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TR2018-021 March 2018

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IEEE Radio and Wireless Symposium (RWS)

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Truly Aliasing-Free Digital RF-PWM Power Coding Scheme for Switched-Mode Power Amplifiers

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Abstract—This paper presents a novel method for multilevel power coding and upconversion to RF frequency, by the means of a digital radio-frequency pulse width modulation (RF-PWM). Delta-sigma modulation ($\Delta\Sigma$ M) and memoryless predistortion are used to cancel spectral aliasing effects, inherent to digital RF-PWM operation, and achieve high linearity of the transmitter. In this method, time-domain characterization of a multilevel digital RF-PWM was fully exploited in order to provide optimal parameter selection for the $\Delta\Sigma$ M, which in turn enables aliasing-free digital RF-PWM that runs at reasonable clock speeds. Experiments with an arbitrary waveform generator are used to demonstrate effectiveness of the proposed novel power encoding scheme. The novel algorithm offers in-band SNR of -45 dB, while maintaining coding efficiency of about 55%, for a 20MHz-bandwidth 64QAM signal, while mere RF-PWM, running at the same clock speed, can achieve SNR of only -10 dB.

I. INTRODUCTION

Radio frequency pulse-width modulation (RF-PWM) has been used as a power coding method in digital transmitters, which employ highly efficient switched-mode power amplifiers (SMPA) [1]. Main drawback of RF-PWM is the high level of in-band harmonic distortion when digitally implemented. In order to reduce spectral aliasing effects [2] and bring harmonic noise to an acceptable level, ultra-fast clock speeds are required ($50 \times f_{RF}$), which makes digital RF-PWM commercially unattractive. In [3] authors propose an intermediate-frequency PWM (IFPWM) scheme, which implements digital RF-PWM at a much lower frequency than the carrier f_{RF} , so that sufficiently large values of the oversampling ratio become feasible. An outphased digital RF-PWM power coding scheme was demonstrated in [4], where delta-sigma modulation ($\Delta\Sigma$ M) is used to reduce resolution of the input RF signal, before it is outphased and power encoded using RF-PWM with significantly lower (usually 3 or 5) number of output levels. Similarly, in [5] authors use $\Delta\Sigma$ M to pre-process RF-PWM input in order to limit minimal pulse width length so to prevent 'pulse swallowing'.

In this paper, we propose a novel digital RF-PWM based power encoding scheme which exploits time-domain relationship between the baseband input signal and the pulsed output of digitally implemented RF-PWM. Delta-sigma modulation ($\Delta\Sigma$ M) and simple memoryless predistortion are used to pre-process the RF-PWM input signal, in order to increase linearity of the overall system. The time-domain input-output relationship is used to optimally select $\Delta\Sigma$ M quantization

parameters and hence minimize in-band distortion caused by spectral aliasing, similar to what was proposed in [6] for carrier based PWM. By matching $\Delta\Sigma$ M parameters to those of the quantization inherent to digital RF-PWM operation, we are able to produce output signal which is truly aliasing-free, and therefore optimal. Non-aliasing distortion of the output signal envelope, introduced by RF-PWM signal generation, is mitigated by an appropriately designed predistortion system in the form of a simple lookup table (LUT). Our novel power encoding scheme offers significant reduction in the sampling rate for low resolution RF-PWM while maintaining very high coding efficiency. In other words, it achieves a high level of linearity as a $\Delta\Sigma$ M, and high coding efficiency as an RF-PWM system, all while running at a relatively low (for digital PWM!) clock rate.

II. $\Delta\Sigma$ M-RFPWM HYBRID ARCHITECTURE

In this section we describe the proposed digital RF-PWM based power coding scheme. An abstract block diagram of our novel scheme is shown in Fig. 1. In the following subsections we discuss each of the respective subsystems, and describe the operation of this scheme.

A. Digital RF-PWM

The main idea of RF-PWM is to modulate an RF signal into a stream of uni-polar or bi-polar pulses, where the envelope and phase are represented by the width and timing of the pulses. In 3-level RF-PWM schemes, a baseband input signal is first upconverted to RF frequency, and the modulated carrier is then compared to a fixed threshold value to produce a pulsed output train [1], as shown in Fig. 2. Let $a[n]$ be the baseband input signal and $x[n] = a[n] \cos(2\pi n/N)$ the amplitude modulated digital RF carrier, where N is the oversampling ratio f_{samp}/f_{RF} of the sampling to RF carrier frequency. Also, let $y[n]$ be the pulsed output train, and V_{th} the value of the RF-PWM threshold (see Fig. 2). It is known ([1]) that the RF-PWM output signal is a quasi-harmonic signal, with the fundamental frequency equal to the RF carrier f_{RF} (or equivalently to the digital frequency $2\pi/N$ for digitally implemented RF-PWM). Therefore, the fundamental of this signal can serve as amplitude modulated carrier bearing input signal information. Finite time resolution of switching instants in digital PWM signals (for both baseband and RF schemes) implies finite resolution of the output pulse widths. In other words, these widths undergo quantization in the process of generating the output

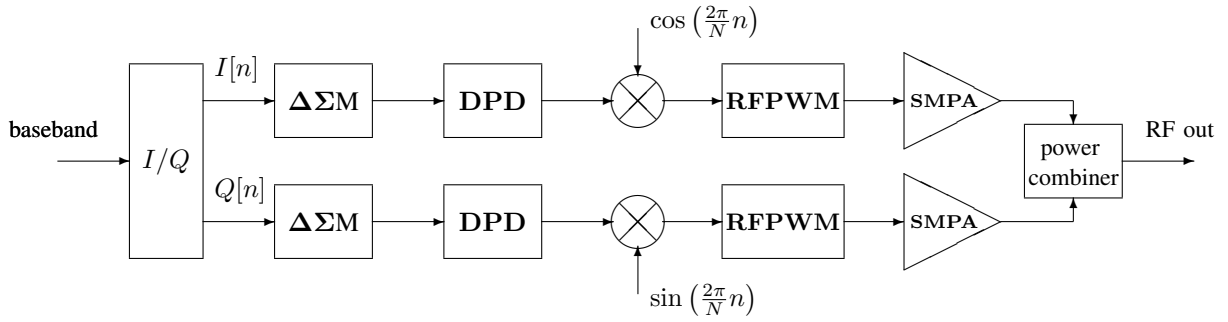


Fig. 1. Abstract block diagram of the proposed power coding scheme.

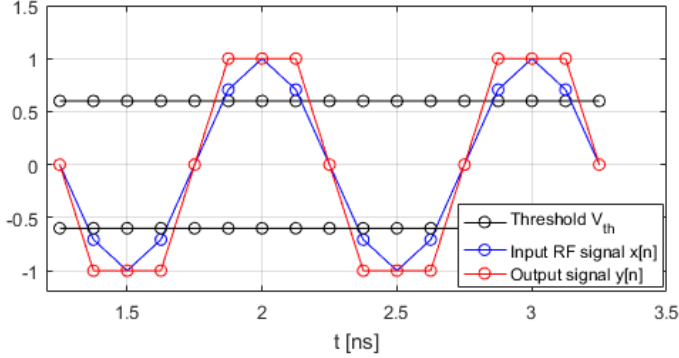


Fig. 2. An example of output signal generation in 3-level RF-PWM. RF frequency is 1GHz, and oversampling ratio is $N = 8$.

signal. In a recent paper [6], authors give a closed-form input-output relation for digital PWM which completely describes this underlying quantization process. Similar to what was given for baseband digital PWM in [6], it can be shown that digital RF-PWM is subject to a similar (hidden) quantization, and the fundamental component $y_{RF}[n]$ of the RF-PWM output $y[n]$ depends on the baseband input signal $a[n]$ as given by the following expression

$$y_{RF}[n] = \frac{2 \sin(\pi d_Q[n])}{N \sin(\frac{\pi}{2N})} \cos\left(\frac{2\pi}{N}n\right), \quad (1)$$

$$d_Q[n] = (\mathbf{Q}d)[n] \quad (2)$$

$$d[n] = \begin{cases} -\frac{1}{\pi} \arccos \frac{V_{th}}{|a[n]|}, & x[n] < -V_{th} \\ 0, & |a[n]| \leq V_{th} \\ \frac{1}{\pi} \arccos \frac{V_{th}}{|a[n]|}, & x[n] > V_{th} \end{cases} \quad (3)$$

where \mathbf{Q} is a uniform quantizer with $N_Q = N + 2$ output levels (due to space constraints, derivation of the above model is omitted from this paper). The RF-PWM model in (1)-(3) implies that aliasing-free digital RF-PWM is possible if and only if the baseband input signal $a[n]$ is pre-quantized in such a way that the output pulse width $d[n]$ corresponds to a quantized version $d_Q[n]$, whose values are defined by the inherent quantization process \mathbf{Q} .

B. DSM design parameters

In order to minimize in-band distortion introduced by the inherent quantization described above, we use a delta-sigma modulator ($\Delta\Sigma M$) to pre-quantize digital RF-PWM input baseband signal, and shape noise to out-of-band frequencies.

The $\Delta\Sigma M$ has $N_Q = N + 2$ levels (e.g. for an oversampling ratio of 9, $\Delta\Sigma M$ should have 11 output levels). The exact values of the $\Delta\Sigma M$ output levels depend on N and are given as a sine of the uniform levels defined for quantizer \mathbf{Q} in (1). Reason for this is the nonlinear AM-AM transfer characteristic from the RF-PWM input signal $x[n]$ to the output fundamental component $y_{RF}[n]$. Also, special care should be given to the values $a[n] \in [-V_{th}, V_{th}]$, since $d[n] = 0$ for such inputs. Thus, for inputs $|a[n]| \leq V_{th}$, $\Delta\Sigma M$ should output value 0. In order to achieve optimal in-band signal-to-noise ratio (SNR), it is crucial that $\Delta\Sigma M$ parameters are chosen in accordance with the derived analytical model. Indeed, if this is not satisfied, additional in-band distortion will be generated by RF-PWM, as confirmed by measurements and shown in the next section. In this paper a first order $\Delta\Sigma M$ is used for simplicity, but higher order $\Delta\Sigma M$ could be chosen as well. In that case an expected improvement in linearity of the overall system is traded for increased implementation complexity, possible stability issues and lower coding efficiency, all of which are associated with higher order $\Delta\Sigma M$.

C. Predistortion

It is clear from (1) that the fundamental component of the output pulse train of a 3-level RF-PWM is proportional to the sine of the pulse width $d[n]$. Also, from (3), it can be seen that the pulse width depends on the baseband signal $a[n]$ in a nonlinear fashion. By combining these two static nonlinearities, and using simple trigonometric identities, it can be shown (see e.g. [3]) that the envelope of the fundamental component $y_{RF}[n]$ is proportional to $f(a[n]) = \sqrt{1 - \left(\frac{V_{th}}{a[n]}\right)^2}$. Therefore, in order to cancel this memoryless nonlinearity, it is necessary to pre-emphasize RF-PWM input signal using the inverse of the above function, i.e. using $f^{-1}(\xi) = \frac{V_{th}}{\sqrt{1-\xi^2}}$. Moreover, since $\Delta\Sigma M$ with N_Q output levels is used to pre-process the DPD input signal, it is enough to realize f^{-1} for just N_Q values of the input. This can be efficiently done by employing a simple LUT.

III. EXPERIMENTAL PERFORMANCE EVALUATION

In order to evaluate performance of the proposed DSM-RFPWM hybrid power coding scheme, measurements have been carried. Performance of the system is measured in terms of achieved coding efficiency (CE) and in-band signal-to-noise ratio (SNR), and proposed DSM-RFPWM power encoder is compared to the one employing only digital RF-PWM, while keeping parameters of the RF-PWM fixed in both cases.

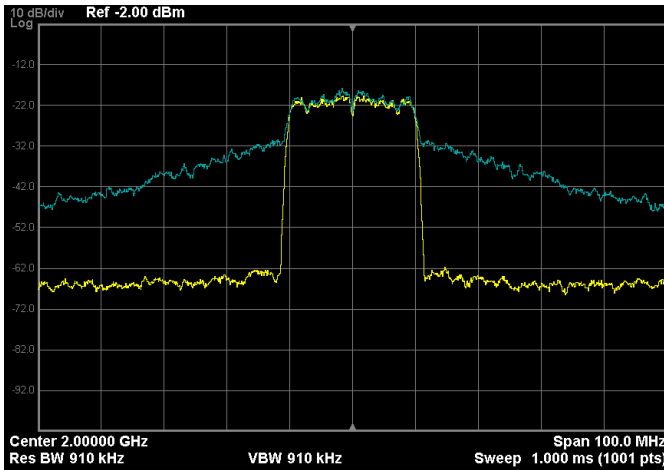


Fig. 3. Measured baseband spectrum of the RF-PWM (blue) and $\Delta\Sigma$ -RFPWM (yellow) outputs.

Baseband input is a 20MHz-bandwidth 64QAM signal, and carrier frequency is set to 2GHz, with $OSR = 9$, thus giving the sampling frequency of 18GS/s. Baseband signal is processed with a first order $\Delta\Sigma$, which employs nonuniform quantizer with 11 output levels. Number of output levels of RF-PWM is set to 3. Matlab simulated output signal file is loaded into an arbitrary waveform generator (AWG-34G from Micram Instruments), which also serves as a D/A converter, in order to generate the signals. Keysight EXA 9010A signal analyzer is used to measure the spectrum. Figs. 3 and 4 compare the measured in-band and wideband spectrum of RF-PWM (yellow) and $\Delta\Sigma$ -RFPWM hybrid scheme (blue) output signals. Measured in-band SNRs are roughly 43% and 10%, respectively, while coding efficiencies are circa 55% and 77% respectively. It is expected that digital RF-PWM alone can achieve better coding efficiency than hybrid $\Delta\Sigma$ -RFPWM, due to the noise shaping property of $\Delta\Sigma$. But coding efficiency of the hybrid can be improved by increasing the number of RF-PWM output levels, e.g. using a 5-level instead of a 3-level RF-PWM. We would like to emphasize again that for optimal cancellation of aliasing effects, $\Delta\Sigma$ quantization parameters have to comply with the time-domain model of digital RF-PWM, otherwise in-band noise would still be unacceptable for moderate clock rates. This is shown in Fig. 5, for various choices of $\Delta\Sigma$ quantization parameters. Clearly, in terms of in-band SNR, our power coding scheme significantly outperforms (by 20dB) the other two cases. CE values are comparable for all three cases and are, as previously noted, around 55%.

IV. CONCLUSION

An RF-PWM based multilevel power coding scheme which provides both high linearity and high coding efficiency has been demonstrated. High linearity is achieved by employing optimal $\Delta\Sigma$ noise shaping, in combination with a LUT predistortion which is used to correct for memoryless nonlinear distortion introduced by the RF-PWM. It was also demonstrated that parameters of the $\Delta\Sigma$ must be chosen in a unique (optimal) way, as suggested by analytic formulas, in order to minimize harmonic distortion caused by spectral aliasing effects inherent to digital RF-PWM operation.

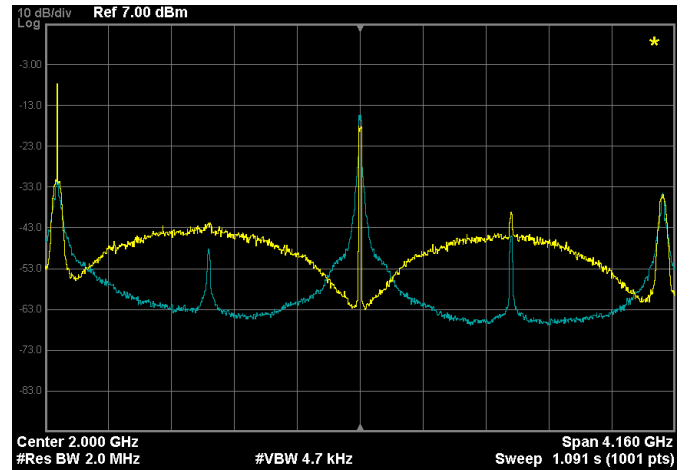


Fig. 4. Measured wideband spectrum of the RF-PWM (blue) and $\Delta\Sigma$ -RFPWM (yellow) outputs.

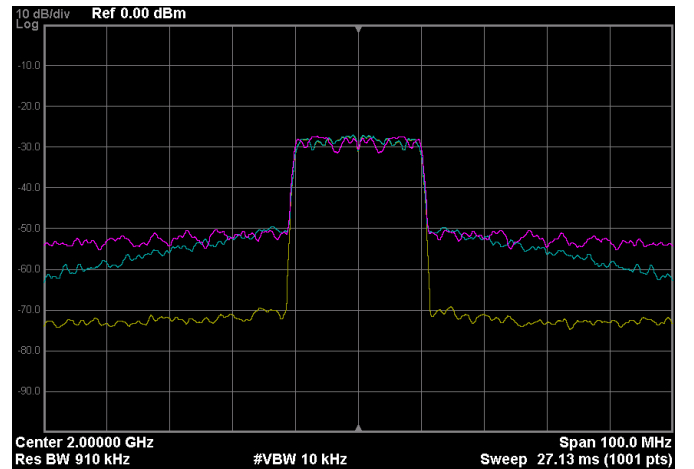


Fig. 5. Measured wideband output spectrum of the $\Delta\Sigma$ -RFPWM for different $\Delta\Sigma$ parameter selections: optimal parameters - nonuniform quantization with 11 levels (yellow), uniform quant. with 11 levels (magenta), nonuniform quant. with 30 levels (blue).

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