Design of Low Power Thinned Smart Antenna for 6G Sky Connection

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https://doi.org/10.26636/jtit.2024.1.1438

Abstract — To improve radio access capability, sky connections relying on satellites or unmanned aerial vehicles (UAV), as well as high-altitude platforms (HAP) will be exploited in 6G wireless communication systems, complementing terrestrial networks. For long-distance communication, a large smart antenna will be used that is characterized by high amounts of power consumed by digital beamformers. This paper focuses on reducing power consumption by relying on a thinned smart antenna (TSA). The performance of TSA is investigated in the sub-6 GHz band. The differential evolution (DE) algorithm is used to optimize excitation weights of the individual dipoles in the antenna array and these excitation weights are then used in TSA for beamforming, with signal processing algorithms deployed. The DE technique is used with the least mean square, recursive least square and sample matrix inversion algorithms. The proposed method offers almost the same directivity, simultaneously ensuring lower side lobes (SLL) and reduced power consumption. For a TSA of 20, 31, and 64 dipoles, the power savings are 20%, 19.4%, and 17.2%, respectively. SLL reductions achieved, in turn, vary from 5.2 dB to 8.1 dB.

Keywords — differential evolution, power saving, signal processing algorithms, smart antenna, thinned array

1. Introduction

One of the attractive features of upcoming 6G solutions is the ability to establish sky connections through satellites, unmanned aerial vehicles (UAV) or high altitude platforms (HAP), to complement the terrestrial network [1]–[3]. Antenna techniques used in 5G/6G include massive MIMO (in both sub-6 GHz and millimeter wave/terahertz bands, i.e. 95 GHz – 3 THz) and inter-satellite/satellite-to-mobile connectivity [4], [5]. Phased array antennas, smart antennas, and holographic antenna techniques are proposed for future 6G sky connectivity solutions [6]. In order to reduce interference originating from and radiated in any undesired direction, lower side lobe levels (SLL) are always welcome in communication. Antenna beamforming is performed with the use of digital beamformers (DBF) units which consume a considerable amount of energy. For a large array, this is a big concern. Therefore, intensive research focusing on reducing power requirements is conducted.

In another class of antenna arrays, known as thinned arrays [7]–[9], radiation patterns, gain levels, and beamwidths that are similar to those achieved with the use of fully populated arrays may be obtained, with a simultaneous reduction

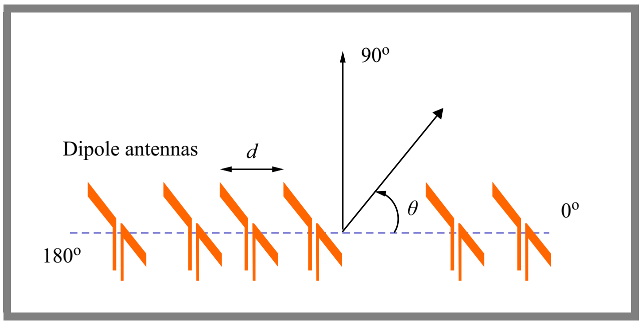

Fig. 1. Linear dipole antenna array.

in the number of antenna elements with reduced SLL. This method reduces the use of DBF for off-state antennas and minimizes power consumption of the antenna system. An antenna array in which all of the antennas are on is known as a fully populated array (Fig. 1).

The ratio of the number of off-state antennas to the number of on-state antennas is known as the thinning ratio. Typically, no antenna element in an array is kept permanently off – its on and off statuses tends to alternate. Matched loads/terminations attached to the antenna connection are used to switch the antennas off. The on/off sequences of an array are determined either by statistical methods [10], [11] or by optimization techniques [7], [8].

Due to their numerous advantages, optimization methods, such as genetic algorithm (GA), particle swarm optimization, differential evolution, and their variants, have become very popular for antenna array thinning [7], [12]–[19].

A smart antenna (SA) system is a specific type of an adaptive array antenna with a signal processor. The SA identifies the direction of arrival (DOA) of the signal from the mobile device and produces a retro-directive beam towards the user [20], [21]. Smart antennas can be divided into two categories: switched beam and adaptive antennas [22], [23]. A switched beam antenna system is capable of forming a radiation beam only in pre-defined directions, whereas adaptive beam antenna systems emit the signals in any direction.

An adaptive smart multi antenna system is shown in Fig. 1. It forms a retro-directive main beam towards the targets and a null towards the undesired interferer. Performance of the adaptive signal processing algorithm is the key factor affecting the performance of the entire SA system. The basics of the SA system and the beamforming algorithms are described in [24]–[27]. The most common algorithms used for beamforming in SA include the LMS algorithm [28]–[30], the

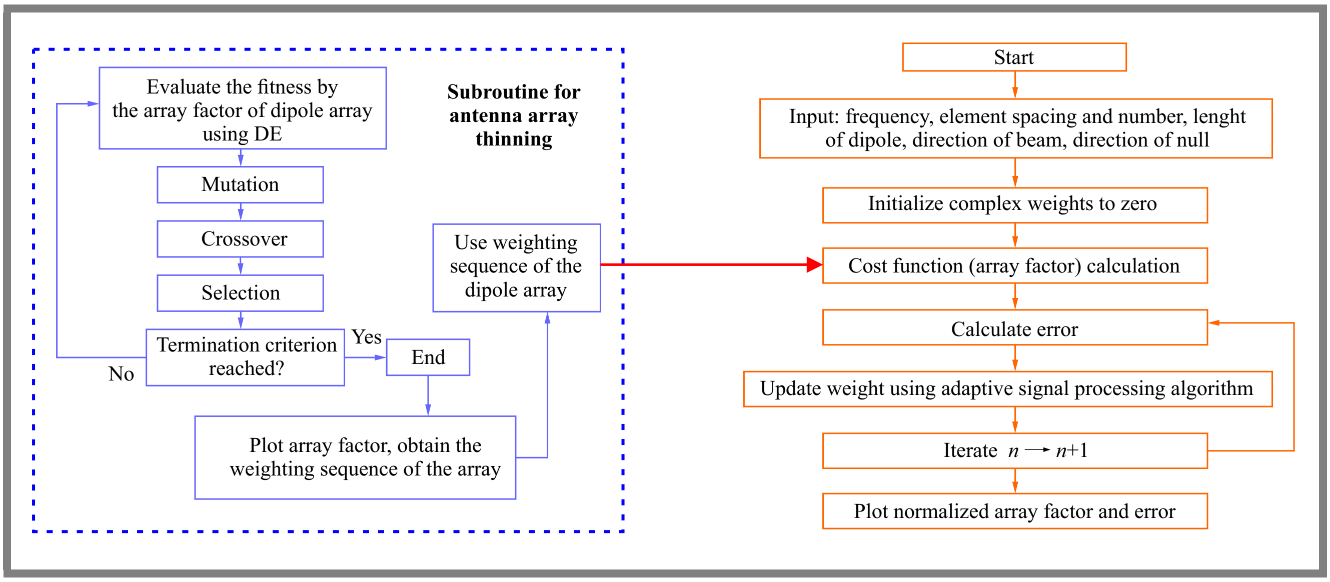

Fig. 2. Procedure for the beamforming of DE thinned smart antenna of dipole array.

RLS algorithm [31], [32], and the SMI algorithm [33], [34]. The beamforming process using the LMS algorithm and the effect of mutual coupling on adaptive smart antennas are described in [28]. The beamforming process relying on the variable step-size LMS algorithm is described in [29], with a lower SLL being achieved. In article [30], various dipole configurations are used in an SA system that is based on the LMS algorithm for 5G and 6G energy harvesting applications.

Tracking properties of the RLS algorithm are used [31] for an adaptive antenna in a flat Rayleigh fading environment to solve the interference cancellation problem. In [32], the performance of SA is studied by varying the spacing between and the number of antennas using LMS, SMI, RLS and the conjugate gradient method (CGM). The block length effect and its impact on the reduction of SLL in linear and planar SAs using the SMI algorithm is reported in paper [33]. To avoid the drawbacks of the traditional SMI algorithm, an adaptive diagonal loading SMI algorithm is used in smart antennas to enhance performance in varying signal-to-noise (SNR) conditions, as shown in [34].

Many other algorithms used in the beamforming process performed by smart antennas are presented in papers [35]–[38]. The minimum variance distortion-less response (MVDR) beamforming approach, capable of estimating the weight vectors for adaptive beam steering, is used in [35], [36] to improve capacity, data rate, null steering, and coverage in a cellular network. The constant modulus algorithm (CMA) is proposed for blind adaptive beam formation and SLL reduction in [37]. In article [38], the modified conjugate gradient method (CGM) is used for adaptive antenna beamforming to reduce the multipath fading problem.

Recently, machine learning (ML) methods have been used [39] for beamforming and SLL reduction in smart antennas, where artificial neural networks, support vector machines, ensemble algorithms, and decision tree algorithms are used. Some reports are available [2], [4], [6], [40], [41] on antennas used for establishing 6G sky connections. In [2], the use of smart antennas is suggested for 6G sky connections with UAVs and HAPs. The highly directional, reduced interference antennas for 6G are proposed for UAV traffic management applications in [4], with this task being made possible by relying on a smart antenna.

A thinning array antenna is considered in [6] as one of the promising candidates for 6G wireless applications. The use of reconfigurable-reflectarray antennas and cylindrical antenna arrays is capable of ensuring better communication between terrestrial and UAV links in 6G [40]. In the case of satellite–terrestrial networks used in 6G systems, a smart antenna is an effective communication solution, as proved in paper [41]. A literature survey revealed that most of the reports deal with antenna arrays made up of isotropic antenna elements, instead of real aerials. Some papers report the use of smart antennas for 6G communications, where massive amounts of machine-to-machine communication (M2M), including both terrestrial and non-terrestrial sources [6], will be encountered. In practice, for sky communication, a high gain antenna with a large array is required, with all elements of the antenna being fed by beamformers and RF power amplifiers that consume up to hundreds of watts of energy per unit [6].

In this paper, an approach allowing to reduce the power consumption of an antenna used for 6G sky communication and relying on a thinned smart antenna is presented. The performance of a thinned SA is investigated here at 4.5 GHz to sub-6 GHz frequencies. Differential evolution (DE) is used to optimize the weighting sequence of individual dipoles in SA, and then excitation weights are used for beamforming via LMS, RLS and SMI signal processing algorithms. This method provides almost the same directivity, simultaneously offering reduced SLL and lower power consumption. For a thinned smart antenna of 20, 31, and 64 dipoles, the power savings are 20%, 19.4%, and 17.2%, respectively, whereas SLL reductions of 5.2 dB to 8.1 dB are achieved.

2. Differential Evolution Algorithm

Here, DE optimization is used to obtain the weight sequence of the dipole array, i.e. the on and off positions of the antenna elements in the array. DE is a simple and efficient global optimization method over continuous spaces [42]–[44]. In DE, the initial population in each generation is obtained by using three operators: mutation, crossover or recombination, and selection. The fitness function evaluates the quality of the proposed solution applied to the problem of the current population. It also evaluates how good a single solution is for a given population.

In DE, the size of the initial population of the target vectors is defined by various parameters of the design problem. For each parameter, the boundary values are defined as $X_i^L < X_{i,j}(0) < X_i^U$. Then, the initial parameter values are randomly selected within the (X_i^L, X_i^U) interval. For each target vector, other parameter vectors are selected randomly. From the parameter vectors, any three vectors $X(t)$, $X_{j,n}(t)$, $X_{m,n}(t)$ are selected and then the weighted difference between any two of the parameters are added to the third vector to form a donor vector $V_{k,n}(t+1)$, as presented in [43], [44]:

$$V_{k,n}(t+1) = V_{m,n}(t+1) + F\left[x(t) - V_{j,n}(t+1)\right] . \quad (1)$$

Scaling factor F is used to estimate the difference between two vectors and is added to the third vector which varies from 0 to 2. The trial vector $T_{k,n}(t+1)$ uses components of the donor vector with probability CR, as given in:

$$T_{k,n}(t+1) = \begin{cases} V_{k,n}(t+1) & \text{if } \operatorname{rand}(0,1) < CR \\ X_{k,n}(t) & \text{otherwise} \end{cases} . \quad (2)$$

After recombination, the trial vector is compared with the original target vector with a better fitness and admitted to the next generation.

3. Adaptive Signal Processing Algorithms

After the array thinning procedure relying on the DE technique, the array weight sequence is used for SA beamforming using the LMS, RLS, and SMI algorithms, with the corresponding methods for thinned smart antenna being DE-LMS, DE-RLS, and DE-SMI, respectively. LMS is an adaptive filtering algorithm with great simplicity [45], [46]. It is basically a stochastic gradient-based algorithm, where the slope vector of the filter tap, weight is utilized to meet the ideal Wiener solution. The filter weights of the adaptive filter are updated in each iteration using the following formula [45], [46]:

$$w(n+1) = w(n) + \mu\, e^*(n)\, x(n) \quad (3)$$

The algorithm minimizes the error $e(n)$ between the array's output and the desired signal as:

$$e(n) = d(n) - w^H(n)\, x(n) \quad (4)$$

Thus, the boundary for the step-size parameter μ is given by:

$$\mu < \frac{1}{2\,\text{trace}[R_{xx}]} \quad (5)$$

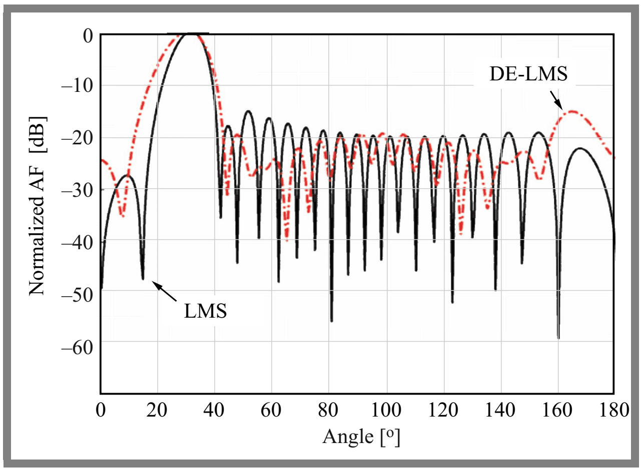

Fig. 3. Array factor for a thinned smart antenna using DE-LMS for $N = 20$.

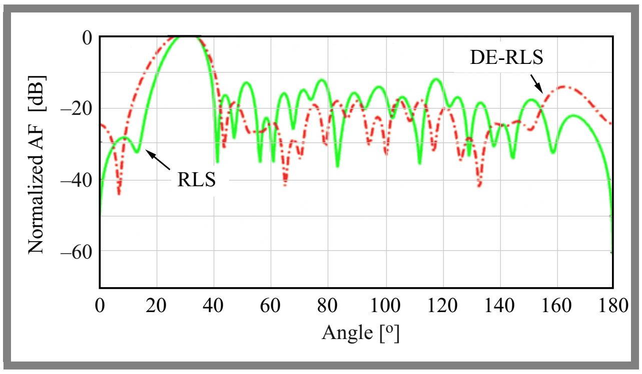

Fig. 4. Array factor for a thinned smart antenna using DE-RLS for $N = 20$.

The main benefit offered by the LMS algorithm is that it is characterized by low computational complexity. Its drawbacks include the following: sluggish convergence, particularly when the auto correlation matrix's maximum λ_{max} and minimum λ_{min} eigenvalues have a wide spread or when $\lambda_{max}/\lambda_{min} \gg 1$. Therefore, there is a need to create more sophisticated algorithms with more parameters in order to ensure faster convergence. The least squares criterion is used in place of the statistical approach based on the MSE criterion, known as recursive least square (RLS), to derive, more quickly, convergent adaptive filtering algorithms [45], [46]. One of the disadvantages of LMS is that the algorithm needs more iterations to achieve convergence. To overcome this, sample matrix inversion (SMI) is used [45], [46]. The sample matrix, using k time samples, is a time average approximation of the array correlation matrix. The temporal average estimate will match the real correlation matrix if the random process is ergodic in the correlation.

4. Design of Thinned Smart Antenna

In this paper, SA of linear, uniform, half-wave dipole antennas is considered (Fig. 1). The dipoles are separated by uniform spacing of d. For a dipole of length l, the far-zone electric

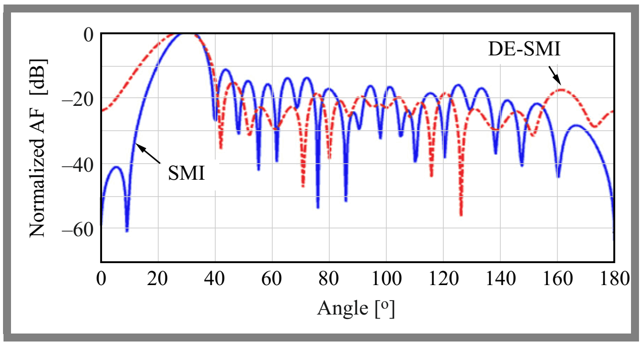

Fig. 5. Array factor for a thinned smart antenna using DE-SMI for $N = 20$.

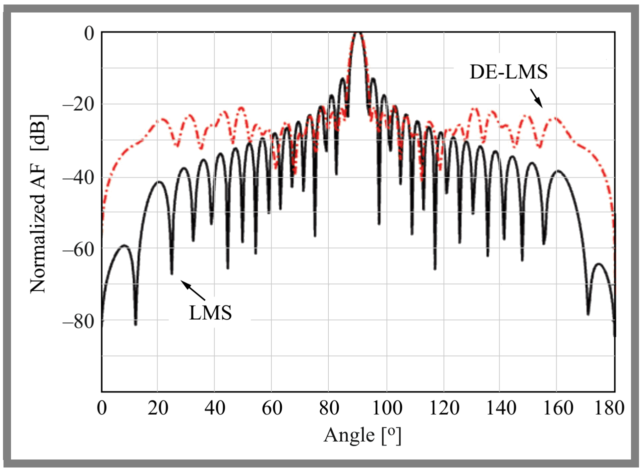

Fig. 6. Array factor for a thinned smart antenna using DE-LMS for $N = 31$.

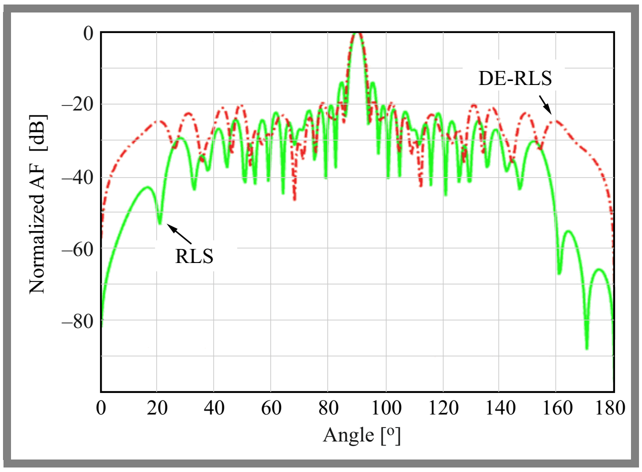

Fig. 7. Array factor for a thinned smart antenna using DE-RLS for $N = 31$.

field is given by [47]:

$$E(\theta) = j\eta \frac{I_0 e^{-j\beta r}}{2\pi r} \left[\frac{\cos(\frac{\beta l}{2} \cos\theta) - \cos\frac{\beta l}{2}}{\sin\theta} \right] , \quad (6)$$

where $\beta = 2\pi/\lambda$ is the propagation constant, I_0 is current amplitude, $\eta = 120\ \pi\Omega$ is the free space impedance and the observation point is located at a distance of r from the array. For N dipoles in the array, the total far-zone field is:

$$E_{total} = E(\theta) AF(\theta) , \quad (7)$$

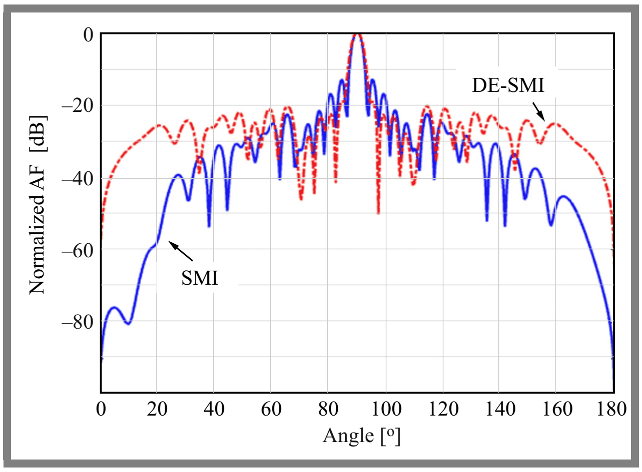

Fig. 8. Array factor for a thinned smart antenna using DE-SMI for $N = 31$.

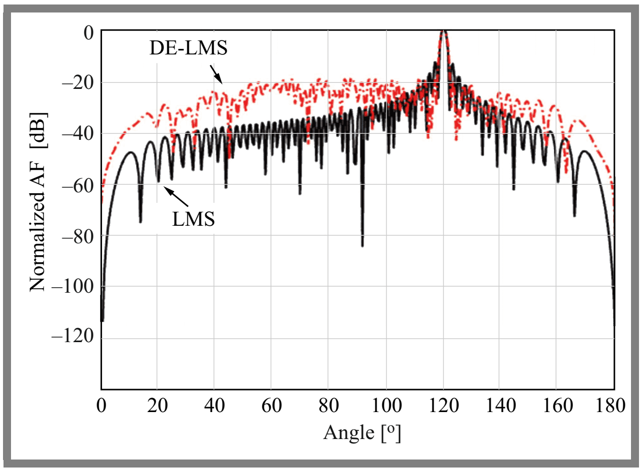

Fig. 9. Array factor for a thinned smart antenna using DE-LMS for $N = 64$.

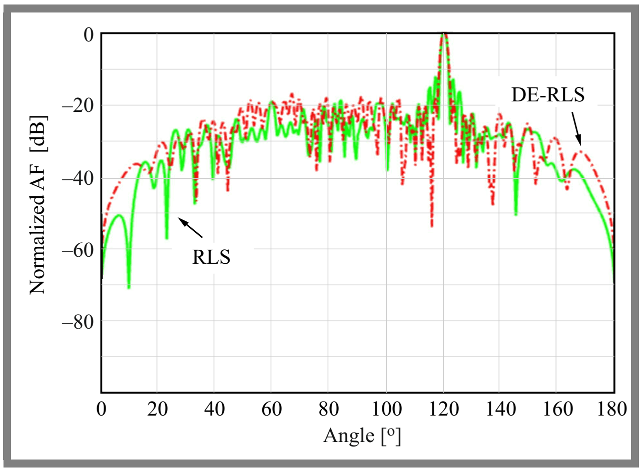

Fig. 10. Array factor for a thinned smart antenna using DE-RLS for $N = 64$.

where $AF(\theta)$ is the array factor for an array of isotropic elements and is given by:

$$AF(\theta) = \sum_{n=1}^{N} I_0\, e^{j(n-1)(\frac{2\pi d}{\lambda} \cos\theta + \alpha)} , \quad (8)$$

where λ is the wavelength, α is the array progressive phase shift and it is assumed that all the antennas are fed by equal current I_0.

The beamforming procedure in a DE thinned smart antenna of a dipole array is shown in Fig. 2. First, the dipole array is thinned by using DE optimization to obtain the on/off sequence for the lowest SLL. Then, this weighting sequence is used along with LMS, RLS, and SMI to generate beam and null directions. Equation (7) for $E_{total}(\theta)$ is the cost function for the thinned smart antenna used to evaluate the performance.

For the beamforming of thinned SA of dipole arrays, the numbers of dipoles in the arrays considered are $N = 20$, $N = 31$, and $N = 64$. The results for beamforming of a thinned smart antenna using DE-LMS, DE-RLS, and DE-SMI techniques for $N = 20$ are compared with the results for SA, obtained without thinning and are plotted in Figs. 3–5.

In Figs. 3–5, the beam direction (BD) and the null direction (ND) are located at 30° and 10° angles, respectively. Compared to SA without thinning, the achieved SLL reductions for a thinned smart antenna using DE-LMS, DE-RLS and DE-SMI are 6.92 dB, 5.2 dB, and 8 dB, respectively.

The results for beamforming of a thinned smart antenna using DE-LMS, DE-RLS, and DE-SMI for $N = 31$ are compared with the results for SA, obtained without thinning and are plotted in Figs. 6–8, respectively. In Figs. 6–8, the BD and the ND are at 90° and 10° angles, respectively. Compared to the SA without thinning, the achieved SLL reductions for a thinned smart antenna using DE-LMS, DE-RLS, and DE-SMI are 8 dB, 8.1 dB, and 7.9 dB, respectively.

Next, the results for beamforming of a thinned smart antenna using DE-LMS, DE-RLS, and DE-SMI for $N = 64$ are compared with the results for SA, obtained without thinning and are shown in Figs. 9–11, respectively.

In Figs. 9–11, the BD and the ND are at 120° and 10° angles, respectively. Compared to a smart antenna without thinning, the achieved SLL reductions for a thinned smart antenna using DE-LMS, DE-RLS and DE-SMI are 6.67 dB, 5.9 dB, and 5.4 dB, respectively.

The summary of results for a thinned smart antenna made up of dipole arrays is presented in Tab. 1. Since the off dipoles are not excited, power savings may be achieved in the smart antenna system. When some dipoles in the array are not excited, the RF amplifiers remain unpowered, which reduces overall energy consumption in the system.

The error graphs for $N = 64$, obtained using DE-LMS, DE-RLS and DE-SMI are shown in Fig. 12, where the convergence of DE-RLS is better than that of DE-LMS and DE-SMI.

The 3 dB beamwidths achieved for the thinned smart antennas, as shown in Figs. 3–11, remain almost the same as those for a smart antenna without thinning, meaning that directivity of the thinned smart antenna does not change significantly. In contrast, SLL decreases appreciably in a thinned smart antenna. All three algorithms (DE-LMS, DE-RLS and DE-SMI) provide the required BD and ND. As shown in Tab. 1, power savings are the same for all the algorithms, because the array sequence is determined by the same DE optimization. However, SLLs – being an important interference-related parameter in wireless communication – are different for all three algorithms.

Total power consumption P_{tot} in a phased array antenna is [48], [49]:

$$P_{tot} = P_{BB} + P_{RFC} + N_{SA} P_{PS} + N_{SA} \frac{P_o^{SA} - P_i^{SA}}{\eta_{SA}} , \quad (9)$$

where NSA is the number of subarrays, and PRFC, PPS, and PBB are the power consumptions of the radio frequency chain (RFC), phase shifter (PS) and baseband (BB) processing, respectively. For a clustered phased array, the condition to minimize total power consumption P_{tot} in comparison to a fully populated array (FPA) is given by [49]:

$$\frac{P_o^{SA} - P_i^{SA}}{\eta_{SA}} \leqslant \frac{1}{1-\mu} \left[P_{PS} + \frac{P_o^{FPA} - P_i^{FPA}}{\eta_{FPA}} \right] - P_{PS}. \quad (10)$$

Therefore, the conditions on power-added efficiency (PAE) of PAs capable of providing energy-saving clustered phased array is [49]:

$$\eta_{SA} > \frac{P_o^{FPA}}{\frac{GSA}{GFPA} \left[\mu P_{PS} + \frac{P_o^{FPA}}{\eta_{FPA}} \right]}, \quad (11)$$

where the gain ratio GSA/GFPA is calculated at the same main beam direction.

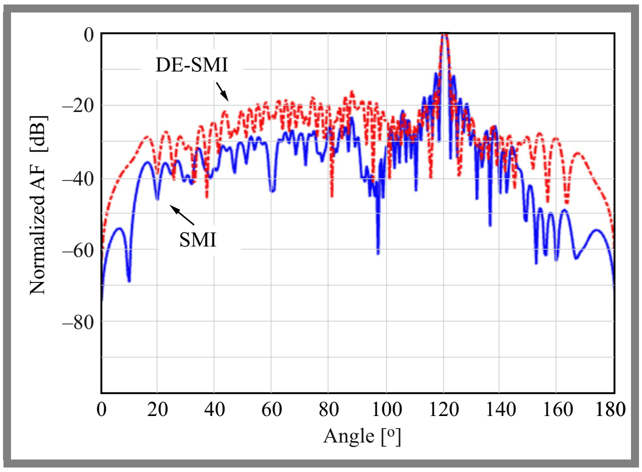

Fig. 11. Array factor for a thinned smart antenna using DE-SMI for $N = 64$.

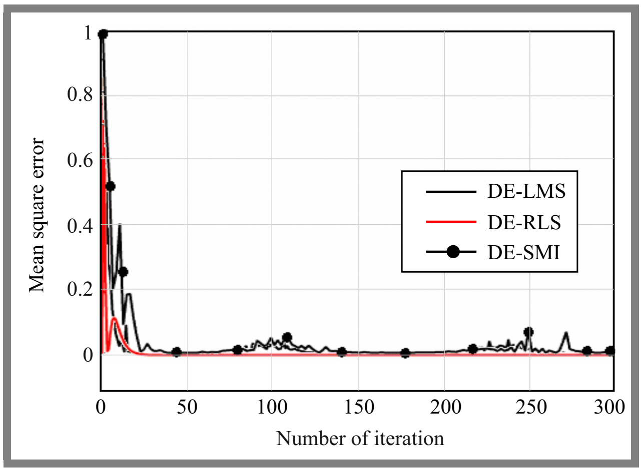

Fig. 12. Mean square error plot for $N = 64$.

Tab. 1. Summary of results for a thinned smart antenna (SA).

Antenna type	No. of dipoles	Beam direction	SLLmax [dB]	On (1) and off (0) sequence	Reduction of SLLmax in thinned SA [dB]	Energy savings
Without thinning (LMS)	$N = 20$	30°	–10.5	All elements are on	–	
	$N = 31$	90°	–13.2	All elements are on	–	
	$N = 64$	120°	–13.13	All elements are on	–	
Thinned (DE-LMS)	$N = 20$	30°	–17.42	00101111111111111110	6.92	20.0%
	$N = 31$	90°	–21.2	1010101011111111111111111101101	8.0	19.4%
	$N = 64$	120°	–19.8	1101001110011011 11111111111111111111111111 1111111110110101010111	6.67	17.2%
Without thinning (RLS)	$N = 20$	30°	–9.9	All elements are on	–	
	$N = 31$	90°	–13.3	All elements are on	–	
	$N = 64$	120°	–13.6	All elements are on	–	
Thinned (DE-RLS)	$N = 20$	30°	–15.1	00101111111111111110	5.2	20.0%
	$N = 31$	90°	–21.7	1010101011111111111111111101101	8.1	19.4%
	$N = 64$	120°	–19.5	110100111001101111111111 11111111111111111111111111 10110101010111	5.9	17.2%
Without thinning (SMI)	$N = 20$	30°	–8.4	All elements are on	–	
	$N = 31$	90°	–13.3	All elements are on	–	
	$N = 64$	120°	–13.4	All elements are on	–	
Thinned (DE-SMI)	$N = 20$	30°	–16.4	00101111111111111110	8.0	20.0%
	$N = 31$	90°	–21.2	1010101011111111111111111101101	7.9	19.4%
	$N = 64$	120°	–18.8	11010011100110111111 11111111111111111111111111 111110110101010111	5.4	17.2%

5. Conclusion

The power consumption budget of a practical antenna array can be greatly reduced by using a thinned smart antenna system in which some of the elements are kept in the off status, without compromising the radiation characteristics. To achieve this, an approach in which DE-LMS is used for beamforming in a thinned smart antenna is compared with DE-RLS and DE-SMI methods. The investigations presented in this paper prove that reduction of both SLL and power consumption is possible when using a thinned smart antenna, without an appreciable change in directivity without thinning. Dipole antennas are proposed here, as these are versatile, easy to design, easy to excite and their installation at the base station is very simple as well.

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