A Wideband Beam forming Antenna Array for 802.11ac and 4.9 GHz

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Abstract — **In this work, a wideband high gain 1x4 beamforming (BF) antenna array has been proposed for 5.17 - 5.85 GHz ISM band and extended coverage for 4.92 – 4.98 GHz licensed band. The key antenna performances of 13.6 dBi realized gain, 24.4° Beamwidth, 12.9 dB Sidelobe at 0° beam and ±40° beam steering capability has been achieved. The proposed antenna intended to provide the enhanced wireless link between the ground base station and the mobile terminals with beamforming concept that allow beam steering to focus on targeted direction and null the interference direction with small beam width. The proposed antenna can be further re-configured with different gain and steering beam to cater the dynamic transportation environments.**

Index Terms—Smart antennas, Antenna Array Design, Beamforming, Broadband Communication

I. Introduction

The advancement of broadband wireless technologies such as LTE, 5G, and 802.11ac multiple input multiple output (MIMO) technology makes the applications such as direct video streaming on the move and transmitting of high throughput data between mobile terminals and base station become possible. This has drawn tremendous interest in the industrial setting to provide efficient and reliable wireless infrastructure to cater for the increase in market demand and to catch up with the higher expectation in user experience perspective. This has led to serious airspace congestion, especially in the license-free spectrum such as 2.4 GHz and 5 GHz Industrial, Medical and Scientific (ISM) and 4.9 GHz licensed band. In the mobile environment, the antenna beam for the mobile terminals and base stations are not always fixed. In the traditional access point deployment [1], both access point and mobile client are deployed with the omnidirectional antenna to provide a total of 360° coverage. The potential issues with the traditional deployment are:

i. More access points are needed due to small cell radius.
ii. Mutual interference between adjacent cells.
iii. High deployment cost to lay cables, poles, power etc.
iv. High maintenance cost due to more equipment.

It's essential to have a smart infrastructure that can adapt itself to the highly congested environment. The smart antenna comes in as a right candidate aimed to harmonize the congested wireless environment. Smart Antenna comes with beamforming capability that steers the beam towards the targeted client and nulls of the interference, adaptive beamforming can be implemented and further enhanced by iterating the beamformer weight on-the-fly, the weight of the phase and amplitude can be altered on-the-fly according to the environment.

Over the year, there were quite a numbers of beamforming antenna arrays proposed in the literature, the beam steering capability and performance were well demonstrated, however, the focus is centered around the 5G and Satellite Communication area, for instant, 5G [2][3][8][11], X-band [10], 2.4 GHz ISM band [12], 2.35 GHz to 2.8 GHz/5 GHz to 5.5 GHz [13]. In the area of 802.11ac standards, there were many good pieces of literature works in the past mainly focused on enhancing the 802.11ac WiFi antenna such as deploying multiple polarizations in [14], a Complementary Split Ring Resonators (CSRR) technique was proposed to reduce antenna size in [15], an eight radiating elements with a gap coupled inset-feed technique [16] to reduce cross polarizations for 11ac application. In [17], a 5.1-5.9 GHz analog beam switching antenna array was proposed, the beam switching was achieved by rotationally switching the pin diodes to enable one of the six parasitic elements to create the desired beam.

A beamforming array consists of multiple Microstrip Patch Antenna (MPA) elements arranged in a horizontal and vertical manner. MPA [4] element is a very common antenna structure used in mobile and automotive devices, this was mainly due to its low cost, flexible structure, and simplicity in design and manufacture. Conventional MPA usually comes with lower gain and narrow operating bandwidth (BW) around 4% BW ratio. Many works have been carried out on MPA including the techniques to enhance the limitation of the MPA such as Gain, operating BW etc. A wideband stacked patch antenna [5] proposed consists of two rectangular patches achieving 14% BW ratio. Ruchika Gupta [6] is introducing high impedance Electromagnetic BandGap (EBG) layer to enhance the BW ratio to 18.68%. An open slot was introduced on the radiating patch [7] to enhance the BW ratio to 22%.

All those works in the 802.11ac area have a common aim to improve the physical antenna performance, however, it does not address the wide frequency operating band in 11ac standards which fall within 5.17 - 5.85 GHz ISM and 4.9 GHz licensed band.

In this work, we will focus on a wideband (4.9 – 5.9 GHz) high gain (13.6 dBi for 1x4 array) digital phase antenna array which allows fine resolution digital beam steering over ±45°, small beam-width (24°) for interference rejection. The proposed flexible structure allows easy beam and gain configuration to serve as a foundation for future re-configurable wideband beamforming antenna array target to further improve the performance and shall bring the user experience in the transportation market to the next level.

This paper is organized as follows. In section II, we presented the design and simulation result for the proposed antenna element, follow by section III the systematic approach to integrate the single element into the beamforming array and the performance was justified by simulation result. Section IV concludes the paper.

II. Design and Simulation of Antenna Element

A. Designing of Single Element MPA

The dual substrate capacitive coupling feed method [9] is adopted in this design due to its wideband and high gain characteristic, the radiator is represented by the larger patch and the energy is feed via a small capacitive patch via capacitive coupling, the capacitive feed method can reduce the mismatch between the radiating patch and the co-axial feed and the dual dielectric substrate layers will enhance the gain and BW of the MPA. The antenna is designed to resonance at 5.5 GHz on a substrate RO3003 with ε_r=3, the dimension of the patch *L* and *W* were calculated using the formula available in the textbook [4], and the capacitive feed length (*t*), width (*s*), distance to patch (*d*), and space of airgap (*g*) can be optimized to achieve the optimum frequency bandwidth. In this work, we reproduce the state of art design from [9] and further optimize the parameters and the performance was simulated using CST simulation tools, wide operating bandwidth and high gain were observed.

Fig. 1. show the geometrical model for the capacitive feed MPA. The antenna parameter was optimized and simulated using CST.

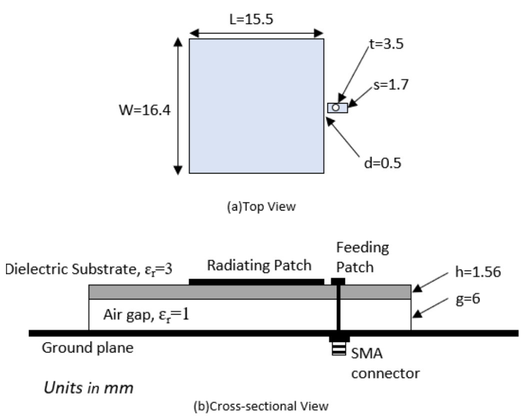
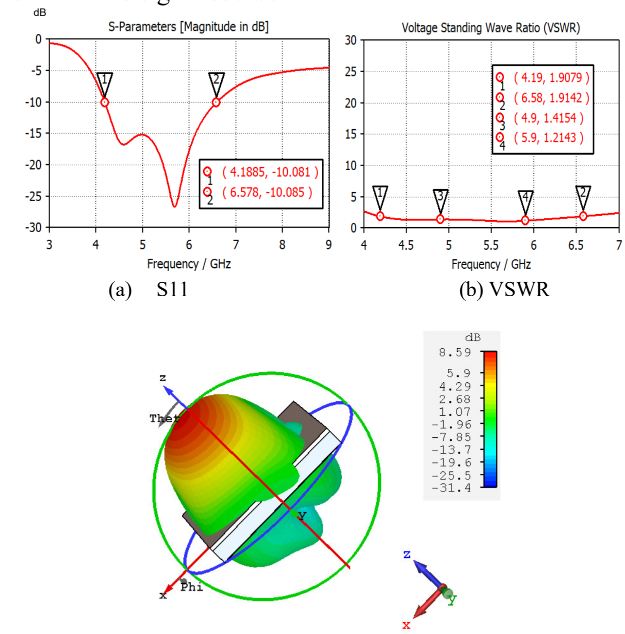


Fig. 1. Capacitive Feed dual-substrate MPA

B. Simulation of the single patch antenna

The CST simulated results are shown in Fig. 2. The dual substrates capacitive feed patch MPA structure has a superior gain of 8.59 dBi and BW ratio of 44.38% (4.19 – 6.58 GHz), the VSWR is less than 2 was observed across the operating frequency range denotes the impedance of the antenna match well with the signal source.



(a) S11 (b) VSWR

(c) Farfield Radiation Pattern

Fig. 2. CST simulation result for Capacitive Feed dual-substrate MPA

The size of the ground plane was evaluated, we notice that the size of the ground plane can be reduced from 150 (Lg) x150 (Wg) mm to 60 x 60 mm, refer to Fig. 3. further reduction of ground plane will degrade the return loss, S11 of the antenna.

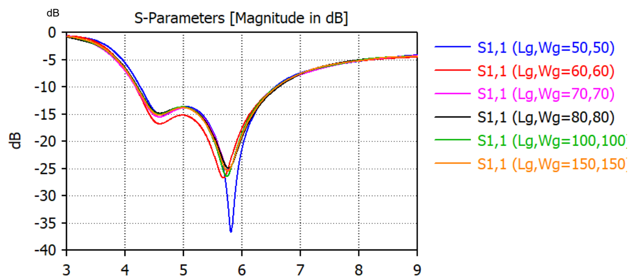


Fig. 3. Effect of Ground Plane

A table of performance compared with the state-of-the-art enhanced MPAs are presented in TABLE I. The proposed antenna has demonstrated more than 44% BW ratio and with superior gain performance and it is the right element for integration into beamforming array for wideband and high gain in the 4.9 - 5.9 GHz band. In the next section, we will integrate the multiple number elements into an array with multiple feeding ports to form a beam steerable antenna.

TABLE I. PERFORMANCE COMPARISON FOR SINGLE ELEMENT MPA

Parameter	[5]	[6]	[7]	Proposed
BW Enhance-ment Technique	Stacked patch	Replace ground plan with EBG	Slot on patch	Dual Substrate Capacitive Feed
Bandwidth (BW)	2.88 - 3.28 GHz	8.7 - 10.5 GHz	8.1 - 10.07 GHz	4.19 - 6.58 GHz
BW Ratio	14%	18.68%	22%	44.38%
Gain	--	--	4.25 dBi	8.59 dBi

III. DESIGN AND SIMULATION OF BEAMFORMING ANTENNA ARRAY

A. Designing a Beamforming Array

The antenna array consists of multiple antenna elements arranged in the horizontal and vertical dimension shown in Fig. 4, elements spacing was evaluated for optimum performance for gain, side lobe, and steering angle.

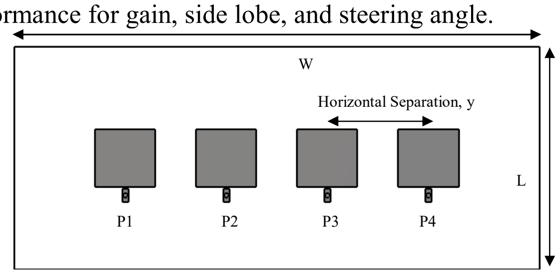


Fig. 4. Illustration of the 1x4 antenna array

The antenna element spacing was first simulated using CST “far field array” function, the simulation results are illustrated in Fig. 5, we notice that with the increases of element separation, the antenna gain increases and the beamwidth decreases, when the element separation increased further to 1λ spacing, the side lobe or grating lobe appeared, two end-fire maximum were created, from this result, we conclude that the antenna separation should keep below 35 mm. The optimum 27.25 mm (slightly below ½ λ) horizontal element separation was chosen for optimum gain, beamwidth, and sidelobe performance. The simulated values are, gain = 13.6 dBi, beamwidth = 24°, Sidelobe @ 0° = 13.1 dB and sidelobe a @ 30° = -9.3 dB.

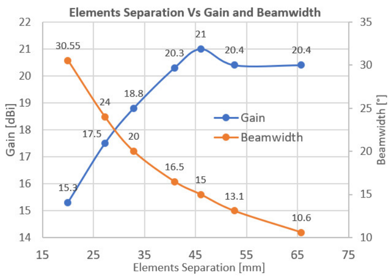


Fig. 5. Gain and Beamwidth performance Vs elements separation.

The proposed antenna is constructed by the dual substrate, the RO3003 material with ε_r=3 and air gap with ε_r=1, the radiating element is separated from the ground by the dielectric substrate and air gap with $g+h$ clearance. The feeding network is introduced at the bottom of the ground plane using substrate RO3003 with ε_r=3 with thickness=h, the mutual coupling can be eliminated by separating the radiating element and feeding network with a ground plane. The cross-sectional view of the proposed antenna construction is shown in Fig. 6.

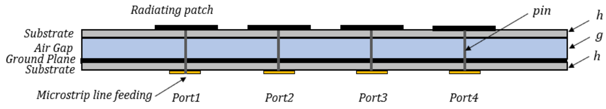


Fig. 6. Construction of antenna array with the microstrip feed

The design parameters are tabulated in TABLE II. The horizontal separation between the element is 27.25 mm. The antenna arrays were then simulated using CST simulation tools, the simulation results are presented in the next section.

TABLE II. DESIGN PARAMETERS FOR THE 1X4 ANTENNA ARRAY

Parameter	Descriptions	Value
h	The thickness of the substrate	1.56 mm
g	The thickness of the air-substrate	6 mm
y	Horizontal element separation	27.25 mm
L	Length of the antenna array	60 mm
W	Width of the antenna array	141.75 mm
ε_r	Relative permittivity	3

B. Simulation Result of the Beamforming Array

To simulate the beam steering capability of the antenna array in CST, we asserted a different phase shift for the signal traveling into P1 to P4. The phase shift for each parts P1/P2/P3/P4 are as follow, 0°/45°/90°/135° for -13° beam, 0°/0°/0°/0° for 0° beam, 135°/90°/45°/0° for +13° beam, 45°/180°/-45°/90° for -40° beam and 90°/-45°/180°/45° for +40° beam.

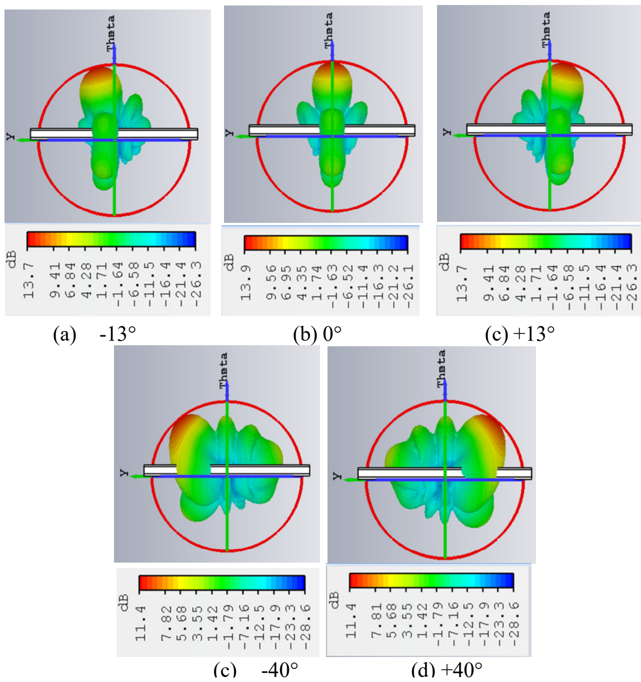


Fig. 7. CST simulated result for a 1x4 array for beam steering capability.

The simulated results are presented in Fig. 7. Peak gain of 13.6 dBi at 0°, steering capability of ±40° with approximate 2.5 dB gain variation and 24.4° to 30.3° beamwidth variation over steering angle was achieved.

The 1 x 4 antenna array was fabricated, and experimentally evaluated, the measured results are presented in Fig. 8. The measured gain is 11.16 dBi and returned loss of less than -10 dB for the frequency band from 4.9 to 5.9 GHz. There was a noticeable shift in the 1st resonance frequency at around 4.5 GHz, this may be due to the manufacturing tolerance of the PCB stack up and the SMA connectors.

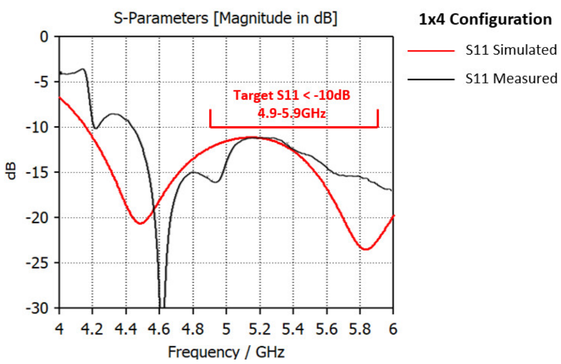


Fig. 8. S11 Measured Result

A comparison with the state-of-the-art antenna array is presented in TABLE III. The proposed antenna demonstrated a superior gain of 13.6 dBi and BW ratio of 50.61% compared to the rectangular MPA and Rectangular capacitive inset-feed MPA. The steering capability of the proposed antenna is ±40° with peak gain, it can be extended to ±45° for operation between 3 dB beamwidth, in [8] the result shows that the antenna can steer beyond 50°, however the result also indicated the multiple maxima occurs at ±50° beam direction and the usable beam direction is unknown.

TABLE III. PERFORMANCE COMPARISON OF BF ANTENNA ARRAY

Parameter	[8]	[16]	Proposed
Antenna Type	Rectangular MPA	Rectangular Capacitive inset-feed	Dual Substrate Capacitive Feed
Array	1x4	2x4	1x4
BW	37.4 - 39 GHz	4.985 - 5.15 GHz	4.19 – 6.58 GHz
BW Ratio	4.1%	3.2%	44.38%
Gain	12 dBi	10.8 dBi	13.6 dBi
Beamwidth	25°	--	24.4°
Beam Steering	±50°	potential	±40°

The proposed 1x4 antenna array with its flexible re-configurable structure is a good candidate for future integration into re-configurable beamforming antenna array for 4.9 - 5.9 GHz application.

IV. CONCLUSION AND FUTURE WORKS

The 1x4 beamforming antenna array was created by integrating multiple single elements (dual substrate capacitive feed technique) into a bigger array with 4 feeding ports. The 1x4 antenna array was simulated using CST software with the realized gain = 13.6 dBi, beamwidth = 24°, Sidelobe @ 0° = -12.9 dB and sidelobe @ ± 40° = -7.3 dB and capable of performing ±40° beam steering. The operating frequency achieved from 4.19 – 6.58 GHz which is suitable for 802.11ac application in 5.17 - 5.85 GHz ISM and 4.9 GHz licensed band. The antennas will be fabricated using standard PCB manufacturing process and will be experimentally evaluated. In future, the 1x4 array can be re-configured to 2x4 and 4x4 high gain array and steering beam of 90°/180°/270°/360° to cater for different needs in the transportation market.

The future work involves experimental measurement of the 1x4 antenna array, re-configure the antenna into 2x4 and 4x4 array with dynamic gain and steering capability, followed by designing of the phase shifter, the power amplifier (PA) and low noise amplifier (LNA) to complete and front-end prototype which will then be miniaturized and productize for use in the future transportation market.

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