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Development of Wideband Power Amplifier for RF / Microwave Front-End Subsystem

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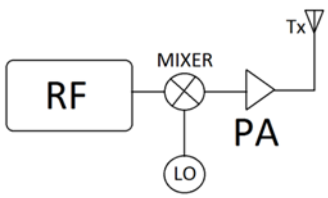
Graphical abstract



Abstract

This paper reviews the Wideband Power Amplifier (PA) that has been developed since 1990. Several journals had been discussed in this paper covers few topics such as Characterization of Power Amplifiers, Power Amplifier Architecture and Linearization Technique. Advantages and disadvantages of the technique used had been highlighted as well as the summary of those cases been compiled in the table form for comparison purposes. Power Amplifier is one of the important parts in transmitter. However, when involve transistor as an active device, it is important to ensure that the signals are stabilized and transmitted at higher efficiency. This leads to the proposal of a new design of Wideband Power Amplifier based on the concept of the multiplexer.

Keywords: Wideband power amplifier; amplifier architecture; linearization technique; characterization of power amplifier

1.0 INTRODUCTION

The rapid growth of mobile telecommunication services has increased demand for low-cost, high-efficiency, and compact equipment. Generally, power amplifier (PA) is one of the most important subsystems for radio frequency (RF) transmitters. In addition, it is also a component which requires a lot of electrical power.

Wideband high power amplifiers are commonly used in military, satellite communications and commercial applications systems [1]. In recent years, there has also been a rising interest in the use of microwaves in chemistry such as organic synthesis, polymer engineering, textile processing, analytical and environmental chemistry, medical treatment and industrial microwave heating applications [2]. Figure 1 shows the conventional transmitter block diagram which consist of RF input, Mixer, Oscillator, Power Amplifier and Antenna.

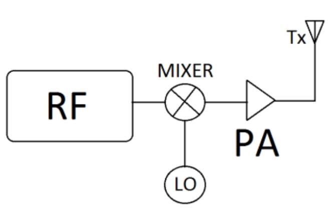


Figure 1 Block diagram of conventional transmitter

Wideband PA's deal with two to three bands which almost narrow bandwidths per band and it usually operated in parallel. Wideband amplifiers which covers manifold octaves have been broadly explored and described in the literature, but the design process mostly depend on time-consuming source/load–pull measurements or simulations deprived of any other technique for the design of the matching networks [3].

Performance parameters for a power amplifier are the level of output power it can achieve, linearity and efficiency. In order to improve the performance of a power amplifier, distortion needs to be reduced. There are four types of distortion which is harmonic distortion, amplitude distortion, phase distortion, and intermodulation distortion. All of the distortion caused by the single tone product except intermodulation distortion which caused by the multi tone product. Another factor that may affect the performance of Power Amplifier is the limitation of the bandwidth. In order to lengthen the bandwidth, an improvement of power-handling capability is needed. However, the design of the end product might not be small due to number of circuit involve.

The main objective of this paper is to provide the readers a wide perspective about the current development of power amplifier couple with cases from the researchers. Basically it covers the type or categories of power amplifier, characteristic, device technology, architecture and linearization technique that has been used to design the power amplifier.

2.0 CATEGORIES OF POWER AMPLIFIER

Amplifiers are classified into several classes such as A, B, C, AB, D, E, and F [4]. In addition, it also can be characterized either as bias point reliant or dependent on the inactive foundations at the output matching network that shape the drain voltage and current as long as the transistor in this case functions as a switch. However, the maximum performance of each class depends on the type of application that they were used. For instance, the class-F amplifier has a better performance in the high output power and the class-E amplifier has better performance in low voltage applications and wideband. There are other types of power amplifiers that they are rarely used in the microwave frequency. Alternatively, Power Amplifier can be classified according to the frequency range. Normal audio amplifier will work at 20 Hz to 20 KHz range while on the frequency 20 KHz and above, it will be described or categorized as a radio-frequency (RF) amplifier.

2.1 Bandwidth

Amplifiers are also classified as narrowband or wideband. Normally, wideband PA's cover two or more bands with relatively narrow bandwidths per band. Peter Wright designed a wide bandwidth via active harmonic load-pull [5]. However for the wideband PAs with octave or broader bandwidth, there's no point to use the harmonic tuning approach as harmonics will fall inside the required bandwidth at its couldn't be differentiate [6]. Researcher continues to develop hybrid J amplifier by using the method of mixing gradually the matching network [3]. In addition, this network estimation technique is based on the clipping contours method, and an altered waveform concept [5, 7]. The latest design in 2013 which can cater for the GSM, UMTS, Wi-Fi and Wi-MAX application had been introduced by using the Simplified Real Frequency Technique (SRFT)[8].

Table 1 Summary cases of power amplifier characteristics

Case	Bandwidth (GHz)	Gain (dB)	Efficiency (%)	Distortion
[3]	1.6 – 2.2	-	55 – 68	21.8 dBc (ACRP)
[5]	1.5 – 2.5	-	60 – 70 (Drain)	-
[6]	0.9 – 2.2	10 – 13	63 – 89	-
[7]	60	20.6	-	-
[8]	2 – 18	18 – 21	5 – 15 (PAE)	-
[9]	1.5	18	11.8 (PAE)	-
[10]	2.6 – 5.4	15.8	34 (PAE)	P1dB -3.4 (input), +11.4 (output)
[11]	1.9 – 2.9	10.8	63 (Drain)	50 dBc (ACPR)
[12]	1.8 – 2.05	-	60 (Drain)	-47, -52 (ACLR)
[13]	2.14	10.2	51 (Drain)	- 49 dBc (ACLR)
[14]	2 – 8	30	-	-39.1,-40.2 (ACLR)
[15]	3.4 – 3.6	39	-	-32 dBc (ACLR)

3.0 CHARACTERIZATION OF POWER AMPLIFIER

There are a few characteristics that need to be considered before starting to design power amplifier. This is to make sure that the design will produce high performance output according to the application that researcher wanted. In Characterization of Power Amplifier, it covers the subtopic of bandwidth, gain, efficiency and distortion which reflect the performance of each power amplifier. Table 1 summarizes all the cases discussed.

3.1 Gain

Output power and gain are among those important properties of an amplifier. In order to reach high gain, one or more transistors can be spilled or combined. As for example, design of a Wilkinson power divider had been used due to its familiarity, low loss and good isolation between ports [9]. Another case reported using different method where it combines two-stage distributed amplifier monolithic microwave integrated circuit (MMIC) with the dual-gate HEMTs [10]. Using the bandwidth of 2-18GHz, the small-signal gain of 20 dB has been achieved in this design. Other than that, the development of amplifier in millimeter-wave application been continued which applied the 90nm CMOS device with a load pull matching networks [11].

3.2 Efficiency

Having good efficiency is another factor that determines the effectiveness of the power amplifier. There is varieties way to enhance the efficiency. By using active load pull system a, Power Added Efficiency (PAE) can be measured accurately [12]. In addition the efficiency in the experiment can be increased from 34% to 43% by using load termination at the output. However, linearization technique such as Digital Pre Distortion (DPD) can reduce the percentage of the drain efficiency, which the PAE drops from 63% to 34.2% [13]. On other case, the Chireix compensation features creates an effectiveness peak at a definite power back-off level and been placed at the input ports [14]. Another technique which can be used to improve the efficiency been portrayed which applied the envelope tracking motion at the drain such that the RF amplifier functions steadily close to saturation [15].

3.3 Distortion

The cause of distortion in phase and amplitude had been discussed which using the combination technique of gain based on predistorter and memory polynomial model [16]. In base station there are two major types of linearizer technique which is Digital Predistortion and Feedfoward [17]. Furthermore the experimental had been done and the Intermodulation Distortion (IMD) results from the experimental shows 30db. Measurement and calibration of AM-AM and AM-PM distortion is important in order to perform better analysis in wireless communications. Shreyas focusing on the AM-AM and AM-PM measurement technique which they been using the sine waves as a test signals [18]. Adjacent Channel Power Ratio (ACPR) is another ratio that been used to quantify the value of distortion generated by cause of nonlinearities in RF components. Other than that, there also other design that describes the new methods to improve the ACPR of the signals [19].

4.0 DEVICE TECHNOLOGY

In order to enhance the capabilities of the devices, varieties technique and technologies had been developed. One of it was the implementation of MMIC technology which using Gan [20]. The key benefits when using GaN on SiC substrates are better current carrying ability, good thermal conductivity, wider frequency of operation and high breakdown voltage. Another study on GaN had been done by using source–pull/ load–pull simulation approach [21]. Large-signal measurement results show78% fractional bandwidth around 3.1-GHz center frequency, less than 2-dB ripple in the gain across the band resulting in an output power between 40–42 dBm and PAE between 50%–62%. Besides, study aptitudes of GaAs E-Mode pHEMTs had been done in relations of power proficiency and competence for high- frequency power switches [22]. Normally the design is used for portable application. In Figure 2, the individual slices are joined in equivalent layout using three-level metal interconnect pattern.

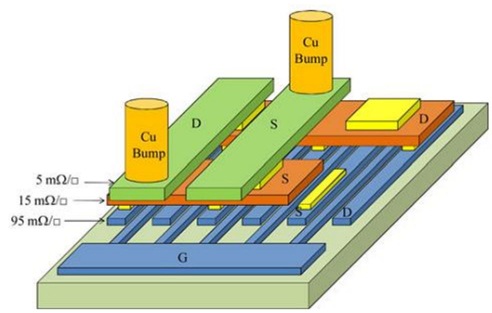


Figure 2 Three-level interconnect scheme for multifinger E-pHEMT [22]

Table 2 Summary of power amplifier architecture

	Push Pull	Balance Amplifier	Power Combiner	Multistage Amplifier
Topology	• Form by connecting the output ports of two identical transistors • The signal to be amplified is first split into two identical signals 180° out of phase	• Two identical amplifiers are fed from an input power splitter which produces two signals in phase quadrature • The outputs being recombined using a similar device connected in reverse.	• One connects their input sides to the output ports of an N-way hybrid power divider, and their output sides to the input ports of an N-way hybrid power combiner.	• Merging the productions of two or more linear RF power amplifiers (PAs) over an impedance-inverting coupler such as a quarter-wave transmission line.
Advantages	• Low distortion • Low ripple voltage	• Excellent impedance match	• Overcome the limitation on the output power and huge bandwidth	• Flexibility in input and output impedance • High gain
Disadvantages	• Bulky and costly transformer	• High power required for two amplifiers	• Insertion loss that could reduce gain.	• Complex circuit design

5.0 POWER AMPLIFIER ARCHITECTURE

There are four main architecture of PA which is Push-Pull, Balance, Power Combiner and Multistage Amplifier as stated in the Table 2.

Most of the Radio Frequency Power Amplifier (RFPA) built for the operation below 500 MHz is from the Push-Pull type [4]. At higher frequencies (into the GHz region) there is also design that used Push-Pull but it faced some problem and requires a Balun to balance the signals. In Toyoda's research, he designed a broadband push pull amplifier by using 3dB 180˚hybrid couplers [23]. This is to solve the phase different between drain and source of FET that become less than 180˚ as the frequencies increased. He then made another design which provides high efficiency [24]. In the previous method, the fundamental wave and the second harmonic amplifier are employed to construct a high efficiency but on the second method, Toyoda make the amplitude of the sinusoidal wave saturated at its maximum.

Integrated antenna concept is applied to Push-Push amplifier [25]. In this approach, antenna was used as Balun which works as an out-of-phase power combiner and tuned load for higher harmonics. Another case of integration between Push Pull Power Amplifier and Antenna come out on 2001 [26]. This time the quasi-Yagi antenna has been used. Through the active combined antenna model, the use of ordinary 180˚ hybrid circuit is rejected at the power amplifier output stage, hence reducing the losses related with the hybrid. The Push-Pull Power Amplifier with a high operation voltage is presented [27]. The high voltage is realized by stacking dc biases of two Push-Pull amplifiers through the virtual ground point, while the radio frequency powers are series combined.

The second architecture of PA's is Balance Amplifier (BA) which two identical amplifiers are fed from an input power splitter. It produces two signals in the phase quadrature and eventually the outputs being recombined using a similar device connected in reverse. One of the papers reported which defines the achievement of an amplifier element that cascades the product of two sub modules to concurrently achieve high output power and varied bandwidth [28]. Each individual component consists of two balanced stage was combined to improved gain achievement and phase matched for maximizing the power. The development of Balanced PA were continued and focused on the Millimeter wave (MMV) application [29]. Measurement results show that a small signal gain of 9dB, an output power of 102mW, and PAE of 8% have been achieved at 94GHz.

In 2011, the evolution of the CMOS technology had provided several advantages such as low cost and high integration with neighboring circuit. Even with the lack of reliability under load mismatch conditions, it does not stop the researcher to find more about it. H. Jeon proposes a highly efficient linear balanced PA in CMOS technology [30]. The balanced PA structure provides immunity to load impedance variations that occur by changes of the antenna impedance and the contacts with conductive surfaces. The new findings on the Balanced CMOS Amplifier had been presented [31]. A triple-mode operation together with a balanced topology is developed to shelter load-insensitivity characteristics thus resulted an improvement of the efficiency.

A waveguide-based power-combining structure at *Ka* -band using double antipodal finline-to microstrip transitions had been developed [32]. No connection wires are desired in mode transition while the Balun is merged into the structure. In returned the structure permits excellent repeatability at millimeter waves and improved efficiency. Other than that, a high-power amplifier using the compact combiner design is built and demonstrated [33]. It provides a bandwidth from 6 to 17 GHz with 44-W maximum output power. Linearity measurement has shown a high third-order intercept point of 52 dBm. A coaxial waveguide was used as the host of the combining circuits for broader bandwidth and better uniformity by equally distributing the input power to each element.

Power combining strategy for Class-E and inverse Class-E amplifiers operating at high frequencies and able to operate into unbalanced loads is proposed [34]. With a given design and specification of 3 V–1.5 W–2.5 GHz, it is shown that a three-branch combiner has a natural 50Ω output impedance. Throughout the investigation performance of the proposed circuits using Nonlinear Component, it shown that the circuits can offer higher instantaneous efficiency relative to the reference method since the impedance by each combiner branch increases.

A broadband radial waveguide power amplifier has been designed using a spatial power dividing/combining technique as in Figure 3 [35]. The measured small-signal gain of the eight-device power amplifier is 12 –16.5 dB over a broadband from 7 to 15 GHz. The measured maximum output power at 1-dB compression is 28.6 dBm at 10 GHz, with a power-combining efficiency approximately 91%.

A power amplifier array created on a slotted-waveguide power divider is offered for quasi-optical uses [36]. It is considering beneficial due to its easy to fabricate and low profile. Moreover, it achieved an efficient heat sinking of power devices. The first millimeter-wave wafer-scale power-amplifier array applied in a 0.13-µm BiCMOS technology had been presented using power combining [37]. The design is tested in free-space using high efficiency on-chip antennas. In addition a 3x3 power-amplifier array also been presented correspond with isotropic radiated power of 33–35 dBm at 90–98 GHz.

One of the papers of multistage amplifier had been presented in 1995 by Leach, W.M., Jr. to investigate the noise [38]. The noise generated by each stage is modeled by a series input voltage and a shunt input current. Furthermore, the analysis is directed toward low-frequency analog circuits so that frequency response effects can be neglected.

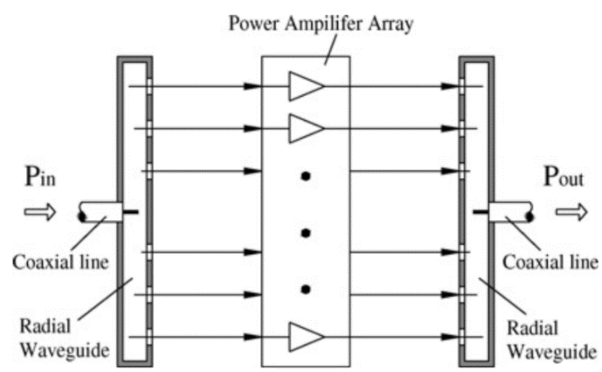


Figure 3 Schematic of radial waveguide power combiner [35]

Paper of a multistage amplifier for low-voltage applications presented which the amplifier contains of basic (noncascode) low gain stages and alleviated by a Nested transconductance-Capacitance Compensation (NGCC) scheme [39]. The consequential topology is analogous to the Nested Miller Compensation (NMC) multistage amplifier. A new multistage operational amplifier topology had been developed which involves merely *N*-2 embedded compensation networks for *N* gain stages [40]. The design were executed in a 0.6-m n-well CMOS process, single-ended three-stage prototype dissipates 6.9 mW at 3.0 V with 102 dB gain, 47 MHz bandwidth and 69 V/s average slew rate. A multistage operational transconductance amplifier through a feedforward compensation scheme which not using Miller capacitors is explained [41]. In order to terminate the negative phase shift of the poles, it uses the positive phase shift of left-half-plane (LHP) zeroes.

Other than that, a new performance-boosting frequency compensation method is explained, which has been called as Transconductance with Capacitances Feedback Compensation (TCFC) [42]. A two capacitors and transconductance stage present negative feedback to a three-stage amplifier, which ominously enhance the performance for instance gain-bandwidth product, slew rate, stability and sensitivity. Furthermore, an optimized

TCFC amplifier has also been developed and fabricated in a 0.35μ m CMOS process. The TCFC amplifier with a 150-pF load capacitor reached 2.9-MHz gain-bandwidth product deplete 45μ W power with a 1.5 V supply as seen in Table 3.

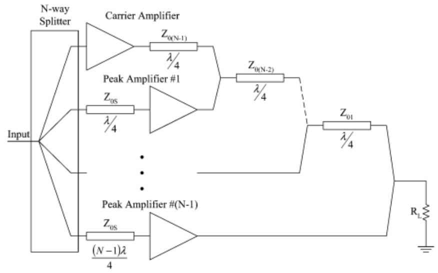


Figure 5 Schematic diagram of multistage Doherty amplifier [43]

6.0 LINEARIZATION TECHNIQUE

Linearization is a procedure of reducing the distortion specified by various techniques, depending upon the specific signal and applications. Usually extra components were added to the design as to maximize the output power and to make it operate at a high level of efficiency. Due to the nonlinear of the amplifier, the aim to perform linearization technique is to produce linear output.

The paper of a linearization Power Amplifier with a new adaptive pre-distortion algorithm had been presented [45]. The improvement of the speed convergence is made using a unique normalization of the coefficients of the polynomial predistortion.

Table 3 Performance comparison on the Multistage PA

	Adc (dB)	CL (pF)	Vdd (V)	Idd (mA)	Power (mW)	GBW (MHz)	SR (V/μS)	FOMs $(\frac{MHz-pF}{mW})$	FOML $(\frac{V/\mu S-pF}{mW})$	IFOMs $(\frac{MHz-pF}{mA})$	IFOML $(\frac{V/\mu S-pF}{mA})$
NGCC	100	20	2.0	0.34	0.68	0.61	2.5	18	74	36	148
NCFF	90	12	2.5	5.6	14	250	-	214	-	535	-
TCFC	>100	150	1.5	0.03	0.045	2.85	1.035	9500	3450	14250	5175

The analysis of a multistage Doherty amplifier presented and the schematic diagram of it shows in Figure 5 [43]. When comparing the Doherty amplifier, the multistage Doherty amplifier is better on producing higher efficiency at output power. The results show 42% power-added efficiency (PAE) at 6-dB output power backoff while at 12-dB the PAE is 27%. In addition, the design is able to give up to 33 dBm output power and deliver maximum adjacent channel power leakage ratio of 35 dBc at 5 MHz offset and 47 dBc at 10MHz.

Chen designed for a multistage gain-flattened fiber Raman amplifiers (FRAs) which using the multi wavelength pumping scheme [44]. This is the first time that this design been used to enhance multistage amplifier simultaneously. Furthermore, it gives a closer overall gain spectrum of chained identical single-stage amplifier.

Another method of digital adaptive pre-distortion for linearization of power amplifiers had been proposed [46]. The method is derived from a post-distortion approach which identifies the PA inverse function. This approach leads to the minimization of a quadratic function of the polynomial coefficients in the case of a polynomial predistorter form and a least square criterion. Examination of the use of crest factor reduction (CFR) as a factor to improve the output power and efficiency in relation pre-distortion linearization systems had been proposed [47].

Referred to Table 4, the CFR of the input signal increases the efficiency by 2.2% in the absence of predistortion improvements. An advanced adaptive baseband/RF predistorter had been presented [48]. It combines the method of the software defined radio technology with the power-amplifier (PA) linearization field. In order to deliver an instantaneous AM–AM and AM–PM curves, the linearizer executes direct characterization of the PA via two digital receivers.

In 2008, a frequency-selective trajectory predistortion linearization system simulated by strong differential memory effects had been presented [49]. As a result, the differential memory reactions can be exposed in two-tone test by the divergence for improving tone-spacing of the vector Volterra coefficients connected with the minimum and maximum intermodulation's tones.

Table 4 Power and efficiency improvement [47].

	With PD		Without PD	
PAR	9.6dB	5dB	9.6dB	5dB
Pout	38.7dBm	40.0dBm	37.3dBm	38.3dBm
Eff.	21.5%	23.9%	18.3%	20.5%

A simple approach to improve the linearity of silicon (Si) laterally diffused metal oxide semiconductor (LDMOS) base-station power amplifiers (PAs) by integrating an analogue pre-distorter (APD) are presented [50]. The Si-LDMOS APD utilizes an unequal power divider/combiner and Si-LDMOS field effect transistors to provide inverse distortion characteristics power divider/combiner and Si-LDMOS field effect transistors to provide inverse distortion characteristics.

Besides, a built-in pre-distortion linearizer using cold-mode MOSFET with forward body bias is presented for 60 GHz CMOS PA linearization on 90 nm CMOS LP [51]. The design shows the

OP1dB has been improving from 7.3 to 10.2 dBm and the operating PAE at *OP1dB* enhance from 5.4% to 10.8%. In addition, the IMD3 present at maximum of 25 dB.

In 2012, Charles presented a method to limit the generation of signal peak power at the output of a digital pre-distorter that is applied to a RF power amplifier (PA) operating in strong compression [52]. The method can be considered as a joint crest-factor reduction and digital pre-distortion (DPD). Another digital pre-distortion (DPD) architecture of a based on the affine projection algorithm (AP) for RF power amplifiers operating in 900 MHz band is presented in 2012 [53]. The linearity of the RF power amplifier with an OFDM signal is significantly improved by employing the proposed DPD system, where the look-up table method is used with nonlinear indexing.

A new technique for linearizing microwave power amplifiers is presented [54]. Analytical and experimental results show that the intermodulation distortion in power amplifiers can be seriously reduced when active feedback networks are employed. In 1995, a power amplifier linearization scheme using RF feedback is proposed [55]. The method incorporates all the signal processing elements in the forward loop of the system as a means of eliminating nonlinear errors and noise introduced by the modulator / demodulator circuits. Other than that, a phase-correcting feedback system which reduces the AM-to-PM distortion of Class E power amplifiers for wireless communication is presented [56]. It comprises a novel limiting amplifier, a phase detector and a phase shifter which operating at 835 MHz.

On other experimental of the feedback circuit, results show that the proposed circuit can prevent the output stage Heterojunction Bipolar Transistor (HBT) from an unwarranted collector voltage swing [57]. In other case on envelope feedback, the linearizers reimburse the gain and phase nonlinearity of power amplifier (PA) simultaneously by adjusting both adjustable attenuator and phase shifter [58]. A phase-alignment system with integration of feedback linearizer is used in the first reported IC [59]. The phase-alignment system absorbs 8.8 mW from a 2.5-V supply and operates a new method for offset-free analog multiplication that allows it to behave without manual trimming.

Table 5 Summary cases of power amplifier linearization technique

Case	Linearization technique	Output power (dBm)	Gain (dB)	Efficiency (%)
[46]	Pre-Distortion	-	-	5
[48]	Pre-Distortion	38.7	-	21.5
[50]	Pre-Distortion	-	38	-
[51]	Pre-Distortion	7.3	11.8	10.4
[54]	Feedback	27	-	-
[56]	Feedback	26.5	-	67
[57]	Feedback	34.5	29.5	52
[58]	Feedback	26	-	-
[59]	Feedback	14.2	-	-

■4.0 CONCLUSION

There are several techniques to design power amplifier and that has been discussed in the previous sections. Basically the main aim of designing a power amplifier depends on what application that is going to be used and the characteristic that wanted to improve. Looking at the trend of the development in power amplifier, people know that the concept of cascade such as power combining and multistage will improve performance of each amplifier especially on the gain and other parameters.

On the other perspectives, the development on the devices such as GaAs HBT or GaN helps others to create a different ways to improve the performances of power amplifier. However, the consideration on the linearity of the active device creates challenges to the designer. It creates more development on a variety of techniques that has been used by the researcher in order to achieve the aims.

An alternative technique to design a power amplifier using multiplexer can be proposed. A multiplexer is mainly used to increase the gain of signals and at the same time eliminating the unwanted signal. The forming of the multiplexer is being developed based on a combination of individual cavity filter. In addition, the technique which is based on the approach relies on splitting a wideband signal to a number of narrowband signals. The signal can then be amplified using individual narrowband amplifiers. Narrowband power amplifiers can produce higher power, higher gain and are easier to match. The outputs of these amplifiers are combined to restore the original bandwidth with the required output level. Each individual amplifier can be designed as a single stage amplifier or multi-stage amplifier if high gain or high output power is required. As a result, greater bandwidth with lower distortion expected to be obtained by implementing this technique.

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