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4 – Element Spatial Power Combiner for High Frequency Communication Systems

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Abstract- A solution to the insertion loss in the Distributed Amplifier configuration is presented. Wilkinson power splitter is employed at the input and wave interference characteristic is considered as the means of combining the transmitted power from active antennas. The overall result of using the power splitter and spatial combination of the signals is found to enhance the strength of the transmitted power by a factor of 16. More gain could be achieved by adding more power splitters and the corresponding active antennas.

Index Terms- Wilkinson Power Divider/Combiner, Distributed Amplifier, Cascode Amplifier, Antenna Array.

I. INTRODUCTION

The rapid development of wireless communication system increased the demand for circuits with very high gain and wide bandwidth for efficient data rate transfer (Kushwaha and Srivastava, 2013).As the data rate in communication system increases such as backhaul unit, corresponding increase in the output power of the signals radiated by a tower-mounted antenna is typically required by a given service area. Thus, migrating an existing system to a higher data rate often requires more output power from the amplifier used in the system and or a reduction of losses associated with components in the system (Yerraw, 2012).

Amplifying devices have inherent limitation of gain-bandwidth products which forced one to compromise the gain at the expense of the bandwidth or vice versa (Philip *et al,* 2000). Philip *et al*, (2000) and Wolf *et al*, (2005) proposed and used Distributed amplifier configuration as one of the solution to the gain bandwidth bottleneck. The distributed amplifier divides the power from a single input to several amplifiers through the use of transmission line. It is evident that, as additional amplifiers are combined, the transmission line length and circuit complexity increase (Harvey *et al*, 2000). Furthermore, as the length increase to add more devices, insertion losses in the transmission lines grow to the extent of eventually exceeding the gain from the amplifiers (Harvey *et al.,* 2000).In addition, large current signal is normally realized towards the output of the last stage in the output transmission line. This large current also heat up the circuit board (Ali and Dambatta, 2000). This work proposes the addition of the signal to be carried out in space instead of in the circuitry and thus avoid the problem of heating the circuit and the corresponding signal losses.

II. METHODOLOGY

The method used is in three stages. Firstly, the power to be amplified will be split into 4 smaller equal parts using Wilkinson power splitters. In the second stage, four high gain broadband amplifiers were used to amplify the split power and finally, the amplified signals are transmitted into space through four equally spaced antennas. At any receiving point, there would be four signals combining to form the final received signal from each of the four antennas.

1.1 Design of the Corporate Feed

The use of three – port power dividers is especially important for antenna array that utilize a power splitting network. The corporate feed is simply a device that splits power between n-outputs with a certain distribution while maintaining equal path length from input to output ports. The array feeding network is a corporate feed type utilizing equal split of the convectional Wilkinson power divider in resistive form with a unique topology (Daniel and Harley, 2010).

Wilkinson describes a device that separated one signal into equal signals of equal phase and amplitude. The in-phase power combiners and dividers are important components of RF and microwave transmitter where it is necessary to deliver a high level of the output power to antenna, especially in array (Abdul-Raheem, 2010). The diagram below shows a Wilkinson splitter.

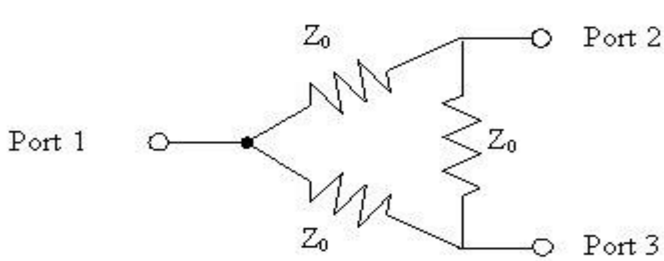

Fig. 1: Wilkinson splitter

Where Z_o are the resistive value in this case.

1.2 **Design of Amplifier**

1.3

A very wide band amplifier stage with appreciable gain is used. It is called a Cascode amplifier (Sedra and Smith, 2004) and (Dogman and Jenkin, 2010). Its design is presented below.

In the design, the same transistors were used in the common emitter and common base stage, hence $\beta_{F1} = \beta_{F2} = \beta_F >> 1$, that is the base current of the transistors is negligible, and base current can be ignored in comparison to the currents through the biasing resistances. Fig. 2 below shows the schematic diagram of a Cascode amplifier. The DC biasing base voltages are given by

$$V_{BB1} = \frac{R_1}{R_1 + R_2 + R_3} V_{CC} \qquad (1)$$

$$V_{BB2} = \frac{R_1 + R_2}{R_1 + R_2 + R_3} V_{CC} \qquad (2)$$

The Collector and emitter currents are given by,

$$I_{E1} \cong I_{C1} = I_{E2} \cong I_{C2} = \frac{V_{BB1} - V_{BE}}{R_E} \qquad (3)$$

The collector emitter voltages are given by

$$V_{CE1} = V_{BB2} - V_{BE2} - (V_{BB1} - V_{BE1}) \qquad (4)$$

$$V_{CE2} = V_{BB2} - R_C I_{C2} - (V_{BB2} - V_{BE2}) \qquad (5)$$

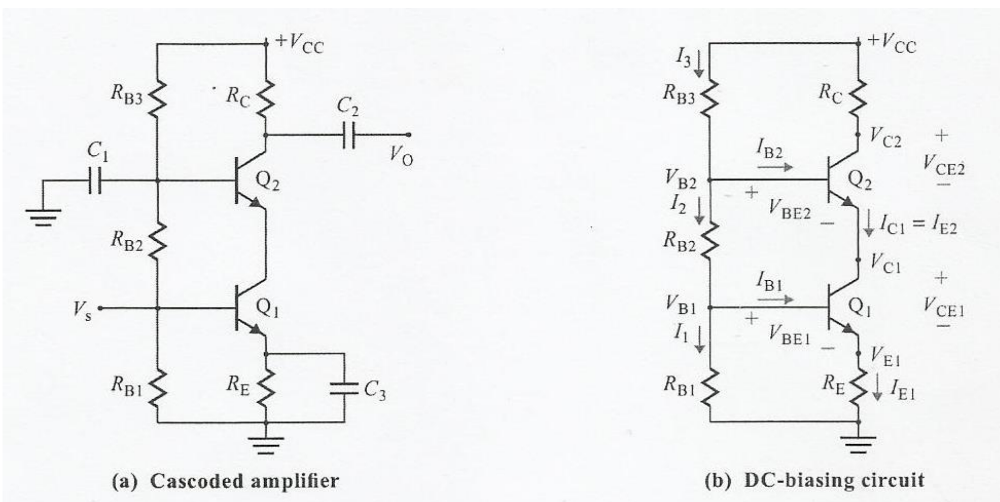

Figure 2: Cascode amplifier (Rashid, 2011).

1.4 **High Frequency Hybrid-π Model of Cascode Amplifier**

The analysis result was obtained by replacing the transistors in the circuits above with the high frequency Hybrid-π Model of the Cascode amplifier. Fig. 3 shows the high frequency Cascode amplifier neglecting r_x and r_o, We have the small signal equivalent circuit of the configurations as shown in Fig. 4.

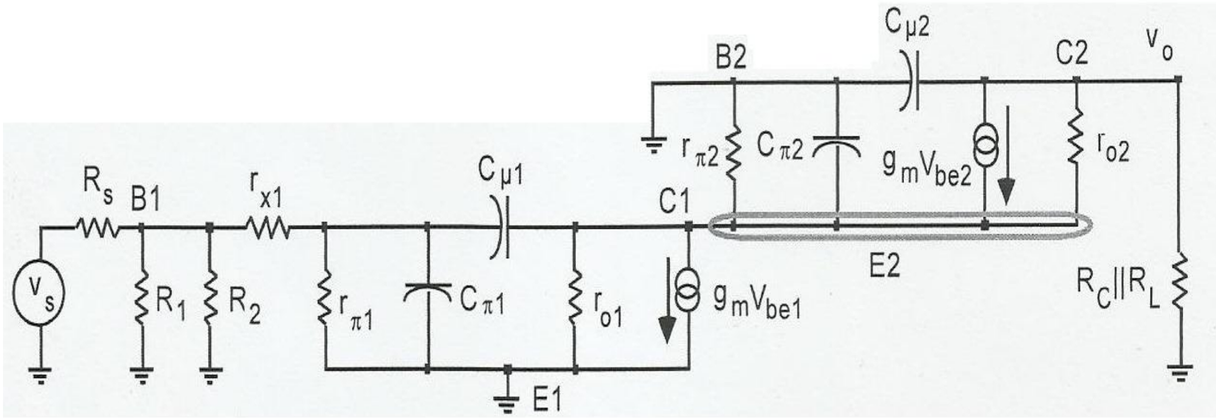

Fig. 3: High frequency equivalent circuit of Cascode amplifier (Sedra and Smith, 2004)

where;

$r_{X1} =$ Ohmic base spreading resistance, g_m = Transistor transconductance

$r_{\pi 1} = r_{\pi 2} =$ Base emitter impedance resistance, $C_{\pi 1} = C_{\pi 2} =$ Dynamic emitter capacitance

$r_{O1} = r_{O2} =$ Output resistance, $C_{\mu 1} = C_{\mu 2} =$ Collector junction barrier capacitance

$V_{be1} = V_{be2} =$ Base emitter voltage , R_C = Collector resistance, R_L = Load resistance

R_S = Source resistance, R_1 = Bias resistor one, R_2 = Bias resistor two

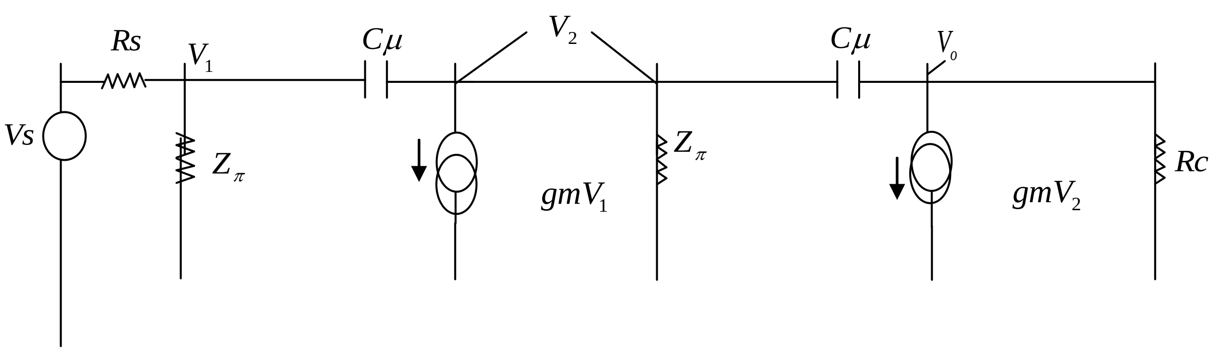

Fig. 4: High frequency Cascode hybrid π model

Where, Z_π is the parallel combination of r_π and c_π, $V_1 = V_{be1}$, $V_2 = V_{be2}$

Nodal equations

At V_1 we have

$$\frac{V_1 - V_s}{R_s} + \frac{V_1}{Z_\pi} + \frac{V_1 - V_2}{X_{cu}} = 0. \quad (6)$$

at V_2 we have

$$\frac{V_2 - V_1}{X_{Cu}} + gmV_1 + \frac{V_2}{Z_\pi} + \frac{V_2 - V_0}{X_{Cu}} = 0 \quad (7)$$

at V_0 we have

$$\frac{V_0 - V_2}{X_{Cu}} + gmV_2 + \frac{V_0}{R_C} = 0 \qquad (8)$$

using equations (6) through (8), we have the transfer function(A_v), V_o/V_s as

$$A_V = \frac{V_0}{V_S} = \frac{G_S(r_\pi SCu - gmr_\pi)(SCu - gm)}{[[SC_\mu + G_C][2r_\pi SC_\mu + SC_\pi r_\pi + 1] - r_\pi SC_\mu[SC_\mu - gm][r_\pi G_S + 1 + SC_\mu r_\pi + SC_\pi r_\pi + 1] - [SC_\mu + G_C](r_\pi SC_\mu - gmr_\pi)(SC_\mu r_\pi)]} \ldots (9)$$

1.5 **The antenna Array**

The amplifier output is being feed to an antenna. The advantage of this active antenna is to amplify the signal before transmission into space. Constructive interference is used to enhance the beam of the 4 – element active antenna on a given direction (Jenkins and White, 1957).The antennas are placed along a line; the axis of the array. A $\lambda/2$ spacing is used in order to have end-fire pattern illustrated in Figure 11.

If the amplitude of the four waves are a_1, a_2, a_3, and a_4, we may write the separate displacement as follows:

$$\left.\begin{aligned} y_1 &= a_1 \sin(\omega t - \alpha_1) \\ y_2 &= a_2 \sin(\omega t - \alpha_2) \\ y_3 &= a_3 \sin(\omega t - \alpha_3) \\ y_4 &= a_4 \sin(\omega t - \alpha_4) \end{aligned}\right\} \qquad (10)$$

ω is the same for all the waves. According to the principle of superposition, the resultant displacement y is merely the sum of y_1, y_2, y_3 and y_4 and we have

$$y = a_1 \sin(\omega t - \alpha_1) + a_2 \sin(\omega t - \alpha_2) + a_3 \sin(\omega t - \alpha_3) + a_4 \sin(\omega t - \alpha_4) \qquad (11)$$

Using the expression for the sine of the difference of two angles we have

$$y = (a_1 \cos\alpha_1 + a_2 \cos\alpha_2 + a_3 \cos\alpha_3 + a_4 \cos\alpha_4)\sin\omega t - (a_1 \sin\alpha_1 + a_2 \sin\alpha_2 + a_3 \sin\alpha_3 + a_4 \sin\alpha_4)\cos\omega t \qquad (12)$$

Since the a's and α's are Constance, we are justified in setting

$$a_1 \cos\alpha_1 + a_2 \cos\alpha_2 + a_3 \cos\alpha_3 + a_4 \cos\alpha_4 = A\cos\theta. \qquad (13)$$

$$a_1 \sin\alpha_1 + a_2 \sin\alpha_2 + a_3 \sin\alpha_3 + a_4 \sin\alpha_4 = A\sin\theta \qquad (14)$$

Squaring and adding both equation 13 and 14 we have

$$\begin{aligned} A^2(\cos^2\theta + \sin^2\theta) &= a_1^{\,2}(\cos^1\alpha_1 + \sin^2\alpha_1) + a_2^2(\cos^2\alpha_2 + \sin^2\alpha_2) + \\ & a_3^{\,2}(\cos^2\alpha_3 + \sin^2\alpha_3) + a_4^{\,2}(\cos^2\alpha_4 + \sin^2\alpha_4) + 2a_1 a_2 \cos(\alpha_1 - \alpha_2) + \\ & 2a_1 a_3 \cos(\alpha_1 - \alpha_3) + 2a_1 a_4 \cos(\alpha_1 - \alpha_4) + 2a_2 a_3 \cos(\alpha_2 - \alpha_3) + \\ & 2a_2 a_4 \cos(\alpha_2 - \alpha_4) + 2a_3 a_4 \cos(\alpha_3 - \alpha_4). \end{aligned} \qquad (15)$$

The schematic diagram of the spatial power combined system is shown in Figure 5. The time average power transmitted across a closed surface s is given by the integral of the real part of one half, the normal component of the complex Pointing vector **E x H***(Kraus, 1988).

$$P = \operatorname{Re} \tfrac{1}{2} \oint sE \times H^* . ds \qquad (16)$$

Where E and H are the peak values of the fields.

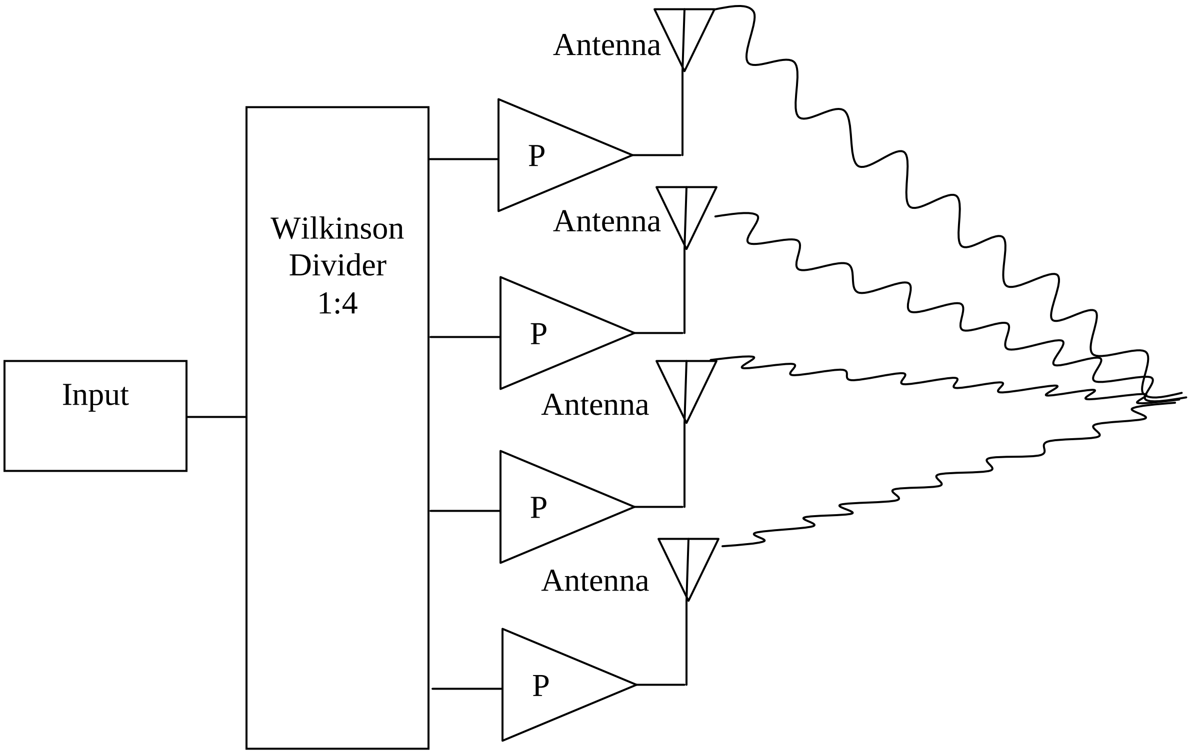

Fig. 5: Schematic diagram of spatial power combiner

III. RESULTS

The Wilkinson divider was designed using resistive splitter for its simplicity being made up from only resistor. A Delta format of power divider was utilized to design a 2:1 divider. A 4:1 power divider was formed by cascading two outputs of a single Wilkinson power divider as shown in Fig. 6 and 7 below.

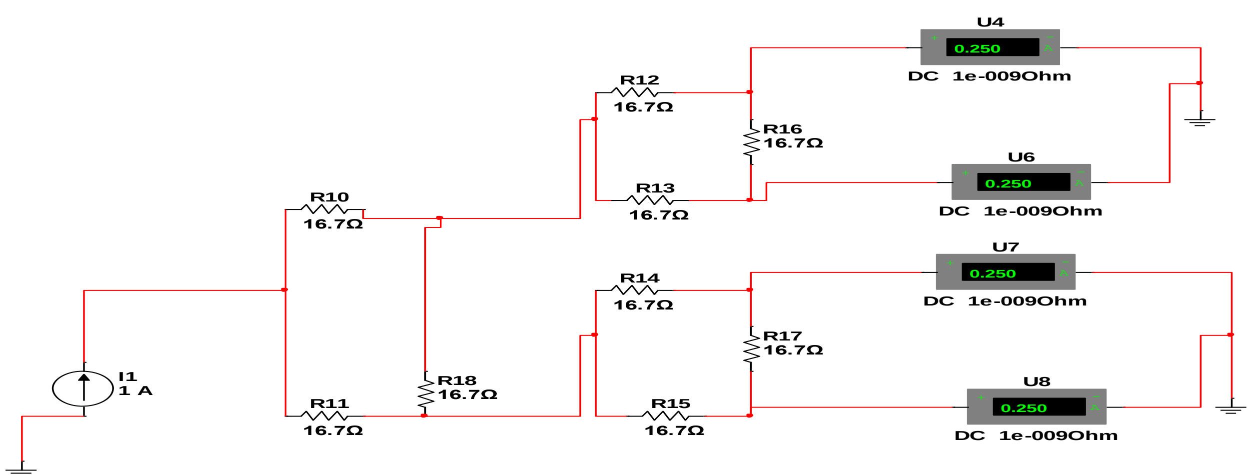

Fig. 6: Four way Wilkinson divider (Current division)

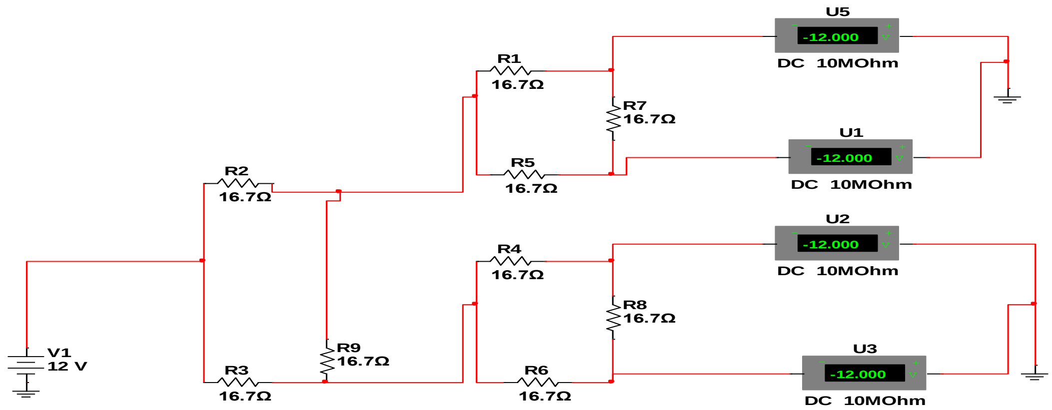

Fig. 7: Four ways Wilkinson divider (Constant voltage)

3.1 Amplifier

The simulated and calculated result of the amplifiers configuration is shown. The gain for the simulation was obtained from the plot of voltage gain against frequency, while that of the analysis were obtained from equation 9 of the Cascode amplifier. And the graphs for the simulation and analysis are shown in Figures 8 and 9 below.

The values of the component used in the design are shown below.

$$R_B = 5.6112\times10^3\Omega,\quad R_1 = 30.0\,ka,\quad R_2 = 6.90\times10^3\Omega$$

$$R_C = 1.34\times10^3\Omega,\quad R_E = 267.22\Omega,\quad C_b = 141pf,\quad C_c = 60pf,\quad C_e = 3\eta f$$

$$C_\pi = 0.15pf,\quad C\mu = 0.55pf,\quad \beta = 70,\quad g_m = 0.112,\quad r_\pi = 6252,\Omega$$

$$G_C = 0.00075\Omega,\quad G_S = 0.000182\Omega$$

When these values are used, the transfer function of equation (9) becomes

$$A_V(S) = \frac{1.418\times10^{-25}S^2 - 5.775\times10^{-14}S + 5.88\times10^{-3}}{4.028\times10^{-23}S^2 - 2.844\times10^{-21}S^2 - 2.319\times10^{-11}S + 8.344\times10^{-4}} \qquad (17)$$

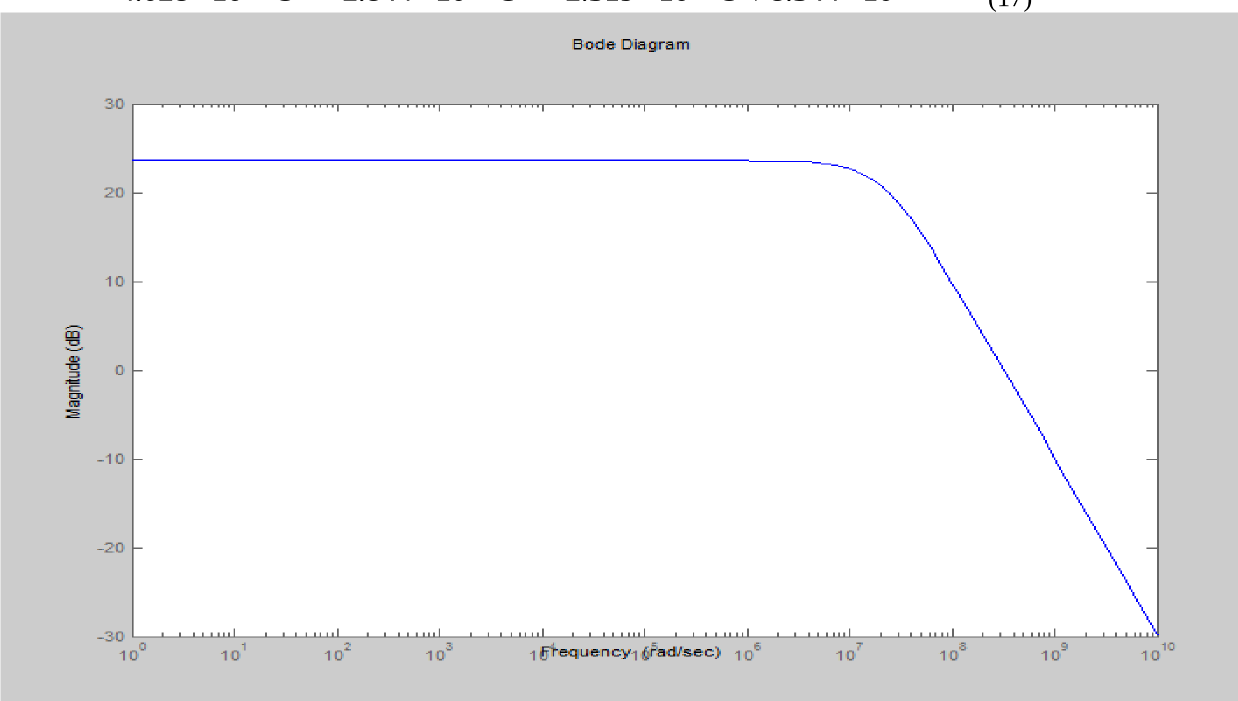

Fig. 8: Theoretical Frequency Response for Cascode Amplifier

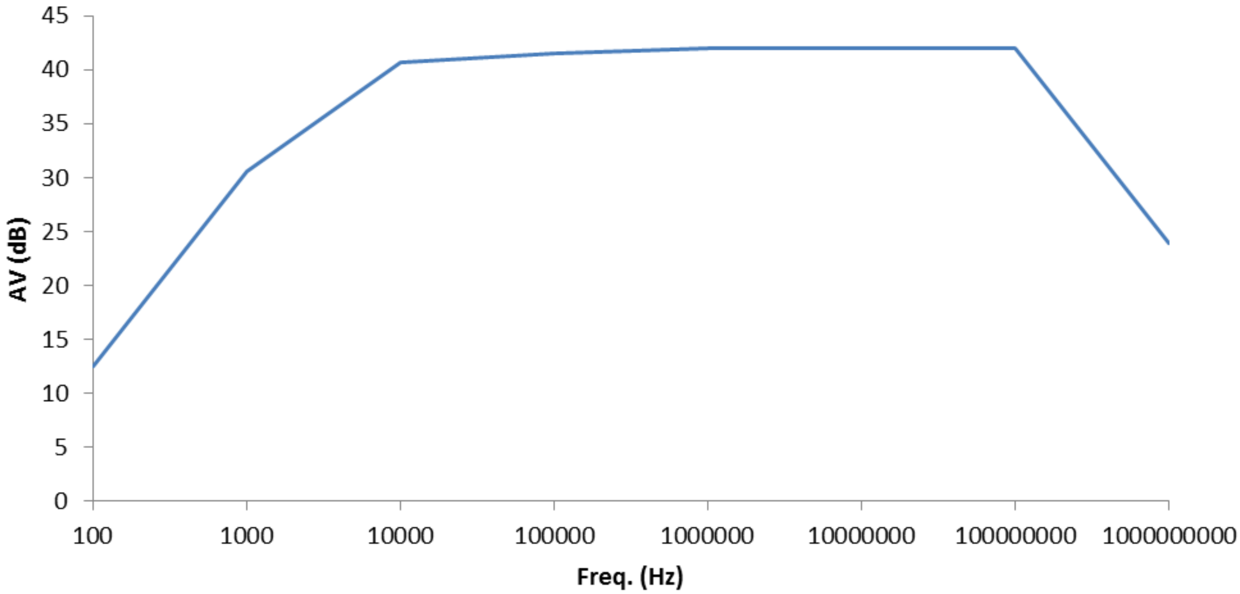

Fig. 9: Simulated Frequency Response for Cascode Amplifier

The gain of the simulated amplifier was found to be 41.94dB with a bandwidth of 478mHz

3.2 The antenna array

An antenna array is a matrix of two or more antenna connected electrically. All the individual radiators of the array are similar and the array element being the half-wave dipole. The discrete antenna detect individually but the total field received is the vectors addition of the field due to each antenna element (Yerraw, 2012). The radiation pattern of the array depends on the relative amplitude and phase of the detected signal of each antenna and the geometric spacing of the array element the four element is one in which all the radiators are in line with equal spacing between adjacent pairs as shown below:

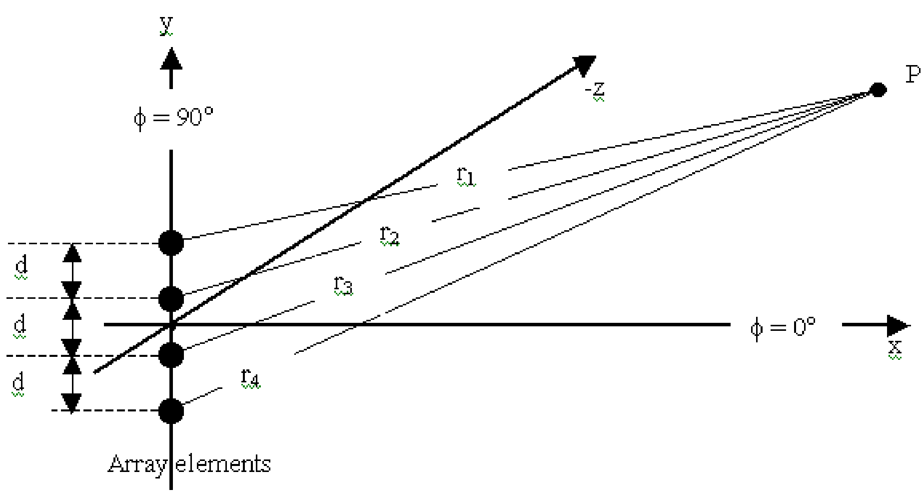

Fig. 10: 4-Element Array Geometry

One of the principal advantages of the array is that the radiation pattern can be in broadside or endfire array. If the maximum intensity is radiated in a direction along the line of the array, “off the end” rather than off the side, hence, the name endfire array as shown in Figure 11.

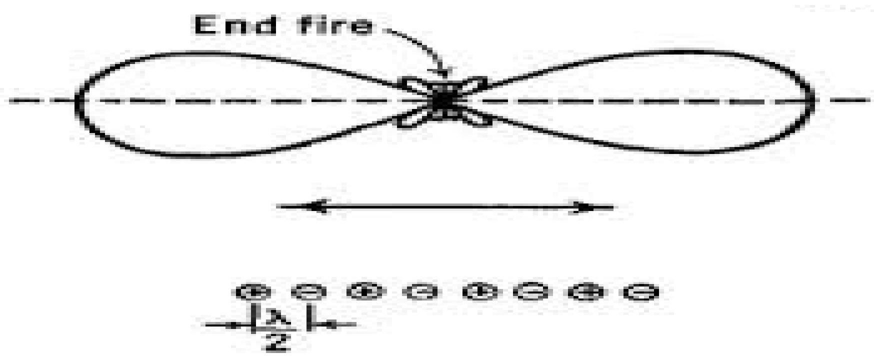

Fig. 11: Endfire Array

If the maximum intensity is in direction perpendicular to the direction of array such configuration is called a broadside array as shown in the Figure 12.

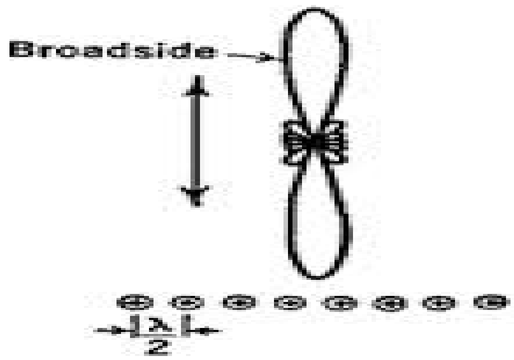

Fig. 12: Broadside Array

The method of analysis is suggested by showing a field point P joined by ray lines to each element such an array is called a linear array. The all element are radiating with equal intensity and the phase different between adjacent element is constant.

From equation (15) if the amplitudes a_1, a_2, a_3 and a_4 are the same with the same phase difference, it is shown that the intensity of the light at any point will be proportional to the squares of the resultant amplitude (Jenkins and White, 1957).

$$I \sim \mathrm{A}^2 = a^2 + a^2 + a^2 + a^2 + 2a^2 + 2a^2 + 2a^2 + 2a^2 + 2a^2 + 2a^2 \quad (18)$$

$$= \mathrm{I} \sim \mathrm{A}^2 = 16a^2 \quad (19)$$

IV. Discussion

We found the addition of the transmitted power in space to overcome the losses of signal strength in the distributed power amplifier configuration to be very useful. This work also eliminates the possibility of overheating the circuit board when adequate heat is developed from the insertion losses.

Adopting the proposed technique at backhaul location would further reduce cost of handling cooling systems due to heat develop in the circuits from the large currents present in the DA configuration.

V. Conclusion

In conclusion, it can be seen that the use of power splitter at the input stage of amplifiers and array antennas at the output section of the active antenna eliminate power lose in the circuit and give more chances of enhancing transmitted power of signals compared to the gain-bandwidth restriction present in the amplifying devices.

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