A Novel All Digital Transmitter With Three-level Quadrature Differential RF-PWM

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Abstract. To solve spectral aliasing of digital pulse width modulation (PWM) signal during digital up-conversion, a novel all-digital transmitter architecture using three-level quadrature differential RF-PWM is presented. By using triangle wave with 90° phase shift as the reference signal of quadrature differential PWM, the pulse coding of complex modulation signal and digital up-conversion will be realized. The feasibility of the transmitter is demonstrated by deriving the output formula of 3-level quadrature differential PWM, the design requirement is also given. Simulation and experiment results with QPSK and 16QAM signals show that the proposed scheme can significantly suppress the transmitter in-band noise, eliminate even harmonics, and effectively reduce the system operating frequency.

1. Introduction

In recent years, with the development of high-speed switching device and high-efficiency switched-mode power amplifier (SMPA), the realization of all-digital transmitter (ADTx) becomes possible, and it will gradually change the topology of traditional analog transmitter. Pulse width modulation (PWM) [1-3] is one of the most popular methods for power encoding in ADTx, it has the advantages of high coding efficiency and low average switching frequency. Owing to the limited time-domain resolution of digital signal, the realization of digital PWM will produce a large number of in-band quantization noise and harmonic [3,4], and then the digital up-conversion will mix these noise and harmonic into the signal band, finally, it affects the quality of the output RF signal.

Various methods for suppressing the quantized noise and spectrum aliasing have been proposed in literature [5]-[7]. A band-limited PWM algorithm is proposed in literature [5] to prevent spectrum aliasing by limiting the band of baseband signal. However, this method is too computationally intensive to be suitable for real-time signal processing. In the literature [6], DSM-PWM is employed to suppress the in-band noise of baseband PWM and reduce the sampling frequency. The literature [7] uses the inherent harmonic characteristics of PWM to accomplish the digital signal up-conversion and reduce the spectrum aliasing. However, this scheme can’t be applied to the quadrature modulation signal.
A novel 3-level quadrature differential PWM transmitter is proposed in this paper. It adopts delta-sigma modulator (DSM) to reduce the in-band noise and DPD to compensate the nonlinear characteristic. Simulation and experiment results show that the proposed transmitter can accomplish the quadrature modulation of complex signals, suppress the in-band noise and spectrum aliasing, eliminate even harmonics.

2. Three-level Quadrature Differential PWM ADTx

The architecture of three-level quadrature differential PWM ADTx is shown in Figure 1. Firstly, the in-phase and quadrature (I and Q, respectively) baseband is digitized by two low-pass (LP) DSMs, and the DPD module compensates for the nonlinearity introduced by the DSM. Then the digital signal will be processed by the 3-level quadrature differential PWM modulator which composed of two triangle waves with 90° difference and 3-level differential PWM. Finally, the I and Q output signals of quadrature PWM are directly added, amplified by switching power amplifier, and filtered by the tunable filter to filter out the fundamental component of the pulse signal, recover the RF signal and suppress the out of band harmonics and noise.

![Fig. 1 ADTx based on three-level quadrature differential PWM](image1.png)

2.1 Three-level differential PWM

The quadrature PWM module proposed in this paper takes three-level differential PWM as the basic unit. The three-level differential PWM designed for pulse code modulation is shown in Fig. 2. The differential PWM module composes of double three-level PWMs [2,3]. It takes the triangle wave with 180° difference as the reference signal. As a result, the output of the two PWMs is subtracted to eliminate even harmonics.

![Fig. 2 Three-level differential PWM](image2.png)

The output of three-level differential PWM in Fig.2 can be described as below:

\[
y[n] = \sum_{i=1}^{\infty} \frac{2\sin(\pi k b[n])}{\pi k} \cos \left[ \frac{2\pi}{N} k(n-n_s) \right] [1-\cos(\pi k)]
\] (1)
Where \( b[n] \) and \( y[n] \) denotes the input and output signal. \( f_s = N f_p \), \( N \) is even number, \( f_p \) is the sample frequency, and \( f_s \) is the frequency of triangular wave, \( n_0 \) is the phase shift sample number. From formula (1), it can be seen that the even harmonics are eliminated when \( k \) is even.

In order to realize the quadrature modulation of I and Q baseband signals, the two triangular wave with phase difference of 90° is taken as the reference waveform for the double three-level differential PWMs in Fig.1.

For the I channel differential PWM module, we take the phase offset \( \pi \), corresponding \( n_0 \) as \( N/2 \). And the phase offset of Q channel differential PWM module should be \( \pi/2 \), corresponding \( n_0 \) as \( N/4 \).

According to the symmetry of Fourier transform, the two outputs of quadrature differential PWM module in Fig.1 are formula (2) and formula (3) respectively.

\[
y_i[n] = \sum_{k=1}^{N/2} \frac{2 \sin(k \pi b_{i}[n])}{N \sin(k \pi/N)} \cdot \cos\left(\frac{2\pi k n}{N}\right) \tag{2}
\]

\[
y_q[n] = \sum_{k=1}^{N/4} \frac{2 \sin(k \pi b_{q}[n])}{N \sin(k \pi/N)} \cdot \cos\left(\frac{2\pi k (n - N/4)}{N}\right) \tag{3}
\]

Where \( b_{i}[n] \)、\( b_{q}[n] \) is uniformly quantized for \( b_i[n] \)、\( b_q[n] \) respectively, the quantized level is \( N \), and the dynamic range is (-1,1), it can be expressed as below:

\[
b_{i}[n] = \text{sign}(b_i[n]) \cdot \frac{1}{N} \left( \frac{N}{2} \left| b_i[n] \right| + 1 \right) \tag{4}
\]

\[
b_{q}[n] = \begin{cases} 
\text{sign}(b_q[n]) \cdot \frac{1}{N} \left( \frac{N}{2} \left| b_q[n] \right| + 1 \right) & N=4M \\
\text{sign}(b_q[n]) \cdot \frac{2}{N} \left( \frac{N}{2} \left| b_q[n] \right| + 1 \right) & N=4M+2 
\end{cases} \tag{5}
\]

When \( k \) is even, \( y_i[n]=0 \), \( y_q[n]=0 \), and the output of the quadrature differential PWM has no even harmonics.

2.2 Quadrature upconversion to digital carrier

The frequency upconversion is done in digital domain. As the carrier frequency is \( f_c \), the frequency \( f_p \) of the reference triangle wave should equal to \( f_c \). The fundamental expression can be got from formula (2) and (3) and listed as below:

\[
y_{\text{fund},i}[n] = -\frac{4 \sin(k \pi b_{i}[n])}{N \sin(k \pi/N)} \cdot \cos\left(\frac{2\pi k n}{N}\right) \tag{6}
\]

\[
y_{\text{fund},q}[n] = \frac{4 \sin(k \pi b_{q}[n])}{N \sin(k \pi/N)} \cdot \sin\left(\frac{2\pi k (n - N/4)}{N}\right) \tag{7}
\]

From formula (6) and (7), we can say that the quadrature frequency upconversion to a digital carrier is achieved by utilizing harmonic nature of the PWM output. The transmitter can sum \( y_{\text{fund},i}[n] \) and \( y_{\text{fund},q}[n] \) as the output, and the other harmonics can be filtered by the tunable filter.

2.3 Nonlinear distortion compensation of PWM

The analysis of equation (6) and equation (7) shows that the distortion of \( y_{\text{fund},i}[n] \) comes from two aspects. The output of \( b_{i}[n] \), \( b_{q}[n] \) is the uniform quantization of input signals \( b_i[n] \) and \( b_q[n] \), and the \( y_{\text{fund},i}[n] \) and \( y_{\text{fund},q}[n] \) is nonlinear to \( b_{i}[n] \) and \( b_{q}[n] \). Aiming at the above two distortion sources, this paper adopts the structure of DSM combined with digital predistortion (DPD) [7,8] to achieve the suppression of PWM noise and spectrum aliasing. The DSM module quantizes the baseband signal, and the DPD module performs nonlinear compensation. Due to the nature of nonlinearity in (6) and (7), it is clear that normalized inverse sine function should be used in the DPD block, with the corresponding transfer function described as:

\[
b(n) = -\frac{1}{\pi} \arcsin(a[n]) \tag{8}
\]
When the baseband signal $I[n]$ and $Q[n]$ is pre-processed by DSM and DPD module, the quantization noise suppression and nonlinear distortion compensation will be completed, the final output of the transmitter can be expressed as formula (9).

$$y_{\text{PP}}[n] = \frac{4}{N \sin(\pi/N)} \left[ I[n] \cos\left(\frac{2\pi}{N} n\right) + Q[n] \sin\left(\frac{2\pi}{N} n\right) \right]$$  \hspace{1cm} (9)

3. Simulation and experiment

In order to evaluate performance of the proposed ADTx based on three-level quadrature differential PWM, simulation and experiments have been carried out. Performance of the system is simulated and measured in terms of achieved ACPR, in-band and out-band noise, coding efficiency (CE), spectrum and constellation of the transmitter output pulse sequence.

3.1 Simulation

We take the complex modulation signal as the input to simulate the signal processing flow of the transmitter, and verify the performance of the transmitter. The transmitter adopts second-order DSM module and three-level differential PWM, and takes QPSK and 16QAM signals with carrier frequency of 360MHz, symbol rate of 5Mps and peak to average ratio (PAPR) of 3.9dB and 5.8dB as input for matlab simulation.

![Fig. 3 ADTx transmitter performance of QPSK and 16QAM with different N values](image)

Fig.3 shows the performance comparison of QPSK and 16QAM transmitters with different N values. As shown in Fig. 3(a), with the increase of N, the quantization level of DSM increases, the in-band noise and out-band of the modulated signal decreases, and the ACPR decreases. The output ACPR curve of the transmitter is basically consistent with that of I and Q DSM, and the output ACPR of DSM is slightly higher than that of transmitter. It shows that the noise shaping performance of DSM determines the in-band noise and signal quality of the transmitter, which is consistent with the theory.

As the out-band noise of DSM is higher than that of in-band, and the out-band noise directly affects the design of the subsequent filter of the transmitter, the in-band noise of 10MHz offset carrier frequency and out-band noise of 100MHz offset carrier frequency is simulated and shown in Fig. 3(b). As shown in Fig. 3(b), the noise curves of QPSK signal and 16QAM signal basically coincide, the output noise of transmitter decreases with the increase of N, and the out-band noise is 25 dB higher than that of the in-band noise, it means that the out-band suppression ratio of filter should be at least 25 dB.

![Fig. 3](image)

Fig. 3(c) shows the output coding efficiency of DSM (I and Q) and ADTx transmitter changes with N. When N increases to a certain value, the coding efficiency of DSM approaches 100%, but the coding efficiency of ADTx transmitter decreases to a certain value (QPSK is about 70% and 16QAM is about 65%).

As shown in formulas (2) and (3), the PWM process produces a large number of harmonic components, which makes the ratio of fundamental signal power to the whole output pulse power decrease, resulting in the decrease of the output coding efficiency of the ADTx transmitter. However, due to the use of differential PWM to eliminate even harmonics, the output coding efficiency of the
transmitter is still more than 65%. As shown in Fig. 3(c), when the value of N is large enough, the output coding efficiency of 16QAM signal is stable at about 70%, and QPSK is about 5 percentage points higher than that of 16QAM signal, which is stable at about 65%.

3.2 Off-line experiment and results

According to the MATLAB simulation, in order to improve the coding efficiency and signal-to-noise ratio of the transmitter, and reduce the out band noise level, the system needs a higher sampling frequency. At present, it is difficult for the general digital signal processor to realize such a high-speed real-time calculation. Therefore, the off-line experiments of the proposed ADTx output characteristics of 16QAM signals are carried out [7] using the arbitrary waveform generator AWG7122C.

The signal processing flow of ADTx is realized by MATLAB. The output pulse sequence of transmitter is calculated by MATLAB software and downloaded to AWG7122C, its length is 120us large enough to ensure the basic signal measurement and analysis, then the output pulse (output signal amplitude is 0.5V) of AWG7122C is finally measured by vector signal analyzer N9030A.

Fig. 4 shows the measured spectrum and constellation of the transmitter output of 16QAM when N=12, f_s=4.32GHz, f_c=360MHz. Fig.4 (a) shows that there is no spectrum aliasing in the output. Through three-level differential PWM, the even harmonic suppression of the output signal is greater than 45dB in Fig. 4 (a). It can be seen and calculated from in Fig. 4 (b) that the ACPR of 16QAM signal is -48.4dBc, and the noise density at 10MHz away from carrier frequency is -122.9 dBm/Hz. In order to further verify the output signal quality of the transmitter, N9030A is adopted to measure and analyse the output signal. As shown in Fig. 4 (c), the EVM of 16QAM signals is 1.07%, and the signal quality is good.
4. CONCLUSION

In this paper, an ADTx based on 3-level quadrature differential PWM is proposed. By using triangle wave with 90° phase shift as the reference signal of quadrature differential PWM, the pulse coding of complex modulation signal and digital up-conversion will be realized. DSM and DPD are adopted to quantize the baseband signal and compensate the nonlinearity, so as to suppress the noise and spectrum aliasing of PWM. Simulation and experiment results show that the proposed transmitter can accomplish the quadrature modulation of complex signals, suppress the in-band noise and spectrum aliasing, eliminate even harmonics. Further work will focus on improving the coding efficiency and third harmonic suppression ratio.

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REFERENCES

[1] Raab F. H. (1973) Radio Frequency Pulse Width Modulation, IEEE Transactions on Communications, 21(8): 958-966.
[2] H. Enzinger, C. Vogel. (2014) Analytical Description of Multilevel Carrier-based PWM of Arbitrary Bounded Input Signals, Proc. 2014 Int. Symp. Circuits Syst., Melbourne VIC: pp.1030-1033.
[3] O. Tanovic, R. Ma, and K. H. Teo. (2017) Theoretical Bounds on Time-Domain Resolution of Multilevel Carrier-Based Digital PWM Signals Used in All-Digital Transmitters. IEEE 60th International Midwest Symposium on Circuits and Systems. Boston, MA: pp.1146-1149.
[4] S. Santi, R. Rovatti, G. Setti. (2004) Spectral Aliasing Effects of PWM Signals with Time-Quantized Switching Instants. 2004 IEEE International Symposium on Circuits and Systems, Vancouver: pp.689-692.
[5] K. Hausmair, S. Chi, P. Singerl, C. Vogel. (2013) Aliasing-Free Digital Pulse-Width Modulation for Burst-Mode RF Transmitters. IEEE Transaction Circuits and Systems- I: Regular Papers,60(2):415-427.
[6] O.Tanovic, R.Ma, K.H.Teo. (2017) Optimal Delta-Sigma Modulation Based Noise Shaping for Truly Aliasing-Free Digital PWM.2017 48th European Microwave Conference, Nuremberg: pp.1-4.
[7] O.Tanovic, R.Ma, K.H.Teo. (2017) Simultaneous Power Encoding and Upconversion for All-Digital Transmitters Using Digital PWM. Proceedings of 2017 Asia Pacific Microwave Conference: pp.837-840.
[8] J.Keyzer, J.Hinrichs, A.Metzger, M.Iwamoto, I.Galton, P.Asbeck. (2001) Digital Generation of RF Signals for Wireless Communications with Band-Pass Delta-Sigma Modulation. Microwave Symposium Digest, IEEE MTT-S International 3: pp.2127-2130.