

Energy Efficient Switched Parasitic Array Antenna for 5G Networks and IoT

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Abstract—This paper includes design and implementation result of an adaptive beam forming antenna for upcoming 5G and Internet of Things (IoT). Switched parasitic array antennas are low cost, small sized and compact circular array antennas that steer beam in a desired direction by variation in switching pattern of parasitic elements. The proposed antenna design has an active center element, which is surrounded by several symmetrically placed parasitic elements. The designed antenna has a gain of 8 dB and is capable of 360 degrees beam steering in steps of 60 degrees each. Simulations are validated with results of the fabricated antenna. Antenna beam is steered by controlling parasitic elements. Future application of Electronically Steerable Parasitic Array Radiator (ESPAR) antennas and switched parasitic array antennas in next generation communication networks and methods for reducing size of the antenna are also highlighted.

Index Terms—Internet of Things, 5G, circular array, reconfigurable, smart antenna, adaptive beamforming, Switched-Parasitic Array

I. INTRODUCTION

Smart antennas are capable of adaptive beam forming in accordance with the environment. Over the last three decades wireless communication has made rapid progress due to better modulation schemes and better error correction schemes. Wireless communication systems are replacing the wired ones. Antenna is an integral part of wireless devices. To meet the ever-increasing demand of higher data rate, smart antennas capable of adaptive beam forming are introduced as a potential solution to increasing data rate and improving signal-to-noise ratio (SNR) in upcoming 5G and Internet of Things (IoT) [1]. By using smart antennas Equivalent Isotropically Radiated power (EIRP) can be increased. EIRP denotes product of the transmit power (P_t) and transmit antenna gain (G_t), i.e.

$$EIRP = P_t \times G_t \quad (1)$$

From (1), it is observed that by using a smart antenna G_t increases, which in turn leads to the increase in the EIRP. The beam of an antenna can be steered by means of mechanical

movement of a directional antenna or by electronic beam steering. Electronic beam steering is resilient and provides more accurate approximation of the desired signal source. Moreover electronic beam steering antenna does not involve moving parts. Therefore, there is less wear and tear on the antenna as compared to mechanical beam steering. Generally electronic beam forming is achieved by using phase shifters coupled with an array of antenna elements. The phase of an individual phase shifter is varied such that there is net constructive interference in the intended direction of the antenna beam and destructive interference in all other directions [2]. Hence, electronic beam steering is preferred over mechanical beam steering.

Electronically Steerable Parasitic Array Radiator (ESPAR) antennas use mutual coupling between antenna elements to steer the beams instead of phase shifters. Design of parasitic array radiator antennas is discussed in [3], [4] in which there is a center active element surrounded by a circular array of passive elements, where each passive element is loaded with a specific reactance. ESPAR antennas are smaller in size as compared to phase array antennas because elements have to be placed at a quarter of wavelength or less distance from each other for effective mutual coupling. Hence, ESPAR antennas are cost effective and space efficient. In such antennas we have only one active element, therefore, only one feed is required. Consequently, ESPAR antennas have lower losses (due to single feed) as compared to phase array antennas [3].

Previously designed antenna Electronically Steerable Parasitic Radiator (ESPAR) antennas have all cylindrical element, including the feed element [6], [7]. In this paper we have proposed design of seven element ESPAR antenna with conical center (active element)¹. Length of conical element is optimized using optimetrics in HFSS. Our proposed antenna has higher bandwidth as compared to previously designed ESPAR antennas. [6], [7]. In multiple-input-multiple-output (MIMO)

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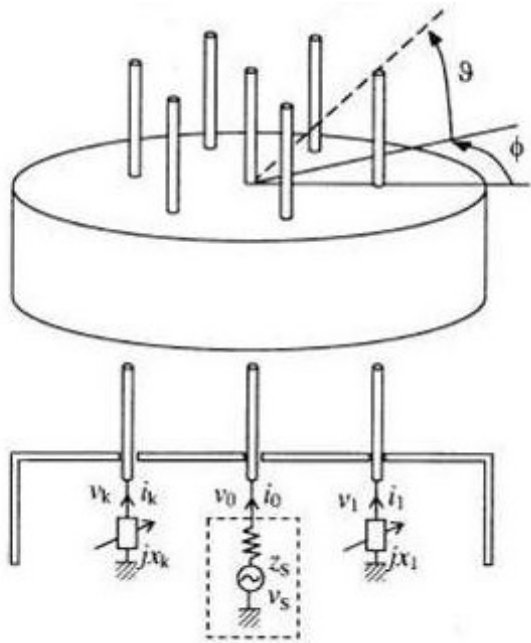


Fig. 1. Seven Element switched parasitic array antenna, ϕ is azimuth angle and θ is elevation angle.

systems there are multiple transmit and receive antennas. Each receive antenna receives signal over different propagation channels yielding diversity gain. The MIMO technique can increase system throughput and reduce propagation losses. Similarly diversity gain can also be achieved by using smart antennas. In particular, we can transmit the same signal in multiple directions through directional beams, such that they experience different propagation channels [4]. Our proposed antenna is more suited for MIMO applications compared to previously designed model because of its higher gain and improved bandwidth efficiency.

This paper focuses on the design of a seven element switched parasitic array antenna. The antenna is first simulated and then it is fabricated. Simulation results are validated with the hardware results. Previously done work on ESPAR and switched array antennas involve cylindrical monopole elements mounted on a ground plane [8] due to cylindrical nature bandwidth of active monopole is confined, subsequently bandwidth of switched array and ESPAR antennas is limited. Instead on cylindrical monopole element we have used tapered conical monopole. Due to tapered design bandwidth is enhanced.

II. SWITCHED PARASITIC ARRAY ANTENNA CONCEPT

The conceptual overview of the switched parasitic array antenna is given in Fig. 1. We have first simulated the antenna with seven monopole elements. There is one element at center which is surrounded by a circular array. Feed is applied to the center element and it is termed as active element, whereas elements in the circular array are parasitic elements. Parasitic array antennas do not involve phase shifters, so that the

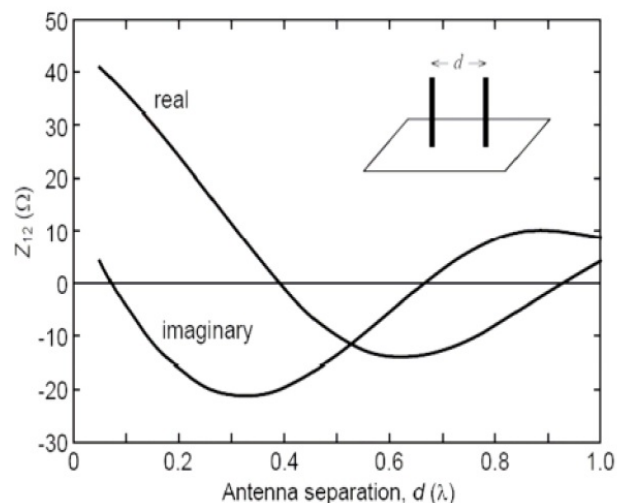


Fig. 2. Z_{21} versus separation distance.

manufacturing cost is less as compared to the phase array antennas. Each element is separated from other element by a quarter of wavelength, thus mutual coupling phenomena comes into account and there is a shift in phase of current in each element because of this mutual coupling phenomenon. Since switched parasitic array antennas offer adaptive beamforming solution with compact size and low cost, they are likely to be used in future communication devices to increase data-rates [6], [7]. Parasitic array antennas have vast potential for usage in laptops, cell phones, WLANs etc.

A. Mutual Coupling

Mutual Coupling is basically the interaction between antenna elements in an array. Since parasitic elements are placed closer to each other (at a distance of $\lambda/4$) there will be mutual coupling. This mutual coupling phenomenon is responsible for a shift in phase of current induced in each element [8]. The current induced by one antenna element in another antenna element [9] is given by (3)

$$I_2 = \frac{Z_{21}}{Z_{22}} \times I_0 \quad (2)$$

$$Z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2=0} \quad (3)$$

$$Z_{21} = \left. \frac{V_2}{I_2} \right|_{I_1=0} \quad (4)$$

Here Z_{22} is constant as it is open-circuit output impedance. Z_{21} is open-circuit transfer impedance from port 2 to port 1 and it can be approximated by graph shown in Fig. 2. From equation (3), beam can be steered in the desired direction by varying the phase of current I_2 [10].

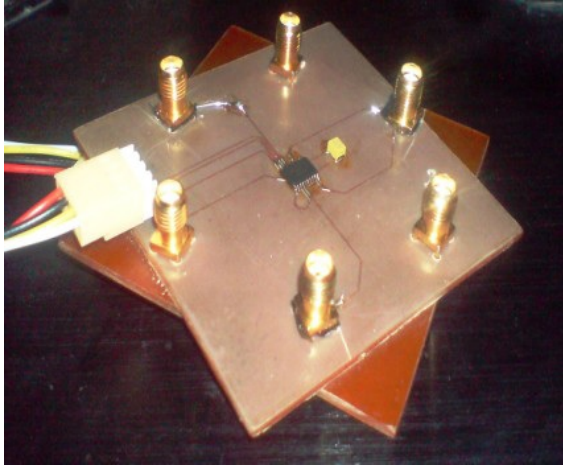


Fig. 3. RF PCB with Analog devices ADG 904 RF switches.

TABLE I
DESIGN PARAMETERS

Parameters	Values
Ground Skirt length	$\lambda/4$
Monopole Length	$\lambda/4$
Frequency	2.45 GHz
Ground Radius	$\lambda/2$
Monopole Radius	$\lambda/200$
Ground Thickness	3 mm

B. Beam Steering Mechanism

In this work the designed antenna is capable of 360° beam steering in steps of 60° . The beam steering is achieved by using two sets of 4:1 Analog devices multiplier switch ADG 904. Fig.3 shows RF PCB designed for beam steering. Beam is steered towards an element which is open. The open element behaves as a director and shorted elements act as reflectors. In order to achieve a maxima at 0° , we make the element 1 open by using RF switch IC while other elements (i.e., elements 2,3,4,5 and 6) are shorted. This mechanism is similar to Yagi-Uda antenna where elements with shorter lengths in front of feed element act as directors and elements at rear of feed element acts as reflectors [11]. In Yagi-Uda antenna feed element is often a dipole or folded dipole.

III. PARASITIC ARRAY ANTENNA DESIGN

Design parameters and mechanical design of antenna is included in this section.

A. Design Parameters

Antenna design parameters are tabulated and the results are optimized using antenna simulation tools. Ground is skirted, since skirted ground provides mechanically sound model for PCB assembly to mount at back of antenna [12]. Skirt is $\lambda/4$ in length similarly each monopole element is $\lambda/4$ in length and $\lambda/200$ is its radius. Table I shows the design parameters for the seven-element switched parasitic array antenna.

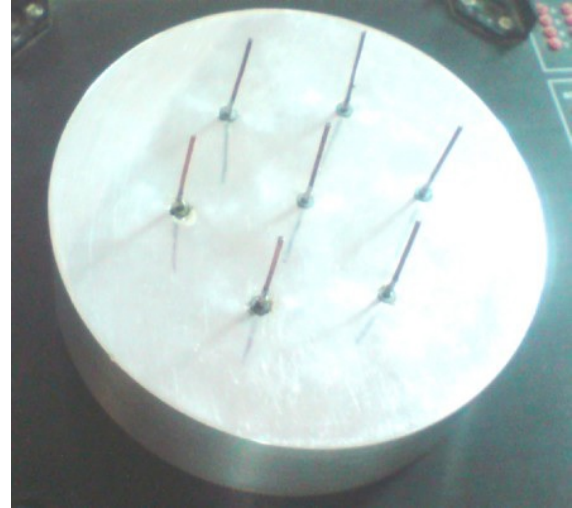


Fig. 4. Designed seven element parasitic switched array antenna.

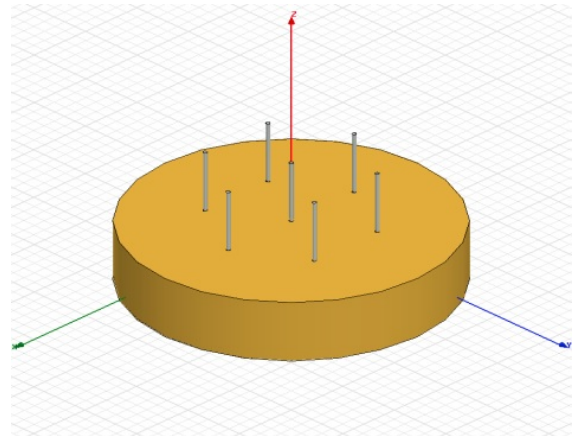


Fig. 5. Simulated antenna model.

B. Mechanical Design

Monopole elements are made by cutting copper wire of desired gauge i.e $\lambda/200$ in radius [13] and these elements are soldered on pin of SMA connectors. Aluminum is used as ground plane. Electromagnetic waves are reflected by the ground. Instead of using seven dipole elements we have used seven monopole elements mounted on the ground plane [14]. Ground is made hollow in order to create space for mounting control circuitry [15]. Fig. 4 shows designed hardware.

IV. ANTENNA SIMULATION AND PLOTS

The antenna is first simulated and then simulated results are compared with the measured results of fabricated antenna. Simulated results were in line with the hardware results and 8 dB gain was observed in simulated results as well as in fabricated antenna. In simulation each of the parasitic element is loaded with lumped port excitation, simulating opening and shorting [16] of monopole elements. Fig. 5 shows simulated model.

TABLE II
MAXIMA PATTERN

Azimuth Angle	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6
0 degree	Open	Short	Short	Short	Short	Short
30 degree	Open	Open	Short	Short	Short	Short

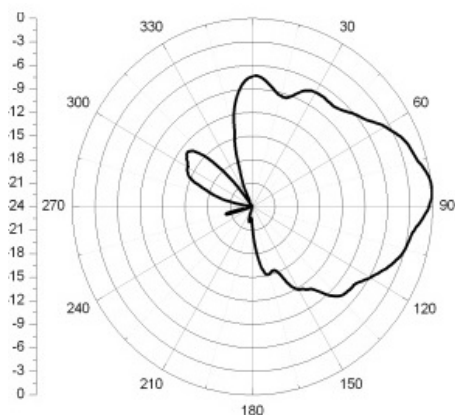


Fig. 6. Anechoic chamber results for $\theta=90^0$ (Beam in elevated because we are using monopole elements with finite ground).

Two dimension polar plots depicts the beam steering in the direction of given elevation angle, theta (θ) and azimuth angle, phi (ϕ). Anechoic chamber results for $\theta=90$ and $\phi=0$ and 30 degrees are shown in Fig. 7 and 8 respectively. Using large ground plane angle of elevation is reduced closer to 90^0 . Fig. 6 shows anechoic chamber result for $\theta=90$ one can observe small elevation form desired x-y axis because of ground skirt [17]. In simulations elevation angle of 85^0 is observed. Fig. 6(a) shows antenna simulated plot for elevation angle θ and Fig. 6(b) shows anechoic chamber results. Anechoic chamber plot of Fig. 7 shows maxima at $\phi=0^0$, in order to get maxima at 0^0 elements from element number 2-6 are shorted and the element 1 is opened. Similarly Anechoic chamber plot of Fig. 8 shows maxima at $\phi=30^0$, in order to get maxima at 30^0 elements from element number 3-6 are shorted and element 1 and element 2 are open.

Traditional ESPAR antenna and switched parasitic array antenna have all cylindrical elements, including the active element [3], [4]. We have made center element conical instead of cylindrical. Due to conical nature of active element response our frequency range and improved. In order to validate the gain enhancement both models were simulated and results were compared. Fig 9. (a) shows conventional design and Fig. 9(b) shows simulated antenna with conical center element. Fig. 10 shows S_{11} plot for cylindrical active element. Considering -8_{dB} as cut off point bandwidth range from 2.358 GHz to 2.51 GHz (0.152 GHz). Fig. 11 shows S_{11} plot for centre conical element, considering 8_{dB} as cut off point bandwidth ranges from 2.36 GHz to 2.555 GHz (0.195 GHz). Therefore my making center element conical we have improved bandwidth as compared to traditional switch array

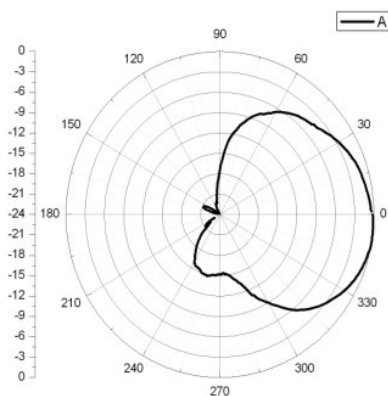


Fig. 7. Anechoic chamber results for $\phi=0^0$.

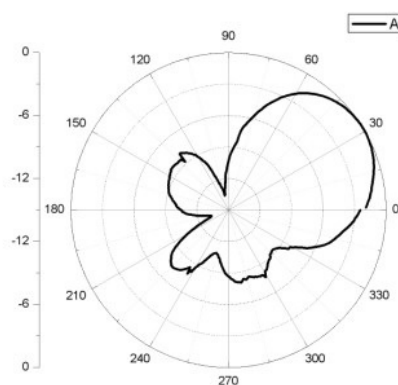


Fig. 8. Anechoic chamber results for $\phi=30^0$.

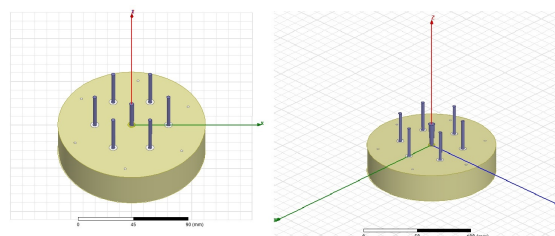
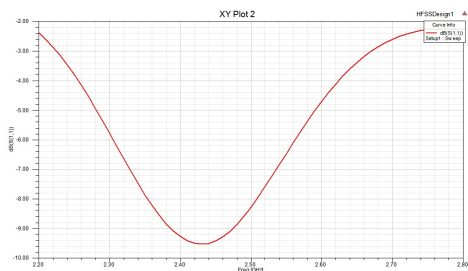
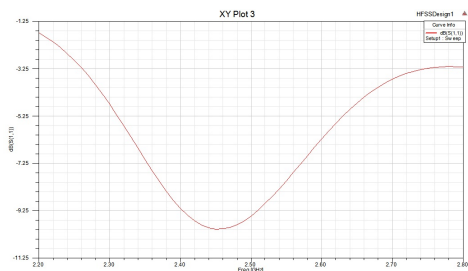


Fig. 9. (a) Conventional ESPAR antenna model with cylindrical Center Element, Fig. 9 (b) Designed ESPAR antenna with conical element for Bandwidth Enhancement.

parasitic antennas. Low profile design for switched parasitic array antennas in also highlighted in [18].

V. FUTURE WORK AND CONCLUSION

5G networks will be designed for device to device, device to human and human to human interactions. High data rates are required to meet demands of 5G systems. One of proposed bands for 5G is in mm-Waves range i.e from 30GHz to 60GHz for such high frequencies path losses are considerable and beam steering antennas are way forward to overcome path

Fig. 10. S_{11} plot for conventional switched array antenna.Fig. 11. S_{11} plot for center conical element switched array antenna.

losses [19]. ESPAR and switched parasitic array antennas provide a cost effective way of incorporating adaptive beamforming in future 5G and internet of Things (IoT) devices [20]. However for the efficient use of ESPAR antennas in mobile terminals the size of the antenna system must be reduced, for this further research on dielectric switched parasitic array antennas is underway. Seven element switched parasitic array antenna is designed that is capable of dynamic beam steering. Gain of 8dB is achieved practically. Simulated results are in line with the anechoic chamber results. Designed antenna increase the channel capacity by improving signal to noise ratio. Gain of 8dB was achieved in specified directions of elevation angle, θ and azimuth angle, ϕ . Antenna is optimized in terms of interference reduction for its use in wireless ad hoc networks, operating at frequency of 2.45 GHz. Bandwidth of designed antenna is 450 MHz and beam is steered in 360° .

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REFERENCES

- [1] M. Rzymowski, P. Woznica, and L. Kulas, "Single-anchor indoor localization using espar antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1183–1186, 2016.
- [2] L. Zhou, F. A. Khan, T. Ratnarajah, and C. B. Papadias, "Achieving arbitrary signals transmission using a single radio frequency chain," *IEEE Transactions on Communications*, vol. 63, no. 12, pp. 4865–4878, Dec 2015.
- [3] V. I. Barousis and C. B. Papadias, "Arbitrary precoding with single-fed parasitic arrays: Closed-form expressions and design guidelines," *IEEE Wireless Communications Letters*, vol. 3, no. 2, pp. 229–232, April 2014.
- [4] M. R. Islam and M. Ali, "Elevation plane beam scanning of a novel parasitic array radiator antenna for 1900 mhz mobile handheld terminals," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 10, pp. 3344–3352, Oct 2010.
- [5] S. Kausar, H. U. Rahman, T. Hassan, and A. Kausar, "Miniaturization of espar antenna using folded monopoles and conical central element," in *Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET), 2015 International Conference on*. IEEE, 2015, pp. 87–91.
- [6] H. T. Liu, S. Gao, and T. H. Loh, "Electrically small and low cost smart antenna for wireless communication," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 3, pp. 1540–1549, March 2012.
- [7] T. H. Loh, H. Liu, and S. Gao, "A cost-effective direct magnitude measurement methodology for smart antennas," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 2043–2050, April 2013.
- [8] F. Khan, K. Ali, A. Kausar, and S. Kausar, "Energy generation capacity analysis of a canal based hydro project," in *2013 Fifth International Conference on Computational Intelligence, Modelling and Simulation*, Sept 2013, pp. 277–281.
- [9] A. Kausar, M. A. Cheema, S. Kausar, H. Rehman, and T. Hassan, "Espar antenna system designing & simulation," in *Proceedings of the 2014 First International Conference on Systems Informatics, Modelling and Simulation*, ser. SIMS '14. IEEE Computer Society, 2014, pp. 193–196. [Online]. Available: <http://dx.doi.org/10.1109/SIMS.2014.37>
- [10] S. Akkar and A. Gharsallah, "Reactance domains unitary music algorithms based on real-valued orthogonal decomposition for electronically steerable parasitic array radiator antennas," *IET Microwaves, Antennas Propagation*, vol. 6, no. 2, pp. 223–230, January 2012.
- [11] S. Kausar, H. u. Rahman, A. Kausar, and T. Hassan, "Espar antenna system for dynamic tracking of active targets," in *Modelling Symposium (EMS), 2013 European*, Nov 2013, pp. 533–535.
- [12] A. Umar Kausar, F. Aslam Khan, T. Hassan, A. Nasser, and S. Kausar, "Adaptive espar antenna system modelling & design," *International Journal of Simulation-Systems, Science & Technology*, vol. 14, no. 4, 2013.
- [13] D. v. B. M. Trindade, C. Miller, M. C. F. D. Castro, and F. C. C. D. Castro, "Metamaterials applied to espar antenna for mutual coupling reduction," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 430–433, 2015.
- [14] S. Kausar, Ahmed Kausar, "Smart adaptive beam forming antenna for interference cancellation," in *Wireless Days (WD), 2013 IFIP*. IEEE, 2013, pp. 1–3.
- [15] A. Kausar, S. Kausar, and T. Hassan, "Smart adaptive beam forming antenna for interference minimization," in *Future Generation Communication Technology (FGCT), 2013 Second International Conference on*. IEEE, 2013, pp. 6–9.
- [16] F. Aslam, E. Ulhaq, A. Nasser, and A. Umar, "Intelligent modeling scheme for detection of line losses in power distribution system," in *Computer Modelling and Simulation (UKSim), 2013 UKSim 15th International Conference on*. IEEE, 2013, pp. 218–223.
- [17] R. Qian, M. Sellathurai, and D. Wilcox, "A study on mvdr beamforming applied to an espar antenna," *IEEE Signal Processing Letters*, vol. 22, no. 1, pp. 67–70, Jan 2015.
- [18] A. Pal, A. Mehta, D. Mirshekar-Syahkal, and H. Nakano, "A low-profile switched-beam dual-band capacitively coupled square loop antenna," in *Antennas and Propagation Conference (LAPC), 2013 Loughborough*, Nov 2013, pp. 563–566.
- [19] A. Kausar, S. Kausar, T. Hassan *et al.*, "Interference cancellation using adaptive beam forming for 3 d beam steering," *International Journal of Simulation-Systems, Science & Technology*, vol. 14, no. 1, 2013.
- [20] M. R. Nikkiah, P. Loghmannia, J. Rashed-Mohassel, and A. A. Kishk, "Theory of espar design with their implementation in large arrays," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 6, pp. 3359–3364, June 2014.
- [21] T. Hassan, A. Kausar, H. Umair, and M. A. Anis, "Gain optimization of a seven element espar antenna using quasi-newton method," in *Microwave technology & computational electromagnetics (ICMTCE), 2011 IEEE international conference on*. IEEE, 2011, pp. 293–296.