New Approach of Efficiency Improvement in 10 dB Doherty Power Amplifier for 4G LTE and 5G Wireless Applications

Suganthi Santhanam [1] and Palavesam Thiruvalar Selvan [2]

[1] Department of Electronics and Communication Engineering
K. Ramakrishnan College of Technology, Trichy, Tamilnadu-621 112, India
tvssugi@gmail.com, suganthis.ece@krct.ac.in

[2] Department of Electronics and Communication Engineering
SRM TRP Engineering College, Trichy, Tamilnadu, India
thriuvalar@gmail.com

Abstract **─** In this research article, the design procedure and comparative analysis of the 10 dB Doherty power amplifier (DPA) with single and double auxiliary amplifier for maximum efficiency has been presented. A new Doherty amplifier structure with parallel two auxiliary amplifiers based on conventional design having optimum value of load resistance of 3.162 ohm has been proposed with higher efficiency of 85.803% and analyzed with n-tone sinusoidal signal. The proposed Doherty power amplifier can achieve drain efficiency of 83.299% & with single and 85.803% with dual auxiliary amplifier at the output power back, off of 10 dB from the saturated power point. The simulated outputs are matched with mathematically derived design values. The simulated n-tone time response shows that the proposed design of DPA can able to handle different modulation standards at different frequencies with compatible structure.

Index Terms **─** Auxiliary amplifier, Doherty power amplifier, efficiency, peak to average power ratio, transceiver, wireless communication.

I. INTRODUCTION

Present wireless industry moving towards 5G communication placed RF transceiver in the proximity of each antenna in MIMO (Multiple Input Multiple Output) system of high data rate and connectivity [1]. To achieve linear performance from power amplifier [2], it should be operated at far back-off level for high data rate enhancement. The modulation envelope in such mobile communication method can be measured by Peak – to – Average Power Ratio (PAPR) [3]. For higher PAPR, the power amplifiers (PAs) should be operated at a larger back off power level from saturation and in wideband [1]. 5G evaluation in modern wireless communication requires multi band [4] operable power amplifier (PAs) with high efficiency. Due to mature implementation and simple in structure [5-6], Doherty Power Amplifier (DPA) is widely used at GHz frequencies than other amplifier configuration such as envelope tracking and out phasing power amplifier [7].

DPA invented in [5] has been popular for the design of power amplifier [8] due to simple topology, self sufficient (no need of external circuit fro efficiency control), efficient amplification with linearity and large PAPR [9] to reduce the energy consumption in 5G communication. The conventional DPA consists of main and auxiliary amplifiers connected by common load with quarter wave transformer. Generally power amplifier is operated at saturation for higher efficiency at which the small increase in input power can push the amplifier from the linear mode to the saturated mode. To ensure the amplifier to operate in linear region we lower the power level from maximum efficiency point. This power level lower is called as power back – off (PBO). The PBO of symmetric DPA is 6 dB while the PAPR of 4G LTE [10] signal is 6 dB to 12 dB. Hence, to fulfill the requirement of 4G and 5G [11], [12] communication, various techniques like linearity and power added efficiency [13], power control technology [14], asymmetric structure [15] and harmonic injection [16] have been introduced to replace symmetric DPA's with extended PBO region. Among these, alternative asymmetric structure is mostly preferred due to its simple design process and structure.

Asymmetric Doherty power amplifier (ADPA) consists of main and auxiliary amplifier in two classes with power divider and power combiner. Generally, class B PA for main amplifier and class C PA biasing for auxiliary amplifiers are mostly preferred and theoretically discussed in [17]. This conventional ADPA can be operated at average output transmitted power in 9 - 12 dB range below the maximum power. It is possible to combine the output power of many PAs to increase the linearity, larger the PBO and to maintain the efficiency

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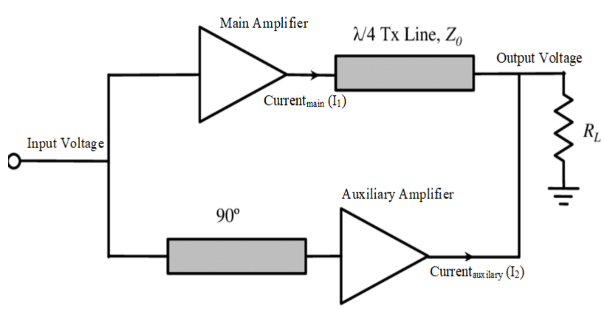
[18] throw out the back off region. This configuration is called as "multistage DPA". In this paper, we have proposed a comprehensive discussion on efficiency enhancement for DPA and for thorough understanding of high efficiency DPA design for 5G wireless transmitters. This paper proposed the comparison of 10 dB back off power DPA with single and double auxiliary amplifier for efficiency improvement as compared to [19]. The proposed DPA with two auxiliary amplifiers delivers power added efficiency (PAE) of 85.803% with output power of 25.04 dB under n-tone test. Design equation for calculating efficiency has been elaborated and mapped with simulation parameters to give insight from theory to practical implementation.

II. THEORY AND DESIGN OF DPA

Power amplifier gains more attention now a day for wideband [19], low cost and high integration applications [20]. It is common in mobile communication to operate the power levels of 10 – 40 dB back off from peek power.

A. Structure of 10 dB DPA

In DPA, the drain current in main amplifier increases linearly from initial value since biased in class B mode. But in auxiliary amplifier drain current does not flow after certain value of input voltage since biased in class C mode. The auxiliary amplifier current starts to increase beyond threshold value (X) with respect to input voltage. In this design, the auxiliary class C amplifier is biased such that no current flows below X=0.3. The output of main amplifier is connected to input of auxiliary amplifier through quarter wave transformer [19] QWT to compensate for a 90° in main amplifier. Both transistors are operated as dependent current source with main amplifier saturate at high power at which auxiliary amplifier is in off state. Hence, the linearity of overall amplifier is improved for high efficiency at high input power level. The block diagram and the equivalent circuit of basic DPA are shown in Figs. 1 (a) & (b) respectively. In Fig. 1 (a), the quarter-wave transformer which connects the output of the main power amplifier and the input of the auxiliary amplifier is used to compensate for a 90c phase shift introduced by the transformer in the main amplifier.



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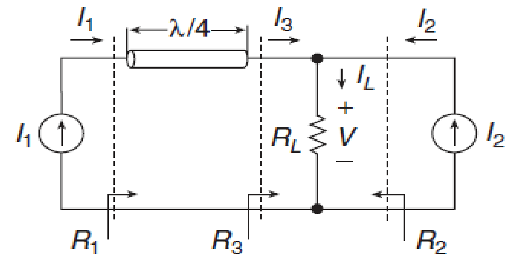


(b)

Fig. 1. Doherty power amplifier: (a) block diagram and (b) equivalent circuit.

In Fig. 1 (b), both amplifiers are represented as current source I_1 & I_2 with load resistance r1 and r3 as the load resistance seen by the drain and source with and without quarter-wave transmission line transformer as an impedance inverter. In Fig. 1 (b), the load resistance is to be increased to maintain the fundamental output voltage as constant. This is achieved by QWT as impedance inverter which is connected between the load R_L and the current source I_1. The relationship between R_1 and R_3 is given by:

$$R_1 = \frac{Z_0^2}{R_3}, \tag{1}$$

where Z_0 is the characteristics impedance of QWT, R_1 is the load resistance of current source I_1 (Main amplifier). The load resistance of current source I_2 (auxiliary amplifier) is given by:

$$R_2 = R_L\left(1 + \frac{I_3}{I_2}\right). \tag{2}$$

B. Calculation of efficiency

In order to analyze the combined effect of main and auxiliary amplifiers and to analyze the efficiency, the two amplifiers current sources equivalent circuit model has been used. The simplified equivalent model of main and auxiliary current sources (I_1 and $-jI_2$) has been drawn in Fig. 2.

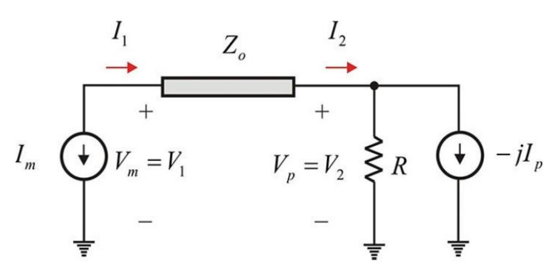


Fig. 2. Doherty amplifier output simplified model.

The drain current from main and auxiliary amplifiers are with 90° phase delay introduced by QWT represented by –j. The ABCD parameter of QWT is given by:

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} 0 & jZ_0 \\ jZ_0 & 0 \end{pmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix}. \tag{3}$$

V_1 can be expressed as:

$$\begin{aligned} V_1 &= jZ_0 I_2 = jZ_0 \left(\frac{V_2}{R} - jI_2 \right) \\ &= -I_1 \frac{Z_0^2}{R} + Z_0 I_2. \end{aligned} \tag{4}$$

Let X is the normalized input voltage at which the main and auxiliary amplifier switches between active and saturation for contributing efficiency. The value of Z_o^2/R is selected in such that X = 0.3 V, the efficiency of DPA becomes the efficiency of main amplifier alone since the auxiliary amplifier is in off state for below X = 0.3. For the above the value of X = 0.3, the auxiliary amplifier turns on for current I_2 to flow and main amplifier is in saturation state. Hence, the efficiency of DPA is:

$$\eta_{DPA/10dB} = \begin{Bmatrix} \eta_1 & X < 0.3 \\ \eta_2 & X > 0.3 \end{Bmatrix}, \tag{5}$$

where η_1 and η_2 depends on I_1 and I_2 in the normalized input voltage X range (0 < X < 1). I_1 and I_2 can be expressed as:

$$\begin{aligned} I_1 &= X \\ I_2 &= \begin{Bmatrix} 0 & X < 0.3 \\ 2(X - 0.3) & X > 0.3 \end{Bmatrix}. \end{aligned} \tag{6}$$

From the equation (4), we found that these two currents are opposite to each other and cancel out each other. This cancellation is done to make the two current terms that have the same slopes for X. But the slope of I_2 is 3.162 for X, and hence Z_o^2/R should be equal to 3.162 Z_o to cancel out each other, and hence Z_0 = 3.162xR. The efficiency of DPA can be calculated by Fourier series analysis of class B and class C PAs. Using Fourier series, the DC current component of main amplifier is expressed as:

$$I_0 = \frac{I_{RF}}{\pi} (\sin\theta - \theta\cos\theta) = I_{RF}\, \gamma_0\,, \tag{7}$$

$$\text{where} \quad \theta = \pm\cos^{-1}\left(\frac{I_q}{I_{RF}} \right). \tag{8}$$

Where Iq and I_{RF} are the DC quiescent in the absence of RF and fundamental drain current. The fundamental wave component of I_1 is given by:

$$I_1 = \frac{I_{RF}}{2\pi} (2\theta - \sin 2\theta) = I_{RF}\, \gamma_1\,. \tag{9}$$

The DC component of main and auxiliary amplifier are expressed as:

$$\begin{aligned} I_{10} &= \frac{2}{\pi} I_1 \\ I_{20} &= I_2 \frac{\gamma_0(\theta)}{\gamma_1(\theta)}, \end{aligned} \tag{10}$$

where conduction angle θ = $\cos^{-1}$ (0.3). From these two current components, we can get the DC power input expressed as:

$$P_{DC} = P_{in} = I_{10} + I_{20}\,. \tag{11}$$

This is the normalized DC power input to DPA by setting the DC supply to 1. The RF power output by two amplifiers due to this input power is given by:

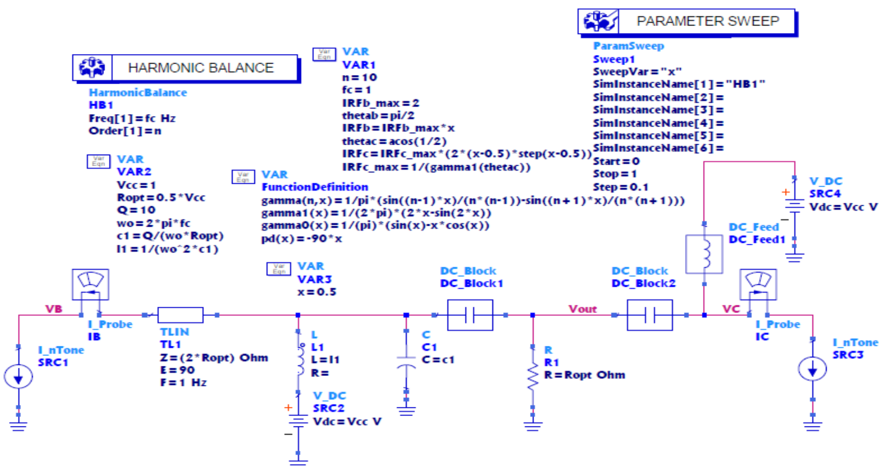
$$P_{RF} = P_{out} = \frac{1}{2}(V_1 I_1 + V_2 I_2). \tag{12}$$

From equations (11) and (12), the efficiency of DPA is calculated as:

$$\%\eta = \frac{P_{RF}}{P_{DC}} x100\,. \tag{13}$$

III. SIMULATION STRUCTURE AND ITS PARAMETERS

The Advanced Design System (ADS) structure that used for simulation of Doherty Power Amplifier (DPA) for 10 dB PBO for high frequency is shown in Fig. 3.



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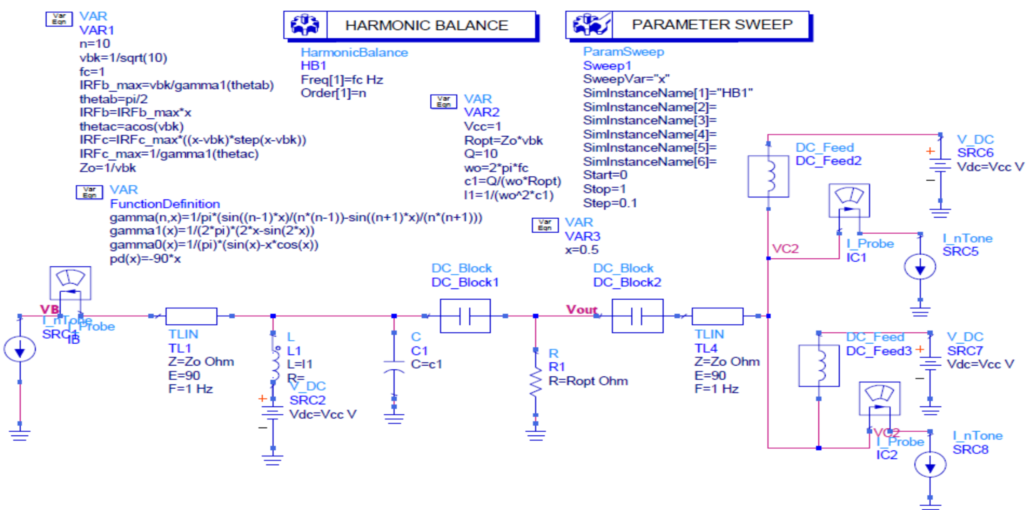


(b)

Fig. 3. Simulated structure of Doherty power amplifier: (a) with single auxiliary amplifier, and (b) with double auxiliary amplifier.

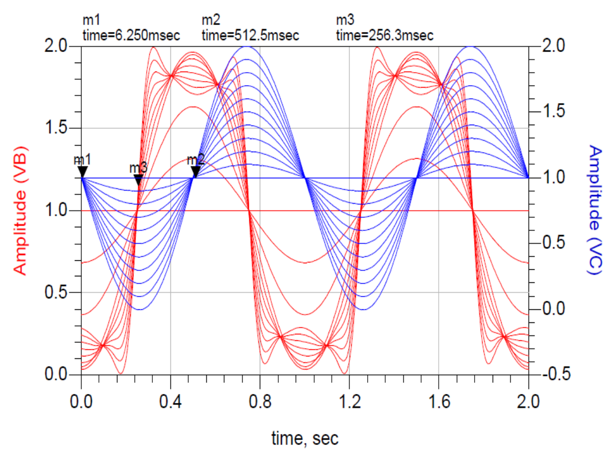
Figure 3 (a) represents the single stage n – tone 10 dB PBO DPA and Fig. 3 (b) represents the DPA that has two auxiliary amplifiers in parallel with same specification. The variable initialization used in simulation structure is defined in Table 1 with its name.

Table 1: Parameters used in ADS simulation

Variable Name	Description	Value
HB1	Nonlinear AC simulation for generation of sinusoidal source at fundamental frequency (freq) and nth harmonic (order) frequency	
Sweep	Normalized input voltage (X) represented as VAR3 from 0 to 1 in 0.1 step along with HB1	
X	Normalized input voltage	0.3
IRFb	Peak value of the Main current source	IRFb_max * X
IRFc	Peak value of the auxiliary current source	IRFc_max*(2*(x–0.5)*step(x–0.5))
IRFb_max	Maximum peak value of the Main current source	Vbk/gamma1(thetab)
IRFc_max	Maximum peak value of the auxiliary current source	1/gamma1(thetac)
Pd(x)	Phase delay between main & auxiliary amplifier	Cos^{-1}(X)

IV. RESULTS AND DISCUSSION

The Doherty power amplifier with 10 dB power back off and n-tone sinusoidal inputs has been simulated with single auxiliary amplifier and double amplifier. Figure 4 represents the simulation results of single auxiliary 10 dB DPA characteristics. Figure 4 (a) shows the simulated output voltage of two amplifier current sources. Both the main and auxiliary current sources have the maximum value of 2 A.



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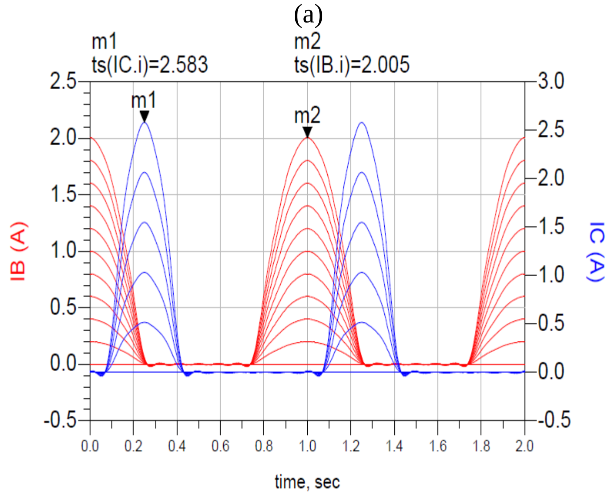

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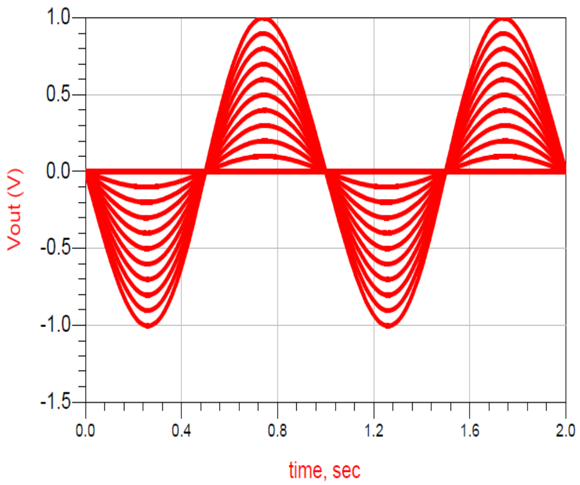

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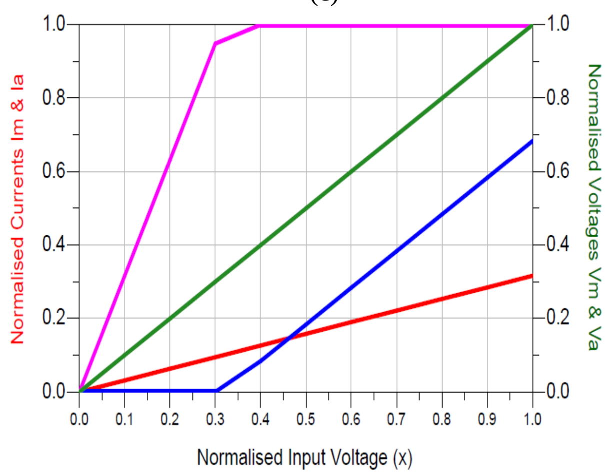
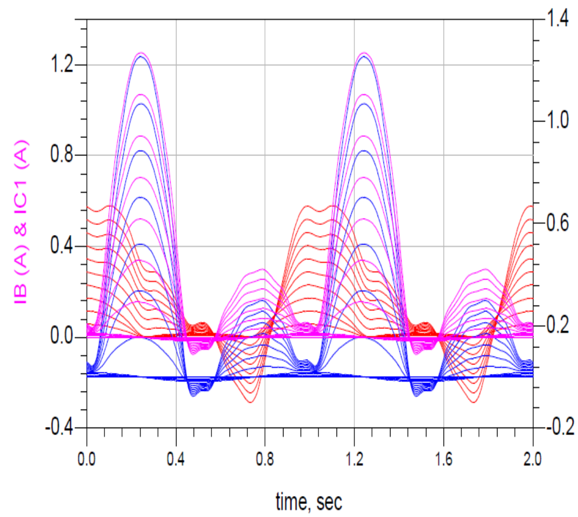


(d)

Fig. 4. Simulated response of Doherty power amplifier with single auxiliary current source. Main & auxiliary amplifier: (a) output voltage, (b) output current, (c) DPA output voltage, and (d) voltage and current in terms of input voltage.

The conduction angle can be found from the width sinusoidal tipped wave form of auxiliary source which is half of the main source (256.3 ms=512.5/2 ms). This validates the theoretical conduction angle of $\theta = \cos^{-1}(0.3)$. Figure 4 (b) shows the variation of two amplifiers output current in terms of input voltage with maximum current capacity of two transistors. It shows that the auxiliary amplifiers operating in class C, a maximum current capacity is 1.533 A while for main amplifier operating in class B, the maximum current capacity is 0.633 A. The parallel resonance L_1C_1 with quality factor 10 to calculate its value has been placed between the two amplifiers. This makes the output voltage close to sinusoidal waveform as shown in Fig. 4 (c). Figure 4 (d) shows the variation of main and auxiliary current sources output voltage and current in terms of input voltage. It shows that the auxiliary current begins to increase beyond threshold voltage (X=0.3). It shows the normalized voltages (V_1 and V_2) and normalized currents (I_1 and I_2) of main and auxiliary amplifiers with its maximum value of equal amplitude.



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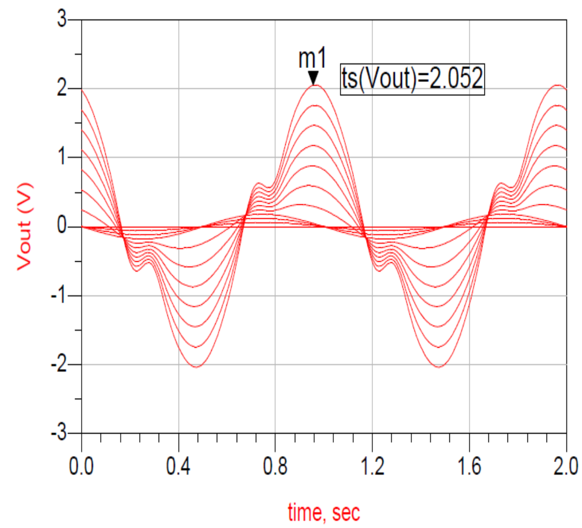

(b)

Fig. 5. Simulated output response of Doherty power amplifier with dual auxiliary current source: (a) currents and (b) voltage.

We have followed the similar procedure for DPA with two auxiliary amplifiers connected in parallel and the outputs derived are shown in Fig. 5. Table 2 shows the variation of efficiency for single auxiliary DPA having efficiency of 83.299% and for double auxiliary amplifiers with higher efficiency of 85.803%. Hence, it is proved that the Doherty power amplifier can be designed for high efficiency application by proper design of main and auxiliary amplifiers in suitable configuration.

Table 2: Comparison of efficiency of DPA with single auxiliary amplifier (EFF) and for double auxiliary amplifier (EFF2b) with $R_{opt} = 1$ ohm and $Z_0 = 3.162$ ohm

X	EFF	EFF2b	X	EFF	EFF2b
0	0	0	0.6	62.86	22.63
0.1	24.84	0.17	0.7	67.16	35.96
0.2	49.67	0.68	0.8	72.19	51.19
0.3	74.51	**1.49**	0.9	77.62	67.91
0.4	61.82	4.36	1.0	83.29	85.80
0.5	**60.13**	11.81			

V. CONCLUSION

The method of designing 10 dB n-tone single and double auxiliary amplifiers Doherty power amplifier for high efficiency application is presented and reviewed. In this method it has been proved that the simplest way of providing a high efficiency at the output back – off region is Doherty power amplifier having load modulation and no additional circuit requirements. The simulated results show that 10 dB output power back off with higher efficiency of 85.803% has been achieved and matched with theoretical design values. The proposed DPA exhibits high efficiency over broad band which covers 5G bands for modern wireless communication standers. The attainment of above 85% efficiency shows that DPA can increase the power efficiency in comparison with class B amplifier operated at saturation level. Future work would be focused on fabrication of dual auxiliary amplifier DPA to validate the simulated results at mm wave spectrum.

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