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DESIGN OF CONVEX AND CONCAVE DUAL BENT ARRAY FOR 5G LENS ANTENNA SYSTEM

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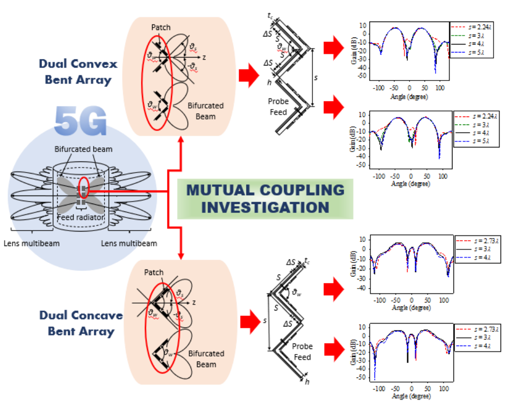
Graphical abstract



Abstract

Previous research on the multi-beam system for the fifth generation (5G) application has shown that the number of feed elements of a lens antenna system at the mobile base station is increasing due to the massive MIMO requirements. The design of the array circuits of the 5G lens antenna systems will be more complicated due to the feeding structure, which consists of the power dividers and phase shifters, thus contributing to higher feeding losses. The antenna fabrication process also becomes more complicated. Besides that, the conventional array feed also produces a single radiation beam only. Thus, a large space is needed, where array feed antennas should be arranged to perform wide-angle beam scanning for 5G massive MIMO operation. Therefore, to overcome these issues, this paper uses a bent array configuration as the lens antenna feed to produce bifurcated beam radiation and has a wide beam angle from the feed radiator to the lens edge. Multiple bent arrays are arranged on the lens axis to generate a multi-beam by cylindrical lens antenna. This paper shows a comparison of the bent array in convex and concave configurations. This process investigates the mutual coupling when more than one bent array is arranged as feed radiators. By comparing the arrays in convex and concave structures, it is observed that the convex structure produces a better-bifurcated beam with a smaller middle lobe. The antenna also produces the same bifurcated beam shifting angle, ϑ_s for both ports, when $s = 4\lambda$ is used. It is verified as the optimum spacing value between two bent array structures by the optimization process.

Keywords: Bifurcated beam, bent array, multi-beam, convex and concave configurations, mutual coupling

1.0 INTRODUCTION

For the 5G mobile communication system, higher operational frequency and multi-beam radiation are requested at base stations to increase the network capacity [1]. A number of array feeds should be arranged to achieve the multi-beam objective. However, the performance will be affected by mutual coupling that is inversely proportional to the spacing distance between the array elements. The effects can be characterized by mutual impedance, S-parameters, gain, directivity, coupling matrix, or antenna-embedded element pattern performances [2, 3, 4].

Figure 1 shows the multi-beam cylindrical dielectric lens antenna that consists of array antennas as the feed radiators. For this configuration, when the element is placed close to each other, the scattered currents by the nearby element will affect the current antenna distribution; thus, the overall antenna performance will be degraded [5, 6]. From the previous work, a single bent array antenna was designed in convex and concave configurations to compare the bifurcated beam radiation when different configurations were adopted. This process investigated the antenna coupling when multiple array elements were arranged as the feed radiators of the cylindrical lens antenna system. The designed antenna's mutual coupling was also discussed based on its radiation pattern and near-field distribution [7]. Thus, in this research, the feed radiator is designed in a dual bent array structure where each bent array can produce a bifurcated beam radiation pattern. To verify the mutual coupling between them, the distance between each bent array, *s* is investigated.

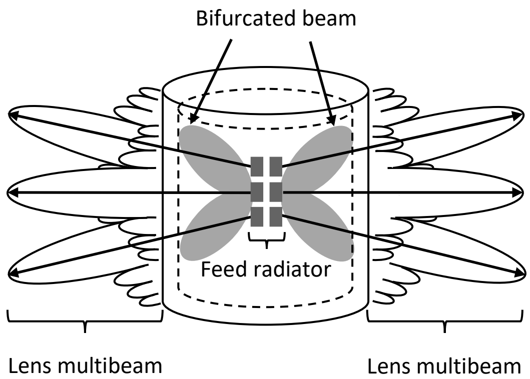


Figure 1 Multi beam cylindrical dielectric lens antenna

2.0 RESEARCH METHODOLOGY – BIFURCATED BEAM ARRAY

From the previous research, a bent array structure was designed to operate at 1.72 GHz to produce a bifurcated beam radiation pattern. The researcher also discussed the relations of array element numbers with the beam shape [8]. From [9], a bent array with a serial feed network was designed. The orientation of electric fields and amplitude of currents at each patch element were considered good because they produced uniform current distribution for the bifurcated beam pattern. The bent array configuration consists of four rectangular patches with serial feed networks [10], arranged in convex and concave structures. In order to produce a convex and concave bent array that can obtain an optimum radiation shifting angle, the structure has been extended by Δ*S*.

Then, in this paper, the dual bent array in convex and concave are arranged as shown in Figure 2. This process is to produce Bifurcated beam array, analyze the mutual coupling, and achieve the optimum bent array configuration. Each bent array structure for convex and concave consists of four patches, substrate, and ground. One of the patch elements is probe-fed by a coaxial cable. As shown in the figure, it is also shown that the bending and radiation shifting angles of this antenna structure are indicated by ϑ_w and ϑ_s, respectively. The ϑ_w and ϑ_s relation are expressed by equation (1):

$$\vartheta_w = 180 - 2\vartheta_s \text{ [deg]}, \quad (1)$$

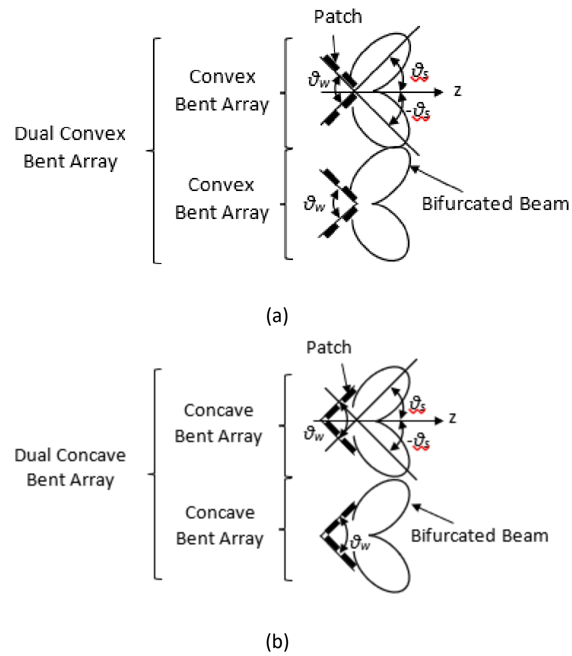


Figure 2 Dual bent array configuration (a) convex configuration (b) concave configuration

The simulation condition and properties of the substrate used for the designed antenna are shown in Tables 1 and 2, respectively.

Table 1 Simulation condition

Simulator	Frequency, *f*
Computer simulation technology (CST)	1.72 GHz

Table 2 Properties of Rogers Duroid (RT 5880)

Properties	Values
Thickness, *h*	1.57 mm
Dielectric constant, ε_r	2.2
Tan δ	0.0009

2.1 Dual Extended Convex Bent Array

Figure 3 shows the simulation of an extended convex bent array in the top, bottom, and side views. The top layer shows that each array structure consists of four patch elements, and the serial feedlines are designed between each element. The feeding technique used for this antenna is a coaxial probe structure where it is fed at one of the radiating patches. For the bottom view, a full ground plane is used, and it can be seen that the bent array angle of this designed antenna is 90 degrees, as shown in the side view. The two bent arrays are arranged as close as possible. The dimensions of an extended convex bent array antenna are shown in Table 3.

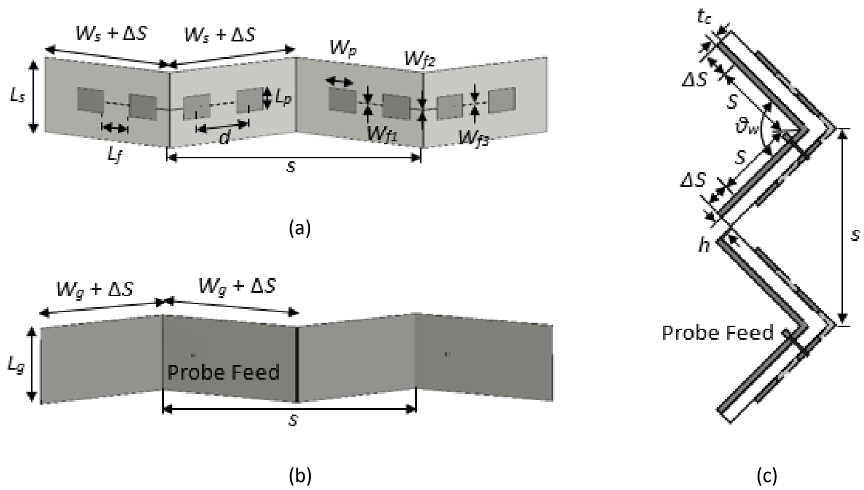


Figure 3 Dual extended convex bent array antenna simulation model (a) top view (b) bottom view (c) side view

Table 3 Dual extended convex bent array antenna dimension

Parameter	Dimension (mm)
W_s	231.565
L_s	117.43
W_p	57.75
L_p	35.00
d	$0.6677\lambda_o$
W_{f1}	1.00
W_{f2}	0.7871
W_{f3}	1.20
L_f	58.71
W_g	229.995
L_g	117.43
h	1.57
t_c	0.035
S	229.995
ϑ_w (degree)	90.00
ΔS	45.00
s	$x\lambda$

2.2 Dual Extended Concave Bent Array

Next, a concave bent array configuration is designed to compare the mutual coupling, as shown in Figure 4. This process is to verify whether this configuration can reduce the mutual coupling or not when the dual concave bent array is used as compared to the convex design. At the initial stage of designing the concave structure, all dimensions are similar to the convex structure. Then, however, the antenna is optimized to obtain an optimum result, as summarized in Table 4.

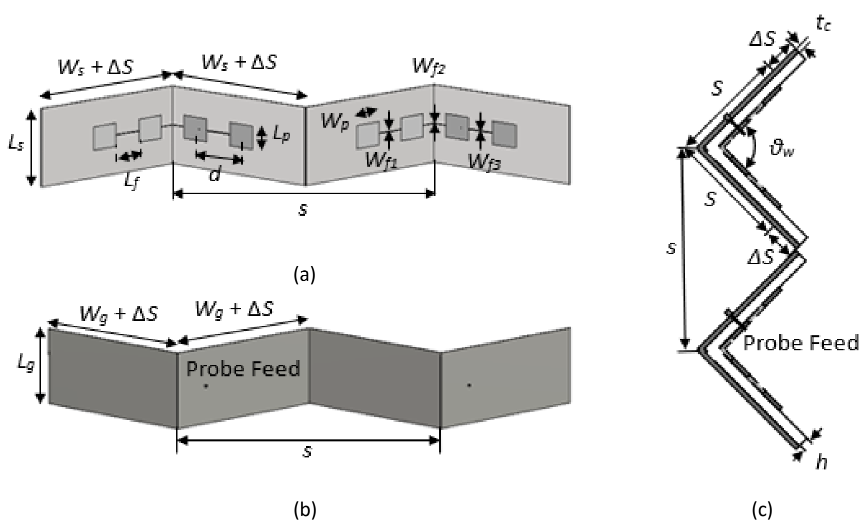


Figure 4 Dual extended concave bent array antenna simulation model (a) top view (b) bottom view (c) side view

Table 4 Dual extended concave bent array antenna dimension

Parameter	Dimension (mm)
W_s	336.92
L_s	117.43
W_p	57.75
L_p	35.00
d	$0.6677\lambda_o$
W_{f1}	1.00
W_{f2}	0.7871
W_{f3}	1.20
L_f	58.71
W_g	336.955

L_g	117.43
h	1.57
t_c	0.035
S	233.205
ϑ_w (degree)	90.00
ΔS	103.75
s	$x\lambda$

For both convex and concave structures, the distance, s values between the two bent arrays are also compared to obtain the optimum distance that can produce the best radiation shifting angle of ϑ_s with respect to the bending angle, ϑ_w.

3.0 RESULTS AND ANALYSIS

3.1 Dual Extended Convex Bent Array

The simulated E-plane radiation pattern for the dual convex bent array with four different s values for port 1 and port 2 are shown in Figure 5 and Figure 6, respectively. For this designed antenna, the optimization started at $s = 2.24\lambda$ until $s = 5\lambda$. The 2.24λ is chosen because this value is the closest spacing distance between the two bent array structures, which directly represents the smallest overall design structure for the proposed cylindrical lens antenna system. The figure also shows that all the designed antennas have a balanced bifurcated beam shape with a middle lobe between the beams. However, when $s = 2.24\lambda$ is used, the antenna produces a higher middle lobe. This situation happened due to the two bent array structures that are placed very closely, causing the interactions between electromagnetic fields, known as mutual coupling, where the nearby elements have modified the total radiation pattern. Therefore, it is important to reduce the mutual coupling between the two bent array structures [11, 12]. In this paper, the method used is by increasing the distance of the two bent array structures, which are $s = 3\lambda$, 4λ, and 5λ. The result shows good bifurcated beam radiation patterns with a small middle lobe are produced as expected based on the theoretical study of mutual coupling, where the mutual coupling will increase when the spacing distance, s is decreased. This situation happened due to the smaller aperture of the array that has caused the reduction of the realized beamforming gain, hence has increased the absorption loss and active reflection in the mutual coupling [13]. When the bending angle, ϑ_w of 90 degrees, is used, the expected ϑ_s value is 45 degrees, as given by equation (1). For these three designs, the antenna with $s = 4\lambda$ produces the closest ϑ_s to the expected ϑ_s, which are 42.5 degrees for both ports. Besides that, the results of the gain, bandwidth, and efficiency for the dual convex bent array for both ports are almost similar to the previous work of a single convex bent array [10]. The summary of antenna performances for this configuration is shown in Table 5. Other parameters such as gain, efficiency, bandwidth, and S_{11} seem very stable, with no significant differences observed between all configurations.

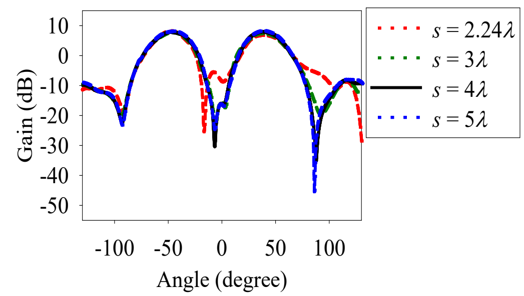


Figure 5 Comparison of simulated results of E-plane radiation pattern for dual extended convex bent array antenna with different s dimension in Cartesian view for port 1

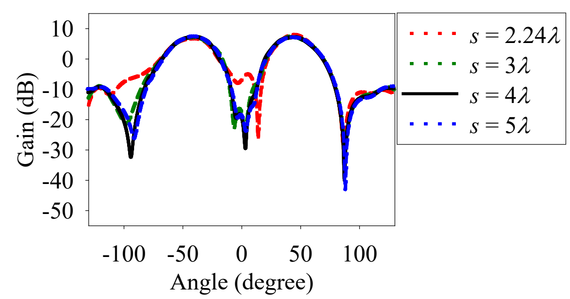


Figure 6 Comparison of simulated results of E-plane radiation pattern for dual extended convex bent array antenna with different s dimension in Cartesian view for port 2

Table 5 Performance summary of dual extended convex bent array structure with different s dimensions for port 1 and port 2

Properties	Port 1				Port 2			
	$s = 2.24\lambda$	$s = 3\lambda$	$s = 4\lambda$	$s = 5\lambda$	$s = 2.24\lambda$	$s = 3\lambda$	$s = 4\lambda$	$s = 5\lambda$
Resonant frequency, f (GHz)	1.72	1.72	1.72	1.72	1.72	1.72	1.72	1.72
Reflection Coefficient, S_{11}, S_{22} (dB)	-22.15	-21.87	-22.09	-21.96	-21.39	-22.14	-22.26	-22.22
Bandwidth, BW (MHz)	9.29	9.32	9.33	9.31	9.32	9.41	9.34	9.36
Gain, G (dB)	8.14	7.58	7.31	7.43	8.02	7.46	7.39	7.52
Directivity (dBi)	9.04	8.48	8.16	8.32	8.93	8.37	8.29	8.42
Efficiency, η (%)	81.42	81.38	81.43	81.34	81.19	81.21	81.26	81.22
ϑ_s (degree)	43.00	42.00	42.50	41.50	42.00	41.50	42.50	41.50

3.2 Dual Extended Concave Bent Array

Figure 7 and Figure 8 show the simulated results of the E-plane radiation pattern for dual extended concave bent array antenna with different s values for port 1 and port 2, respectively. The figures show that the simulated radiation pattern is compared with three different s parameter values, which are 2.73λ, 3λ, and 4λ. The bifurcated beam shapes for all antennas are almost similar. However, it is observed that the middle lobes between the beams are larger than the convex bent array. It is due to the mutual coupling originating from the arrangement of the two planes, specifically because the radiated waves generated face the same direction and produce higher mutual coupling. For the concave bent array antenna, the ϑ_w is 270 degrees, and the ϑ_s value that should be produced is 45 degrees. The *s* comparison shows that for $s = 3\lambda$, the ϑ_s are 45.5 degrees and 44.5 degrees for port 1 and port 2, respectively, which shows a good agreement with the expected shifting angle compared to other *s* values.

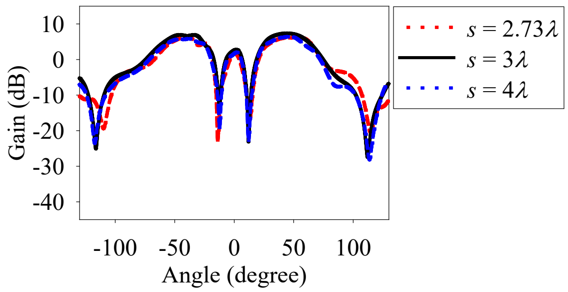


Figure 7 Comparison of simulated results of E-plane radiation pattern for dual extended concave bent array antenna with different *s* dimension in Cartesian view for port 1

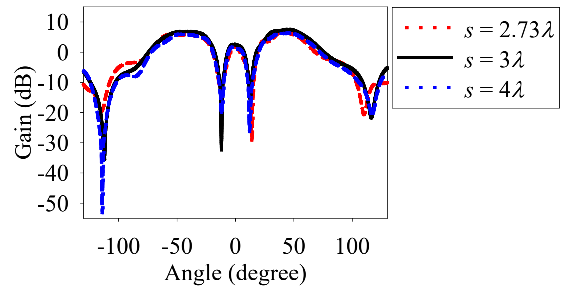


Figure 8 Comparison of simulated results of E-plane radiation pattern for dual extended concave bent array antenna with different *s* dimension in Cartesian view for port 2

Table 6 summarizes the simulated results of dual concave bent array antennas. Other parameters such as gain, efficiency, bandwidth, and S_{11} seem very stable, with no significant differences observed between all configurations.

Table 6 Performance summary of dual extended concave bent array structure with different *s* dimensions for port 1 and port 2

Properties	**Port 1**			**Port 2**		
	$s = 2.73\lambda$	**$s = 3\lambda$**	**$s = 4\lambda$**	**$s = 2.73\lambda$**	**$s = 3\lambda$**	**$s = 4\lambda$**
Resonant frequency, f (GHz)	1.72	1.72	1.72	1.72	1.72	1.72
Reflection Coefficient, S_{11}, S_{22} (dB)	-24.45	-35.18	-36.43	-25.33	-35.39	-36.73
Bandwidth, *BW* (MHz)	9.92	10.24	10.21	9.99	10.25	10.23
Gain, *G* (dB)	6.63	6.20	6.43	6.79	6.38	6.30
Directivity (dBi)	7.74	7.34	7.57	7.89	7.50	7.43
Efficiency, η (%)	77.39	77.02	76.86	77.48	77.13	77.00
ϑ_s (degree)	47.00	45.50	42.50	47.00	44.50	47.00

4.0 CONCLUSION

This paper compares the performance of the dual bent array antenna between convex and concave structures. The antennas are also designed and studied with different spacing distances between array structures, *s* to obtain better performance with the lowest mutual coupling. After achieving the optimum result, the ϑ_s of each antenna are compared with respect to the ϑ_w. This study shows that the dual convex bent array antenna can produce a better-bifurcated beam pattern and the middle lobe of the beam shape is also smaller than the dual concave bent array structure. Based on the comparison of many *s* parameters for a dual convex bent array, the $s = 4\lambda$ is chosen because it produces an optimum and good value of ϑ_s for both ports. It is because the dual convex bent array structure with $s = 4\lambda$ produces the closest ϑ_s value for both ports to the expected ϑ_s (theoretical). Furthermore, the results of this antenna design's gain, bandwidth, and efficiency are almost similar to the single convex bent array in the previous study.

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References

[1] Saada, M. H. A. 2017. Design of Efficient Millimeter Wave Planar Antenna for 5G Communication Systems. Thesis (Master's), Research and Postgraduate Affairs, Faculty of Engineering, The Islamic University of Gaza.

[2] Vo, T. T., Ouvry, L., Sibille, A. and Bories, S. 2018. Mutual Coupling Modelling and Calibration in Antenna Arrays for AOA Estimation. *2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC).*1-4. DOI: http://doi.org/10.23919/URSI-AT-RASC.2018.8471273

[3] Lakshmi, C. R. 2013. A Review on Mutual Coupling in Antenna Arrays and Decoupling Methods in MRI Antenna Arrays. *IOSR Journal of Engineering (IOSRJEN).* 3(12): 46-49. DOI: http://doi.org/10.9790/3021-031234649

[4] Lai, Q. X., Pan, Y. M., Zheng, S. Y. and Yang, W. J. 2021. Mutual Coupling Reduction in MIMO Microstrip Patch Array Using TM10 and TM02 Modes. *IEEE Transactions on Antennas and Propagation.* 69(11): 7562-7571. DOI: http://doi.org/10.1109/TAP.2021.3090520

[5] Ren, R. J., Peng, Z. and Becerra, D. R. 2012. Mutual Coupling Effect of Microstrip Antenna Array. *Procedia Engineering*. 29: 1984-1988. DOI: https://doi.org/10.1016/j.proeng.2012.01.248

[6] Tescor, I. 2013. Mutual Coupling Effects and Optimum Architecture of a Sparse Antenna Array. Thesis (Master's), Radio Communication Systems Group, KTH, Stockholm, Sweden.

[7] Chen, Y. S., Chen, S. Y. and Li, H. J. 2010. Analysis of Antenna Coupling in Near-Field Communication Systems. *IEEE Transactions on Antennas and Propagation*. 58(10): 3327-3335. DOI: http://doi.org/10.1109/TAP.2010.2055782

[8] Tengah, Z., Ali, M. T., Abd. Rahman, N. H., Ibrahim, I. P., Abd. Rashid, N. E. and Yamada, Y. 2016. Achievement of a Bifurcated Beam by a Bend-Array Configuration. *2016 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC)*. 126-129. DOI: http://doi.org/10.1109/APWC.2016.7738137

[9] Tengah, Z., Ali, M. T., Abd. Rahman, N. H., Pasya, I., Abd. Hamid, S., Baba, N. H. and Yamada, Y. 2016. Design of Serial Feeds for a Bifurcated Beam of Bend-Array Configuration. *2016 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE).* 43-46. DOI: http://doi.org/10.1109/APACE.2016.7916471

[10] Tengah, Z., Ali, M. T., Abd. Rahman, N. H., Pasya, I., Abd. Hamid, S., Subahir, S. and Yamada, Y. 2018. Design of Serial-Fed Bend-Array and Measured Result. *Journal of Telecommunication, Electronic and Computer Engineering*. 10(1-6): 29-33. https://jtec.utem.edu.my/jtec/article/view/3663/2547

[11] Akbari, M., Ghalyon, H. A., Farahani, M., Sebak, A. R. and Denidni, T. A. 2017. Spatially Decoupling of CP Antennas Based on FSS for 30-GHz MIMO Systems. *IEEE Access*. 5: 6527-6537. DOI: http://doi.org/10.1109/ACCESS.2017.2693342

[12] Ayari, M., Touati, Y. E. and Altowaijri, S. 2019. Mutual Coupling between Antennas in a Periodic Network using the Advanced Transverse Wave Approach for Wireless Applications. *International Journal of Advanced and Applied Sciences*. 6(1): 99-105. DOI: https://doi.org/10.21833/ijaas.2019.01.014

[13] Chen, X., Abdullah, M., Li, Q., Li, J., Zhang, A. and Svensson, T. 2019. Characterizations of Mutual Coupling Effects on Switch-Based Phased Array Antennas for 5G Millimeter-Wave Mobile Communications. *IEEE Access*. 7: 31376-31384. DOI: http://doi.org/10.1109/ACCESS.2019.2902951