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Abstract

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Recent Advances in Power Encoding and GaN Switching Technologies for Digital Transmitters

(Invited Paper)

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***Abstract*- Green and flexible digital transmitter is envisioned as the evolving trend for future cellular base station, which is required to operate with multi-standard and multi-band radio signals. To energy efficiently amplify the spectrum-efficient modulated signals with high peak-to-average power ratio (PAPR>10 dB) is challenging. Compared with traditional analog solutions using Doherty Power Amplifier (DPA) or Envelope Tracking (ET), switch-mode digital power amplifier (e.g. class-S PA) in digital transmitter is offering good agility as well as theoretically 100% efficiency thanks to its unique operation principles.**

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***Index Terms*—Digital Transmitter, GaN, Power Encoding, Class-S**

I. INTRODUCTION

Digital transmitter is known for its flexible operation through software reconfiguration with minimum hardware change, which is very promising to transmit complex radio signals for 4G LTE-Advanced and future 5G wireless communications [1]. For instance, inter-band carrier aggregation (CA) requires simultaneous transmission of dual bands or more RF signals, which could be apart from each other with frequency spacing >1 GHz. Traditional analog transmitter would need separate radio block (e.g. RF power amplifier) for each RF band, or relying on less efficient / low performance wideband solutions.

Moreover, RF signals with high dynamic envelope (>10 dB PAPR) result in power amplifiers operating at largely backed-off power level with significantly dropped energy efficiency Different from conventional Doherty or Envelope Tracking (ET) efficiency enhancement techniques, class-S digital switch-mode power amplifier is efficiently (ideally 100% efficiency) operating at either ON or OFF status (similar to class-D/D^{-1}, no overlap between current and voltage), and its input signal is a high speed (~ several Gbps) digital-RF bit train, regardless envelope amplitude of original signal [2]. This is attributed to power encoder. It generates single bit or multi-bit digital signal via encoding the original base band I/Q signals or RF signals, using various algorithms including pulse-width modulation (PWM), delta-sigma modulation (DSM), and pulse position modulation (PPM). The switching amplifier stage then simply amplifies the input signal's amplitude, and its output is restored to analog signal by means of band-pass filter.

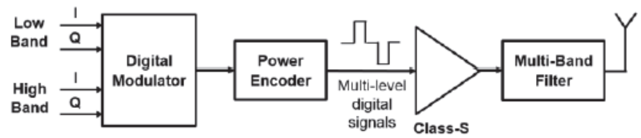


Figure 1. Digital transmitter architecture for concurrent dual-band transmission.

Fig. 1 shows a typical system diagram of all-digital transmitter for transmitting a low-band and high-band signals as in inter-band CA case. In this case, a multi-level encoded digital signal is provided at the input of class-S PA, in which GaN HEMT (high electron mobile transistor) can be excellent candidate for RF power applications. This paper will discuss the importance and challenges of power coding functionalities of digital transmitter in section II; advances on recent GaN switching technologies will be reviewed in section III. At the end, future research directions on digital transmitter will be summarized.

II. POWER ENCODING

Power encoding plays a central role affecting the whole system distortion (ACPR and EVM), power efficiency of the digital transmitter. Its basic function is to provide the optimal switching control signal at the input of the switching amplifier stage, and usually is connected with the driver stage before final switching stage. In practice, power encoder block can be implemented using ASIC (Application-specific Integrated Circuits) or with FPGA (Field Programmable Gate Array).

To date, DSM is the main power encoding technique for class-S PA in the reported works, with the key advantages of very good signal to noise ratio (SNR) due to high over sampling ratio and noise shaping function. And, it is also inherently a linear transformation [3]. However, it usually has very low power coding efficiency (below 20%) for modulated signals, caused by large amount of out-of-band noise from quantization and noise-shaping thus limiting the switch-mode PA and overall TX efficiency [3]. Power coding efficiency is defined by the ratio of in-band desired signal power over the total spectrum signal power.

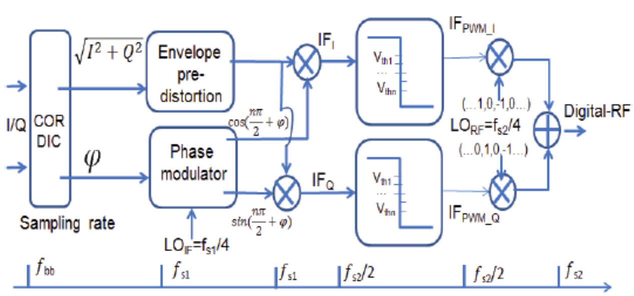
Another major scheme is pulse width modulation (PWM) with higher power coding efficiency [4]. However, to perform PWM at cellular bands would require extremely high sampling speed (>20x RF carrier frequencies) for accurate oversampling. Although this can be done using specially designed PWM modulator RFIC operating in continuous-time (analog) domain, it is not suitable for all-digital transmitter applications because of the inflexibility.

Recently, several advanced power coding algorithms have been proposed and verified with industrial LTE signal.

A. ML-IF-PWM

Zhu *et al.* proposed a new power coding scheme called ML-IFPWM (multi-level intermediate frequency pulse width modulation) in 2014 as shown in Fig. 2 [5].

Instead of performing the PWM at RF carrier frequency, it introduces the discrete-time power encoding process at an IF of around 60MHz for RF carrier of 2GHz. The most advantage features is that it lower the required sampling rate more than 10 times compared to RFPWM. In addition, a linearizer is designed using look up table to minimize the nonlinear effect of PWM. The authors demonstrated the measured power coding efficiency more than 70% using a 5-level IFPWM for 20MHz LTE signal for single band transmission, implemented using commercial available FPGA.



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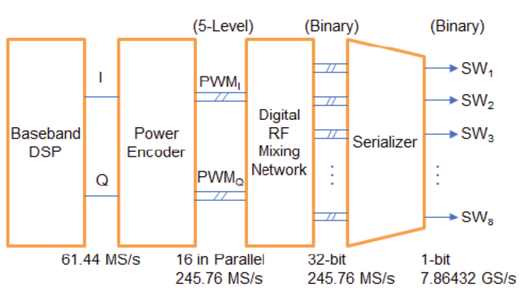

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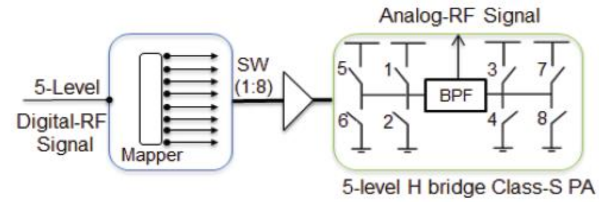


(c)

Figure 2. (a) Multi-level discrete-time IFPWM power encoding diagram, (b) All-digital transmitter FPGA implementation for generating the switching signal for multi-level class-S, and (c) FPGA control and topology of 5-level class-S PA [5].

B. MDPC

Chung et al. proposed a MDPC (multidimensional power coding) very recently [6]. It is very difficult to transmit multi-band signals in digital transmitter due to the very challenging power encoding requirement and limitation of single power encoding scheme. MDPC leverages the advantages of PWM, DSM as well as outphasing concepts and improve the performance of multi-band applications.

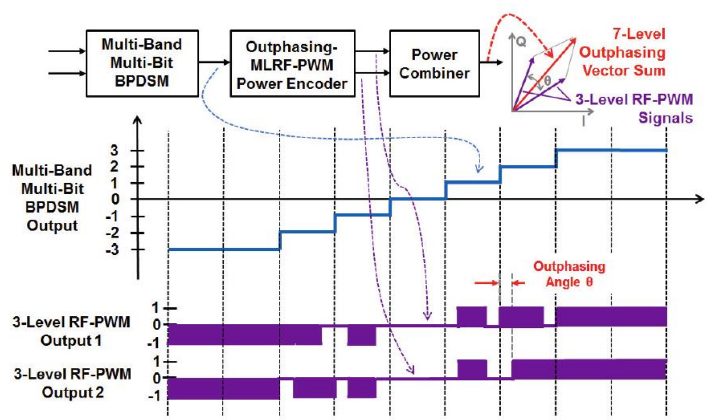


Figure 3. Power encoder for outphasing two 3-level RF PWM singals that are mapped from a 7-level BPDSM signal [6].

As depicted in Fig. 3, it shows an example operation of a two-dimensional power encoder, which transforms the single-stream 7-level BPDSM output signals into dual-stream 3-level PWM outphasing multi-level RF PWM singals. Discrete outphasing is applied to each pulse, so that power combiner can recover the original 7-level BPDSM output signals. The actual number of output levels can be determined on performance requirements on linearity and out-of-band emission. And the sampling rate of the power encoder determines the minimum outphasing angles (resolution). A higher sampling rate allows a larger number of BPDSM output levels can be transformed into multi-level RFPWM. A measured high power encoding efficiency approximately 47%

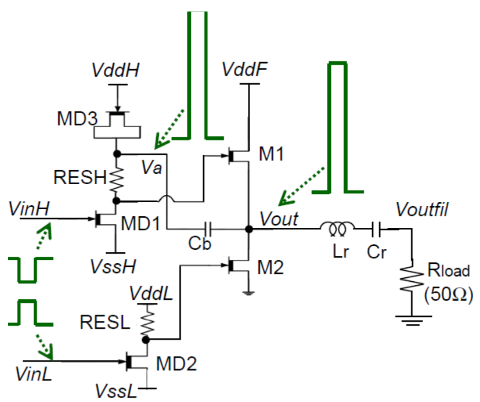
is reported for transmitting 856MHz and 1450MHz LTE signal concurrently with ACPR better than -43dBc for both bands.

III. GaN Switching Technologies

GaN HEMT has been demonstrated as ideal wide band gap III-V device technology for class-S high speed switch-mode high power application on the basis of its high power density, high switching speed and high breakdown voltage, in contrast to CMOS is showing excellent performance for lower power level application.

In recent years, VMCD (voltage-mode class-D) has been demonstrated and compared for GHz class-S applications with relative simple architecture, whereas CMCD (current-mode class-D) requires more sophisticated external circuitry (Balun).

However, it is notorious that driving the upper switching transistor of the final stage in VMCD is very challenging (requiring input voltage in the range of 30~50V swing) due to the lack of p-type of GaN HMET so far. This has significant impact on the line-up efficiency. Recently, Nakamizo *et al.* has demonstrated the VMCD with bootstrap drive topology with 0.25µm gate length GaN HEMT [7]. Fig. 4 shows the circuit schematic and chip. Drain efficiency of 77.2% and PAE of 66.6% with Pout of 3.3W is reported at 465 MHz.



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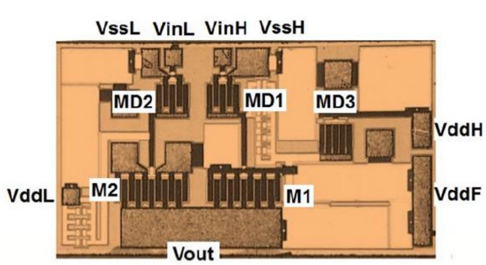

(b)

Figure 4. (a) Circuit schematic of proposed VMCD power amplifier, and (b) photograph of GaN MMIC chip; chip size is 1.63mm x 0.905mm [7].

IV. Summary and Outlook

All-digital transmitter is showing the exciting progress towards truly software defined radio as key enabling technology. Power encoding and switching amplifier stages are two fundamental pillar blocks for digital TX from architecture and hardware implementation point of view. There remain significant challenges to be solved including developing advanced power encoding schemes, in particular, to enhance system linearity considering the distortion and memory effect of switching-stage, as well as further improved the power encoding efficiency for multi-radio. It is expected integrated solution such as SoC (system on chip) with possibly heterogeneous integration of Si (for signal processing) and GaN (for power amplification) on the basis of novel circuit architecture with improved semiconductor process [8].

Acknowledgment

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