Planar Yagi-Uda ESPAR Array for mm-Wave Communications

Ectis Velazquez, Jr., Murat Yuksel, and Xun Gong
Department of Electrical and Computer Engineering, University of Central Florida, Orlando, FL 32816 USA

***Abstract*—A planar Yagi-Uda electronically steerable parasitic array radiator (ESPAR) antenna array is proposed for mm-Wave communications. The array is comprised of three Yagi-Uda antennas, each with a dipole element and a shared ground plane reflector. The design operates with a 30 GHz center frequency and a 20% usable fractional bandwidth. By terminating the parasitic element feeding lines with adjustable reactive loads, the array is capable of beam steering to establish 90° coverage in simulation with 7dBi gain.**

***Index Terms*—antenna, beamforming, beam steering, ESPAR, mmWave, phased array, Yagi-Uda**

1. Introduction

More and more the wireless community is focusing on harnessing bandwidth for attaining gigabit-per-second transfer rates. To do this, the wireless community is looking to the millimeter wave (mm-Wave) frequency bands, particularly 30-100 GHz, for a solution. There continues to be an increasing demand for low-cost, beam-steerable antennas. Traditional beam steering solutions, particularly at the mm-wave frequency, can be both prohibitively expensive, and for most designs, unreasonably lossy. A commercial phase shifter such as the TGP2100 has an insertion loss of 7dB. Research into low-cost beam steering at mm-wave frequency has explored many solutions, but one relatively unexplored solution at this frequency is the use of electrically steerable parasitic array radiator (ESPAR) antennas. ESPAR has a long history as an alternative beam steering method that seeks to reduce the cost and complexity of wireless communication systems. In traditional beam steering each antenna element in an array is connected to a phase shifter and RF source, but in the ESPAR array, only one center element is fed with a signal, with the other two parasitic elements relying on the mutual coupling from the center element to induce current in them. By terminating the parasitic elements with tunable reactive loads, the resultant radiation pattern can be steered. ESPAR works primarily use dipole or monopole antenna elements such as in [1] mainly concentrated around the 2.4 GHz range, with some using other topologies such as slot antennas [2]. However, there are several advantages to using Yagi-Uda antenna elements, beginning with their high directivity. The end-fire nature of a Yagi-Uda array is also advantageous in that it creates the possibility of using a single board/panel to cover 360° in the azimuthal plane, thus reducing size and complexity of the communication system. In this paper, we present one unit cell which can cover one quadrant using ESPAR beam steering, which when combined with 3 other cells, can cover the entire azimuthal plane.

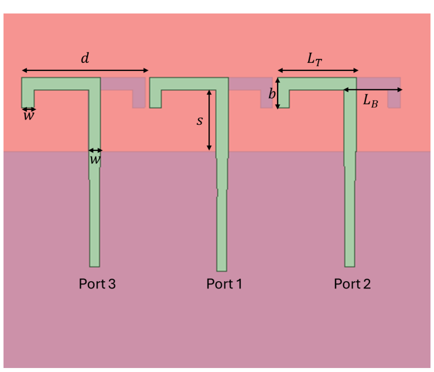

Fig. 1: ESPAR array with microstrip feeding. Substrate is made transparent to show the bottom arms of each element. $L_T = 4.08$ mm, $w = 0.32$ mm, $s = 2.16$ mm, $L_B =$, $d = 3.4$ mm, $b = 0.8$ mm.

2. ESPAR Array Design

A. Antenna Design

Planar Yagi-Uda antennas have been demonstrated in numerous previous works, such as in [3], where a microstrip-fed Yagi-Uda antenna design was presented where one arm of the driven element was located on the bottom surface of the dielectric substrate, and the other arm on the top surface. With one director element, one driven element, and one ground plane reflector, this design methodology presented a planar Yagi-Uda antenna that can be made on a printed circuit board (PCB) and operates at 11 GHz. The planar Yagi-Uda can be extended to the mm-wave frequency, as demonstrated in [4], achieving a gain of 10.9 dBi at 24 GHz using 5 director elements and a half-power beamwidth (HPBW) of 44°. Another Yagi-Uda antenna in [5] was presented for software-defined radio (SDR) applications at 30GHz with 5dBi

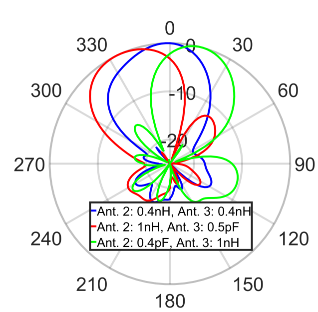

Fig. 2: Normalized radiation patterns for reactive load configurations covering 90°.

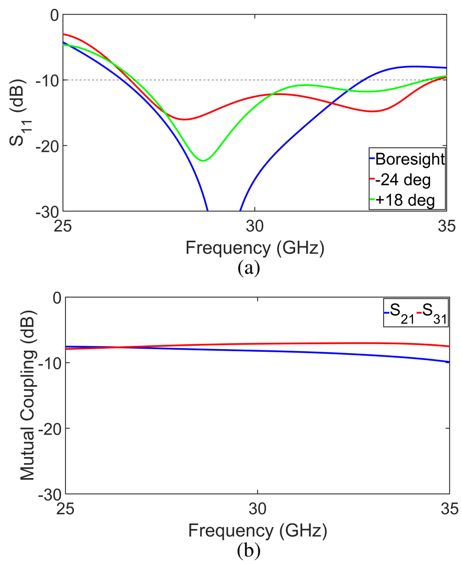

Fig. 3: (a) S_{11} of each configuration (b) Mutual coupling between antenna elements.

gain and 90° HPBW using only a driven element and ground plane reflector.

In this work, the antenna in [5] is modified for use in an ESPAR. For a half-wavelength dipole, the two ends of the antenna are where the current is at minimum. Since ESPAR relies on the mutual coupling of antenna elements, the dipoles have been modified with 90° bends at the ends of the dipole to enhance the mutual coupling by inducing magnetic field coupling. In a complete system, all 360° in the azimuthal plane should be covered. To achieve this, four ESPAR arrays must be used where each will cover 90° using beam steering. With all this in consideration, the antenna element is designed as shown in Fig. 1.

B. ESPAR Design

The ESPAR Yagi-Uda phased array is comprised of a driven element and two parasitic Yagi-Uda antennas. The geometry of the array is shown in Fig. 1, where port 2 and port 3 are loaded with reactive elements. Antenna 1 (driven) is fed by an RF source and the parasitic Antenna 2 and 3 are excited by Antenna 1 through mutual coupling. The shorter spacing between the driven antenna and parasitic radiators is primarily responsible for determining the mutual coupling. To maximize coupling without hurting the array factor (AF), a spacing of $0.35\lambda_0$ is chosen. As discussed previously, the ends of the dipoles are bent to further enhance mutual coupling. The phase shifts between the antenna elements are tuned by changing the reactance of the lumped element loads. This causes the radiation pattern of the array to steer in the desired direction. To determine the relationship between reactive load and direction, the antennas can be analyzed as a three port network. Using network analysis the voltage and current can be related by the Z matrix, and by solving for current ratios in terms of the current at port 1, I_1, the AF can be determined as shown in (1). When multiplied with the element factor (EF)

TABLE I: Summary of Load Inductance/Capacitance, Simulated Realized Gain and Efficiency η at 30 GHz

Scan Angle (deg)	Port 2 Load	Port 3 Load	Gain (dBi)	η (%)
-24	1 nH	0.5 pF	7.3	92.5
-20	0.5 nH	0.5 pF	7.4	93.5
-2	0.4 nH	0.4 nH	7.4	94.8
10	0.5 pF	0.5 nH	7.3	94.3
18	0.4 pF	1.0 nH	7.4	94.3

this gives the resultant radiation pattern. The most common way to realize a tunable reactive load is using a varactor. However, as shown in [2], it is beneficial to use the inductive region of the Smith chart by adding a fixed inductor and delay line to give greater beam steering range and fractional bandwidth (FBW).

$$AF = 1 + \frac{I_2}{I_1} e^{-jkdcos(\theta)} + \frac{I_3}{I_1} e^{jkdcos(\theta)} \tag{1}$$

3. Simulation Results

The array is simulated using ANSYS High Frequency Structure Simulator (HFSS). The reactive loads are simulated by using lumped element boundaries at the termination of the ports of Antenna 1 and 2. Fig. 2 shows the radiation pattern of each configuration. From Fig. 3(a), the FBW can be calculated as 20% while beam steering. Fig. 3(b) shows the mutual coupling between antenna elements is sufficiently high. The array has a gain of 7dBi with >88% radiation efficiency across the bandwidth and 42° beam steering range at 30GHz when tuning the reactive loads. However, when HPBW is considered, the radiaton achieves 90° coverage. Table I summarizes the equivalent reactive loads used, simulated gain, and simulated efficiency at 30 GHz. In combination with three identical arrays, 360° coverage can be achieved on a single board.

4. Acknowledgement

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