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DESIGN OF THINNED SMART ANTENNA OF SEMI-CIRCULAR DIPOLE ARRAY FOR 5G MASSIVE MIMO SYSTEM

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Abstract. *In a multi-user environment, wireless networks should be massive MIMO (MMIMO) systems consisting of multiple antennas. MMIMO installs antenna arrays at base stations and uses hundreds of transceivers and other RF modules to form a very narrow and focused beam, thus reducing interference. The disadvantage of MMIMO systems is large power consumption, and the RF module beamforming network for multiple antennas is significant in terms of power consumption. This paper presents a new low power beamforming technique for MMIMO systems. The proposed semicircular array thinned smart antenna (TSA) can form a secure beam for user terminals while reducing interference. In a thinned array, selected antennas are kept off, which reduces power consumption but the array pattern remains the same as the built-in array, and the sidelobe level (SLL) is reduced. The thinned array antennas are designed at 5 GHz of the sub-6GHz band. The differential evolution (DE) algorithm is utilized to determine the optimal array sequence and least mean square (LMS), recursive least square (RLS), and sample matrix inversion (SMI) algorithms are used for beam generation of the TSA and the algorithms are DE-LMS, DE-RLS and DE-SMI. A maximum of 48% energy savings is achieved. Using the DE-LMS, DE-RLS and DE-SMI algorithms, TSA achieved maximum SLL reduction of 11 dB, 11 dB and 9 dB, respectively.*

Key words: *Smart antenna, thinning, beamforming, signal processing, differential evolution, power saving*

1. INTRODUCTION

Multiple-input multiple-output (MIMO) system places multiple antennas between the transmitting and the receiving ends for the enhancement of capacity and the quality of the radio link. MIMO uses multiplexing and spatial diversity to transmit data [1-3]. In multi-user MIMO (MU-MIMO), the same frequency and time are used to transmit different data to different users to increase network capacity [4,5]. In MMIMO system, larger antenna arrays with advanced technologies are used for beam formation [6-9]. MMIMO is the main

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building block of the new fifth-generation radio (5G NR), which provides many advantages to mobile operators and end users [10, 11]. An MMIMO system with a large array can produce a 3D beam in both horizontal and vertical planes towards users, which is known as full-dimension MIMO (FD-MIMO). FD-MIMO increases capacity and data rates for all users, especially in urban areas with high-rise buildings [12-14]. Because of large number of antennas with RF modules, the power consumption of MMIMO systems is quite high. This paper presents a new method of energy savings for large antenna array in MMIMO.

2. Related Work

There are many methods to design highly directive beams in MMIMO [15-24]. In [15], both dipole and microstrip arrays were used for the MMIMO, and experimental results were reported for microstrip arrays. The change of thegain model was examined by integrating the array. In [16], a hybrid MMIMO antenna array for different LTE bands was reported and its impact on the user was examined. [17] provides an overview of various beamforming techniques in 5G MMIMO systems. An algorithm for beamforming for MU-MMIMO is reported in [19]. The Text [20] shows a beamforming method for MU-MIMO systems. In [21], a dual-band MIMO antenna is proposed for LTE and 5G applications. Chebyshev cone has been proposed for generating radiation beam in MU-MMIMO systems to suppress side lobes using antenna layer [22]. A review article [23] was published describing the design and construction of 5G MMIMO systems. The highly directive beams in a MMIMO system can be generated in several ways [15-24]. Although the beamforming method is used in MMIMO systems, large antenna arrays are needed and this causes high energy consumption. The specific problem of reducing power consumption in MMIMO systems has not been addressed in the literature. This article introduces the smart antenna concept for installation in MMIMO systems. This beamforming approach leverages the features of smart antennas (SA) [24-28] and exploits the properties of thinned antenna arrays to reduce power consumption by firing any antenna in the array. The SA determines the direction of arrival (DOA) of the signal coming from the cell and ensures that the signal returns to the user [24]. The efficiency of signal processing algorithms is important in the operation of SA [26]. Using a thinned antenna array, almost the same beamwidth with lower side lobe level (SLL) and lower power consumption can be achieved [29 -31]. If all the antennas are in the "ON" state, the array is called a fully populated array. The ratio of the number of "OFF" antennas to the number of "ON" antennas is called thinning ratio. There is actually no antenna in the permanent "OFF" position; toggle “OFF” and “ON” as needed. The matched loads or terminations, connected to the antennas, are used to "turn off" the antenna. Generally, the "OFF" and "ON" intervals in the sequence are determined by optimization methods. Generally, optimization techniques such as genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution (DE) are used to obtain the array sequence [32-34]. In this paper, a semicircular dipole antenna array is used to examine the properties of a TSA. The circular, semicircular or elliptical arrays in mobile towers have some advantages [35-39].

3. Differential Evolution Algorithm

Here, DE optimization [40-42] is used for the design of thinned antenna array. The different steps of using the DE algorithm are as follows:

Step 1: Create an initial population of test vectors or parent vectors of population size P, where each vector contains ’n’ number of genes. Each gene represents a specific antenna parameter. Before starting the algorithm, the value of each vector in the initial population is calculated. Each gene is represented by $X_G(i,j)$; where G is the symbol of the i^{th} parent vector and the j^{th} gene of the parent vector.
Step 2: For the i^{th} vector, three other mutually exclusive vectors are chosen, different from ‘i’. An intermediate donor vector $V_G(i, 1\ldots..n)$ corresponding to $X_G(i, 1\ldots\ldots\ldots n)$ is formed as

$$V_G(i,j) = X_G\ (nbest, j) + \ F.(\ (X_G\ (n1, j) - \ X_G\ (n2, j))) \qquad (1)$$

here F is the scaling factor and varies from 0 to 2. The ‘nbest’ is the best member of population for the fitness at the current time step and generated randomly in the program using DE/rand/1scheme of algorithm. The $n1$, $n2$ are the number of genes, related to the antenna parameters and generated during the simulation.
Step 3: A binary crossover operation is performed between the donor vector and the parent vector using a crossover probability CR. This provides a target vector, $T_G(i,1\ldots\ldots\ldots n)$ and a random number ‘y’ is generated.

$$T_G\ (i,j) = \ V_G\ (i,j)\ if\ y \le CRor\ j = j_{rand} \qquad (2)$$

$$T_G\ (i,j) = \ X_G\ (i,j)\ otherwise$$

Step 4: Evaluate the target vector for its cost and if it has a lower cost than the corresponding parent vector $X_G(I,1\ldots\ldots n)$, then in the next generation the target vector will replace the parent vector .

Up to the maximum number of generations or up to the termination criterion, steps 2 to 4 are repeated.

4. Adaptive Signal Processing Algorithms

After using DE optimization, array weights are used for generation beam of SA using LMS, RLS and SMI algorithms respectively. LMS is an adaptive gradient based algorithm which is stochastic in nature [43, 44] and the filter weights are used to obtain the optimal Wiener solution of the gradient vector. The weights of the variables are adjusted in each iteration as [43, 44]

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

This error $e(n)$ between the adaptive beamformer array outputs $y(n)= w^H(n)x(n)$ and desired signal $d(n)$ is

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

Here, $w^H(n)$ is the Hermitian transpose or conjugate transpose of weight $w(n)$.

The step-size parameter (μ) bound is

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

In the RLS algorithm, the convergence speed is controlled by the replacement of the step size μ by the gain matrix. To obtain a fast-turnaround replacement algorithm, the least squares method is used instead of statistical method, based on the MSE method [43, 44]. In the RLS algorithm, the weight vector is changed as

$$\bar{w}(k) = \bar{w}(k-1) + \bar{g}(k)[d^*(k) - \bar{x}^H(k)\bar{w}(k-1)] \quad (6)$$

Where, $\bar{g}(k) = \hat{R}_{xx}^{-1}(k)\bar{x}(k)$ is gain vector, $\hat{R}_{xx}$ is correlation matrix

$$\hat{R}_{xx}(k) = \propto \hat{R}_{xx}(k-1) + \bar{x}(k)\bar{x}^H(k) \quad (7)$$

The forgetting factor ‘α’ is a positive constant, $0 \le \alpha \le 1$.

The SMI algorithm needs less number of iteration [43-45] for convergence to be satisfactory and uses K-time samples. In the SMI algorithm, the time-averaged prediction is equal to the real correlation matrix [25, 45]

$$R_{xx}(n) \approx \frac{1}{N}\sum_{n=1}^{N} x(n)\, x^H(n) \quad (8)$$

$$r(n) = \frac{1}{N}\sum_{n=1}^{N} d^*(n)\, x(n) \quad (9)$$

The matrix $x_N(n)$is the n-th block of vectors *x* ranges over N -data snapshots.

The weights in the SMI algorithm are updated as [25, 45]

$$w_{SMI}(n) = R_{xx}^{-1}(n)r(n) = [\, x_N(n)\, x_N^H(n)\,]^{-1} d^*(n) x_N(n) \quad (10)$$

and the expected signal is [25, 45]

$$d(n) = [\, d(1+nK)\ \ d(2+nK)\ \ d(3+nK)\ \ \dots\dots\dots\ \ d(N+nK)\,] \quad (11)$$

5. Design of Thinned Semi-Circular Smart Antenna Array of Dipoles

A uniform circular array (UCA) and uniform semi-circular array (USCA) of dipoles are shown in Fig. 1(a) and in Fig. 1(b) respectively. The uniform dipole spacing is ‘*d*’.

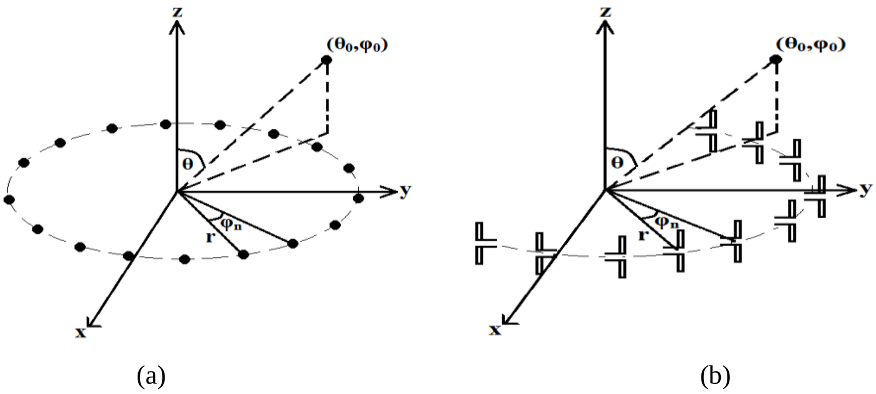

Fig. 1 (a) Uniform circular array (b) Uniform semi-circular array of dipole antennas

For a dipole antenna of length ‘*l*’, the radiation electric field is [37]

$$E(\theta) = j\eta \frac{I_0 e^{-j\beta r}}{2\pi r}\left[\frac{\cos\left(\frac{\beta l}{2} cos\theta\right) - \cos\left(\frac{\beta l}{2}\right)}{sin\theta}\right] \tag{12}$$

Here, $\beta = 2\pi/\lambda$ is the propagation constant, $\eta = 120\pi\Omega$ is the free space impedance, and I_0 is current amplitude. For N number of dipoles, the total electric field is

$$E_{total} = E(\theta)AF(\theta) \tag{13}$$

where, $AF(\theta)$ is the array factor (AF) for for circular array of isotropic antennas [37]

$$AF(\theta) = \sum_{n=1}^{N} I_0 e^{j[krsin\theta\cos(\varphi_0 - \varphi_n) + \beta_n]} \tag{14}$$

Where, β_n is the phase excitation of nth antenna, d_i is the spacing factor of the i-th element, and k_r and φ_n are

$$kr = \frac{2\pi r}{\lambda} = \sum_{i=1}^{N} d_i \tag{15}$$

$$\varphi_n = \frac{2\pi}{kr}\sum_{i=1}^{n} d_i \tag{16}$$

For a semi-circular array, half number of elements of a circular array is taken, so that the array factor becomes

$$AF(\theta) = \sum_{n=1}^{N/2} I_0 e^{j[krsin\theta\cos(\varphi_0 - \varphi_n) + \beta_n]} \tag{17}$$

The method of application of DE, in the design of TSA, is shown in Fig. 2. The DE optimization provides the "ON" and "OFF" sequence with lowest SLL. Then this weight sequence is used along with LMS, RLS and SMI to generate beam and null of TSA. For the cost function for thinned smart antenna Eq.(13) for $E_{total}(\theta)$is used.

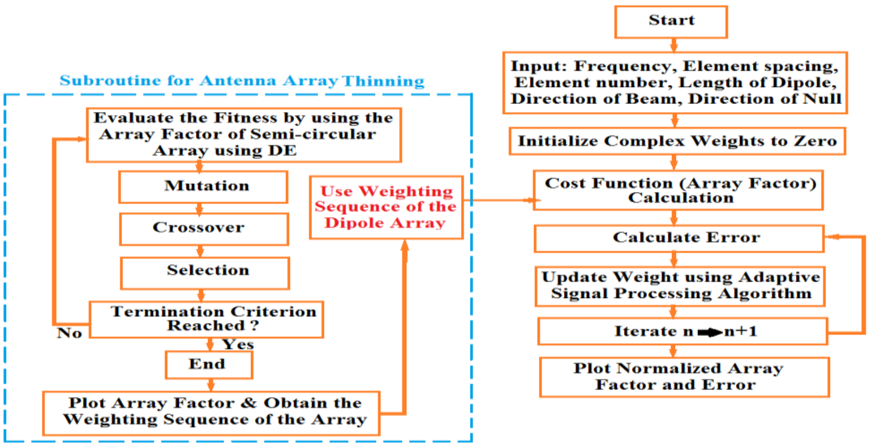

Fig. 2 Beamforming method of TSA

The subroutine of Fig. 2 is a part of the main program for thinned smart antenna and therefore the input parameters are same as the main program of Fig. 2. The simulation parameters for the design of TSA for various beam directions (BD) and null directions (ND), are presented in Table 1.

The comparison between TSA using DE-LMS and SA without thinning, for 20 dipoles and 31 dipoles, is shown in Fig. 3, Fig. 4 and Fig. 5.

Table 1 Simulation Parameters

Parameters	Values
Number of dipoles (N)	N=64, 31, 20
Dipole separation in the array	0.5λ
Frequency	5GHz
Length of dipole	λ/2 =0.03m
Signal-to-noise ratio	20dB
Value of μ in DE-LMS	0.002
Value of α in DE-RLS	0.9
Value of K in DE-SMI	800
Iteration number	800
Population size in DE optimization	48

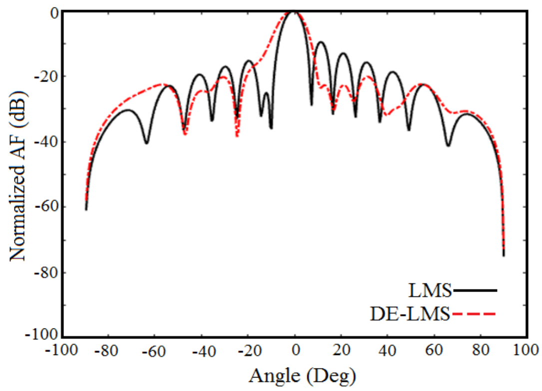

Fig. 3 Normalized AF for DE-LMS for N=20, BD=0^0, ND=10^0

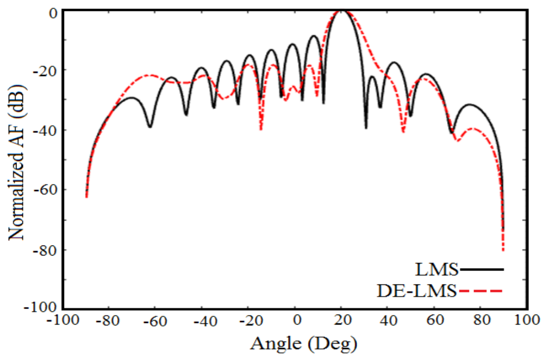

Fig. 4 Normalized AF for DE-LMS for N=20, BD=20^0, ND=10^0

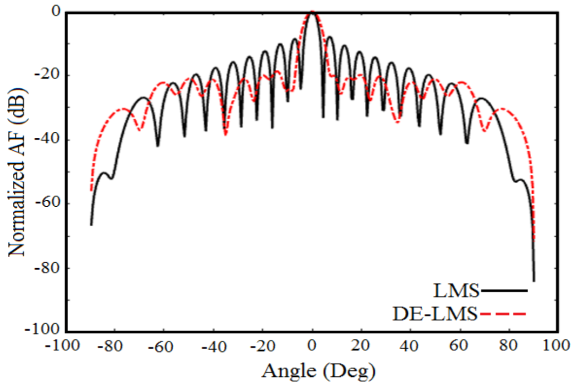

Fig. 5 Normalized AF for DE-LMS for N=31, BD=0^0, ND=10^0

The SLL is lowered in DE-LMS by 10 dB when N=20, BD=0^0, 10 dB when N=20, BD=20^0, and 11 dB when N=31, BD=0^0.

The comparison between TSA using DE-RLS and SA without thinning, for 20 dipoles and 64 dipoles, is shown in Fig. 6 and Fig. 7.

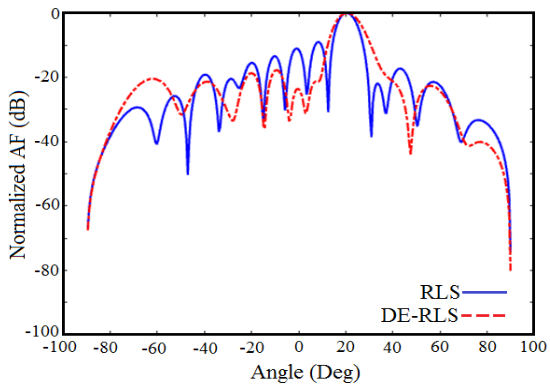

Fig. 6 Normalized AF for DE-RLS for N=20, BD=20^0, ND=10^0

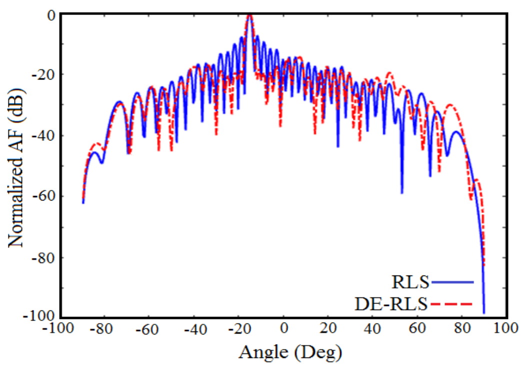

Fig. 7 Normalized AF for DE-RLS for N=64, BD=-15^0, ND=10^0

In Fig. 6, and 7, the SLL is lowered in DE-RLS by 10 dB when N=20 and 6 dB when N=64.

The comparison between TSA using DE-SMI and SA without thinning, for 20 dipoles and 64 dipoles, is plotted in Fig. 8 and Fig. 9.

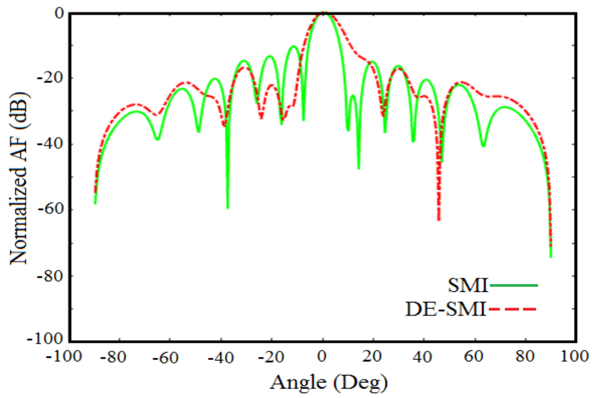

Fig. 8 Normalized AF for DE-SMI for N=20, BD=0^0, ND=10^0

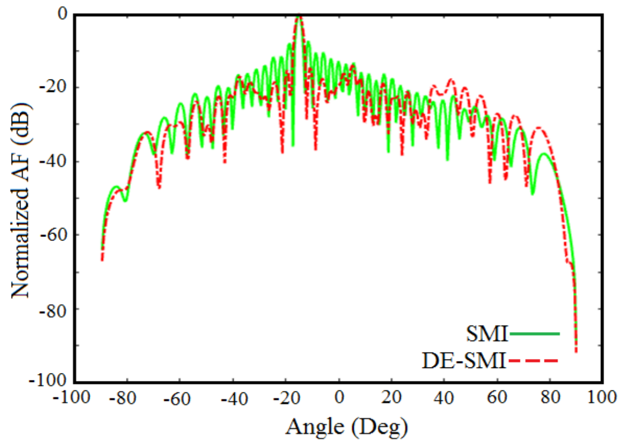

Fig. 9 Normalized AF for DE-SMI for N=64, BD=-15^0, ND=10^0

In Fig. 6, and 7, the SLL is lowered in DE-SMI by 7 dB when N=20, 9 dB when N=64. The performance comparison of TSA with SA is presented in Table 2.

Table 2 Results for TSA

Antenna type	Dipolenumber	BD	SLL_{max} (dB)	ON (1) & OFF (0) sequence	Reduction of SLL_{max} in (dB)	Power saving
SA Without Thinning (LMS)	N=20	0^{0}	-10	All ON	-----	NIL
	N=20	20^{0}	-9	All ON	-----	NIL
	N=31	0^{0}	-9	All ON	-----	NIL
	N=64	-15^{0}	-9	All ON	-----	NIL
Thinned SA (DE-LMS)	N=20	0^{0}	-20	0 0 1 0 0 1 0 1 1 1 1 1 1 1 0 1 0 0 1 0	10	45%
	N=20	20^{0}	-19	1 0 0 1 0 1 1 1 1 1 1 1 1 0 1 0 0 1 0 0	10	40%
	N=31	0^{0}	-20	1 0 0 0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0 0 1 0 0 0 0 0 0	11	48%
	N=64	-15^{0}	-20	1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 1 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0 0 1 0 0 1 0 1 0 0 1 1 0 0 0	11	42%
SA Without Thinning (RLS)	N=20	0^{0}	-10	All ON	-----	NIL
		20	-8	All ON	-----	NIL
	N=31	0^{0}	-7	All ON	-----	NIL
	N=64	-15^{0}	-8	All ON	-----	NIL
	N=20	0^{0}	-20	0 0 1 0 0 1 0 1 1 1 1 1 1 1 0 1 0 0 1 0	10	45%
	N=20	20	-18	1 0 0 1 0 1 1 1 1 1 1 1 1 0 1 0 0 1 0 0	10	40%
Thinned SA (DE-RLS)	N=31	0^{0}	-18	1 0 0 0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0 0 1 0 0 0 0 0 0	11	48 %
	N=64	-15^{0}	-14	1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 1 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0 0 1 0 0 1 0 1 0 0 1 1 0 0 0	6	42%

SA	N=20	0^0	-10	All ON	-----	NIL
Without		20	-11	All ON	-----	NIL
Thinning	N=31	0^0	-7	All ON	-----	NIL
(SMI)	N=64	-15^0	-7	All ON	-----	NIL
	N=20	0^0	-17	0 0 1 0 0 1 0 1 1 1 1 1 1 1 0 1 0 0 1 0	7	45%
	N=20	20	-14	1 0 0 1 0 1 1 1 1 1 1 1 1 0 1 0 0 1 0 0	3	40%
Thinned SA	N=31	0^0	-16	1 0 0 0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0 0 1 0 0 0 0 0 0	9	48 %
(DE- SMI)	N=64	-15^0	-16	1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 0 1 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 0 0 0 1 0 0 1 0 1 0 0 1 1 0 0 0	9	42 %

The 3dB beamwidths for the SA and TSA are compared in Table 3.

Table 3 Simulated 3 dB beamwidths (BW) for SA and TSA

No. of dipole Antennas	Beam direction	3dB BW for SA without thinning (LMS)	3dB BW for TSA (DE-LMS)	3dB BW for SA without thinning (RLS)	3dB BW for TSA (DE-RLS)	3dB BW for SA without thinning (SMI)	3dB BW for TSA (DE- SMI)
20	0^0	8.2^0	9^0	7.1^0	8^0	6.8^0	7^0
	20^0	9.3^0	10^0	5.5^0	6^0	9.2^0	10^0
31	0^0	2.5^0	3^0	2.3^0	3.2^0	3.5^0	3.9^0
64	-15^0	3^0	3.5^0	3^0	3.1^0	2.8^0	2.9^0

The 3dB beam width of TSA (Table 3) is still almost the same as that of the smart antenna, which means that the behavior of the smart antenna has not changed much. However, as the smart antenna gets thinner, SLL (Table 2) decreases. The DE-LMS, DE-RLS, and DE-SMI algorithms provide the desired BD and ND. In the above table, the benefit is the same for all the algorithms since the sequence is optimized by the same method. However, SLL varies in all cases. The maximum SLL reduction of 11 dB and power saving of 48% are achieved for TSA using DE-LMS; the maximum SLL reduction of 11 dB and power reduction of 48% are achieved for TSA using DE-RLS; and the maximum SLL reduction of 9 dB and power reduction of 48% are obtained for TSA using DE-SMI. The power reduction of 48% is achieved for TSA using DE-LMS because in the antenna array 48% of the total number of antennas are off while almost same 3-dB beamwidth is achieved (effectively no change of directivity). Therefore, 48% power of a fully populated array is not required.

The profiles of best cost values (magnitude of the array factor) when N=64, N=31, and N=20 are shown in Fig. 10.

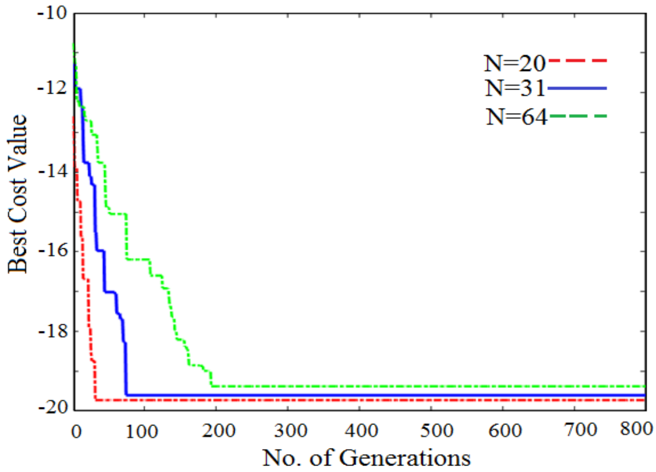

Fig. 10 Best cost value for dipole antenna array

The error graphs for TSA of N= 64, using different algorithms are shown in Fig. 11.

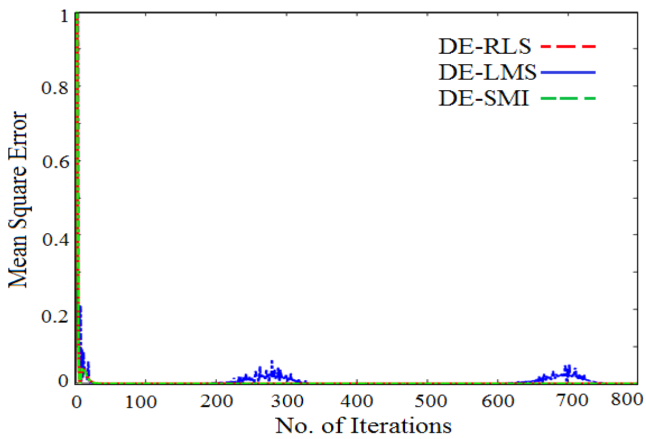

Fig. 11 Error graphs for N= 64

6. Conclusion

TSA is a new concept that combines the advantages of thinned antennas and smart antennas. By using TSA, the power budget in array design can be minimized without affecting the properties of the array. The main task of the present work is the use of a new energy-saving hybrid method for the design of large smart antennas, in which optimization algorithms are combined with signal processing algorithms. Large arrays are required in massive MIMO systems. The thinned array will provide many features such as desired beam and null formations, SLL reduction, power consumption reduction according to the user's needs. DE-LMS is easier to implement than DE-SMI and DE-RLS algorithms. The simulation time is almost the same for all the algorithms, but when the dipole number in the antenna array increases, the simulation time increases. When N=20 and N=31, the simulation times are 1.5 minutes and 3 minutes respectively. The laptop configuration is: 11th Generation Intel(R) Core TM i3-1115G4 @ 3.00 GHz, 2901 MHz, 2-core, 4 logical processors. Since there is no similar published data, the simulation results of the proposed algorithm can't be compared with other data.

REFERENCES

[1] A. J. Paulraj, D. A. Gore, R. U. Nabar and H Bolcskei, "An Overview of MIMO Communications-a Key to Gigabit Wireless", *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198–218, 2004.

[2] M. R. Amin and S. D. Trapasiya, "Space Time Coding Scheme for MIMO System-literature Survey", *Procedia Eng.* vol. 38, pp. 3509–3517, 2012.

[3] S. Yang and L. Hanzo, "Fifty Years of MIMO Detection: The Road to Large-scale MIMOs", *IEEE Communication Survey Tutor.* vol. 17, pp. 1941–1988, 2015.

[4] H. V. Poor, D. Reynolds and X. Wang, "Multiuser MIMO Systems" *Space-Time Wireless Systems: From Array Processing to MIMO Communications* (Vol. 9780521851053, pp. 406-425). 2006. Cambridge University Press. https://doi.org/10.1017/CBO9780511616815.021

[5] A. Immanuel and M. Suganthi, "Performance Analysis of Low Power Channel Estimator for Multi-user MIMO-OFDM System", *Wireless Personal Communication*, vol. 107, pp. 341–350, 2019.

[6] E. G. Larsson, O. Edfors, F. Tufvesson and T.L. Marzetta, "Massive MIMO for Next Generation Wireless Systems", *IEEE Communication Magazine*, vol. 52, no. 2, pp. 186–195, 2014.

[7] L. Zheng, K. Zhao, J. Mei, B. Shao, W. Xiang and L. Hanzo, "Survey of Large-scale MIMO Systems", *IEEE Communication Survey Tutor.* vol. 17, 1738–1760, 2015.

[8] N. Hassan and X. Fernando, "Massive MIMO Wireless Networks: An Overview", *Electronics*, vol. 6, no. 3, 63, pp. 1–29, 2017.

[9] Y. Su, H. Gao and S. Zhang, "Secure Massive MIMO System With Two-Way Relay Cooperative Transmission in 6G networks", *EURASIP Journal on Wireless Communications and Networking*, vol. 2023, no. 73, pp. 1–22, 2023.

[10] F. Wen, H. Wymeersch, B. Peng, W. P. Tay, H. C. So and D. Yang, "A Survey on 5G Massive MIMO Localization", *Digit. Signal Process.* vol. 94, pp. 21–28, 2019.

[11] M. Belgiovine, K. Sankhe, C. Bocanegra, D. Roy and K. R. Chowdhury, "Deep Learning at the Edge for Channel Estimation in Beyond-5G Massive MIMO", *IEEE Wireless Communication*. vol. 28, pp. 19–25, 2021.

[12] G. Xu, Y. Li, J. Yuan, R. Monroe, S. Rajagopal, S. Ramakrishna, Y. H. Nam, J-Y. Seol, J. Kim, M. Gul, A. Aziz and J. Zhang, "Full Dimension MIMO (FD-MIMO): Demonstrating Commercial Feasibility", *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 8, pp. 1876–1886, Aug. 2017.

[13] N. Qu, L. Liu, R. Shafin, B. Li, M. Liu and F. Gong, "Interference Alignment Meets Multi-cell Multi-user Massive FD-MIMO Systems in DoA-based Precoding", *IEEE Trans. on Wireless Communications*, vol. 20, no. 11, pp. 7460–7474, Nov. 2021.

[14] J. Hoydis, S. Brink and M. Debbah, "Massive MIMO in the UL/DL of Cellular Networks: How Many Antennas do We Need?", *IEEE J Selected Areas Communication*, vol. 31, no. 2, pp. 160–171, 2013.

[15] C.-M. Chen V. Volski, L.V.D. Perre, G.A.E. Vandenbosch and S. Pollin, "Finite Large Antenna Arrays for Massive MIMO: characterization and system impact", *IEEE Trans. Antennas Propag*, vol. 65, no. 12, pp. 6712–6720, 2017.

[16] Y. Li, C.-Y.-D. Sim, Y. Luo and G. Yang, "12-port 5G Massive MIMO Antenna Array in Sub-6GHz Mobile Handset for LTE Bands 42/43/46 Applications", *IEEE Access*, vol. 6, pp. 344–354, 2017.

[17] E. Ali, M. Ismail, R. Nordin and N. F. Abdulah, "Beamforming Techniques for Massive MIMO Systems in 5G: Overview, Classification, and Trends for Future Research", *Frontiers of Information Technology & Electronic Engineering*, vol. 18, no. 6, pp. 753–772, 2017.

[18] S. El-Khamy, K. Moussa and A. El-Sherif, "A Smart Multi-user Massive MIMO System for Next G Wireless Communications Using Evolutionary Optimized Antenna Selection", *Telecommunication Systems*," vol. 65, pp. 309–317, 2017.

[19] S. El-Khamy, K. Moussa and A. El-Sherif, "Performance of Enhanced Massive Multiuser MIMO Systems Using Transmit Beamforming and Transmit Antenna Selection Techniques", *Wireless Personal Communications*, vol. 94, pp. 1825–1838, 2017.

[20] S. J. Shim, S. Lee, W. S. Lee, J. H. Ro, J. L. Baik and H. K. Song, "Advanced Hybrid Beamforming Technique in MU-MIMO Systems", *Applied Sciences*, vol. 10, p. 5961, 2020.

[21] P. Ranjan, S. Yadav and A. Bage, "Dual Band MIMO Antenna for LTE, 4G and Sub–6 GHz 5G Applications", *FACTA Universitaits Series Energetics and Electronics*, vol. 36, no. 1, pp. 43–51, 2023.

[22] T. S. Priya, M. Kondala and P. Periasamy, "Hybrid Beamforming for Massive MIMO using Rectangular Antenna Array Model in 5G Wireless Networks", *Wireless Personal Communication*, vol. 120, pp. 2061–2083, 2021.

[23] S. K. Ibrahim, M. J. Singh, S. S. Al-Bawri, H. H. Ibrahim, M. T. Islam, M. S. Islam, A. Alzamil and W. M. Abdulkawi, "Design, Challenges and Developments for 5G Massive MIMO Antenna Systems at Sub 6-GHz Band: A Review", *Nanomaterials*, vol. 13, no. 3, pp. 1–40, Jan 2023.

[24] A. Dhar, A. Senapati and J. S. Roy, "Direction of Arrival Estimation for Smart Antenna Using a Combined Blind Source Separation and Multiple Signal Classification Algorithm", *Indian Journal of Science and Technology (IJST)*, vol. 9, no. 18, pp. 1–8, 2016.

[25] K. Ghatak, A. Senapati and J. S. Roy, "Investigations on Adaptive Beam Forming for Linear and Planar Smart Antenna Arrays Using Sample Matrix Inversion Algorithm", *International Journal of Computer Applications*, vol. 117, no. 8, pp. 47–50, 2015.

[26] A. Khan, A. Senapati and J. S. Roy, "Adaptive Signal Processing Algorithm Applied to the Design of Smart Antenna in a Cellular Network Considering Phase Quantization Error", *2nd Intl. Conf. on Data Science and Applications (ICDSA 2021), Kolkata, Springer Lecture Notes in Networks & Systems*, April 10-11, 2021, vol. 288, pp. 563–575, Nov. 2021.

[27] B. Samantaray, K. K. Das, and J. S. Roy, "Performance of Smart Antenna in Cellular Network Using Variable Step Size Algorithms", *International Journal of Microwave and Optical Technology (IJMOT)*, vol. 15, no. 2, pp. 179–186, 2020.

[28] M. Atzemourt, A. Farchi, Y. Chihab, and Z. Hachkar, "Performance Evaluation of LMS and CM Algorithms for Beamforming", *Advances in Materials Science and Engineering*, Article ID 7744625, pp. 1–6, 2022.

[29] R. L. Haupt, "Adaptively Thinned Arrays", *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1626–1633, 2015.

[30] M. Salucci, G. Gottardi, N. Anselmi, and G. Oliveri, "Planar Thinned Array Design by Hybrid Analytical-stochastic Optimization", *IET Microwaves, Antennas & Propagation*, vol. 11, no.3, pp. 1–5, 2017.

[31] A. S. Karasev, and M. A. Stepanov, "Genetic Algorithm For Antenna Array Thinning With Minimization of Side Lobe Level", In Proceedings of the IEEE 15th International Conference of Actual Problems of Electronic Instrument Engineering (APEIE), IEEE Xplore,2022, pp. 268–272.

[32] R. L. Haupt, "Thinned Arrays Using Genetic Algorithms", *IEEE Transactions on Antennas and Propagation*, vol. 42, no.7, pp. 993–999, 1994.

[33] R. Bera, and J. S. Roy, "Thinning of Elliptical and Concentric Elliptical Antenna Arrays Using Particle Swarm Optimization", *Microwave Review*, vol. 19, no. 1, pp. 2–7, 2013.

[34] A. Suresh, C. Puttamadappa, and M. K. Singh, "Thinning Approach Based on Sides Lobe Level Reduction in the Linear Array Antenna Using Dynamic Differential Evolution", *SSRG International Journal of Electrical and Electronics Engineering*, vol. 10, no. 2, pp. 61–74, Feb. 2023.

[35] R. Sanudin, and T. Arslan, "Semi-circular Antenna Array for Azimuth DOA Estimation", In Proceedings of the Loughborough Antennas & Propagation Conference (LAPC), Nov. 12-13, 2012, IEEE Xplore, p. 1–4.

[36] P. Das and J. S. Roy, "Thinning of Semi-Elliptical and Quarter-Elliptical Antenna Array using Genetic Algorithm Optimization", *International Journal of Emerging Technologies in Computational and Applied Sciences (IJETCAS)*, vol. 8, no. 4, pp. 335-339, May 2014**.**

[37] C. A. Balanis, *Antenna Theory: Analysis and Design*, John Wiley, 4th Ed., 2016.

[38] A. Khan, J. S. Roy, "Thinned Smart Antenna of a Semi-Circular Dipole Array for Massive MIMO Systems", *Advanced Electromagnetics*, vol.12, no. 4, pp. 17–25, Dec. 2023.

[39] J. Qi, H. X. Zheng, M. Wang, R. Liu, C. Tang and E. Li, "A Phased Array Composed of Dipole With Semicircular Ring for 5G", In Proceedings of the International Conference on Microwave and Millimeter Wave Technology (ICMMT), 2019, pp. 1–3.

[40] R. Strong and K. Price, "Differential Evolution – a Simple and Efficient Heuristic for Global Optimization Over Continuous Spaces", *Journal of Global Optimization*, vol. 11, pp. 341–359, 1997.

[41] A. Deb, J. S. Roy, and B. Gupta, "Performance Comparison of Differential Evolution, Particle Swarm Optimization and Genetic Algorithm in the Design of Circularly Polarized Microstrip Antennas", *IEEE Trans. Antennas & Propagation*, IEEE, vol. 62, pp. 3920–3928, 2014.

[42] A. Deb, J. S. Roy, and B. Gupta, "A Differential Evolution Performance Comparison: Comparing how Various Differential Evolution Algorithms Perform in Designing Microstrip Antennas and Arrays," *IEEE Antennas & Propagation Magazine*, vol. 60, pp. 51–61, 2018.

[43] B. Widrow and S. D. Stearns, *Adaptive Signal Processing*, Prentice Hall, 1985.

[44] S. Haykin, *Adaptive Filter Theory*, 4th Ed, Pearson Education, 2002.

[45] W. A. E. Ali, D. A. E. Mohamed, and A. H. G. Hassan, "Performance Analysis of Least Mean Square Sample Matrix Inversion Algorithm for Smart Antenna System", In Proceedings of the Loughborough Antennas & Propagation Conference, 11-12 Nov., 2013, IEEE Xplore, pp. 624–629.