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A Classification and Comparative Overview of CMOS Radio-Frequency Power Amplifiers

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Abstract: This paper presents a comprehensive classification and comparative overview of CMOS radio-frequency (RF) power amplifiers (PAs) and proposes novel insights into their design and applications. Our research focuses on the significance of RF CMOS power amplifiers in contemporary communication systems, specifically their role in enabling the advancements of emerging technologies such as 5G. We delve into the various RF CMOS power amplifier classes, including linear PA classes (A, AB, B, and C) and switching PAs (Class D, Class E, and Class F). By evaluating essential performance metrics such as output power (P_out), drain efficiency (DE), and power-added efficiency (PAE), we provide a thorough understanding of the operational principles and distinct characteristics of each class. This comparative analysis offers a range of options to meet specific requirements and ensures seamless signal transmission in modern communication systems. With a particular emphasis on the demands of 5G networks for high-speed and high-capacity wireless communication, we emphasize the importance of these power amplifiers in achieving reliable and efficient connectivity. Our research contributes to the advancement of RF CMOS power amplifier design and offers valuable insights for the development of future communication systems.

Keywords: Power amplifier, class A power amplifier, linear power amplifier classes, switching Power amplifier, class F power amplifier

1. Introduction

RF CMOS power amplifiers play a crucial role in contemporary communication systems, particularly in the context of emerging technologies like 5G. These PAs are essential components that enable the long-distance transmission of high-frequency signals. Their significance lies in their ability to efficiently amplify signals while minimizing power consumption and preserving signal integrity. In the case of 5G networks, which operate at significantly higher frequencies compared to previous generations, RF CMOS PAs are indispensable for achieving faster data transmission speeds and greater capacity [1][2]. They contribute significantly to expanding coverage, improving network capacity, and enhancing the overall user experience promised by 5G. Moreover, the integration of CMOS technology allows for cost-effective mass production, making RF CMOS PAs a practical and viable choice for the widespread deployment of 5G infrastructure [3]. As the demand for high-speed and high-capacity wireless communication continues to surge, the importance of RF CMOS PAs in ensuring reliable and efficient connectivity cannot be overstated.

The classification of RF CMOS PAs provides a comprehensive understanding of their operational characteristics and performance. These PAs are typically classified into different categories, including linear amplifier classes. The initial group consists of traditional operation modes, namely class A, AB, B, and C, where the device functions as a current source [4][5]. The key distinction among these classes lies in the bias voltage applied to the gate, which determines the conduction angle of the current. As the conduction angle (θ) decreases from class A to C, the linearity of these PAs diminishes. However, reducing the conduction angle offers the advantage of increased efficiency [6]. The second category encompasses switching PAs that utilize the transistor as a switch to modulate the output voltage or current. Although class F is typically recognized as a switching PA, it can also operate as a transconductance PA based on the intensity of the active device's drive [7]. These PAs fall under the switched-mode classes, such as D, E, and F [8][9]. Each class presents distinctive characteristics in terms of power efficiency, linearity, and distortion, offering a range of options to meet specific requirements and effectively contribute to the seamless transmission of signals in modern communication systems, including 5G.

In this paper, we provide a comprehensive classification and comparative overview of CMOS RF PAs, focusing on their significance in contemporary communication systems, particularly in the context of 5G. We aim to bridge the gap in the existing literature by presenting a thorough examination of various PA classes, their operational principles, and performance metrics. By understanding the distinct characteristics of each class, researchers and engineers can make informed design choices to ensure reliable and efficient connectivity in modern communication systems. The subsequent sections of this paper delve into the detailed analysis and comparison of RF CMOS PA classes, providing valuable insights into their strengths, weaknesses, and applications. This paper is structured as follows: In Section 2, we delve into the Linear PA Classes A, B, AB, and C. We discuss the design principles, and operational theories, and provide calculations for efficiency, output capacity, power capability, and conduction angle for each class. Furthermore, a comprehensive comparison of these classes is presented. Moving on to Section 3, we explore the popular types of high-efficiency (switching) PAs, including harmonic enhancement class A, class D, class E, and class F. Section 4 covers an overview of other common PA classes, namely classes G, I, S, and T, highlighting their significant differences. In Section 5, we thoroughly compare the various linear and switching PA classes, identifying the key advantages and disadvantages associated with each class. Finally, we present the conclusions drawn from this manuscript in the final section.

2. Linear Power Amplifier Classes

2.1. Class-A Power Amplifiers

Class-A PAs are described as devices in which the transistor stays ON across the input and output range and functions linearly. Figure 1 depicts a typical class A output stage. Most traditional small-signal PAs come under the class-A classification, wherein the drain voltage is a duplicate of the insert voltage, and the relation between the two (voltage gain) remains constant or nearly constant quantity. To guarantee that the transistor does not switch off at any time during the signal excursion, the current in transistor bias is set greater than the highest signal current. After instance, just because the transistor is constantly ON doesn't mean the PA is sufficiently linear: in Figure 1 (a), if $I_1 = 5 * I_2$ the transconductance of the device fluctuates significantly from t_1 to t_2, despite the fact even though class-A requirement still applies. At this point, class-A becomes ambiguous. However, we may still state that class A operation is necessary if linearity is required [10].

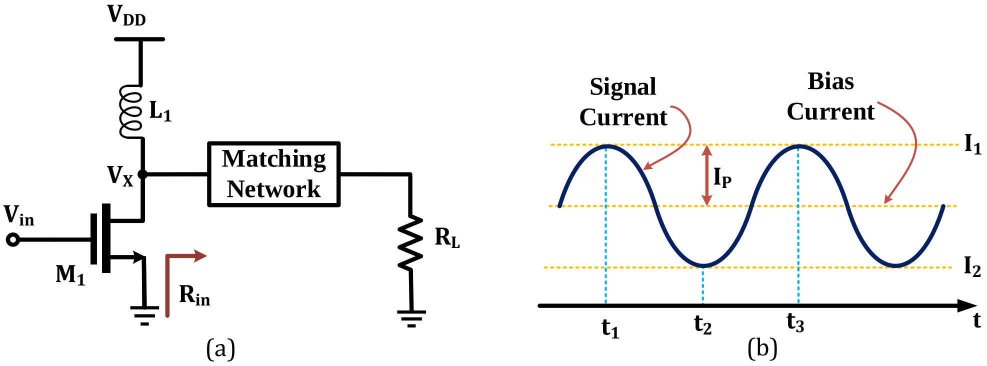


Figure 1. (a) Generic Class-A/B/C PA in one stage, (b) Class-A PA drain current waveform.

To find out the maximum DE of Class-A PA, allow V_X in Figure1(a) o reach $2V_{DD}$ and close to zero. Because of this, the power sent to the matched network is about equivalent to

$$P_{out,d} = \frac{\left(\frac{2V_{DD}}{2}\right)^2}{2R_{in}} = \frac{V_{DD}^2}{2R_{in}} \tag{1}$$

If the matching network is lossless, it is likewise provided to RL. A continuous current of V/Rin is also carried by the inductive load from the supply voltage. Thus,

$$\eta = \frac{V_{DD}^2/(2R_{in})}{V_{DD}^2/R_{in}} = 50\% \tag{2}$$

The M_1 itself dissipates the remaining 50% of the supplied power. There are numerous assumptions that result to Class-A stage efficiency of 50%: (1) the peak-to-peak output voltage oscillate is double the input, i.e., the device can hold up a bias voltage of $2V_{DD}$ beside no dependability or collapse problems; (2) the device just hardly turns OFF, i.e., the non-linearity caused by the device's huge variation in the transconductance is acceptable; (3) The antenna and the device output are connected through a lossless matching network.

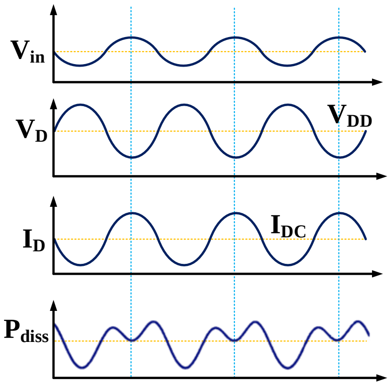


Figure 2. Time-domain signals in a class A PA.

Class A stage efficiency often ranges between 20 and 30% in practice because of swings that are less extreme than their highest and losses in the passive elements. Class A of PAs offers the greatest linearity at the price of efficiency in all classes. The huge amount of power dissipated in a class A amplifier's output device may also be seen by checking at the device's sinusoidal current and voltage waveforms, as shown in Figure 2. The current-voltage product, which equals the power dissipation in the transistor, is considerable and non-zero during the whole duration of the input sinewave.

A implementation measured that is sometimes utilized to comparison PA stages of different classes is P_{out} divided by the product of the maximum voltage ($v_{DS,max}$) over and maximum current ($i_{D,max}$) throughout the amplifying device. The power capability (P_{Cap}) statistic calculates the amount of strain placed on the device for a specific output power, is expressed as follows:

$$P_{Cap} = \frac{P_{out}}{v_{DS,max} \times i_{D,max}} \tag{3}$$

The P_{Cap} of a class A PA stage may be easily estimated as follows:

$$P_{Cap} = \frac{V_{DD}^2/(2R_L)}{(2V_{DD})(2V_{DD}/R_L)} = \frac{1}{8} \tag{4}$$

The "**conduction angle (θ)**" of the output transistor of PA classes can be used to differentiate them. It can calculated by multiplying the fraction of the input duration that the device remains on by 360°. Because the output transistor is always on in class-A stages, the $\theta = 360°$ [10].

2.2. Class-B Power Amplifiers

Over time, the classification of a class-B working has evolved. The classic class-B amplifier has both transistors in parallel, each with a value only $\theta = 180°$, resulting in a better efficiency than the class A equivalent. Figure 3 depicts a conventional class B PA, in which transformer T_1 combines the drain currents of M_1 and M_2. Class-B process necessitates that each device be turned off for half of the time. As a result, the bias voltage in the device's gate is tuned to be about equivalent to their threshold voltage [11].

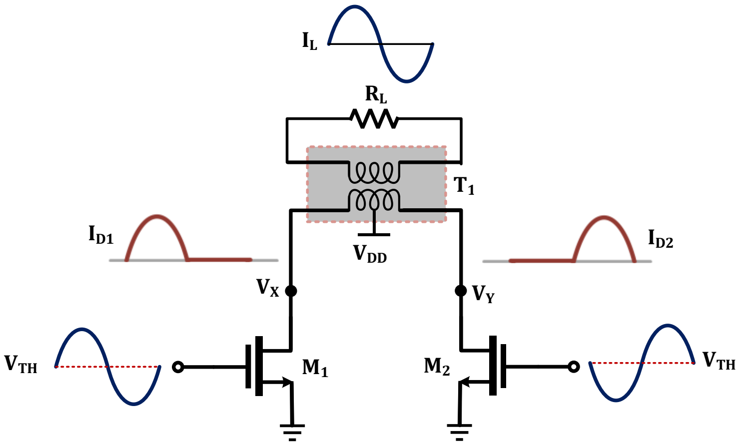


Figure 3. The traditional class B Amplifier.

In Figure 3, the V_X and V_Y are similarly simple half wave rectifier circuit that oscillate nearby V_{DD}, when the parasitic capacitances are small, and the primary/secondary inductances are big as shown in Figure 4. The oscillate over V_{DD} is lower than half of V_{DD}, which is unfavourable since it leads to inefficiency. As a result, a parallel capacitance is used to adjust the transformer's secondary (or primary) in order to damp the distortion of the simple rectifier network at X and Y, permitting identical fluctuations above and below V_{DD}.

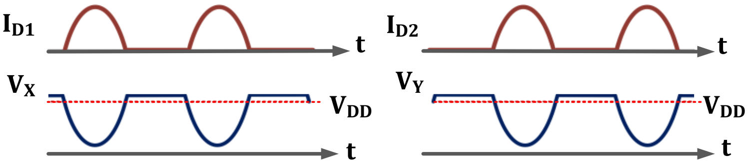


Figure 4. Class B stage's current and voltage output waveforms.

Assume that each device gets a maximum current of Ip from the main inductor in order to calculate efficiency for the class B stage. Because the other half of the primary winding has no current, this current passes through half of it. With the turns ratios indicated in Figure 5, we can see that a halfcycle sinusoidal current, $I_{D1} = I_P \sin \omega_0 t,\ 0 < t < \pi/\omega_0$, creates a comparable current in the secondary inductor, however with $(\frac{m}{n}) I_P$ as the peaking, generating an output voltage equal to:

$$V_{out}(t) = \frac{m}{n} I_P R_L \sin \omega_0 t \tag{5}$$

and delivering an average power of:

$$P_{out} = (\frac{m}{n})^2 \times \frac{R_L I_P^2}{2} \tag{6}$$

Each transistor draws an average half-wave rectification current of (I_P/π). Since V_{DD} receives both of this current wave for each time period, the medium power generated by V_{DD} is equal to:

$$P_{DC} = \frac{2 I_P V_{DD}}{\pi} \tag{7}$$

The DE of class B PA is calculated by dividing Eqs. (6) by (7):

$$\eta = (\frac{m}{n})^2 \frac{\pi I_P R_L}{4 V_{DD}} \tag{8}$$

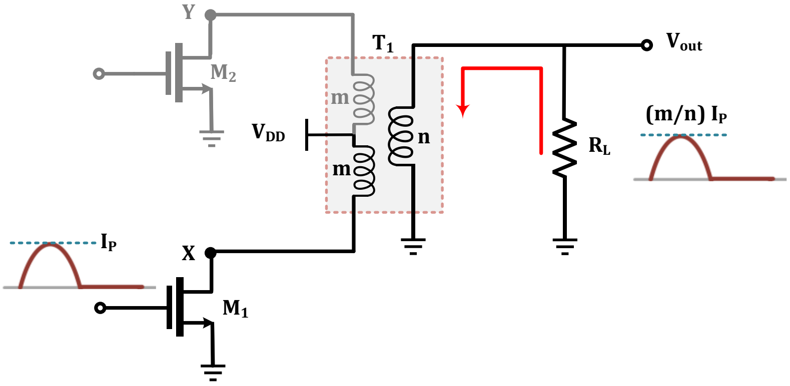


Figure 5. Class B circuit for efficiency calculation.

Due to the resonance's suppression of the upper harmonic's components of the simple rectifier period, the voltage swings at V_X and V_Y approximate sinewave with a dc value equal to V_{DD} and are 1800 out of phase. Which is:

$$V_X = V_P \sin\omega_0\, t + V_{DD} \quad and \quad V_Y = -V_P \sin\omega_0\, t + V_{DD} \qquad (9)$$

The peak swing V_P can be calculated as:

$$V_P = I_P R_L (\frac{m}{n})^2 \qquad 0)$$

To maximize efficiency, can choose V_P=V_{DD}, which we get from Eq (8):

$$\eta = \frac{\pi}{4} \approx 79\,\% \qquad (11)$$

Class B operation is frequently used in current RF design literature to refer to half of the circuits depicted in Figure 3, with the device conducting for just half cycle. Of course, a nonlinear circuit like this one has a maximum DE of π/4.

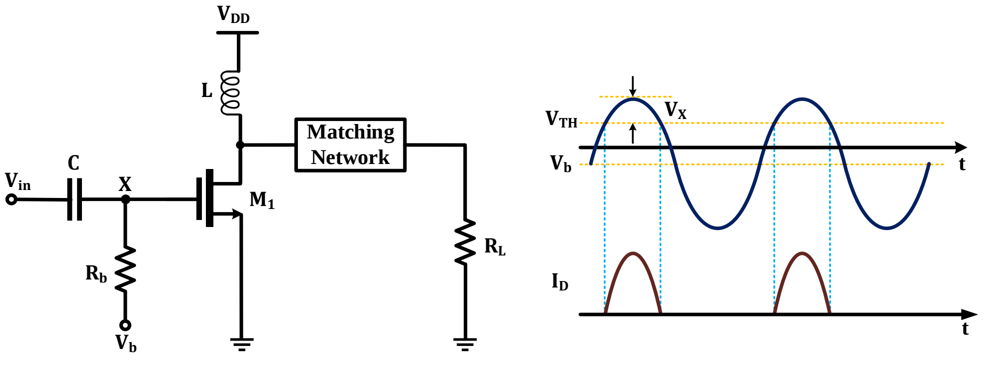
2.3. Class AB Power Amplifiers

Between classes A and B PAs performance, whose conduction angle ranges from 180^0 and 360^0 and an output transistor turn-off time of under half a second, are selected as the device bias conditions in class-AB. The biasing current ranges from 5 to 30% of the all PA current, according to the operating frequency, noise figure, efficiency, and linearity specifications. The class-AB is frequently utilised in single-ended PAs because it is more effective than class A and has greater linearity than class-B.

This is commonly as a result of the lowering bias voltage fluctuate and so move away from the 1dB compression point. Despite this, the designation "class AB" still ambiguous. The theoretical DE of a class AB is between 50 % and 79 % [12].

3.4. Class C Power Amplifiers

A decreased conduction angle provides a larger efficiency, according to our studies on class A, B, and AB stages. This angle is lowered further in class C circuits, and the circuit becomes more nonlinear [13]. Figure 6(a) shows how to adapt the class A topology to work in class C. The circuit is biased in Figure 6(a) so M_1 switches ON when the maximum value of V_{in} rises V_X beyond V_{TH}. Figure 6(b) demonstrates that V_X surpasses V_{TH} for a portion of the time. The outcome is a transient pulse of current at the output every cycle from the gadget.

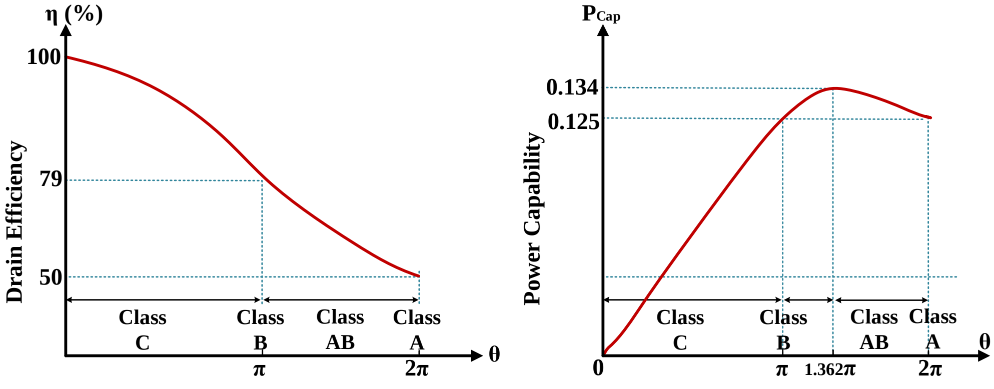


(a) (b)

Figure 6. (a) Class-C schematics, (b) Voltage and current signals for class-C PAs

The matching network should have some filtration to limit harmonic components at the antenna. In actuality, the matching circuit's input impedance is tuned to resonate at the desired frequency, resulting in a sinusoidal drain voltage. The difference between classes C and B PAs with one transistor is the conduction angle. The PA is switched ON for a decreasing proportion of the fundamental time, dissipation less power (P_{diss}). On the other hand, the PA supplies less power to R_L. If M_1's current through drain is supposed to be the maximined portion of a sinewave and the collector voltage is undertaken to be a sinewave using a highest value of V_{DD}, therefore the DE is [11]:

$$\eta = \frac{\theta - \sin\theta}{4\left[\sin\left(\frac{\theta}{2}\right) - \left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right)\right]} \tag{12}$$



(a) (b)

Figure 7. (a) Maximum DE as a parameter of conduction angle, (b) P_{Cap} as a parameter of conduction angle.

As θ approaches zero, this relationship (seen in Figure 7(a)) predicts a 100 percent efficiency. The class C stages' maximum efficiency of 100 percent is frequently cited as a distinguishing feature [14]. The actual power provided to the load, on the other hand, is an important factor to consider. It can be demonstrated that:

$$P_{out} \propto \frac{\theta - \sin\theta}{1 - \cos\left(\frac{\theta}{2}\right)} \tag{13}$$

Class C has a lesser power capacity than classes A and B PAs, as indicated in Figure 7(b). At a conduction angle of 1.362π, Class AB PAs have the highest P_{Cap} of 0.134. Although Figure 7(a) shows that when the conduction angle approaches zero, 100 percent efficiency may be reached, the power capability drops dramatically for tiny conduction angles, limiting the amount of conduction angle that can be decreased. Class C operation has been supplanted in contemporary RF design by more effective amplification methods that don't call for so massive transistors.

3. High-Efficiency Power Amplifiers

The output signal from the transistor in class A, B, and C PAs have always been assumed to be sinusoidal. Higher harmonics can be used to increase performance if this concept is abandoned. A big amplitude signal is used to drive the output waveform in a switching PA, which turns the device on and off like a switch. Amplifiers in this category are classified as class D, class E, and class F. The waveforms in the following topologies are shaped by specialized output passive networks, which reduce the amount of time the output device is carrying a significant current and maintaining a great voltage. This method lowers the transistor's power consumption while increasing efficiency. However, these amplifiers are frequently employed for power amplification of constant amplitude signals since the signal level at the amplifier's output does not significantly rely on the input signal [15][16].

3.1. Harmonic Enhancement Class A

Remember from a review of the class A circuit, that the transistor current swings a lot for maximum efficiency, causing nonlinearity. Presume the fundamental input impedance of the matching network is low, and the second harmonic input impedance is large [17].

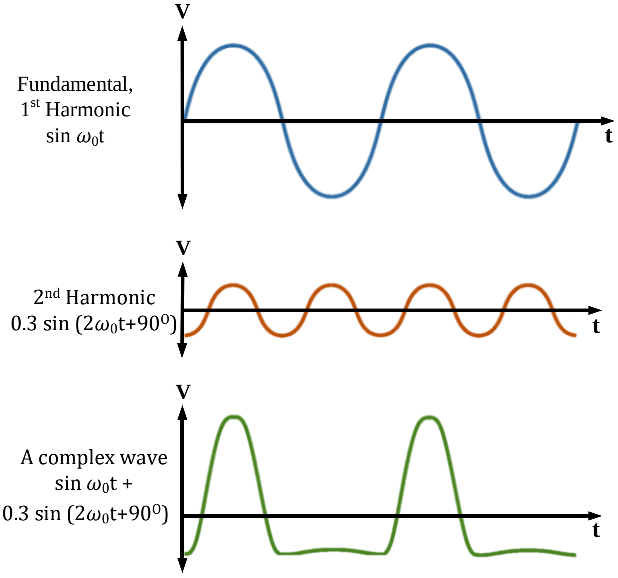
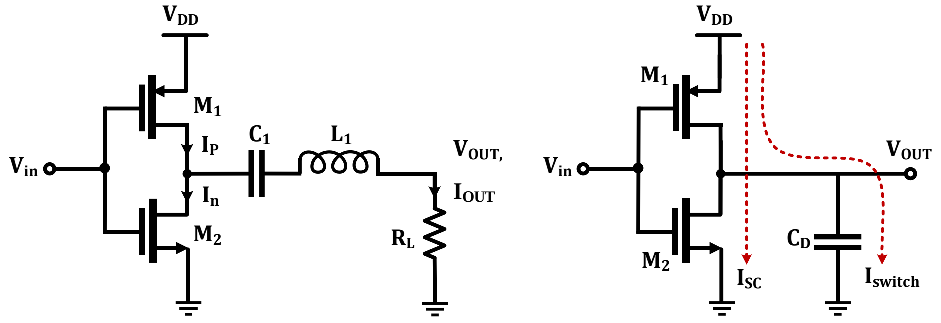


Figure 8. Example of Complex Waveforms due to the second harmonic.

The sum of the generated voltage waveforms, as shown in Figure 8, has thinner pulses than the center frequency, shortening the period across the output device's voltage and current. As a result, the output transistor's average power consumption falls and its efficiency rises. It's worth noting that the above change has no effect on the signal's harmonic content when delivered to the load [18]. The method only use various ports impedances for various harmonics to allow the output voltage from drain to approximate a square signal. This improvement technique can also be used with other PA classes.

3.2. Class D Power Amplifiers

A highly efficient PA may be constructed utilising inverters, as shown in Figure 9(a), by taking use of complementary MOS devices. Transistors are now employed as switches rather than current sources, enabling the output voltage to alternate between ground and V_{DD}. The fundamental concept underlying the great efficiency may be seen in Figure 10's IV characteristics, which show that while the transistors are conducting current, there is no voltage across them. Correspondingly, the current is zero when there is voltage across the switch [19][20].



(a) (b)

Figure 9. (a) Class-D PA construction, (b)CMOS inverter design with dynamic currents

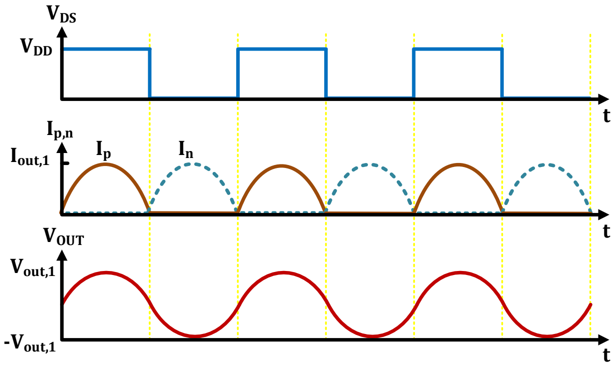


Figure 10. Class-D amplifier waveforms

However, in this amplifier class, there is no direct linear correspondence between the amplitude of the input and the output signals. However, it is possible to alter the output voltage amplitude by adjusting the duty cycle of the driving signal. When the driving signal has a duty cycle of 50%, the output signal will also have the same duty cycle. The square output signal waveform's Fourier coefficients indicate that power will be wasted in the harmonics Eq (14). To function as a BPF at the fundamental frequency, a filter, consisting of a capacitor (C_1) and inductor (L_1) in series with the load (R_L), is required. This indicates that the fundamental frequency is compelled to receive full power. Furthermore, we have the ability to compute the fundamental element of the output voltage over the load resistance and the load current utilizing equation (14). This calculation allows us to determine the output power specifically associated with the fundamental component as described in equation (15).

Upon establishing all the relevant relationships, the drain efficiency (DE) is computed to be 100 percent based on equation (16). However, it should be noted that such an ideal and completely lossless filter does not actually exist in practice. As a result, unless we offer a perfect filter, which is not feasible in real-world implementations, a large amount of power is lost in the harmonics. Due to factors such as the charging and discharging of the drain capacitance (C_D) and the presence of short-circuit power, the actual efficiency is lower than 100%. These elements introduce losses that contribute to a decrease in overall efficiency. The power dissipation of the amplifier output stage may be separated into dynamic and static power as shown in Figure 9(b). Switching and short-circuit power are the sources of dynamic power, whereas leakage is the source of static power.

$$b_n = [1-(-1)^n]\frac{V_{DD}}{n\pi} = v_{out,n} \tag{14}$$

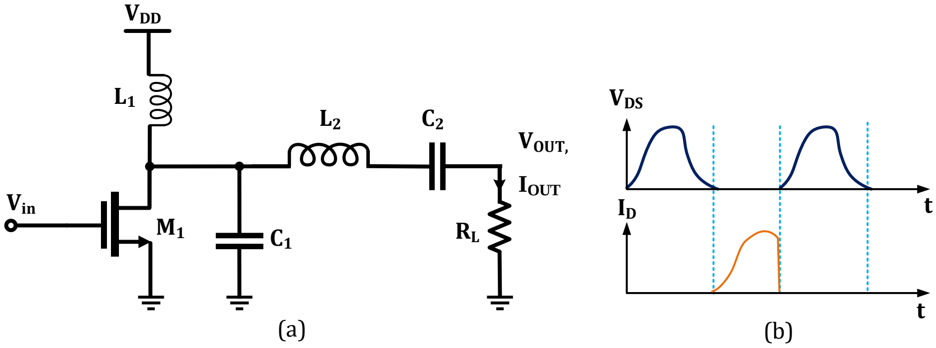
$$P_{out,1} = \frac{(v_{out,1}\times i_{out,1})}{2} = \frac{\left(\frac{2V_{DD}}{\pi}\right)\times\left(\frac{2V_{DD}}{\pi R_L}\right)}{2} = \frac{2V_{DD}^2}{\pi^2 R_L} \tag{15}$$

$$DE = \frac{P_{out,1}}{P_{DC}}\times 100 = \frac{2V_{DD}^2/\pi^2 R_L}{V_{DD}I_{DD}}\times 100 = \frac{2V_{DD}^2/\pi^2 R_L}{V_{DD}(2V_{DD}^2/\pi^2 R_L)}\times 100 = 100\ \% \tag{16}$$

3.3. Class E Power Amplifiers

Nonlinear amplifiers with Class E stages attain efficiency approaching 100% while supplying full power. The advantages of a switching technique in a class-D amplifier are eclipsed at high frequencies to the losses incurred by current and voltage interfere pending the device changeover. For solve this problem, the class-E PA design was created to reduce the interfere zone by controlling the amplifier's output network's transient response as shown in Figure 11(a). To minimise the current and voltage interfere in the amplifier during the device turn-off transient, The transistor voltage's amplitude and derivative are both zero when the device turns off thanks to the way the network at the output is constructed [20],[21].

Figure 11(b) shows the waveforms that correspond to this configuration. These requirements may be satisfied utilizing the network at output in Figure 11(b), as illustrated. According to an analytical derivation, the capacitors (C_1,C_2) and inductor (L_1,L_2)in a class-E design must have the succeeding values to meet the criteria at device turn-off [22]:



(a) (b)

Figure 11. (a) class-E PA stage, (b) Output waveforms

$$L_2 = \frac{QR_L}{\omega} \tag{17}$$

$$C_1 = 1/\left[\omega R_L\left(\frac{\pi^2}{4}+1\right)\left(\frac{\pi}{2}\right)\right] \approx \frac{1}{5.447\omega R_L} \tag{18}$$

$$C_2 \approx C_1\left(\frac{5.447}{Q}\right)\left(1+\frac{1.42}{Q-2.08}\right) \tag{19}$$

Where Q is the output matching network's quality factor. The class E design has the advantage of including a capacitor (*C_1*) at the transistor's drain. This design approach allows for the inclusion of parasitic capacitance at the drain of the device in the overall PA design. Consequently, there is no performing degradation or the need to eliminate this capacitor through resonance techniques. However, class-E architecture presents two significant drawbacks. According to the study, the voltage at the device's output can reach a maximum of 3.6 times the supply voltage (VDD). This substantial voltage swing poses limitations on implementing class-E PAs in modern CMOS technology, especially when compared to the maximum voltage swing of 2 times V_{DD} for classes A, B, and C PAs. The requirement of a input voltage greater than 1V effects in the drain voltage fluctuating up to 3.6 times V_{DD}, which exceeds the breakdown value of 3.5V in standard technology, leading to potential failure.

Class-E amplifiers have the drawback of reducing current and voltage interference during the turn-off transients. However, they do not address the issue of current and voltage interference during the turn-on transients, where significant overlap can still occur and potentially decrease power efficiency [23]. Despite these challenges, numerous effective integrated class E RF PA solutions have been published.

The P_{out} of a class-E PAs is:

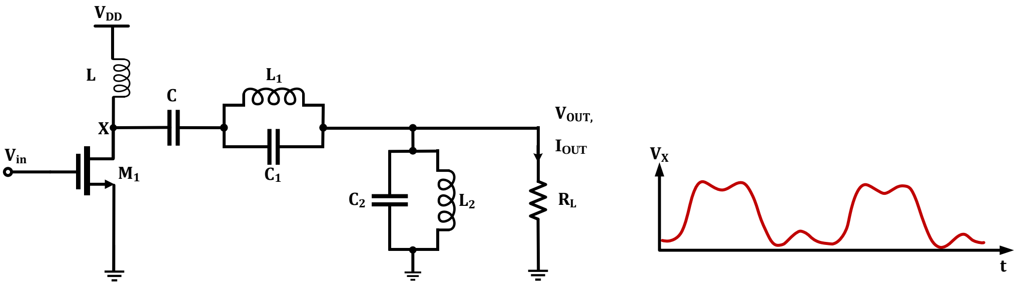
$$P_{out} = 0.5768 \times \frac{V_{DD}^2}{R_L} \tag{20}$$

and the power capability is:

$$P_{Cap} = \frac{P_{out}}{v_{DS,max} \times i_{D,max}} \approx 0.098 \tag{21}$$

3.4. Class F Power Amplifiers

Class F PAs were created to improve power efficiency by reducing the time necessary for voltage and current alterations across the output. This leads to transitions that are much sharper compared to those achieved with a sinusoidal waveform. When looking at the Fourier analysis of a square waveform with the sharpest transitions conceivable, it's clear that adding the signal's odd harmonics to its fundamental component results in sharper transitions. It can be demonstrated that simply adding the third harmonic improves efficiency significantly [24].



(a) (b)

Figure 12. (a) A class-F power amplifier stage, (b) Class-F amplifier waveforms

Figure 12(a) shows a third harmonic peaking class F amplifier stage. A parallel LC (L_1, C_1) circuit adjusted to the carrier frequency's 3rd harmonic is connected in series with the R_L to produce a high output impedance at the device's third harmonic drain. In order to eliminate all the harmonics, an additional parallel LC circuit (consisting of L_2 and C_2) tuned to the fundamental frequency is introduced in parallel with the load. Because both tuned circuits have a low second harmonic impedance, the total impedance observed by the amplifier's drain at the 2nd harmonic is small. This method of termination adds a third harmonic to the amplifier's drain voltage waveform, resulting in stronger switching transient transitions. With the adding of the 3rd harmonic, (V_X) approaches a rectangular waveform, as illustrated in Figure 12(b).

Using a large voltage to turn on and off the output transistor and a perfect square wave on the output load, the power at output of a class-F PA is [25]:

$$P_{out} = \left(\frac{4}{\pi}\right)^2 \times \frac{V_{DD}^2}{2R_L} \approx 0.811 \times \frac{V_{DD}^2}{R_L} \tag{22}$$

and the power capability is:

$$P_{Cap} = \frac{P_{out}}{v_{DS,max} \times i_{D,max}} \approx 0.16 \tag{23}$$

Class-F PAs present a higher output power for a provided input voltage and a higher P_{Cap} than class-E PAs. For a delivered P_{out} level, this corresponds to less stringent requirements for amplifier size and failure voltage for a class-F amplifier than for a class E amplifier. Several effective applications of class-F PAs have been prompted by these benefits.

4. Additional Popular Power Amplifier Classes

- **Class G Amplifier** — This type of amplifier improves on the original class AB design. Class G makes use of numerous power supply terminals with varied voltage levels and dynamically switches between them based on the input signal fluctuations. This continuous switching mechanism helps to reduce the typical power usage and subsequently minimizes the amount of energy lost due to heat dissipation. By intelligently managing the power supply voltages, Class G amplifiers offer improved efficiency and better utilization of power resources, resulting in enhanced performance [26].
- **Class-I Amplifier** — A Class-I PA employs two components are used in a parallel push-pull arrangement of complementary output switching transistors, both selection the identical input signal. Similar to Class B amplifiers, the waveform's positive and negative halves are switched by different devices. By employing a 50 percent PWM duty cycle, the two transistors element are s switched ON and OFF simultaneously, effectively eliminating any high-frequency signals when the signal reaches the zero-crossing point or there is no input signal. The duty cycle of the negative switching transistor is lowered, and vice versa, to produce the negative

half of the output waveform. The duty cycle of the positive switching transistor is raised to produce the positive half of the waveform. At switching frequencies higher than 250 kHz, the Class-I amplifier is known alternatively as a "interleaved PWM amplifier" due to the interleaved behaviour of the two switching signal currents at the output [22], [27].

- **Class S Amplifier** — This type of amplifier operates similarly to a class-D PA in that it is a non-linear switching mode PA. The class-S PA customs a delta-sigma modulation to transform analogue enter signals to digital square wave pulses, amplifies them to boost output power, and then demodulates them with a bandpass filter. Because the switching amplifier's digital signal is always completely "ON" or "OFF" (theoretically power dissipation $(P_{diss}) = 0$), and DE up to 100% are conceivable[28], [29].
- **Class-T Amplifier** — The class T amplifier is another type of digital switching amplifier. Because digital signal processing (DSP) chips and multi-channel surround sound amplifiers are more widely available, Class-T amplifiers are becoming more popular as a form of audio amplifier. These amplifiers utilize a conversion process where analog signals are transformed into digital PWM signals for amplification, resulting in improved DE. Class T amplifier designs combined the desirable traits of low distortion signal levels found in class AB amplifiers with the power efficiency of class D amplifiers. This combination allows Class T amplifiers to deliver high-quality audio reproduction with enhanced power efficiency, making them an attractive choice for audio applications.[30].

5. Comparison of Power Amplifiers classes

As well as variations in the proportion of the device's cycle that it is turned on or the conduction angle, various PA classes exhibit varying degrees of signal overload on the output stage. Using these traits as a basis, Figure 13 compares various PA classes. In the lower portion of the graph are illustrated amplifier classes like Class A, B, C, and AB that operate the output transistor more like a current source. In comparison to Class D, E, and F amplifiers, the overdrive voltage of the device is lower in these classes. The graph also introduces two additional modes of operation: saturated Class A and Class C. These modes involve driving the output stage with increased signal levels to enhance efficiency at the expense of linearity.

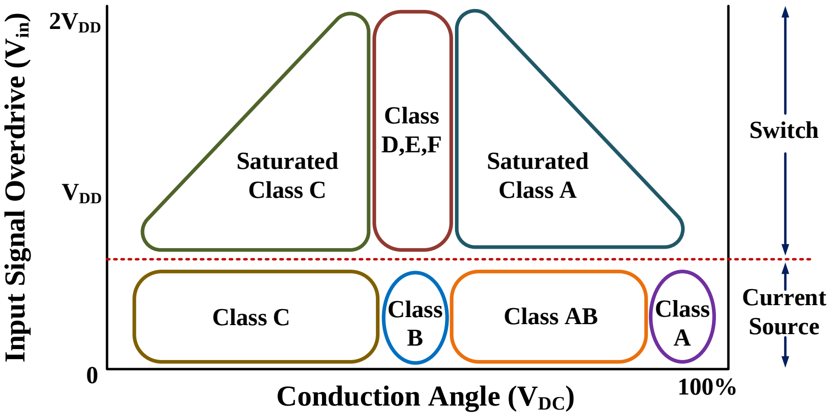


Figure 13. Contrasts several amplifier classes according to drive level and conduction angle.

Table 1. An overview of the characteristics of several PA classes.

Class	Max. efficiency (%)	conduction angle	Power output capability	Max. output power	Peak drain current	Peak drain voltage	Gain	Linearity
A	50	100%	0.125	$V_{DD}^2/2R$	$2V_{DD}/R$	$2V_{DD}$	Large	Good
B	79	50%	0.125	$V_{DD}^2/2R$	$2V_{DD}/R$	$2V_{DD}$	Moderate	Moderate
C	100	<50%	0.125	$V_{DD}^2/2R$	$2V_{DD}/R$	$2V_{DD}$	Small	Poor
D	100	50%	0.32	$\frac{2V_{DD}^2}{\pi^2 R}$	V_{DD}/R	V_{DD}	Small	Poor
E	100	50%	0.098	$0.57\frac{V_{DD}^2}{R}$	$1.7\frac{V_{DD}}{R}$	$3.6\,V_{DD}$	Small	Poor

F	100	50%	0.16	$0.81\frac{V_{DD}^2}{R}$	$\frac{8\,V_{DD}}{\pi\,R}$	$2.5\,V_{DD}$	Small	Poor

The features of several amplifier classes are summarized in Table 1. Class-A and B PAs are often employed in usages when linearity is critical, whereas switching amplifiers like class-E and F are utilised in situations when linearity can be traded for improved power efficiency.

6. Conclusions

In conclusion, the significance of CMOS RF PAs as essential components of transmitters cannot be overlooked. The efficiency, linearity, output power capability, and power dissipation in the circuit are influenced by the chosen amplifier class. Therefore, this paper provides a comprehensive classification of linear and high-efficiency (switching) CMOS RF PA classes, accompanied by a comparative analysis of their efficiency, conduction angle, power output capability, gain, and methods for calculating maximum drain current, voltage, and output power for each class. Each class of CMOS PAs is examined in terms of design and operational principles, highlighting their unique characteristics and trade-offs. Linear amplifier classes (A, AB, B, and C) exhibit varying levels of linearity and efficiency. Class A PAs prioritize maximum linearity at the cost of efficiency, while Class B PAs offer improved efficiency through alternative conduction angles. Class AB amplifiers strike a balance between efficiency and linearity, making them suitable for single-ended applications. Class C amplifiers, with lower conduction angles, deliver higher efficiency but with limited power capacity. Additionally, high-efficiency PAs such as Classes D, E, F, G, I, S, and T utilize specialized output networks to enhance performance and reduce power consumption. Switching PAs introduce innovative techniques leveraging higher harmonics and passive networks for improved efficiency. The integration of CMOS technology enables cost-effective mass production of RF PAs, making them practical and feasible for global deployment in 5G infrastructure. By understanding the characteristics and trade-offs of various CMOS RF PA classes, designers can make informed decisions to meet the specific requirements of modern communication systems and contribute to the successful implementation of 5G technology. Future research and development endeavors should focus on exploring innovative technologies to further enhance the efficiency, linearity, and overall performance of CMOS RF PAs.

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