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ANALYSES OF A CLASS G POWER AMPLIFIER WITH CONTROLLED NONLINEAR DISTORTION FOR LTE-SIGNAL

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Abstract. The work considers an analysis of nonlinear distortions in a class G power amplifier and an analysis of an envelope tracking power amplifier with a proposed combined envelope amplifier scheme for LTE cellular base stations. Both considered envelope amplifier schemes feature an additional shaping function to compensate for the AM-AM conversion of the power amplifier, as well as DPD correction for the AM-PM conversion of the amplifier. The analysis results showed that switching between 18 supply voltage levels in the class G power amplifier allows achieving an ACPR characteristic of the output LTE signal at an acceptable level of –50 dBc. Simulation has proved that a standard predistortion technique based on LUT or a Volterra series can be applied to a class G power amplifier at N = 18. The number of supply voltage levels can be reduced to N = 10 using the proposed combined scheme or by applying additional voltage supply filtration of the envelope amplifier.

Keywords: class G power amplifier, nonlinear distortions, drain efficiency, DPD, LTE

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АНАЛИЗ УСИЛИТЕЛЯ МОЩНОСТИ КЛАССА G С КОНТРОЛИРУЕМЫМ УРОВНЕМ НЕЛИНЕЙНЫХ ИСКАЖЕНИЙ ДЛЯ LTE-СИГНАЛА

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Аннотация. В работе показан анализ нелинейных искажений усилителя мощности класса G и усилителя мощности с непрерывным отслеживанием огибающей на основе предложенной комбинированной схемы усилителя огибающей для базовых станций сотовой связи стандарта LTE. Обе рассмотренные схемы усилителей огибающей имеют дополнительную формирующую функцию для компенсации АМ-АМ конверсии усилителя мощности, а также DPD коррекцию АМ-ФМ конверсии усилителя. Результаты анализа показали, что коммутация между 18 уровнями напряжения питания в усилителе мощности класса G позволяется получить характеристику ACPR выходного LTE-сигнала на допустимом уровне –50 дБн. Моделированием доказано, что к усилителю мощности класса G возможно применить стандартную методику предыскажений на основе LUT или рядов Вольтерра при N = 18. Количество уровней возможно уменьшить, используя предложенную комбинированную схему усилителя огибающей до 10 или применить дополнительную фильтрацию выходного сигнала усилителя огибающей.

Ключевые слова: усилитель мощности класса G, нелинейные искажения, КПД, DPD, LTE

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Introduction

The widespread use of orthogonal frequency-division multiplexing (OFDM) signals with a high peak-to-average power ratio (PAPR) requires an improvement in radio frequency power amplifier (RFPA) schemes. Designing 4G base stations using OFDM technology requires high-efficiency LTE signal transmission. An envelope tracking power amplifier (ETPA) is a relevant solution to this problem in multiband applications.

An ETPA includes an envelope amplifier (EA) module (Fig. 1). The EA input ($U_{\text{in env}}$) receives an envelope detector signal with a maximum voltage 3.3 or 5 V. The EA output ($U_{\text{out env}}$) provides a variable supply voltage with a maximum value (e.g., 28 V) and the current required by the RFPA. Therefore, EA efficiency determines overall efficiency of the ETPA in many applications. Numerous studies [1–4] are devoted to improvements in the EA efficiency. An ETPA has maximum efficiency when the RFPA has a continuous supply voltage variation, as show in Fig. 3, *a*. Today, hybrid envelope amplifier (HEA) schemes, combining the pulse and linear parts (Fig. 2), are widely used. However, due to the presence of inductance (L_{th}) and other reactive elements, HEA efficiency is limited to 75–85% [4–7]. There are various modifications of HEA schemes [4], that can solve this problem, but improving HEA efficiency remains a relevant challenge.

There are EA schemes based on pulse-width modulated DC-DC power converters with an efficiency of over 90%. In such schemes, the high clock frequency of the pulse-width modulator makes

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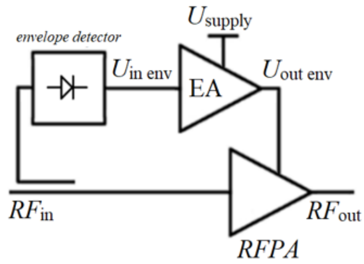

Fig. 1. ETPA

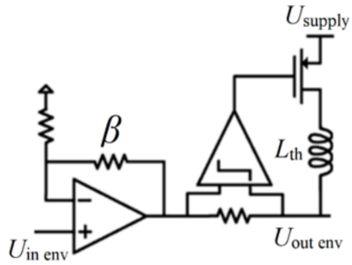

Fig. 2. HEA

it difficult to use these EA for signals with a bandwidth of over several tens of MHz. It is possible to reduce the clock frequency of this EA scheme by moving from continuous supply voltage variation (Fig. 2, *a*) towards discrete supply voltage switching (Fig. 2, *b*). An RFPA with discrete supply voltage switching is called a class G RFPA [8–11]. The disadvantage of class G RFPA is that the gain vs input power dependence has points of discontinuity. The presence of these points necessitates the use of non-standard digital pre-distortion (DPD) techniques.

Also, discrete supply voltage switching can be used to improve HEA efficiency. A supply voltage waveform for this scheme is shown in Fig. 2, *c*. The proposed scheme is called the combined envelope amplifier (CEA) and have better efficiency than HEA. An EA efficiency in a class G RFPA is 97% [11], and the HEA efficiency is only 60%. If the CEA switches the supply voltage discretely with a probability of 7/8 and continuously tracks the envelope with a probability of 1/8 using the HEA, then the total efficiency of such a CEA will be equal to 7/8·97% + 1/8·60% = 92.4%. With a probability of 15/16, the total CEA efficiency is 94.7%, which is only 2.3% lower than the class G RFPA efficiency. Therefore, the use of discrete supply voltages switching in the HEA can increase efficiency from 60% to 94.7%. This purpose of this study is to analyze the CEA and the class G EA to determine the optimal parameters for achieving minimal distortion of an LTE signal.

Analysis and synthesis of the EA for the class G RFPA or CEA involves finding the number of discrete supply voltages and their value, as well as the levels of U_{in} env at which the discrete supply voltages will switch. For example, the EA development for the class G RFPA in [11] showed that five discrete supply voltages are enough for achieving maximum efficiency. However, the analysis and synthesis of the EA for the class G RFPA can be considered in terms of nonlinear distortions rather that the efficiency of the class G RFPA and CEA. Adjacent channel power ratio (ACPR) is a useful RFPA characteristic showing the impact of nonlinear distortion on output signal. In this work, ACPR characteristic is used as a nonlinear RFPA distortion indicator. According to the 3GPP standard, the permissible ACPR level for an LTE signal should not exceed –50 dBc.

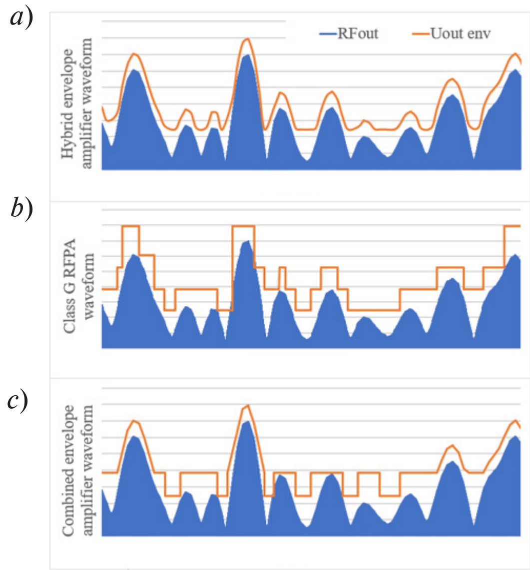

Fig. 3. Supply voltage waveform: ETPA with continuous supply voltage (*a*), class G RFPA (*b*), ETPA with CEA (*c*)

Thus, the article presents an analysis of two schemes: the EA for the class G RFPA and CEA. The schemes were analyzed using an LTE signal with a bandwidth of 20 MHz in the E-TM 3.1 test configuration. The work uses a nonlinear model of the main RFPA operating in the 700–1000 MHz frequency range, with a saturated power of 44.5 dBm at 28 V supply voltage; its measurement results are given in [10]. The analysis results show how the nonlinear distortions of the output LTE signal (reflected in ACPR) change under different configurations of these EA schemes.

Results

ACPR is influenced by several factors, such as AM-AM and AM-PM conversions, inertial effects of passive components etc. AM-AM and AM-PM conversions play a key role in increasing the nonlinear distortion level. It is possible to correct AM-AM conversion in an ETPA by using the shaping function module [12]. The shaping function compares $U_{\text{out env}}$ with $U_{\text{in env}}$. The gain coefficient β (Fig. 2) of an operational amplifier can be used as the shaping function in the HEA. Let us consider the operation principles of the shaping function using the ETPA model in CAD VSS and Microwave Office as an example (Fig. 4).

Fig. 4 shows the gain vs input power function at different supply voltages (dotted lines) for the nonlinear RFPA model. An increase in supply voltage leads to an increase in gain, resulting in AM-AM conversion in the ETPA. The shaping function should change supply voltage in such a way that the gain compression compensates for this gain increase. The gain vs input power function for the ETPA with the shaping function is shown in Fig. 4 (solid line). However, the shaping function cannot correct AM-PM conversion in the ETPA (Fig. 5). The standard DPD technic, using a look-up table (LUT) or Volterra series, can correct AM-PM conversion. Fig. 6 shows the power spectral density (PSD) of output signal with and without DPD (Fig. 6), which corrects only the AM-PM conversion in the ETPA with the shaping function. The use of DPD has improved ACPR by 13 dB from –42 dBc to –55 dBc. For cellular base stations, according to the 3GPP specification, the allowed ACPR level is –50 dBc. The shaping function for the class G RFPA defines a strict relationship between the supply voltage and the reference voltages of the comparators, which determines the moment of supply voltage switching, according to $U_{\text{in env}}$. Furthermore, this article assumes that at a certain supply voltage, the comparator reference voltage level will be calculated automatically, according to the shaping function.

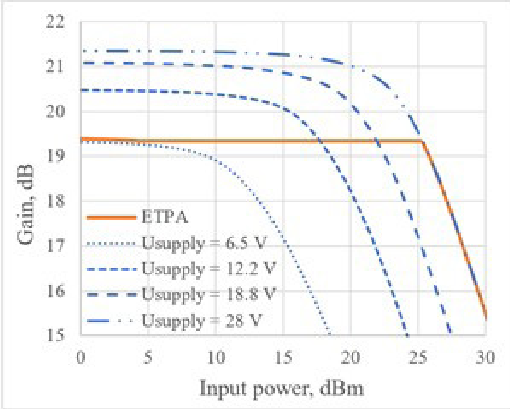

Fig. 4. AM-AM conversion

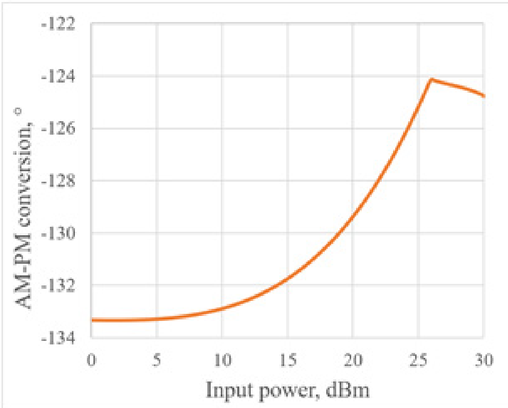

Fig. 5. AM-PM conversion

The class G RFPA model switches the nonlinear models of the main RFPA in CAD VSS. Each nonlinear model has a certain supply voltage from 6.5 V to 28 V, as shown in [10, 11]. Initially, the number of the nonlinear models is 55, the step between supply voltage is from 0.125 to 1 V, depending on the probability density function of LTE signal, which allowed to obtain ACPR of the output signal of –55 dBc. Each nonlinear model is analyzed using the APLAC harmonic balance method, which is more suitable for extremely nonlinear circuits analysis. Furthermore, the class G RFPA is analyzed with a different number of supply voltage levels (N) from 55 to 10. Using CAD LabVIEW [13], optimal supply voltage levels at which ACPR is minimal have been determined. The CEA analysis is similar to the class G RFPA analysis, with N reduced within the range of 6.5–12.2 V. The remaining maximum number of levels is between 12.2 and 28 V, simulating HEA.

The saturation power of the class G RFPA is 44.5 dBm; therefore, the minimum ACPR is achieved at an average power of 32.8 dBm when the output power is below saturation power by the PAPR value (11.7 dB for the LTE signal). In Fig. 7, ACPR degrade at powers below 33 dBm due to the nonlinear behavior of the main RFPA at a power supply voltage of 6.5 V, since it operates in class AB and has an individual type of AM-AM and AM-PM conversions, which are not taken into account by the shaping function and DPD. At $N = 18$, the ACPR of the output signal is equal to the acceptable value of –50 dBc.

The findings do not prove that the EA output voltage ($U_{out\ env}$) can be improved by RFPA supply voltage filtration [14, 15]. Of course, if a low-pass filter with a cutoff frequency equal to the signal

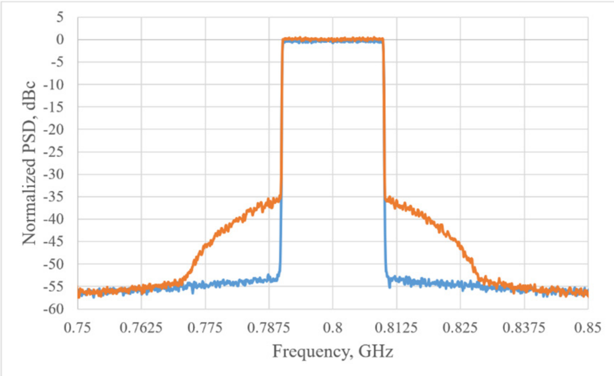

Fig. 6. Output signal specter

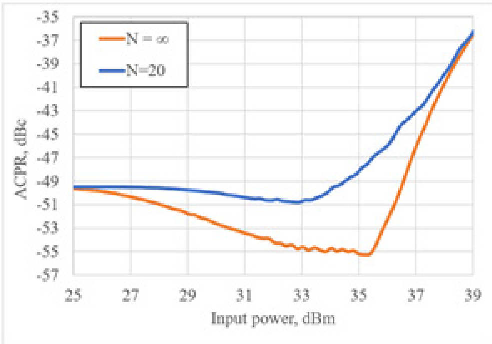

Fig. 7. ACPR vs output power

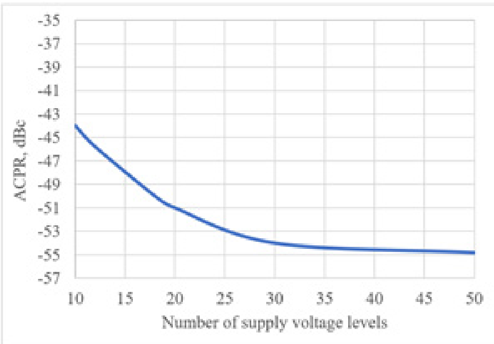

Fig. 8. ACPR vs N

bandwidth is applied, it is possible to achieve an optimal N less than 18. However, the use of filtering leads to the dependence of ACPR on signal bandwidth. Therefore, $N = 18$ is the optimal value for multiband applications where signal bandwidth varies.

Conclusion

This analysis has shown that the class G RFPA with the shaping function and a standard DPD based on LUT can provide an ACPR of –50 dBc at $N = 18$. The standard DPD technique, based on a LUT or Volterra series, can be applied to the class G RFPA without the shaping function. In this case, the number of supply voltage levels required to achieve an ACPR of –50 dBc will be different. Moreover, the use of an additional filter can improve linearity for a fixed signal bandwidth. The previous work showed that five supply voltage levels are sufficient to achieve maximum efficiency in the class G RFPA. These five levels must be formed using highly efficient DC-DC pulse converters so that the total system efficiency remains at a high level. Therefore, it is enough to develop an 18-level class G RFPA with five DC-DC pulse converters, and to form the remaining 13 supply voltage levels using linear voltage converters. Also, the class G RFPA analysis showed that 10 of 18 supply voltage levels are in the voltage range from 6.5 to 12.2 V. An ETPA with the CEA can provide an ACPR of –50 dBc at N = 10. Therefore, CEA design is a challenging task, as it helps reduce the number of supply voltage levels by almost half.

Nomenclature

- OFDM – Orthogonal Frequency-Division Multiplexing;
- PAPR – Peak-to-Average Power Ratio;
- ETPA – Envelope Tracking Power Amplifier;
- EA – Envelope Amplifier;
- HEA – Hybrid Envelope Amplifier;
- DPD – Digital Pre-Distortion;
- CEA – Combined Envelope Amplifier;
- ACPR – Adjacent Channel Power Ratio;
- LUT – Look-Up Table;
- PSD – Power Spectral Density.

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