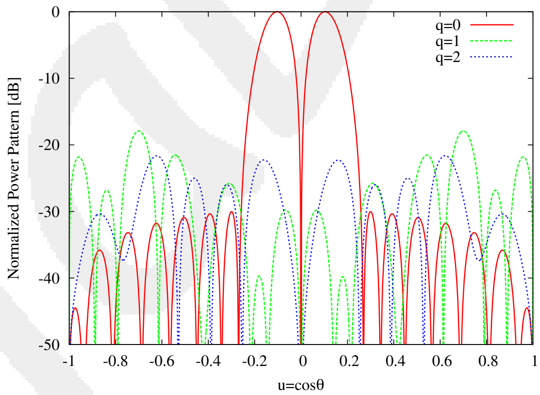


**Fig.86 - Short Dipole - Pattern(u)**

## Zolotarev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=2 - Short Dipole Elements Array

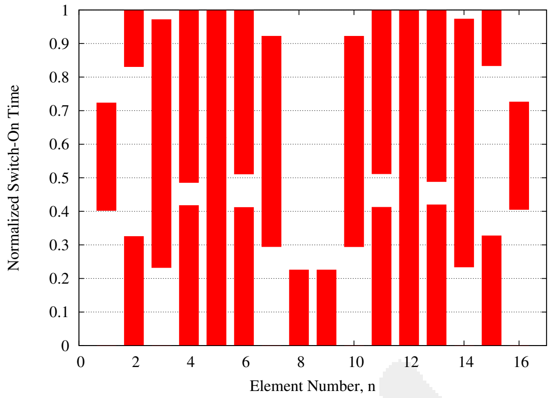


**Fig.87 - Pulse Sequence**

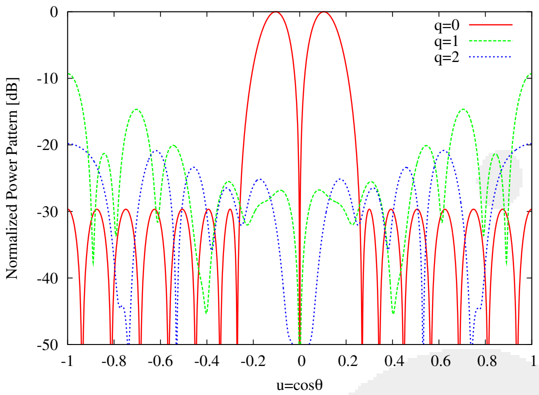


**Fig.88 - Isotropic - Pattern(u)**

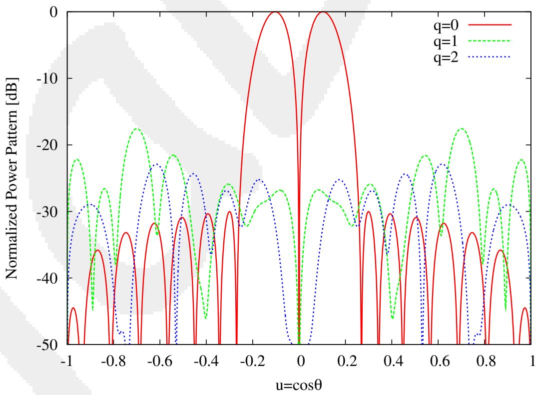


**Fig.89 - Short Dipole - Pattern(u)**

**Zolotarev Pattern, SLL=-30 dB - PS-PSO, SR Min. H=100 - Short Dipole Elements Array**

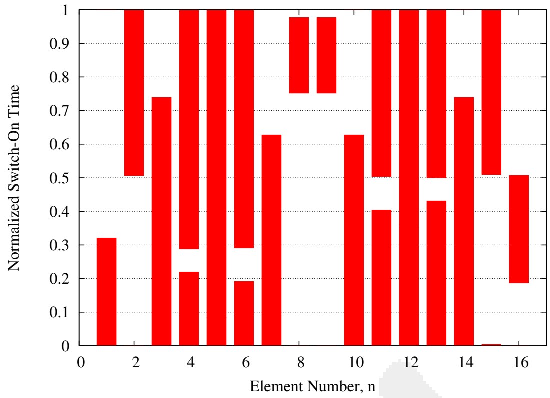


**Fig.90 - Pulse Sequence**

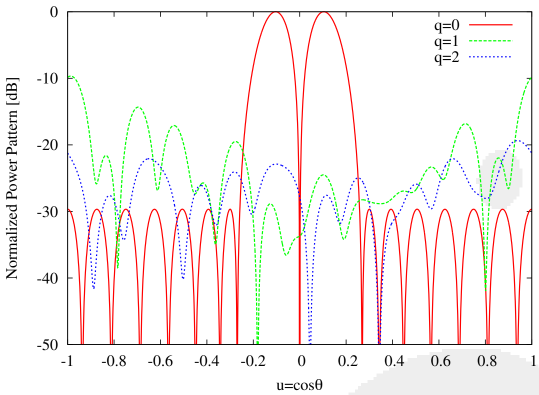


**Fig.91 - Isotropic - Pattern(u)**

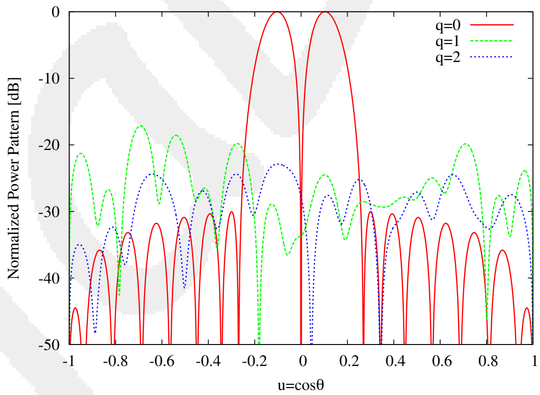


**Fig.92 - Dipole - Pattern(u)**

| | $SLL\,[dB]$ | $SBL\,[dB]$ | $SBL_1\,[dB]$ | $SBL_2\,[dB]$ | $BW\,[deg]$ | $SR\,[\%]$ |
|---|---|---|---|---|---|---|
| $Zolotarev$ | $-30.03$ | $-13.67$ | $-13.67$ | $-20.19$ | 6.5 | 19.60 |
| $End-Fire\,h=1\,Pattern$ | $-30.03$ | $-16.36$ | $-16.36$ | $-20.19$ | 6.5 | 14.49 |
| $Analytic\,Steering\,End-Fire\,Max\,h=1$ | $-30.03$ | $-15.73$ | $-15.73$ | $-20.18$ | 6.5 | 14.91 |
| $PS-PSO,\,SR\,Min.\,H=1$ | $-30.03$ | $-17.89$ | $-17.89$ | $-21.64$ | 6.5 | 11.41 |
| $PS-PSO,\,SR\,Min.\,H=2$ | $-30.03$ | $-17.57$ | $-17.57$ | $-22.91$ | 6.5 | 11.41 |
| $PS-PSO,\,SR\,Min.\,H=100$ | $-30.03$ | $-17.14$ | $-17.14$ | $-22.89$ | 6.5 | 11.45 |

**Tab.6 - Sidelobe Lebel ($SLL$), Sideband Level ($SBL$), -3 dB Beamwidth ($BW$), Sideband Radiation ($SR$).**

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