Chapter 2
Efficiency Enhancement

Abstract This chapter presents some basic principles of RF power amplifiers, mainly dealing with the linearity–efficiency trade-off, to prepare the reader for the design of a dynamic supply CMOS RF power amplifier, subject of the next chapter. It also surveys the main efficiency-enhancement techniques found in the literature to establish a basis for comparison with the results presented in Chap. 4

2.1 Introduction

According to Kundert in [16], the two primary goals in a transmitter design are:

> First, they must transmit a specified amount of power while consuming as little power as possible. Second, they must not interfere with transceivers operating on adjacent channels.

Figure 2.1 depicts a simplified block diagram of a direct conversion transmitter. The RF power amplifier is the last component in the transmitter chain. Hence, the objectives stressed by Kundert are also valid for a PA design. These goals are better expressed through two performance metrics: efficiency and linearity. Therefore, the PA should be as efficient as possible and as linear as required by the system in which it operates. The major problem is that efficiency and linearity sit at opposite sides of a seesaw: when one goes up, the other goes down. This is the well-known linearity–efficiency trade-off inherent to RF power amplifier design.

2.2 Basic Principles

2.2.1 Linearity

The linearity of a PA is not of fundamental importance[1] in communication system transceivers with constant envelope modulation schemes. Since the RF signal

[1] But care should be taken to respect spurious emission limits.

P.A. Dal Fabbro, M. Kayal, *Linear CMOS RF Power Amplifiers for Wireless Applications,* Analog Circuits and Signal Processing,
DOI 10.1007/978-90-481-9361-5_2, © Springer Science+Business Media B.V. 2010

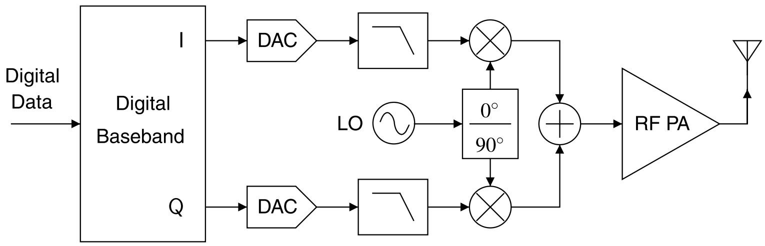

Fig. 2.1 Simplified block diagram of a direct conversion transmitter

amplitude bears no information, amplitude distortion does not alter the data to be transmitted. Constant envelope modulation schemes are used, for example, in the Advance Mobile Phone System (AMPS), Digital Enhanced Cordless Telecommunications (DECT), Global System for Mobile (GSM) communication, or Bluetooth.

On the other hand, systems employing variable envelope modulation schemes require linear RF PAs. In such a case, the RF signal amplitude contains part of the information to be transmitted. Therefore, if the RF signal undergoes amplitude distortion, the signal will not be correctly received. Variable envelope modulation schemes are used, for instance, in the North American Digital Cellular (NADC), Enhanced Data rates for the GSM Evolution (EDGE), Universal Mobile Telecommunication System (UMTS), or WLAN.

2.2.1.1 Metrics

Depending on the system, the linearity can be evaluated in a variety of ways. A linearity metric commonly used is the Adjacent Channel Power Ratio (ACPR) which measures the leakage of the RF signal into the adjacent channels. Another common linearity metric is the EVM which measures the vectorial difference between the location of the constellation points of the transmitted signal and its ideal location. A widely used method of evaluating the linearity—useful when the modulation signal cannot be generated by the available test equipment—is the 2-tone test [14, Chap. 2], [7, Chap. 9]. The linearity metric in this case is the IMD3. It is the ratio between the power of the strongest 3rd-order intermodulation product and the power of the corresponding fundamental tone. Intermodulation products of higher orders—5th or 7th—can also be used as linearity metrics as well as multi-tone tests can be performed. However, the IMD3 results of a 2-tone test are already good indicators of the linearity of a PA.

2.2.2 Efficiency

The efficiency of the PA is very important in wireless communication systems, mainly when they are employed in mobile devices. In this case, higher efficiency means longer battery lifetime which translates directly into user comfort. For non-portable applications, efficiency is also important as heat dissipation is often an issue.

2.2.2.1 Metrics

In the context of RF power amplifiers, two main efficiency metrics are commonly used: drain efficiency (η_d) and Power-Added Efficiency (PAE). The drain efficiency is calculated as the output power (P_{out}) divided by the DC power consumption (P_{DC}) as expressed below:

$$\eta_d = 100 \times \frac{P_{out}}{P_{DC}}. \tag{2.1}$$

The PAE is defined by Giannini and Leuzzi in [10, p. 164] as

> the ratio between the RF power *added* by the amplifier and the DC power required for this addition,

as shows the following equation.

$$\mathrm{PAE} = 100 \times \frac{P_{out} - P_{in}}{P_{DC}}. \tag{2.2}$$

The PAE is a better indicator than the drain efficiency because it includes the input power (P_{in}) and, hence, the gain of the power amplifier. When the power gain (G) is higher than 10 dB, the PAE can be approximated by the drain efficiency with an error smaller than 10% as suggested by the equations below:

$$G = \frac{P_{out}}{P_{in}}, \tag{2.3}$$

$$\mathrm{PAE} = \eta_d\left(1 - \frac{1}{G}\right). \tag{2.4}$$

2.3 Overview of the Main Efficiency-Enhancement Techniques

The linearity–efficiency trade-off is a problem that the RF PA designer has been trying to solve for a long time. Linearization as well as efficiency-enhancement techniques are possible solutions and the choice between them depends on the application and on the expertise of the designer. For application in WLAN, the requirement on the PA linearity is very stringent and, hence, it makes sense to choose to use a linear PA (class A, AB, or B) together with an efficiency-enhancement technique.

This chapter provides a review of the most important works recently published in the field of efficiency enhancement of RF power amplifiers. For more details regarding linearization techniques, the interested reader can refer to a dedicated textbook [14].

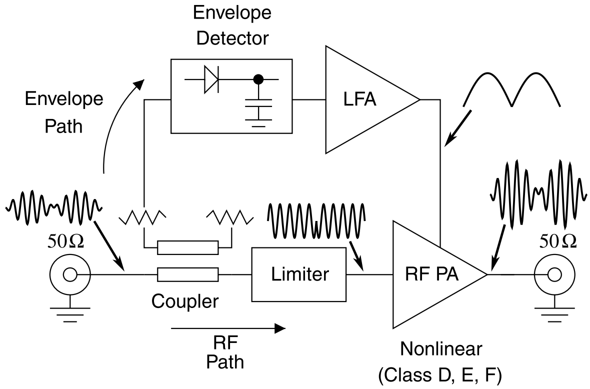

Fig. 2.2 EER technique—illustrative diagram

2.3.1 Envelope Elimination and Restoration

The Envelope Elimination and Restoration (EER) technique, also known as the Kahn technique [22], was introduced in the fifties by Kahn in [13]. Originally, Kahn developed this scheme to solve the problem of high cost and low efficiency in single-sideband[2] transmitters where typically a series of cascaded linear RF amplifiers were required. As the name suggests, in the EER technique, the *envelope* is first *eliminated* from the input RF signal, the remaining phase-modulated signal is amplified, and then, the envelope information is *restored* at the amplified output signal.

2.3.1.1 Classic Architecture

In classic EER transmitters, the envelope of the input RF signal is first detected and, then, the resulting low-frequency envelope signal is amplified by a highly-efficient, Low-Frequency Amplifier (LFA). This is the envelope path. In the RF path, the input signal passes through a limiter that removes the envelope from it. The phase-modulated signal is amplified by a highly-efficient nonlinear RF PA. The amplified envelope signal is then used to modulate the amplified output RF signal as shown in the block diagram of Fig. 2.2. Examples of classic EER systems can be found in [3, 21, 32].

2.3.1.2 Modern Architecture

In modern EER, the amplitude and phase information are generated separately in the baseband by a Digital Signal Processor (DSP). The phase-modulated signal is

[2]Single-sideband signals have both amplitude and phase modulation and, hence, require linear amplification.

upconverted to the RF frequency and amplified. In this case, EER becomes a misnomer since there is neither elimination nor restoration of the envelope [7, p. 311]. However, the name is still in use [17, 35].

Another name that is usually found in the literature referring to these modern EER implementations is *polar transmitter* [4, 15, 23]. This name stems from the fact that the baseband signals are converted to polar format—amplitude and phase—prior to amplification. However, this gives rise to some confusion [9, 28][3] due to the existence of a linearization technique called *polar-loop transmitter*, whose name was coined by Petrovic and Gosling in [19]. In the polar-loop transmitter, the output of the PA is sampled and converted to an Intermediate Frequency (IF) and used to linearize the power amplifier. The use of a feedback loop and baseband data in amplitude/phase domain, justifies the name of polar-loop transmitter. Examples of recent implementations of the polar-loop transmitter can be found in [1, 28].

In this book we use the term EER when referring to any system where the phase-modulated RF signal is amplified through a nonlinear amplifier and the low-frequency envelope amplitude signal is used to modulate the amplified output RF signal. In order to avoid confusion, we keep the term *polar* exclusively for polar-loop transmitters.

2.3.1.3 Advantages and Drawbacks

The main advantage of EER is the possibility of using, in variable envelope modulation systems, an efficient, nonlinear, switched-mode RF PA (class D, E, or F) instead of a low-efficiency, linear RF PA (class A, B, or AB). However, the requirements of the envelope amplifier or modulator—the output of the envelope amplifier modulates the amplitude of the output RF signal—are very stringent because it is responsible for passing the amplitude information to the output.

In order not to cancel out the benefits of the efficiency enhancement brought by the EER technique, the modulator itself must be very efficient. High-efficiency modulators are realized in practice with DC-DC converters. The stringent requirements of the EER translates into the maximum acceptable ripple at their output. A low-ripple DC-DC converter, in turn, requires a switching frequency (f_s) that is much higher than the maximum envelope bandwidth so that the low-pass filter can provide a high attenuation at f_s while passing the signals within the envelope bandwidth. However, high switching-frequency DC-DC converters are difficult to accomplish because of the losses in the switching elements. Hence, high envelope bandwidth systems can be prohibitive for the application of the EER technique.

[3] In [9], there is actually the elimination and restoration of the envelope. In [28], the author further separates polar transmitters in those using polar modulation prior to the PA and those using polar modulation with open-loop PA amplitude control.

2.3.1.4 CMOS IC Implementations (Refer also to Table 2.1)

Among the cited works about EER, only two are full-CMOS implementations [23, 32]. In the other works, different technologies are used. In [15], a SiGe BiCMOS technology is used to implement a class E n-FET PA and a class F Heterojunction Bipolar Transistor (HBT) PA. In [9], a 0.5 μm SiGe BiCMOS process is used to implement a bipolar variable-gain amplifier. In [3, 4], a discrete GaAs Heterojunction FET (HFET) is used to implement the PA, whereas the modulator is implemented in a CMOS technology.

Su and McFarland in [32] showed that a CMOS power amplifier using EER could reach 33% peak PAE and 3.4% EVM at an output power of 28 dBm (631 mW). The PA was designed for NADC applications, in which the signal has a Peak-to-Average Power Ratio (PAPR) of 3.5 dB [18]. The modulator attained 80% efficiency with a maximum bandwidth of 100 kHz.

Reynaert and Steyaert in [23] developed a CMOS power amplifier for EDGE transceivers in a 0.18 μm technology that attained a PAE of 22% at a maximum power of 23.8 dBm (240 mW) and 1.7% EVM (rms value). It is worth mentioning that Digital PreDistortion (DPD) and delay compensation were used in order to meet the spectral mask requirements, to improve the EVM performance, and to reestablish the spectrum symmetry.

2.3.2 Dynamic Supply RF Power Amplifier

An important drawback of the EER technique is the precision required for the amplitude modulator in replicating the input RF envelope at the supply of the PA. Another technique, called dynamic supply [8, 12, 27], solves this issue by removing the limiter from the RF path and, therefore, keeping the phase and amplitude modulation present on the signal to be amplified by the PA, as shown in the block diagram of Fig. 2.3. This, of course, requires a linear PA—which is not the case for EER—and, hence, makes the efficiency enhancement brought by this technique not as high as that achieved with EER.

In the dynamic supply technique, the power supply of the PA is varied according to the instantaneous value of the input RF signal envelope. Like EER, the envelope is extracted from the input RF signal by an envelope detector and fed to a high-efficiency modulator that transforms the low-level envelope signal into a high-level supply to the RF PA [6, Chap. 8]. However, differently from EER, in the dynamic supply PA the envelope signal is not used to modulate the PA, but only to provide a DC supply level that is just enough for the PA to amplify the input RF signal without compression [14, Chap. 8], [25]. Nevertheless, the name *modulator* for this block remains because it modulates the power supply; that is, its function is to change the amplitude of the power supply according to the instantaneous input RF signal envelope to increase the efficiency of the power amplifier.

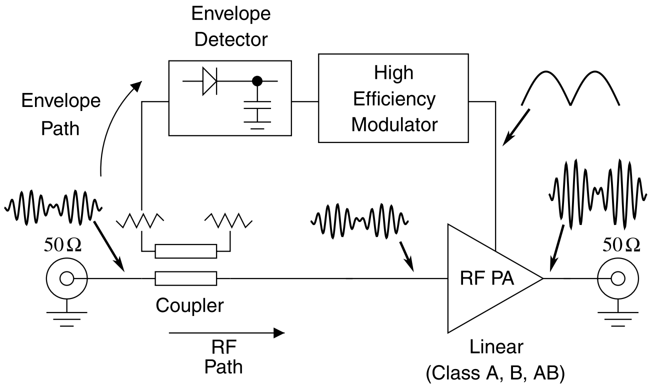

Fig. 2.3 Dynamic supply RF power amplifier block diagram

2.3.2.1 A Note on the Name of the Technique

This technique is also known under other names: *envelope tracking* (*ET*) [5, 17, 33], *bias adaption* [6, Chap. 8], and *envelope following* (*EF*) [29, 30]. However, the name *envelope tracking* is employed by Staudinger et al. in [31] to define a system in which the supply voltage of the PA is varied according to the long-term rms value of the input RF signal envelope. The name *bias adaption* might suggest that the PA operates in different classes according to the envelope amplitude, which is not the case. Although *envelope following*, used in [30, 31], could be an alternative name and a subclassification in *wideband*, *average*, and *step* for ET exists [35], in this book we use the term *dynamic supply* to avoid confusion.

2.3.2.2 Works on Dynamic Supply PAs (Refer also to Table 2.1)

Hanington et al. developed a boost converter using GaAs HBTs operating at a switching frequency of 10 MHz to improve the efficiency of a GaAs MEtal Semiconductor FET (MESFET) power amplifier operating at 4 GHz [11] and 950 MHz [12]. In [11], the supply voltage of the PA could be varied from 5 to 9 V which allowed the global efficiency of the PA to be improved by 45% (including 74% efficiency of the DC-DC converter). The PA attained an output power of 22 dBm (158 mW) with an efficiency of 43% at an IMD3 of −30 dBc. In [12], the supply voltage could be varied from 3 to 10 V, thereby improving the overall PA efficiency by 64% (74% DC-DC converter efficiency included). At 20 dBm (100 mW) output power, the efficiency was 14% and the ACPR was kept below the maximum IS-95[4] level of −26 dBc (30 kHz main channel bandwidth).

In [2, 24], the power supply voltage of a GaAs MESFET power amplifier can take two values (4 or 8 V), depending on the instantaneous value of the RF input

[4] IS-95—Interim Standard 95 (CDMA).

signal envelope. Instead of a DC-DC converter, a video amplifier is used to drive a bipolar transistor in an emitter-follower configuration with the envelope signal. The collector of this transistor is connected to the high-value power supply and its emitter to the drain of the GaAsFET (through an RF choke). When the envelope signal is low, the drain voltage of the GaAsFET is supplied by a low-voltage power supply through a diode. When the envelope signal reaches a certain level, the bipolar transistor conducts and supplies the voltage to the drain of the GaAsFET while turning-off the diode. With this scheme, 45% DC power consumption could be saved for operation at 4 GHz in a communication system employing Trellis Coded Modulation (TCM) with 8 dB PAPR. At 36 dBm (4 W) output power, with a 4-tone input, the intermodulation distortion was kept below −50 dBc.

Schlumpf et al. in [25–27] describe a dynamic supply PA in which the modulator is implemented in a 0.35 μm CMOS technology and the PA is realized with discrete bipolar transistors. A sliding-mode modulator controlled by hysteresis varies dynamically the supply of the PA according to the input RF signal envelope. The delay introduced by the modulator plays the role of hysteresis and together with the phase shift of the LC filter defines the switching frequency. Therefore, a small delay is desired in order to increase the switching frequency, thereby reducing the output ripple. A delay of 4 ns was achieved allowing a maximum switching frequency of 16 MHz. The system was designed for CDMA applications, for which the standard IS-95 defines a maximum Adjacent Channel Leakage Ratio (ACLR[5]) of −45 dBc (1.23 MHz main channel measurement bandwidth). The dynamic supply PA improves by 5% the PAE—a factor of 1.1 in relative terms—in comparison to the same PA operating under a constant 3.3 V power supply at the maximum linear output power (20 dBm at −45 dBc ACLR). At low output power levels, a relative improvement in efficiency of a factor of 2.1 is achieved. The rms value of the measured EVM at the maximum linear output power is 4.9% (25% peak) for the dynamic supply PA and 3.8% (19% peak) for its constant supply counterpart.

In [33], a dynamic supply PA based on discrete components is described. The modulator is implemented with discrete MOSFETs and the class AB RF PA with GaAs HFETs. The system is intended for application in WLAN transceivers operating at 2.4 GHz (IEEE 802.11g). In order to attain acceptable EVM levels, predistortion is used. An output power of 15.1 dBm (32.3 mW), a PAE of 25%, and a gain of 8 dB are attained at an EVM of 3.2%. This compares to an output power of 11 dBm (12.6 mW), a PAE of 8.2%, a gain of 10.7 dB at an EVM of 2.8% attained by the constant supply (4.4 V) power amplifier. Although the dynamic supply PA presents a much better performance than its constant supply counterpart, the comparison does not make much sense because the power amplifiers used are not the same (a MWT-871 GaAs MESFET for the constant supply and an SHF-0289 HFET for the dynamic supply PA).

[5] ACLR and ACPR are different names for the same linearity measurement.

Table 2.1 Summary of the main performance metrics of works on efficiency-enhanced PAs

Reference	[32]	[23]	[2]	[12]	[27]	[33]	[35]
Year	1998	2005	1995	1999	2004	2004	2006
Technique	EER	EER	Dyn.	Dyn.	Dyn.	Dyn.	Switched Dyn.
Technol. PA	CMOS	CMOS	Discr.	GaAs	Discr. Bip.	Discr. GaAs	Discr. Bip.
Technol. Mod.	CMOS	CMOS	Discr. GaAs	GaAs	CMOS	Discr. MOS	Discr. MOS
Supply (V)	3	3.3	–	3.6	3.3	6	5.5
f_c (GHz)	0.835	1.75	4	0.95	1.9	2.4	2.4
P_{out} (dBm)	28	23.8	36	20	20.5	15.1	19
PAE (%)	33	22	11.7	14	32	25	28
ACPR (dBc)	–	–	–	−26	−45	–	–
EVM (%)	3.4	1.7	–	–	4.9	3.2	2.8
IMD3 (dBc)	–	–	−50	–	−30	–	–
Mod. Eff. (%)	80	–	–	74	85	75	60
f_s (MHz)	–	–	–	10	16	7	6
Linearization	–	DPD	–	–	–	DPD	DPD
Application	NADC	EDGE	TCM	CDMA	CDMA	WLAN	WLAN

Note: Technol. = Technology; Mod. = Modulator; Eff. = Efficiency; Discr. = Discrete; Bip. = Bipolar

2.3.2.3 Dynamic Supply with Switched-Mode PA

Wang et al. in [35] call their system *hybrid EER* because the signal at the input of the PA is still a complex-modulated signal (like in the dynamic supply PA) and the PA operates in switched-mode (like in EER). However, there is neither elimination nor restoration of the envelope and, hence, the name EER for this technique is also a misnomer. As it was stated previously, the dynamic supply technique requires a linear PA so that the maximum distortion constraints can be respected. Hence, in [35], the authors used predistortion in order to circumvent the inherent distortion problems. An important contribution from their work, however, was the detailed description of the implementation of a split-band modulator. This modulator solved the problem of limited bandwidth by using a linear regulator to provide the dynamic supply when the envelope frequency is high and a buck converter to provide the dynamic supply when the envelope frequency is low. The system presented a PAE of 28% and an EVM of 2.8% at an output power of 19 dBm (80 mW). The same split-band modulator was also used in [20, 33, 34, 36].

2.4 Conclusion

This chapter presented the motivation and some basic concepts of efficiency enhancement of RF PAs. The main works dealing with PA supply modulation for efficiency enhancement purposes were covered. It was discussed that using envelope elimination and restoration can result in a high efficiency improvement, but it places a very stringent requirement on the modulator design. The dynamic supply technique, although offering lower efficiency improvement than EER, has looser modulator requirements and, hence, is a good compromise for the implementation of efficiency-enhanced PAs. Table 2.1 summarizes the main performance metrics of the most important works on efficiency enhancement found in the literature. It shows that the performance of the EER and the dynamic supply techniques are comparable and that none of the works on dynamic supply integrates both the modulator and the RF power amplifier on the same die. In the next two chapters, the design and experimental characterization of a full-CMOS implementation of the dynamic supply RF power amplifier are presented.

References

1. Akamine Y, Tanaka S, Kawabe M, Okazaki T, Shima Y, Masahiko Y, Yamamoto M, Takano R, Kimura Y (2007) A polar loop transmitter with digital interface including a loop-bandwidth calibration system. In: IEEE Int Solid-State Circuits Conf Dig Tech Pap (ISSCC'07), San Francisco, CA, pp 348–608
2. Buoli C, Abbiati A, Riccardi D (1995) Microwave power amplifier with 'envelope controlled' drain power supply In: Eur Microw Conf (EuMC'95), Bologna, Italy vol 1, pp 31–35
3. Chen JH, U-yen K, Kenney JS (2004) An envelope elimination and restoration power amplifier using a CMOS dynamic power supply circuit. In: IEEE MTT-S Int Microw Symp Dig (IMS'04), Fort Worth, TX, vol 3, pp 1519–1522
4. Chen JH, Fedorenko P, Kenney JS (2006) A low voltage W-CDMA polar transmitter with digital envelope path gain compensation. IEEE Microw Wirel Compon Lett 16(7):428–430
5. Clifton JC, Albasha L, Lawrenson A, Eaton AM (2005) Novel multimode J-pHEMT front-end architecture with power-control scheme for maximum efficiency. IEEE Trans Microw Theory Tech 53(6):2251–2258
6. Cripps SC (1999) RF Power Amplifiers for Wireless Communications, 1st edn. Artech House, Norwood
7. Cripps SC (2006) RF Power Amplifiers for Wireless Communications, 2nd edn. Artech House, Norwood
8. Dal Fabbro PA, Meinen C, Kayal M, Kobayashi K, Watanabe Y (2006) A dynamic supply CMOS RF power amplifier for 2.4 GHz and 5.2 GHz frequency bands. In: IEEE Radio Freq Integr Circuits Symp (RFIC'06), San Francisco, CA, pp 169–172
9. Elliott M, Montalvo T, Murden F, Jeffries B, Strange J, Atkinson S, Hill A, Nandipaku S, Harrebek J (2004) A polar modulator transmitter for EDGE. In: IEEE Int Solid-State Circuits Conf Dig Tech Pap (ISSCC'04), San Francisco, CA, vol 1, pp 190–522
10. Giannini F, Leuzzi G (2004) Nonlinear Microwave Circuit Design. Wiley, Chichester
11. Hanington G, Chen PF, Radisic V, Itoh T, Asbeck PM (1998) Microwave power amplifier efficiency improvement with a 10 MHz HBT. In: IEEE MTT-S Int Microw Symp Dig (IMS'98), Baltimore, MD, vol 2, pp 589–592
12. Hanington G, Pin-Fan C, Asbeck PM, Larson LE (1999) High-efficiency power amplifier using dynamic power-supply voltage for CDMA applications. IEEE Trans Microw Theory Tech 47(8):1471–1476

13. Kahn LR (1952) Single-sideband transmission by envelope elimination and restoration. Proc IRE 40(7):803–806
14. Kenington PB (2000) High-Linearity RF Amplifier Design. Artech House, Boston
15. Kitchen JD, Deligoz I, Kiaei S, Bakkaloglu B (2006) Linear RF polar modulated SiGe class E and F power amplifiers. In: IEEE Radio Freq Integr Circuits Symp (RFIC'06), San Francisco, CA, pp 475–478
16. Kundert KS (1999) Introduction to RF simulation and its application. IEEE J Solid-State Circ 34(9):1298–1319
17. Larson L, Asbeck P, Kimball D (2007) Multifunctional RF transmitters for next generation wireless transceivers. In: Proc Int Symp Circuits and Syst (ISCAS'07), New Orleans, LA, pp 753–756
18. McCune JEW (2003) Multi-mode and multi-band polar transmitter for GSM, NADC, and EDGE. In: IEEE Wirel Commun Netw Conf (WCNC'03), New Orleans, LA, vol 2, pp 812–815
19. Petrovic V, Gosling W (1979) Polar-loop transmitter. Electron Lett 15(10):286–288
20. Popp J, Lie DYC, Wang F, Kimball D, Larson L (2006) A fully-integrated highly-efficient RF class E SiGe power amplifier with an envelope-tracking technique for EDGE applications. In: IEEE Radio Wirel Symp (RWS'06), San Diego, CA, pp 231–234
21. Raab FH, Sigmon BE, Myers RG, Jackson RM (1998) L-band transmitter using Kahn EER technique. IEEE Trans Microw Theory Tech 46(12):2220–2225
22. Raab FH, Asbeck P, Cripps S, Kenington PB, Popovic ZB, Pothecary N, Sevic JF, Sokal NO (2002) Power amplifiers and transmitters for RF and microwave. IEEE Trans Microw Theory Tech 50(3):814–826
23. Reynaert P, Steyaert MSJ (2005) A 1.75-GHz polar modulated CMOS RF power amplifier for GSM-EDGE. IEEE J Solid-State Circ 40(12):2598–2608
24. Riccardi D, Abbiati A, Buoli C (1995) Linear microwave power amplifier with supply power injection controlled by the modulation envelope. International Patent, WO 95/34128
25. Schlumpf N (2004) Adaptation dynamique de la compression d'un amplificateur RF pour des signaux modulés en amplitude et en phase. PhD thesis, EPFL, Lausanne, Switzerland. URL http://library.epfl.ch/theses/?nr=3020
26. Schlumpf N, Declercq M, Dehollain C (2003) A fast modulator for dynamic supply linear RF power amplifier. In: Proc IEEE Eur Solid-State Circuits Conf (ESSCIRC'03), Estoril, Portugal, pp 429–432
27. Schlumpf N, Declercq M, Dehollain C (2004) A fast modulator for dynamic supply linear RF power amplifier. IEEE J Solid-State Circuits 39(7):1015–1025
28. Sowlati T, Rozenblit D, Pullela R, Damgaard M, McCarthy E, Koh D, Ripley D, Balteanu F, Gheorghe I (2004) Quad-band GSM/GPRS/EDGE polar loop transmitter. IEEE J Solid-State Circ 39(12):2179–2189
29. Staudinger J (2002) An overview of efficiency enhancements with application to linear handset power amplifiers. In: IEEE Radio Freq Integr Circuits Symp (RFIC'02), Seattle, WA, pp 45–48
30. Staudinger J, Gilsdorf B, Newman D, Norris G, Sadowniczak G, Sherman R, Quach T, Wang V (1999) 800 MHz power amplifier using envelope following technique. In: IEEE Radio Wirel Conf (RAWCON'99), Denver, CO, pp 301–304
31. Staudinger J, Gilsdorf B, Newman D, Norris G, Sadowniczak G, Sherman R, Quach T (2000) High efficiency CDMA RF power amplifier using dynamic envelope tracking technique. In: IEEE MTT-S Int Microw Symp Dig (IMS'00), Boston, MA, vol 2, pp 873–876
32. Su DK, McFarland WJ (1998) An IC for linearizing RF power amplifiers using envelope elimination and restoration. IEEE J Solid-State Circ 33(12):2252–2258
33. Wang F, Ojo A, Kimball D, Asbeck P, Larson L (2004) Envelope tracking power amplifier with pre-distortion linearization for WLAN 802.11g. In: IEEE MTT-S Int Microw Symp Dig (IMS'04), Fort Worth, TX, vol 3, pp 1543–1546
34. Wang F, Kimball D, Popp J, Yang A, Lie DYC, Asbeck P, Larson L (2005) Wideband envelope elimination and restoration power amplifier with high efficiency wideband envelope amplifier

for WLAN 802.11g applications. In: IEEE MTT-S Int Microw Symp Dig (IMS'05), Long Beach, CA, pp 645–648

35. Wang F, Kimball DF, Popp JD, Yang AH, Lie DY, Asbeck PM, Larson LE (2006) An improved power-added efficiency 19-dBm hybrid envelope elimination and restoration power amplifier for 802.11g WLAN applications. IEEE Trans Microw Theory Tech 54(12):4086–4099
36. Wang F, Kimball DF, Lie DY, Asbeck PM, Larson LE (2007) A monolithic high-efficiency 2.4-GHz 20-dBm SiGe BiCMOS envelope-tracking OFDM power amplifier. IEEE J Solid-State Circuits 42(6):1271–1281

Springer

http://www.springer.com/978-90-481-9360-8

Linear CMOS RF Power Amplifiers for Wireless Applications
Efficiency Enhancement and Frequency-Tunable Capability
Dal Fabbro, P.A.; Kayal, M.
2010, XIV, 220 p., Hardcover
ISBN: 978-90-481-9360-8