Optimization of DSM Sampling Frequency and Interleaving Frequency for Bilevel Quadrature-Modulation EPWM Transmitter

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Abstract

We previously proposed a bilevel quadrature-modulation (QM) envelope-pulse-width-modulation (EPWM) transmitter using half a side of a trilevel EPWM architecture. However, the optimum relationship between the $\Delta\Sigma$ modulation (DSM) sampling frequency (f_s), the interleaving frequency (f_i) and the carrier frequency (f_c) for a bilevel QM EPWM transmitter has not been investigated. This paper presents this optimum relationship, with the error vector magnitude (EVM) and the coding efficiency (CE) as figures of merit (FOMs).

1. Introduction

A major part of the power consumption of mobile communication transmitters is consumed in power amplifiers (PAs). Therefore, PAs with linearity and high power efficiency are needed. To meet these requirements, the envelope pulse-width modulation (EPWM) technique [1]-[12] has been intensively investigated owing to its potential high power efficiency and linearity. Among the EPWM transmitter architectures the quadrature-modulation-type (QM) EPWM transmitter [2], [4]-[6], [8]-[12] is promising. First, QM EPWM enables a lower sampling rate for pulse-width modulators such as $\Delta\Sigma$ modulators (DSMs). In addition, the QM architecture is suitable for integration in a digital LSI because it does not include a complex phase modulator. Moreover, in principle it has superior quantum noise performance to a polar-modulation EPWM architecture [1], [3], [7], [9] which has nonlinearity in conversion from quadrature to polar coordinates [5].

In a QM EPWM architecture, a trilevel DSM is used to represent the “off” state which presents the burst RF signal from achieving high efficiency [9]-[10]. This architecture requires two PAs, one for positive pulses and one for negative pulses, with a combiner after the PAs [9]-[10]. The H-bridge configuration with a transformer as a com-

biner [7], [10] is a representative configuration for this method. However, in this configuration the chip area and power loss are large owing to the existence of a transformer [13] which must be connected with a single-ended device such as a microstrip antenna. To solve this problem, we previously proposed a bilevel QM EPWM transmitter using a half side of a trilevel QM EPWM architecture [11]-[12]. This transmitter can achieve high efficiency because the trilevel DSM used in the transmitter represents the “off” state which stops a burst RF signal [11]. In addition, this transmitter enables the bilevel operation of a PA and only one PA is needed [12]. Therefore, the chip area and power loss are small owing to the omission of the transformer necessary for combining positive and negative signals in a trilevel transmitter [12]. However, the optimum relationship between the DSM sampling frequency (f_s), the interleaving frequency (f_i) and the carrier frequency (f_c) for a bilevel QM EPWM transmitter has not been investigated [11]-[12]. This paper presents this optimum relationship, with the error vector magnitude (EVM) and the coding efficiency (CE) as figures of merit (FOMs).

2. Bilevel QM EPWM Transmitter

The architecture of the bilevel transmitter is shown in Fig. 1. This architecture is the positive part of the trilevel architecture shown in Ref. [12]. In addition, this trilevel transmitter is a simpler equivalent form of the transmitter that we proposed in Ref. [11]. Node A is the trilevel DSM I-channel positive output. Node B is an f_c cosine clock (CLK). Node C is the I-channel U/C positive output. Node D is an f_i sine CLK. Node E is the f_c interleaving output. Node F is the RF output. The “negative” and “positive” logical outputs from the DSM are up-converted up to f_c with MUX 1 and MUX 2. As a result, in-phase and quadrature-phase carries exist in the I- and Q-channels, respectively. MUX 3 operates as an interleaver that outputs, I- and Q-channel signals alternately. After that, the RF signal is outputted in only the carrier frequency band by a band-pass filter (BPF).

3. Optimum Relationship between f_s, f_i and f_c

Up-conversion (U/C) mixes the output pulses from the DSM with the f_c cosine or minus sine CLK as shown in Fig. 1. In addition, the interleaver acts as a mixer for the up-converted signal. Therefore, the waveform and spectrum of the RF signal is affected by the operation of the U/C and the interleaver. To output the RF signal properly it is necessary to properly determine the DSM sampling frequency (f_s), the interleaving frequency (f_i) and the carrier frequency (f_c). The optimum relation between f_s, f_i and f_c can be represented as follows:

(I) Relation between f_s and f_c :

$$f_s = 2^m f_c \quad (m = 0, \pm 1, \pm 2, \dots) \quad (1)$$

$$f_s \leq f_c \quad (2)$$

(II) Relation between f_i and f_c :

$$f_i = 2^n f_c \quad (n = 0, \pm 1, \pm 2, \dots) \quad (3)$$

$$f_i \leq 2f_c \text{ and } f_i \neq f_c \quad (4)$$

(III) Relation between f_i and f_s :

$$f_i \geq f_s \quad (5)$$

When Eqs. (1)-(5) are satisfied, the signal is accurately demodulated. In addition, CE is the maximum when $f_i = 2f_c$ is satisfied. The reasons for this are described in Sects. 3.1-3.3.

3.1 Relationship between f_s and f_c

Figures 2 and 3 show the waveforms at nodes A, B and C in Fig. 1, where (a) and (b) show good and bad patterns respectively. As shown in Figs. 2 and 3, it is necessary for f_s and f_c to satisfy Eqs. (1) and (2).

3.2 Relationship between f_i and f_c

First, it is necessary for f_i and f_c to satisfy Eq. (3) for the same reason as for (1). Secondly, it is necessary for f_i and f_c to satisfy (4). The reason is shown in Figs. 4 and 5. Figure 4 shows the constellation of the demodulated signal for the bilevel QM EPWM transmitter for QPSK as an example. The condition for proper demodulation is $f_i \leq 2f_c$. Figure 5 shows the spectra at nodes C and E in Fig. 1. The up-converted spurious component by the interleaver interferes with the RF signal when $f_i = f_c$. Therefore, the condition for proper demodulation is $f_i \neq f_c$. The CE is maximum when $f_i \neq 2f_c$ as shown in Sect. 5.

3.3 Relationship between f_i and f_s

It is necessary for f_i and f_s to satisfy (5), which shows the waveforms at nodes A, D and F in Fig. 1. The reason for which is shown in Fig. 6.

Figure 1: Bilevel QM EPWM transmitter: Node A is the trilevel I-channel DSM positive output. Node B is an f_c cosine CLK. Node C is the I-channel U/C positive output. Node D is an f_i sine CLK. Node E is the interleaving output. Node F is the RF output.

Figure 2: The waveforms at nodes A, B and C in Fig. 1: (a) $f_s = 2^m f_c$ ($m=0$) (Good case: Node C has equal-interval pulses. This is also the case for $m=0, \pm 1, \pm 2, \dots$). (b) $f_s \neq 2^m f_c$ (Bad case: node C has unequal-interval pulses. Therefore, the EVM degrades owing to unnecessary harmonics.).

Figure 3: Waveforms at nodes A, B and C in Fig. 1: (a) $f_s = f_c$ (Good case: node C is up-converted to carriers that are represented by a cosine clock. This is also the case for $f_s < f_c$). (b) $f_s = 2f_c$ (Bad case: the latter part of the pulses of the cosine clock vanishes at node C. Therefore, it is impossible to demodulate the signal properly. This is also the case for $f_s > 2f_c$.).

4. Simulation Method

Using MATLAB/Simulink (Mathworks, Inc.), a sequence of 16-QAM baseband (BB) signals is generated and separated into I- and Q-channels [9], [12]. Next, a root roll-off filter is used to perform up-sampling and frequency band limitation of the signal. After that, the signal is modulated by the EPWM part to generate an RF burst signal. The EPWM signal is outputted in only the carrier frequency band by the BPF. Finally, quadrature detection is performed. After the down-sampling and band limitation with the root roll-off filter, the BB signal is demodulated. Table 1 shows the simulation parameters used in the MATLAB simulation.

The evaluation for this transmitter is performed with the EVM and CE as FOMs as given by (6) and (7).

$$EVM = \frac{R. M. S. \text{ for Error Vector}}{R. M. S. \text{ for True Vector}} \quad (6)$$

$$CE = \frac{\text{Desired Signal Power}}{\text{Overall Power for All Band Frequencies}} \quad (7)$$

5. Simulation Results

Figure 7 shows the EVM and CE dependences on f_i/f_c for f_s of $0.5f_c$ to $4f_c$ obtained by computer simulation with MATLAB/Simulink.

5.1 EVM

For all f_s , the EVM is significantly degraded when $f_i/f_c \geq 4$. This is the reason that the I- and Q-channel phases are advanced and delayed by $\pi/8$ rad, respectively, owing to the mixing by the interleaver for $f_i \geq 4f_c$. Therefore, it is necessary to satisfy $f_i \leq 2f_c$. In addition, EVM also degrades when $f_i < f_s$ because part of the RF signal vanishes. The EVM also degrades when $f_s \geq 2f_c$ and $f_i/f_c = 1$. In the case of $f_s \geq 2f_c$, the pulses of f_c cosine or sine clocks vanish when the DSM output is up-converted to f_c that are represented with f_c cosine and sine clocks. In the case of $f_i/f_c = 1$, the up-converted spurious component interferes with the RF signal at around f_c . Therefore, it is impossible to demodulate the signal properly in this case. As a result, the minimum EVM is about -44 dB in the cases of $f_s = 0.5f_c, f_c$ and $f_i = 2f_c$.

5.2 CE

When $f_i \geq 4f_c$, the interleaver chops the f_c cosine or sine clocks and produces unnecessary noise. Therefore, the CE is degraded because the noise increases as f_i becomes large in this case. For this reason, the CE reaches a maxi-

um value of about 28% when $f_i = 2f_c$.

Figure 4: Constellation of the demodulated signal for the bilevel QM EPWM transmitter for QPSK as an example: The interleaver acts as a mixer between the I/Q-channel carriers and the interleaving clock. (a) $f_i = 2f_c$ (Good case: the constellation is a square shape owing to the orthogonality between the I- and Q-channels. This is also the case for $f_i < 2f_c$). (b) $f_i = 4f_c$ (Bad case: the I- and Q-channels phase are advanced and delayed by $\pi/8$ rad, respectively, owing to the mixing by the interleaver. Therefore, the constellation becomes a diamond shape. This is also the case for $f_i > 4f_c$).

Figure 5: Spectra at nodes C and E: The spurious component around DC is up-converted in the interleaver output spectrum. (a) $f_i = 0.5f_c$ (Good case: the up-converted spurious component does not interfere with the RF signal at around f_c . This is also the case for $f_i = 2f_c$). (b) $f_i = f_c$ (Bad case: the up-converted spurious component interferes with the RF signal at around f_c . Therefore, it is impossible to demodulate the signal properly.).

6. Conclusions

This paper presented the optimum relationship between the DSM sampling frequency (f_s), the interleaving frequency (f_i) and the carrier frequency (f_c), with the EVM and CE as FOMs, for a bilevel QM EPWM transmitter using half a side of a trilevel EPWM architecture. To accurately demodulate the signal for this transmitter, the im-

Figure 6: Waveforms at nodes A, D and F in Fig. 1: (a) $f_i = f_s$ (Good case: RF signal is correctly output for patterns 1 and 2. This is also the case for $f_i > f_s$.) (b) $f_i = 0.5f_s$ (Bad case: RF signal vanishes for pattern 2. Therefore, the baseband signal cannot be demodulated properly. This is also the case for $f_i < 0.5f_s$.)

part of mixing by the U/C and the interleaver must be considered. Therefore, it is necessary to satisfy $f_s = 2^m f_c$ ($m=0, \pm 1, \pm 2, \dots$), $f_s \leq f_c$, $f_i = 2^n f_c$ ($n=0, \pm 1, \pm 2, \dots$), $f_s \leq f_i \leq 2f_c$ and $f_i \neq f_c$. In addition, the CE is maximum when $f_i = 2f_c$. This is because the noise due to the chopping of carrier clocks by the interleaver is decreased. A computer simulation with MATLAB/Simulink was performed. As a result, the EVM and CE were about -44 dB and 28%, respectively, for $f_s = 0.5f_c, f_c$ and $f_i = 2f_c$.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP15K06086. Part of this work was carried out with the aid of the Telecommunications Advancement Foundation. This work was supported by VLSI Design and Education Center (VDEC), the University of Tokyo, in collaboration with Agilent Technologies Japan, Ltd.

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Table 1: MATLAB simulation parameters

Modulation		16-QAM
Symbol rate (f_{sym})		10 Msymbol/s
No. of data symbols		1000 symbols
Roll-off filter	Type	Root raised cosine
	Roll-off factor (α)	0.7
	Length of impulse response	16
	Up sampling factor	f_s / f_{sym}
$\Delta\Sigma$ modulator (DSM)	Order	2
	Over sampling ratio	50, 100, 200, 400
	Sampling frequency (f_s)	$0.5f_c, f_c, 2f_c, 4f_c$
	Carrier frequency (f_c)	1 GHz
Interleaving frequency (f_i)		$0.5f_c, f_c, 2f_c, 4f_c, 8f_c$
BPF	Order	4
	Type	Butterworth
	Center frequency	f_c
	Bandwidth	$0.5f_c$
	Quality factor (Q)	2

Figure 7: EVM and CE dependences on f_i/f_c for f_s of $0.5f_c$ to $4f_c$

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