This article was presented at

German Microwave Conference (GeMiC 2020), Cottbus, Germany, 2020

https://ieeexplore.ieee.org/document/9080191

Switching Mode Power Amplifier Concept Combining Multi-Level and Pulse-Width Modulation

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***Abstract*—This paper presents system simulation results of a digital RF transmitter chain concept using a digital pulse-width and pulse-position modulator (DPWPM) and a multi-level switching mode power amplifier (SMPA). The effect of the limited output bandwidth of a SMPA on the signal quality is discussed, which leads to deteriorating values for the adjacent channel leakage ratio (ACLR) and the code efficiency η_C. Therefore a new concept by using a 4-level SMPA with four output levels instead of a conventional one with only two output levels is proposed. By using the four-level SMPA (4L-SMPA) with a 256-QAM signal at a symbol rate of 31.25 MBaud on a 2 GHz carrier, the ACLR can be improved from -38 dB to -44 dB in the adjacent channel (ACLR1) and from -36 dB to -45 dB in the alternate channel (ACLR2). Especially the code efficiency can be improved from 63 % to 85 %.**

I. Introduction

Due to the growth of mobile data traffic, future mobile communication transmitters require increasing bandwidth and carrier frequencies as well as high linearity and efficiency. For non-constant-envelope signals the efficiency degrades for linear power amplifiers. Fig. 1 shows the concept of a RF transmitter using a digital pulse-width and pulse-position modulator (DPWPM) [1], which proves high linearity for the bipolar output signal. This output signal is amplified using a switching mode amplifier (SMPA). The following bandpass filter removes the harmonics from the radio frequency (RF) signal. The limited output bandwidth of the SMPA hampers the amplification of narrow pulses, which limits the dynamic range of the system [2].

This paper analyzes the effect of the limited output bandwidth of a DPWPM-SMPA-system and proposes a new approach using the DPWPM from [1] together with a 4-level SMPA from [3]. The benefits of this concept are proven by simulations.

The organization of this paper is as follows: in Section II the mathematical basics for the DPWPM are described for a better understanding. The effect of the limited output bandwidth of a DPWPM-SMPA-system is analyzed and discussed in Section III. The new concept is introduced in Section IV and the benefits regarding signal quality are presented. Section V concludes this paper.

II. Mathematical Basics of the DPWPM

The output of the DPWPM is a digital bipolar signal $p(t)$, as shown in Fig. 2. It consists of a fundamental and several harmonics of higher frequencies. The desired modulated RF-signal is contained in the fundamental. Therefore the fundamental of the DPWPM-signal is analyzed using a complex Fourier-series. First the complex coefficients c_k of the Fourier-series are derived, where f_C is the carrier frequency [4]:

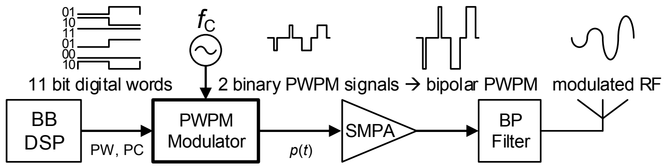

Fig. 1. RF transmitter chain with bipolar DPWPM modulator, SMPA and bandpass reconstruction filter [1].

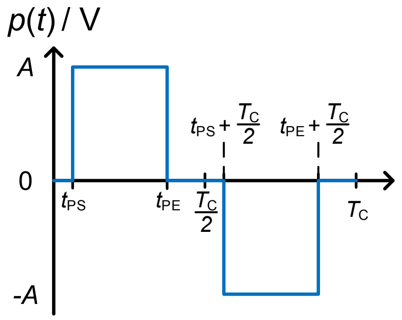

Fig. 2. Bipolar output pulse of an ideal DPWPM.

$$c_\mathrm{k} = \frac{2}{T_\mathrm{C}} \int_0^{\frac{T_\mathrm{C}}{2}} p(t)\, e^{-2\pi j k f_\mathrm{C} t}\, \mathrm{d}t. \tag{1}$$

For the fundamental the determination of c_1 is sufficient:

$$c_1 = \frac{2}{T_\mathrm{C}} \int_0^{\frac{T_\mathrm{C}}{2}} p(t)\, e^{-2\pi j f_\mathrm{C} t}\, \mathrm{d}t \tag{2}$$

$$= \frac{2Aj}{2\pi} \left(e^{-2\pi j D_\mathrm{PS}} - e^{-2\pi j D_\mathrm{PE}} \right). \tag{3}$$

$D_\mathrm{PS} = \frac{t_\mathrm{PS}}{T_\mathrm{C}}$ and $D_\mathrm{PE} = \frac{t_\mathrm{PE}}{T_\mathrm{C}}$ are the pulse start (PS) and pulse end (PE) times normalized to the carrier period T_C. The normalized pulse width is $D_\mathrm{PW} = D_\mathrm{PE} - D_\mathrm{PS}$. Hence, the normalized pulse center (PC) can be determined to $D_\mathrm{PC} = D_\mathrm{PS} + 0.5 D_\mathrm{PW} = D_\mathrm{PE} - 0.5 D_\mathrm{PW}$. c_1 can be rearranged to:

$$c_1 = \frac{2A}{\pi} \sin(\pi D_\mathrm{PW}) e^{-2\pi j D_\mathrm{PC}}. \tag{4}$$

$p(t)$ represents a real time signal, therefore $c_{-1} = c_1^*$. The complex Fourier-series for the fundamental is described as:

$$u_1(t) = c_{-1}\, e^{-2\pi j f_\mathrm{C} t} + c_1\, e^{2\pi j f_\mathrm{C} t}. \tag{5}$$

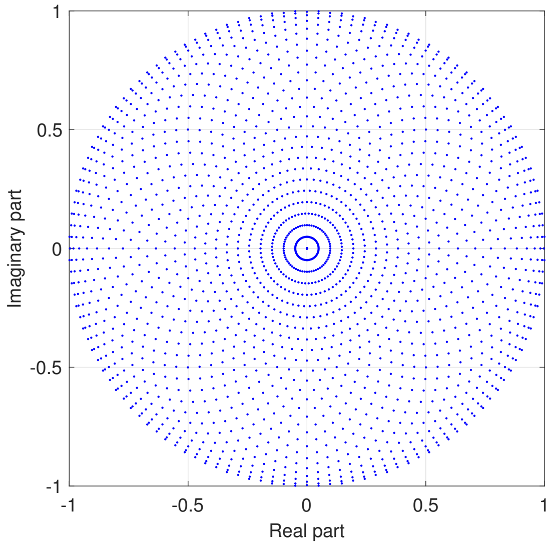

Fig. 3. Ideal constellation diagram for a DPWPM with a 2-level SMPA.

By inserting the complex Fourier-coefficients and simplifying the equation, u_1 can be described as a real valued signal:

$$u_1(t) = \underbrace{\frac{4A}{\pi}\sin(\pi D_{\mathrm{PW}})}_{\text{Amplitude } \widehat{u_1}} \cos(\omega_{\mathrm{C}} t \underbrace{-2\pi D_{\mathrm{PC}}}_{\text{Phase } \varphi_{u_1}}). \tag{6}$$

In the used DPWPM a carrier period is divided into $N = 64$ quantization intervals and the signal amplitude has its maximum at $D_{\mathrm{PW}} = 0.5$. So the following values are feasible for $D_{\mathrm{PW}} = \frac{n_{\mathrm{PW}}}{N}$:

$$0 \leq \frac{n_{\mathrm{PW}}}{N} < 0.5 \quad \Rightarrow \quad n_{\mathrm{PW}} \in \left[0\,;\, \frac{N}{2} - 1\right]. \tag{7}$$

The range of values for the phase $D_{\mathrm{PC}} = \frac{n_{\mathrm{PC}}}{N} + \frac{1}{2N}(n_{\mathrm{PW}} \bmod 2)$ can be determined likewise:

$$0 \leq \frac{n_{\mathrm{PC}}}{N} + \frac{1}{2N}(n_{\mathrm{PW}} \bmod 2) < 1 \quad \Rightarrow n_{\mathrm{PC}} \in [0\,;\, N-1]. \tag{8}$$

Equations (6), (7) and (8) can be used to construct the ideal constellation diagram in Fig. 3. This diagram is normalized to a maximum amplitude of 1. The amplitude of the constellation points is $\widehat{u_1}$ and the phase is φ_{u_1}.

The number N_{Konst} of constellation points in Fig. 3 can be calculated by the overall number of all PW/PC combinations minus the number of zero pulse width pulses, which appear once per each n_{PC}, according to

$$N_{\mathrm{Konst}} = 2^{N_{\mathrm{PW}}+N_{\mathrm{PC}}} - 2^{N_{\mathrm{PC}}} + 1. \tag{9}$$

For $N = 64$ quantization intervals $N_{\mathrm{PW}} = \log_2(\frac{N}{2}) = 5$ is the bit width of the binary word that adresses all possible pulse widths n_{PW} and $N_{\mathrm{PC}} = \log_2(N) = 6$ is the bit width of the binary word that adresses all possible pulse centers n_{PC}. The number of all adressable points in the constellation diagram is $N_{\mathrm{Konst}} = 1985$ according to equation (9).

III. Impact of Limited Output Bandwidth

The limited output bandwidth impacts the performance of the DPWPM-SMPA-system. Real power amplifiers are not capable of generating infinite steep output signal slopes. In a DPWPM-system, the pulse width quantization interval $\Delta W_{\mathrm{Pulse}}$ is equal to the carrier period T_{C} divided by the number N of quantization intervals:

$$\Delta W_{\mathrm{Pulse}} = \frac{T_{\mathrm{C}}}{N} = \frac{1}{f_{\mathrm{C}} \cdot N}. \tag{10}$$

For a carrier frequency of $f_{\mathrm{C}} = 2$ GHz and $N = 64$ this results in a pulse width quantization interval $\Delta W_{\mathrm{Pulse}}$ of 7.8 ps. The pulse width quantization interval shortens for higher carrier frequencies. In a system with a SMPA the output rise and fall times are much larger than this minimum pulse width quantization interval. In previous work the minimum pulse width value for a 3 V output swing SMPA in 65 nm CMOS is determined to about 100 ps [5]. Therefore, a pulse-width-limit W_{lim} is defined, which sets the minimum pulse width of the DPWPM-SMPA-system to a multiple of the pulse width quantization interval. With equation (11), the normalized minimum pulse width can be derived as

$$w_{\mathrm{Pulse,min}} = \left\lceil \frac{W_{\mathrm{lim}}}{\Delta W_{\mathrm{Pulse}}} \right\rceil = \lceil W_{\mathrm{lim}} f_{\mathrm{C}} N \rceil, \tag{11}$$

where $\lceil X \rceil$ implies rounding up of X to an integer. Considering a 2 GHz-carrier and the measured minimum pulse width value mentioned above, the normalized pulse-width-limit is $w_{\mathrm{Pulse,min,2L}} = 100ps/7.8ps \approx 13$ for the 3 V-SMPA. In a system simulation using a PRBS $2^{11} - 1$ input signal with 256-QAM mapping, a symbol rate of 31.25 MBaud at a carrier frequency of 2 GHz and a raised-cosine pulse-shaping-filter, the impact of the limited output bandwidth and thus the missing constellation points can be seen in Fig. 4. Compared to the ideal case of $w_{\mathrm{Pulse,min,2L}} = 1$, the noise floor is increased by about 20 dB. The simulation results are summarized in Table II. The

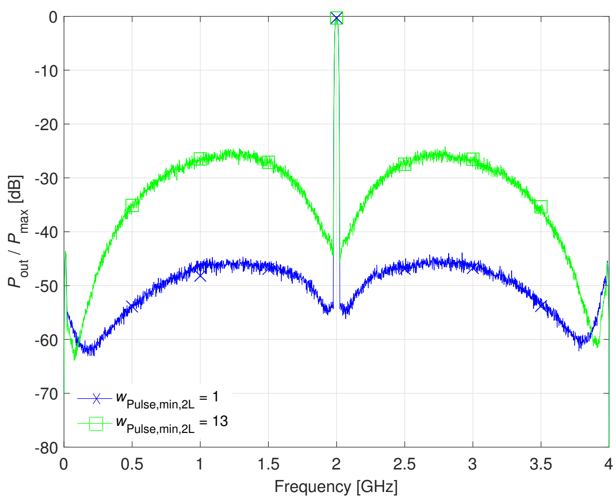

Fig. 4. Simulated normalized output spectra of the ideal DPWPM with a conventional two-level (2L) constellation diagram depicted in Fig. 3 and the pulse-width limit $w_{\mathrm{Pulse,min,2L}}$ set to 1 (ideal case) and 13 (realistic case).

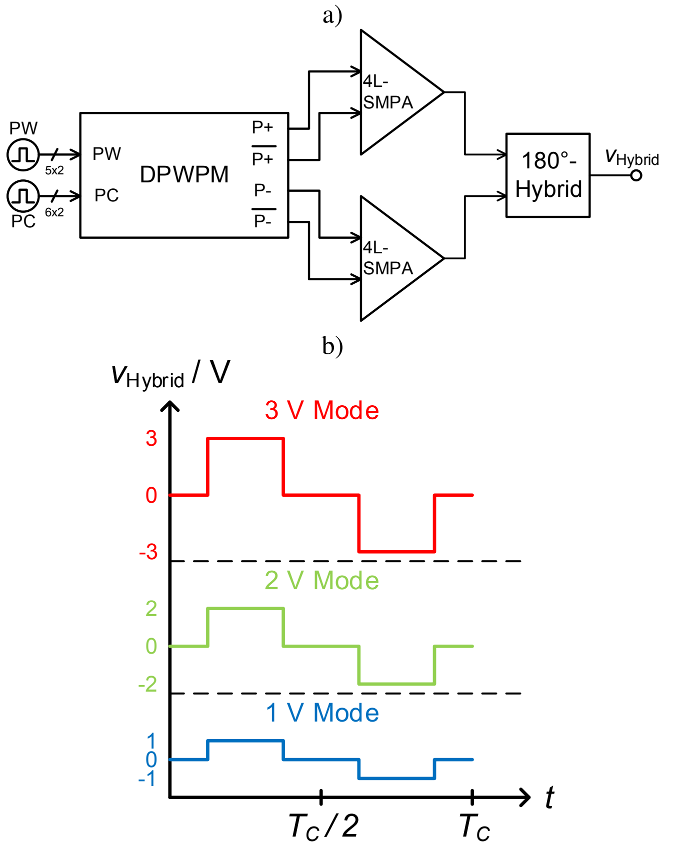

Fig. 5. a) Block diagram of the proposed DPWPM-4L-SMPA-system. b) Output signal with possible output swings of the 4L-SMPA.

$\mathrm{EVM_{RMS}}$ and SNR don't deteriorate much because of the used baseband Delta-Sigma-Modulation [4]. The code efficiency η_C, which is the ratio of the fundamental signal power P_Sig to the total signal power P_tot,

$$\eta_\mathrm{C} = \frac{P_\mathrm{Sig}}{P_\mathrm{tot}}, \tag{12}$$

degrades only slightly. But the ACLR values degrade heavily due to the increased quantization noise floor.

IV. DPWPM with Additional Multi-Level Amplitude Modulation

According to equation (6) a small pulse width D_PW represents a small amplitude $\widehat{u_1}$. If the output stage of the DPWPM-SMPA system is able to discretely vary the amplitude of the output pulse, then the output amplitude of the fundamental can be controlled by both the pulse width as well as by the pulse amplitude. The idea is to replace short pulses with large amplitude by long pulses with small amplitude, to decrease bandwidth requirements on the SMPA output. In this work, a SMPA with four output voltage levels (4L-SMPA) 0 V, 1 V, 2 V and 3 V according to [3] is assumed. This amplifier supports output swings of 1 V, 2 V and 3 V. Two SMPAs are required for the two output signals Pulse-Plus (P+) and Pulse-Minus (P-) of the DPWPM. A 180°-Hybrid generates the bipolar signal.

TABLE I
DETERMINATION OF THE QUANTIZED PULSE WIDTH $n_\mathrm{PW,MIN}$ FOR THE THREE OUTPUT-SWING-MODES OF THE AMPLIFIER.

Mode	A_Pulse	V_Th	$n_\mathrm{PW,min}$	$n_\mathrm{PW,max}$
3 V	3 V	2 V	15	31
2 V	2 V	1 V	11	31
1 V	1 V	0 V	0	31

The block diagram is depicted in Fig. 5 a). The possible output swings in such a system are illustrated in Fig. 5 b). For the ideal constellation diagram of the DPWPM-4L-SMPA-system the thresholds of the minimum pulse width for the 3 V and 2 V output swing need to be calculated in order to prevent overlapping of the constellation points:

$$A_\mathrm{Pulse}\,\sin\left(\pi\frac{n_\mathrm{PW,min}}{N}\right) \geq V_\mathrm{Th}. \tag{13}$$

The resulting minimum phase width for each output amplitude is summarized in Table I. The normalized maximum pulse width $n_\mathrm{PW,max}$ is 31 for each output amplitude. The resulting constellation diagram is depicted in Fig. 6 with normalization to a amplitude of 1V. The amount of all constellation points $N_\mathrm{Konst,4L}$ with the 4L-SMPA is:

$$N_\mathrm{Konst,4L} = N_\mathrm{Konst} + N_\mathrm{Konst,2V} + N_\mathrm{Konst,3V}, \tag{14}$$

with the number of constellation points for the 2 V and 3 V output amplitude:

$$N_\mathrm{Konst,2/3V} = (2^{N_\mathrm{PW}} - n_\mathrm{PW,min,2/3V}) \cdot 2^{N_\mathrm{PC}}. \tag{15}$$

For a DPWPM with $N = 64$ and the proposed 4L-SMPA this results in a total number of $N_\mathrm{Konst,4L} = 4417$ constellation points.

With the additional degree of freedom the amplitude of the fundamental can be represented by different pulse-width and pulse-amplitude combinations. It is possible to recalculate

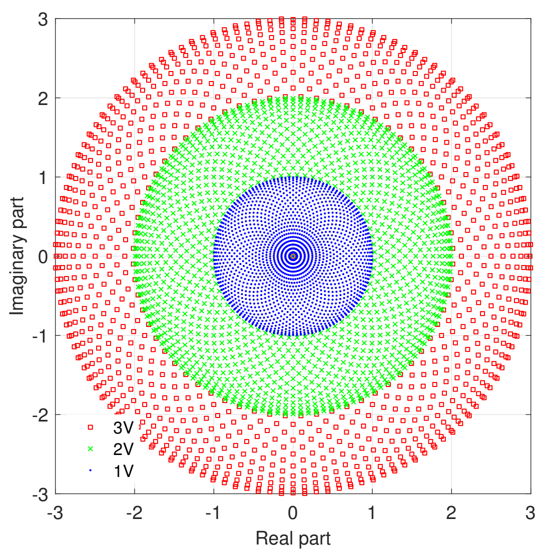

Fig. 6. Ideal constellation diagram for DPWPM combined with a 4-level SMPA.

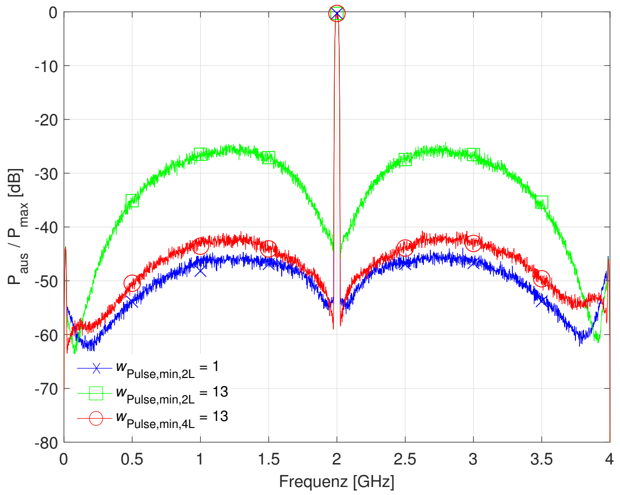

Fig. 7. Simulated normalized output spectra of the ideal DPWPM with a 2L-SMPA using the conventional constellation diagram (Fig.3) and a 4L-SMPA using the enhanced constellation diagram (Fig. 6).

TABLE II
SUMMARY OF SYSTEM SIMULATION RESULTS OF THE IDEAL DPWPM WITH TWO- AND FOUR-LEVEL SMPA ON A 2 GHZ CARRIER. CHANNEL BAND WIDTH (CH.-BW): 46.875 MHZ, CHANNEL SPACING (ΔCH): 50 MHZ

SMPA-Model	2-level	2-level	2-level	4-level	4-level
$w_{\text{Puls,min}}$	1	13	20	1	13
EVM_{RMS} [%]	1.44	1.51	1.56	1.43	1.43
SNR [dB]	36.84	36.41	36.14	36.89	36.88
η_C [%]	64.1	62.6	57.3	84.5	85.1
ACLR1l [dB]	-43.06	-37.83	-37.14	-43.38	-43.11
ACLR1u [dB]	-43.56	-37.99	-37.18	-43.91	-43.55
ACLR2l [dB]	-45.38	-36.41	-34.39	-45.93	-44.64
ACLR2u [dB]	-45.58	-36.48	-34.41	-46,00	-44.69

the pulse-width for a different pulse-amplitude with the use of equation (6). Amplitude $\widehat{u_1}$ doesn't change and thus the following equations are valid:

$$A_{\text{Pulse},2}\sin(\pi D_{\text{PW}_2}) = \widehat{u_1} = A_{\text{Pulse},1}\sin(\pi D_{\text{PW}_1}), \qquad (16)$$

$$D_{\text{PW}_2} = \frac{1}{\pi}\arcsin\left(\frac{A_{\text{Puls},1}}{A_{\text{Puls},2}}\sin(\pi D_{\text{PW}_1})\right). \qquad (17)$$

The minimum pulse widths in the 2 V- and 1 V-modes can be mapped to equivalent pulse widths providing for the same fundamental signal output power in the 3 V-mode using equation (17) and $D_{\text{PW}} = \frac{n_{\text{PW}}}{N}$. A normalized pulse width of $n_{\text{PW}_1} = 13$ with a 1 V-amplitude corresponds to a normalized 3 V-amplitude pulse width of $n_{\text{PW}_2} = 4.0174$. Similar to that a normalized pulse width of $n_{\text{PW}_1} = 13$ with a 2 V amplitude corresponds to a normalized pulse width of $n_{\text{PW}_2} = 8.2027$ with a 3 V amplitude. This example shows the capability of the DPWPM-4L-SMPA-system: the minimum normalized pulse width of 13 can be reduced to an equivalent 3 V-value of about 4 by using the additional smaller amplitude levels of 2 V and 1 V.

The signal from section III is analyzed using the proposed DPWPM-4L-SMPA-system. The simulation results for the normalized minimum pulse widths of $w_{\text{Pulse,min,2L}} = 1$ and $w_{\text{Pulse,min,2L}} = 13$ for the conventional system with 2 output levels and the normalized pulse width of $w_{\text{Pulse,min,4L}} = 13$ for the proposed system with four output levels are depicted in Fig. 7. By replacing short pulses with large amplitude by longer pulses with smaller amplitude and because of the almost doubled number of constellation points the noise floor decreases by about 15 dB for $w_{\text{Pulse,min,4L}} = 13$ compared to the two-level-SMPA. The EVM_{RMS}- and SNR-values stay constant, the ACLR1- and ACLR2-values are again comparable with the values of the ideal DPWPM. The code efficiency improves even for $w_{\text{Pulse,min,4L}} = 13$ to a very good value of 85 %. This proves, that a DPWPM with a 4-level SMPA emits very little power into the harmonics of the signal. The requirements for a following bandpass-filter can be reduced. The simulation results are summarized in Table II.

V. CONCLUSION

This article discusses the effect of limited amplifier output bandwidth on a non-ideal DPWPM-SMPA-system. This affects the ACLR, where the ACLR1 and ACLR2 worsen by about 6 dB and 11 dB respectively. Due to the used DSM and its noise shaping at the carrier frequency the EVM_{RMS}- and SNR-values are less affected. The proposed four-level SMPA tackles the problem of limited output bandwidth. Instead of using short pulses with high amplitude but using longer pulses with lower amplitude, the ACLR reaches values similar to the ideal DPWPM-SMPA-system with 2 levels. Especially the code efficiency can be greatly improved by about 21 % to 85 % in comparison to the ideal DPWPM and an ideal 2-level SMPA. Therefore less power is emitted into the harmonics of the RF-signal and the requirements of the following bandpass-filter can be lowered.

This paper presents results based on simulations of a power amplifier system. A hardware system using the investigated combination of multi-level switching mode power amplifier ICs and a pulse-with modulator IC will be subject of an upcoming research project.

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