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# A 5-level RF-PWM method with third and fifth harmonic elimination for all-digital transmitters

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## Abstract

To relax the requirement of the filter and reduce the control complexity of the SMPA, this paper proposes a 5-level RF-PWM method for all-digital transmitters with 3rd and 5th harmonic elimination. The method is achieved by changing the threshold signal to control the pulse width of the 3-level sub-pulses. Finally, the feasibility of the method is verified by simulation. For the 16QAM signal with a carrier frequency of 200MHz, the proposed method can achieve -46.24dBc and -54.05dBc respectively when the coding efficiency reaches 77.51%.

# A 5-level RF-PWM method with third and fifth harmonic elimination for all-digital transmitters

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To relax the requirement of the filter and reduce the control complexity of the SMPA, this paper proposes a 5-level RF-PWM method for all-digital transmitters with 3rd and 5th harmonic elimination. The method is achieved by changing the threshold signal to control the pulse width of the 3-level sub-pulses. Finally, the feasibility of the method is verified by simulation. For the 16QAM signal with a carrier frequency of 200MHz, the proposed method can achieve -46.24dBc and -54.05dBc respectively when the coding efficiency reaches 77.51%.

*Introduction:* All-digital transmitter [1-3] (ADTx) has flexible reconfigurability and programmability and meets the demand of software-defined radio (SDR) technology which implements most of the functions in the digital domain. However, the broadband requirement of SDR is a pressing issue in the engineering implementation of ADTx.

RF-PWM [4] is one of the most suitable pulse coding algorithms [5] for ADTx, but its implementation still has challenges. Plenty of high-order harmonics in the RF-PWM output pulse not only place high demands on the tuning filter but also require the modulator and SMPA to have the ability to handle wideband signals.

To improve coding efficiency and dynamic range, the multilevel RF-PWM scheme [6] is proposed to reduce quantization noise and harmonic distortion by increasing the number of quantization levels but still needs a high Q filter to suppress harmonics. Theoretically, the increase of quantization levels improves the coding efficiency and dynamic range and reduces harmonic distortion. However, it will increase the control complexity of the SMPA. Considering the control complexity of SMPA and the demand of performance, the 5-level scheme is a good compromise [7]. To eliminate harmonic components and relax output filtering requirements, a 5-level RF-PWM method with 3rd harmonic elimination is proposed [8]. The method enhances output filter bandwidth by eliminating the 3rd harmonic but has limited effect. Therefore, eliminating the 3rd and 5th harmonics simultaneously can significantly improve the output filter bandwidth.

In this paper, a 5-level RF-PWM method for broadband ADTx is proposed. The method achieves the 3rd and 5th harmonic cancellation of 5-level RF-PWM by controlling the pulse width and the center position of the 3rd-level sub-pulses the generation of the 5-level RF-PWM signal by changing the threshold signals. Compared with existing RF-PWM methods, the method proposed in this paper can achieve simultaneous elimination of the 3rd and 5th harmonics, relax the requirement for output filters, and improve the broadband performance of ADTx.

*The 3rd and 5th harmonics elimination by waveform control:* The multilevel RF-PWM signal can be obtained by the linear superposition of multiple 3-level pulses [11]. The normalized 3-level pulse signal waveform $q(t)$ with an arbitrary period of $T_c$ and a pulse width of $W$ is shown in Figure 1 where $w_c$=$2\pi/T_c$ is the angular frequency, and $t_0$ is the pulse center position. $(2m+1)$ level RF-PWM signal can be obtained by linear superposition of $m$ 3-level sub-pulse signals $q_n(t)$ ($n$=1, 2, ..., $m$), expressed as:

$$p(t)=\frac{1}{m}\sum_{n=1}^{m}\sum_{k=1}^{+\infty}\frac{4\sin\left(\pi k d_n\right)}{\pi k}\cos\left[k w_c\left(t-t_n\right)\right] \quad (1)$$

where $k$ is a positive odd number, $d_n$=$W_n/T_c$ is the duty cycle of the $n$-th 3-level sub-pulse, and $t_n$ is the pulse center position of the $n$-th 3-level sub-pulse.

By changing the duty cycle $d_n$ and the center position $t_n$ of the 3-level sub-pulse signal $q_n(t)$, the fundamental component of the multi-level RF-PWM signal $p(t)$ can be proportional to the input RF signal $S_{\text{in}}(t)$=$a(t)\cos[w_c t-\varphi(t)]$ and the 3rd and 5th harmonic components are cancelled. The pulse parameters satisfy the equation as follows:

$$\begin{cases}\frac{1}{m}\sum_{n=1}^{m}\varepsilon_n\sin\left(\pi d_n\right)\cos\left[w_c\left(t-t_n\right)\right]=c\pi a(t)\cos\left[w_c t-\varphi(t)\right]/4\\ \sum_{n=1}^{m}\varepsilon_n\sin\left(3\pi d_n\right)\cos\left[3w_c\left(t-t_n\right)\right]=0\\ \sum_{n=1}^{m}\varepsilon_n\sin\left(5\pi d_n\right)\cos\left[5w_c\left(t-t_n\right)\right]=0\end{cases} \quad (2)$$

where $\varepsilon_n$= ±1 is the weighting coefficient, the value is determined by the envelope amplitude $a(t)$ of the input signal, and $c$ is the gain of the modulator.

In order to simplify the solution of (2), this paper gives a simplified condition which assumes $m$=4, $t_0$=$\varphi(t)/w_c$, $d_1$=$d_3$, $d_2$=$d_4$, $t_1$=$t_0$+$\Delta t_1$, $t_3$=$t_0$-$\Delta t_1$, $t_2$=$t_0$+$\Delta t_2$, $t_4$=$t_0$-$\Delta t_2$. When $\Delta t_1$=$\Delta t_2$=$\Delta t$. Taking the maximum of the modulator gain $c$ to solve (2), four 3-level sub-pulse parameter combinations can be obtained and shown in Table 1. The four parameter combinations can generate two different waveforms. The output waveforms of combinations 1 and 3 are denoted as WI; the output waveforms of combinations 2 and 4 are denoted as WII.

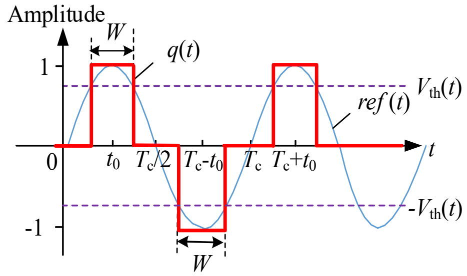


**Fig 1** *Diagram of any 3-level pulse with threshold comparison*

*Table 1. Parameter groups of 3-level pulses when $\Delta t_1=\Delta t_2$.*

| Parameters of sub-pulses | Simplified conditions | Parameter combination *i* 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Pulse position | $t_1=t_2$ | $\varphi(t)/w_c+T_c/12$ | $\varphi(t)/w_c+T_c/12$ | $\varphi(t)/w_c+3T_c/20$ | $\varphi(t)/w_c+T_c/20$ |
| | $t_3=t_4$ | $\varphi(t)/w_c-T_c/12$ | $\varphi(t)/w_c-T_c/12$ | $\varphi(t)/w_c-3T_c/20$ | $\varphi(t)/w_c-T_c/20$ |
| Duty-cycle | $d_1=d_3$ | $1/5+\arccos(a(t))/\pi$ | $2/5+\arccos(a(t))/\pi$ | $1/3+\arccos(a(t))/\pi$ | $1/3+\arccos(a(t))/\pi$ |
| | $d_2=d_4$ | $1/5-\arccos(a(t))/\pi$ | $2/5-\arccos(a(t))/\pi$ | $1/3-\arccos(a(t))/\pi$ | $1/3-\arccos(a(t))/\pi$ |

*The 5-level RF-PWM method*: The change of the input signal amplitude $a(t)$ brings the change of the duty cycle of 3-level sub-pulses, so that the level number of the multi-level RF-PWM signal synthesized by the superposition of four 3-level pulse signals changes. According to the relationship between the pulse width and the pulse center position, the range of the normalized envelope amplitude $a(t)$ under different levels can be calculated.

In the four 3-level sub-pulse signals $q_1(t)$, $q_2(t)$, $q_3(t)$ and $q_4(t)$, the pulse width of $q_1(t)$ and $q_3(t)$ is $W_1=2\pi d_1$;. The pulse width of $q_2(t)$ and $q_4(t)$ is $W_2=2\pi d_2$, and $W_1>W_2$. From the superposition and position relationship of the 3-level sub-pulses, when $0<W_1\leq 2\Delta t$, the output signal is 3-level; when $(W_1+W_2)/2<2\Delta t\leq W_1$, the output signal is 5-level; when $W_2<2\Delta t\leq (W_1+W_2)/2$, the output signal is 7-level; when $2\Delta t<W_2$, the output signal is 9-level. The relationship between the output levels of the two waveforms and the envelope amplitude $a(t)$ is shown in Figure 3. As $a(t)$ increases, the level number of WI and WII gradually increases according to the changing trend of 3, 5, 7 to 9.

The 3-level sub-pulse $q_{ij}(t)$ that meets any combination of pulse parameters in Table 1 can be generated by threshold comparison. After the input signal is normalized, two different reference signals $ref_1(t)$ and $ref_2(t)$ are obtained according to the pulse center position. The pulse width is determined by the intersection of threshold $V_{th}(t)$ with $ref(t)$. When $|ref(t)|\leq V_{th}(t)$, $q_{ij}(t)=0$; when $ref(t)>V_{th}(t)$, $q_{ij}(t)=1$; when $ref(t)<-V_{th}(t)$, $q_{ij}(t)=-1$.

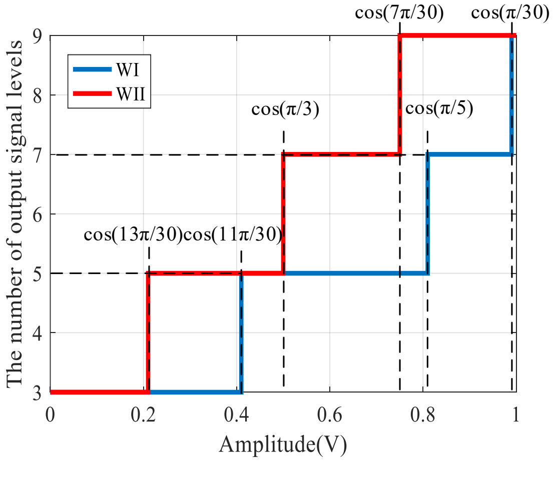


**Fig 2** *Diagram of the relationship between the number of levels and a(t) under WI and WII*

Taking parameter combination 1 as an example, the threshold signal and reference signal can be expressed as follows:

$$\begin{cases} V_{th1}=\sin\left[3\pi/10-\arccos\left(a(t)\right)\right] \\ V_{th2}=\sin\left[3\pi/10+\arccos\left(a(t)\right)\right] \\ ref_1(t)=\sin\left[w_c t-\varphi(t)-\pi/6\right] \\ ref_2(t)=\sin\left[w_c t-\varphi(t)+\pi/6\right] \end{cases} \tag{3}$$

In order to simplify the output signal from 9 levels to 5 levels, the envelope amplitude $a(t)$ of the normalized signal can be controlled. Thus, the output signal of different levels can be obtained. However, the signal envelope needs to be preprocessed which complicate the modulator structure. In this paper, by changing the expression of the threshold signal, the coefficient $l$ is added before $a(t)$ in (3), and the threshold signal is expressed as:

$$\begin{cases} V'_{th1}=\sin\left[3\pi/10-\arccos\left(la(t)\right)\right] \\ V'_{th2}=\sin\left[3\pi/10+\arccos\left(la(t)\right)\right] \end{cases} \tag{4}$$

where $l$ is denoted as the attenuation coefficient. For the normalized amplitude of envelope $a(t)$, the level number of the output signal can be simplified from 9 to 5 by controlling the value of $l$.

As shown in Figure 2, when the output signal is 5-level, the adjustable range of the amplitude of WI is larger, so WI is used as the output waveform of the 5-level RF-PWM signal, and the range of $l$ is $\cos(11\pi/30)\leq l<\cos(\pi/5)$.

The method proposed in this paper can adjust the level of the output signal by changing the expression of the threshold signal, which is equivalent to controlling the amplitude of the envelope. Meanwhile, the threshold signal can be obtained through the look-up-table method which is easier to realize the adjustment of the threshold. Considering the performance such as the coding efficiency of the output signal, the method takes the maximum value of $l$. Thus, a 5-level RF-PWM method for 3rd and 5th harmonic elimination can be obtained.

*Simulation results and analysis:* In order to verify the feasibility of the proposed scheme and analyze its influence on the performance, taking the single-tone signal and the complex modulation signal as the input signal, three methods are simulated. Among them, the 5-level RF-PWM method with a fixed threshold is denoted as SI, and the fixed threshold values are 0.1 and 0.3. The 5-level RF-PWM method of 3rd harmonic elimination based on adaptive threshold is denoted as SII and the proposed method is denoted as SIII.

A single-tone signal with a 200-MHz carrier is used as the input signal for the simulation of different schemes. The time domain waveforms of the output signal and the input RF signal of SIII are given in Figure. 3 which proves the generation of a 5-level RF-PWM signal. The effect of the input signal amplitude on coding efficiency for the three methods is given in Figure 4. The coding efficiency of SIII is significantly lower than the other two methods. The decrease of the pulse width brought by the attenuation coefficient in SIII makes the coding efficiency lower.

To analyze the main output performance of the proposed

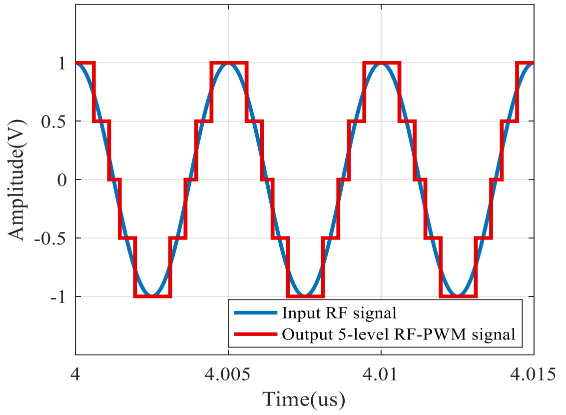


**Fig 3** *Waveform of the RF input and output signals at a 200-MHz carrier under SIII*

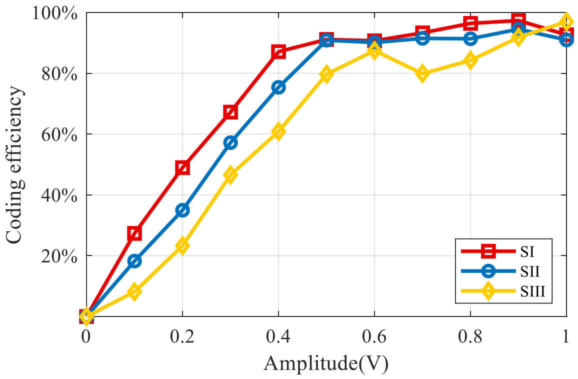


**Fig 4** *Coding efficiency of three methods under different amplitude*

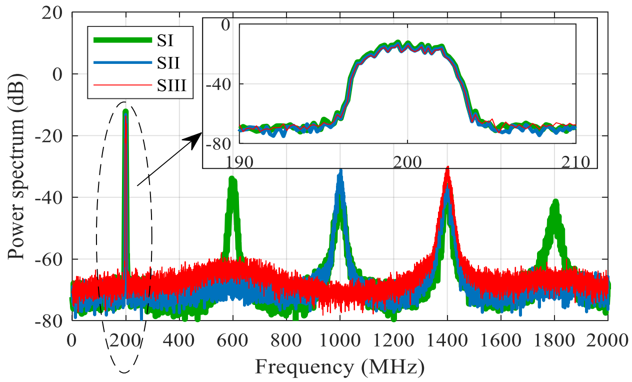


**Fig 5** *The spectrum of three methods with the 16QAM signal*

*Table 2. Performance of three methods under the 16QAM signal*

| Performance | SI | SII | SIII |
|---|---|---|---|
| Fundamental power (dB) | -6.45 | -7.41 | -7.97 |
| Coding Efficiency (%) | 89.95 | 85.69 | 77.51 |
| Third harmonic suppression(dBc) | -22.90 | -51.99 | -46.24 |
| Fifth harmonic suppression(dBc) | -25.60 | -18.43 | -54.05 |
| ACPR (dBc) | -50.27 | -50.44 | -47.87 |
| EVM (%) | 0.84 | 0.81 | 0.87 |

method under complex modulated signals with variable envelopes, a 16QAM signal with PAPR of 5.27 dB at a 200-MHz carrier is used as input. The spectrums of three methods are given in Figure 5. Compared with SI and SII, SIII achieves the 3rd and 5th harmonic cancellation and the performance comparison is given in Table 2. The coding efficiency of SIII is lower than those of SI and SII by about 9.5% and 13.8% while the 5th harmonic cancellation effect of SIII can reach about -54dBc. Finally, the ACPR of SIII is also reduced by about 3dBc Therefore, SIII has a better 3rd and 5th harmonic elimination effect with other performances than existing methods.

*Conclusion:* This paper proposes a 5-level RF-PWM method with 3rd and 5th harmonic cancellation. Based on the multilevel RF-PWM method with 3rd and 5th harmonic cancellation, the output signal is simplified from 9-level to the 5-level by changing the expression of the threshold signal determined by the attenuation coefficient. For a 16QAM signal with a 200-MHz carrier and a 5.27-dB PAPR, the proposed method has a good 3rd and 5th harmonic suppression effect. Meanwhile, the coding efficiency and ACPR are reduced compared with existing methods. Therefore, this method is a compromise of the harmonic elimination and code efficiency.

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